Exploring the Growth Potential of Deep Tech and Other Emerging Technologies in Slovenia

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EXPLORING THE GROWTH POTENTIAL OF DEEP TECH AND OTHER EMERGING TECHNOLOGIES IN SLOVENIA

Editors

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Published by

Časnik Finance, d. o. o.

Ljubljana, November 2025

CIP - Kataložni zapis o publikaciji
Narodna in univerzitetna knjižnica, Ljubljana
330.341.1(497.4)(082)
EXPLORING the growth potential of deep tech and other emerging technologies in Slovenia / editors Polona Domadenik Muren, Matjaž Koman, Tjaša Redek. - 1st printing. - Ljubljana : Časnik Finance, 2025
ISBN 978-961-6541-66-4
COBISS.SI-ID 253969923

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PREFACE

The book **"Exploring the Growth Potential of Deep Tech and Other Emerging Technologies in Slovenia"** is the outcome of a year-long research effort undertaken by a multidisciplinary team of academics and practitioners. The project was carried out by a group of researchers from the University of Ljubljana, School of Economics and Business as well as other experts - Andreja Cirman, Barbara Čater, Tomaž Čater, Zhonghui Ding, Polona Domadenik Muren, Eva Erjavec, Daša Farčnik, Aleksander Gerbec, Jurij Giacomelli, Matjaž Koman, Hana Končan, Mitja Kovač, Klara Ljubi, Denis Marinšek, Slaven Mičković, Tamara Pavasović Trošt, Tjaša Redek and Peter Trkman — together with the students of the 32nd generation of the International Master Programme in Business and Organisation (IMB) and two students from ISCTE - University Institute of Lisbon, Portugal. Their analytical contributions and systematic approach significantly shaped the findings presented in this publication.

We would like to express our sincere appreciation to more than fifty executives and experts from Slovenian companies and institutions active in the fields of deep and high technologies. Their participation in interviews conducted in August and September 2025 provided relevant empirical insights regarding the development of innovation ecosystems in selected industries in Slovenia. The information shared by these stakeholders contributed to a more accurate assessment of the technological, organisational and regulatory conditions associated with emerging technologies in a volatile economic context.

The research team acknowledges the financial support, based on the contract between University of Ljubljana and Slovenian Research and Innovation Agency (ARIS), for the project *"Quantum technologies for transportation and communications in the 21st century – KTTK21"* (no. SN-ZRD/22-27/0510), and *"Advanced Climate-Resilient Solutions for Sustainable Bio-Economy and Socio-economic development"* (no. SN-ZRD/22-27/0510), Slovenian Research and Innovation Agency (ARIS) grants O7-50185 *"Uvajanje prebojnih tehnologij v slovenskih podjetjih: Izzivi in priložnosti"*, V5-24020 *"Analiza pomanjkanja kadrov za potrebe slovenskega gospodarstva in družbe: Kadri za visoko-produktivno, inovativno gospodarstvo in dvojni prehod v digitalno iz zeleno družbo"* and P5-0128 *"Izzivi vključujočega in trajnostnega razvoja v prevladujoči paradigmi ekonomskih in poslovnih znanosti"*.

A heartfelt thank you goes to Meta Česnik for her precise and thorough proofreading, to Ciril Hrovatin for his technical editing and design expertise, and to Jera Jakše for her creative work on the cover design. We also acknowledge the technical support provided by Rishabh Kumar Raikwar and Eva Erjavec. Particular recognition is due to Jasna Špende from Časnik Finance, whose continuous involvement from the early stages of production substantially facilitated the technical preparation of this book. Her timely coordination and operational support significantly contributed to the efficiency of the publication process.

Ljubljana, November 2025

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EXPLORING THE GROWTH POTENTIAL OF DEEP TECH AND OTHER EMERGING TECHNOLOGIES IN SLOVENIA

1 Introduction

Deep tech ecosystems are foundational for catalysing new industries, economic growth, and addressing societal challenges, such as sustainability and ageing. Understanding their dynamics is crucial for fostering innovation, especially in regions aiming to become leaders in emerging technologies (Peña & Jenik, 2023). Deep tech ecosystems are shaped by the interplay of resources, actors, and supportive environments that enable the transition from scientific discovery to market-ready solutions. Successful deep tech ventures often emerge from robust innovation ecosystems that provide tailored support, including specialised accelerators, venture builders, and public-private partnerships (Kask & Linton, 2023; Romme et al., 2023). Due to the fact that breakthroughs rarely happen without massive public interventions, it is reasonable to expect that the state could focus on how the created value is distributed, supporting both growth and contributing to societal well-being, while minimising the impact on inequality (Piketty & Cantante, 2018).

Well-functioning economic policy today actively supports key factors of successful business and innovative ecosystems. Many European efforts to strengthen Europe's capacity in deep tech and other emerging technologies have been shaped by Silicon Valley as a benchmark (Baumann et al., 2018; Ester, 2017). However, while the USA has a strong internet platform economy largely based on software innovations, the EU has a rather manufacturing-oriented economy supported by universities and research institutions that excel in fields, such as new materials and hardware innovations (Romme, 2022; Romme et al., 2023); therefore, approaches should differ. Policies and strategies introduced to boost Europe's innovation capacity include programs for improving entrepreneurship education (Ndou et al., 2018), incentive schemes for entrepreneurship (Román et al., 2013), the creation of technology transfer offices (Baglieri et al., 2018), start-up studios (Baumann et al., 2018), and innovation intermediaries (De Silva et al., 2018). To date, these initiatives have had limited impact. Addressing Europe's unique challenge calls for long-term, coordinated actions involving a broad range of actors (Ferraro et al., 2015; Howard-Grenville et al., 2019) and hybrid models, such as public–private partnerships (Luo & Kaul, 2019).

This chapter provides an introduction to the book "Exploring the growth potential of deep tech and other emerging technologies in Slovenia," which examines the structure, dynamics, and future prospects of Slovenia's deep tech ecosystem in general, and bio-tech, green-tech and space-tech in particular. Through in-depth interviews with a range of stakeholders and detailed case studies, policy-relevant conclusions were developed and are presented throughout the book.

In this chapter, the concepts of ecosystem and deep tech business ventures are introduced, followed by an overview of key challenges based on technological, financial and collaborative risks faced by deep tech stakeholders. It concludes with a policy perspective.

2 An ecosystem perspective on deep tech innovation

Over the past two decades, the concept of "ecosystems" has gained widespread attention in strategy discourse, as scholars and practitioners seek to understand what drives exceptional value creation in complex, interdependent environments. Therefore, the term "ecosystem" has evolved to include a wide range of interpretations. A useful distinction can be drawn between two broad perspectives: (a) the ecosystem-as-affiliation view, which defines ecosystems as communities of interconnected actors linked through networks and platform memberships[1]; and (b) the ecosystem-as-structure view, which conceptualises ecosystems as organised configurations of activities centred around a shared

1 Business ecosystems are described as networks organised around a central "keystone" actor, comprising many loosely connected participants who rely on each other for mutual success (Iansiti & Levien, 2004; Autio & Thomas, 2014). The concept emphasises the breakdown of industry boundaries, growing interdependence, and the potential for symbiotic relationships, focusing on access and openness – measured through factors, such as the number of partners, network density, and centrality – and applies to broad contexts, such as the "Silicon Valley ecosystem" or the "Microsoft ecosystem." Strategic emphasis is placed on increasing participants to enhance centrality, bargaining power, and the potential for serendipitous value creation through network effects (Adner & Kapoor, 2016).

value proposition (Adner, 2016). It begins with a value proposition and seeks to identify the set of actors that need to interact for the proposition to come about (Adner, 2006, 2013; Adner & Feiler, 2016; Adner & Kapoor, 2010).

In order to evaluate the potential for a deep tech ecosystem in Slovenia Adner's ecosystem-as-structure offers a clear and operational framework for (i) understanding the system-level coordination challenges specifically attributed to deep tech innovation and commercialisation where innovation is rarely delivered by a single firm;[2] (ii) evaluating co-innovation and adoption risks that refer to the risks that complementary innovations are not ready and/or complementary actors (manufacturers, regulators, customers, infrastructure providers, etc.) are not aligned[3] (timing, incentives and capabilities); (iii) identifying ecosystem bottlenecks and pathways for coordination and sequencing that is crucial in the scaling phase; (iv) ecosystem mapping, helping deep tech ventures and policymakers identify where intervention is needed (e.g., in regulation, funding for co-innovation, or talent development); and (v) understanding why certain technologies stall despite technical readiness because the surrounding ecosystem is incomplete or misaligned.[4]

The slow and complex adoption of deep tech innovations could be understood by the concept of ecosystem substitution (Adner & Kapoor, 2016). Unlike traditional technologies that replace existing components within stable systems, deep tech often requires changes across an entire ecosystem, ranging from infrastructure and regulation to user capabilities and complementary technologies[5]. This systemic interdependence means that even highly advanced innovations may experience delays in adoption not due to technical shortcomings, but due to misaligned or underdeveloped complements. For deep tech ventures and policymakers, this highlights the importance of orchestrating ecosystem readiness alongside technological development to enable successful market entry and value realisation. It demands strategic efforts to mobilise, influence, or co-develop the ecosystem, including working with regulators, infrastructure providers, or other actors from the public sector. For policymakers, this reframing supports the case for targeted ecosystem development policies, rather than

2 For example, a quantum computing venture may depend on advances in materials science, hardware integration, algorithm design, regulatory certification, and education – each requiring coordination across institutional and industrial boundaries.

3 In deep tech ecosystems, misalignment can be fatal. For example, an advanced AI chip may fail if data standards are not in place, or if energy infrastructure cannot support its deployment.

4 This framing helps explain why deep tech ventures face longer development timelines and higher uncertainty. It also provides a lens for designing strategies to reduce risk through partnerships, staged development, or ecosystem orchestration (Adner & Kapoor, 2016).

5 Hydrogen fuel cells do not just need new vehicles but also an entirely new fuelling infrastructure, safety regulations, and maintenance standards (International Energy Agency, 2019).

just R&D funding[6] (Adner & Kapoor, 2016). The concept of ecosystem substitution also helps explain why some deep tech ventures succeed faster than others – not necessarily because of superior technology, but because they align better with existing systems or strategically reduce barriers to ecosystem substitution.

3 The concept and characteristics of deep tech

Deep tech is commonly defined in the academic literature as a set of new developments that combines knowledge from a number of new disciplines (Siota & Prats, 2021). In general, broadly, it can be further divided into several subcategories, based on its core science/engineering bases: (1) computing and information (AI, quantum, next-gen compute, advanced cryptography), (2) physical sciences and engineering (advanced materials/nano, photonics, robotics, advanced manufacturing, aerospace/space), (3) life sciences and bio-engineering (biotech/synbio, medtech/neurotech, agri-food), and (4) energy, climate and environment (greentech/climate tech: clean generation, storage/fuels, grids, industrial decarbonisation, carbon management, water/waste/circularity, sustainable mobility); boundaries blur across pillars (e.g., synbio for low-carbon materials).[7]

Although the term "deep tech" is often associated with Fourth Industrial Revolution technologies (advanced materials, artificial intelligence, big data, blockchain, drones and robotics), it is important to distinguish between companies that leverage existing digital technologies to enhance processes and gain a competitive edge (Urbinati et al., 2019) and those that, as defined by Chaturvedi (2015), the CEO of the venture capital firm Propel(x), are *"founded on a scientific discovery or meaningful engineering innovation"*. Most digital-enabled ventures have innovative business models but are based on pre-existing or existing technologies, while the deep tech companies create value by proposing novel technological solutions based on scientific technological discovery to address existing problems. The source of their competitive advantage is the use of deep technologies (AI, Big Data, robotics, quantum, etc.), rather than an innovative business model. Therefore, it is not surprising that most deep tech ventures originate from spin-offs of research institutions and collaborate closely with the research sector[8] (Scarrà & Piccaluga, 2020).

6 Adner's model explains why venture capital alone may not be sufficient for deep tech. If complementary innovations or infrastructure are missing, private investors may hesitate due to the perceived "delay" in returns. This supports the case for public-private partnerships, patient capital, and coordinated efforts to build out enabling ecosystems (Adner, 2016).

7 This division follows the categorization introduced by the European Institute of Innovation and Technology (2023).

8 As deep tech start-ups are usually founded by highly qualified entrepreneurs (PhDs or postgraduates), they could be related to concepts, such as scientific/academic entrepreneurship (Etzkowitz, 1998; Sapir & Oliver, 2016; Stuart & Ding, 2006) or knowledge-intensive entrepreneurship (Malerba & McKelvey, 2020; Fischer et al., 2016).

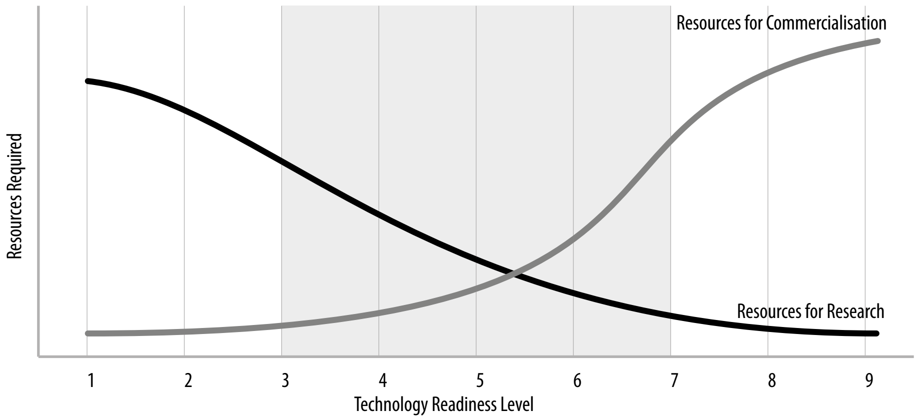
Deep tech ventures differ from other tech or digital ventures along four main characteristics: (i) they are built on scientific and engineering foundations rooted in breakthrough research or significant innovation, often emerging from university labs or research institutes (Siegel & Krishnan, 2020; Peña & Jenik, 2023; Romme et al., 2023); (ii) they tackle complex, interdisciplinary problems with the potential to evolve from near-impossible to widely adopted solutions (Siegel & Krishnan, 2020); (iii) they involve long development cycles that require substantial upfront investment and carry high technical and market risks before reaching commercialisation (Raff-Heinen & Murray, 2025; Kask & Linton, 2023; Pasupuleti, 2025); and (iv) they have a transformative impact by catalysing new industries, disrupting existing ones, and addressing major societal challenges, such as climate change, health, and economic development (Schutselaars et al., 2023; Raff-Heinen & Murray, 2025).

As a consequence, deep tech start-ups often rely on strong intellectual property (IP), making their innovations difficult to replicate and providing a sustainable competitive advantage (Reisdorfer-Leite et al., 2023), but they require specialised talent and significant capital, often more so than digital or business model innovation start-ups (Raff-Heinen & Murray, 2025; Peña & Jenik, 2023). The transition from lab to market is particularly challenging, as many ventures struggle to secure funding and navigate the "valley of death" (Barr et al., 2009; Ellwood et al., 2022; Romme et al., 2023), a concept that will be elaborated in the subsequent section.

4 Key challenges of deep tech business ventures

The concept of the "valley of death" from entrepreneurship development literature (Barr et al., 2009; Savaneviciene et al., 2015) provides a useful lens for examining the key challenges associated with deep tech innovation and entrepreneurship if compared with other innovative digital firms. The concept, which applies to entrepreneurship in general, can further highlight the significant risks to which deep tech ventures are exposed, reflecting their inherently high-risk yet potentially high-reward nature. While they pose substantial uncertainties for both entrepreneurs and investors, they also hold the potential to deliver considerable benefits. Figure 1, adapted from Romme (2022), depicts the valley of death, where the horizontal axis shows time-to-market via the Technology Readiness Level (TRL) scale and the vertical axis represents the resources needed for technology development and commercialisation. Typically, it spans TRL 2–3, with proof of concept or lab-scale prototypes, to TRL 7–8, when a prototype functions successfully in an industrial setting (Romme et al., 2023). For deep tech ventures, the valley of death tends to be both deep and prolonged, reflecting substantial resource requirements and an extended time-to-market. Investors often view such ventures as nascent and highly complex, frequently lacking a clear narrative and, therefore, suffering from limited understanding or even misperceptions (Portincaso et al., 2021).

Figure 1. Valley of death in deep tech firm



Source: Adapted by Romme (2022).

Deep tech venturing is considerably more challenging and risky than traditional ventures (as evidenced by their elevated failure rates[9]) due to three main factors (Barr et al., 2009; Ellwood et al., 2022; Romme et al., 2023): (i) **technological risk** from the extreme complexity of integrating advanced hardware and software, finding compatible existing technology architecture, making application and scaling difficult (De la Tour et al., 2017; Siegel & Krishnan, 2020; Perelmuter, 2021; Adner, 2016); (ii) **financial risk** due to a long time-to-market, often exceeding five to seven years, and the need for substantial capital – for example, literature mentions €10–20 million in the first round and potentially hundreds of millions later (Degeler, 2021); and (iii) **collaborative risk** from relying on a broad innovation ecosystem whose suppliers, distributors, and other partners must commit resources and co-develop components or services to deliver the venture's value proposition (Kapoor, 2018; Adner & Kapoor, 2010; Talmar et al., 2020; Walrave et al., 2018). Each of the three risks – technological, financial, and collaborative – can independently lead to

9 Although specific data for deep tech ventures are lacking, evidence from technology-driven ventures, showing failure rates of over 90 percent (Marmer et al., 2011) and around 80 percent (Song et al., 2008), suggests that deep tech ventures, as the riskiest segment, likely exceed a 90 percent failure rate (Romme et al., 2023).

the failure of a deep tech venture. Their strong interdependence means that an issue in one area, such as the loss of a key supplier or underperforming technology, can quickly escalate into other areas, creating persistently high overall risk levels (Romme et al., 2023).

Key challenges to deep tech business ventures are technology sourcing, attracting talent and acquiring financial resources.

4.1. Technology sourcing

Technology sourcing is a critical and complex challenge for deep tech industries, which rely on advanced, often novel, technologies to drive innovation and address grand societal challenges. The literature highlights several key barriers and considerations (Romme et al., 2023; Raff-Heinen & Murray, 2025).

Deep tech ventures often originate from breakthroughs in research institutes (e.g., European Council for Nuclear Research (CERN) and European Space Agency (ESA)). Sourcing these technologies requires not only identifying promising inventions but also building comprehensive support systems and robust ecosystems, including university-industry partnerships, government support, and specialised infrastructure (Romme et al., 2023). Deep tech ventures often face significant hurdles in integrating sourced technologies due to high complexity, technological distance, and incompatibility between knowledge bases. Asymmetric alliances, such as those between high-tech and low-tech firms, are particularly prone to difficulties in knowledge transfer, collaboration routines, and mismatches in innovation capability, which can delay or distort technology implementation (Simms & Frishammar, 2024).

Deep tech technologies (e.g., new materials, photonics and AI) are typically more complex, riskier, and require longer development cycles than conventional tech, which increases the difficulty of sourcing, as ventures must evaluate not just the technical fit but also regulatory, market, and ecosystem readiness (Raff-Heinen & Murray, 2025). Deep tech ventures benefit from structured frameworks that combine agile development, design thinking, and rigorous evaluation at each stage of technology transfer and commercialisation. These models help manage risk and ensure that only viable technologies progress (Kruachottikul et al., 2023).

4.2. Acquiring financial resources

Financing deep tech ventures is a widely debated topic, drawing on multiple research streams due to the high risks and long development cycles associated with these ventures. Early-stage deep tech firms can secure funding from both traditional and alternative sources, including public grants, subsidies, business angels, venture capitalists (VCs), and recent mechanisms, such as crowdfunding (White & Dumay, 2020; Bessière et al., 2020; Ibrahim & Isichei, 2023). Among these, VCs play a central role by bridging the gap between capital-rich investors and entrepreneurs with high-potential ideas but limited resources (Gompers & Lerner, 2001). They mitigate principal–agent problems through pre-investment screening, contractual design, and post-investment involvement, reducing adverse selection via rigorous opportunity evaluation and moral hazard through incentive alignment and active oversight (Kaplan & Strömberg, 2001). Beyond financing, VCs add value through strategic guidance, governance support, talent acquisition, and network access, acting as selectors, gatekeepers, and catalysts in the entrepreneurial ecosystem (Gompers et al., 2020).

Empirical evidence shows that VC firms are highly selective, screening around 200 opportunities annually but investing in only about four. They prioritise the quality of the management team over technology, business model, or market factors, even in deep tech contexts (Gompers et al., 2020). This approach implies that technical excellence must be paired with strong leadership and execution capabilities. Through sustained engagement, VCs shape industry trajectories, recycle talent and capital, and contribute to regional growth, making them pivotal in channelling high-risk capital efficiently (Fisher et al., 2016; Vossen & Ihl, 2020). However, traditional financial institutions often lack the expertise to assess deep tech ventures, making alternative finance channels, such as incubators, accelerators, technology transfer offices, and patent investment funds, critical for reducing risk, signalling credibility, and connecting start-ups to strategic partners (Collewaert & Manigart, 2016; Li et al., 2019; Gai et al., 2025).

Despite a growing number of funding options, deep tech start-ups face persistent challenges in convincing investors of their long-term viability. Effective signalling – via patents, founder investment, personal networks, or high-profile funding rounds – helps reduce information asymmetry and attract capital (Ciuchta et al., 2018; Davila et al., 2003). Yet high technological and market risks, intertwined with the difficulty of forecasting unit costs before a product is market-ready, make early-stage evaluations inherently uncertain (Portincaso et al., 2021). Often, costly prototype development must be financed before market disruption potential can be verified, increasing the "cost of learning". Nonetheless, evidence suggests that ventures backed by investors who foster a culture tolerant of failure tend to be more innovative[10].

4.3. Attracting talent

Attracting and retaining top talent is widely recognised as a critical success factor for deep tech ventures, given their reliance on specialised knowledge, innovation, and the ability to navigate complex technological and market challenges.

Deep tech ventures can attract highly skilled knowledge workers by (i) signalling credibility and future potential through ties with prominent venture capitalists and strong alliance networks, which reduce information asymmetry and enhance appeal to candidates (Zhang et al., 2020); (ii) leveraging communication and employer branding, as ventures that clearly convey the innovativeness of their products and whose founders display authentic, moderate passion are more likely to draw talented applicants (Piva & Stroe, 2022); and (iii) building comprehensive support systems that source talent from leading research institutes and integrate recruitment with technology sourcing, entrepreneurial finance, and ecosystem development (Romme et al., 2023).

In specialised fields, such as quantum technology, where talent shortages hinder commercialisation and scaling, start-ups rely on recruiting rare, highly skilled scientists and engineers to bridge the gap between research and market-ready solutions (Pasupuleti, 2025). Government policies and local innovation environments, including infrastructure, support services, and venture culture, also significantly influence the ability of deep tech ventures to attract and retain talent (Wang, 2021).

10 Biotechnology is a notable example of a deep tech industry that consistently attracts substantial venture capital investment (Nanda et al., 2015). One reason for this may be that biotech firms are able to generate and sell intermediate results from their experiments, providing early signals about a project's likelihood of success. Paul and others (2010) estimate that, while more than 24 drug candidates are typically needed in the initial discovery phase to achieve a single successful launch, the odds improve considerably once a drug enters the first clinical phase, with approximately one in nine candidates eventually reaching the market. Moreover, the scientific basis of these experiments is verifiable, and the presence of a robust patent system offers start-ups temporary monopoly rights over their innovations. These factors enable established firms to acquire promising drug candidates before they reach full commercial viability, making the sector particularly attractive to venture capitalists (Nanda et al., 2015).

5 Concluding remarks: The role of policymakers

Policymakers play a pivotal role in shaping and sustaining deep tech ecosystems, with research highlighting several mechanisms and best practices for fostering innovation, entrepreneurship, and long-term resilience. Effective ecosystems rely on a coordinated mix of policy instruments – funding, infrastructure, education, and regulatory measures – tailored to the needs of ventures at different stages and other stakeholders. As evidence shows, well-designed combinations are more impactful than isolated interventions (Wang et al., 2023).

Moving beyond traditional innovation systems focused on linear R&D and commercialisation, policy must enable dynamic innovation ecosystems by promoting cross-boundary collaboration, supporting bottom-up initiatives, and embedding sustainability and inclusivity in governance frameworks (Zheng et al., 2022). While many regions have strong knowledge ecosystems, connecting these to business ecosystems remains a challenge (Owen & Vedanthachari, 2022). Financial support must, therefore, be paired with measures that accelerate research translation, strengthen commercialisation pathways, and engage private sector actors. Although there are some positive outcomes supporting early-stage ventures, the main challenges remain in scaling finance, bridging the gap from research to commercialisation, and sustaining investor interest beyond the early stages.[11]

Because the effectiveness of interventions is highly context-dependent, policies should be adaptive to regional, sectoral, and maturity differences. Ecosystem orchestrators, such as policy-affiliated intermediaries and cluster agencies, should align public and private interests, building infrastructure, attracting talent, and fostering international collaboration.

11 A recent study examined the influence of the UK government policy on the development of the university entrepreneurial finance ecosystem for cleantech ventures by actively promoting cleantech as a priority sector, leveraging universities as key innovation hubs. Government interventions, through grants, competitions, and funding schemes, have been instrumental in supporting early-stage finance for cleantech start-ups, especially given their long development cycles and high capital requirements. Policies have encouraged collaboration among universities, investors, and industry partners; however, gaps remain in scaling finance, bridging the gap from research to commercialisation, and sustaining investor interest beyond the early stages (Owen & Vedanthachari, 2022). The study finds that while UK policies have successfully stimulated early-stage activity and strengthened networks, challenges persist in creating a fully integrated and sustainable cleantech finance ecosystem, particularly in addressing the "valley of death" between academic research and market-ready ventures.

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EVALUATING DEEP TECH ECOSYSTEM POTENTIAL IN SLOVENIA

1 Introduction

Deep technology refers to ventures built on scientific or engineering breakthroughs. It is characterised by long development cycles, high technological risk, and transformative industrial and societal potential (MIT REAP, 2022; European Commission, 2023c). Unlike "shallow tech," which focuses on business model innovations or incremental improvements, deep tech relies on mission-driven research and development (R&D), tangible products, and ecosystems that link universities, firms, and governments (Basilio et al., 2022; European Commission, 2023d). Core domains commonly identified in the literature include artificial intelligence, semiconductors, quantum technologies, photonics, robotics, clean energy, and biotechnology (de Apodaca et al., 2023).

For Europe, the challenge is not only producing excellent science but translating it into globally competitive firms. Among the world's largest firms by market capitalisation, only one, SAP, originates from Europe, while the United States and China dominate the rankings. Europe hosts a vibrant research community and early-stage ventures, but it lags the USA and China in later stages of the innovation cycle. From around technology readiness level (TRL) 6 onwards, projects increasingly depend on substantial private investments to progress toward market-ready scale-up (Dealroom, 2023). In the deep technology domain, however, this financing gap emerges even earlier, as technologies require significant patient capital for development before they can reach the scale-up phase.

Slovenia reflects these dynamics. Research excellence is visible in high publication rates, supported by European programmes, such as Horizon Europe, the EIC Accelerator, and EuroHPC JU, as well as national instruments, including the Slovenian Research and Innovation Agency (ARIS) and Strategic Research and Innovation Partnerships (SRIPs). Yet fragmented financing constrains firms from scaling and internationalising. Examples of promising ventures include Ecubes, SkyLab, Beyond Semiconductor, ReCatalys, Sunrise Robotics, Cosylab, Genialis, and AtomQL. These illustrate the breadth of activity but also the early-stage nature of many initiatives, not all of which emerged directly as research spin-offs.

The aim of this chapter is to evaluate Slovenia's emerging deep tech ecosystem. It addresses four questions: (i) which sectors and organisations can be identified as part of Slovenia's deep tech ecosystem; (ii) what are its main strengths and weaknesses; (iii) which barriers hinder the translation of science into scalable ventures; and (iv) which measures could enhance Slovenia's deep tech competitiveness. The analysis is based on a literature review and qualitative semi-structured interviews with deep tech stakeholders (firms, investors, universities, and institutions), complemented by secondary data. The chapter first outlines the deep tech industry in Europe, then situates Slovenia in the European context, and finally presents interview evidence before drawing policy implications.

2 Deep tech industry in Europe

Europe hosts world-class universities and research institutes, including Oxford, Cambridge, ETH Zurich, EPFL, and the Technical University of Munich, which rank among the top institutions producing high-value research and spin-outs (Dealroom, 2023). European firms also lead globally in sectors such as aerospace (Airbus), semiconductor lithography (ASML), and advanced manufacturing (Siemens) (OECD, 2024).

The European Commission has identified ten critical technology areas, including AI, quantum, semiconductors, biotech, robotics, advanced materials, and clean energy, as central to competitiveness and sovereignty (European Commission, 2023a). These priorities were reinforced in 2024 with the Net-Zero Industry Act (NZIA) and the Critical Raw Materials Act, adopted under the Green Deal Industrial Plan, which together provide the legislative foundation for strengthening Europe's deep tech sector (European Commission, 2023b). This reflects Europe's response to intensifying competition with the United States and China, both of which invest heavily in frontier domains.

Structural weaknesses. Despite its scientific strength, Europe struggles to scale disruptive innovation. R&D intensity has stagnated at 2.2 percent of GDP, compared to 3.5 percent in the US and 2.4 percent in China (Fuest et al., 2024). While Europe produces a high volume of publications, its ability to convert research into globally competitive firms remains weaker. Commercialisation is also limited: high-tech goods account for just 15 percent of EU exports, compared with nearly 30 percent in China (Dietrich et al., 2024). For Slovenia, the European Innovation Scoreboard 2025 data show average business R&D expenditures but markedly below-average non-R&D innovation spending (European Commission, 2024e). This may reflect a real weakness in non-R&D activity, although it could also be partly a measurement artefact caused by tax incentives that encourage firms to classify investments as R&D (OECD, n.d.).

Public support mechanisms. Policy instruments address different stages of the venture cycle: (i) early-stage R&D (Horizon Europe, Germany's SPRIND); (ii) start-up support (European Innovation Council, blending grants and equity); (iii) scale-up finance (European Tech Champions Initiative, pooling institutional resources); and (iv) strategic sovereignty measures (Important Projects of Common European Interest (IPCEI) frameworks, Chips Act, Net-Zero Industry Act (NZIA), Critical Raw Materials Act). Compared with the flexible Advanced Research Projects Agency (ARPA) model in the US or China's state-backed mega-funds, Europe's approach remains fragmented but is moving toward greater coordination (European Investment Bank, 2023; Azoulay et al., 2019).

A unique challenge. Europe has often benchmarked itself against Silicon Valley, but this is problematic. Whereas the US innovation model is software and platform-driven, Europe's strengths lie in hardware-intensive sectors, such as new materials, photonics, and advanced engineering (Romme, 2022). Crucially, these capabilities are rooted in **Europe's strong industrial tradition**, which provides a durable foundation for deep tech development (European Commission, 2023f). In Slovenia, this foundation is visible in a solid engineering base and globally competitive niche manufacturers, such as Kolektor (automotive), Dewesoft (space technology), and Pipistrel (aeronautics) (Vienna Institute for International Economic Studies, 2023). Leveraging this heritage requires long-term, multi-actor interventions, including public-private partnerships and hybrid governance models that combine state, market, and research actors to coordinate investment and innovation (Ferraro et al., 2015; Luo & Kaul, 2019).

Persistent barriers. Several challenges continue to constrain ecosystem development. The "middle-technology trap" keeps resources concentrated in mature sectors (Dietrich et al., 2024; Bergeaud, 2024). Deep tech ventures require significantly more patient capital than typical start-ups, yet late-stage funding is scarce, pushing many firms toward foreign investors (Hall & Lerner, 2010; Gompers et al., 2020). Bureaucracy and risk aversion in EU programmes contrast with the flexibility of US models (EconPol, 2024). Finally, human capital remains a bottleneck: annually, about 1.2 million STEM students graduate in the EU, compared to 5.8 million in China and 700,000 in the USA (European Commission, 2019g; Hanson, 2024; Chosun Ilbo, 2025). China and the USA are highlighted because they are Europe's main competitors in frontier technology. Beyond numbers, Europe also faces skill mismatches, especially shortages of entrepreneurial and managerial expertise needed to scale science-based ventures (Cao & Shi, 2021).

3 Deep tech industry in Slovenia

Slovenia is active across most EU-defined deep tech domains, although activity is concentrated in a few niche firms and spin-offs rather than broad clusters. Table 1 identifies the Slovenian stakeholder share in these domains. Most of these clusters, however, operate as parts of wider European or global networks rather than independent domestic clusters.

Most Slovenian deep tech firms are embedded in EU programmes and value chains. Horizon Europe and Eurostars projects connect start-ups and research institutes into international consortia focusing on AI, robotics, materials, and biotech (European Commission, 2023c). Infrastructure, such as the EuroHPC Vega supercomputer in Maribor, and participation in the European Space Agency further position Slovenia within pan-European initiatives (EuroHPC Joint Undertaking, 2021; SkyLabs, 2023). Companies like Elaphe have secured growth funding from EIT InnoEnergy, while biotech spin-offs frequently rely on EU collaborative grants (EIT InnoEnergy, 2020). EU membership and participation in these programmes provide a vital foundation in terms of resources, legitimacy, and market access that would otherwise be unattainable for a small economy. Yet this is only a necessary first step, not sufficient on its own: sustained national support and domestic financing are equally needed for ecosystem growth.

Slovenia's record in competitive EU instruments highlights these limits. In the first two years of the European Innovation Council (EIC) Accelerator, Slovenian start-ups obtained only €2.45 million in grants, among the lowest totals in the EU (Science|Business, 2023). This reflects both a relatively small number of applications and weaknesses in proposal preparation. By contrast, France secured about €350 million and Germany €420 million in the same period. Adjusted for GDP, Slovenia would have needed roughly €7–8 million to match France and Germany on a proportional basis, underscoring the depth of the gap. Overall, Slovenia leverages EU programmes as an essential framework for growth; however, underrepresentation in later-stage funding demonstrates the need to reinforce national commercialisation and financing mechanisms.

Table 1: Slovenia's presence across deep tech domains

Domain	Breakthrough focus	Firms & spin-outs (selected examples)	Main research institutions
Artificial intelligence	Applied AI for education, logistics, smart manufacturing	Qlector, OriginTrail, AstraAI, Orange	University of Ljubljana (FRI); University of Maribor (FERI)
Semiconductors & HPC	Processor IP design, HPC services, EuroHPC supercomputer	Beyond Semiconductor, Arctur	EuroHPC Vega (Maribor)
Quantum technologies	Neutral-atom quantum hardware, control systems	AtomQL, Cosylab	Jožef Stefan Institute (IJS)
Photonics	Advanced laser systems	Fotona, Optotek	University of Ljubljana (FE, FMF); Jožef Stefan Institute (IJS)
Robotics	Manufacturing robotics, foreign direct investment	Sunrise Robotics, Yaskawa	University of Ljubljana (FE, FRI); Jožef Stefan Institute (IJS); University of Maribor (FERI)
Clean energy	Electric aircraft, in-wheel motors	Pipistrel (Textron), Elaphe, Ecubes, ReCatalyst	University of Ljubljana (FS); University of Maribor (FS), National Institute for Chemistry (KI)
Space technologies	Nanosatellites, Earth-observation platforms	SkyLabs, Sinergise, Dewesoft	Space-related EU projects
Biotech & life sciences	Computational biology, bioprocessing; University spin-offs	Genialis, BIA Separations	National Institute of Biology (NIB); National Institute of Chemistry (KI); Jožef Stefan Institute (IJS); University of Ljubljana (BF, MF)
Advanced computing	Distributed computing, RISC-V for space	XLAB, SkyLabs	University of Ljubljana (FS, FE, FMF); Jožef Stefan Institute; University of Maribor (FERI)

Source: Dealroom (2025). Examples are illustrative, not exhaustive or ranked.

4 Empirical insights from selected deep tech companies and other stakeholders

4.1 Methodology

The research questions, developed through a combination of literature review, expert consultations, and industry discussions, called for an in-depth description and evaluation of the landscape, stakeholder opinions, and underlying reasoning. Consequently, a qualitative approach based on semi-structured in-depth interviews was selected. This method provides rich, nuanced data which uncover underlying issues which might not be captured through structured quantitative surveys (Corbin & Strauss, 2008). Interview topics were initially identified based on existing research and refined through feedback from academic and professional experts, ensuring relevance to both theoretical and practical perspectives.

Table 2. Key sample characteristics

Stakeholder	Ecosystem position	Industry	Size*	Role	Gender	Code
Institution 1	Univ./ TTO	Education/ Research	N/A	TTO Officer	Male	DEEP1
Institution 2	Incubator	Services	Small	Incubator Head	Male	DEEP2
Institution 3	Venture Capital	Finance	Small	Partner	Female	DEEP3
Company 1	Start-up/ Spin-out	R&D	Small	CEO	Male	DEEP4
Company 2	Software/ IT	IT	Medium	CEO	Male	DEEP5
Company 3	Start-up	R&D	Small	CEO	Male	DEEP6
Company 4	Software/ R&D	IT	Medium	CEO	Male	DEEP7
Institution 4	Univ. research project	Biotech	N/A	Project Lead	Male	DEEP8
Company 5	Start-up/ Spin-out	Pharma	Small	Founder	Male	DEEP9
Company 6	Start-up	IT	Small	CEO	Male	DEEP10
Company 7	Development bank	Finance	Large	Senior Executive	Male	DEEP11
Company 8	Start-up	Robotics	Small	CEO	Male	DEEP12
Institution 5	Venture Capital	Finance	Small	Managing Partner	Male	DEEP13

Notes: TTO = Technology Transfer Office; *Small company: 10–49 employees; Medium company: 50–249 employees; Large company: 250+ employees; N/A = Not applicable.

Source: Own work.

To generate insights into the Slovenian deep tech ecosystem, semi-structured interviews were conducted, designed around the core research questions. The interviews aimed not only to capture the ecosystem's dynamics but also to identify key challenges faced by stakeholders, explore opportunities for commercialisation and growth, and assess the implications for policy and ecosystem development. Data collection included 13 semi-structured interviews with stakeholders, including universities, technology transfer offices, incubators, venture capital funds, and start-ups. The interviews were conducted between August 20 and September 8, 2025, each lasting between 90 and 120 minutes. The respondents represented organisations of different sizes and sectors, from research-intensive spin-outs to financial institutions. Table 2 presents the key characteristics of the interviewed organisations and their representatives.

4.2 Universities and early-stage funding

In Slovenia, as in other countries, deep tech ventures typically originate within universities and public research institutes, where scientific work generates ideas with commercialisation potential. However, the transition from research to entrepreneurship remains limited. Universities are aware of the need to connect academic output with industry, yet mechanisms for such collaboration are still underdeveloped. *"Universities are very interested in working with companies, because companies are the ones who convey information about what makes sense to develop and how"* (DEEP1). Yet others stressed that collaboration alone is not enough if researchers remain only partly engaged. *"Slovenia lacks a system where top researchers can go all-in into entrepreneurship. Many remain advisors on a slide deck, but when it comes to execution, there are no hands"* (DEEP2).

The system of academic incentives and career progression further constrains commercialisation. Publications and habilitation progress are mandatory requirements for maintaining an academic position and advancing in rank. In this context, patents or spin-outs are often treated as distractions that can slow career progression. While there are options in place for researchers to temporarily suspend their employment, for example, by taking sabbatical leave to work at foreign universities, the key issue is not the formal type of leave but the practical constraints and limitations they face, such as the need for managerial approval, ensuring substitute arrangements, and maintaining continuity of work. These requirements make it difficult for researchers to engage in other activities, such as contributing to a spin-out company based on their research results. In the absence of more flexible arrangements, they remain unable to temporarily leave their institutions to develop start-ups derived from their own inventions. As a result, many remain in science despite promising business opportunities. *"Most researchers want to obtain a higher academic rank, and they achieve this by* *progressing through habilitations all the way to full professor, which is the end goal for the majority. Very few even consider starting a company"* (DEEP2). The ownership issue reinforces this hesitation: *"Universities demand too large a share of IP, which immediately scares off investors"* (DEEP9), discouraging those who might otherwise consider entrepreneurship.

Some initial incentives have emerged to encourage commercialisation. Since 2020, the University of Ljubljana (UL) Innovation Fund has allocated approximately €150,000 annually to early-stage projects, typically awarding €5,000 to €25,000 per team to develop technology and test market potential. While these grants provide a valuable first step, their scale is extremely modest in the context of deep tech, where resource needs are substantially higher. For systemic impact, such mechanisms would need to be expanded and supported at the national level. The contrast with leading ecosystems is striking; for example, Sweden's KTH Royal Institute of Technology operates an innovation fund that supports projects with over €3.5 million in total funding distributed annually (KTH Innovation, n.d.). This difference underlines the structural gap in resources available for scaling up Slovenian deep tech ventures.

4.3 Bridging science and financial resources

The gap between how researchers think and what investors expect remains substantial. A prototype developed in a controlled laboratory is seen as a breakthrough in academia, but for investors, what matters are customer interviews, potential buyers, and a credible business plan. Deep tech start-ups require patient capital, which many investors fail to recognise, as they expect faster returns typical of software-based ventures. Even Technology Readiness Levels (TRLs) are interpreted differently: *"We often get researchers who say, 'I am TRL 6,' and then venture capital comes in, looks at it from their own perspective, and says, 'This is closer to TRL 2 – there is not enough market validation yet'"* (DEEP 1). This illustrates a broader challenge: TRLs are not an objective measure, and their credibility depends on the perspective of the assessor – whether a researcher, investor, or policymaker – leading to frequent misalignment in expectations.

Some initiatives are trying to close this gap. Technology transfer offices (TTOs) run programs that bring scientists and entrepreneurs together, often in "matchmaking" formats where researchers pitch projects and entrepreneurs decide whether to collaborate (DEEP1). A small but growing community of enterprising researchers also meets regularly to exchange experiences and reduce the sense of isolation: *"We have a community of researchers who meet every few months... so that others feel they are not alone"* (DEEP2). Such networks provide psychological support and may gradually shift attitudes.

Even when ideas advance to the prototype stage, access to capital is a major bottleneck. Slovenia's deep tech ecosystem remains underfunded, with a particularly acute shortage of investment in the early stages. *"In general, there simply are not enough financial resources for start-ups in Slovenia. We have a few small funds, but there is no capital for the subsequent stages. Deep tech is specific because development cycles are longer and capital needs are larger"* (DEEP3). The most critical gap is the so-called "first million" needed for equipment, testing, and initial validation: *"Who will give you the first million for ideas like these? It does not exist"* (DEEP4). Without this support, many prototypes remain undeveloped, and researchers return to academic work. A stakeholder from the financial sector described this void as structural: *"For TRL 1–3 you can usually get grants, but stages 4–6 are no longer eligible for grants and still too early for private investors, which is exactly the gap we aimed to address"* (DEEP11). At the same time, some entrepreneurs argue that the bottleneck lies not in the funding itself but in the people who can attract it. *"There is more than enough money; what we lack are world-class entrepreneurs who can, with almost no money, identify a real problem and convince someone to invest millions"* (DEEP12).

This gap is particularly acute in the life sciences and biotech sectors, where development requires expensive trials and certifications. *"In the next year, to bring this to market, we will need around €40,000 just to cover regulatory requirements. Later, to establish production in Slovenia, we will also need about €1 million"* (DEEP8). This illustrates how even relatively modest sums can represent decisive hurdles, while larger capital needs remain out of reach without systemic support.

At the European level, investors emphasise that structural changes are necessary to maintain the viability of early-stage deep tech finance across smaller markets. As one interviewee put it: *"You need to mobilise on a grander scheme of things throughout Europe and that needs regulatory change... [and] take a very standardised European approach"* (DEEP13). This reinforces that national instruments alone are insufficient; cross-border integration and predictable rules are prerequisites for financing long-cycle ventures.

4.4 Infrastructure and intellectual property

Some research teams nevertheless manage to combine university-based research with spin-off development. A quantum technology start-up emphasised how the first substantial investment enabled them to purchase equipment. *"That investment, that million, went more or less entirely to equipment. The idea was not to build a quantum computer, as you would need €10-20 million for that, but with that initial million, we could take the first steps"* (DEEP4). This example underlines that deep tech is fundamentally different from the software industry, where products can be built with modest resources. Deep tech development depends on access to costly infrastructure and laboratory space, which are often lacking in Slovenia. *"There is basically no infrastructure here. If the university had 5,000 square meters of labs, they would fill at least three quarters of them"* (DEEP 10).

This distinction between deep tech and high tech has strategic implications for Slovenia. With limited domestic resources, it is unrealistic to expect a broad deep tech ecosystem. A more feasible approach is targeted support for certain niches within the broader domains of quantum, space, or biotechnology, which may attract less interest from global players. At the same time, Slovenia can be highly competitive in high-tech fields, where capital requirements are lower and returns are faster. The boundary between deep tech and high tech is not always sharp, but the differences in investment intensity and commercialisation timelines remain critical. External investors caution that building hubs also requires political will: *"It takes a dedicated, top-down approach from regional governments and universities to build functioning hubs; otherwise, you end up with a shell that could be filled with life but is not"* (DEEP13). *"In Croatia, the University of Zagreb and Ruđer Bošković Institute invested money together and built a biotechnology lab that start-ups can immediately use for experiments – for example, installing and operating their own bioreactors on site"* (DEEP2).

Intellectual property (IP) ownership further complicates commercialisation. For investors, company-owned patents are essential: *"Above all, you want the patent to be owned by the researcher, the potential entrepreneur. That is the only way they have freedom of action"* (DEEP4). In Slovenia, however, inventions legally belong to the employer (research institutions or firms). Investors and potential co-founders often expect public research organisations to give away their IP, disregarding the institutional and public resources behind it. *"They would probably not agree to such terms if they were in TTO roles, so we must meet somewhere in between. We share the same mission"* (DEEP1). Researchers may receive compensation, but negotiations are often ad hoc: universities defend their rights, investors insist on company ownership, and researchers try to secure favourable terms. This uncertainty weakens the confidence of all stakeholders. As the financial expert highlighted, even the valuation process slows deals: *"Universities must get an external IP valuation before transferring ownership. In Slovenia, there are only two licensed IP evaluators, and none can realistically assess biotech or deep tech projects"* (DEEP11).

"In principle, the TTO is interested in licensing. It is not in their interest for IP to sit unused on the shelf. The university itself is also motivated to have more spin-outs, since this is a new metric for evaluating performance" (DEEP8). This suggests that institutional incentives are gradually shifting in favour of commercialisation, even if negotiations remain complex.

However, founders emphasise that rhetoric and practice do not always align. *"Today, everyone officially supports entrepreneurship and start-ups, but in practice, there is still no real support; for example, even signing a necessary document often does not happen"* (DEEP9). This shows how the knowledge transfer process, while moving in the right direction, is still hampered by bureaucratic inertia, leaving founders frustrated in moments when swift action would be essential.

Given the constraints on equity participation, Slovenian universities often rely on licensing agreements to transfer knowledge. *"Through a licensing contract, yes, because we do not enter as a shareholder. The law would allow us to take an equity stake in a company, but in practice every such entry must be approved by the government"* (DEEP1). Income from licenses is divided, with typically 40 percent going to the researcher, 40 percent to the laboratory, and up to 20 percent to the university, which allocates it to IP protection costs, which creates some incentives to disclose inventions. For long-term ecosystem growth, licensing in Slovenia needs to evolve into more flexible collaboration models that provide stable funding streams for continued innovation. An interesting case to explore is Sweden's so-called Professor's Privilege, which grants researchers automatic ownership of their inventions (Uppsala University, 2025). This system simplifies commercialisation by removing the need for prolonged negotiations with universities and strengthens researcher motivation to engage in entrepreneurship.

4.5 The valley of death in Slovenia

Already during prototyping, the differences between Slovenia and more developed ecosystems become clear. *"A good practice example is Sweden – Stock-*

holm, the KTH University" (DEEP3). The valley of death represents the critical point where science meets capital. In science, recognition comes mainly from publications and citations, while investors value business models, growth, and market potential. In Slovenia, this transition is particularly difficult. *"Start-ups find initial interest, but there is no capital to support this area systematically. Austria, for instance, has five serious deep tech funds with assets of €250 million under management. Slovenia has €45 million at best"* (DEEP2). Slovenian funds lack both the expertise and the risk appetite needed for deep tech. *"On paper, everything is deep tech, but, in practice, they end up backing the safer projects"* (DEEP4). In highly regulated sectors, such as pharma, this fragility is compounded: *"You need a 'godfather' to bring your product to market. Without one, you can be blocked or bought out; sometimes a godfather is more important than ten million euros"* (DEEP10).

Bureaucratic hurdles and specific obstacles to foreign investment further add to the challenges faced by Slovenian start-ups. For example, American investors must prove the source of capital, which is often impractical when the investor is a fund registered abroad. In addition, a foreign investor must physically come to Slovenia to sign a notarial deed, even for small investments. These requirements discourage inflows of fresh capital. At the same time, there are advantages: opening a company in Slovenia is simple and inexpensive, with limited liability companies established within a week at relatively low cost (DEEP6).

Contracting with universities or public agencies often takes months, leaving young teams in uncertainty: *"The bureaucratic part is too slow – it takes several months to finalise and sign contracts"* (DEEP3). Such delays are particularly damaging in small ecosystems, where competitors abroad can move faster. Finally, entrepreneurs face legal and regulatory rigidities. Slovenia, like many continental European systems, follows a tradition of highly formalistic legal interpretation, where rules are applied rigidly with little room for pragmatic adjustment. While this may work in larger economies, in a two-million-person environment, it hinders flexibility and slows down entrepreneurial progress. *"I need someone who understands that I have human problems that are not black-and-white, but grey"* (DEEP5). Even when spin-offs do get started, financing is often inadequate: *"One case received around €300,000, while development costs were close to a million. That is a weak spin-off"* (DEEP11).

Seed funding illustrates the problem. *"Seed investments in Slovenia start at €50,000. That is nothing. They should start at €200,000"* (DEEP2). Founders often seek funding abroad, but foreign investors hesitate to engage in a small and little-known market. As a result, Slovenian start-ups frequently rely on EU programs, such as Horizon or the EIC, which offer larger sums but involve slow and complicated procedures (DEEP3).

4.6 Talent and human resources

Talent and human resources are widely seen as a critical bottleneck for the deep tech ecosystem. Stakeholders emphasise that Slovenia educates capable young researchers; however, the motivation and incentives for them to pursue entrepreneurship remain weak. Many top graduates leave for opportunities abroad: *"Who leads Google's AI? A European. Who leads OpenAI's AI? Two Europeans. Our best talent goes to America because the support is not here"* (DEEP2). The reasons extend beyond salaries to infrastructure, mentorship, and early investment. To address these gaps, some start-ups adopt a global recruitment model: *"We search for talent globally, like scouts in sports. The first interview always focuses on culture fit regardless of the role"* (DEEP12).

However, not all agree. Most stakeholders agreed that talent is available and the main constraint lies in infrastructure: *"In science, the biggest problem is equipment and infrastructure. I can find people to do the work"* (DEEP4). Investors, meanwhile, highlight the importance of strong ties with academia, which ensure that *"researchers have ongoing access to PhD students who may later join a company"* (DEEP4). More broadly, Slovenia lacks the flexibility of ecosystems where "revolving doors" allow researchers to move into business and later return to academia without career penalties. Building such mechanisms would strengthen both entrepreneurial capacity and academic renewal. Other firms stress the need to cultivate talent internally: *"We trained most of the people we work with today ourselves. They started as students or interns and stayed on"* (DEEP10).

Researchers also face the challenge of becoming entrepreneurs, often lacking the skills to pitch effectively: *"When they pitch, especially if they are true researchers, they do not know how to pitch"* (DEEP3). This is where support institutions matter. Venture capital funds, TTOs, and incubators not only provide limited financing but also help researchers translate scientific results into business terms, build networks, and prepare investor-ready projects. While useful, these programs remain too small to address the structural funding gap. *"The most critical period is between the prototype and clinical trials... and this is where most deep tech companies fail"* (DEEP9).

Finally, start-ups struggle with limited industry engagement. *"Industry has little involvement in university governance, which reflects the weakness of capital in Slovenia"* (DEEP5). In practice, only a small number of companies actively engage with universities on applied research or curriculum development. Even when interest exists, bureaucratic procedures, rigid governance, and misaligned incentives act as significant barriers. While basic research rightly remains the domain of universities and research institutes, applied research and curricula could involve industry more directly, ensuring alignment with the skills and knowledge future graduates will need. Regional comparisons underline the gap: in Serbia, universities in Niš and Belgrade maintain strong ties with IT companies, with joint study programs and collaboration producing visible results (University of Belgrade, n.d.).

4.7 Internationalisation and cultural barriers

For Slovenian start-ups, scaling typically requires integration into ecosystems abroad. *"If you are building a start-up, you have to be there to meet people and integrate into the ecosystem"* (DEEP6). "There" usually means Vienna, Berlin, Paris, Stockholm, or Silicon Valley. External investors highlight this structural limitation: *"You cannot put a €500 million early-stage deep tech fund into Slovenia because there simply are not enough targets. That is why cross-border thinking is essential"* (DEEP13).

Despite the challenges, some founders maintain global ambitions: *"The goal is to build, in ten years, a company that is relevant in Europe if not globally, leading in at least one segment of quantum technologies"* (DEEP4). Positive shifts are visible: *"Exits, such as Outfit7, created new investors who are reinvesting in the next generation of founders"* (DEEP6).

International success requires more than strong science. Especially in pharmaceuticals and biochemistry, marketing and sales often lag. *"If I had a €5 million investment, I would devote most of it to marketing and sales"* (DEEP7). Building a sales network and establishing a presence in foreign markets is decisive. At the same time, companies seek strategic partners who can open doors to the global market. *"It really helps if you have a partner who can introduce you to the right customers, but you still want to keep your independence"* (DEEP7).

To successfully enter foreign markets, Slovenian companies often rely on credible partners who can provide legitimacy and open doors. However, such partnerships also require careful balancing. *"Partnerships greatly facilitate entry into foreign markets if a trusted partner supports you. It is an important element. Yet we must always be careful not to become subordinate. Whenever we engage in strategic partnerships, we make sure to remain independent"* (DEEP7). This highlights the tension between dependence on global corporations and the need to preserve autonomy, which is essential for long-term innovative capacity.

Cultural differences also shape outcomes. Estonia, with 12 unicorns, shows how openness and entrepreneurial drive can build momentum. *"They opened up from the outset; we keep closing off"* (DEEP3). In Slovenia, negative public perception and even scepticism toward success persist: *"In Slovenia, people who succeed are looked at a bit askance: 'Oh, they must have done something shady"* (DEEP8). Yet this mindset can change by celebrating success as an achievement of the system rather than an exception. *"Slovenia could begin to create its own snowball effect, something that Estonia achieved after Skype but which Slovenia has yet to replicate"* (DEEP5). One entrepreneur added that this insularity is visible on a day-to-day basis: *"In Slovenia, we talk too little to each other. Everyone is cultivating their own small garden, especially among more introverted technical staff"* (DEEP10).

4.8 Opportunities and prospects

Despite many barriers, there are domains where Slovenia holds real potential for global reach. Pharmaceuticals and biotechnology stand out. *"Slovenia has everything needed to become a regional hub for biopharma companies. If the state and industry recognised the potential, the Ljubljana-Zagreb corridor could become a centre for all of Southeast Europe within the next five years"* (DEEP2). Establishing such a start-up centre could attract innovation from Central and Eastern Europe and enable the growth of additional biopharma firms.

Infrastructure is a pressing bottleneck. *"We have an enormous number of offices and coworking spaces if you want to do a software start-up. However, if you want to set up a bioreactor or a quantum system, your only options are a small garage or an entire industrial hall"* (DEEP2). In Germany, Fraunhofer institutes help spin-offs access modern infrastructure, development expertise, and a strong network that supports scaling tech ventures and bringing new technologies to market (Fraunhofer, 2024). Slovenia lacks such facilities, even though demand would be strong. *"We would quickly fill up a 5,000 square meter hall. We had potential tenants. We just needed the money to buy and equip it"* (DEEP2).

A key insight from stakeholder discussions is that Slovenia's current ecosystem is not yet ready for large venture funds to deploy tens of millions into single projects. As noted, *"at the moment that would not really be feasible; the ecosystem is not prepared. We do not have a built funnel of venture funds"* (DEEP2). To develop this infrastructure in the long term, a staged construction of the investment environment is needed: first, a broad base of pre-seed backers and small funds providing tens to hundreds of thousands; then funds in the several million range; and only later those with tens of millions. Building this funnel is a long-term process.

The role of changing attitudes towards state investment is crucial. Stakeholders emphasised the need to normalise failure: *"We need to stop, as taxpayers, saying 'Look, they invested a million there, why did it not work out?' Because not everything works out"* (DEEP4). Even more important is the state's signalling role. *"A foreign investment fund told us that if even the state does not believe in us, they will not invest either"* (DEEP4). Early public co-investment can provide credibility by signalling that due diligence has been carried out: *"If the state believes in you, new investors can come more easily, because someone has already checked that the thing works"* (DEEP4).

5 Conclusion

Slovenia has a strong scientific base, but structural weaknesses hinder breakthroughs and scaling. Universities and research institutes generate internationally competitive knowledge and engage in European projects. Yet, the translation from lab to market remains slow, constrained by limited risk capital, fragmented support, and a weak entrepreneurial culture.

Progress is nonetheless visible: spin-outs are emerging, investors are showing rising interest, and policymakers are recognising the importance of technological sovereignty. Building on its industrial tradition and research capacity, Slovenia can turn these signals into stronger ecosystem foundations. To advance, universities must streamline technology transfer, investors must adapt to long development cycles, and public agencies should reduce regulatory barriers while co-investing in strategic projects.

This study shows that Slovenia's ecosystem consists of universities, spin-outs, and innovative firms integrated into EU programmes, with a growing but limited investor base. Strengths lie in science, industrial tradition, and EU integration; weaknesses include financing, coordination, and entrepreneurial skills. Barriers include scarce patient capital, regulatory hurdles, and talent shortages. Policy measures should focus on niche specialisation, better technology transfer, and stronger financing mechanisms (Table 3).

Table 3. Summary of key empirical findings

Theme	Key findings
Universities and early-stage funding	• Deep tech originates mainly from universities and research institutes. • Academic incentives encourage publications but not patents and spin-outs. • UL Innovation Fund exists, but remains small-scale (about €150,000 per year; €5,000–25,000 per project); not sufficient to support deep tech ventures, especially compared with large-scale funds, such as KTH's in Sweden (about €80 million per year). • Seed tickets are undersized (about €50,000 vs. about €200,000 benchmark); reliance on Horizon/EIC grants.
Bridging science and capital	• Researchers and investors interpret TRL differently (academic vs. market readiness). • Sabbaticals support scholarly placements, not business engagement, hindering revolving doors between academia and industry. • Access to early-stage capital — often referred to as the "first million" for validation — continues to be a critical bottleneck for innovators. • Bureaucracy and legal literalism slow contracting and limit flexibility. • Support programs (TTO "matchmaking", researcher communities, incubators) help reduce isolation, but capacity is limited.
Infrastructure and intellectual property	• Deep tech requires heavy infrastructure and capital intensity. • In Slovenia, inventions belong to employer institutions, and ad hoc negotiations reduce investor interest. • Licensing is common, with a revenue split.
Talent and human resources	• Brain drain: leading researchers leave for the USA and global opportunities. • Divergent views: some say talent is the bottleneck; others cite infrastructure as a bigger issue. • Lack of "revolving doors": hard to move between academia and entrepreneurship. • Investors value strong university ties and a steady flow of PhD talent. • Industry has a limited role in applied research and curricula, weakening skill alignment.
Internationalisation and cultural barriers	• Scaling requires integration abroad (Vienna, Berlin, Paris, Silicon Valley). • Founders maintain global ambitions despite obstacles. • Marketing and sales are weak compared to a strong scientific base. • Firms balance independence with the need for global partners. • Negative public perception and scepticism toward success; Estonia's "snowball effect" is absent.
Opportunities and prospects	• Ljubljana-Zagreb biopharma corridor has high potential as a regional hub. • Infrastructure gaps persist, particularly the absence of mid-scale laboratories and pilot halls. • The venture-capital funnel is gradually maturing, from pre-seed to seed to larger funds, on a long-term horizon. • Normalising failure and positioning public/anchor investors as signalling co-investors can help attract foreign capital.

Notes: TRL = Technology Readiness Level; TTO = Technology Transfer Office; EIC = European Innovation Council.

Source: Own work.

Slovenia's opportunity lies in positioning itself as a complementary node in Europe's innovation map. By building on strengths while addressing systemic weaknesses, it can develop distinctive niches, avoid the middle-technology trap, and secure a more resilient role in the European deep tech economy.

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SPACE TECH IN A NUTSHELL: FIRM-LEVEL PERSPECTIVES ON THE DEVELOPMENT OF SLOVENIA'S SPACE ECOSYSTEM

1 Introduction

The global space economy represents the full range of *"space-related goods and services, both public and private, that (i) are used in space, or directly support those that do, (ii) require direct input from space to function, or directly support those that do, or (iii) are associated with studying space"* (Highfill et al., 2022, p.10). Over the last 15 years, it has shifted from a centralised, government-dominated sector to a dynamic commercial landscape driven by private enterprise and innovation. This evolution, often termed "New Space", is particularly prominent in the emerging deep tech ecosystem (Denis et al., 2020; Peeters, 2021). This chapter focuses on this intersection, defining deep tech in the context of space as foundational technologies, such as advanced materials and specialised electronics, which require significant R&D investment and long-term development cycles. The global market for this industry is estimated to be close to €400 billion. It is projected to reach €1 trillion by 2040, with a growth rate higher than the global GDP (Government of the Republic of Slovenia, 2023).

The Slovenian space sector, characterised by a dynamic mix of companies, research institutions, and dedicated support organisations, provides an excellent case study of this evolution. Alongside agile start-ups and SMEs specialising in high-tech products and services, the institutional infrastructure plays a central role. The Slovenian Space Office acts as a key public coordinator of national space activities and the interface with the European Space Agency (ESA). In parallel, the Defence Industry Cluster of Slovenia (GIZ-GOIS) brings together companies and other stakeholders active in the fields of defence, protection, and security. As an autonomous, non-profit industry association, GIZ-GOIS fosters cooperation with state authorities, facilitates networking, and promotes its members at home and abroad. Although its core mandate lies in the defence sector, several Slovenian space companies participate in its platforms, which provide visibility, links to international alliances, and opportunities for dual-use applications.

A key factor in the sector's recent growth has been robust institutional support, notably Slovenia's attainment of full ESA membership on 1 January 2025. This strategic move not only provides enhanced access to new programs but also funnels a majority of the country's contribution back into the domestic industry through the "geographical return" principle, offering a stable funding source, especially for SME with more focus in the space sector (Ministry of the Economy, Tourism and Sport, Republic of Slovenia, 2025a).

The goal of this chapter is to provide a firm-level perspective on the development of the Slovenian space ecosystem, highlighting its competitive advantages and future prospects. The chapter examines how Slovenian companies access markets, overcome financial and structural barriers, and interact with public institutions, such as the European Space Agency (ESA).

The chapter is structured as follows: first, an overview of the European and Slovenian space industries is provided. Next, the relevant literature on the structural challenges and trends within the "New Space" era is reviewed, followed by the empirical analysis based on the interview findings. Finally, the chapter concludes with a summary of key insights and recommendations for policymakers and industry stakeholders.

2 Overview of the space industry

2.1 European space industry

The development of Europe's space sector has been fundamentally shaped by geopolitical dynamics and strategic institutional evolution. Early initiatives in the Cold War era, such as the European Space Research Organisation (ESRO) and the European Launcher Development Organisation (ELDO), both established in 1964, were driven by the need for a unified European effort to compete with the United States and the Soviet Union. These two entities were eventually merged in 1975 to create the European Space Agency (ESA), providing a cohesive institutional framework for European space activities. The EU involvement, however, developed more slowly, gaining an explicit competence in space policy only with the Treaty of Lisbon in 2007. This institutional foundation has enabled Europe to become more competitive in launch services, scientific exploration, and Earth observation (European Space Agency, 2023). Today, the sector operates under the EU Space Programme 2021–2027, with a €14.88 billion budget dedicated to key projects, such as Galileo and Copernicus, and is preparing to harmonise regulations with the upcoming EU Space Act and the IRIS2 satellite constellation (European Commission, 2021).

This strong public-sector foundation has, in turn, facilitated a significant commercial transformation, leading to a focus on profitability and a sharing of risk among private organisations, resulting in the emergence of new business models and value chains (Baber & Ojala, 2024). The space industry is broadly divided into two main segments – upstream and downstream. The upstream segment encompasses core manufacturing, including satellite and rocket production, as well as launch services. The downstream segment, on the other hand, focuses on leveraging satellite data and space infrastructure to create commercial products and services for both space and non-space industries (Bousedra, 2023).

The industry's focus is on commercial applications, leveraging space-derived assets for diverse terrestrial sectors. Large players, like Elon Musk's SpaceX, have the capability to provide significant investments and are breaking the mould of traditional approaches (Robinson & Mazzucato, 2019). These companies, while often working with government agencies on major projects, are spearheading the commercialisation of space through innovations that significantly reduce costs and increase launch cadence. For instance, companies like Planet Labs have introduced a new business model using many small, inexpensive, and easily replaceable satellites for Earth observation (Robinson & Mazzucato, 2019).

While the sector's landscape is dominated by new, agile players, large legacy firms, such as Airbus, Thales, Leonardo (including Telespazio) and OHB, continue to play central roles with strategies that span defence, aviation, and space. For instance, Airbus' Defense and Space division generated approximately €5.81 billion in first half of fiscal year (H1) 2025, with its performance buoyed by institutional contracts (Airbus, 2025). Thales' Aerospace business in the first half of 2025 accounted for roughly €2.76 billion of its total €10.27 billion in sales, with most of the remainder coming from defence (Thales, 2025). Leonardo's dedicated Space division is smaller in economic scale, with €436 million in H1 2025, but is growing within its group's broader portfolios, which include helicopters, defence electronics, and security (Leonardo, 2025).

Their business models emphasise long-term, government and institutional contracts (ESA, national defence ministries, etc.), high reliability, and custom engineering. Because of their scale and technological capacities, many innovations developed in space or defence spill over into civilian applications in aviation, environmental monitoring, communications, and infrastructure (Cao et al., 2020).

Within the European ecosystem, entrepreneurial spirit is exemplified by companies specialising in environmental and resource management, such as ConstellR, which uses thermal remote sensing data for agricultural insights, and SuperVision, which applies AI to satellite data for infrastructure monitoring. While the observed firms predominantly operate within the downstream segment, the portfolio also includes critical upstream firms that develop core space technologies. Examples include Isar Aerospace Technologies, which focuses on launch vehicle components, and D-Orbit, a provider of in-orbit transportation and logistics. A notable feature of this ecosystem is the emergence of hybrid firms, such as Yuri, which serve both upstream and downstream markets by providing in-orbit microgravity platforms for research, thereby bridging traditional value chain segments (European Space Agency, n.d.).

2.2 Slovenian space industry

The development of the Slovenian space sector has a long history, with a well-defined niche, characterised by a focus on high-tech, specialised products and services, particularly within the downstream segment of the space value chain (Republic of Slovenia, Ministry of the Economy, Tourism and Sport, 2025b). The "Slovenian Space Strategy 2030" outlines a vision to expand space technologies, promote entrepreneurship, and foster academic spin-offs, creating a dynamic environment where new companies can thrive (Government of the Republic of Slovenia, 2023). A key feature of the Slovenian ecosystem is the presence of slightly larger players, such as Dewesoft, which serve as foundational anchors for the ecosystem and pave the way for newer entrants. Dewesoft is a leading provider of data acquisition (DAQ) and analysis solutions, with proven applications in aerospace testing ranging from ground station telemetry to launchpad instrumentation. Its equipment is used by ESA, NASA, and SpaceX in mission-critical projects, which demonstrates the credibility and export potential of Slovenian firms (Slovenian Business Club, 2024).

The Slovenian ecosystem is underpinned by robust institutional support. A pivotal development was the establishment of the Slovenian Space Office in April 2023. Slovenia's cooperation with ESA began in 2008 with the Plan for European Cooperating States (PECS) agreement, followed by an association agreement in 2016 and an upgraded association agreement in 2020. After a review process in 2023–2024, Slovenia attained full ESA membership on 1 January 2025, opening access to new programs and increasing funds for participation in ESA programs. This strategic alignment links Slovenian space activities to both the ESA and the EU frameworks (Ministry of the Economy, Tourism and Sport, Republic of Slovenia, 2025b).

While the Slovenian space sector is steadily growing, the catalogue of the Slovenian Space Industry represents 36 companies and 15 research institutions, directly employing around 2,800 people in total (Ministry of the Economy, Tourism and Sport, 2025a). Their activities span upstream manufacturing (e.g., electronics, precision engineering and materials) and downstream services (e.g., Earth Observation and data applications), with strong dual-use links to defence, aviation, and ICT. The largest segment is upstream manufacturing and hardware, with a total of almost 1,500 employees and a value added of € 80,000 per employee. On the other hand, an average of €140,000 of value added per employee was recorded in companies operating in the testing instruments and ground systems segment in 2024 (Table 1).

Table 1. Overview of the Slovenian space sector

Category	No. of firms	Total number of employees	Min. number of employees	Max. number of employees	Mean Value Added per employee
Downstream applications & software	11	438	1	150	€ 41,891
Upstream manufacturing & hardware	12	1439	5	960	€ 78,692
Testing instruments & ground systems	8	698	10	300	€ 137,112
Dual-use cross-sector	5	204	15	82	€ 33,074
Total	36	2,779	1	960	€ 72,692

Note: data on the numberof employees and value added refer to 2024

Source: Own work based on AJPES data.

Besides larger companies such as Dewesoft, Slovenia's space ecosystem is further complemented by smaller, tech-driven disruptors operating across different segments of the value chain. A leading hardware-focused company in the upstream segment, SkyLabs, is advancing the space market through disruptive, miniaturised on-board data-handling solutions and an innovative approach to space engineering. Originating from a group of postdoctoral researchers at the University of Maribor in 2009, SkyLabs has evolved into a key contributor to Slovenia's space value chain, having equipped more than 60 operational satellites across 10 constellation missions (SkyLabs, 2025). Today, the company employs around 50 experts and plans to double its workforce while investing €6 million to expand its production capacity and strengthen its position in the global space industry (The Slovenia Times, 2024).

Another noteworthy example is Sinergise, one of the most successful Slovenian space-oriented software companies, acquired by Planet Labs PBC in 2023. Sinergise developed Sentinel Hub, an award-winning cloud-based service for archiving, processing, and distributing satellite imagery. The platform processes hundreds of millions of requests per month and manages over 50 petabytes of Earth Observation data from missions including Sentinel, Landsat, PlanetScope, and SkySat. Its solutions support applications in agriculture, environmental monitoring, water resource management, and disaster response worldwide, making Earth Observation more accessible to institutions, companies, and citizens alike. Through its partnership with Amazon Web Services (AWS), Sinergise has made Copernicus data globally available in the cloud, demonstrating how Slovenian technological expertise can scale to international markets (European Commission, 2025).

3 Space industry: A literature review

The "New Space" era has also exposed significant structural challenges. This section reviews the financing and structural challenges faced by deep tech start-ups in the space sector, and the role of public institutions in addressing these challenges.

3.1 The financing challenge

The traditional model of public funding, which supported national agencies and large incumbent firms, is being re-evaluated in the face of private-sector entry and the need for new funding models (Orlova et al., 2020). The primary challenge for deep tech start-ups in the space sector is the inherent mismatch between the long-term horizons for development and return on investment and the shorter-term expectations of traditional venture capital (VC) investors (Lerner et al., 2016).

The space industry, with its high capital requirements and long product development cycles, presents a unique investment profile. Upstream activities, such as rocket and satellite manufacturing, require substantial investments in fixed capital, including specialised testing facilities and physical infrastructure (OECD, 2024).

This contrasts with the typical VC model, which often seeks quicker returns from scalable software or service-based businesses. This divergence creates a critical structural void. The need for a different form of investment, known as patient capital, has become increasingly apparent in an economy where only a low share of private companies' profits is reinvested back into productive investments (Mazzucato, 2015). This scarcity is driven by the increasing short-termism of corporations, particularly the rise of the "shareholder-value" model of corporate governance (Mazzucato, 2015). As a result, firms have become less willing to undertake long-term investment projects and are more focused on short-term profits, even at the expense of innovation (Mazzucato, 2015). This short-termism leaves innovative ventures to struggle for survival, as traditional investors often fail to recognise the need for longer development cycles.

3.2 The role of public institutions

In contrast to a purely private-sector-driven model, the European space industry operates under a unique paradigm where public funding acts not merely to correct market failures, but as a proactive, market-creating force. This approach aligns with the "Entrepreneurial State" concept, where public institutions are seen as active investors in high-risk, mission-driven sectors (Mazzucato, 2013). Public-private partnerships (PPPs) in fostering outer space innovations are designed to provide a superior research and development platform, increasing the probability of successful breakthroughs and avoiding "tragedy of the commons" dilemmas that can arise from excessive competition for space resources (Rausser et al., 2023).

The European Space Agency (ESA), through its strategic procurement and R&D support, functions as a foundational customer and strategic investor (Ministry of the Economy, Tourism and Sport, Republic of Slovenia, 2025b). This model de-risks projects for emerging companies, often providing them with upfront funding for development and long-term contracts. This support mechanism is far more "patient" than typical venture capital, allowing firms to focus on foundational scientific and engineering work without the pressure of generating returns within conventional investment time horizons. These partnerships can also eliminate coordination failures by aligning incentives and integrating resources, which in turn elicits more capital investments for both basic and applied research that generates public goods and commercialised technologies (Rausser et al., 2023).

4 Practical insights from industry

4.1 Methodology

Following the findings from the theoretical background, the empirical part addressed three research questions: (1) What strategies for market access and commercialisation are employed by Slovenian companies that are either fully dedicated to space activities or that primarily operate in other industries but pursue opportunities in the space sector? (2) What financial and structural challenges hinder the growth and scaling of these firms, and how do they navigate such barriers? (3) How do public institutions, particularly the European Space Agency (ESA), shape the development of the Slovenian space ecosystem and act as a substitute for private market deficiencies?

The empirical analysis is based on 15 in-depth interviews with 12 firms, investors, and public bodies active in the Slovenian space ecosystem, conducted between August 21 and September 17, 2025. The selection of participants followed a purposive sampling strategy, specifically the maximum variation method, designed to capture perspectives from across the ecosystem (including companies, investors, and public institutions). This approach ensured heterogeneity in organisational roles while revealing common patterns across cases (Corbin & Strauss, 2008). The interview sample was based on the catalogue of the Slovenian space industry, which provides a comprehensive overview of organisations that have identified themselves as active in the national space sector. Table 2 summarises the basic data on the interviewed organisations.

Table 2. Interviews conducted with Slovenian space ecosystem stakeholders

Company/ Organisation	Primary industry	Position in the space ecosystem	Interviewees	Size*	Code
Company 1	Finance	Venture financing for deep tech	COO	Large	SPACE1
Company 2	Measuring instruments	Upstream hardware; test & measurement	Chief of Applications	Large	SPACE2-1
			Advisor to the Board		SPACE2-2
Company 3	Scientific instruments	Upstream systems; instrumentation	Head of Business Unit	SME	SPACE3
Company 4	Electronics	Upstream; edge computing	Founder	Micro	SPACE4
Company 5	PCB manufacturing	Upstream electronics; PCB design	CTO	SME	SPACE5
Company 6	Precision engineering	Upstream assemblies	Managing Director	SME	SPACE6
Company 7	Metals	Mission-grade alloys	CEO	Large	SPACE7-1
			Researcher		SPACE7-2
			Director of Development & Control		SPACE7-3
Company 8	Manufacturing/ coatings	Advanced coatings; conductive nanolayers	Head of Research	Large	SPACE8
Institution 1	Public administration	Gov. space coordination office	Head of Office	Not applicable	SPACE9
Institution 2	Finance	National development finance	Head of the Development Department	Large	SPACE10
Company 9	Precision mechanisms	Upstream assemblies	Researcher	SME	SPACE11
Company 10	Satellite platform producer	Fully space-oriented	Co-Founder	SME	SPACE12

Note: *Company size in Slovenia is defined by the Companies Act (ZGD-1), based on three criteria: (i) average number of employees in the financial year, (ii) net sales revenue, and (iii) value of assets (companies must meet at least two of the criteria). Micro: less than 10 employees, less than €700,000 revenue, less than €350,000 assets; SME (small and medium-sized companies): less than 250 employees, less than €40 million revenue, less than €20 million assets; Large: companies exceeding these thresholds (ZGD-1, 2023).

Source: Own work.

4.2 Market access and commercialisation

The "New Space" economy emphasises commercialisation as the dominant trend, with downstream applications gaining priority and upstream capabilities increasingly structured around private contracts, as the interviewees noted. For Slovenia, the challenge lies in transforming highly specialised expertise, often originating in adjacent fields, such as metallurgy, nanotechnology, or precision electronics, into market products for the space sector. At the same time, companies must navigate procurement barriers and intense price competition. Slovenian firms deliberately seek opportunities in technological niches that are overlooked by larger incumbents, where flexibility and custom engineering are valued more than scale. *"We have certain products that are technologically superior to the competition. However, it is hard to compete on price with companies that produce much larger volumes than we do. However, it is also true that, because we are small, we are perhaps more flexible. In larger companies, such a small production would be seen as a disturbance, and they would say it is not worth dealing with such small matters. For us, that is precisely where we see opportunity"* (SPACE11).

Several firms occupy highly specialised positions in the European space value chain. Some have developed compact high-frequency RF telecommunication systems that reduce launch costs and enable higher data throughput. *"We just got a very big contract to supply a telecommunication system for the biggest European satellite constellation, basically providing similar services to Starlink but fully European, so with all European suppliers"* (SPACE4). Niche products based on very specialised technological expertise provide value. *"With our products, we are in the high-tech front end, and some technologies just do not work without them"* (SPACE11).

At the same time, many firms remain confined to supplier roles, producing housings or components for satellites designed by others. *"We are, for now, just suppliers for more high-tech firms, like SkyLabs. The share of space products in turnover is about five percent"* (SPACE6). However, high-value-added is not achieved through subcontracting, and many space tech companies are aware of this. *"Our strategy is to build complete measurement solutions, not just single components"* (SPACE2-1).

Downstream and upstream-oriented innovators encounter different commercialisation paths. One company has pivoted towards nanotechnology and is developing conductive nanogold inks for satellite filters. However, commercialisation depends on ESA validation: *"This is a proof-of-concept project. If confirmed, then we move towards commercialisation"* (SPACE8). While they expect demand to grow with ESA membership and the reshoring of strategic supply chains, tenders remain difficult to win, with smaller Slovenian firms often priced out when competing in segments dominated by large incumbents or cheaper Eastern European suppliers. Yet not all market segments are shaped by economies of scale. Opportunities for Slovenian firms lie in solutions with specialised niche technologies where flexibility, quality, and unique expertise outweigh cost advantages. *"Our* *strategy is to have full control over our own innovative core technologies that make our products extremely resilient to radiation and are consequently enabling us to deliver to market competitive and radiation robust satellite platforms. Our customers are then focusing on the overall system business case and the delivery of satellites into space"* (SPACE12). The metallurgy sector offers another perspective: a company with a long tradition in the steel industry has successfully certified its steel for space applications. *"We can only say that our product goes into space, not who the customer is"* (SPACE7-1).

Together, Slovenian firms demonstrate the opportunities of niche specialisation but also the vulnerabilities of scale. Market access depends less on open competition and more on integration into the European ecosystem, long-term supplier relations, and institutional programs.

4.3 Technological innovation and absorptive capacity

The literature stresses that absorptive capacity is a key determinant of competitiveness in deep tech sectors (Orlova et al., 2020). In the space domain, this involves not only technological novelty and the ability to translate research into mission-critical applications, but also the capacity to adapt such solutions for dual-use contexts, where technologies serve both civilian and defence purposes.

Leveraging its experience in telecommunications and automotive electronics, one company is repurposing its founders' know-how to develop compact RF communication systems. *"Our technology is one of a kind, because compared to other companies, they work at very low frequency, so they have limited data capabilities. We converted previous experience into the space environment, did a lot of testing, and in five years became a small diamond in Europe"* (SPACE4). Upstream innovation requires long development cycles, and constant technological renewal drives absorptive dynamics. *"If you are not part of what is coming, you risk being left behind. It is a mistake not to be part of new revolutions"* (SPACE3).

Even traditional industries, such as metallurgy, reveal the process of innovative adaptation. *"Testing for space takes years; you need to prove that a batch of steel will behave identically in ten years"* (SPACE7-2). A company achieved certification for specialised steels used in nuclear and space applications. *"We improved material properties by more than 150 percent. Our steel cores are now part of fusion and aerospace applications"* (SPACE7-2).

4.4 Non-technological innovation, financing and business model dynamics

In the "New Space" economy, technological breakthroughs alone are insufficient; complementary business-model innovation is required to finance extended development cycles, manage risk, and secure market access (Baber & Ojala, 2024).

One company in the sample deliberately avoided dependence on grants in the early years, as it did not initially focus on space specifically. However, later, opportunities arose to work in space niches. *"I am happy to say that we built our company from scratch with our own resources. Everything was self-funded, so no venture capital, no institutional help at all"* (SPACE4). Other firms highlight dual-use strategies that stretch business models beyond space. A company emphasised that their turn to nanotechnology was supported by industrial diversification: *"We started with nanogold for dental and biomedical use. Later, we applied it to satellite filters, because high frequencies require smooth conductive surfaces"* (SPACE8).

The financing challenge also shapes how companies frame their growth. *"Deep tech is specific, because development cycles are longer, the need for capital is bigger, and returns come later. That is why many investors avoid it"* (SPACE1). Financing risky investments is underdeveloped. *"If Slovenia wants deep tech, it needs scale-up funds; seed money alone just creates start-ups that hit the wall"* (SPACE10). Firms still rely heavily on public funding and cross-subsidising. *"We have moved in the last years more and more from one-off projects towards product development; as such strategy addresses a broader market it allows repeated sales and stronger, faster and more reliable scaling of business"* (SPACE2-2). Profitable "cash cow" products developed for other markets often finance the development of "new space" technologies, bridging the gap until external funding becomes available. *"Without EU programmes we could not even start R&D for space – it is too risky to finance alone"* (SPACE7-3). Some companies focused exclusively on space and choose to grow organically without VC funds or diversification into other sectors. *"We never had external funding. Everything was built on our own investments of time and savings, and later, we reinvested revenues. That is why our growth has been gradual, but sustainable"* (SPACE12). *"Our entire revenue depends on space; we cannot cross-subsidise, so every project must stand on its own legs"* (SPACE12).

4.5 Organisational culture, talent development and human resources

Research on deep tech ecosystems emphasises that human capital is one of the most scarce and strategic resources (Lerner et al., 2016; OECD, 2024). Talent shortages are amplified in space industries because they require cross-disciplinary expertise in physics, engineering, and data science. At the same time, long product cycles demand employees willing to commit to uncertain payoffs (Mazzucato, 2015).

Looming shortages in metallurgical skills were highlighted. *"Companies do not have a problem now because they have enough students on scholarships, but in the next ten to twenty years, there will be a shortage"* (SPACE8). Salary expectations are creating mismatches, especially for start-ups. *"In the early stages of a start-up company, there is no budget to offer high salaries... and especially if we talk about experienced professionals from the corporate world with €20,000 gross salaries per month; no start-up can afford that"* (SPACE1). This illustrates the structural financing–talent gap identified in the literature: investors avoid early-stage deep tech because of cost and time horizons (Orlova et al., 2020); however, without financing, start-ups cannot offer competitive conditions to retain experts.

The importance of flexibility and international exposure was emphasised, describing Slovenia's ecosystem as still undeveloped compared to Western countries but with a unique advantage: *"Here you can call someone in the ministry and have a meeting. There is more personal involvement"* (SPACE4).

4.6 Collaboration and ecosystem connectivity

Innovation systems theory emphasises that the competitiveness of deep tech sectors depends not only on individual firms but also on the density and quality of inter-firm, institutional, and international linkages (Borrás & Edquist, 2019).

A non-competitive, complementary profile of Slovenian space companies has been underlined. *"There are around 40 companies, and everyone is specialised in something. The good thing is that we are not competitors with each other"* (SPACE4). Yet their most meaningful partnerships are cross-border. *"We have a lot of partners in Germany, France, Denmark. Sometimes they are suppliers, sometimes customers and sometimes co-design partners"* (SPACE4). Cooperation with domestic peers is described as sporadic, often limited to conferences or clusters. *"On the space field, the ecosystem is still relatively small. We know each other, but projects together are rare; mostly we help each other to get ESA references"* (SPACE3). For suppliers, the barriers are more structural: *"We do not collaborate with other Slovenian firms. We are too small. Large projects always go to big firms; we survive as subcontractors"* (SPACE6). At the same time, suppliers emphasise that informal collaboration matters when meeting ESA requirements. *"Without ESA certification, we would not even be considered. Getting the certification was only possible because partners from the ecosystem showed us what tests are needed and how to prepare for them"* (SPACE7). The role of informal ties has been pointed out: *"We connect companies and institutes. We encourage them not to see each other as competitors but as complementary"* (SPACE9). *"Our goal is not just high returns but building an ecosystem; firms that survive and keep talent in Slovenia"* (SPACE10).

4.7 Challenges and barriers to scaling

Deep tech start-ups in space face disproportionate barriers to growth, including long development cycles, capital intensity, and procurement structures that favour incumbents (Lerner et al., 2016; Orlova et al., 2020). Finding early investors is particularly difficult. *"We looked for a VC, but without experience and references, we did not meet the requirements. It was like a dog chasing its tail; we could not get money because we had no revenues, and we could not get revenues because we had no money"* (SPACE4).

Bureaucracy and regulation are also perceived as obstacles, though interviewees differ in emphasis. *"You cannot build a proper business plan if rules change every year"* (SPACE5). More commonly, firms pointed to the demanding certification processes required by ESA as the key bottleneck. *"We invested heavily in clean-room processes because without them, we cannot even apply for an ESA contract"* (SPACE5). *"The hardest part is traceability. ESA wants to know every step of the production chain, down to which worker operated which machine"* (SPACE7-3). Securing the certifications is essential to enter the supply chain, but the costs and complexity can be particularly burdensome for smaller firms without prior references.

There is a challenge of competing with global giants. *"Our products are at this moment used by ESA, NASA, SpaceX, and as a young Slovenian company, we understand that we must be convincing with our technology. This drives us,* *and so far, we have succeeded in competing with the world's leading tech companies"* (SPACE2-1). Global competition also brings structural disadvantages of size. *"For ESA projects, we are always too expensive. Eastern Europeans are cheaper, or big firms underbid because for them losing €100,000 is nothing. For us, it is survival"* (SPACE6). One option is to focus on niche products, as *"Slovenia is too small for competing programs; the only way is to position ourselves in niches where ESA needs partners"* (SPACE9). At the same time, not all ESA contracts are price-driven; in highly specialised segments, quality and reliability are prioritised over cost, opening opportunities for smaller firms. *"Most European steelmakers are already Chinese-owned. If policy does not change, we risk becoming just a colony of Chinese production"* (SPACE7-1), but also pointing to the solution: *"competing with special steels that others cannot produce"* (SPACE7-1).

4.8 Institutional and regulatory environment

Institutional frameworks play a constitutive role in shaping space industries, not only correcting market failures but actively creating markets (Mazzucato, 2013). Slovenian firms consistently highlighted the transformative role of ESA membership. *"We fell into the space segment by accident. Engineers from NASA approached us, and a year later our product went to the International Space Station"* (SPACE3). With ESA, opportunities are now more systematic. *"Since Slovenia became a full member, more programs are open. More money is available, and our goal is to upgrade our products and launch in this segment"* (SPACE3). *"Before full membership, we did very little for ESA. Now, since we contribute more money, more will come back, and for companies like ours, this is the only chance to get work"* (SPACE6).

Institutional pathways can be difficult to navigate. *"ESA procurement is highly structured and involves significant bureaucracy. Tenders demand proof of relevance across multiple use cases and typically move at a slower pace than direct B2B contracts"* (SPACE2-2). "*When working with ESA, the main challenge is not only the development of the technology, but the procurement process. ESA procedures are highly structured and require specific knowledge, which often takes as much time and effort as engineering the technology itself"* (SPACE2-1). At the same time, several interviewees emphasised that ESA procedures are not as complex as many other public procurement schemes. While the process is formalised and time-consuming, it is generally seen as transparent and predictable once firms gain experience, especially compared to national or EU-level funding instruments. *"ESA recognised us because of our niche* *technology and has been supportive all along. The paperwork takes time, but it is manageable, still much easier than some other public projects"* (SPACE11).

4.9 Technology spillovers and policy levers

Space activity generates measurable productivity and technology spillovers in adjacent sectors, strengthening national innovation systems through standards, testing and skills formation (Corrado et al., 2023; London Economics, 2019; European Commission, 2025). *"Success in space opens doors elsewhere, meeting space requirements makes automotive or aviation feel easy"* (SPACE2-1). The empirical evidence points in the same direction. *"We learn a lot from aerospace; the requirements there later flow back to improve our industrial grades"* (SPACE7-2).

The Slovenian opportunity lies in transforming mission-grade know-how into exportable modules. A frontier project illustrates the path: *"Commercialising relativistic positioning in five to seven years would be a breakthrough for the company and for the region"* (SPACE3). A component-level example shows the same logic: *"If our proof of concept succeeds, this could be the first nanogold technology of its kind, transforming space electronics and biomed"* (SPACE8). These projects demonstrate how in-depth physics and materials research can lead to a family of products beyond space, once certification and manufacturability are proven.

Spillovers also run through dual-use channels. Teams keep defence optionality while avoiding early compliance drag. They enter on the civil side, where cycles are faster and documentation lighter, then expand into defence once processes are mature. *"The aerospace and space sectors are inseparable, and collaboration differs significantly between the public and private sectors. Whether working with ESA or SpaceX, we rely on our measurement solutions to deliver the best results for our customers"* (SPACE2-2). This approach reduces costs, helps build references and keeps future strategic options open (EUR-Lex, 2021; European Space Agency, 2025b). EU's strategic autonomy and secure supply chains enable sensitive work to remain in Europe, which increases the expected payoff for qualifying Slovenian suppliers (European Commission, 2025).

Spillovers materialise faster when organisations treat missions as platforms. Space projects generate internal spin-offs when a subsystem earns its own customer, and spin-ins when a non-space module is adapted for orbit. Both paths are easier within dense regional networks where firms, labs and agencies interact repeatedly. *"Our mission is to build a technology-transfer ecosystem so innovations do not stay locked in faculties or research institutes"* (SPACE1). Slovenia already has the local buzz. The missing piece is a set of formal pipelines that carry knowledge through to bids and orders.

Technological advances with spillover potential are being generated, but scaling these into broader industrial impact is constrained by three recurring needs: access to customers, financing for certification and testing and skilled personnel. Policy can amplify spillovers by directly addressing these bottlenecks:

1) Access to large European projects depends on visibility and matchmaking. *"In Italy, you are just a number in a queue of 200 companies; in Slovenia, the ministry actually asks us for input on the ten-year plan"* (SPACE4). Companies value this proximity but still lack systematic channels to reach foreign prime contractors. A national bid office that maintains partner maps, compliance libraries, and reusable proposal templates could respond to this expressed need, aligning Slovenian specialisations with ESA and EU opportunities (Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2021; European Space Agency, 2025a).

2) Market demand is usually the main driver, but public incentives accelerate development. *"State support has given us valuable wind in the sails and helped open many doors in the space industry. With the help of the government, we can move faster on opportunities we might not have pursued otherwise"* (SPACE2-2). Instruments already exist at ESA and the EIB, but tranche structures tied to verified technical milestones could make them more responsive to firms' actual bottlenecks (Toth et al., 2019; European Space Agency, 2025b).

3) Human capital shortages remain a struggle. *"The biggest barrier is finding specialised engineers. Even nearby universities produce very few graduates"* (SPACE4). Apprenticeships linked to live missions and subsidies for junior engineers could ease entry, while supporting firm participation in European standards bodies would help accumulate reputational capital (Cedefop, 2024; European Space Policy Institute, 2022). *"We nurture talent from high school onward; several engineers started as teen interns and stayed through university"* (SPACE3).

In short, the industry needs targeted brokerage, commercialisation finance and mission-linked skills support, as highlighted in Table 3. Policy can provide these levers, ensuring that technological advances in Slovenia translate into high-tech exports, industrial renewal, and sustained value added.

Table 3. Summary of key empirical findings

Theme	Key findings
Market access and positioning	• Commercialisation-led New Space. • Niche wins: flexibility > scale. • ESA validation is critical. • Price pressure is high; credibility matters.
Technology and absorptive capacity	• Cross-domain know-how repurposed. • Continuous testing drives learning. • Metallurgy upgrades prove adaptation.
Business models and financing	• Deep tech: long cycles, capital-heavy. • Bootstrap, cross-subsidise, dual-use common. • Public programs & anchors fill VC gap.
Talent and organisation	• Skills scarce, salaries high. • Culture fit & pipelines matter. • Proximity to policymakers helps.
Collaboration and ecosystem connectivity	• Firms are complementary, not competitors. • Cross-border partnerships dominate. • ESA standards = common entry ticket
Barriers to scaling and competition	• High certification costs. • Hard vs incumbents & low-cost rivals. • Niche reliability beats price in ESA.
Institutions and procurement	• Full ESA membership expands access. • Procurement is slower than B2B. • Transparent once experienced.
Spillovers, dual-use, and policy levers	• Space standards lift other sectors. • Civil-first, defence-later path. • Policy: bid office, milestone finance, talent support.

Source: Own work.

5 Conclusion

This chapter explains how Slovenian firms enter and scale in the European space economy, what holds them back, and how institutions shape their choices. Slovenia's space ecosystem demonstrates strong potential but remains constrained by limited scale, long development cycles, and financing gaps. Certification requirements, procurement structures, and reliance on small domestic demand create additional barriers to commercialisation. Companies respond by focusing on narrow technological niches where flexibility and quality can offset the disadvantages of size. Export orientation is unavoidable yet exposes firms to intense competition from both large incumbents and lower-cost Eastern European suppliers. At the same time, integration into European value chains and the credibility gained through ESA programs provide an essential foundation for international growth.

The sector's competitiveness rests on three main pillars. First, specialisation and dual-use strategies enable firms to leverage expertise from adjacent industries to develop space-grade solutions while retaining options for defence markets. Second, the ESA membership acts as a structural enabler, both through procurement and as a risk-sharing partner; however, bottlenecks persist at mid-development stages, where patient capital is scarce. Third, spillovers from space standards strengthen adjacent industries, from metallurgy and electronics to health and energy, with the potential to multiply once formalised pipelines between research, firms, and international prime contractors are established.

To grow, Slovenia must focus on a small number of targeted priorities. First, improve access to financing for the critical stage between prototype and market entry. Instruments should release funding in stages, tied to verified milestones, such as successful tests or certifications. This approach reduces risk for investors and helps firms cover the high costs of testing and qualification, which are often the main barrier to commercialisation. Second, establish a national bid office to lower entry barriers to ESA tenders and systematically position Slovenian firms within European consortia. Third, strengthen the talent base through apprenticeships, junior engineer subsidies, and structured participation in European standards bodies. Concentrating on these levers would allow Slovenia to convert its specialised expertise into sustained exports and a more resilient high-technology economy.

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COSYLAB'S JOURNEY IN DEEP TECH INNOVATION AND ECOSYSTEM DYNAMICS

1 Introduction

Deep technological innovation has emerged as one of the defining forces of contemporary industrial and scientific progress. Unlike incremental improvements in consumer products, deep tech rests on fundamental advances in science and engineering, marked by long development cycles, high capital intensity, and close interaction between public and private actors (Siota et al., 2025).

This chapter examines the case of Cosylab, a mid-sized Slovenian company that has become globally recognised in control systems for big science and oncology. The central question is how active involvement in the ecosystem, technological innovation, and non-technological enablers interact to sustain competitiveness in demanding global markets. These three elements form the red thread of the analysis: ecosystem embedding enables technological progress, while organisational and human resource (HR) practices complement and sustain it.

The study aims to generate insights relevant to both managers in deep tech firms and policymakers designing innovation frameworks in mission-oriented sectors. Methodologically, the analysis is based on qualitative data, combining interviews with Cosylab's leadership and document analysis of company reports and strategy papers.

First, the methodology is presented, followed by a case overview of the company, its history, markets, strategy and business model. Then, the company's ecosystem integration is analysed, followed by an examination of its technological innovation and absorptive capacity. The chapter then discusses non-technological innovation in HR, organisation, and leadership, and concludes with a summary of key findings.

2 Methodology

Methodologically, the study employs a qualitative case study design. Primary data were collected through semi-structured interviews with Cosylab's leadership (see Table 1). The interviewees represented key executive functions, providing first-hand perspectives on the company's strategy, innovation practices and ecosystem interactions. The goal of these interviews was to understand how Cosylab has built and sustained competitiveness in deep tech, with particular attention to ecosystem integration, technological development, and human resource practices. To complement the firm-level view, an additional interview was conducted with the Head of the Slovenian Space Office, offering an ecosystem-level perspective on institutional support and national positioning. Additional insights were obtained from document analysis, which covered company reports, strategy papers, and relevant news coverage. Triangulating these sources enables a more robust and multifaceted understanding of Cosylab's strategic positioning and innovation practices.

Table 1. An overview of interviewees

Code	Position of the interviewee
COSYLAB1	Chief Executive Officer
COSYLAB2	Chief Operating Officer
COSYLAB3	Chief Delivery Officer
COSYLAB4	Chief Financial Officer
COSYLAB5	Deputy Chief Operating Officer
COSYLAB6	Head of the Slovenian Space Office

Source: Own work.

3 Cosylab in the deep tech landscape: An overview

3.1 Company profile

Cosylab was founded in 2001 as a spin-off from the Jožef Stefan Institute, building directly on Slovenia's long-standing tradition in physics and its early involvement in European big-science infrastructures. From the beginning, the company specialised in control systems for particle accelerators and other highly complex facilities, areas where standard industrial solutions were simply not sufficient (Cosylab, 2025c). Over the years, this scope has expanded to include fusion projects, astronomy, and, most notably, medical applications.

The company has grown into a truly international player, with offices in five countries and more than 200 employees, over 70 percent of whom hold at least a university degree (Cosylab, 2025b).

The financial data (see Table 2) reveal both the opportunities and risks inherent in such a trajectory. In 2020, Cosylab reported revenues of €14.8 million and a profit of €0.65 million (Cosylab, 2021). In the following year, revenues surged to €24.5 million and net income reached nearly €3 million, supported by large international contracts (Cosylab, 2022). The year 2022, however, turned into a major setback. While revenues still exceeded €22 million, the company reported a net loss of €5.9 million, primarily due to financial write-offs rather than poor operational performance (Cosylab, 2023). In 2023, the situation stabilised, with revenues at €23.7 million and a profit of €0.22 million (Cosylab, 2025b). At the same time, employment rose steadily to 226, and value added per employee recovered strongly. *"We accept mistakes as an investment in tomorrow"* (COSYLAB1) is a statement that reflects the learning orientation that has helped the company recover.

Table 2. Key financial indicators of Cosylab (2020–2024)

Indicator	2020	2021	2022	2023	2024
Revenue (€)	14,788,465	24,501,004	22,432,570	23,719,907	20,445,501
Net result (€)	646,121	2,988,718	–5,892,737	216,070	422,655
Employees (mean)	194	240	263	240	226
Value added per employee (€)	58,974	78,720	62,452	79,124	69,867

Source: Own work based on Cosylab Annual Reports (2020–2024).

3.2 Evolution and strategic milestones

Several milestones marked Cosylab's evolution. The first was the so-called "5M plan", which set a turnover target of €5 million. *"We set the target, and even though we reached it in different markets than expected, the focus forced us to mature"* (COSYLAB1). Another turning point was the company's participation in major international projects, such as ITER, FAIR and the European Spallation Source, which boosted its reputation and facilitated internationalisation (Cosylab, 2025c).

A decisive step was the entry into medical technologies, particularly through the development of OncologyOne. This platform, into which more than 120 person-years and over €10 million of investment have already been devoted, embodies the long innovation cycles characteristic of deep tech (Cosylab, 2025c). *"This is not a product for one year but a platform for decades"* (COSYLAB5).

Organisationally, the company introduced a matrix structure after Covid-19, combining domain-oriented pillars (fusion, accelerators, medicine, quantum) with functional departments. *"My role is to build an organisation that works, to remove bottlenecks, and make sure domains and functions stay aligned"* (COSYLAB3). At the same time, the painful experience of 2022, when equity-for-work arrangements collapsed, triggered stricter financial controls and clearer accountability (COSYLAB4). These changes are consistent with the literature on complex product systems (Hobday, 2000) and ecosystem strategy (Adner, 2017; Jacobides et al., 2018).

3.3 Core business and markets

Cosylab's activities span two interconnected domains: scientific infrastructures and medical technology. In science and industry, the company delivers end-to-end control system engineering, covering requirements analysis, system architecture, software development, and integration. Reference projects include CERN's Large Hadron Collider in Geneva, the world's most powerful particle accelerator where Cosylab contributed to the development and integration of advanced control systems; the ITER tokamak fusion facility in southern France, a multinational project aiming to demonstrate the feasibility of nuclear fusion as a large-scale energy source, where the company has been involved in diagnostics and software integration; and the FAIR antiproton and ion research centre in Darmstadt, Germany, designed to provide beams of ions and antiprotons for cutting-edge physics experiments, where Cosylab delivers key project management and system integration expertise. By participating in these large-scale infrastructures, Cosylab helps mitigate the risks of delays and cost overruns that often affect billion-euro scientific projects (Cosylab, 2025d).

In medicine, the focus is on OncologyOne, a software suite that supports radiotherapy devices across modalities. Its modules, WorkflowOne, TreatmentOne, PositionOne, and SupervisorOne, cover planning, delivery, and quality assurance (Cosylab, 2025b). Partnerships with the Mayo Clinic, Leo Cancer Care, and Neutron Therapeutics embed the firm in oncology innovation ecosystems (COSYLAB1). *"People stay because the projects matter. Curing cancer beats a higher salary in a morally grey industry"* (COSYLAB2), with the term "morally grey industry" referring to high-paying sectors, such as gambling and adult entertainment.

Both domains align with mission-oriented sectors, where technological breakthroughs are pursued in service of societal goals (Mazzucato, 2018). In science, Cosylab enables fundamental discoveries in physics and energy; in medicine, it contributes to life-saving treatments. This positioning strengthens its attractiveness to talent, investors, and partners in a global deep tech ecosystem.

3.4 Vision, mission, and strategy

Cosylab's mission is to advance science and improve health by developing reliable control solutions for the world's most complex systems (Cosylab, 2025a). Strategically, it must sustain competitiveness in environments defined by long development cycles, high capital intensity, and regulatory complexity (Siota et al., 2025).

The firm responds through diversification, expanding from accelerators to fusion, semiconductors, and quantum, as well as from ions/Boron Neutron Capture Therapy (BNCT) to photon therapy (Cosylab, 2025b). It emphasises governance discipline, with stricter financial controls after 2022, and a human capital strategy prioritising cultural fit and mission commitment over pure salary competition (COSYLAB2).

Cosylab also embeds itself in ecosystems to spread risks and strengthen knowledge inflows. Ties with CERN, ITER, and the Mayo Clinic exemplify how absorptive capacity (Zahra & George, 2002) allows external expertise to be internalised and reconfigured. *"I try to be the 'optional extra', the team must run without me; I step in as 'special forces' when needed"* (COSYLAB1). Such strategies illustrate how deep tech firms align long-term bets with short-term resilience, sustaining competitiveness despite uncertain payoffs.

3.5 Current business model and revenue streams

Cosylab's model combines service contracts with product revenues, reflecting ambidexterity between exploration and exploitation (O'Reilly & Tushman, 2013). Services generate stable income from long-term projects with milestone-based payments, while products aim for scalable licensing and recurring maintenance fees (Cosylab, 2025a).

In fiscal year 2024, consolidated revenue totalled €23.82 million, with €20.45 million generated by the Slovenian parent and the rest distributed across subsidiaries in the US, Switzerland, Poland, China, and Japan. Only 3.3 percent of sales came from Slovenia, underscoring the company's global orientation (Cosylab, 2025a). OncologyOne remains a minority contributor but represents the firm's long-term growth bet. *"If it succeeds, it can carry the company"* (COSYLAB1).

The collapse of start-ups in 2022, in which Cosylab had exchanged work for equity, exposed the risks of venture dependency. *"Now, we focus on contracts that ensure cash flow; equity is no longer our default"* (COSYLAB4). Since then, profit responsibility has been delegated to domain leaders, embedding financial discipline into daily operations (COSYLAB2).

4 Ecosystem integration

4.1 Global market reach

Cosylab's global presence has been deliberate rather than opportunistic, rooted in the recognition that Slovenia's domestic market was too small to sustain a deep tech firm. The company *"had to be global from the very beginning"* (COSYLAB1). Embedding early in international ecosystems provided credibility and positioned Cosylab to access projects far beyond its home base (Adner, 2017).

The Mayo Clinic project was a decisive milestone. *"The US market only started opening after Mayo; if you can work with them, you can work with anyone"* (COSYLAB4). This reputational cascade, whereby one flagship reference client creates legitimacy across borders, illustrates how credibility in highly regulated environments can act as a market catalyst. Similarly, COSYLAB3 emphasised that systematic knowledge transfer amplified global reach. Methods honed in accelerator projects were intentionally adapted for use in clinical software, making Cosylab an innovation partner rather than a mere subcontractor.

Cosylab's market reach also reflects geographic diversification. European clients value reliability and continuity. US clients prioritise speed and innovation. Asian clients emphasise trust and state approval in contracting. These differences required Cosylab to build localised teams, adapt documentation, and develop cultural awareness that later increased its capabilities for expansion. Together, these experiences confirm that Cosylab's global reach rests on three reinforcing factors: flagship projects as reputational catalysts, deliberate learning from regional differences, and systematic embedding in trust-based ecosystems (Adner, 2017).

However, geographic diversification has its limits. For service activities, Cosylab now concentrates on Western markets, where collaboration dynamics align more closely with its way of working. In Asia, particularly in Japan and China, projects tend to involve stronger internal engineering teams at customer organisations, making external partnerships more difficult to sustain. Combined with distinct business cultures and longer, resource-intensive sales cycles, these factors lower the probability of success. Consequently, management places greater emphasis on Western markets for services, while maintaining a global outlook for the product business, where standardised offerings, such as OncologyOne, can scale internationally with less dependence on direct relationship-building (COSYLAB3).

4.2 Ecosystem partnerships

Cosylab's integration into ecosystems has always centred on long-term partnerships with leading scientific and medical institutions, rather than short-term contracts or formal alliances. *"Ecosystems are networks of people who know and trust each other, not just conferences or funding schemes"* (COSYLAB1). This trust-based logic explains why the company invested in sustained collaborations with CERN, ITER, the European Space Agency (ESA), and later with flagship hospitals, such as the Mayo Clinic (Cosylab, 2025a; Cosylab, 2025c).

These partnerships span scientific infrastructures, space, and medicine. At CERN, Cosylab developed and integrated control-system software for particle accelerators, including mission-critical subsystems for large-scale facilities (Cosylab, 2025b).

In ITER and other fusion programs, Cosylab contributed to the CODAC (Control, Data Access and Communication) framework and developed simulation platforms, such as the Fusion Plant Simulator (Cosylab, 2025a; Cosylab, 2025c). These roles demonstrated the company's ability to manage risk, safety, and integration in one of the world's most complex engineering projects.

With ESA, Cosylab has been active in the European Ground Systems Common Core (EGS-CC) program and the General Support Technology Programme, focusing on standardised mission-control software and reliability engineering

(Cosylab, 2025b). Exposure to ESA's rigorous engineering standards later informed Cosylab's approach to medical device software (Cosylab, 2025c). In medicine, partnerships with the Mayo Clinic, Leo Cancer Care, and Neutron Therapeutics gave Cosylab access to frontline clinical expertise and regulatory validation (Cosylab, 2025a).

Beyond bilateral collaborations, Cosylab participates in more than 65 innovation projects under Horizon Europe, EIT Health, and EUROfusion, which extend its ecosystem reach and provide early exposure to frontier technologies (Cosylab, 2025a; Cosylab, 2025c). These projects diversify funding streams while embedding the company in international consortia. By acting as an intermediary between big science and healthcare, Cosylab has positioned itself as a pivotal node in global deep tech ecosystems (Cosylab, 2025a).

4.3 Barriers and challenges to ecosystem integration

Operating in deep tech ecosystems requires overcoming multiple layers of barriers beyond technology. Credibility barriers were the most severe in the early years. *"As a small Slovenian company, we had to convince CERN that we were not just students hacking in a garage"* (COSYLAB1). This perception problem echoes broader findings that European scale-ups must prove reliability in environments dominated by incumbents and state-backed institutions (Siota et al., 2025).

Regulatory complexity represented the next major challenge, particularly when transitioning from research infrastructures to medicine. *"At CERN, if something does not work, you fix it on the fly. In medicine, if something does not work, a patient could die"* (COSYLAB3). Transitioning to oncology, therefore, required cultural adaptation and the introduction of new processes in quality assurance, documentation, and risk management.

Cultural and market barriers also shape Cosylab's geographic strategy. In Asia, particularly in Japan and China, strong in-house engineering capabilities at customer organisations and distinct business cultures make service sales more demanding. Sales cycles are typically longer and more resource-intensive, with lower success probabilities. Consequently, management prioritises Western markets for its service business, where collaboration styles align more closely with Cosylab's organisational routines and innovation-driven approach. At the same time, for the product business, the company targets global markets, as product sales require less ongoing resource commitment and are therefore more easily scalable across regions (COSYLAB3).

Financial barriers remain tied to the long innovation cycles of deep tech. Building and deploying radiotherapy systems may take five to ten years before the first patient is treated, creating pressure to secure patient investors, public R&D funding, or long-term client commitments (EIC, 2024).

Finally, institutional support in Slovenia has been limited. *"We had to seek growth capital and markets abroad; local institutions could not follow us at the scale we needed"* (COSYLAB5). This observation resonates with evidence from the European Investment Bank (2024), which shows that Europe continues to underinvest in scaling deep tech ventures compared to the US and Asia. At the same time, ecosystem-oriented institutions, such as the Slovenian Space Office, have played a supportive role in connecting companies with academia and partners. *"We link industry with academia. We have to work hand in hand … so that the product, the service, can be sold on the market"* (COSYLAB6). Together, these barriers highlight the multidimensional challenges of deep tech scaling – credibility, compliance, cultural alignment, financing, and institutional support – that require resilience and strategic adaptation at every level of the organisation.

5 Technological innovation and absorptive capacity

5.1 R&D and key technologies

Cosylab's R&D has consistently been guided by specialisation in niche, mission-critical technologies. The company is *"a niche in a niche: control systems for big science and now oncology"* (COSYLAB1). This deliberate focus reflects Adner's (2017) argument that firms succeed in ecosystems by embedding themselves deeply in interdependent structures rather than competing broadly.

A central example is proton and ion therapy for cancer treatment. Developing control software for medical accelerators requires higher levels of precision, safety, and redundancy than in research contexts. While a scientific accelerator can tolerate iterative fixes, medical devices must ensure millimetre accuracy and immediate fault detection, as patient safety is paramount. This shift illustrates how Cosylab transformed the expertise built in physics laboratories into clinically robust systems. Beyond oncology, R&D contributions to CERN's particle accelerators, ITER's fusion reactor, and ESA's space projects created the technical foundation for this transition, embedding reliability and compliance into Cosylab's culture.

Recent strategic scanning shows that the company also monitors frontier technologies, including semiconductor lithography, quantum computing, and advanced fusion. This reflects a strategy of focused diversification, applying a specialised capability in control systems across multiple adjacent domains. In this way, Cosylab reconciles Adner's (2017) emphasis on deep ecosystem embeddedness with the observation of Siota and others (2025) that deep tech firms must pursue parallel bets. Diversification thus spreads risk while reinforcing the firm's niche competence.

5.2 Technology absorption

Cosylab's transition from scientific to medical applications exemplifies absorptive capacity: the ability to acquire, assimilate, transform, and exploit external knowledge (Zahra & George, 2002). *"Much of what we do in oncology is possible because of the experience from CERN and ITER"* (COSYLAB3).

Knowledge from accelerator projects was acquired and assimilated through decades of collaboration in big science. A transformation occurred when practices were adapted to medicine, in which *"you cannot restart a patient"* (COSYLAB3). Exploitation followed in OncologyOne, which reconfigured scientific know-how into regulatory-compliant medical software. This process illustrates how organisational learning mediates technology transfer across contexts (Crossan & Apaydin, 2010).

Absorption also depends on organisational practices. Cross-project teams ensure that lessons learned in one domain migrate to another, reducing costs and accelerating delivery. For example, error detection methods from physics accelerators were systematically adapted for hospitals. Cosylab also deliberately hires physicists and engineers with interdisciplinary skills. *"We deliberately hire people who can switch domains, because flexibility is as important as expertise"* (COSYLAB2). This recruitment philosophy ensures the cognitive diversity needed to re-contextualise knowledge across ecosystems.

5.3 Competitive positioning

Cosylab operates alongside much larger global players in radiation therapy and related domains, such as Varian and Elekta, which run extensive training academies and structured career pathways (Varian, 2025; Elekta, 2025). By contrast, Cosylab offers smaller project teams, broader ownership of deliverables, and proximity to scientific users. Engineers at Cosylab frequently engage with specification, safety, integration, and commissioning within a single project arc, offering exposure to complexity rather than narrow specialisation.

Focused software firms, such as RaySearch Laboratories, provide another benchmark. RaySearch leverages close collaborations with clinics and produces a steady flow of scientific publications that feed directly into its product pipeline (RaySearch, 2025). Cosylab shares this collaborative instinct but differentiates itself by maintaining a foothold in big science delivery, which exposes it to frontier facilities and unusual system constraints that later inform the design of medical software.

Cosylab's competitiveness ultimately depends on how it organises learning. While its scale is modest, the firm has sought to integrate knowledge transfer and talent development into its everyday practice. A relevant benchmark is ASML, the European leader in semiconductor lithography, which has industrialised learning by treating it as a production system through global internships, strong university links, and internal mobility programs (ASML, 2025). Cosylab cannot replicate such scale, but the underlying principle is transferable: learning must be embedded as a routine, not offered as a perk (Crossan & Apaydin, 2010).

However, unlike these firms, Cosylab does not face many direct commercial rivals because its niche is narrow. Instead, the main competitor is often the customer's own team. In science, this typically means the internal IT or accelerator group at major research facilities, while in medicine, it includes the engineering divisions of established vendors. *"Our biggest competitor is usually the laboratory itself"* (COSYLAB3). Cosylab differentiates itself by offering integrative expertise that laboratories and OEMs prefer not to build internally.

6 Non-technological innovation

Cosylab's competitiveness rests on its people – a workforce that combines scientific depth with disciplined delivery. The company employs more than 250 employees, with many of them holding advanced degrees and doctorates (Cosylab, 2025a; Cosylab, 2025b). This talent base is consistent with the demands of accelerator control and medical device software, where technical excellence and regulatory compliance intersect. Weekly internal lectures, biannual development talks, and ISO-certified processes create a learning architecture that integrates external ideas from laboratories, clinics, and device makers into repeatable practice. Such routines exemplify the acquisition, assimilation, transformation, and exploitation processes described in the absorptive capacity literature (Zahra & George, 2002).

6.1 Talent acquisition and development

Cosylab's recruitment pipeline is anchored in universities and the big science community. Engineers are drawn not only by salaries but by the opportunity to work on globally significant projects. *"The strongest pull factor is the chance to work on complex global projects rather than on narrow tasks"* (COSYLAB3). Reputation also plays a role: founder visibility at lectures and conferences attracts engineers who value challenge and impact (COSYLAB2). Internships and project-based collaborations often convert into full-time positions, creating a steady inflow of talent (COSYLAB5).

Within the company, employees encounter a structured learning cadence. Weekly lectures maintain a shared technical vocabulary across domains, while biannual development talks set milestones for growth during long project cycles (Cosylab, 2025b). Mentorship and project reviews support the transfer of tacit knowledge across teams and sites. Leaders describe these practices as a response to increasing organisational complexity and global expansion (COSYLAB3). In the medical division, ISO 13485 competence management ensures traceability and documented training, embedding regulatory standards directly into people development (Cosylab, 2025a).

6.2 Organisational culture and HR innovations

Cosylab has shifted from a functional structure to a matrix organisation, reflecting the need to balance technical expertise with market orientation. On one axis, functional departments (delivery, HR, finance, sales) remain; on the other, domain units (fusion, medicine, accelerators, quantum) provide strategic focus. Domain leaders lack formal authority over functional staff, relying instead on influence and consensus-building. *"Our leadership works through persuasion and trust, not command"* (COSYLAB5).

This structure has cultural implications. It requires employees and managers to operate collaboratively across boundaries, reinforcing a project-driven mindset. From an HR perspective, Cosylab introduced HR business partners to bridge functions and domains, ensuring that recruitment, development, and conflict resolution are grounded in delivery realities (COSYLAB3). Leaders credit this innovation with reducing bottlenecks and mitigating the risks of departmental "tribalism" during growth.

The matrix also supports motivation and retention by exposing employees to multidisciplinary projects. *"The company's greatest strength is attracting people who want challenges, not routine"* (COSYLAB1). This resonates with research highlighting that non-technological innovations in structures and HR practices directly enhance innovation outcomes (Crossan & Apaydin, 2010).

6.3 Leadership complementarity through the PAEI lens

The interviews reveal how Cosylab's leadership team covers the complementary roles described by Adizes' (1999) PAEI model. The CEO embodies the entrepreneur, generating vision and taking risks. *"I step back so the team can learn by doing, even when mistakes are costly"* (COSYLAB1). The COO acts as an integrator, stabilising collaboration and translating between technical and organisational agendas (COSYLAB2). The CDO plays the role of a producer, focused on project throughput and removing delivery bottlenecks (COSYLAB3). The CFO represents the administrator, institutionalising financial discipline and portfolio visibility (COSYLAB4).

Creative tension between these roles is accepted as a condition of deep tech work. COSYLAB3 remarked that if only integrators were in charge, *"the company would move too slowly,"* while if only entrepreneurs led, *"chaos would follow"*. The balance between entrepreneurial exploration and administrative discipline reflects the ambidexterity required for deep tech competitiveness (O'Reilly & Tushman, 2013). It also connects to the ecosystem perspective, where leadership is less about internal heroics and more about managing interdependencies with laboratories, device manufacturers, clinics, investors, and regulators (Adner, 2017).

6.4 Linking HR and corporate strategy

This competitive reality has strategic implications for HR and incentives. To add credible value, Cosylab must cultivate people who can integrate with client teams rather than merely replicate them. That requires engineers skilled in domain storytelling, requirements discovery, and integration discipline, alongside technical excellence. Incentives must reward partner outcomes, not just internal milestones. The company has already moved in this direction through stronger domain leadership, reusable product modules, and more professionalised sales (Cosylab, 2025c). These adjustments reflect a broader lesson: in deep tech, the line between partner and competitor often blurs, and firms must position themselves as indispensable collaborators within ecosystems (Adner, 2017).

While Cosylab's reputation is built on high-end engineering, non-technological innovation has been equally decisive for performance (Cosylab, 2025c; Crossan & Apaydin, 2010). As Crossan and Apaydin (2010) argue, organisational and business model innovations can amplify technological advances in knowledge-intensive industries.

Cosylab's shift from one-off projects to long-term service-level agreements (SLAs) and maintenance contracts stabilised cash flows and created feedback loops that improved the software (Cosylab, 2025c). This business model innovation has been transformative in terms of scalability and risk profile (Cosylab, 2025b; Crossan & Apaydin, 2010). Process innovations, such as standardisation, certification (ISO 13485), and quality management, have further reduced risk for clients and differentiated the firm from competitors (Cosylab, 2025c).

Cultural and HR innovations also reinforce competitiveness. A flat hierarchy and project-driven teams allow senior scientists and young developers to collaborate directly, promoting rapid problem-solving in complex environments. Mentorship, doctoral support, and weekly technical lectures embed learning into routines, consistent with the absorptive-capacity lens (Zahra & George, 2002). *"If someone completes a PhD while working on a project, we all gain; the person grows, the team grows, and the company grows"* (COSYLAB2). This aligns with evidence that digital and entrepreneurial skills must be continuously cultivated in deep tech firms (Kaminsky et al., 2024), suggesting Cosylab could extend its system with modules on regulatory strategy and product management.

Together, Cosylab's innovation system integrates technological and non-technological dimensions. By reconfiguring business models, codifying processes, and investing in people, the firm ensures that scientific breakthroughs are translated into sustainable products and services within demanding multi-partner markets. Further progress could come from formalising shared talent pools with universities and partners. European evidence shows that cross-company mobility and joint doctoral supervision grow scarce skills (Siota et al., 2025). For Cosylab, structuring these collaborations could reduce hiring friction and accelerate onboarding.

7 Conclusion and future outlook

The case study of Cosylab shows how a mid-sized European deep tech firm sustains global competitiveness by combining technological specialisation with ecosystem integration and organisational innovation. From its origins at the Jožef Stefan Institute to its current role in science and oncology, the company illustrates that excellence in engineering alone is insufficient; non-technological innovations in governance, HR, and business models are equally decisive.

The main insights and their strategic implications are summarised in Table 3. The findings underscore three forward-looking priorities. First, diversification across domains, such as photon therapy, semiconductors, and quantum, will help balance risks tied to long development cycles. Second, OncologyOne represents the most promising vehicle for scalable growth and, therefore, warrants sustained commercialisation efforts. Third, strengthening professionalised sales and marketing capabilities is essential to translate technical credibility into broader market penetration, especially in the United States and Asia.

Table 3. Key findings and strategic implications for Cosylab

Dimension	Key findings	Implications/recommendations
Technological innovation	Cosylab's specialisation in control systems for big science created a base for oncology applications through absorptive capacity.	Continue diversifying into adjacent domains (photon therapy, semiconductors, quantum) to mitigate long-cycle risks.
Ecosystem integration	Trust-based partnerships with CERN, ITER, and the Mayo Clinic opened access to highly regulated markets.	Deepen ecosystem participation to secure early access to frontier technologies and legitimacy.
Human resources & culture	A highly educated workforce, a matrix structure, and internal learning routines sustain competitiveness despite a small scale.	Maintain talent pipelines and embed HR practices that connect directly to ecosystem strategy.
Governance & leadership	Balanced leadership roles (PAEI) and stricter financial discipline, implemented after 2022, ensured resilience.	Preserve ambidexterity between entrepreneurial exploration and administrative control.
Market engagement	Strong foothold in the US and EU; cultural misfit has limited progress in China.	Prioritise Western markets in the near term; treat Asian expansion selectively and opportunistically.
Growth trajectory	OncologyOne is currently a minority revenue stream, but it has the potential to carry the company.	Invest in OncologyOne commercialisation and strengthen professional sales/marketing to scale globally.

Source: Based on own analysis of interviews, company reports, and secondary sources.

More broadly, Cosylab's trajectory highlights the importance of trust-based ecosystems, absorptive capacity, and talent pipelines for scaling deep tech ventures. For Slovenia's innovation system, the case suggests that patient capital, international integration, and mission-oriented programs remain critical enablers of firms seeking to compete in high-risk, high-reward sectors.

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EVALUATING BIOTECH ECOSYSTEM POTENTIAL IN SLOVENIA

1 Introduction

The global biotechnology sector is expanding rapidly, driven by scientific breakthroughs, investment, and sustainability pressures. It plays a pivotal role across health, agriculture, energy, and industry, making it central to the emerging bioeconomy (Wei et al., 2022). Multiple countries have adopted bioeconomy strategies to boost competitiveness, with biotechnology serving as both a driver and a beneficiary. Slovenia shares common Central and Eastern European constraints – limited risk capital, a small market, talent bottlenecks, and fragmented policy support (Szczygielski et al., 2022). Yet it benefits from a skilled workforce, still relatively favourable labour costs, which are increasing due to higher taxes, and international connections (European Commission, 2024a). Recent investments by Novartis, Sandoz, Porton Pharma and Sartorious, including new production and development facilities, underscore the sector's national importance (Davis Plüss & Stegmüller, 2024).

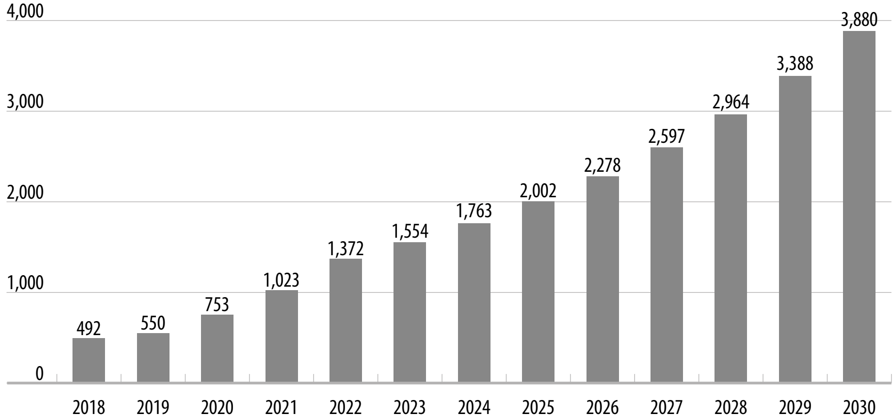
This chapter evaluates the current state and future potential of Slovenia's biotechnology ecosystem. It aims to identify the barriers, strengths, and pathways for Slovenia to position itself as a regional biotech hub. It begins with an overview of the industry, followed by an analysis of key drivers of competitiveness: financing and investment, talent and human capital, and policy frameworks and governance. Building on this foundation, the chapter presents empirical insights from interviews with Slovenian biotech stakeholders, before concluding with a discussion of the broader implications and the strategic pathways needed to support the development of a more dynamic and innovation-driven biotech ecosystem.

2 Industry overview

Biotechnology is increasingly recognised as a transformative force in addressing some of humanity's most pressing challenges: an ageing population and rising healthcare needs, the demand for sustainable food and energy systems, and the scientific breakthroughs driving the green transition. Biotechnology is often defined as the application of science and technology to living organisms, their parts, products, and models, to alter living or non-living materials for the production of knowledge, goods, and services (European Council, 2023). This cross-disciplinary nature is reflected in its applications: red biotechnology (medical and pharmaceutical), green biotechnology (agri-food), white biotechnology (industrial and environmental), and the emerging field of blue biotechnology (marine and aquaculture). Together, these domains address urgent societal challenges while creating new business opportunities (Kafarski, 2012).

Globally, more than 60 countries have adopted dedicated bioeconomy strategies, recognising biotechnology's potential to reduce dependence on fossil resources, stimulate innovation, and generate high-value jobs (Wei et al., 2022). Among the current frontrunners, the United States stands out for its translation capacity. A patent-family analysis covering the period 2000–2019 attributes 53 percent of 105,493 biotechnology patent families to the US, and shows strength at mid-levels of technology readiness and export orientation (Quintella et al., 2024). China's scale-up is driven by top-down programmes and sustained science-and-technology investment (approximately 2.2 percent of GDP in 2019, the second largest expenditure after the USA), alongside dense high-tech zones that host much of the country's biomedical and biotechnology R&D (Schmid & Xiong, 2021). Within Europe, Germany and France remain central drivers of biotechnology, leveraging their industrial scale and strong pharmaceutical industries, supported by national bioeconomy strategies and innovation councils (Motola et al., 2018). Switzerland has established itself as a global leader in life sciences, with world-class research institutions and a dynamic biotech industry that accounts for a significant share of national exports (Swiss Biotech Association, 2025). Ireland has become a premier location for multinational biotech and pharmaceutical R&D, attracting substantial investment through favourable policy frameworks and strong public–private collaboration (Sakellaris et al., 2023). The Nordic countries, particularly Denmark and Sweden, stand out through Medicon Valley, one of Europe's strongest life-science clusters. Hosting more than 1,100 life-science companies and over 65,000 employees, the region demonstrates how cross-border collaboration can generate critical mass in biotech R&D, talent development, and investment attraction (Medicon Valley Alliance, 2024).

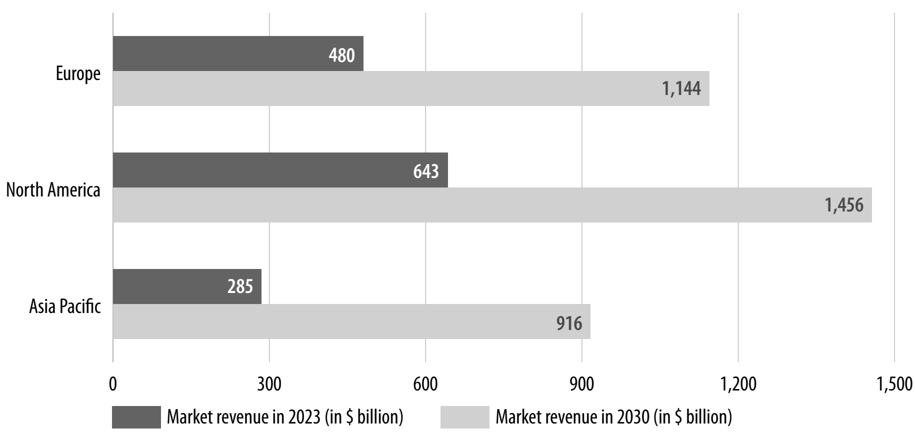
Figure 1. Global biotech market size and outlook from 2018 to 2030 (in $ billion)



Source: Grand View Research (2023).

The global biotechnology market reached $1,554 billion in 2023 and is projected to expand to $3,880 billion by 2030, which implies a compound annual growth rate (CAGR) of approximately 14 percent from 2024 to 2030 (Figure 1, Grand View Research, 2023). The trajectory reflects steady growth since 2018 and is underpinned by continued investment in biopharmaceuticals, synthetic biology, and biomanufacturing, as well as the broader diffusion of bio-based processes into industrial applications (Omega Consulting, 2025).

Figure 2. Market revenues in the biotechnology sector in 2023 and 2030 (forecast) in Europe, North America and the Asia-Pacific region



Source: Grand View Research (2023).

North America remains the largest market, increasing from roughly $643 billion in 2023 to around $1,456 billion by 2030 (with a CAGR of around 12.4 percent). Europe is expected to grow from approximately $480 billion to roughly $1,144 billion (CAGR around 13.2 percent). The Asia-Pacific region is the fastest-growing region, rising from around $285 billion in 2023 to approximately $916 billion by 2030 (with a CAGR of around 18.2 percent) (Figure 2, Grand View Research, 2023). These patterns are consistent with Europe's established cluster base in Germany, France, Switzerland, Ireland and the Nordics, and the rapid scaling of biomanufacturing capacity across Asia. At the same time, the next wave of innovation is increasingly shaped by the convergence of biotechnology with digital technologies, including AI-enabled design and advanced automation (OECD, 2025).

Slovenia's biotechnology ecosystem is not young (company Lek was for example established already in 1946) and is recently evolving faster, especially with investments of Sandoz and Novartis. It brings together universities and public research organisations, emerging start-ups and scale-ups, pharmaceutical manufacturers, and support institutions. For the purposes of this analysis, the core of the sector is defined using the NACE Rev. 2 code 72.1 (research and experimental development on natural sciences and engineering) and includes pharmaceutical manufacturing, where relevant, under code 21 (manufacture of basic pharmaceutical products and pharmaceutical preparations) (European Union, 2025). In 2023, the Slovenian pharmaceutical manufacturing sector (NACE 21) employed 1,871 people in R&D, while research activities under NACE 72.1 accounted for 1,794 people. Together, this represents more than 3,600 people engaged in biotechnology-relevant R&D across the business sector (SURS, 2024a). Spending patterns reflect this dual structure: internal R&D expenditure reached €322.5 million in pharmaceutical manufacturing compared to €89.1 million in research activities (SURS, 2024b). Manufacturing clearly dominates in both employment and spending, while the lower levels in 72.1 point to a structural imbalance between Slovenia's strong scientific base and its more limited commercial scaling capacity. Additionally, unlike some larger countries, Slovenia does not maintain an official list of companies classified under biotechnology; in practice, most industrial activity is concentrated in pharmaceuticals and the medical segment of biotech.

While direct R&D data specific to biotechnology remains limited, broader indicators from Slovenia's life sciences infrastructure provide valuable insights. The Natural Science & Engineering Research industry in Slovenia, which encompasses life sciences, pharmaceuticals, biotechnology, and medical and health sciences, achieved a market size of €496.6 million in 2025, supported by 1,112 businesses, with a CAGR of 4.9 percent between 2019 and 2024 and continued growth expected in the coming years (IBISWorld, 2024). Complementing this, the Slovenian Biotech Database identifies around 38 active biotech-related firms across sub-sectors, including therapeutics, diagnostics, R&D services, medical technology (medtech), and digital health (Venture Valuation, 2025). The sector is anchored by leading pharmaceutical manufacturers, such as Lek (Sandoz), and Novartis Slovenia, which together accounted for more than two billion of euros in annual revenues in 2024 and major investments, positioning Slovenia as a regional hub in pharmaceuticals and life sciences.

Together, the patterns in Figures 1 and 2 situate biotechnology as a large and fast-growing domain, organised as an ecosystem, which means an interdependent network of actors (universities and public research organisations, firms across NACE 72.1 and 21, intermediaries, investors, regulators and end-users) linked by knowledge flows, shared infrastructures and formal rules. In such systems, outcomes depend less on any single organisation and more on coordination across complementary assets: scientific capability and skilled labour, access to risk finance, fit-for-purpose facilities, effective technology transfer and standards/regulation, and access to lead markets at home and abroad (Cobben et al., 2022; Wohlfahrt et al., 2019). In Slovenia, the combination of a strong research base and expanding biopharma production puts these complements at the centre of near-term priorities – financing, talent, commercialisation capacity and policy coordination. However, Slovenia really lacks shared infrastructure in area of biotechnology.

3 Key drivers of biotech competitiveness

The competitiveness of biotechnology ecosystems typically depends on a set of interrelated drivers: (i) access to financing and investment, (ii) availability of skilled human capital, and (iii) policy and regulatory frameworks (National Academies of Sciences, Engineering, and Medicine, 2020). These drivers provide the analytical framework for the empirical assessment of Slovenia's biotech ecosystem in the following sections.

3.1 Financing and investment landscape

Biotech is capital-intensive, with long development cycles and high regulatory costs. In the EU, Horizon Europe is the main source of non-dilutive funding, with success rates of around 16 percent and narrowing gaps between Widening and non-Widening states – a benefit for smaller economies, such as Slovenia (European Commission, 2024b; Van Schaijik, 2025).

At the national level, co-investment and guarantee schemes help attract private capital. Austria exemplifies this trend, with research intensity exceeding three percent of GDP in 2024, supported by significant public co-funding (OECD, 2024a). Croatia has channelled EU Recovery and Resilience Facility funds into research infrastructure and technology transfer, though its venture market remains underdeveloped (European Commission, 2024b). Hungary leverages the NKFIH Innovation Fund to de-risk early-stage research (European Commission, 2025), Slovakia operates the Slovak Investment Holding co-funding scheme (Slovak Investment Holding, 2024), and Italy combines regional incentives with the Fondo Nazionale Innovazione VC vehicle (CDP Venture Capital, 2024). These cases highlight how Slovenia competes within a broader Central and Eastern European financing ecosystem.

Slovenia has begun deploying similar instruments. The EIF–SID Bank InvestEU guarantee of €42 million[1] is unlocking new lending for innovation, while the Slovene Equity Growth Investment Programme (SEGIP) commits public anchor capital into private funds (European Investment Fund, 2023). "Vesna" deep tech VC vehicle now targets technology transfer and Intellectual Property (IP) protection in Slovenia and Croatia (Vesna VC, n.d.).

Biotechnology competitiveness also depends on specialised infrastructure. Slovenia has used EU Recovery and Resilience Facility funds to upgrade laboratory and digital research capacity, and universities are expanding shared facilities for start-ups. Still, OECD assessments highlight persistent gaps in pilot-scale labs and bioprocessing facilities, often forcing firms to seek partnerships abroad (OECD, 2022).

Demonstrating successful exits is essential for attracting later-stage capital. Slovenia provides such an example: BIA Separations, based in Ajdovščina, was acquired by Sartorius for €360 million in 2020 – proof of the region's scale potential (Sartorius, 2020).

1 Program SID DIGITALEN.

3.2 Talent and human capital development

Biotechnology competitiveness hinges on specialist talent – from scientists and bioprocess engineers, skilled civil engineers, physics, biochemists, biotechnologists, biologists, chemical engineers, IT engineers to regulatory and clinical managers. Slovenia has a strong academic foundation. Its share of adults holding a doctoral degree is among the highest in the world (World Population Review, 2025). Its Science, Technology, Engineering, and Mathematics (STEM) pipeline is also robust: between 2016 and 2022, the share of tertiary STEM graduates increased by 4.5 percentage points to 29.5 percent, surpassing the EU average of 26.6 percent. Yet this strength coexists with warning signs. In 2023, tertiary attainment among 25–34-year-olds declined to 40.7 percent, slipping below the EU average for the first time in a decade (European Commission, 2024b). More broadly, the EU still lags behind global competitors, such as China and the USA, in producing large cohorts of STEM specialists (UNESCO, 2023), underscoring why Slovenia must safeguard and retain its talent base. This divergence suggests that while Slovenia produces a strong share of STEM graduates in the EU context, its broader education system may be losing momentum. Combined with the country's small market size, this increases the risk of talent out-migration and a shortage of experienced managers needed to scale biotech firms.

Policymakers have begun to address these pressures. New study programs that cover the fields of biotechnology were established, for example bioinformatics at the University of Ljubljana and pharmacy at the University of Maribor. In 2025, Slovenia introduced a five-year reduction of seven percent in the personal income tax base, applicable to both returning Slovenians and foreign experts relocating to the country (Kovačič, 2024). The measure aims to strengthen the domestic talent pool by attracting internationally experienced professionals.

Nevertheless, these initiatives remain fragmented and insufficiently scaled. Interviewees and prior studies stress that without more robust mechanisms – particularly for mid-stage commercialisation support and managerial training – the talent gap will persist (European Commission, 2024a). Fiscal incentives alone cannot offset structural weaknesses in education–industry linkages.

3.3 Policy frameworks and governance

At the European level, research and innovation (R&I) policy has shifted from funding excellence alone toward knowledge capitalisation – ensuring publicly funded research is translated into economic and societal value. The Council Recommendation (EU) 2022/2415 establishes common principles for technology transfer, intellectual asset management and stakeholder co-creation across Member States, providing a benchmark for national systems (European Council, 2022).

Slovenia has articulated long-term industrial and innovation priorities that are relevant for biotechnology. The Industrial Strategy 2021–2030 targets a "green, creative and smart" transformation, with objectives to raise productivity, strengthen entrepreneurship and innovation, and align incentives over the decade (Ministry of Economic Development and Technology, 2022). These commitments complement higher-education entrepreneurship and Technology Transfer Office (TTO) efforts already underway, and they provide a formal policy scaffold for life-science specialisations.

Despite the policy intent, implementation is constrained by structural issues in R&I governance. The OECD Economic Survey of Slovenia identifies persistent weaknesses in knowledge and technology transfer, including unstable TTO funding, limited incentives for researchers, and lengthy, cumbersome procedures for establishing university and public research organizations (research institutes) spin-offs – including the need for government consent – which reduce speed and clarity around IP and discourage commercialisation (OECD, 2022). A recent Technical Support Instrument diagnostic further concludes that governance is fragmented across ministries, cross-sector coordination is weak, and funding is unstable and insufficiently integrated across the innovation chain, leading to gaps in Technology Readiness Level (TRL) stages and limiting strategic continuity (European Commission, 2024a).

4 Analysis of the biotech sector in Slovenia

4.1 Research goals and methodology

The primary objective of this study is to examine the current state of Slovenia's biotechnology sector, focusing on its challenges, opportunities, and systemic barriers. The analysis is structured around five key themes: resources and infrastructure, human and institutional capabilities, market orientation and competitiveness, the business environment, and the sector's strategic outlook.

Table 1. Sample characteristics

Organisation	Interviewees	Size*	Code
Company 1	Chief Scientific Officer	SME	BIOTECH1
Company 2	Managing Director	SME	BIOTECH2
Company 3	Managing Director	SME	BIOTECH3
Company 4	Managing Director	SME	BIOTECH4
Company 5	Managing Director	Micro	BIOTECH5
Company 6	Managing Director	SME	BIOTECH6
Company 7	Managing Director	SME	BIOTECH7-1
	Chief Commercial Officer		BIOTECH7-2
Financial stakeholder	Investor	SME	BIOTECH8
Research Institution 1	Managing Director	Not applicable	BIOTECH9-1
	Chief Quality Officer		BIOTECH9-2
Research Institution 2	Managing Director	Not applicable	BIOTECH10-1
	Head of Technology Transfer Office		BIOTECH10-2
Company 8	Chief Business Officer	Micro	BIOTECH11
Company 9	Managing Director	Large	BIOTECH12-1
	Strategic Program Manager		BIOTECH12-2
Financial Institution	Head of Development	Large	BIOTECH13-1
	Development Specialist		BIOTECH13-2
Business Accelerator	Managing Director	Micro	BIOTECH14
Company 10	Managing Director	SME	BIOTECH15
Company 11	Member of the Board	SME	BIOTECH16

* Company size in Slovenia is defined by the Companies Act (ZGD-1), based on three criteria: (i) average number of employees in the financial year, (ii) net sales revenue, and (iii) value of assets (companies must meet at least two of the criteria). Micro: less than 10 employees, less than €700,000 revenue, less than €350,000 assets; SME (small and medium-sized companies): less than 250 employees, less than €40 million revenue, less than €20 million assets; Large: companies exceeding these thresholds (ZGD-1, 2023).

Source: Own work.

Semi-structured, in-depth interviews were conducted with directors, executives, researchers, investors, and representatives of key organisations in Slovenia's biotech ecosystem, with particular focus on smaller firms. Sample characteristics are presented in Table 1. In total, 16 interviews were conducted between August 25 and September 4, 2025, mostly at organisational premises, with three carried out via video call. Open-ended questions captured diverse perspectives on barriers and enablers shaping the Slovenian biotech ecosystem.

4.2 Insights from the interviews

The development of biotechnology in Slovenia can be understood through the lens of a start-up journey – not because the ecosystem is limited to start-ups, but because this perspective captures the sequence of challenges that shape the entire sector. Unlike digital ventures, where an idea and a laptop may be sufficient, biotechnology demands capital-intensive infrastructure, such as wet and dry laboratories, pilot manufacturing, testing with or in living organisms, patient capital, and regulatory approvals from the very beginning. *"Slovenia could be the new Switzerland in biotech. Not literally, of course, but the potential is there if we can channel pharma expertise into start-ups, provide labs and infrastructure, and build an ecosystem"* (BIOTECH2).

4.2.1 Resources and infrastructure

Risk aversion has long been identified as a structural weakness in Slovenia's innovation system, where both researchers and investors tend to prioritise safe choices over uncertain ventures. This stigma creates a bottleneck at the first step: deciding whether to start a company at all. Researchers in particular are cautious about entrepreneurship, worried that failure would damage their academic careers and reputations. *"The system does not push them to take risks. Researchers do not want to risk their careers on failure – they were always excellent students, excellent researchers, and they do not want mistakes on their record. In the US, if you are 30 and have not failed at least once, people worry you are not trying hard enough. Here, failure is seen as a career-ender. That is a mindset issue"* (BIOTECH1).

The contrast with international practice was repeatedly emphasised: while failure abroad is seen as a necessary step toward success, in Slovenia it remains stigmatised. *"An American colleague told me he was amazed by how smart Slovene people are, but also how afraid they are to make mistakes. In the US, it is widely accepted that nine out of ten start-ups fail. Here we are too cautious"* (BIOTECH6). This cultural caution is reinforced by negative public perceptions of entrepreneurial success. *"In society, there is resentment toward success. If an entrepreneur makes money, people say it must be shady. But if a cyclist earns millions, everyone applauds. This mentality holds us back"* (BIOTECH7-1).

This mindset has consequences beyond personal hesitation. Even when researchers or entrepreneurs are willing to take the leap, the lack of adequate infrastructure makes the path far more difficult. Unlike digital ventures, which can start with little more than a laptop, biotechnology requires specialised laboratories, equipment, and compliance structures from the outset. In Slovenia, these conditions are often missing, forcing founders to improvise. *"Starting up in Slovenia is much harder compared to Germany. When we set up our lab, we literally bought equipment on Alibaba and built it ourselves. In Germany, you have access to fully equipped labs from the start"* (BIOTECH2). *"Starting a biotech company here is like starting Formula One – you need labs, equipment, and money upfront. In IT, you only need a laptop. That is why there are thousands of IT start-ups, but few biotech ones"* (BIOTECH2). However, *"some municipalities, Ajdovščina for example, is planning to build Biotechnopoli, research and technological park, which will combine research, innovation and business in the fields of biotechnology, green technologies and digitalization. This will allow the playground for start-ups in biotechnology field"* (BIOTECH6).

Others stressed that Slovenia's challenge is not unique but reflects a gap compared to international standards. *"In well-developed biotech ecosystems, like for example Cambridge (MA), Minneapolis (MN) in the USA, or in countries, such as the UK, Austria, Germany, Denmark, laboratory infrastructure is built through public and/or private investments and is available for any biotech venture founder"* (BIOTECH16). Without similar support, Slovenian start-ups face higher costs and greater risk, making them less attractive to investors and talent.

Even when infrastructure barriers are addressed, financing emerges as one of the most critical bottlenecks in Slovenia's biotechnology ecosystem. Biotech ventures require patient capital to survive long development cycles, but interviewees agreed that domestic funding remains scarce, short-term oriented, and poorly suited to the sector's needs. This mismatch leaves start-ups vulnerable in what many call the "valley of death" – the precarious stage after seed money is used up but before revenues are generated. *"Investors expect you to know the steps to access capital, and to understand the 'valley of death' stage – when you have had your first injection of capital, but your products are not yet generating revenue, and you are running short of cash. That is a dangerous stage"* (BIOTECH1).

This gap forces entrepreneurs into precarious strategies, from relying on foreign banks to using personal savings. *"Slovenian banks are not open to high-risk investments. We survived thanks to some foreign banks that were more open to risk. Without them, we would not have made it"* (BIOTECH2). Others described fully self-funding their ventures, even at great personal cost: *"My wife and I invested the initial capital of about half a million euros. Since then, we have been sustaining ourselves entirely from our own operations"* (BIOTECH4).

Instead of long-term investment strategies, the financing culture in Slovenia is often geared toward short-term gains, leaving biotech ventures without the long-term capital they need. *"In Slovenia, private long-term capital is basically non-existent. Investors want returns in two to three years, which works well for IT or digital start-ups, but not for biotech companies. Biotech takes five, ten years, sometimes more. Without patient money, it is almost impossible"* (BIOTECH8). The problem goes beyond limited capital to a deeper cultural issue: even when major exits occur, the returns are rarely reinvested in innovation. *"We have had only one real unicorn in Slovenia, and even that one reinvested mostly in real estate, not start-ups. That is a big problem – successful exits should recycle capital back into risky ventures, especially biotech"* (BIOTECH8). Without this reinvestment loop, the ecosystem remains dependent on scarce grants or foreign capital, making it difficult for biotech firms to scale beyond the early stages.

Some institutional innovations are beginning to emerge, such as Slovenia's first deep tech technology transfer fund, Vesna, though interviewees questioned whether it has the scale to meet sectoral needs. *"The gaps in Slovenia are huge, the needs are big, but the opportunities are also there. Vesna is still a relatively small fund, the first of its kind. They are now in a flagship position in the region – they need to prove this model can attract private investors. If they succeed, follow-on funds will come, maybe several"* (BIOTECH13-1). Even at the European level, however, biotech capital remains concentrated in Western hubs, resulting in the region being underrepresented. *"Major ticket size investors or venture capitalists that systematically invest in biotech innovations in Europe can be counted on fingers of both hands, and they are mostly located in Western European start-up hubs, and none of them are present in or truly actively or systematically scout for investments and/or invest in Eastern and South Eastern European countries"* (BIOTECH16).

Additionally, *"with the recent commitment of EU to boost €800 billion in European plan for defence spending, there is a momentous opportunity for Slovenia to leverage on its knowledge and skill in the sector and instead in arms, invest in critical infrastructure, that can be leveraged for dual use for production of strategically important active pharmaceutical ingredients (e.g. antibiotics) that are in high demand and where Europe is highly dependant on supply of these from other global superpowers (e.g. China, India)"* (BIOTECH16).

4.2.2 Human and institutional capabilities

Even when infrastructure and financing are in place, companies still face a fundamental question: who will drive the science forward? Slovenia produces capable graduates, but the pool of specialised biotech professionals is small, creating intense competition for talent. *"Another big obstacle is the lack of people. There are simply not enough biotech professionals in Slovenia. Right now, we are literally fighting for people"* (BIOTECH3). *"The shortage is most acute in highly specialised roles, where the search can take months"* (BIOTECH4).

Retention is equally challenging. Interviewees described constant "poaching" between companies, with younger generations, in particular, being quick to change jobs for small salary differences. *"Retention is a big challenge. There is a lot of 'stealing' of talent between companies. With Gen Z, it is even harder – they switch jobs much faster, sometimes for just €100 or €200 more"* (BIOTECH3). Large pharmaceutical investments exacerbate the issue, draining universities and start-ups of their best researchers. *"On a scale from one to ten, I would describe the situation as a nine – very, very difficult to recruit and retain people. With all these investments by big pharmaceutical companies, they will recruit thousands. That will drain universities and institutes, and it is already a problem"* (BIOTECH15).

The academic sector is already feeling the consequences. *"This year is the first year we did not have enough applications for PhD scholarships – the first time ever. After finishing PhDs here, almost all of them move to industry, mainly because salaries in academia are much lower"* (BIOTECH9-1). Others emphasised that public sector salary regulations further limit competitiveness. *"The system of salaries in the public sector is strictly regulated by classes of salaried employees, and so is the system for rewarding employees, which makes salaries in the public sector uncompetitive compared to salaries of employees in the private sector, where no legal limitations exist"* (BIOTECH16).

Start-ups try to adapt by hiring younger graduates and investing in their training. *"Our strategy is to hire young people straight out of university. That makes recruitment somewhat easier, but it means more investment from our side"* (BIOTECH2). To retain them, companies emphasise soft factors, such as environment and purpose. *"We also try to create a good working environment, not just good projects: soft skills training, work–life balance, certifications. It is not easy, but surveys in Slovenia show that money is only the fourth motivator"* (BIOTECH10-1). Others stressed that many researchers are also intrinsically motivated. *"Some genuinely want to contribute to society – for example, in biotech, to develop something useful for humanity. Others want to build a success story for themselves. So, there are motivations beyond salary"* (BIOTECH13-2).

Still, interviewees agreed that policy disincentives undermine the sector's ability to attract the kind of senior, internationally experienced professionals that are most needed to scale. Taxation was mentioned repeatedly. *"We still have too much taxation on salaries. For example, we proposed removing the age limit on the seven percent relief for returnees and increasing it to 17 percent. That would significantly increase the net income of highly educated workers, allowing Slovenia to compete for highly skilled and talented individuals with other European countries"* (BIOTECH14). Others criticised the way performance rewards are taxed. *"Highly skilled and well-paid professionals in Slovenia are, in a way, penalised when receiving periodic bonuses for their personal or business performance, as the taxation on such rewards or bonuses is not limited, but in fact potentially substantially increases the tax on income"* (BIOTECH16). The administrative burden of bringing in talent from abroad was also flagged as a barrier. *"Employing a highly educated, skilled and trained individual from the third country and bringing them to Slovenia can take several months, with significant time required to navigate complex and often unclear bureaucratic procedures"* (BIOTECH16).

Even when firms manage to recruit and train teams despite the competitive labour market, the question remains how to channel this talent into viable businesses. This makes spin-outs and technology transfer a crucial, yet fragile, link in Slovenia's biotechnology ecosystem. Despite recent legal reforms allowing research organisations to create spin-offs, progress is slow due to bureaucratic hurdles and weak institutional support. "*A public research organisation can only create a spin-off if it first adopts internal rules approved by the Ministry. So far, only two such rulebooks have been submitted, and both are stuck in inter-ministerial coordination. This means that in practice, no spin-offs are being created"* (BIOTECH13-1). The absence of structured support leaves many ventures underdeveloped. *"Our spin-outs are premature babies. We need incubators within institutes, supported by the government, until companies mature enough to go out on their own"* (BIOTECH11).

Even when spin-outs are established, protecting intellectual property remains a major challenge. Knowledge is recognised as the main commercial asset, yet resources to defend it are limited. *"IP is our main asset. If we protect knowledge, that is something we can commercialise. The problem is that we do not* *have enough resources to protect all our patents. Ideally, we would patent and commercialise quickly, but it is not always possible"* (BIOTECH10-2). Without stronger IP protection, even promising innovations risk being lost before reaching the market.

Despite these difficulties, several interviewees emphasised the potential of spin-offs and spin-outs as an effective path into biotech entrepreneurship. By leveraging university resources and lowering costs, they can provide a bridge between research and commercialisation. *"Spin-offs and spin-outs are one of the best ways to start biotech companies in Slovenia. They can still use university equipment, get support from professors, and build with much lower costs"* (BIOTECH3). Research institutions are also beginning to adapt. *"Researchers are not very skilled in developing products or technologies for commercialisation. That is why we encourage younger researchers to go on this path, and we offer them education, lectures, and support"* (BIOTECH9-1). Another highlighted the significance of the legal shift: *"Until 2022, we were not allowed to generate spin-offs – the legislation did not allow it. These existing spin-outs have attracted more than €6 million in the last decade and employ more than 20 highly skilled people"* (BIOTECH9-2). Yet these examples remain the exception rather than the rule. Experiences from related deep tech sectors suggest that systemic barriers persist, with technology transfer offices underfunded and reliant on informal networks, leaving many researchers dependent on personal connections rather than institutional support (Domadenik Muren et al., 2025).

4.2.3 Market orientation and competitiveness

The next challenge is turning science into sales. Interviewees agreed that commercialisation is one of the weakest points of the ecosystem, with scaling from research to marketable products requiring credibility, specialised skills, and large amounts of capital. *"The biggest obstacle is financing the scale-up phase. Research may succeed, but scaling requires millions. Independent start-ups struggle to find partners who can provide capital and access to markets"* (BIOTECH14).

Beyond financing, commercialisation is hindered by a shortage of business development and sales expertise. Several interviewees stressed that scientific excellence alone does not translate into market success. *"Where we really struggle is with sales talent. There is a mentality in Slovenia that sales is not prestigious. But in reality, all R&D and innovation is wasted if you cannot sell what you develop"* (BIOTECH7-2). The same interviewee recalled the difficulty of recruitment. *"It took me more than six months to find one good salesperson – and I eventually hired her from the Netherlands. In Slovenia, there are simply no proper courses or training for sales"* (BIOTECH7-2). Others went further, pointing to structural disincentives within academia itself. *"Public grants focus more on technical sciences than life sciences, and they are too often geared more toward producing publications rather than innovations with commercial potential. Publishing before patenting significantly reduces the chance of commercialisation. Even PhD students are incentivised to publish papers, not patents – which means there is a direct disincentive to generate innovation for commercialisation"* (BIOTECH16).

To overcome these limitations, some firms frame themselves as solution providers rather than product providers, bundling technologies with services and expertise. *"Our role is to be a solution provider. It is not just about one device – it is an entire workflow"* (BIOTECH3). Despite such adaptations, most firms accept that commercialisation cannot happen at home – Slovenia's market is far too small. Nearly all start-ups are "born global", targeting international partners and clients from the outset. *"International is everything. At least 90 percent, maybe more, of our work is with foreign partners. Slovenia is just too small"* (BIOTECH4). For many, the US market dominates, and so does its biotechnology sector. *"Most of our clients are international – mainly in the USA, with some in Europe and China. In Slovenia, there is really only one potential client"* (BIOTECH11). *"For us, it was always international. The USA is by far our biggest market – sometimes 80 percent of sales. Europe is second, Asia third. Slovenia itself is negligible"* (BIOTECH6).

This global orientation, however, comes with its own credibility hurdles. *"Being Slovenian makes you marginal in the global space. You need to build alliances with bigger players"* (BIOTECH11). Efforts are underway to bridge this gap, for example, through Slovenia BiotechHills and Spirit Slovenia (Business Development Agency), which promote start-ups during international delegations. *"To promote start-ups abroad, we are working with companies, Spirit Slovenia, embassies and ministries. When government delegations travel, we push for biotech and pharma start-ups and SME to join"* (BIOTECH14). Some highlighted the potential of stronger collaboration among domestic firms, arguing for *"building consortia of Slovenian companies that can jointly participate in larger projects abroad. Instead of each company creating opportunities individually, through collaboration and combined expertise, they could win tenders for major international projects. With a joint approach, Slovenian knowledge could stand out and generate a multiplier effect, also internationally"* (BIO-

TECH16). While these international linkages offer opportunities, they also expose Slovenian firms to tougher competition and higher expectations. The presence of multinational hubs, such as Novartis and Sandoz, may help boost credibility, but interviewees warned that without a stronger domestic commercialisation capacity, Slovenia risks remaining a subcontractor in global value chains rather than a leader.

4.2.4 Business environment

While international orientation creates opportunities for Slovenian biotech firms, the domestic business environment often hinders them through excessive bureaucracy, slow governance, and weak policy support. These structural barriers consume time and resources that start-ups can scarcely afford to lose. Many highlighted that government-backed support, while valuable in principle, often comes with hidden costs. *"If I get one euro from an investor, it is worth much more than one euro from the government, because with government money, I spend huge amounts of time justifying it before I even get paid. That slows down young, dynamic companies"* (BIOTECH1). Others compared international experiences, noting that European grants are far more rigid than those in the United States. *"Both EU and Slovenian grants are bureaucratic. Compared to the USA, Europe is much more bureaucratic. When we received a US grant, reporting was just half a page – extremely flexible. That was a big advantage"* (BIOTECH5). Research institutions voiced similar frustrations, pointing to the excessive complexity of national applications. *"Slovenian project applications are unbelievable – the administration is crazy. It seems as if the evaluators mostly review administrative requirements and that the content is secondary. Particularly applications for innovation projects shall be shorter and more focused"* (BIOTECH10-1).

Beyond individual projects, several respondents argued that Slovenia is falling behind its neighbours in reforming regulatory frameworks. They noted that neighbouring countries had already updated their laws to streamline biotech-related procedures, leaving Slovenia lagging. *"Unlike surrounding countries – Italy, Austria, Hungary, and Croatia – which already have new laws and are one or two steps ahead, Slovenia has not changed its legislation. That is the biggest obstacle"* (BIOTECH15). These frustrations usually referred to rules on technology transfer, spin-offs from research institutions, clinical trial approvals, and the building of new infrastructure. At the same time, Slovenia does outperform in some areas, for example, by offering full corporate income tax deductions for R&D expenditure, a measure not always available elsewhere.

Still, overregulation within the European Union remains a persistent challenge. *"Slovenia, and Europe in general, is overregulated. Start-ups can spend years just trying to get approvals. You can test something here, but the results do not count in Germany or France. So, you need to repeat testing abroad – at ten times the cost"* (BIOTECH8).

Administrative burdens also limit the country's ability to attract top international talent. The recruitment of non-EU experts is often slowed by months of paperwork. *"Hiring a non-EU PhD can take over a year due to administrative hurdles. That is unacceptable when the talent is already highly qualified. We have pushed for improvements, but it is still not good enough. We will have to work on that in the future"* (BIOTECH14). Although some progress has been made, interviewees argued that much more is needed. *"It still takes too long, but improvements have been made. We would welcome a fast track for PhDs with five years' experience – just one office, one-day processing"* (BIOTECH12-2).

Interviewees linked these practical frustrations to deeper governance shortcomings. Rather than acting as an enabler of innovation, the state was described as fragmented and inconsistent. Several pointed to Croatia as an example of more decisive governance. *"Ten years ago, Croatia was far behind Slovenia. But in a decade, they produced six or seven unicorns, while Slovenia produced just one. The difference is that in Croatia, government decisions are implemented quickly, while in Slovenia, coordination between ministries is often slow and fragmented"* (BIOTECH8). This lack of alignment undermines investor confidence and encourages investors to relocate. *"If Croatia or another neighbour is cheaper and more attractive, investors will push start-ups to relocate. This is already happening – some Slovenian start-ups moved operations across the border because of cost and taxation"* (BIOTECH14).

Taxation policy was identified as one of the most tangible levers for improvement. Several respondents highlighted the absence of targeted incentives that exist in nearby countries. *"Unlike most European countries, Slovenia offers no tax breaks for companies investing in start-ups. In Austria, Hungary, even Romania and Bulgaria, companies can reduce their profit tax by €300,000–€500,000 if they invest in start-ups. If Slovenia had such an incentive, we could generate €20–30 million annually in new start-up financing"* (BIOTECH8). Company leaders proposed extending existing R&D incentives as a straightforward solution. *"A straightforward approach would be allowing us to fully deduct investments into start-ups from our tax base. Slovenia is actually one of the rare countries where you can already fully deduct investments into R&D*

from corporate income – 100 percent. This is a direct incentive to boost development capabilities in Slovenia. Extending this model to start-up investments would make sense" (BIOTECH12-1). These accounts show that bureaucracy and fragmented governance weigh heavily on Slovenia's biotechnology ecosystem.

4.2.5 Strategic outlook

Having navigated the barriers of resources, capabilities, commercialisation, and governance, interviewees often stepped back to reflect on the bigger picture. Their accounts converge on a simple but decisive point: Slovenia's biotechnology sector is at a crossroads. The fundamentals are in place – strong academic institutions, skilled researchers, and the presence of global pharmaceutical leaders – but the direction forward depends on whether these strengths can be connected into a coherent strategy. *"Because big players are already here, they will not pack up and leave. That is a huge opportunity. The challenge is to create an ecosystem where small and medium companies can survive alongside them"* (BIOTECH11).

The sector already carries significant weight in the national economy, and some argue that this gives Slovenia a leading position in Europe. *"Big pharmaceutical companies together contribute over six percent of Slovenia's GDP and employ around 13,000 to 14,000 people directly. By that measure, Slovenia is a leader in Europe"* (BIOTECH12-1). Yet interviewees agreed that without stronger links to the start-up ecosystem, these benefits risk remaining locked within big pharma rather than spreading across the biotech landscape.

Looking forward, many framed the moment as an opportunity for Slovenia to reposition itself as a regional hub. *"For Slovenia, the biggest opportunity is to consolidate and expand our role as a pharma hub. We already have three global players here, a strong academic base, and a growing infrastructure. If we align academia with industry and create better conditions for start-ups, Slovenia could position itself as a true European hub"* (BIOTECH12-1). But realising this vision requires more than technical ability – it calls for political prioritisation. *"Slovenia has to decide what it wants to be. Estonia became Europe's IT hub, and Ireland a pharmaceutical hub. Slovenia could become a biotech hub – but only if the government prioritises it"* (BIOTECH3). Table 2 summarises the key findings of the research.

Table 2. Summary of key empirical findings

Topic	Findings
Resources and infrastructure	• Risk aversion and stigma discourage entrepreneurship. • Success is often viewed with suspicion. • Limited lab space, high setup costs. • Domestic patient capital is absent, and the "valley of death" is critical. • Heavy reliance on personal savings and foreign banks. • New deep tech fund (Vesna) is promising but small. • Capital concentrated in Western Europe.
Human and institutional capabilities	• Severe talent shortage and fierce competition. • Large pharma drains universities and start-ups. • High taxation and long hiring delays reduce attractiveness for foreign experts. • Spin-offs are legally possible since 2022 but remain rare. Before only spin-outs were legally possible but were not very common. • IP protection is underfunded.
Market orientation and competitiveness	• Commercialisation is seen as the weakest link. • Scaling products requires capital, credibility, sales skills. • Shortage of business sales talent. • Grants/academia reward publications over patents. • Domestic market too small, so firms are "born global". • Alliances/consortia seen as potential strength.
Business environment	• Bureaucracy drains time and resources. • Slovenia lags behind neighbours in reforms. • EU-wide overregulation. • Governance is fragmented and slow to act. • High taxes drive some relocation. • No tax breaks for start-up investors.
Strategic outlook	• Strong academia and pharma base create opportunity. • Chance to consolidate into a coordinated hub. • Strategic and political prioritisation needed to position as EU biotech hub. • Without a strategy, the risk of stagnation as a pharma subcontractor.

Source: Own work.

6 Discussion and conclusion

Slovenia's biotechnology sector is at a turning point. While smaller than established international hubs, it benefits from strong scientific foundation, well established base of skilled multidisciplinary professional and the presence of major pharmaceutical anchors. Interviews confirm that knowledge and talent exist, yet systemic barriers prevent Slovene companies from becoming globally competitive. Without reforms, Slovenia risks remaining a bystander while others advance.

Lowering entry costs is crucial. Shared laboratories and incubation facilities would reduce fragility and attract investors. The government could accelerate this by granting tax reductions or other incentives for firms that build facilities accessible to start-ups. Without such infrastructure, Slovenia will keep generating knowledge without translating it into commercial outcomes.

Financing and taxation reforms are equally important. Extending R&D tax deductions to cover broader start-up investments, combined with salary tax relief, would address two of the sharpest bottlenecks: the "valley of death" financing gap and high costs of attracting and retaining talent. Adjustments here would shift the financial logic of biotech from survival to growth, reducing the risk that promising ventures collapse or relocate abroad.

Addressing bureaucracy is the third pillar. Current procedures for creating spin-offs and commercialising research are slow and fragmented. Clearer expectations and incentives for universities and public research organizations, combined with streamlined approvals, would help convert academic excellence into entrepreneurial outcomes.

In conclusion, Slovenia does not lack expertise, talent, or industry anchors – it lacks a coherent national strategy. Biotech should play a central role because it generates the highest value added per employee in Slovenia, builds on Slovenia's academic strengths, leverages major pharma and aligns with global demand. With targeted infrastructure, fiscal, and governance reforms, Slovenia could establish itself as a regional biotech hub. Without these reforms, it risks stagnation and dependence on external actors.

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ACIES BIO – STRATEGIC INNOVATION AND ECOSYSTEM INTEGRATION IN INDUSTRIAL BIOTECHNOLOGY

1 Introduction

Biotechnology is often framed as a cornerstone of future industrial development; however, its growth depends on unusually long innovation cycles, tacit knowledge, and regulatory hurdles, where "the product is the process" (Bettanti et al., 2022). Much of the existing research emphasises the role of multinational corporations in large economies with deep capital markets and dedicated national strategies for their development. Less attention has been given to how biotechnology evolves in smaller countries, where firms must innovate under structural constraints. Even in strong ecosystems, the presumed benefits of large corporations may be overstated: *"the current consensus, which states that their effects are entirely beneficial, is superficial"* (Herzog et al., 2024, p.1295).

Acies Bio provides a valuable case. Founded in 2006 in Ljubljana, it grew from a start-up into a globally embedded contract development and manufacturing organisation (CDMO). It was profitable from its first year and currently generates more than 99 percent of its revenues abroad (ACIES BIO, 2025a). Acies Bio illustrates both the opportunities and the limitations of biotechnology in small-country contexts. Studying its trajectory not only explains how one firm overcame domestic structural constraints but also contributes to broader debates on SME-led growth in biotechnology ecosystems without strong anchor corporations.

This chapter employs a qualitative methodology that combines a review of academic and policy literature with structured interviews. The interviews were conducted with Acies Bio's Head of Business Development (coded as ACIESBIO1) and its principal investor and Member of the Board (coded as ACIESBIO2). Together, these perspectives illuminate both Acies Bio's firm-level strategies and the broader systemic conditions shaping the Slovenian biotechnology sector.

The chapter is structured in four parts. First, Acies Bio's ownership structure and strategic positioning are described, followed by an analysis of its business model and main strategic choices. Then, the chapter examines how absorptive capacity shapes cross-industry innovation and situates the firm within both the Slovenian and global biotechnology ecosystems. Finally, its future prospects and challenges are assessed and presented.

2 Positioning Acies Bio in the biotech landscape

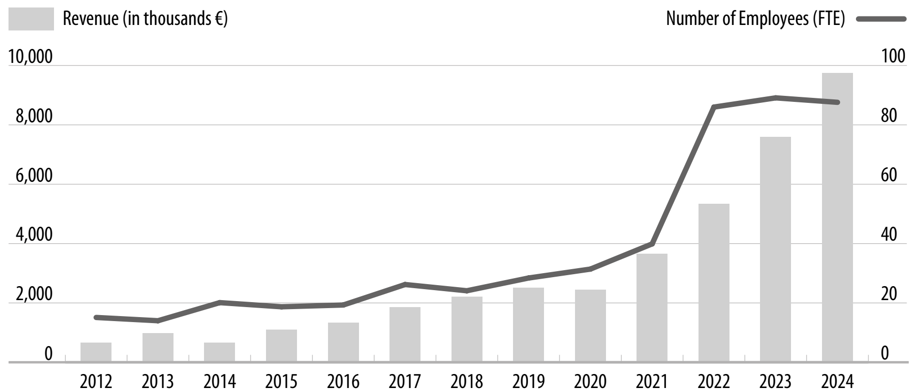
The company was founded in 2006, and the same year, it was recognised as the Slovenian Start-up of the Year. *"The start of Acies was at the faculty... but it was not possible to actually grow"* (ACIESBIO1). A team of four scientists established their first laboratory and secured initial contracts, becoming one of the first Slovenian biotechnology firms to focus on microbial strain development and fermentation technologies. From the outset, the company could not rely on venture capital and had to survive on revenues from real projects, which shaped its pragmatic, market-oriented approach. As recalled in the interview, *"we had to go directly to the market and get paying projects, otherwise we would not survive"* (ACIESBIO1).

By 2009, the firm had relocated to Ljubljana's Technology Park, a move that provided the company with autonomy and flexibility as a business, while maintaining its proximity to university partners and researchers. This step marked the transition from a small laboratory operation to a recognised player in Slovenia's emerging biotech scene.

Between 2013 and 2015, Acies Bio expanded its range of services and attracted international clients in the pharmaceutical and agricultural sectors. These projects validated the company's technical expertise and established the first long-term relationships beyond Slovenia's borders, confirming that it could compete internationally. By 2015, Acies Bio had increased its revenues to €1.7 million and expanded its team to 19 employees (Figure 1).

The period from 2016 to 2018 brought new strategic resources. Chinese investors Desano and Acebright joined the ownership structure, strengthening the firm's capital base and giving it a foothold in Asian markets. In 2016, Acies Bio opened a demonstration-scale fermentation and pilot production facility in Kamnik, enabling it to scale processes from laboratory to industrial levels—a rare achievement in Central and Eastern Europe. By that year, the firm had expanded to a workforce of 37 employees and achieved revenues exceeding €5 million. (ACIESBIO1).

Figure 1. Growth of revenues and employment in Acies Bio, 2012–2024



Source: Own work based on Ebonitete (2024).

In 2021, Archer Daniels Midland (ADM) Europe B.V. became a shareholder, embedding Acies Bio into global supply chains and signalling trust from one of the world's largest agricultural and food multinationals. By the end of 2024, the company had grown into an international contract development and manufacturing organisation with 88 scientists, €9.8 million in revenue, more than 20 patent families, and an export share exceeding 99 percent (ACIESBIO1). From its beginnings in a small Ljubljana lab, Acies Bio has become a globally embedded firm recognised for its ability to bridge research with industrial application.

As emphasised during the interview, *"our innovation is not in discovering new drugs or molecules with novel modes of action, but in making sure our clients can develop and survive in the market"* (ACIESBIO1). This service- and partnership-oriented model differentiates Acies Bio from typical biotech firms that focus on high-risk, product-based R&D cycles.

Acies Bio's activities are structured around three core business pillars (Table 1). The first is **contract development and manufacturing services** (CDMO), through which the company provides microbial strain engineering, fermentation process development, and pilot-scale production for global clients. This model generates stable revenues and has positioned Acies Bio as a reliable service partner. The second pillar consists of **co-creation partnerships**, where the firm enters joint development projects under risk-sharing agreements, often accompanied by milestone payments and royalties. Such arrangements allow Acies Bio to capture part of the long-term value created by client innovations. The third pillar consists of proprietary **product development**, encompassing both owned and co-owned products, through which the company leverages its platforms and microbial chassis, often in collaboration with partners, to develop solutions in agricultural biotechnology and the food sector. These projects concentrate on sustainable alternatives to traditional production processes, complementing the firm's service- and partnership-oriented activities with selective, higher-risk innovation pathways. *"We have 10,000 litres of fermentation volume now and already have long-term manufacturing contracts bringing about 20 to 30 percent of revenue"* (ACIESBIO1). This is white-label manufacturing, meaning they produce and pack without the Acies Bio label. *"We are taking first steps this year and are moving toward 30,000 litres of fermentation volume next year, positioning ourselves as a niche producer for new technologies that are too small for big players. Contract manufacturing organisations need five to ten years to grow in the market. Currently, there are no providers there"* (ACIESBIO1).

Table 1. Acies Bio's core business areas

Business area		Revenue model	Time-to-market	Risk–return
CDMO services	• Contract strain engineering • Fermentation & pilot/ demo production	• Fee-for-service • Per-batch/per-kg fees	Short (weeks, months)	• Low risk • Medium returns • Steady cash flow
Co-creation partnerships	• Joint R&D with clients • Use of SmartRoute & SynBio platforms	• Mixed: fees + royalties/equity	Medium (months, years)	• Medium risk • Higher returns • Long-term value capture
Proprietary product development	• Own/co-owned products in AgBio & Food • Sustainable biopesticides, proteins, lipids	• Licensing • Royalties • Direct sales	Long (several years)	• High risk • Highest return potential

Source: Own work based on AciesBio (2025a).

Acies Bio's strategic niche lies in its ability to combine deep scientific expertise with reliable industrial scale-up capabilities. The dual infrastructure of Ljubljana (research) and Kamnik (pilot production with a maximum capacity of 30,000 litres) allows the company to cover the full innovation pipeline, from discovery to pilot validation. This positioning is rare in Central and Eastern Europe, where few firms can offer an integrated contract development and manufacturing organization (CDMO) model (AciesBio, 2025a).

Acies Bio faces only a limited number of genuine competitors in its niche (ACIESBIO1). In Europe, the closest equivalent is BRAIN Biotech in Germany, which combines a wide technological scope with its own production facilities, built partly through acquisitions. In the United States, clients often compare Acies Bio with Ginkgo Bioworks, regarded as a leading name in synthetic biology. Yet, Ginkgo's heavy reliance on automation makes it less flexible for short or highly customised projects, creating space for Acies Bio's more adaptive approach (ACIESBIO1). Arzeda in the US and the Bio Base Europe Pilot Plant in Belgium are only partial competitors. However, both differ in important respects: Arzeda is more narrowly focused on computational design, while the Pilot Plant operates as a non-profit scaling facility. These references illustrate that Acies Bio is not competing with a crowded field of direct rivals but rather is positioned between traditional producers on one side and a small set of global synthetic biology firms on the other. Its advantage, as emphasised in the interview, lies in agility and integrated know-how, enabling it to serve diverse industries with tailor-made microbial processes rather than standardised products (ACIESBIO1).

3 Business model, strategy and governance

At the heart of Acies Bio's positioning lies its platform, which combines semi-finished microbial chassis with accumulated expertise in strain engineering, fermentation, and bioprocess design. The chassis provides a concrete starting point: microorganisms with defined properties that can be further tailored to customer needs, allowing them to bypass a substantial portion of the steep development curve as opposed to developing it entirely from scratch. This accelerates the innovation process in a field where product development is otherwise constrained by the slow biological cycles of cell growth and testing (ACIESBIO1).

Alongside the chassis, Acies Bio's value also stems from its broad know-how. Years of experience across pharmaceuticals, agriculture, food, and speciality chemicals allow the company to identify the right technological approach, anticipate pitfalls, and integrate regulatory or industrial requirements early in the process. Together, the chassis and accumulated expertise form a robust platform that underpins all of Acies Bio's activities.

The contract development and manufacturing organisation (CDMO) model forms the foundation of Acies Bio's business model. The company provides microbial strain engineering, fermentation development, and downstream optimisation to international clients (AciesBio, 2025b). Activities are split between Ljubljana, where early-stage strain design and process development take place, and Kamnik, which offers pilot-scale validation and technology transfer. This integrated setup enables clients to move from discovery to scalable production within a single partner organisation. The CDMO model generates stable fee-for-service revenues, which have provided the financial backbone of Acies Bio's growth, while also establishing its reputation as a reliable development partner known for technical expertise rather than proprietary products. Characterised by short time-to-market and relatively low risk, this pillar offers predictability and continuity in a sector otherwise marked by uncertainty (AciesBio, 2025a).

The third pillar focuses on the development of owned and co-owned products. In this domain, Acies Bio leverages its platforms and microbial chassis, often in collaboration with partners, to generate solutions in agricultural biotechnology and the food sector. Although these projects target sustainable alternatives to conventional production processes, they are characterised by long time-to-market horizons, high levels of risk, and the potential for correspondingly high returns. Together, these three pillars—CDMO services, co-creation partnerships, and proprietary product development—define Acies Bio's core business areas (AciesBio, 2025a, 2025b). This structure balances short-term stability with long-term opportunity, allowing the company to compete in R&D-intensive environments while preserving its independence. It also reflects broader dynamics of the biotechnology industry, where "the product is the process" and firms must rely on ecosystems of partners to survive and grow (Bettanti et al., 2022).

4 Market engagement and ecosystem participation

The biotechnology industry depends on the interplay of multiple stakeholders, including governments, universities, investors, financial institutions, and industrial partners (Bettanti et al., 2022). A strong ecosystem is not limited to sector-specific policies but also includes broader public support for education, research, and innovation. Regions, such as Lombardy in Italy, illustrate how coordinated policies, research institutions, and industrial actors can reinforce each other and generate a critical mass in biotechnology (Bettanti et al., 2022).

Slovenia also demonstrates core elements of such an ecosystem. In 2023, gross domestic expenditure on R&D reached 2.13 percent of GDP, with business enterprises contributing 69 percent of this total (SURS, 2025). According to SloveniaBusiness (n.d.), by 2024, the life sciences and healthcare sector comprised 371 companies, employing 16,535 people and generating €4.7 billion in revenues. Slovenia also ranks near the top globally in doctoral attainment, with approximately 3 percent of adults aged 25–64 reported as holding a PhD degree or equivalent (OECD, 2024). Universities and public research institutes, such as the National Institute of Biology and the National Institute of Chemistry, provide both infrastructure and scientific expertise to firms with whom Acies Bio works and cooperates closely. Collaborations with these institutions are not limited to grants but also extend to commercial projects, since *"sometimes we are outsourcing analytics to them or asking them for consultations"* (ACIESBIO1). On the other hand, having built its technological platforms in close collaboration with local research institutions and Slovenian scientists, Acies Bio also contributes to the national ecosystem by *"bringing diversity. We are the only player that is really working in this more industrial biotech space"* (ACIESBIO1).

A central feature of Acies Bio's growth has been its ability to attract highly trained researchers. While many small firms struggle to compete with larger international employers, Acies Bio has developed a reputation for offering meaningful scientific work and professional stability. As noted, *"we are very proud of bringing people back ... people from Slovenia who went abroad for postdocs, for PhDs ... we offer them a good position here and they can return"* (ACIESBIO1). By providing modern facilities, international projects, and opportunities to work at the interface of research and industrial application, the company signals that scientific careers in Slovenia can match those in larger biotech hubs. This capacity to reverse brain drain has been critical, enabling Acies Bio to build a strong talent base while reinforcing the broader Slovenian research ecosystem.

Furthermore, industry partners play an important role in Acies Bio's business ecosystem. They provide not only revenue but also critical feedback on regulatory requirements, market demand, and product performance, which Acies Bio integrates into its development processes. As explained by ACIESBIO1, collaborations are structured so that commercialisation and regulatory milestones directly shape the project: *"The commercialisation payment is usually linked to different events in the technology. Either they got the regulatory approval for their product, or they got it on the market. Depending on the situation, we* *usually structure it in a few instalments, allowing them to truly appreciate the value of their development project. Whether it is coming on the market, selling the product for the first time or something like this"* (ACIESBIO1). Among all industrial partners, pharmaceutical companies have been particularly important since Acies Bio's early internationalisation: *"Between 2013 and 2015, Acies Bio expanded its range of services and attracted international clients in pharmaceuticals and agriculture. These projects validated its technical expertise and established the first long-term relationships beyond Slovenia's borders"* (ACIESBIO1). Today, pharmaceuticals remain one of the firm's diversification pillars, ensuring stability and cross-sector learning: *"Diversification across food, feed, agriculture, chemicals, and pharmaceuticals reduces exposure to setbacks in any single field"* (ACIESBIO1).

At the same time, several challenges constrain the potential of this ecosystem. One of the most pressing concerns is the difficulty smaller firms face in attracting and retaining talent, given the intense competition from large pharmaceutical companies and international biotechnology players. As also noted by a respondent, a Slovenian business angel and long-standing Board Member of Acies Bio, *"Slovenian banks do not have patient money. They cannot wait ten years to see results. They want to see quarterly reports, short-term results. This is not how biotech works"* (ACIESBIO2). Venture capital remains scarce, and sector-specific policy support is fragmented compared to established clusters abroad. As observed, *"Slovenia does not have a proper biotech strategy, we are forced to connect to the global ecosystem"* (ACIESBIO1). For Acies Bio, this has meant structuring its business model around international contracts and multinational partners rather than relying on a domestic biotech cluster.

In response to these structural gaps, the Biotech Hills cluster was recently established as a collaborative initiative aimed at fostering biotechnology in Slovenia. Acies Bio's relationship with Biotech Hills is twofold. On one hand, the firm is an active member, contributing its expertise, infrastructure, and international network. On the other hand, the cluster provides Acies Bio with a national platform to engage policymakers and advocate for a more supportive environment, as well as an international platform for broader market exposure (ACIESBIO1). Yet the company's global orientation, with more than 99 percent of its revenues derived from exports, shows that domestic clustering alone cannot substitute for systemic national support.

This global orientation is also evident in Acies Bio's benchmarking practices. The firm participates in three to four specialised conferences annually in Europe and the United States, which provide visibility, competitive intelligence, and relationship-building opportunities (ACIESBIO1). These engagements have shaped key strategic lessons. Diversification across food, feed, agriculture, chemicals, and pharmaceuticals reduces exposure to setbacks in any single field. Dual growth—horizontally through platforms and vertically through process development—enables end-to-end client support. And credibility remains central: *"We live from real projects and contracts,"* as ACIESBIO1 emphasised, highlighting the firm's refusal to overpromise.

5 Absorptive capacity and innovation in Acies Bio

Absorptive capacity refers to a firm's ability to acquire, assimilate, transform, and exploit external knowledge for innovation and competitive advantage (Zahra & George, 2002). According to Zahra and George (2002), acquisition and assimilation form potential absorptive capacity, while transformation and exploitation constitute realised absorptive capacity. The case of Acies Bio illustrates how absorptive capacity operates as a dynamic capability to succeed in a small country biotech context.

Acquisition of external knowledge at Acies Bio is highly diversified. The company draws on *"really good collaborations with the Faculty of Chemistry and Chemical Engineering, Biotechnical Faculty at the University of Ljubljana, the National Institute of Biology, the National Institute of Chemistry"* (ACIESBIO1), as well as long-standing international links, such as Imperial College London: *"We have been collaborating with Imperial College London for many years. Now we have people in London [on our] scientific advisory board from the institution, and especially for EU-level projects"* (ACIESBIO1). In addition to these connections, Acies Bio maintains close collaboration with more than 20 top-tier universities and research institutes worldwide (AciesBio, 2025a). These relationships not only provide access to cutting-edge research but also generate a pipeline of doctoral candidates and Erasmus students who bring fresh methods into the firm. Knowledge inflows also come from business and industry stakeholders, exemplified by the long-standing involvement of a business angel, ACIESBIO2, who added market and financial expertise, guiding the shift to a B2B-only model. In contrast, the Scientific Advisory Board, composed of academic experts and industry veterans, provides project-specific insights on both technical and commercial feasibility. In addition, EU-funded consortia expose the company not only to new technologies but also to regulatory experts and multinational corporations, giving Acies Bio insights into development pathways and compliance requirements (ACIESBIO1).

Assimilation occurs through organisational practices. Joint supervision of doctoral students ensures that scientific insights are embedded into the firm's research routines, while collaboration with Scientific Advisory Board members translates external expertise into strategic decision-making. Acies Bio has also learned from past missteps. In some cases, clients left after a single project because the firm did not communicate its broader capabilities. This experience led to a more systematic onboarding process that emphasises long-term collaboration and visibility of the firm's full-service portfolio (ACIESBIO1).

Transformation at Acies Bio is reflected in the codification of project-based knowledge into reusable technological and organisational assets, such as the SmartRoute workflow for process optimisation and microbial chassis strains that can be customised across industries. Internally, cross-departmental teams and project-based training embed tacit knowledge, prevent silos, and foster learning across domains. Exploitation builds on these foundations, as the SmartRoute workflow and microbial chassis are applied in pharmaceuticals, agriculture, food, and speciality chemicals. Commercial outcomes are realised through licensing agreements, risk-sharing partnerships, and collaborations with multinational firms, such as ADM, BASF, and Desano. One multinational client, for example, expanded its engagement from a single process to multiple products after seeing Acies Bio's optimisation capabilities (ACIESBIO1). Today, more than 20 patent families protect the company's technological assets, while its export orientation demonstrates the global reach of its innovation model (AciesBio, 2025a).

Organisational practices also reinforce the firm's absorptive capacity. The decision-making process is lean. The flat hierarchy and autonomy for scientist project leaders enable rapid experimentation and integration of new ideas. Knowledge sharing occurs more informally through daily interactions among scientists, as well as formally through cross-departmental project teams. Low employee turnover ensures continuity of expertise, allowing the company to retain tacit knowledge. However, ACIESBIO1 also pointed out the limitations – Slovenia's ecosystem lacks senior professionals with biotech scaling experience, making it difficult for Acies Bio to recruit managerial talent with international commercialisation expertise.

6 Future prospects: Opportunities and challenges

In terms of the future prospects for Acies Bio, the respondent revealed a paradox for Acies Bio and the wider industry, stating, *"The opportunities and challenges are actually the same"* (ACIESBIO1). On the policy front, the European Union actively supports biotechnology through Horizon Europe and related frameworks, which prioritise sustainability, food security, and climate transition. Slovenian policymakers have also identified biotechnology as a strategic pillar of national development, and, as ACIESBIO1 emphasised, *"The ecosystem is growing here and this is very good for the future of biotech in Slovenia"* (ACIESBIO1). These shifts create new avenues for Slovenian firms to participate in consortia and access research infrastructure. However, ACIESBIO1 noted that Slovenia lacked a comprehensive biotech strategy. Slovenia lacks measures, subsidy schemes, or incentives to attract highly trained PhDs back from abroad. Therefore, without systematic national support, firms must rely on international collaborations. On the market side, global biotechnology continues to expand at double-digit rates, with pharmaceutical, agricultural, and food companies increasingly outsourcing R&D to contract development and manufacturing organisation (CDMO). This industry trend aligns directly with Acies Bio's integrated capabilities. However, global CDMO competition is intensifying. Large international players benefit from economies of scale, established regulatory expertise, and global distribution networks. Acies Bio must therefore continue to differentiate itself through flexibility, scientific rigour, and sustainability in order to remain competitive. On the financial dimension, access to capital remains limited domestically. *"In biotech, money is a problem because compared to IT or low tech, in biotech you cannot succeed quickly with the money you raise"* (ACIESBIO1). However, venture capital interest at the European level is growing. Combined with EU climate and green transition policies, which are stimulating demand for sustainable microbial processes, these dynamics position Acies Bio to capture opportunities both regionally and globally. Nevertheless, as noted by Ng & Sánchez-Aragón (2024), biotechnology is inherently high-risk, with long development cycles, uncertain outcomes, and a tendency to yield diminishing returns on R&D spending. Financing proprietary projects is particularly difficult in Slovenia, where venture capital and patient investors are scarce. ACIESBIO2 repeatedly emphasised that Slovenian banks lacked the patient capital necessary to support biotechnology ventures, a situation he considered incompatible with the sector's inherently long development cycles (ACIESBIO2). Limited domestic financing capacity thus forces firms like Acies Bio to seek European-level funding or international partnerships to sustain innovation.

7 Conclusion

In conclusion, the case of Acies Bio has shown how a biotechnology SME in a small country has thrived since its establishment. Founded in 2006, the firm has grown into one of the most successful biotechnology firms in Slovenia, despite operating in a fragmented domestic ecosystem. It has become an internationally embedded contract development and manufacturing organisation (CDMO) with dual facilities, a strong patent base, and over 100 scientists. Its success stems from a business model that balances contract development, co-creation partnerships, and selective proprietary projects —a strategic niche that integrates scientific expertise with industrial scale-up —and a strong absorptive capacity that turns external knowledge from universities, investors, and global partners into reusable platforms, such as microbial chassis and the SmartRoute workflow. This trajectory reflects the firm's own systemic framing of the innovation process—education provides skilled scientists, partnerships bring access to knowledge and resources, innovation transforms these inputs into new solutions, technology enables scale-up, and industry embeds them into global value chains.

At the same time, Acies Bio's case also highlights Slovenia's paradoxical environment. The country offers excellent research institutions, high levels of human capital, and growing policy interest; however, it lacks patient capital, a cohesive strategy, and anchor firms. These gaps have compelled Acies Bio to internationalise from the outset and depend on multinational partnerships. Looking ahead, EU policy support, global outsourcing trends, and the green transition create major opportunities; however, financing constraints, regulatory hurdles, and intensifying competition remain persistent challenges. As such, Acies Bio represents a promising yet still evolving case, serving as a reminder that broader sectoral development will require stronger ecosystems and long-term financial and policy support.

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GREEN TECH FROM LABS TO MARKETS: DRIVERS, BARRIERS, AND PATHS TO SCALE

1 Introduction

Green technologies have become a central part of reaching the European Union's Green Deal goals, which aim to reduce emissions by at least half by 2030 (European Commission, 2025a). Slovenia is part of this transition; it has a comparatively strong knowledge base and innovation capacity, with almost half of the companies introducing new products, processes, and services, which exceeds the EU average of 39 percent (EIB, 2024). Nearly 30 percent of graduates come from fields such as ICT, engineering, mathematics, or natural sciences (Slovenia Business, 2025), and dedicated industry-research platforms (TCI Network, 2024) connect various stakeholders to advance the green transition. Despite these strengths, scaling green solutions is hindered by the small domestic market, infrastructure gaps, fragmented support, and unfavourable policy frameworks.

The chapter aims to examine Slovenia's green technology ecosystem, with a particular focus on the opportunities it creates and the barriers that hamper its development. Based on interviews with companies and organisations that are part of this ecosystem, it investigates how market dynamics and regulatory frameworks influence the pace and direction of the green transition and identifies key enablers and barriers. Addressing these issues contributes to a better understanding of the sector's competitiveness and its role in shaping Slovenia's green transition and sustainable future.

First, a theoretical overview defines green technology and innovation, market dynamics, policies, and regulations within the sector. It explores the enablers and barriers of green technology development, as well as the role of collaboration and innovation. The second section presents empirical findings drawn from 14 interviews with stakeholders of the Slovenian green technology ecosystem, including both innovators—such as start-ups developing green solutions—and users, i.e., established firms that adopt and implement them, in order to capture the entire value chain.

2 Green technology: Literature review

2.1 Definition and concepts

Any technology intended to lower the adverse effects of human activity on the environment is referred to as green technology (hereafter, green tech) (Safdie, 2025). To increase productivity while reducing the use of natural resources, green tech seeks to balance environmental protection with economic growth (Gonnect, 2023). Closely related is the concept of green innovation, which denotes the development and application of sustainable and environmentally friendly goods, services, and processes (Kumar & Rao, 2023).

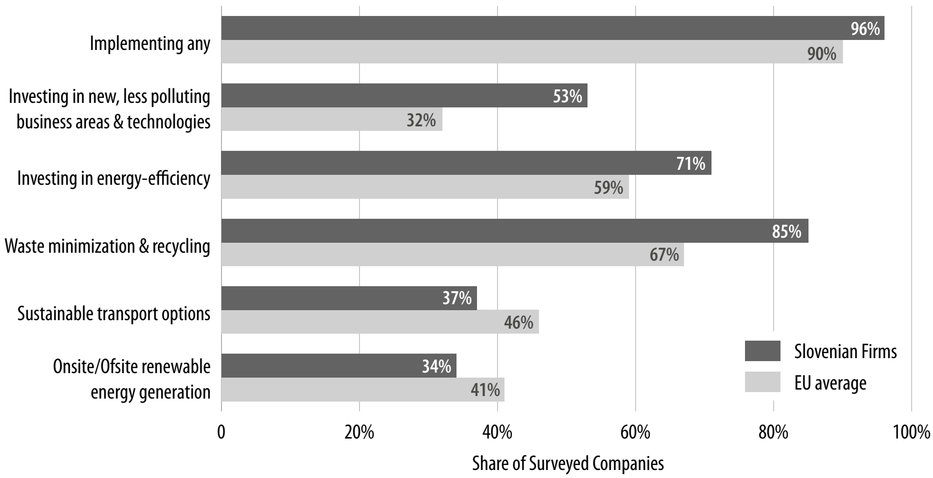
In the European context, green tech is most visibly represented by the eight strategic technologies promoted under a central measure of the European Green Deal, the Net Zero Industry Act: onshore wind and offshore renewable energy; batteries and storage; heat pumps and geothermal energy; electrolysers and fuel cells; biogas/biomethane; carbon capture and storage (CCS); and grid technologies, such as electric vehicles (EV)and fast charging (European Commission, 2023; Becker et al., 2022).

Importantly, green tech is not confined to products alone. It also encompasses environmentally friendly production processes and supply chains (Jark, 2025). More broadly, it can be understood as the use of technology and science to protect the environment (European Patent Office, 2019), covering the development and implementation of sustainable products, processes, and systems (The Business Research Company, 2025).

2.2 Key drivers

From a business perspective, the adoption of green technology is driven by both regulatory and market dynamics. Companies are increasingly facing pressure to comply with stricter climate policies, which impose costs on traditional polluting practices while rewarding low-carbon solutions (European Commission, 2024b). Moreover, firms are motivated by efficiency gains. For example, investments in energy-efficient processes, such as asset replacement and modernisation, material reuse, and process optimisation, can significantly reduce operating costs and improve resilience to volatile energy markets (Becker et al., 2022). Figure 1 illustrates the measures undertaken by Slovenian and EU firms to reduce greenhouse gas emissions, often through the implementation of green technologies in their processes (EIB, 2024). In Slovenia, 96 percent of firms take action to reduce greenhouse gas emissions, compared to the EU average of 89 percent (EIB, 2024).

Figure 1. Actions to reduce emissions – Slovenian firms vs. EU average



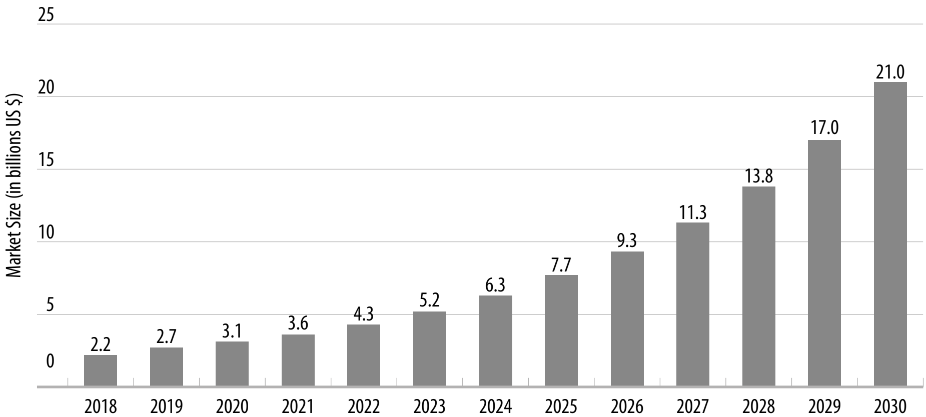
Source: EIB (2024).

Opportunities and incentives to produce and implement green tech exist along the whole value chain, but they differ. For example, suppliers of raw materials are pressured to provide "green" inputs. At the same time, manufacturers increasingly rely on clean energy to maintain competitiveness in terms of cost-effectiveness, reliability, efficiency, and a positive brand image (KP Group, 2025). Underlying all these pressures is the growing importance of sustainability in financing decisions (Bell, 2021). Investors are increasingly rewarding firms with strong ESG (Environmental, Social, Governance) performance, with higher ratings associated with lower financing costs in both equity and debt markets (Malich & Husi, 2024). At the same time, consumers support these dynamics by showing an increasing willingness to pay more for sustainable products, which further drives the demand across industries (Vereb, 2025).

2.3 Market orientation and opportunities

Although the green tech market is still relatively small, it is expanding rapidly. North America currently represents the largest market, while the Asia-Pacific region and other emerging economies show the fastest growth (The Business Research Company, 2025). In Europe, projections for the growth of green tech and the sustainability market are also strong (Figure 2).

Figure 2. European green tech and sustainability market 2018–2030



Source: Grand View Research (2024).

In terms of current green tech solutions, energy leads with renewables, storage, and carbon capture, followed by construction with green buildings and efficient technologies. Water and waste management and mobility also hold strong potential (The Business Research Company, 2025).

2.4 Enablers and barriers

Access to finance, shortages of skilled labour, and bureaucratic red tape are among the key barriers to scaling green technologies in Europe (Draghi, 2024; EIB, 2024; IMD, 2025). Regulatory burdens further exacerbate these challenges, as complex procedures and administrative delays raise costs and slow down adoption, particularly for small and medium enterprises (SMEs) (Dennison & Engström, 2024; Draghi, 2024). At the same time, enablers such as EU funding instruments and national subsidies (EIB, 2024; European Commission, 2025b), along with institutions that connect research, business, and public actors (TCI Network, 2024), play an important role in promoting innovation.

A key barrier to venture capital investment in green tech is its sensitivity to public policy orientation. When policymakers signal strong environmental commitment, green tech ventures attract substantial funding (Noailly et al., 2024). In the EU, the absence of this engagement is visible in the recent decline of green VC flows, which dropped from €11.6 billion in 2023 to €8.8 billion in 2024 (Cleantech for Europe, 2025). European VC capital markets remain underdeveloped compared to the US, leaving innovative firms with limited access to market-based finance (Fratto et al., 2024).

Furthermore, Europe's heavy reliance on banks makes it hard for green tech SMEs to get the funding they need, since banks are not designed to support risky or intangible projects (Draghi, 2024). This problem is even worse for companies in early stages, which often struggle with trust gaps and their broader social and environmental value being overlooked (de Haan Montes et al., 2023). The challenges identified are not limited to green tech alone, but affect companies more broadly. At the seed stage, EU investment is approximately 80 percent lower than in the US; at the early stage, it is 73 percent lower; and at the later stage, it is 82 percent lower (Draghi, 2024).

Another significant challenge is the shortage of skilled workers. Although the demand for green jobs[1] grew by 11.6 percent between 2023 and 2024, the supply rose only by 5.6 percent. If this trend continues, the gap will expand dramatically, resulting in a projected shortfall of 101.5 percent by 2050 (LinkedIn Economic Graph Research, 2024). Although 88 percent of Slovenian firms report long-term shortages of skilled staff across all sectors (EIB, 2024), Slovenia offers one of the most competitive workforces in the region – nearly 30 percent of graduates are in ICT, engineering, math, or natural sciences, and labour productivity ranks highest in Central and Eastern Europe (Slovenia Business, 2025).

2.5 Policy and regulation

The European Green Deal is the central growth strategy to make the EU climate-neutral, resource-efficient, and competitive by 2050 (European Commission, 2025b). Covering climate, energy, agriculture, transport, industry, and finance (European Commission, 2025a), it includes the Green Deal Industrial

1 Green jobs are forms of employment that place sustainability at the core of their activities and rely on the application of green skills. Green skills are competencies and expertise that enable individuals to mitigate, adapt to, or address the impacts of climate change (LinkedIn Economic Graph Research, 2024).

Plan, which strengthens Europe's net-zero sector by fostering supportive ecosystems through simplified regulation, faster funding, skills, and open trade (European Commission, 2024b).

Europe's green transition efforts are, however, constrained by fragmented governance, as 27 member states pursue their own policies instead of the centralised approach seen in China (Dennison & Engström, 2024). Member states diverge on how to pursue green industrial policy. Some countries see subsidies as essential, others fear unfair competition, some prefer low-cost imports (including Slovenia), and a few even question the green transition itself (Dennison & Engström, 2024). Additionally, the three key bottlenecks hindering the EU are finance (including the availability of funding and investment resources for green tech projects), skills, and regulation (Dennison & Engström, 2024).

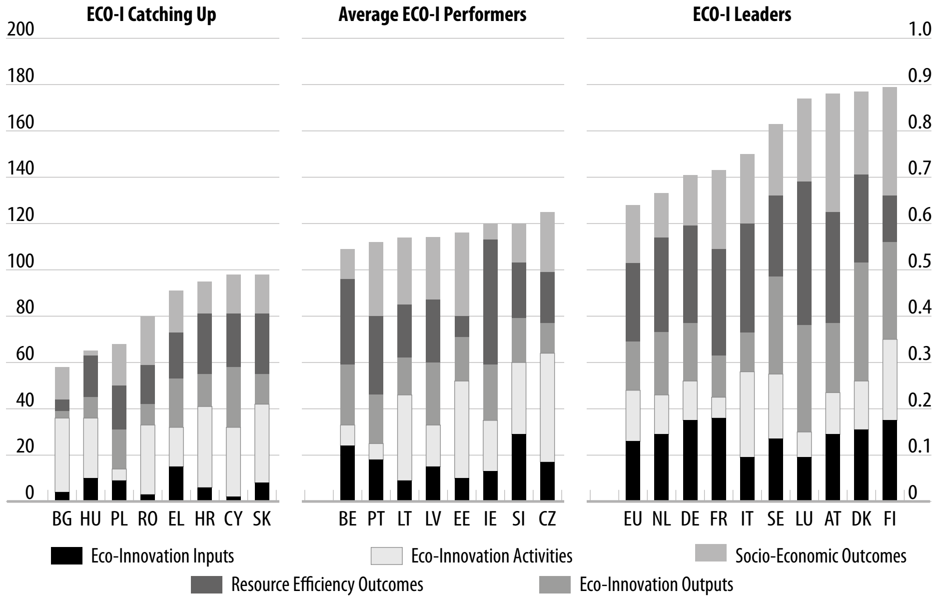
Moreover, Europe struggles to translate innovation into commercially successful products due to fragmented and restrictive regulations, which create barriers for companies at every stage, and this challenge extends well beyond the green tech sector (Draghi, 2024). Over 60 percent of EU companies see regulation as a barrier to investment, while 55 percent of SMEs cite regulatory and administrative burdens as their main challenge (Draghi, 2024).

2.6 Ecosystems, innovation, and collaboration

Slovenia ranks slightly below the EU average in eco-innovation (Figure 3) and belongs to the "average eco-innovation performance" group, lagging the "eco-innovation leaders". Nevertheless, between 2014 and 2024, it has demonstrated progress in eco-innovation, largely because of improvements in eco-innovation-related academic publications. However, it recorded a decline in eco-innovation patents and exports (European Commission, 2024a).

Innovation alone is insufficient; scaling requires strong ecosystems. A good example is Austria's Green Tech Valley in Styria, which unites over 200 firms and research institutions, including TU Graz and Montanuniversität Leoben (Green Tech Valley Cluster, 2017). Specialising in hydropower, bioenergy, recycling, and green construction, it coordinates more than 100 innovation projects annually, engages in EU networks, and exports over 90 percent of its output, making international collaboration essential due to its limited domestic scale (Green Tech Valley Cluster, 2017). Moreover, Germany's GreenTech Made in Germany is a nationally coordinated ecosystem that employs 3.4 million people and contributes 9 percent of the country's GDP (Bechhaus et al., 2025). It integrates federal policy, Fraunhofer institutes, universities, and industry consortia across energy, water, recycling, and mobility (Büchele et al., 2021; Bechhaus et al., 2025). In 2023, exports totalled €132 billion, more than half of which were within the EU (Bechhaus et al., 2025).

Figure 3. Eco-innovation contribution of each theme to the summary index, 2024



Source: European Commission (2024a).

Slovenia's most established initiative in this area is the energy innovation cluster TECES, founded in 2001. It connects leading Slovenian companies from the electronics and electro-industry, the energy sector, providers and users of green technologies and energy-efficient solutions, top research and educational institutions, as well as professional associations and other stakeholders of the national innovation ecosystem (TCI Network, 2024).

Together, Austria and Germany showcase complementary models: Austria as a specialised, network-driven regional hub (Green Tech Valley Cluster, 2017), and Germany as a globally scaled, policy-driven leader (Büchele et al., 2021; Bechhaus et al., 2025). Despite its efforts, Slovenia's TECES scale and impact appear modest compared to the far more developed and internationally competitive ecosystems in Austria and Germany.

3 Practical insights into green tech in Slovenia

3.1 Research methodology

Table 1. List of interviewed organisations

Organisation	Core business	Size	Interviewees	Position in the ecosystem	Code
1	Production of catalysts for hydrogen fuel cells	Micro	CEO	Innovator	GREEN1
2	Public transport	Large	Deputy CEO	User	GREEN2
3	Implementing urban green solutions	Micro	Managing Director	Innovator	GREEN3
4	Manufacturing lead-acid and lithium-ion batteries	Large	CEO	User	GREEN4
5	Electricity distribution	Large	Advisor to the Board	User	GREEN5
6	Decarbonisation solutions through ESCO models	Small	CEO	User	GREEN6
7	Precision laser micromachining services	Medium	CEO	Innovator	GREEN7-1
			R&D Engineer		GREEN7-2
			Product Developer		GREEN7-3
8	Public transport, charter, and travel services	Large	Chief Travel and Mobility Officer	User	GREEN8
9	Electric motors and components	Medium	CEO	User	GREEN9
10	An institution promoting development and export	Medium	Director of Program Development and European Programs Department	Other	GREEN10
11	A platform connecting academic and scientific institutions and the business community	Micro	Coordinator	Other	GREEN11
12	Waste management	Large	Managing Director	User	GREEN12
13	Environmental technology and engineering	Micro	CEO & CTO	Innovator	GREEN13
14	Polymers and synthetic fibres, R&D hub for the circular economy	Large	ESG Specialist	User	GREEN14

Source: Own work.

This chapter analyses Slovenia's green tech ecosystem, drawing on qualitative data from interviews, focusing on three key dimensions: market dynamics and drivers, enablers and barriers, and policy and environmental aspects. An empirical analysis comprised 14 in-depth interviews with Slovenian companies and organisations operating in the green tech sector, conducted between 22 August and 10 September, 2025. The sample was designed to cover the whole ecosystem, ranging from innovators, such as start-ups and research-driven organisations, to users who apply these solutions. Table 1 summarises the basic data about the interviewed organisations and companies.

3.2 Market dynamics

3.2.1 Key drivers

Private companies stated that macroeconomic changes, such as volatility and unpredictable energy costs, are the biggest drivers for development. *"Clients care about costs. Green solutions are not just about sustainability, they save money. That is the biggest driver"* (GREEN6). Moreover, the growth in demand for renewable energy solutions, combined with shifts in clients' perspectives, has become a key driver. *"We have moved from the 'boiler room to the boardroom'. Decarbonisation is now a board-level priority"* (GREEN6). This shift in perspective is driven by reputational benefits – sustainability commitments enhance brand value and align with the growing preferences of consumers and employees for environmentally responsible products (WEF, 2022).

Another driver is the pressure from EU business partners who aim to refine their supply chains and the end products to be more environmentally friendly. *"Scope 3 emissions are pushing entire supply chains to act. For example, Slovenian automotive suppliers face pressure from German partners"* (GREEN6). Private companies also highlight subsidies and external capital as contributors to their operations in the green tech sector. *"Overall, subsidies for renewable investments have been a key driver across Europe"* (GREEN4). Start-ups, research institutions, and public companies point to subsidies as the main driver for their innovation and existence. *"Investing in new technologies is not feasible without strong government support"* (GREEN2).

The majority of interviewed companies also acknowledge the *"strict EU environmental targets and pressures"* (GREEN9) that push the industry toward green tech solutions. Many companies identify significant opportunities in this sector, especially in terms of government support for R&D, which is a driver for further innovation and product development. *"Competition is also increasing. From utilities, small engineering firms, technology companies, and even financial investors moving directly into this space"* (GREEN6).

3.2.2 Market orientation and global positioning

For all of the interviewed companies, the domestic market is too small. Some of them also produce component products, so export is inevitable. *"We do have some partnerships and suppliers here, but everything we have sold has gone to the EU, the US, Japan, South Korea, or even South Africa"* (GREEN1). Although Slovenian companies engage in trade domestically, the key components needed for their operations are usually imported. *"Some Slovenian companies handled construction, piping, and electrical work for our hydrogen station, but the core technology is imported"* (GREEN2). And, similarly, *"We try to keep EPC (Engineering, Procurement, and Contracting) and O&M (Operations and Maintenance) local, but for core technologies, we source internationally"* (GREEN6). Most of the interviewed companies trade primarily with EU countries, and it is there that they see the biggest potential for market growth and expansion (GREEN1, GREEN6, GREEN8). *"Markets like Germany and France, with strong chemical and automotive industries, are where real growth is happening. Slovenia is still lagging behind"* (GREEN1). Or, as GREEN6 stated, *"Our north star is Germany."* Having said that, for innovators, internationalisation is the only path to growth, while for users, it means integration into established European supply chains.

Slovenia's small domestic market and reliance on exports to EU countries are less concerning than the competitive threats the EU faces globally. *"China and the US are investing much more in research and development"* (GREEN5). Likewise, concerns were raised about China's extensive subsidisation of hydrogen technologies, which mirrors earlier strategies in the solar and battery sectors. *"One big concern is China. They are heavily subsidising hydrogen technologies, just as they did with solar and batteries. The risk is Europe allowing history to repeat itself"* (GREEN1). Limited funding also constitutes a barrier within the EU, while simultaneously creating opportunities for the US. *"At this stage, many companies are bought by Americans, and Europe loses valuable knowledge"* (GREEN13).

Additionally, China is feared to undermine Europe's competitiveness, given the EU's lack of awareness and strategic vision. *"Europe is at least 5 to 10 years behind China in battery development and industrialisation. China has a clear strategy and invests heavily, while in Europe, the environment and education system are still lacking"* (GREEN4). Beyond this, the economic rivalry between China and the US puts European companies in a vulnerable position. *"Competition from China is strong. With restrictions in the US, more Chinese products are entering Europe, which creates additional pressure"* (GREEN4).

3.2.3 Market opportunities

Table 2 provides an overview of the types of green technologies used or produced by the interviewed firms, categorised according to the classification outlined in the Net Zero Industry Act, the market in which these technologies are currently applied, and new market-wise opportunities. While applications already span the energy, transport, and industrial sectors, many opportunities are still underdeveloped, such as battery recycling or residential solar.

Table 2. Main growth markets and new segment opportunities

Type of green technology	Usage/ production	Current operating market	New segment opportunities
Solar photovoltaic and solar thermal	Usage	• Industrial • Hospitality & Business • Public sector • Urban infrastructure	• Energy-intensive industries • Residential buildings
Batteries and storage	Production	• Industrial mobility • Renewable energy storage	• Battery recycling innovation
Heat pumps and geothermal energy	Usage	• Industrial • Hospitality & Business • Public sector	• Energy-intensive industries • Data centres
Electrolysers and fuel cells	Production and usage	• Transport • Carbon-intensive industries • Hydrogen buses	• Glassmaking
Biogas/ biomethane	Usage	• Biomethane transition for CNG buses • Hydrogen production and charging infrastructure	N/A
Grid technologies (including EVs, smart & fast charging)	Usage	• Battery electric buses • Electricity distribution and renewable integration	N/A

Source: Own work.

3.3 Enablers and barriers

3.3.1 Innovation and scaling

In terms of innovation, some companies *"have strong R&D capacities and are active in prototyping and testing"* (GREEN9). However, one interviewee stressed their strength in applied solutions and business models rather than original R&D. *"Our strategy is to actively monitor market trends and developments, then adapt quickly"* (GREEN4). This contrast reflects a divide: users described their innovation as adaptation and application of solutions, while innovators pointed to challenges in translating research into market-ready solutions. *"One problem is the gap between research ideas and actual execution"* (GREEN1). This is consistent with the European Commission's Eco-Innovation Index, which shows growth in eco-innovation academic publications but a decline in patents and exports (European Commission, 2024a).

Consequently, the EU R&D ecosystem and project funding mechanisms were criticised as insufficient in supporting the execution of ideas, particularly in terms of practical outcomes, further noting that the EU is overly lenient rather than performance-driven. *"I have never heard of an EU project officially failing. But if everything is always a success, it is suspicious. If you are 100 percent sure a project will succeed, you do not need public funding – you go to the bank, take a loan, and make money"* (GREEN5). Similarly, *"Too often we end up with colourful reports – and that is it"* (GREEN5).

When it comes to scaling existing operations, hydrogen companies, for example, are constrained by fuel prices and view scaling as the main solution to their pricing challenge. *"The technologies work, but competing economically with fossil-based alternatives is hard until scale is reached"* (GREEN1). However, it was noted that scaling is almost impossible without external capital, operational capacity, and human resources (GREEN1, GREEN4, GREEN6, GREEN9). In addition, excessive bureaucracy was emphasised as an obstacle to both scaling and innovation. *"Grants are important to accelerate development, but they also come with heavy responsibilities – reporting, compliance, administration. Many start-ups underestimate this"* (GREEN6).

3.3.2 Human capital

Across the Slovenian green tech sector, a shortage of multi-skilled talent emerges as a serious problem. *"We need people who can simultaneously handle electrical systems, coding, and mechanical tasks. Such profiles are hard to find"* (GREEN3). Similarly, for companies in high-tech industries, retaining strong engineering teams is vital for maintaining competitiveness and innovation (GREEN4, GREEN6, GREEN7-2, GREEN9, GREEN12).

In 2023, Germany recorded 800,000 new green job openings, bringing the total employment in the sector to 3.4 million, with an annual growth rate of 2.2 percent (German Environment Agency, 2025). Against this backdrop of rising regional demand, Slovenia's shortage is further compounded by difficulties in attracting senior foreign talent due to salary gaps. *"It is harder to bring experienced foreign professionals here. Slovenia has a great quality of life, but salaries in Germany or Switzerland are much higher"* (GREEN1).

To close this gap, GREEN11 is developing a competency model to identify skill gaps, design training, and align education with labour market needs for the green-tech sector in Slovenia. Despite this effort, challenges in talent availability continue, which may be linked to the sector not yet being perceived as particularly attractive to students. *"We are working to connect universities more closely with companies. For example, companies are offering scholarships to students, but they do not receive enough applicants"* (GREEN11).

3.3.3 Financing

Access to finance is both an enabler and a barrier across the green tech sector. Start-ups rely heavily on venture capital and European funds, as the Slovenian ones are insufficient. *"Slovenian funds are less than 10 percent of what we have raised compared to venture capital and EU projects"* (GREEN1). Even though early research is usually well supported by EU grants, *"once you get beyond the laboratory and close to commercialisation, the money is simply not there"* (GREEN13). This financing gap in the development stages, from TRL (technology readiness level) 4 to TRL 6, was further confirmed and mentioned as a stage where most EU grants end, and private investors are hesitant (GREEN1, GREEN10).

Private companies have mixed views. Some note that while EU grants are effective, they believe *"tax incentives and national support schemes could be more ambitious and long-term tools to help companies scale their solutions"* (GREEN9). Another interviewee mentioned financing *"through external capital providers, mainly institutional investors"* (GREEN6). For a company like GREEN14, the importance of government subsidies for renewable investments is highlighted. Nonetheless, some companies, including GREEN14, rely more on internal cash flow and bank financing, with the coexistence of innovation costs and competitiveness being a key consideration in top management strategies.

3.3.4 Infrastructure

Infrastructure remains an immediate challenge. The growth in the use of renewable energy sources, for example, places pressure on the existing infrastructure, which was not designed for many small, decentralised energy sources.

"Almost all renewables, except large hydro, are connected to the distribution grid. This creates major challenges for stability, especially since energy generated in the summer cannot be stored for the winter" (GREEN5). The issue is not just of a technical nature, as even smaller infrastructure upgrades can take decades due to lengthy environmental and administrative approval processes (GREEN5, GREEN8, GREEN14).

For young companies trying to scale, the absence of ready-to-use facilities, such as laboratories, can be an immediate challenge. *"Slovenia lacks ready-made facilities where start-ups can just rent and start. In other EU countries, you would get a grant and be 100 percent financed, but in Slovenia this does not exist"* (GREEN1). For them, the race to commercialise a breakthrough in green technology may not be stalled by science but by the lack of physical space that would allow development.

In the World Competitiveness Ranking 2025, Slovenia ranked 39th in terms of infrastructure, whereas countries such as Germany and Austria placed 13th and 14th, respectively (IMD, 2025). Slovenia is lagging behind: *"In Slovenia, researchers simply do not have access to ready-made labs. In Rijeka, Croatia, you can rent a lab; here, that does not exist"* (GREEN10). However, there are some efforts to stimulate the development of green technologies. *"We want to connect research and industry. Our role is to provide infrastructure and help small companies or municipalities develop and test solutions they could not manage on their own"* (GREEN3).

3.4 Policies and environment

3.4.1 Policies and regulation

A fragmented system of organisations competing for limited project funding was repeatedly mentioned. *"All these entities are fighting for survival [...] instead of working together, we often end up competing for the same project schemes"* (GREEN3). Moreover, technical arguments sometimes come secondary. *"The green transition is primarily a political project"* (GREEN5). For innovators, this rigidity is translated into slow projects and missed opportunities. *"Often, we are caught in the middle of development and legislation, and our hands are tied"* (GREEN7-1). Additionally, *"Slovenia does not have a clear strategy or vision"* (GREEN8). Thus, innovators emphasised weak incentives for investment, while users highlighted uncertainty from frequent regulatory changes and administrative burdens. One of the weaknesses of the current framework also lies in oversights and enforcement. *"The most important thing is proper monitoring of actors. [...] We see a lot of grey-economy activity, wrongdoing, even criminal acts, and these are not adequately addressed. That is the biggest drawback of the current system"* (GREEN12).

3.4.2 Collaboration in the green tech ecosystem

The importance of partnerships with higher education institutions and institutes, such as Jožef Stefan, was repeatedly emphasised as a driver of innovation (GREEN2, GREEN9). Active collaboration was also seen as vital. *"With the Faculty of Mechanical Engineering, we [...] collaborate on optical systems development"* (GREEN7-3). And, similarly, *"We share experiences with Vienna and may join them in an EU project soon"* (GREEN2). When it comes to the domestic ecosystem, it was described as fragmented and lacking in trust, with actors frequently targeting the same funding instruments instead of pursuing joint activities (GREEN3, GREEN12).

3.4.3 Competitiveness at risk and the dialogue gap

Meanwhile, users of green tech solutions worry that European regulation itself may create new competitive disadvantages. *"The new [industry] regulation creates significant bureaucracy. We must comply thoroughly, but I doubt all Asian competitors will meet the same standards"* (GREEN4). In the IMD World Competitiveness Ranking, Slovenia ranked 46th out of 69 countries, while China, the USA, and Germany ranked 16th, 13th, and 19th, respectively (IMD, 2025). Furthermore, a key challenge identified for Slovenia was the need to enhance the efficiency and effectiveness of public service delivery, as well as reduce administrative burdens (IMD, 2025). This concern is further emphasised by GREEN11: *"Bureaucratic complexity is the biggest obstacle private companies face in developing or implementing green technologies."*

Another layer of difficulty arises from the way that EU regulations are transposed into Slovenian law. Even though European frameworks are designed to create a level playing field, the interviewees described how national authorities often introduce additional layers of complexity. *"In Germany, you do not always need certificates or warranty lists, but here we do. In Slovenia, with a complicated regulatory framework, we sometimes forget about common sense"* (GREEN7-3). Constant changes in the national legislation are another challenge. *"Energy is a highly regulated sector, and frequent regulatory changes* *are disruptive. This year in Slovenia, a change in rules completely destroyed some of our plans"* (GREEN6).

Furthermore, the lack of real dialogue between policymakers and the business community results in slower development and a loss of competitiveness, as Slovenian companies devote disproportionate resources to meeting requirements that competitors in other markets do not face. *"Those on the other side, government and regulators, need to look further ahead and come closer to us. We have many highly successful companies here. [...] But how often do decision-makers actually listen to them? Very rarely"* (GREEN7-1). Table 3 presents key empirical findings in the green tech area.

Table 3. Summary of key empirical findings

Aspect	Findings
Market dynamics	• Development is mainly driven by EU targets, subsidies, and rising energy costs. • Green solutions adopted both to cut costs and strengthen reputation. • Domestic demand is too limited; companies are export-oriented. • Pressure from global competitors, especially the US and China. • Growth opportunities in renewables, storage, sustainable mobility, circular-economy applications.
Enablers and barriers	• Strong technical expertise, patents, applied innovation. • Weak commercialization and scaling due to limited financing and bureaucracy. • Lack of support at mid-development stages. • Shortage of skilled and cross-disciplinary workforce. • Infrastructure bottlenecks and lengthy permitting processes slow down the implementation of projects.
Policies and environment	• Unstable regulatory frameworks, with frequent changes and rigid transposition of EU law. • Stakeholders compete rather than collaborate, fragmenting the ecosystem. • Limited dialogue between policymakers and the business community. • Excessive bureaucracy and unclear rules undermine competitiveness. • Positive cases of collaboration exist in clusters and cross-border partnerships.

Source: Own work.

4 Conclusion

Slovenia's green tech ecosystem shows solid potential but remains constrained by limited scale, financing barriers, talent shortages, infrastructure gaps, and fragmented regulatory frameworks. These challenges manifest differently along the value chain: innovators tend to struggle most with financing barriers and commercialisation, whereas users are more affected by infrastructure gaps, fragmented regulation, and competitive pressures.

Companies are driven by EU climate targets, volatile energy costs, and supply chain pressures, yet struggle to translate innovation into scalable, competitive products. Export dependence, combined with rising competition from China and the US, further exposes vulnerabilities. At the same time, Slovenia benefits from strong applied solutions and integration into European markets.

To unlock growth, Slovenia must focus on a few critical priorities. First, improve access to scale-up finance through investment tools that de-risk commercialisation, for example, by simplifying bureaucratic EU instruments, covering co-financing requirements that may force start-ups to sell ownership stakes, introducing tax incentives for private investors, and targeting mid-development stages (TRL 4 to TRL 6), where the financing gap is the greatest. Second, streamline regulation, reduce administrative burdens, and align more closely with EU standards. Third, invest in infrastructure, particularly grids, storage, and shared R&D facilities, that support both established firms and start-ups. Fourth, address talent shortages with targeted education, international recruitment, and cross-disciplinary training. Finally, stronger collaboration through clusters and partnerships, particularly with Austria and Germany, would amplify impact and global competitiveness. Concentrating on these key areas, Slovenia could move from reactive adaptation to a proactive strategy, turning current challenges into a foundation for long-term green tech development.

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BALANCING EXPLOITATION IN AQUAFIL'S EXPLORATION INTO THE CIRCULAR ECONOMY LANDSCAPE

1 Introduction

Green technologies (green tech) play a central role in reducing environmental impacts while sustaining economic growth. In Europe, they underpin the green transition, supported by the European Green Deal (European Commission, 2019), the Circular Economy Action Plan (European Commission, 2020), and the EU Strategy for Sustainable and Circular Textiles (European Commission, 2022). These initiatives build on ecodesign, extended producer responsibility, and digital product passports. For textiles—among the most resource-intensive industries, with high emissions, pollution, and waste—addressing these challenges requires systemic innovation and the adoption of circular business models.

Aquafil, an Italian company with major operations in Slovenia, illustrates how a traditional manufacturer can pioneer a strategic transformation by embedding sustainability at its core. By aligning circularity with its long-term strategy, the company has emerged as a European leader in green tech, demonstrating both opportunities and challenges of industrial transformation (Aquafil, 2024; BloombergNEF, 2024).

This chapter analyses Aquafil's role as a green tech leader through four themes: technological innovation, ecosystem partnerships, human resources, and regulatory environment. It draws on semi-structured interviews with Aquafil managers, technical experts, and partners, complemented by company publications, sustainability reports, and other secondary sources. The aim is to extract lessons for firms pursuing circular practices and for policymakers supporting Europe's green transition.

First, the theoretical background is outlined, and Aquafil is situated within the global textile and nylon landscape. Then, the methodology and key findings are presented. The chapter concludes by linking these findings to the research questions and reflecting on implications for sustainable industrial transformation.

2 Theoretical background

Green technologies, broadly defined, refer to innovations that reduce environmental impacts while supporting sustainable growth (Resco, n.d.). In Europe, these technologies are central to the advancement of the Green Deal, with the textile sector highlighted as a priority due to its particularly heavy environmental footprint. This makes textiles a useful test case for exploring the transition to a circular economy. The challenge is substantial: the industry is highly resource-intensive, responsible for around ten percent of global carbon emissions and generating massive volumes of waste each year, most of which end up in landfills or incineration (Shamsuzzaman et al., 2025). The prevailing "take–make–dispose" model is unsustainable, prompting policymakers to adopt the EU Strategy for Sustainable and Circular Textiles, which promotes ecodesign standards, extended producer responsibility, and digital product passports as levers to reduce waste and increase transparency across supply chains (European Commission, 2022).

In response to these pressures, circular business models have emerged as alternatives that extend product lifecycles, regenerate resources, and transform waste into new inputs. Examples include fibre-to-fibre recycling, repair and reuse systems, and take-back schemes, which illustrate how circular principles are applied in practice (Singh et al., 2019; Shamsuzzaman et al., 2025). Yet circularity depends not only on technological innovation but also on governance mechanisms across supply chains and active consumer engagement. The structure of the industry reinforces these dynamics: value chains are fragmented globally, but a small group of large players strongly influence standards and adoption (Shamsuzzaman et al., 2025). While resistance from incumbents can slow change, leadership from key firms can accelerate systemic shifts (Adner, 2016). The textile sector represents both a high-impact and high-potential arena for circular innovation. However, the success of corporate circular transformations depends on how firms develop the capabilities needed to exploit and renew such solutions, as well as what determines whether companies can respond effectively.

The concept of absorptive capacity provides a useful explanation. First introduced by Cohen and Levinthal (1990) as the ability to recognise, assimilate, and apply external knowledge, it was later redefined by Zahra and George (2002) as a dynamic capability embedded in routines and processes that allows firms to adapt and innovate over time. Their framework distinguishes between potential absorptive capacity (PACAP), which relates to acquiring and assimilating knowledge, and realised absorptive capacity (RACAP), which refers to transforming and exploiting that knowledge. PACAP determines how receptive firms are to new information, while RACAP explains whether they can turn it into innovations or process improvements. The interaction of both is critical. Zahra and George (2002) describe this as an "efficiency factor" – the extent to which realised capacity approaches potential capacity. High efficiency signals that knowledge is not only absorbed but also meaningfully applied, creating the foundation for competitiveness.

Absorptive capacity is cumulative and path-dependent, shaped by prior investments in R&D, strategic alliances, and learning-by-doing; however, it can also be reactivated by external shocks, such as regulatory changes or crises (Zahra & George, 2002). This makes it particularly relevant in the context of sustainability, where firms face constant pressure to meet evolving environmental standards and adapt to shifting expectations from regulators, consumers, and supply chain partners. In relation to circular business models, absorptive capacity explains why some companies succeed in embedding recycling technologies, sustainability practices, and collaborative approaches into scalable operations while others lag behind. It bridges the macro-level pressures of the industry with the micro-level strategies of individual firms, helping us understand how circular innovations move from technical feasibility to tangible impact.

No company innovates in isolation. In sectors such as circular textiles, success depends on how effectively multiple actors coordinate and align their activities. Adner (2016) defines an innovation ecosystem as *"the alignment structure of the multilateral set of partners that need to interact in order for a focal value proposition to materialise"* (p. 42). This structural view shifts attention from the firm itself to the web of interdependencies that bind stakeholders together. Unlike traditional supply chains, which can often be reduced to bilateral exchanges, ecosystems require multilateral alignment. Two risks are central: **co-innovation risk**, which arises when complementary innovations must be developed across multiple actors, and **adoption chain risk**, which occurs when downstream partners are unwilling to adopt a new solution. Both show that the fate of an innovation is frequently shaped by forces outside the focal firm's direct control, making orchestration and alignment essential (Adner, 2016).

To complement this structural perspective, the **Quadruple Helix model** expands the traditional Triple Helix of university–industry–government relations (Etzkowitz & Leydesdorff, 2000) by adding a fourth sphere: civil society. Carayannis and Campbell (2009) argue that innovation arises not only from firms, policymakers, and researchers, but also from the involvement of NGOs, consumers, and media actors, who provide legitimacy and social acceptance. In sustainability transitions, this fourth dimension is particularly relevant, as it mobilises awareness, trust, and behavioural change. Together, these frameworks underline that scaling circular business models is not just a matter of technology or firm strategy. It requires coalitions of actors, aligned incentives, and orchestration across domains of society (Adner, 2016; Carayannis & Campbell, 2009). The ecosystem-as-structure perspective highlights the coordination of activities around a focal value proposition, while the Quadruple Helix model stresses the diversity of institutions involved. Both converge in showing that systemic change, such as closing material loops in textiles, is an inherently collective endeavour.

3 Aquafil in the green tech landscape

Understanding Aquafil's position requires a brief look at the B2B nylon value chain, a global, capital-intensive system in which specialised fibre producers supply flooring, fashion, and automotive manufacturers. The chain is fragmented across regions yet shaped by a few large buyers and fibre makers, so standards and adoption can shift quickly when lead firms align. Regulation is tightening: the European Green Deal and the EU Strategy for Sustainable and Circular Textiles are pushing ecodesign, extended producer responsibility, and digital product passports, thereby raising the bar on traceability and end-of-life management. Within this context, nylon 6 remains critical for performance (strength, durability), but is fossil-based and carbon-intensive. Its chemical depolymerisation pathway, however, makes it a prime candidate for circular models if firms solve feedstock logistics, process reliability, and downstream adoption (Shamsuzzaman et al., 2025). This landscape frames the analysis through the lenses of absorptive capacity (firm-level learning and exploitation) and ecosystem orchestration (multilateral alignment).

Founded in 1965 in Arco, Italy, Aquafil has grown into a global nylon player (fibres and polymers) supplying thousands of brands across Europe, North America, and Asia (Aquafil, n.d.-a). A pivotal step was the 1994 acquisition of Julon in Ljubljana, now the group's largest hub. In 2011, Aquafil launched the ECONYL® Regeneration System, which recycles nylon-6 waste (e.g., fishing nets and carpets) into a material that is virgin-equivalent while reducing emissions by up to 80 percent (Aquafil, n.d.-b). By 2024, ECONYL® accounted for over half of fibre revenues (Aquafil, 2024), indicating market acceptance across luxury fashion, flooring, and automotive sectors. Recent performance further shows that circular innovation can be scaled without undermining financial stability, a point elaborated in the section on technology exploitation and finance. Key milestones are presented in Table 1.

Table 1. Aquafil's key milestones

Year	Milestone
1965	Foundation in Arco, Italy
1990	Patent for "lactamic waters" recovery
1994	Acquisition of Julon in Ljubljana (strategic Central European hub)
1999	Foundation of Aquafil USA
2007	Foundation of Aquafil Asia Pacific
2009	A private equity fund enters the company's capital.
2010	Foundation of Aquafil China
2011	Launch of ECONYL® Regeneration System
2013	Foundation of Healthy Seas
2017	Listing on the Italian stock exchange
2018	Foundation of USA Aquafil Carpet Recycling
2018	Launch of the Effective project
2020	Foundation of Aquafil Carpet Collection
2021	Acquisition of 31 percent of Nofir
2022	Foundation of Aquafil Chile
2024	ECONYL® exceeds 50 percent of fibre revenues.
2025	First demo plant for chemical separation of elastic fibres from nylon

Source: Own work, based on Aquafil (n.d.-a; 2024), BloombergNEF (2024).

The Ljubljana site integrates depolymerisation, polymerisation, and textile yarn production, thereby concentrating a good example of a full nylon-6 loop in one place (Aquafil, 2024). Co-location with engineering talents and collaboration with various universities, including the University of Ljubljana, accelerate learning-by-doing, quality routines, and process control, which represent classic absorptive capacity in action (PACAP: acquisition/assimilation of external waste-stream knowledge; RACAP: transformation/exploitation into stable industrial output). At the ecosystem level, partnerships with NGOs, waste operators, and EU projects reduce co-innovation and adoption-chain risks, aligning the actors needed for circularity at scale. Through these moves (Table 1), Aquafil has shifted from a traditional yarn producer to a circular pioneer in nylon 6, providing an ideal vantage point for the findings on technology exploitation and finance, partnerships and ecosystem orchestration, and human resources and talent management.

4 Methodology

The analysis is guided by three research questions. First, how can a firm exploit and renew its core recycling technology without falling into technological lock-in, while sustaining absorptive capacity? Second, how can it orchestrate partnerships and achieve multilateral alignment across industry, academia, government, and civil society to scale circular value chains? And third, how can human resource strategies support innovation and competitiveness in the green tech sector?

Table 2. Sample characteristics

Position in the company	Years in the company	Years of industry experience	Interviewee code
CEO	39	39	AQUAFIL1
Head of R&D	6	6	AQUAFIL2
R&D Projects Supervisor	15	21	AQUAFIL3
Strategic Procurement Manager	25	35	AQUAFIL4
Finance & Admin Officer	6	14	AQUAFIL5
ESG Specialist	2	2	AQUAFIL6
Innovation Research & Development Coordinator	7	31	AQUAFIL7
Marketing & Sales (Customer)	20	20	AQUAFIL8
Business Developer (Supplier)	1	1	AQUAFIL9

Source: Own work.

This case study combines desk research with semi-structured interviews conducted between August 28 and September 12, 2025. The research team conducted online interviews with Aquafil's CEO and partner representatives, and visited the company's production site to gain firsthand insights into its operations. In addition, written responses were provided by professionals from different Aquafil departments (Table 2). All interviews and responses were coded thematically and triangulated with company publications, sustainability reports, and policy documents. While not all financial and R&D data are publicly available, triangulation with secondary sources strengthens the reliability of the findings.

5 Technology exploitation and financing innovation

Aquafil's innovation capability rests on its ability to both acquire knowledge and translate it into scalable industrial solutions. Financing acts as the enabling mechanism for this transition, ensuring that capital-intensive projects can be pursued without undermining financial stability.

To secure inputs and knowledge, Aquafil has embedded itself in global waste collection networks. Partnerships with Nofir in Norway for fishing nets, carpet collection schemes in the United States, and aquaculture operations in Chile not only guarantee feedstock but also generate technical insights into diverse waste streams (Aquafil, 2024). While NGOs and awareness campaigns raise visibility, the operational backbone of collection lies in established industry channels, such as net lofts and fisheries. *"This is where most of the discarded nets pass through naturally"* (AQUAFIL9). These systems ensure a steady flow of nylon-6 waste into Aquafil's regeneration process, reinforcing the role of PACAP in securing high-quality external inputs that can be transformed into scalable innovations.

Healthy Seas, co-founded by Aquafil in 2013, combines recovery of discarded nets (also known as "ghost nets", which account for a small portion of the total amount of recovered fishing nets from the aquaculture industry) with environmental expertise, while participation in EU Horizon projects exposes the firm to regulatory and technological developments. These external channels are reinforced by consistent R&D commitments, with €10.7 million invested in 2023 and €8.2 million in 2024 (BloombergNEF, 2024; Aquafil, 2024).

Resource allocation follows the annual business plan, which defines capital expenditures and strategic priorities. The company funds innovation primarily through self-generated cash, specific project financing, bilateral agreements with major banks, and EU contributions. A very good example is the Effective project, which was financed through the EU Horizon programme, where many partners of Aquafil's value chain collaborated to demonstrate the feasibility of transforming bio-based raw materials (i.e., sugar) into caprolactam. At the same time, financial assessments based on ROI and payback periods guide investment decisions (Aquafil, 2024). This disciplined financing enables the transition from potential to realised innovation.

Building on these foundations, Aquafil demonstrated realised absorptive capacity by converting external knowledge into tangible technologies. The flagship example is the ECONYL® Regeneration System, which depolymerises nylon waste into caprolactam, identical to virgin nylon. Operated from the Ljubljana plant, the process allows nylon to be recycled repeatedly without quality loss, reducing carbon emissions by up to 80 percent (Aquafil, n.d.-b). Each ton of ECONYL® saves approximately seven barrels of oil and nearly five tonnes of CO_2 (Aquafil, n.d.-b). ECONYL®'s market success stems from its technical equivalence to virgin materials combined with its lower carbon footprint. *"The raw material has the same properties as traditional caprolactam; coming from fossil resources, the only difference is its origins"* (AQUAFIL2). For investors, this achievement signalled that Aquafil had proven circularity performing at an industrial scale, making it a reliable industry leader. *"The company funds its activities and innovative technologies mainly through self-generated cash ... and bilateral agreements with major banks ... as well as EU contributions"* (AQUAFIL5).

Scaling, however, posed risks. Early attempts without a dedicated reverse logistics chain caused major problems, including two full plant shutdowns within the first nine months. *"Only nylon-6 waste can be transformed into nylon 6 again. Other components created a lot of problems"* (AQUAFIL2). These lessons reinforced the need for strong collaboration with partners, reliable financing, and careful risk assessment before large-scale investments.

Transformation extends beyond ECONYL®. The company is testing new circular technologies, including a carpet "disassembling machine," a technology to chemically separate nylon from elastomeric fibres, a PET recycling plant, and the MAGRITTE project on 3D printing compounds (Aquafil, 2024). Financing ensures that these exploratory projects can be pursued in parallel, using diversified funding sources while maintaining profitability. Transparency further strengthens investor confidence. Aquafil began publishing sustainability reports as early as 2007, long before it was legally required (AQUAFIL6). With the adoption of the EU Corporate Sustainability Reporting Directive (CSRD) in 2024, the company integrated financial and environmental disclosures into a single Consolidated Sustainability Statement. Both financial and ESG metrics are closely tracked. *"There are two types of KPIs that shareholders find* *interesting. The first group includes financial indicators, particularly EBITDA, EBITDA margin, and NFP. The second group is a series of KPIs Aquafil uses to track its progress toward the ESG goals outlined in its sustainability plan. The most scrutinised indicator is definitely the percentage of ECONYL revenue out of the total fibres revenue"* (AQUAFIL5), which surpassed 60 percent in 2025.

ECONYL® has scaled to TRL 9 (Technology Readiness Level 9) and has become a recognised input across industries, illustrating how absorptive capacity enables the transition from potential to realised innovation. Governance mechanisms reinforce this process. Part of the Executives' incentives are directly linked to sustainability outcomes, including ECONYL®'s revenue share and the amount of post-consumer waste collected (Aquafil, 2024). This alignment helps Aquafil to enforce sustainability into the corporate strategy and, at the same time, demonstrates to stakeholders and shareholders that sustainability is not only an external obligation but is considered a real competitive advantage.

At the same time, Aquafil has sought to avoid falling into a "competency trap" by diversifying into exploratory projects beyond the ECONYL® Regeneration System. Initiatives in elastomeric fibre separation, as well as PET and composite recovery, serve as safeguards against overreliance on a single technology. This balance between financial discipline and environmental leadership positions Aquafil as a credible long-term partner for both investors and policymakers. The company itself underscores this risk: *"If we do not restart to innovate and to bring new things to the market with better technologies, we will lose"* (AQUAFIL1). Sustaining competitiveness, therefore, relies on both ECONYL® and the continuous ability to transform external knowledge into industrial applications, a process maintained by robust routines and financial structures.

6 Partnerships and ecosystem orchestration

Aquafil's technological achievements can be understood by taking an ecosystem perspective, which involves a structure of aligned activities, actors, and positions that allow a value proposition to materialise. As one interviewee recalled, *"When we started the ECONYL's journey, the rest of the industry was very sceptical about our possibility to succeed"* (AQUAFIL1), underlining the initial doubtfulness that surrounded the launch of the ECONYL® Regeneration System. Yet this system illustrates the logic of ecosystem alignment clearly. While the technological exploitation provided the capability of depolymerising nylon waste at scale, its success depended on the coordination of suppliers, NGOs, regulators, brands, and consumers.

Following the Quadruple Helix model, Aquafil's interactions among four actor groups—industry, academia, government, and civil society—can be highlighted in shaping innovation outcomes. Aquafil has relied on universities for testing and scientific expertise, NGOs for waste collection and legitimacy, government and EU bodies for regulatory frameworks and funding, and brands/consumers for partnerships, adoption and scaling. *"We tend to choose the partners we collaborate with based on similar views and way of thinking, and this is valid for all NGOs, universities, brands, etc. Regarding the universities, of course, it is important that the technical support they can provide to us, for example, is based on the instrumentation that is not present in Aquafil"* (AQUAFIL4).

The widespread adoption of ECONYL® across fashion, flooring, and automotive sectors reinforces this point. Approximately 1,900 brands have integrated the fibre in their products and collections (Aquafil, 2024; Aquafil, n.d.). European plants, and Slovenian plants in particular, play a crucial role in managing waste flows from multiple geographies, showing how local capacity can underpin a global expansion. In continuing, some illustrative examples are provided.

A long-term partnership with Radici, an Italian textile company active since 1950 in the contract, marine, sports, and automotive sectors, shows how Aquafil's ecosystem creates customer value. The companies have collaborated for over 50 years, with ECONYL® providing product advocacy and credibility in the sustainability market. *"Usually, we say ECONYL®, and everybody was like, okay, it is fine. We know everything"* (AQUAFIL8). Joint innovation has produced Bloomback, a 100 percent polyamide carpet that can be fully recycled at Aquafil's Ljubljana plant, adopted by cruise operators such as Costa and AIDA. Yet the company also pointed to bottlenecks: *"We need to work together with Aquafil and other partners to create a take-back programme that truly works within the complex waste regulation framework"* (AQUAFIL8), highlighting the regulatory barriers around waste recovery. At the same time, slow adoption remains a challenge: *"While it is indeed a difficult market to change, we are beginning to see some rewarding signs from the market, albeit very slowly"* (AQUAFIL8). This highlights both the opportunities and challenges of scaling circular solutions, showing that ecosystem orchestration depends not only on technology but also on regulation and customer acceptance.

The supplier perspective further illustrates the challenges of ecosystem orchestration. Although collaborations with NGOs, municipalities, and shipowners support visibility, *"in our daily operations, the majority of our collection comes directly through established channels, such as net lofts and service stations in the aquaculture and fisheries sector. The backbone of the system is the cooperation we have with the industry actors at the operational level"* (AQUAFIL9). Beyond logistics, the partnership with Aquafil also enhances the supplier's sustainability reputation, as demonstrated by the Circular Fish Farming Net project, where ECONYL® provided a tangible proof point for circularity (AQUAFIL9). From a market perspective, ECONYL® strengthens trust with clients who value transparent end-of-life solutions, while bureaucratic barriers in cross-border waste shipments continue to complicate recycling compared to disposal.

Aquafil's long-term partnerships further illustrate interdependencies. Universities provide decisive support through rapid testing and insights (AQUAFIL3). NGOs, upstream value chain partners, customers and brands play critical roles in waste recovery and in co-creating circular products, such as carpets under the R2R initiative. The collaborative approach has upgraded supplier capabilities and strengthened buyer loyalty. This reflects both co-innovation risk and alignment of the adoption chain: success depends not only on Aquafil's own efforts but also on partners and customers innovating alongside it. Despite progress, transferring knowledge from research to industrial application remains a recurring challenge. *"Something that works on a small plant does not always work in a big one"* (AQUAFIL3). Flexibility and resilience, therefore, come from continuous optimisation and learning.

7 Human resources and talent management

Organisational culture, embedded in resilience and in a commitment to sustainability and reinforced by human resources practices, plays a decisive role in how Aquafil copes with innovation. Corporate culture has been transformed through the company's strategic decision to replace fossil-based materials with regenerated ones. This shift was not a marketing initiative but a redefinition of the firm's identity. *"For us, the must-have is to change the industry, it is not just to launch a new product"* (AQUAFIL1). This clarity of mission created a motivated workforce, particularly among younger employees who are attracted by the opportunity to contribute to meaningful change. Sustainability commitments are integrated into everyday operations. This value-driven orientation sets Aquafil apart from competitors and acts as a magnet for talent seeking purpose in their work. Furthermore, Aquafil communicates its culture and commitments through sustainability reports, employer branding, and partnerships, which strengthen its reputation in both labour and product markets.

Early in this journey, many industry observers doubted Aquafil's ability to succeed where larger competitors, such as BASF and DSM, had failed (BloombergNEF, 2024). The company's persistence in pursuing circularity despite scepticism cultivated an internal culture of resilience. Employees learned that long-term commitment and teamwork could overcome external doubt, reinforcing loyalty and creativity within the organisation. Inspiration from sustainability pioneers, such as Ray Anderson of Interface, one of their biggest customers, also shaped this ethos, showing that cultural change can precede and sustain technological breakthroughs. *"Once our people understood the vision, the response was incredibly positive. The results have returned very, very positively"* (AQUAFIL1).

Human resources practices further reflect and reinforce this culture. The ECO PLEDGE® framework integrates sustainability into employee engagement, emphasising values such as circular design, environmental responsibility, and community ties (Aquafil, 2024). This orientation is supported by a range of HR policies and programmes. Aquafil has adopted a Diversity, Equity and Inclusion (DE&I) policy, started a project focused on Talent management, organised corporate volunteering, obtained the UNI/PdR 125 Gender Equality certification, and introduced anti-discrimination and anti-harassment training to ensure equal treatment across the workforce.

Talent retention and motivation are strongly tied to Aquafil's green mission. Engagement tools, such as onboarding, mentoring, and training platforms like Aquapedia, as well as the Do ut Des programme, support this sense of belonging and renewal over time. The company's strong ties to academic institutions, with many universities in different countries, have also been central to developing a pipeline of skilled talent. These partnerships not only provide technical expertise but also help align research and industrial practice. The Ljubljana plant is the company's largest facility, hosting the ECONYL® depolymerisation system and related operations. Its success depends heavily on the skills of the local workforce, supported by graduates from the University of Ljubljana, for example. *"We found a very strong educational system, in particular with the Faculty of Chemistry and Chemical Technology in University of Ljubljana. We financed graduations and doctorate studies, and many of those graduates now work with us"* (AQUAFIL1).

Beyond talent, the plant's operational significance is also emphasised: *"Slovenia is an important hub. In Ljubljana, we have our ECONYL® depolymerisation system, nylon-6 polymer production, and textile yarn filaments, almost the full set of products inside one single operation"* (AQUAFIL1). Yet the constraints of this context are clear. Slovenia's small size and political uncertainties sometimes make it difficult to attract and retain talent or to plan long-term growth.

Maintaining cohesion across a growing multinational group is a cultural challenge. The company leadership stresses that Europe's future depends on continuous innovation and the ability to support younger generations. Within Aquafil, this translates into sustaining a culture of openness to new technologies, including artificial intelligence, which is being developed in-house to improve efficiency and reduce waste. *"For us, artificial intelligence is not about Google or Apple. It is about improving yields, efficiency, and office automation"* (AQUAFIL1). The emphasis on internal capabilities reflects a culture of self-reliance and adaptability, reinforcing the company's resilience against larger-scale competitors.

8 Regulatory framework

Aquafil's sustainability strategy is shaped not only by technology, culture, and finance, but also by regulatory environments across the markets in which it operates. *"The European Union's ambitious push for a circular and sustainable economy, particularly within the textiles and fashion sectors"* (AQUAFIL7) is particularly significant.

One of the greatest challenges comes from regulatory fragmentation and bureaucracy. *"One of the problems that Aquafil must face is given by the regulatory differences between the EU and other countries, as we interact with partners from all over the world. The regulatory risk that concerns us the most is the long time required to obtain the authorisations to work, either to obtain some materials or to modify some parts of industrial plants"* (AQUAFIL7). Suppliers echo this concern: *"One of the main challenges we face is not the logistics themselves – we have established efficient collection and transport systems – but rather the bureaucracy surrounding the cross-border movement of waste. Export permits, customs procedures, and varying national regulations often make the process time-consuming and unpredictable"* (AQUAFIL9). This imbalance highlights a weakness in the regulatory environment – circular options remain more burdensome than linear disposal.

Additional regulatory pressures include growing scrutiny of microplastics and chemical restrictions under the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) framework, areas flagged as regulatory priorities for the sector. The transparency requirements under the Corporate Sustainability Reporting Directive (CSRD) add further pressure, obliging firms to integrate financial and ESG reporting into their governance systems. On the other hand, these requirements represent an opportunity to integrate ESG factors into risk management processes and corporate strategy. Extended producer responsibility (EPR) schemes are a key source of both opportunity and risk, since their effectiveness depends on whether they truly incentivise high-quality recycled inputs, such as ECONYL® (AQUAFIL7).

Table 3. Summary of key findings

Topic	Key findings
Technology & finance	• Industrial-scale recycling proves circular innovation is viable when backed by consistent feedstock and diversified technologies. • Financial discipline and mixed funding sources enable alignment of sustainability with profitability.
Ecosystem partnerships	• Scaling requires orchestration across suppliers, NGOs, regulators, and brands within a coherent ecosystem. • Partnerships with universities, NGOs, and brands strengthen legitimacy and drive adoption.
Human resources & talent management	• A resilient culture and sustained investment in people support long-term competitiveness. • Strong ties with local institutions help secure talent, though small labour pools remain a constraint.
Regulatory environment	• Regulatory clarity and harmonisation are critical, as fragmented rules and bottlenecks hinder scaling. • EU frameworks and active industry engagement create legitimacy and shape future policy.

Source: Own work, Aquafil (n.d.), Aquafil (2024), BloombergNEF (2024).

At the same time, regulation also creates opportunities (Table 3). Upcoming EU rules that make the use of recycled plastics compulsory could accelerate demand for ECONYL® and similar circular products. Aquafil actively engages in shaping and anticipating these developments by participating in industry associations, such as the European Chemical Industry Council (Cefic) and the European Man-Made Fibres Association (CIRFS), which provide early insights and coordination. In this context, the company is preparing for the EU's Digital Product Passport (DPP), which will require significant investment in IT systems and collaboration across the supply chain to ensure full material traceability.

As a result, industrial recycling scales more slowly despite its environmental superiority. Regulation is both a constraint and a catalyst, making it essential to address inconsistencies while leveraging supportive frameworks to sustain Aquafil's role as a green tech pioneer.

Conclusion

Aquafil's case illustrates how a firm commitment to sustainability can be transformed into a source of competitiveness when strategy, technology, partnerships, culture, and finance are effectively aligned within a coherent ecosystem. The success of ECONYL® demonstrates that circular innovation is achievable at an industrial scale, but only when supported by long-term commitments and systemic collaboration.

With respect to the research questions, the analysis shows that balancing exploitation and exploration requires both disciplined optimisation of core technologies and selective investment in new solutions; that effective orchestration across suppliers, customers, NGOs, and regulators is essential to mitigate co-innovation and adoption risks; and that human resource strategies centred on resilience and purpose reinforce the absorptive capacity necessary for sustained innovation.

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RISK TYPOLOGIES IN GREEN HYDROGEN INFRASTRUCTURE: MAPPING MULTI-LEVEL RISKS ACROSS BUSINESS MODELS IN EARLY-STAGE INVESTMENT CASES

1 Introduction

An urgent need for carbon neutrality has placed green hydrogen at the centre of the energy transition. As countries and industries look for alternatives to decarbonise their economies and reduce fossil fuel consumption, green hydrogen is a promising solution. Hydrogen can play a decisive role in decarbonising hard-to-abate sectors, such as heavy industry, chemicals, transport, and heating, making it a versatile element in decarbonisation (Giacomelli et al., 2024).

However, early-stage investments in green hydrogen infrastructure face uncertainties and complex risks that can deter investment, postpone innovation and slow down progress. A competitive market for green hydrogen is still in its early stages of development. Reports predict moderate growth until 2030, after which the growth is expected to accelerate. Most hydrogen projects are in the pre-commercial phase (PricewaterhouseCoopers, 2021). The absence of a developed market infrastructure, proven business models, and sustainable pricing mechanisms represents a major barrier to its emergence.

This chapter aims to address these challenges by developing a typology of risks associated with early-stage investment in green hydrogen, which could provide a systematic approach for a better understanding and management of these risks. By combining theoretical views, existing risk assessment studies, and insights from the Local Hydrogen Alliance emerging from a pilot case in Velenje[1], the chapter seeks to establish a framework that will help investors understand, evaluate, and manage risks in hydrogen projects.

The chapter begins with an overview of hydrogen's properties and its dynamic value chain (DVC), followed by a review of business model archetypes. It then introduces a risk mapping framework and applies it to the Velenje case study, before concluding with final thoughts.

2 Role of hydrogen in the transition to renewable energy sources

Hydrogen is a colourless, odourless energy carrier with high energy density by weight but low by volume. Hydrogen produces zero emissions at use, releasing only water and heat (Min et al., 2025). It is versatile, powering fuel cells, engines, and industry, making it vital for hard-to-abate sectors (McGregor et al., 2025). It can be produced from renewable (green hydrogen) or fossil sources (other types of hydrogen) (Levikhin & Boryaev, 2024). The production of hydrogen from renewables avoids fossil fuels entirely and provides the most sustainable option for long-term decarbonisation (McGregor et al., 2025; OECD & The World Bank, 2024). For the purposes of this chapter, green hydrogen will be referred to as hydrogen.

2.1 The challenges of the commercial production and distribution

Hydrogen's physical and chemical characteristics create fundamental **safety and storage barriers.** Its low energy density by volume makes efficient storage and transport difficult. The element's low boiling point complicates liquefaction, and its tendency to leak and high flammability, coupled with the danger of invisible flames, introduce significant safety risks. Hydrogen can cause metal embrittlement, which undermines the durability of infrastructure (Levikhin & Boryaev, 2024; Min et al., 2025). These **element-specific properties** set the baseline for handling and infrastructure challenges across the value chain.

1 Part of the North Adriatic Clean Hydrogen Investment Platform (NACHIP), co-financed by the European Union.

Beyond elemental characteristics, the hydrogen sector faces systemic obstacles that limit large-scale adoption. As part of **storage and transport inefficiencies**, liquefaction causes losses of over 40 percent of energy, while compressed hydrogen transport loses around 18 percent of energy. Pipelines are cheaper for short distances, but long-range transport may rely on HVDC[2] transmission (McGregor et al., 2025; OECD & The World Bank, 2024). This part largely depends on the choice of carrier.

Another challenge is **high costs**. Electrolyser deployment in the EU is estimated to require €170–240 billion by 2030 (McGregor et al., 2025). Current production costs of hydrogen ($3.50–6.00/kg)[3] are more than double those of grey hydrogen ($1.50–2.50/kg) (Curcio, 2025). Financing gaps are especially evident in developing countries, where markets face a gap of $10-40 billion annually until 2030 (OECD & The World Bank, 2024). Another major challenge is **public acceptance**, as concerns about safety and accident risks reduce public trust. Initiatives, such as H2 Student programs, aim to raise awareness and improve acceptance (Hildebrand et al., 2024; Giacomelli et al., 2024). Finally, limited **technology maturity** poses a barrier, since many hydrogen technologies are still at a pre-commercial stage, exposing manufacturers, integrators, and R&D ventures to risks linked to durability, efficiency, and delayed scaling (McGregor et al., 2025; Giacomelli et al., 2024).

2.2 Hydrogen dynamic value chain

A dynamic hydrogen value chain is the process of hydrogen production, transport, storage, and end-use applications designed to adapt as technologies, markets, and policies evolve. Unlike a static supply chain, it accommodates multiple production pathways, flexible transport and storage options, and shifting end uses. This adaptability helps reduce risk and capture opportunities as costs, regulations, and demand change (Mock et al., 2023). For the purpose of this chapter, the items have been grouped into five links of the dynamic value chain.

Hydrogen production consists of electrolysing water with renewable power, storing energy without emissions (McGregor et al., 2025). Production is costly due to energy, electrolyser, and financing prices, keeping average total costs elevated (Giacomelli et al., 2024). Achieving EU targets requires a large scale-up and investment, but current technologies face reliability and lifespan issues

2 High-voltage direct current (HVDC) electric power transmission.
3 Hydrogen production cost ranges in the research paper (Curcio, 2025) are denominated in US Dollars ($).

(McGregor et al., 2025). To meet EU strategy goals, €24–42 billion of investment in electrolysers is needed by 2030; however, less than two percent of planned capacity was under development in 2022 (EIB, 2022). While average total costs are expected to decline after 2050 due to economies of scale, learning effects, and technological progress, early pilots depend on government support and initiatives, such as Hydrogen Valleys, to drive deployment (OECD & The World Bank, 2024; Giacomelli et al., 2024).

Hydrogen **storage and transport** are major cost drivers, often comparable to production costs (Hildebrand et al., 2024). Pipelines are suitable for shorter distances and can reuse existing gas infrastructure, while intercontinental shipping adds costs and complexity (McGregor et al., 2025; OECD & The World Bank, 2024). Storage capacity is insufficient, with salt caverns being the most cost-effective (OECD & The World Bank, 2024; McGregor et al., 2025). Infrastructure gaps, combined with hydrogen's safety concerns, increase costs, regulatory burdens, and public acceptance challenges, impacting financing and project timelines (McGregor et al., 2025; Hildebrand et al., 2024).

In the next stage, hydrogen is distributed to end users or converted into secondary energy carriers. It can generate electricity via fuel cells, with proton exchange membrane fuel cells (PEMFCs) suited for transport and stationary uses, while solid oxide fuel cells offer higher efficiency but have durability and temperature challenges. These systems require high-purity hydrogen and costly catalysts, which increases complexity and limits large-scale adoption (Min et al., 2025; OECD & The World Bank, 2024). Hydrogen can also be converted into e-fuels, ammonia, or methanol to decarbonise sectors like aviation and shipping (McGregor et al., 2025), but high conversion losses and dependency on supportive EU policies remain significant constraints (European Commission, 2025; Min et al., 2025).

Industry is expected to drive hydrogen demand for end use, primarily because it offers one of the few viable pathways to decarbonise energy-intensive sectors that cannot easily electrify. The drive can be led by steelmaking (FCHEA, 2025), where hydrogen-based direct reduction can decrease emissions by over 90 percent (McGregor et al., 2025), and by the chemicals sector for ammonia and methanol production (OECD & The World Bank, 2024). Transport applications focus on heavy-duty trucks, shipping, and aviation, where hydrogen and derived fuels are being piloted (Min et al., 2025; Hildebrand et al., 2024). Hydrogen also enables seasonal energy storage for renewables (OECD & The World Bank, 2024). Key risks include uncertain demand, high capital costs, regulatory delays, and safety-related public acceptance issues (Hildebrand et al., 2024).

And finally, hydrogen adoption flows through interconnected mechanisms across the value chain. EU policies, such as the Hydrogen Strategy and REPowerEU, target 10 Mt of domestic production and 10 Mt of imports by 2030 (European Commission, 2025). National subsidies and EU programmes reduce investment risk because projects undergo evaluation before approval, helping investors see their viability. Market-based instruments, such as carbon contracts for difference and carbon markets, provide predictable revenue streams and price signals that further stimulate demand (OECD & The World Bank, 2024). Innovation plays a key role in enabling later cost declines through technology development and risk-sharing initiatives (e.g., NAHV), but early projects still face high average total costs and financing gaps, requiring coordinated regulation and funding (Giacomelli et al., 2024; McGregor et al., 2025).

2.3 The hydrogen business model archetypes

Infrastructure developers play a crucial role in the hydrogen economy, as they are responsible for designing, constructing, and operating key infrastructure for hydrogen storage, transport, and distribution. Their role covers assets, such as pipelines, refuelling stations, shipping terminals, and large-scale storage facilities. These capital-intensive projects have long asset lifetimes and face risks related to energy losses, inefficiencies, and stringent safety regulations (Giacomelli et al., 2024; OECD & The World Bank, 2024). Market uncertainties, including infrastructure gaps and fluctuating hydrogen demand, further hinder project financing and development. However, public-private partnerships and government support under EU programmes can enhance bankability through subsidies, preferential financing, and risk-sharing (Giacomelli et al., 2024; OECD & The World Bank, 2024). Additionally, retrofitting existing gas infrastructure can reduce costs and speed deployment (Končan et al., 2024). Thus, infrastructure developers are essential to scaling hydrogen markets by ensuring reliable storage, transport, and distribution capacity, which underpins the competitiveness of hydrogen.

Component manufacturers play a central role in the hydrogen value chain by designing and producing key technologies, such as electrolysers, storage tanks, and gas-handling equipment, which are critical for hydrogen production and storage (McGregor et al., 2025). The performance and reliability of these components significantly influence the cost and competitiveness of hydrogen. To meet global deployment targets, electrolyser manufacturing capacity must more than triple by 2030, presenting challenges related to durability, supply chain constraints, and production scalability (McGregor et al., 2025). Manufacturers also face cost volatility driven by fluctuations in raw material prices and increasing energy input demands, which adds to market uncertainty. Nonetheless, policy-driven demand, government incentives with **circular feedback**, and long-term supply contracts enhance business prospects. Innovation and economies of scale further enable efficiency improvements, longer component lifespans, and cost reductions, positioning manufacturers advantageously in the fast-growing hydrogen market (McGregor et al., 2025).

System integrators play a vital role in the hydrogen economy by delivering turnkey solutions that integrate diverse technologies, such as renewable power, electrolysers, compression units, and storage, into fully operational systems (McGregor et al., 2025). Their expertise covers production, storage, and distribution phases by linking components into cohesive projects with circular feedback in mind (local and EU legislation). This model faces integration risks, including technical incompatibilities, delays, and cost overruns, making effective risk management and coordination with suppliers and financiers critical (OECD & The World Bank, 2024). However, increasing demand for hydrogen boosts their market position, as large-scale deployment relies on specialised system design and implementation. By simplifying complexity, ensuring technology interoperability, and delivering bankable projects, system integrators play a key role in enabling early growth of the hydrogen market, with competitiveness tied to reliability, execution, and adaptability to evolving standards (McGregor et al., 2025; OECD & The World Bank, 2024).

R&D business models focus on early-stage hydrogen technologies at low technology readiness levels (TRL 0–4), laying the groundwork for future deployment (Giacomelli et al., 2025). Their contributions span production, storage, and conversion phases, with innovations in electrolysers, storage media, and fuel cells influencing efficiency, reliability, and cost reduction. Funding primarily comes from public grants, university collaborations, and research partnerships, as commercial revenues remain limited. Value is generated through patents, prototypes, and intellectual property rather than immediate returns (Giacomelli et al., 2025). Key challenges include long development timelines, limited market uptake, and the "valley of death," where technologies stall due to funding gaps and risk aversion (Yue et al., 2022; Giacomelli et al., 2025). Nonetheless, R&D

actors are critical for fostering innovation, accelerating learning, and driving long-term cost declines across the hydrogen value chain (McGregor et al., 2025).

Commercialisation ventures bridge research and market readiness by scaling hydrogen technologies to higher TRLs (5–9), transforming prototypes into commercially viable systems (Giacomelli et al., 2025). They operate across the production, storage, transport, and conversion stages, integrating technologies into pilot projects and market-ready systems, while also considering legislative barriers (circular feedback). Financing typically involves private equity, project finance, and public-private partnerships that enable capital investment and risk mitigation (FinanCE, 2016). Cross-border initiatives, such as the European North Adriatic Hydrogen Valleys (NAHV), enhance commercialisation through pooled financing, expertise, and knowledge exchange, fostering transnational collaboration (Giacomelli et al., 2024). However, the high capital expenditure for large-scale facilities and regulatory uncertainties pose significant risks and can delay deployment. Despite these challenges, these ventures are essential for advancing the hydrogen infrastructure and moving toward cost competitiveness and market expansion.

3 Research methodology

The goal of this chapter is to develop a typology of risks associated with early-stage investments in green hydrogen infrastructure, thereby supporting a systematic understanding and management of these risks. It further aims to provide a framework, informed by theory and the Velenje pilot case, to help investors evaluate and mitigate these risks across the hydrogen value chain. This study combines desk research with semi-structured interviews conducted in August and September 2025. The review covered scientific studies and reports analysing risks in hydrogen infrastructure, and seven interviews with ten key actors captured a diverse perspective across business model archetypes and segments of the hydrogen value chain. Interviewee characteristics are presented in Table 1.

The interviews were conducted between August 31 and September 8, 2025, in person and via Zoom. Based on an overview of theory and insights from interviews, important risks have been recognised through the hydrogen DVC, and their typical impacts have been described. The impact of these risks on accounting statements, such as Profit and Loss, Balance Sheet, and Cash Flow, was assessed, and the most important impacts were presented.

Table 1. Sample characteristics

Organisation	Size	Business model archetype	Interviewee	Gender	Code
Company 1	Large	Infrastructure developer	Researcher	Female	HYDROGEN1-1
			Project manager	Male	HYDROGEN1-2
Company 2	Micro	Component manufacturer	CEO	Male	HYDROGEN2
Company 3	Medium	System integrator	Head of R&D and Informatics	Female	HYDROGEN3
Research institution 1	Not applicable	R&D business model	Researcher	Male	HYDROGEN4
Research institution 2	Not applicable	R&D business model	Researcher	Male	HYDROGEN5
Local public administration body	Not applicable	Commercialisation venture	Project leader	Female	HYDROGEN6-1
			Project member	Male	HYDROGEN6-2
			Project member	Female	HYDROGEN6-3
International-level industry network	Not applicable	Commercialisation venture	Strategic coordinator	Male	HYDROGEN7

Source: Own work.

4 Typology of risks in early-stage investment

The hydrogen economy relies on a value chain with interdependent stages, actors, and challenges. Understanding the stages and their interactions is crucial for assessing hydrogen's decarbonisation potential, and early identification of risks enables us to mitigate them.

The dynamic hydrogen value chain is subject to multiple interconnected risks. Technology risks arise from the immaturity of key technologies, including limited electrolyser reliability, inefficiencies in fuel cells, and challenges in converting hydrogen to e-fuel. Timing risks emerge from potential delays in achieving EU targets, which are influenced by slow infrastructure rollout and pilot project development. Safety risks are associated with hydrogen's flammability, leakage potential, material embrittlement, and hazards in storage and transport. Operational risks include securing adequate resources, infrastructure, and logistics, which are further compounded by constrained production and storage capacities. Financial risks involve high capital and operating costs, reliance on subsidies, and limited bankability of nascent projects. Commercial risks stem from uncertain demand, underdeveloped markets, absence of stable long-term offtake agreements, and volatile pricing mechanisms. Lastly, geostrategic risks relate to import dependency, exposure to international trade and currency fluctuations, and the risk of "energy colonialism" (Klingl, Altgelt & Österlein, 2024).

Tables 2 to 5 present key risks for all stages of the DVC, and their triggering ESG (Environmental, Social, Governance) factors, showing how ESG risks act as transmission channels that exacerbate other risks, such as technology, financing, geostrategic, or operational risk.

Table 2. Risks in the production stage of the hydrogen DVC

Key risks	Typical impact	Opportunities	Financial impact*
		ENVIRONMENTAL	
Environmental footprint & land use conflicts (Tech/Operational)	Permit delays, land-use pressure, reputational risk	Optimise site selection, integrate renewable planning	P/L: higher OPEX due to permits/ compensations; CF: upfront costs. Operating leverage↑, Quick ratio↓, Asset turnover↓
Water scarcity & high electrolysis demand (Operational/ Geostrategic)	Reduced social acceptance, ecosystem stress	Water-efficient electrolysers, circular water use	P/L: expenses for water optimisation. BS: asset impairment. Operating leverage↑, Quick ratio↓, Asset turnover↓
		SOCIAL	
Social opposition & workforce skill gaps (Commercial/ Operational)	Project delays, reputational risk, slower adoption	Community engagement, training	P/L: consultation/training costs. CF: delayed outflows/inflows. Operating leverage↑, Quick ratio↓, Asset turnover↓
		GOVERNANCE	
Regulatory uncertainty & subsidy instability (Timing/Financial)	Stranded investments, reduced investor activity	Policy engagement, diversified financing	P/L: lower revenues. CF: lost inflows. BS: possible asset impairment. Operating leverage↓, Quick ratio↑, Asset turnover↓
Supply chain transparency & safety compliance (Commercial/Safety/ Technological)	Reputational risk, sanctions, higher safety costs	ESG-certified suppliers, robust safety management	P/L: compliance costs, higher OPEX. CF: delayed inflows. BS: inventory/asset impairment. Operating leverage↑, Quick ratio↓, Asset turnover↓

Note: * Financial impact refers to how risks affect accounting statements: BS = Balance Sheet, P/L = Profit and Loss, CF = Cash Flow. OPEX = operating expenses, CAPEX = capital expenditures, Operating leverage = sensitivity of profits to changes in revenue, Quick ratio = short-term liquidity, Asset turnover = efficiency of asset use.

Source: Own work adapted from GH2 (2023); Anekwe (2025); Caiafa (2025).

Table 2 focuses on production stage risks. As of right now, a market for hydrogen is still developing, but "*Market creation is likely to be led by energy-intensive and hard-to-abate industries, such as steel, cement, and glass, which can benefit from public support and drive economies of scale*" (HYDROGEN2). At this stage, the main risks come from the high costs of building and running electrolysers, as well as uncertainty surrounding long-term subsidies. Water and land use also create challenges. The most important financial impacts at this stage are higher operating costs, costs of consulting, and costs of educating employees. *"Negative electricity prices can improve hydrogen production economics, but high costs remain the main barrier, as green hydrogen is currently more expensive than grey hydrogen, limiting its business case"* (HYDROGEN4). Cash flow can also be impacted, especially in connection with high initial investments and delays. High electrolyser costs and uncertainty over subsidies create financial risks, including potential stranded assets.

Table 3 focuses on storage and transport risks. The main challenge comes from the characteristics of hydrogen. Since it is flammable, it poses a safety risk. However, *"We have established safety procedures for handling hydrogen, which ensure that the technology and transport can be operated safely"* (HYDROGEN4).

But storage technologies already exist and only have to be adapted for the use of hydrogen. *"Compressed gas storage is the most mature technology, with innovation focused on improving working pressure, reducing cylinder weight, and lowering costs using advanced materials, such as carbon fibre"* (HYDROGEN1-1). *"Alternative storage options include liquid, LOHC, and ammonia carriers, but in many cases, compressed storage remains essential. Supply-side risks are limited due to mature technologies, established materials, and regulatory frameworks, whereas demand-side risks persist because market uptake remains uncertain and difficult to forecast"* (HYDROGEN1-2).

For now, there is a lack of a comprehensive regulatory framework. There is an existing EU hydrogen strategy; however, Slovenia has yet to adopt its own hydrogen strategy. There is still a lot of *"red tape relating to the usage of hydrogen"* (HYDROGEN5), but *"fortunately, regulations for our products in hydrogen applications have already been developed or are currently being developed within a well-structured and coherent framework, which provides a solid foundation for compliance and market readiness"* (HYDROGEN1-1). Recent initiatives and ongoing efforts indicate that regulatory frameworks for hydrogen are gradually improving, making the market more accessible and predictable.

The risks associated with the distribution and conversion stage are presented in Table 4. The main challenge in conversion and storage is related to energy losses, as many carriers are not energy-efficient. However, according to the interview, certain innovative breakthroughs have been made. *"Electricity-to-hydrogen conversion entails energy losses, but system-level efficiency can be optimised depending on the storage and transport method. For instance, in the* *steel sector, one hydrogen carrier achieves approximately 70 percent efficiency, while another, leveraging otherwise wasted industrial heat, exceeds 90 percent system-level efficiency and avoids storage degradation, making it suitable for long-term use"* (HYDROGEN2).

Table 3. Risks in the storage and transport stage of the hydrogen DVC

Key risks	Typical impact	Opportunities	Financial impact*
		ENVIRONMENTAL	
Hydrogen leakage (Safety/Technology)	Environmental externalities, reputational risks	Advanced leak detection, robust containment, safety protocols	P/L: OPEX for monitoring/compliance; CF: safety-related outflows; BS: asset impairment. Operating leverage↑, Quick ratio↓, Asset turnover↓
High energy demand for compression, liquefaction, ammonia conversion (Operational/ Financing)	Reduced carbon benefits, weaker sustainability credentials	Energy-efficient compression, integration with renewables	P/L: higher energy expenses; CF: reduced operational inflows. Operating leverage↑, Quick ratio↓, Asset turnover↓
		SOCIAL	
Public opposition to pipelines/storage (Commercial/Timing)	Project delays, increased consultation costs, reputational risk	Community engagement, transparent planning	P/L: higher consultation/transaction costs; CF: delayed inflows; BS: impairment if projects fail. Operating leverage↑, Quick ratio↓, Asset turnover↓
Occupational safety risks (Safety/Operational)	Accidents, social backlash, liability	Worker training, automated handling, strict safety protocols	P/L: higher insurance/training costs; CF: compensation/downtime. Operating leverage↑, Quick ratio↓ Asset turnover↓
		GOVERNANCE	
Lack of harmonised international standards (Technological/ Geostrategic)	Barriers to cross-border trade, delayed market integration	Standardisation initiatives, participation in international consortia	P/L: higher compliance costs; CF: delayed inflows. Operating leverage↑, Quick ratio↓, Asset turnover↓
Supply chain vulnerability for storage materials (Geostrategic/ Commercial)	Supply interruptions, price volatility, dependency on critical materials	Diversified sourcing, recycling, alternative materials	P/L: higher procurement costs; CF: volatile cash flows. Operating leverage↑, Quick ratio↓, Asset turnover↓
High CAPEX for storage & transport infrastructure (Financing/Timing)	Stranded assets, difficulty getting investments, subsidy dependence	Public-private partnerships, phased investments, blended finance	P/L: high financing costs; CF: delayed investor contributions. Operating leverage↑, Quick ratio↓, Asset turnover↓

* Financial impact refers to how risks affect accounting statements: BS = Balance Sheet, P/L = Profit and Loss, CF = Cash Flow. OPEX = operating expenses, CAPEX = capital expenditures, Operating leverage = sensitivity of profits to changes in revenue, Quick ratio = short-term liquidity, Asset turnover = efficiency of asset use.

Source: Own work adapted from GH2 (2023); Anekwe (2025); Caiafa (2025).

Table 4. Risks in the distribution and conversion stage of the hydrogen DVC

Key risks	Typical impact	Opportunities	Financial impact*
ENVIRONMENTAL			
High energy demand & carbon intensity (Operational/ Technology)	Lower carbon benefits, higher lifecycle emissions, reputational risks	Efficient conversion, renewable integration	P/L: higher OPEX; CF: reduced inflows. Operating leverage↑, Quick ratio↓, Asset turnover↓
Chemical spills or accidents (SafetyOperational)	Local contamination, social opposition	Advanced containment, spill response planning	P/L: fines/clean-up costs; CF: unplanned outflows. Operating leverage↑, Quick ratio↓, Asset turnover↓
SOCIAL			
Public resistance to conversion/distribution sites (Commercial/ Timing)	Permitting delays, reputational damage	Community engagement, transparent planning	P/L: consultation costs; CF: delayed inflows; BS: impairment if cancelled. Operating leverage↑, Quick ratio↓, Asset turnover↓
Occupational health risks (Safety/ Operational)	Worker accidents, reputational harm	Training, automation, strict safety protocols	P/L: insurance, costs; CF: accident payouts; BS: liability provisions. Operating leverage↑, Quick ratio↓, Asset turnover↓
GOVERNANCE			
Unclear regulatory frameworks for cross-border distribution (Geostrategic/Timing)	Legal uncertainty, trade barriers, delayed scaling	Harmonised standards, active policy engagement	P/L: legal, compliance costs; CF: delayed inflows. Operating leverage↑, Quick ratio↓, Asset turnover↓
Dependence on critical infrastructure (Financing/Operational)	Stranded assets, long payback periods, subsidy reliance	Phased investment, public-private partnerships	P/L: financing costs; CF: delayed inflows; BS: high CAPEX. Operating leverage↑, Quick ratio↓, Asset turnover↓
Supply chain complexity & ESG certification (Commercial/ Geostrategic)	Greenwashing risk, market exclusion	ESG-certified suppliers, traceability systems	P/L: certification, monitoring costs; CF: lower inflows. Operating leverage↑, Quick ratio↓, Asset turnover↓

* Financial impact refers to how risks affect accounting statements: BS = Balance Sheet, P/L = Profit and Loss, CF = Cash Flow. OPEX = operating expenses, CAPEX = capital expenditures, Operating leverage = sensitivity of profits to changes in revenue, Quick ratio = short-term liquidity, Asset turnover = efficiency of asset use.

Source: Own work adapted from GH2 (2023); Anekwe (2025); Caiafa (2025); Lillie (2023).

Table 5. Risks in the end-use stage of the hydrogen DVC

Key risks	Typical impact	Opportunities	Financial impact*
ENVIRONMENTAL			
Industry – high energy demand (Operational/ Technology)	Lower climate benefits, emissions, reputational risks	Efficient processes, renewable integration	P/L: higher energy costs; CF: increased outflows. Operating leverage↑, Quick ratio↓, Asset turnover↓
Transport – environmental footprint (Technology/ Commercial)	Limited climate benefit	Low-carbon fuel certifications, lifecycle assessment	P/L: higher costs; CF: reduced profitability. Operating leverage↑, Quick ratio↓, Asset turnover↓
Power – inefficiency in energy conversion (Technological/ Financing)	Reduced competitiveness, energy waste	High-efficiency fuel cells, hybrid systems	P/L: electricity costs; CF: increased outflows. Operating leverage↑, Quick ratio↓, Asset turnover↓
SOCIAL			
Industry – workforce transition & job displacement (Operational/ Commercial)	Reskilling costs, labour resistance, social opposition	Workforce retraining programs, social dialogue	P/L: reskilling costs; CF: delayed inflows; BS: provisions for liabilities. Operating leverage↑, Quick ratio↓, Asset turnover↓
Transport – public safety concerns(Safety/ Operational)	Delays in rollout, public resistance	Safety standards, community engagement	P/L: engagement, insurance costs; CF: delayed inflows; BS: possible impairment. Operating leverage↑, Quick ratio↓, Asset turnover↓
Power – public opposition (Commercial/Timing)	Delays, loss of social license to operate	Community engagement, transparent planning	P/L: engagement costs; CF: delayed inflows; BS: impairment. Operating leverage↑, Quick ratio↓, Asset turnover↓
GOVERNANCE			
Industry – uncertain incentives for green products(Financing/ Timing)	Reduced investment, stranded assets, scaling difficulty	Policy engagement, diversified revenue streams	P/L: compliance/certification costs; CF: delayed/reduced inflows. Operating leverage↓, Quick ratio↑, Asset turnover↓
Transport – a lack of global standards (Geostrategic/ Technological)	Market fragmentation, trade barriers	Participation in standardisation, international consortia	P/L: revenue instability; CF: unpredictable inflows. Operating leverage↑, Quick ratio↓, Asset turnover↓
Power – volatile markets & lack of policy frameworks (Financing/ Geostrategic)	Dependence on subsidies or contracts	Hedging, diversified contracts, advocacy	P/L: revenue instability; CF: unpredictable inflows; BS: stranded assets. Operating leverage↑, Quick ratio↓, Asset turnover↓

* Financial impact refers to how risks affect accounting statements: BS = Balance Sheet, P/L = Profit and Loss, CF = Cash Flow. OPEX = operating expenses, CAPEX = capital expenditures, Operating leverage = sensitivity of profits to changes in revenue, Quick ratio = short-term liquidity, Asset turnover = efficiency of asset use.

Source: Own work adapted from Saadat (2024); Sustainability Directory (2025).

In Slovenia, *“legislative barriers have already complicated pilot deployment, forcing projects to adopt containerised solutions instead of conventional boiler rooms”* (HYDROGEN5). As another interviewee highlighted, *“the critical issue is how to store and handle hydrogen safely... otherwise equipment quickly becomes too expensive to make sense”* (HYDROGEN3). To mitigate these risks, HYDROGEN5 explained that pilots in Velenje deliberately use highly trusted community sites, such as fire stations, allowing firefighters to train directly with hydrogen and demonstrate safety standards to the public. HYDROGEN3 agreed, stressing that engineers must also acquire new competencies and practical skills in handling hydrogen safely, which can lead to additional financial impacts, especially regarding insurance or potential accident payout costs. Financial impacts of these risks include higher operating and financing costs, reduced profitability, and the need to include provisions for liabilities in the company’s financial statements.

The transition from pilot projects to large-scale hydrogen use is still in its very early stages. *“End use of green hydrogen faces key challenges, including an unstable market, limited demand, insufficient equipment, lack of trained personnel, and evolving safety standards. Adoption depends on price competitiveness and reliable system design, requiring integrated optimisation of equipment, operation, and market dynamics to guide investment decisions”* (HYDROGEN4). At the same time, practical demonstrations are essential to prove technical and economic feasibility. *“Industrial pilots are critical to demonstrate large-scale energy storage, minimise transport losses, and validate technology at TRL 7, while successful scaling also requires workforce training, organisational adaptation, and operational know-how”* (HYDROGEN3).

Regulatory risk fundamentally envelopes and amplifies all other risk categories in the green hydrogen value chain, shaping market conditions, investment incentives, and operational feasibility across production, transport, storage, and utilisation. *“Short-term competition from low-cost fossil fuels and potential shifts in political will move toward or away from net-zero targets and add to regulatory uncertainty”* (HYDROGEN7). Current regulation lags behind rapid technological innovation due to fragmented legislative frameworks and a lack of harmonised technical standards, compounded by low public trust and legal uncertainties. These factors amplify technological, financial, operational, social, and governance risks by increasing costs, delaying projects, and deterring long-term capital commitments. For example, fluctuating subsidies or carbon pricing create unstable revenue streams and undermine profitability. Environmental and social factors, such as emission reduction pressures and uneven policy support, further complicate these dynamics by increasing the risk of asset stranding and regional disparities. Governance challenges, including inconsistent incentives and market distortions, increase capital costs and limit access to premium markets. Collectively, these circular feedback mechanisms highlight the critical need for stable, transparent, and coherent regulatory frameworks to reduce risk exposure, enhance investor confidence, and enable scalable and sustainable deployment of hydrogen (ISS Insights, 2024).

5 Case study: Linking hydrogen risk typologies with the pilot project in Velenje

The city of Velenje in the Šaleška Valley is currently undergoing a critical phase of transformation in its energy system. It is transitioning from its coal-based district heating system, which has long relied on the local lignite mine and the Šoštanj Thermal Power Plant (TEŠ), which still consumes 80 percent coal and 20 percent natural gas, to 100 percent renewable energy by 2033 (EU Covenant of Mayors, 2025). Despite serving 40,000 residents and 12,000 consumers, the system suffers 26.4 percent thermal losses and emits up to 80,000 tons of CO_2 annually (Interreg Central Europe, 2025; EU Covenant of Mayors, 2025). *"The municipality of Velenje is also participating in the EU Mission 100 Climate-Neutral and Smart Cities that aim to achieve net-zero by 2033, so to achieve that, we included hydrogen in their strategy, both in the form of pilots and in our future energy mix"* (HYDROGEN6-2). In response to these challenges, Velenje has emerged as a pilot area within both national and European frameworks to test sustainable heating solutions and accelerate its decarbonisation trajectory. Velenje is testing woody biomass, shallow geothermal, and solar thermal energy under the HEAT 35 initiative (Interreg Central Europe, 2025), while the NACHIP project supports hydrogen-based pilots. Within this framework, the hydrogen pilot in Velenje represents a pilot case for the companies ETRA and ECUBES as the key technological players, meant for urban use. Together with FER[4], the company KSSENA, and the Jožef Stefan Institute, which are building the supporting environment for the pilot, the project also pilots governance structures within a Local Hydrogen Alliance (NACHIP, n.d.).

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5.1 Project design specifics

The NACHIP[5] hydrogen pilot in Velenje is part of the North Adriatic Hydrogen Valley (NAHV), a transnational initiative involving 37 partners from Slovenia, Croatia, and Italy, designed to demonstrate the entire renewable hydrogen value chain, from production to end use (HSE, 2023a; HSE, 2023b). In Velenje, the pilot establishes a localised closed-loop hydrogen system in two public buildings in Škale, a community centre and a fire station, thereby testing hydrogen-based urban heating solutions within a controlled environment (Serichim, 2023). Rooftop photovoltaic (PV) systems supply electricity to an electrolyser, producing green hydrogen that is stored in pressurised containers compliant with Slovenian safety regulations. The stored hydrogen is subsequently converted into heat and electricity through fuel cells, with the thermal energy used to meet building demand, and the surplus electricity allocated to a nearby electric vehicle (EV) charging station (NACHIP, n.d.). Waste heat from the electrolyser is additionally captured for space heating, thereby enhancing overall system efficiency. This configuration exemplifies multi-sector coupling, linking electricity generation, heating, and mobility, while embedding the entire hydrogen value chain within a single distributed energy system. Within the broader NAHV framework, the pilot aims to produce more than 5,000 tonnes of renewable hydrogen annually and is supported by €25 million in EU funding through the Clean Hydrogen Partnership (HSE, 2023a). *"The Velenje pilot provides a testbed for the replication of hydrogen-based heating and mobility solutions across the Šaleška Valley and other urban districts in Slovenia"* (HYDROGEN6-1). One interview was particularly insightful regarding the importance of pilots, such as the one in Velenje. *"Hydrogen technologies are key to the energy systems of the future, enabling cross-sector integration of renewable energy and cost-effective seasonal storage. By unlocking these opportunities, hydrogen can make the energy transition more affordable for society. Pilot projects like the one in Velenje are essential to build a viable hydrogen market and showcase best practices"* (HYDROGEN 2).

5 NACHIP (North Adriatic Clean Hydrogen Investment Platform) is an EU-funded project that accelerates the development and market uptake of clean hydrogen technologies through validation, pilot projects, and an acceleration programme in the North Adriatic region. It is co-financed by the European Union through the I3 Instrument implemented by EISMEA (European Innovation Council and SMEs Executive Agency), granted under the Call Interregional Innovation Investments Strand 2a (I3-2023-INV2a) (NACHIP, n.d.).

5.2 Risk typologies in practice

The Velenje hydrogen pilot project exemplifies how theoretical risks manifest in practical applications across the hydrogen value chain. Each business model archetype is represented, starting with infrastructure developers, dealing with financing and timing risks in establishing local storage and distribution systems. Component manufacturers are challenged by electrolyser reliability and costs, while system integrators face coordination risks in linking PV, electrolysers, storage, and heating systems. R&D actors provide experimental setups and data collection, and commercialisation ventures embed the pilot into wider EU frameworks, such as the NAHV. In this way, Velenje functions as a microcosm of the hydrogen economy, where abstract categories of risks and challenges converge into concrete investment realities. The implications of theory in practice will be presented, with a focus on different risk typologies.

Interviewees expressed that *"At its current small scale, risks remain largely confined to regulatory compliance, with safety protocols effectively managed and community acceptance secured"* (HYDROGEN6-1). However, scaling the project introduces increased production risks associated with variable solar and wind resources, site selection complexities, and storage technology choices (Min et al., 2025; Younus, 2025; HYDROGEN6-3). Storage and transport stages raise safety concerns, demand substantial CAPEX, and pose uncertain financial returns, which may be mitigated through the selection of appropriate storage technologies (Levikhin & Boryaev, 2024; OECD & The World Bank, 2024). The distribution and conversion phases face multifaceted environmental, social, and governance challenges, including public scepticism, Not-In-My-Backyard (NIMBY) opposition, and permitting delays, which exacerbate commercial, timing, and reputational risks (Hildebrand et al., 2024; Forbes Slovenia, 2025). End-use integration, notably for district heating, offers significant emission reduction benefits but requires substantial infrastructure adaptation, workforce training, and adherence to updated safety protocols, heightening operational risk considerations (Min et al., 2025; HYDROGEN6-3). Persistent governance risks stem from regulatory uncertainty and fluctuating subsidy regimes, with low public trust further amplifying risks throughout all value chain stages (European Commission, 2025; Khan, 2024; Singh, 2025). *"A comprehensive feasibility study has been conducted to inform the safe and effective scale-up of this initiative"* (HYDROGEN6-1).

Interviews identified several key risks. The first one is connected with storage. *"Storage location remains uncertain, with options including salty, carbonated water or existing TEŠ infrastructure, raising safety and feasibil-*

ity concerns" (HYDROGEN6-3). The next risk is associated with distribution and conversion. *"Distribution and conversion stages face social acceptance risks, as some residents associate hydrogen pipelines and refuelling stations with potential hazards"* (HYDROGEN3). However, the use of hydrogen also presents opportunities for businesses. *"Expanding hydrogen use also presents opportunities for local innovation and economic development through the establishment of business and technology hubs"* (HYDROGEN6-1). Key risk typologies for the Velenje pilot project are summarised in Table 6.

Table 6. Hydrogen risk typologies in practice in the case of scaling hydrogen use in Velenje

Hydrogen DVC stage	Key risks	Business models archetypes	Velenje case example in the case of scaling hydrogen use
Production	Land-use conflicts, water availability, shortage of skilled workforce, lack of infrastructure for production	Component manufacturers, R&D ventures	Solar PV avoids major land-use conflicts, but water use and a lack of skilled staff remain; also, a lack of sufficient infrastructure for production and storage of hydrogen.
Storage and transport	Hydrogen leakage, safety compliance, lack of harmonised EU standards, lack of local standards	Infrastructure developers, system integrators	Compressed storage risks leaks, safety regulations raise CAPEX, unclear EU transport standards.
Distribution and conversion	Scaling costs, permitting delays, chemical conversion risks	System integrators, infrastructure developers	The pilot avoids distribution scale; district heating integration may face high costs and permitting risks, a lack of local trust.
End use	Round-trip inefficiency, public safety perception, stranded investments	Commercialisation ventures, system integrators	Hydrogen for heating and EV charging faces efficiency limits and public scepticism, a lack of implementation.

Source: Own work adapted from Elazab (2025); McGregor (2025); Hildebrand (2024); Forbes (2025).

5.3 Socioeconomic and environmental impacts

The Velenje hydrogen pilot could transform the city's energy, social, and environmental landscape. It aims to reduce CO_2 emissions from 80,000 tons to near zero (EU Covenant of Mayors, 2025). The pilot is thus positioned as a strategic lever for aligning Velenje with the EU's decarbonisation trajectory, while also exploring opportunities with geothermal, solar, and waste-heat recovery technologies (Interreg Central Europe, 2025). However, this transition comes with an energy efficiency trade-off: hydrogen conversion and storage are resource-intensive, which could reduce the net carbon benefits if not carefully optimised (McGregor et al., 2025).

The socioeconomic impacts are more complex. On the one hand, the project has already attracted investments, positioned Velenje as a hub for hydrogen innovation, and created opportunities for local partnerships involving research institutions, firms, and the municipality (META Group, 2025). *"We will soon open a call for local businesses, which are already working with hydrogen, to apply for grants and spearhead our hydrogen development"* (HYDROGEN6-1). Hydrogen pilot projects also support workforce reskilling, as operators of coal-based systems must transition to hydrogen safety and maintenance training, offering prospects for long-term employment stability (Giacomelli et al., 2024). On the other hand, the pilot faces a trust gap with citizens, particularly in coal-dependent communities where scepticism toward new technologies is higher. Residents have voiced concerns about hydrogen's safety, effectiveness, and whether it represents an "experimental" solution imposed from above (Hildebrand et al., 2024; Forbes Slovenia, 2025; Velenjčan, 2025). This mistrust could slow public acceptance and hinder the realisation of socioeconomic benefits. If citizens resist the adoption of hydrogen, the project risks failing to deliver on its promise of an inclusive, community-based energy transition. In effect, the pilot's social impacts are conditional on the success of engagement and trust-building strategies.

Environmentally, the project can play a significant role in reducing local air pollution and improving public health, offering measurable benefits beyond climate mitigation (Martins, 2024). Socioeconomically, its legacy will depend on whether Velenje succeeds in coupling technical success with citizen confidence in the safety and fairness of hydrogen. Without social acceptance, even technically successful pilots risk limited scalability and diminished long-term value.

5.4 Financing and scalability

The financing of hydrogen infrastructure, particularly in early-stage pilots, such as Velenje, is inherently exposed to high capital intensity and uncertainty. A critical financing challenge is linked to social acceptance. Investors assess not only technological feasibility but also the degree of local legitimacy and social license to operate. In Velenje, scepticism from citizens about the safety and necessity of hydrogen infrastructure introduces financing risks, as opposition can delay permitting, increase transaction costs, and heighten reputational risks for both public authorities and private firms (Hildebrand et al., 2024; Forbes Slovenia, 2025). This dynamic translates directly into higher perceived risk premiums for investors, potentially limiting the pool of capital available to support hydrogen projects.

Scalability further depends on regulatory stability and market integration. Fragmented governance frameworks or shifting subsidy regimes increase the risk of stranded assets, particularly for infrastructure developers exposed to long payback periods (OECD & The World Bank, 2024b; Singh, 2025). Moreover, unresolved standardisation issues in hydrogen transport and certification create barriers to scaling projects beyond the pilot stage (European Commission, 2025). A new ICT platform plays a significant part in the pilot. The Jožef Stefan Institute plans to gather data to determine if the pilot was successful and how the data can be used to scale up hydrogen use. However, that is not so simple to achieve. *"As of right now, we have no idea where the data will come from and how we are going to collect it. It is a work in progress, but that is our biggest risk at the moment"* (HYDROGEN5).

Despite these challenges, the Velenje pilot illustrates pathways for overcoming financing barriers. By embedding the project within broader European alliances, such as the NACHIP and North Adriatic Hydrogen Valley initiatives, local stakeholders can leverage risk-sharing mechanisms that distribute technological, financial, and reputational risks across multiple actors (Giacomelli et al., 2024). However, long-term scalability will require co-creation with citizens, ensuring that local communities perceive hydrogen not as an imposed experiment but as a trusted part of the regional transition strategy. Without this, financing streams may remain fragmented, and investor confidence may be constrained, ultimately slowing both the decarbonisation of Velenje and the replication of hydrogen pilots in strategies for a coal phase-out.

6 Conclusion

Hydrogen technologies are set to play a central role in future energy systems by enabling cross-sector integration and providing seasonal storage. Pilot projects, such as the one in Velenje, are therefore essential, as they help demonstrate practical solutions, test business models, and build confidence in the emerging hydrogen market. Yet, green hydrogen business models face very different risk profiles. Infrastructure developers are exposed to financing and timing risks due to their capital-intensive nature and regulatory dependencies. At the same time, component manufacturers struggle with technological maturity, raw material availability, and scaling challenges. System integrators take on coordination and operational risks in complex projects, and R&D ventures face uncertainty in market readiness and intellectual property protection. At the same time, each of these actors also has unique opportunities—from securing long-term offtake contracts and benefiting from policy support, to establishing technological leadership, building strategic partnerships, and tapping into grant programmes or innovation funds.

The Velenje pilot illustrates how these risks and opportunities intersect in practice, with public actors, firms, and research institutions carrying distinct but interconnected exposures. Advancing the hydrogen economy, therefore, requires not only investment but also robust risk governance and citizen engagement to secure social acceptance. Tailored policy interventions are needed to address the specific needs of each business model: predictable regulation and financing for infrastructure developers, industrial policies to stabilise supply chains for component producers, coordination platforms for system integrators, and targeted R&D support to close funding gaps. By linking risk-opportunity strategies to each segment of the hydrogen value chain, policymakers can reduce uncertainty, attract private capital, and accelerate the transition toward a functioning hydrogen market.

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AN ANALYSIS OF PATENT ACTIVITY IN HYDROGEN TECHNOLOGIES IN THE NORTH ADRIATIC REGION AND OTHER EU LARGE-SCALE HYDROGEN VALLEYS

1 Introduction

The European Union's transition toward a hydrogen economy is one of the most defining technological and policy projects of this century (European Commission, 2020; Hydrogen Europe, 2019). Within this process, hydrogen valleys (regional ecosystems that integrate production, distribution, and end uses) have been promoted as strategic platforms for scaling technologies and coordinating investment (FCH JU, 2021; IEA, 2019). They function as real-world testbeds not only for technical solutions but also for institutional arrangements.

While much has been written on the strategic positioning and governance of hydrogen valleys (Giacomelli et. al, 2024), far less attention has been given to innovation outcomes and patent activity. Patents are widely recognised as a robust proxy for inventive effort and technological advancement (Griliches, 1990; Hall et al., 2001; Akcigit & Kerr, 2018), yet their relationship with institutional design in hydrogen valleys remains underexplored. This chapter seeks to address this gap.

Four large-scale European hydrogen valleys were analysed: the North Adriatic Hydrogen Valley (NAHV), spanning Italy, Slovenia, and Croatia; HEAVENN in the Northern Netherlands; WIVA P&G in Austria; and the Castilla y León Hydrogen Valley (CyL H2) in Spain. Each represents a distinct institutional and technological configuration, allowing a comparison of how governance, funding, and regional capacity shape both opportunities and barriers to patenting.

Building on theories of regional innovation systems (Cooke et al., 1997; Asheim & Gertler, 2005), technological innovation systems (Bergek et al., 2008), and institutional economics (North, 1990; Acemoglu et al., 2005), the chapter examines how institutional factors, such as human capital development, research funding, administrative efficiency, regulatory frameworks, and entrepreneurship support, influence hydrogen-related innovation outcomes.

First, the relevant literature on innovation, institutional quality, and hydrogen technologies is reviewed. Then, the institutional configurations and strategic dynamics of four European hydrogen valleys were analysed, followed by an examination of patterns of patent activity and innovation gaps across these valleys, situating them within European and global trends. The chapter concludes with a development of policy pathways to enhance Europe's capacity to translate hydrogen R&D into patentable technologies and to strengthen the innovation potential of hydrogen valleys.

2 Literature review

Innovation is widely recognised as a central driver of economic growth, productivity, and sectoral transformation (Solow, 1965; Schumpeter, 1942; Griliches, 1979). Institutional quality has long been highlighted as a decisive factor in shaping these outcomes, as strong governance reduces transaction costs, facilitates cooperation, and enables sustained development (North, 1990; Acemoglu et al., 2005; Rodríguez-Pose, 2013). In this context, patents serve as a robust proxy for inventive effort, offering measurable and comparable indicators of technological progress while reflecting the institutional and industrial environments in which they are generated (Griliches, 1990; Hall et al., 2001).

The literature on patents underlines both their strengths and limitations. They provide standardised evidence of innovation output, yet patenting intensity varies by technology and region (Akcigit & Kerr, 2018). Spatial concentration is particularly notable: leading regions combine higher rates of collaboration, institutional density, and stronger innovation ecosystems (Bernini, 2023). Hydrogen-specific studies indicate that Europe, the United States, Japan, and China collectively account for the majority of hydrogen-related patents, with electrolysis, storage, and fuel cells being the primary areas of focus in filings

(Yang et al., 2024; Sebastian et al., 2023). These trends reinforce the need to examine patent activity in relation to institutional capacity and policy frameworks, rather than in isolation.

Hydrogen valleys have emerged as geographically concentrated ecosystems that integrate hydrogen production, storage, distribution, and end use (FCH JU, 2021; IEA, 2019). Beyond technical demonstration, they act as institutional laboratories where funding schemes, governance structures, and industrial partnerships can be observed in practice. Their strategic importance lies in addressing hard-to-abate sectors while advancing Europe's decarbonisation targets, with more than 100 valleys worldwide representing investments exceeding €150 billion (Upham & Maristany, 2025).

Recent studies emphasise that valley performance is shaped less by technical design than by institutional mechanisms (Bergek et al., 2008; Cooke et al., 1997). Regulatory clarity, administrative efficiency, and targeted funding instruments, such as the Important Projects of Common European Interest (IPCEI) and the European Hydrogen Bank, create enabling conditions for innovation (Vezzoni, 2024; Bonafé et al., 2023). Likewise, human capital and skills development emerge as critical channels: projections estimate one million skilled hydrogen jobs in the EU by 2030 and 5.4 million by 2050 (Atanasiu, 2021), highlighting the role of institutional capacity in training and mobilising a specialised workforce (Sörum & Banjac, 2024). These institutional factors not only influence the implementation of valleys but also shape the likelihood of generating patentable outcomes.

Comparative studies of hydrogen valleys illustrate this relationship. Northern European valleys, such as HEAVENN, benefit from established gas infrastructure, strong regional innovation systems, and cross-border coordination, while Southern European initiatives emphasise solar-based production and export strategies (Squintani & Schouten, 2023; Upham & Maristany, 2025). Institutional variation thus channels technological pathways and determines whether valleys become sources of patented innovation or remain primarily demonstration-oriented.

Overall, the literature suggests that hydrogen valleys succeed when institutional quality, funding mechanisms, and human capital align with technological objectives. Patent activity emerges as both an indicator and an outcome of these institutional interactions, making it a valuable analytical lens for comparing cases, such as the NAHV, HEAVENN, WIVA P&G, and CyL H2.

3 Institutional configurations and strategic dynamics of European hydrogen valleys

Hydrogen valleys are more than technological projects; they function as arenas where governance, industry, and research intersect. Each valley reflects its regional setting while aligning with broader European ambitions, making them institutional showcases for the energy transition. The four cases (NAHV, HEAVENN, CyL H2, and WIVA P&G) were selected because they illustrate diverse geographical and institutional configurations within the EU. Together, they show how governance structures and regional capacities shape both technological pathways and the potential for patenting and innovation.

3.1 Institutional models for European hydrogen transition

The North Adriatic Hydrogen Valley (NAHV) is the EU's first transnational hydrogen valley, integrating Slovenia, Croatia, and the Friuli Venezia Giulia region of Italy. Established through a trilateral agreement in 2022, it involves 34 partners from academia, government, and industry under a quadruple-helix governance model (Clean Hydrogen Partnership, 2023; NAHV, 2024). Its institutional design emphasises cross-border policy harmonisation, supported by Horizon Europe funding, and aligns directly with the European Green Deal and REPowerEU. NAHV plans to produce over 5,000 tons of renewable hydrogen annually, with 20 percent of this volume being traded across borders, while coordinating 18 demonstration projects in industrial and mobility applications (European Commission, 2023). This model highlights both the opportunities and governance challenges of multi-jurisdictional innovation ecosystems.

HEAVENN in the Northern Netherlands represents Europe's most advanced hydrogen demonstration project, integrating production, storage, distribution, and diverse end uses within a single regional ecosystem. Supported by Horizon 2020 funding and a consortium of 31 partners from six countries, HEAVENN benefits from strong academic–industry linkages and access to existing gas infrastructure (CORDIS, 2020; HEAVENN, 2024). Its institutional strength lies in consortium coordination and the capacity to scale technologies from demonstration to commercial readiness. By leveraging offshore wind and underground storage, HEAVENN has positioned itself as both a technological pioneer and a model for regulatory and business frameworks in hydrogen development (Hydrogen Central, 2024).

The Castilla y León Hydrogen Valley (CyL H2) is coordinated by Fundación CARTIF, with a planned investment of €380 million, including €20 million from Horizon Europe (Cartif, 2024). Its consortium of 35 partners spans nine countries and is supported by the Hydrogen Valley Smart Advanced Virtual Tool (HVSAVT), a digital twin platform for monitoring and optimisation (Castilla y León H2 Valley, 2024). With a planned annual production of over 16,000 tons, CyL H2 integrates pilots across the industry, mobility, and power sectors, while aligning with Spain's National Hydrogen Roadmap. Its institutional significance lies in embedding hydrogen development within regional socio-economic revitalisation, targeting job creation, decarbonisation, and industrial renewal (Cadenaser, 2025).

Austria's **WIVA P&G** is a national showcase project recognised as the Hydrogen Valley of the Year in 2023. Coordinated by the WIVA P&G Association, the initiative represents a €258 million investment and produces approximately 2,000 tons of hydrogen annually. Its institutional model is notable for coordinating diverse stakeholders across the full hydrogen value chain (from renewable energy inputs to mobility and industrial end uses) within a single national framework (h2v.eu, 2023). By operating as a "living laboratory", WIVA P&G demonstrates how coherent national governance and strong stakeholder networks can provide both stability and replicability, making it a reference model for Austria's broader energy transition.

Table 1. Institutional models in four European hydrogen valleys

	Governance & institutional setup	Value chain integration	Strategic role & policy alignment
NAHV	Quadruple-helix governance; 34 partners across Slovenia, Croatia, and Italy; trilateral agreement (2022)	18 pilot projects; production (>5,000 t/yr), storage, distribution, industry and mobility	EU's first transnational valley; cross-border harmonisation; aligned with Green Deal and REPowerEU
HEAVENN	Consortium of 31 partners from 6 countries; strong academic–industry–government coordination	Full value chain: electrolysis, storage, pipelines, diverse end uses (industry, heating, mobility)	EU flagship under Horizon 2020; integrated with Hydrogen Valley Campus Europe; regulatory/business model pioneer
CyL H2	Coordinated by Fundación CARTIF; 35 partners from 9 countries; €380 million investment with Horizon Europe	9 confirmed pilot projects, the 10th project is planned; annual output >16,000 t; HVSAVT digital twin for coordination	Aligned with Spain's National Hydrogen Roadmap; supports reindustrialisation and socio-economic revitalisation
WIVA P&G	Coordinated by WIVA P&G Association; €258 million investment; Hydrogen Valley of the Year (2023)	Multiple renewables; PEM & SOE electrolysis; compressed storage; pipelines and trucks; wide end uses	Austria's flagship, national "living lab", scalable template for replication in the EU

Source: Own work.

The four valleys show how governance models shape hydrogen innovation (Table 1). NAHV highlights both the promise and the complexity of cross-border coordination. HEAVENN demonstrates the advantages of a deeply integrated regional ecosystem. CyL H2 illustrates how hydrogen development can drive regional reindustrialisation. WIVA P&G underscores the efficiency of centralised national governance. Together, these cases confirm that institutional design is a key determinant of innovation outcomes and patent activity (Clean Hydrogen Partnership, 2024; Giacomelli et al., 2024).

3.2 Strategic capacities and institutional challenges in European valleys

As hydrogen valleys emerge as central components of the European green transition, their institutional and strategic configurations play a decisive role in shaping innovative outcomes. This subsection interprets the position of four major European valleys through the lens of institutional economics and innovation systems theory (Cooke et al., 1997; Bergek et al., 2008; Acemoglu et al., 2005). The comparative overview (Table 2) identifies institutional capacities, structural constraints, strategic leverage points, and systemic risks, offering insights for both regional competitiveness and EU-wide hydrogen governance.

Table 2. Comparative analysis of strategic factors from European hydrogen valleys

Factor	NAHV	HEAVENN	CyL H2	WIVA P&G
Institutional capacities	Transnational; quadruple-helix governance	Full value-chain integration; 31 partners	Strong research base; alignment with national strategy	Operational maturity; diverse technologies
Structural constraints	Cross-border complexity; demand gaps	High complexity; costly transition from demo to market	Pre-operational; labour market issues	Limited scale; transparency gaps
Strategic leverage points	Integration into H2 backbone; regional decarbonisation	EU-first mover; innovation potential	Reindustrialisation; biohydrogen niches	Replication template; strong network
Systemic risks	Low-cost export competition; political divergence	Tech/operational risk; funding dependency	Infrastructure delays; uncertain demand	Funding gaps; global tech leapfrogging

Source: Own work.

Across the four valleys, institutional capacities illustrate how regional assets translate into innovative potential. HEAVENN's complete value-chain integration reflects a mature regional innovation system, while WIVA P&G demonstrates the benefits of operational maturity in translating pilot projects into systemic deployment. NAHV's transnational structure provides an inclusive quadruple-helix governance model, while CyL H2 leverages Spain's renewable endowment to anchor future growth.

At the same time, all valleys reveal structural constraints that align with the literature on technological innovation systems (Bergek et al., 2008). NAHV faces administrative complexity due to cross-border coordination, CyL H2 must overcome pre-operational uncertainties, and HEAVENN struggles with the high cost of scaling from demonstration to market. Even WIVA P&G, despite its maturity, is limited in scale relative to larger international competitors.

Strategic leverage points highlight the pathways through which valleys can strengthen their institutional design. NAHV is positioned to integrate with the European Hydrogen Backbone, enhancing cross-border energy security. CyL H2 can contribute to regional reindustrialisation and bio-based hydrogen niches, while HEAVENN's status as an EU-first mover allows it to shape standards and regulatory practices. WIVA P&G provides a replication model for industrialised regions seeking to transition from fossil-based to renewable energy systems.

Finally, systemic risks emerge from global and structural dynamics rather than valley-specific features. International cost competition, supply chain bottlenecks, and funding volatility mirror blocking mechanisms identified in technological innovation system studies (Sörum & Banjac, 2024; IEA, 2023). The sustainability of all valleys ultimately depends on balancing EU-level policy stability with local institutional adaptation, ensuring that valleys evolve beyond demonstration sites into durable components of Europe's hydrogen economy.

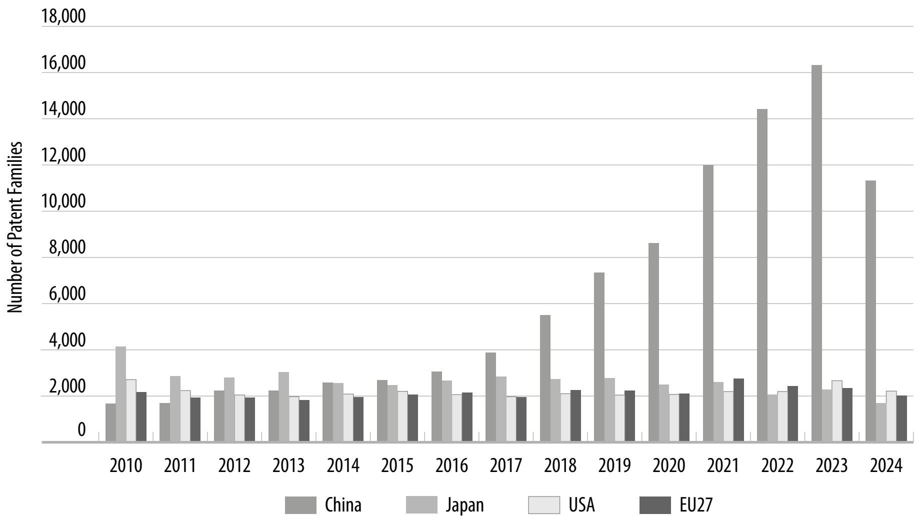
4 Patent dynamics and innovation gaps in hydrogen valleys

Patents tell a different story from policy documents or project blueprints. They offer a tangible record of where innovation is happening, and where it is not. In the case of hydrogen, global competition is intensifying, and Europe's valleys find themselves both as testbeds and as contenders. Examining patent dynamics reveals the extent to which these ambitious projects are translating investment and cooperation into lasting intellectual property.

4.1 The global patent landscape

Patent activity provides a useful lens for assessing technological leadership and the pace of innovation in hydrogen technologies. Using data from the EPO's PATSTAT database (CPC subclasses Y02E 60/30, Y02E 60/32, Y02E 60/34, Y02E 60/36, Y02E 60/50), which cover hydrogen technologies, storage, distribution, electrolysis, and fuel cells, the trajectory from 2010 to 2024 reveals a decisive global realignment. In 14 years, China expanded its global share of hydrogen-related patent families from less than 20 percent to nearly 70 percent, while the share of the EU27 declined from about a quarter to just over ten percent. The United States peaked in the mid-2010s before entering a gradual downturn, and Japan has seen a steady decline since its early specialisation in fuel cells (Figures 1 and 2).

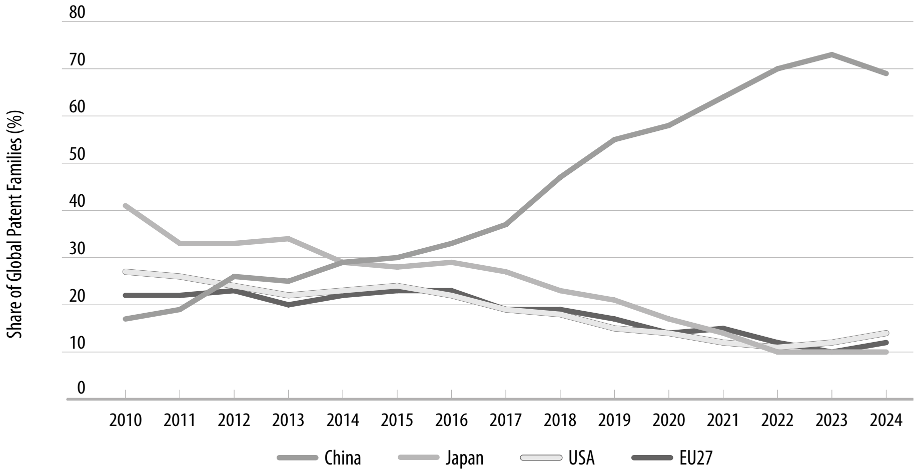
Figure 1. Hydrogen technology patent families – China, Japan, the US, and EU27



Source: EPO PATSTAT (Worldwide Patent Statistical Database).

These shifts reflect differences in institutional and policy approaches. China's surge is closely tied to massive state-led investment in hydrogen research, subsidies for industrial deployment, and explicit patenting incentives (Yang et al., 2024). Japan's declining share illustrates the limits of long-term specialisation without market expansion. Despite decades of leadership in fuel cells, Japan has struggled to scale beyond niche applications (IEA, 2019). The United States shows the volatility of market-driven innovation, characterised by strong entrepreneurial activity but weaker continuity in public support, which has contributed to fluctuations in patenting.

Figure 2. Share of global hydrogen technology patent families by country/region



Source: EPO PATSTAT (Worldwide Patent Statistical Database).

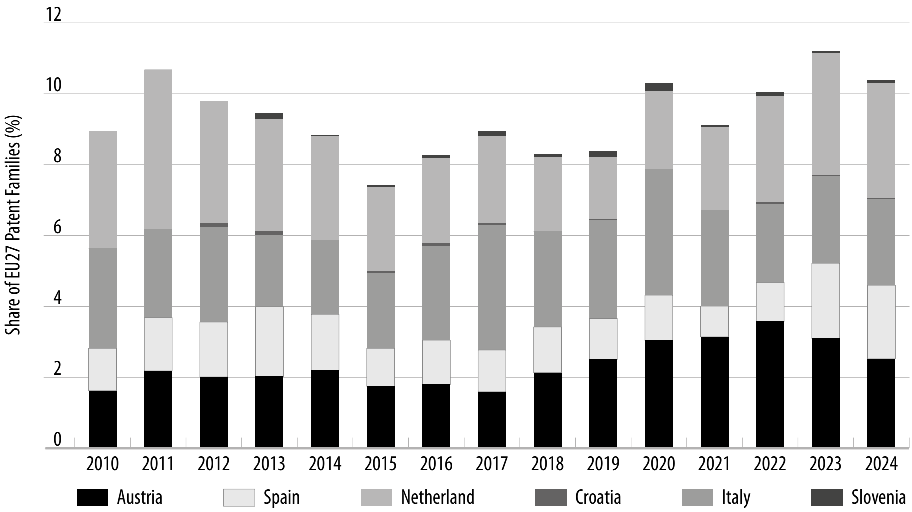
In Europe, the concern lies not in irrelevance but in relative stagnation. The EU has invested heavily in hydrogen through Horizon programs, the Clean Hydrogen Partnership, and IPCEIs, yet its fragmented national systems dilute the overall effect. Patenting remains concentrated in a few member states, while many regions lag behind (Bernini, 2023; Vezzoni, 2024). This suggests that Europe's strength lies in building integrated demonstration ecosystems, but translating those into intellectual property remains an unresolved challenge.

Hydrogen valleys, such as the NAHV, HEAVENN, CyL H2, and WIVA P&G, have been designed as institutional laboratories to address this problem. They bring together industry, academia, and government in regionally anchored ecosystems, aiming to convert demonstration activity into patentable innovation. The global context makes their role particularly significant. Unless these valleys can evolve from pilot projects into engines of intellectual property, Europe risks deepening its innovation gap with China, the US, and Japan.

4.2 Patent activity in the EU and selected hydrogen valley countries

Within the European Union, hydrogen-related patent activity is highly uneven. Germany and France dominate, together accounting for around 40 percent of EU27 filings (PATSTAT, 2024), while the countries associated with the four valleys under study (Italy, Slovenia, Croatia, Spain, Austria, and the Netherlands) occupy secondary positions (Figure 3). This concentration shows that, despite large-scale EU investments, patent generation remains clustered in a few member states.

Figure 3. Share of EU27 hydrogen patent families by countries associated with the four selected valleys



Source: EPO PATSTAT (Worldwide Patent Statistical Database).

Italy is the strongest contributor among the valley countries, consistently ranking near the top of EU patenting, although this is concentrated in specific industrial regions rather than nationwide (European Commission, 2023; PATSTAT, 2024). The Netherlands also performs well, reflecting its robust institutional base in energy innovation and aligning with HEAVENN's mature ecosystem. Austria contributes modest but steady filings, in line with WIVA P&G's focus on deployment rather than upstream R&D. Spain, despite vast renewable resources, lags in hydrogen patenting, underlining the gap between energy potential and inventive output. Slovenia and Croatia remain marginal players, with only single-digit annual filings. Of these, roughly ten are linked to the National Institute of Chemistry (Kemijski inštitut), which is not a formal NAHV member, underscoring the weak direct contribution of valley stakeholders to patenting.

Together, the six countries linked to the NAHV, HEAVENN, WIVA P&G, and CyL H2 account for only ten percent of EU27 hydrogen-related patents in 2024 (Table 3). This disparity illustrates what Bernini (2023) refers to as the "demonstration–innovation gap": large-scale projects have yet to translate into proportional intellectual property generation. Fragmented IP regimes, reliance on EU-level rather than national mechanisms, and weak commercialisation pathways contribute to this outcome (Noailly & Ryfisch, 2015; Vezzoni, 2024).

Table 3. Hydrogen patent families by countries associated with selected valleys and by EU27 (2024)

Subclasses*	Austria	Spain	Croatia	Italy	Netherland	Slovenia	EU27
Y02E 60/30	0	2	0	1	2	0	19
Y02E 60/32	11	6	1	7	9	0	261
Y02E 60/34	0	2	0	0	0	0	10
Y02E 60/36	12	16	0	30	19	0	516
Y02E 60/50	28	16	0	27	19	2	1215
Total	51	42	1	65	49	2	2021

* CPC subclasses Y02E 60/30, Y02E 60/32, Y02E 60/34, Y02E 60/36, and Y02E 60/50 refer to various energy storage technologies, including electrochemical, lithium-ion, redox flow, supercapacitor, and thermal storage systems.

Source: Own work.

Within this broader picture, NAHV highlights the specific challenges of transnational cooperation. Italy's relatively strong position contrasts with the marginal contributions of Slovenia and Croatia, creating an asymmetry that complicates cross-border innovation. Friuli Venezia Giulia itself accounts for only a fraction of Italy's filings, leaving most of NAHV's territory outside Europe's core hydrogen patenting hubs (PATSTAT, 2024). By comparison, HEAVENN benefits from a dense R&D and industrial ecosystem in the Northern Netherlands, correlating with higher patent intensity (Yang et al., 2024). WIVA P&G shows that coherent single-country governance can support steady, if modest, inventive activity, while CyL H2 demonstrates the lag between ambitious regional planning and actual patent output (Cartif, 2024; Clean Hydrogen Partnership, 2024).

Overall, Europe's hydrogen valleys reflect uneven innovation capacities. NAHV faces asymmetries across its jurisdictions, HEAVENN translates institutional coherence into stronger R&D outcomes, WIVA P&G leverages operational maturity for gradual progress, and CyL H2 remains primarily a socio-economic transition project. These contrasts reinforce the central insight that institutional design is inseparable from patenting performance, shaping whether valleys evolve into engines of intellectual property or remain largely demonstrative initiatives.

5 Conclusion with policy recommendations

The comparative analysis of hydrogen valleys highlights a persistent gap between Europe's ambitious institutional experimentation and its comparatively modest patent activity. While projects, such as the NAHV, HEAVENN, WIVA P&G, and CyL H2, demonstrate substantial investment and governance innovation, the data show that Europe continues to lag global leaders, particularly China, in translating hydrogen R&D into patentable technologies (Yang et al., 2024; OECD, 2023). Addressing this gap requires coordinated policies that strengthen Europe's intellectual property frameworks and reduce institutional bottlenecks.

First, harmonising EU-level intellectual property procedures should be a priority. Fragmentation across member states creates uncertainty and transaction costs for firms seeking to patent hydrogen technologies across multiple jurisdictions. As highlighted in the Spanish valley response and anecdotal evidence, delays in filing and differences in national regimes discourage firms from protecting intellectual property. A unified EU patenting channel for hydrogen-related technologies, accompanied by simplified administrative processes, would reduce friction and accelerate filings (Noailly & Ryfisch, 2015).

Second, EU innovation funds should more explicitly link financial support to patent outcomes. Initiatives, such as the Important Projects of Common European Interest (IPCEI) and the European Hydrogen Bank, provide critical de-risking mechanisms, yet they primarily reward demonstration capacity rather than patent generation. Introducing patent-oriented benchmarks, such as requiring consortia to file joint EU-level patents, would align funding with measurable innovation outcomes and incentivise collaborative intellectual property creation (Vezzoni, 2024).

Third, targeted support is necessary for smaller member states. Valleys, such as the NAHV, illustrate how asymmetrical innovation capacities – Italy's relatively strong patenting versus Slovenia and Croatia's marginal activity – limit cross-border projects. Dedicated EU programs to strengthen human capital, research infrastructure, and intellectual property training in these smaller states would help level the playing field and foster more balanced contributions to European patent activity (Bernini, 2023; Clean Hydrogen Partnership, 2024).

Fourth, public–private partnerships should be leveraged to convert demonstration projects into patent-generating ecosystems. Evidence from HEAVENN and WIVA P&G shows that strong academic–industrial linkages are correlated with higher inventive output. Scaling such linkages across valleys would create the institutional density required to move from demonstration to invention (Yang et al., 2024).

Finally, Europe must respond strategically to global competition. China's dominance in hydrogen patenting reflects the effectiveness of coordinated industrial policy and massive R&D investment (Yang et al., 2024; OECD, 2023). While the EU should not replicate state-led models wholesale, it can emulate aspects of coordination, such as aligning valley initiatives with EU-level patenting goals, while preserving regional diversity and democratic governance traditions. Such a balance would allow Europe to close the innovation gap without sacrificing institutional pluralism.

In short, the future competitiveness of European hydrogen valleys depends not only on their ability to demonstrate technologies but on their capacity to generate intellectual property that secures Europe's position in global markets. Harmonised frameworks, patent-linked funding, and stronger institutional support for smaller regions can transform hydrogen valleys from symbolic demonstration sites into engines of innovation leadership.

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THE USE OF GENERATIVE ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING IN SLOVENIAN COMPANIES

1 Introduction

Artificial intelligence (AI) and digitalisation are reshaping how companies operate and compete. Digitalisation integrates technologies, such as cloud systems, big data analytics, and the Internet of Things, into business processes to enhance efficiency, inform decision-making, and improve customer service. AI plays a central role in this shift, enabling automation, customer support, and data-driven strategy (Bughin et al., 2021).

Businesses are achieving significant benefits by integrating AI—such as machine learning and computer vision—into their core operations. When supported by strong leadership and skilled staff, this leads to faster decisions, improved quality and output, and reduced costs (OECD, 2024).

However, the adoption of AI is uneven. In Slovenia, for example, the number of firms using AI nearly doubled from 2023 to 2024, jumping from 11% to 21%. This growth is being led by large companies, while small and medium-sized enterprises (SMEs) are falling behind, creating a gap in who can capture AI's advantages (Statistical Office of the Republic of Slovenia, 2024).

These technological shifts are also transforming the workplace. As routine tasks are automated, demand is increasing for more complex, higher-skilled work. Research shows that companies which actively involve their employees and invest in reskilling programs see better results and greater acceptance of these changes (Domadenik Muren et al., 2023).The goal of this chapter is to assess the implications of AI adoption for firms, with a focus on organisational performance and labour. The chapter first outlines the main types of AI and their current applications in companies, examines how AI adoption influences business processes and performance, and then provides an overview of the main drivers and obstacles shaping its uptake. Particular attention is given to labour impacts, focusing on changes in tasks, skills, and employee participation. The chapter also compares Slovenia's adoption trends with those of the EU and presents original survey results to highlight how Slovenian firms are responding to these challenges.

2 Literature background

2.1 Key types of artificial intelligence

Artificial intelligence (AI) is one of the transformative digital technologies, together with big data analytics, cloud computing, the Internet of Things (IoT), blockchain, and robotics (Li, 2024). AI is developing especially fast and is becoming a key force behind automation and digital transformation (OECD, 2024).

OECD describes AI as a general-purpose technology with wide applications (OECD, 2024). There are many possible classifications of AI, but we rely on the Eurostat classification, which is widely applied in European statistics and policy analysis (Eurostat, 2025a). According to Eurostat, several common types of AI are currently in use. **Machine learning** (ML) uses algorithms to identify patterns in data and make predictions, often applied in planning, forecasting, or risk management (Razzaq et al., 2025). **Deep learning**, a subfield of ML, relies on neural networks with many layers to recognise complex patterns in speech, images, and large datasets, and is widely used in voice assistants, autonomous driving, and fraud detection (Razzaq et al., 2025). **Natural language processing** (NLP) allows computers to interpret and generate human language, powering chatbots, translation tools, and customer service applications (Duan et al., 2021). **Computer vision** interprets images and videos, enabling quality checks in manufacturing, medical image analysis in healthcare, or facial recognition in security systems (Duan et al., 2021). **Robotics** and process automation handle repetitive work in industrial production or office processes (OECD, 2023b). **Autonomous systems**, such as service robots, drones, or self-driving vehicles, represent some of the most advanced but least widespread AI applications (Eurostat, 2024). One of the earliest AI applications, **expert systems**, uses rule-based logic and stored knowledge to support decision-making in areas such as diagnostics, customer support, or compliance monitoring (Duan et al., 2021).

Beyond the functional categories, AI can also be viewed through its levels of functionality, which demonstrate how systems evolve in terms of autonomy and capability. **Reactive AI** is the earliest stage, where systems respond directly to inputs without memory or planning (Russell & Norvig, 2021). In the EU, the most common forms are text mining (approximately used by 6 percent of EU firms), natural language generation (approximately used by 5 percent of EU firms), and speech recognition (also used by around 5 percent of EU firms), mainly used in customer service and quality control (Eurostat, 2025b). **Generative AI** takes it a step further by creating new outputs, such as text, images, or code, from large datasets. These tools are spreading quickly in the EU, where firms use them for text mining and speech recognition to analyse unstructured data and improve decision-making (Duan et al., 2021). They enable applications in marketing, design, and analysis, but still depend on human prompts and lack independent goals. **Agentic AI** is the most advanced stage of AI development. These systems are goal-oriented, capable of setting sub-goals, planning actions, interacting with external tools, and adapting over time (Sapkota et al., 2025). Related technologies include machine learning (used by around 6–7 percent of EU firms), robotic process automation, and autonomous systems (used by less than 1 percent) (Eurostat, 2025b).

2.2 Impacts on business processes

AI is becoming an integral part of business functions, with the main areas of AI use including strategic planning, process improvements, innovation, quality management, and customer relations (OECD, 2023a). The use of AI is improving efficiency, supporting planning, accelerating innovation, strengthening quality control, and enhancing customer relations, contributing positively to firm performance. Efficiency gains arise because AI, especially when combined with cloud computing, big data, and the Internet of Things, allows firms to process large volumes of data, detect patterns, and act on insights in real time. This reduces duplicated work, lowers error rates, and enables faster and more accurate decisions. Automation further streamlines operations by taking over routine tasks, while predictive analytics helps firms anticipate demand, optimise resources, and improve service delivery (Duan et al., 2021). Strategic planning benefits from AI through faster and more data-driven decision-making, as firms can evaluate scenarios and adjust their strategies in real time (Csaszar et al., 2024). Process improvements are supported by automation and advanced analytics, which cut costs and increase efficiency (OECD, 2023a).

Empirical studies show that more than three-quarters of firms already use AI in at least one business function, with adopters reporting productivity gains, reduced error rates, and stronger governance outcomes (McKinsey, 2025b; OECD, 2025). Innovation activities also gain from AI, since data-driven tools accelerate experimentation and the design of new products and services, contributing to higher growth and product innovation (Rabhi et al., 2025; Babina et al., 2024). Quality management and customer relations are likewise strengthened, as AI improves defect detection, compliance, personalisation, and responsiveness, leading to better performance and higher customer satisfaction (OECD, 2023; Mayer et al., 2025).

2.3 Drivers and obstacles to AI adoption

Despite increasingly clear benefits, the actual decision for implementation and use reflects the impact of several drivers and obstacles to AI adoption, which often appear in parallel and impact the actual use (Table 1). The same factors that enable adoption for some companies act as barriers for others.

Table 1. Drivers and obstacles to AI adoption

Category	Drivers	Obstacles
Technology	• Cloud computing • Big data • IoT	• Limited data access • Computing power in large firms
Cost & competition	• Cost reduction • Efficiency gains • Market pressure	• High upfront costs • Uncertain returns
Organisation & skills	• Workflow redesign • Managerial support	• Skill shortages • Few AI specialists
Employees	• Training • Reskilling	• Job insecurity • Fairness & trust concerns
Innovation	• Low-code tools • Absorptive capacity	• SME competitiveness gap
Expectations	• Strong investment plans • 90% will increase spending	• Regulatory uncertainty • Slow policy support

Source: Eurostat (2025c), Mayer et al. (2025), Kergoač̌h & Héritier (2025), Lane et al. (2023), Koundouri et al. (2023), Singla et al. (2025), OECD (2019).

Technology provides the foundation for the adoption of AI. Cloud computing, big data, and the Internet of Things provide firms with the infrastructure to collect and process information, as well as integrate AI into planning, forecasting, and automation (Eurostat, 2025d). Yet access to high-quality data and advanced computing power is often concentrated among large firms, creating structural disadvantages for SMEs (OECD, 2019).

Cost and competition pressures encourage firms to adopt AI to reduce costs, raise efficiency, and strengthen their market position (Singla et al., 2025). In competitive sectors, adoption is often seen as essential for survival, while leaders use it for differentiation. Yet implementation is expensive: infrastructure, integration, and maintenance involve high upfront costs, and expected returns are uncertain. These risks weigh most heavily on smaller firms, which have limited financial and technical resources (Mayer et al., 2025). In fact, more than one-third of non-adopting firms in the EU report high costs as the main reason for holding back investment (Eurostat, 2025a).

Organisation and skills determine how successfully AI can be embedded. Firms that redesign workflows and secure managerial support report stronger performance outcomes (Singla et al., 2025). Companies that redesign processes and involve managers in AI governance – actively setting priorities, aligning projects with strategy, and integrating digital tools across workflows – report stronger gains in productivity and profitability (Singla et al., 2025). But skill shortages remain one of the most persistent barriers, with SMEs particularly constrained in attracting or training specialists (Kergroach & Héritier, 2025).

Employees' adaptation plays a crucial role. Training and reskilling programs make transitions smoother and more inclusive (Lane et al., 2023). OECD surveys show that firms providing training and involving workers in decision-making achieve not only stronger performance but also better working conditions. Approximately 80 percent of workers reported that AI improved their performance, while around 60 percent said their job satisfaction increased (OECD, 2025b). Nevertheless, many employees remain concerned about job security, fairness, and trust in AI, and surveys show that fear of job loss and a lack of trust are among the most frequently mentioned barriers to adoption in European firms (Lane et al., 2023; Eurostat, 2025c).

Innovation capacity is supported by accessible tools such as low-code platforms, which reduce technical barriers and enable experimentation (Singla et al., 2025). AI also strengthens absorptive capacity, allowing firms to integrate new knowledge and turn it into productivity and innovation gains. At the same time, uneven adoption risks are widening competitiveness gaps, particularly between large firms and SMEs (Kergroach & Héritier, 2025). EU surveys confirm this pattern, showing that innovation leaders adopt AI at more than twice the rate of lagging firms (Eurostat, 2025a).

Finally, **expectations** strongly shape adoption. Over 90 percent of firms already using AI report plans to increase spending within the next three years, showing confidence in its long-term value (Eurostat, 2025b). At the same time, unclear rules on data use, liability, and ethics, combined with slow policy support, increase risks and leave smaller firms without sufficient guidance or resources (OECD, 2019).

2.4 Impacts on labour

AI mainly affects work by changing the structure of tasks, rather than by eliminating large numbers of jobs (Salari, 2025). Earlier research has shown that routine tasks, often concentrated in medium-skilled occupations, such as clerical, administrative, or technical roles, are most exposed to automation, while non-routine activities tend to be more resilient (Autor et al., 2003). Unlike earlier digital technologies that focused on repetitive tasks, generative AI extends into knowledge work, such as writing, coding, and data processing (Acemoglu & Restrepo, 2024). This increases the importance of human skills that complement AI. A recent studies confirm that these technologies affect a broad set of occupations by reshaping tasks and altering the required skill profiles (Microsoft, 2023; OECD, 2023a). The impact of AI on labour is also not defined by technology alone. It also depends on the organisational and institutional choices that decide whether AI will mainly replace jobs or create new opportunities for workers (OECD, 2024).

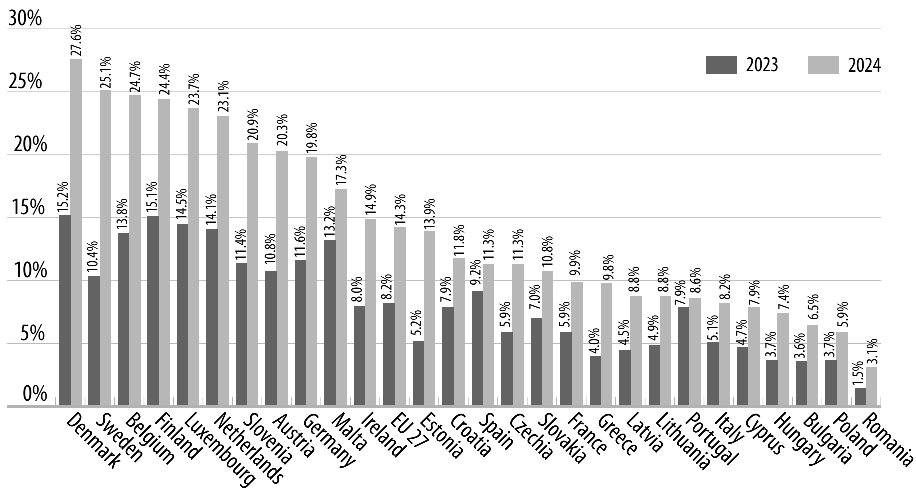
Successful implementation and adoption depend on workers' involvement in the process. Companies aiming for successful AI adoption must actively involve workers and create conditions for continuous skill development. Analytical reasoning, creativity, digital literacy, problem-solving, and socio-emotional skills are becoming increasingly valuable in combination with AI (Mäkelä & Stephany, 2024). Although workers often demonstrate a willingness to adapt, company initiatives to support reskilling remain limited, resulting in uneven adjustments and missed opportunities (Salari, 2025). Without employee participation, AI is more likely to be applied primarily for labour substitution, reinforcing inequality and reducing the potential benefits (Acemoglu & Restrepo, 2024). By contrast, companies that systematically invest in reskilling programs, include employees in decision-making, and engage them in design processes are more likely to achieve augmentation, improve job quality, and secure long-term competitive advantages (Kochan, 2023).

3 AI adoption trends in the EU and Slovenia

In 2024, 74 percent of EU firms reported using at least one advanced digital technology, showing steady growth in recent years (EIB, 2024). Within this trend, the uptake of artificial intelligence is advancing quickly: the share of firms using AI grew from 8.6 percent in 2023 to 13.5 percent in 2024 at the EU level (Eurostat, 2025e; Figure 1). In Slovenia, the adoption of AI rose from 11.2 percent in 2023 to 20.9 percent in 2024, placing it above the EU average and highlighting its strong digital readiness.

Adoption patterns vary significantly across the EU, with Northern and Western countries, such as Denmark, Sweden, and Finland, standing out as leaders, with adoption rates above 24 percent in 2024. Luxembourg and Austria also moved ahead rapidly. By contrast, countries such as Romania, Croatia, and Bulgaria remain among the lowest adopters, with less than 10 percent of firms reporting AI use. These contrasts underline both the opportunities and challenges of AI diffusion across Europe, emphasising the role of policies, sectoral structures, and innovation ecosystems in shaping adoption (Eurostat, 2025b).

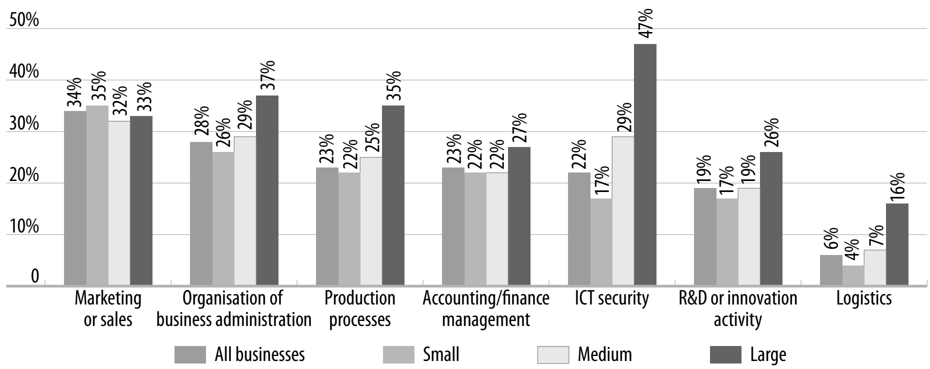
Figure 1. Share of companies using AI (EU, 2023–2024)



Source: Eurostat (2025e).

At the EU level, around 14 percent of firms report using AI, with marketing and sales being the most common application area, accounting for roughly one-third of adopters (Eurostat, 2025a; Figure 2). Other frequent uses include business administration, production processes, and finance. Larger firms stand out with higher adoption rates in ICT security, where nearly half report using AI compared to less than one-fifth of small firms. Similar gaps appear in production processes and R&D activities, where adoption in large companies is almmost double that of smaller enterprises. By contrast, areas such as marketing and sales show a more even spread across firm sizes, reflecting lower barriers to adoption and easier integration into existing work processes (Eurostat, 2025a).

Figure 2. Share of companies among all AI using companies, that are using AI for different purposes (EU, 2024)



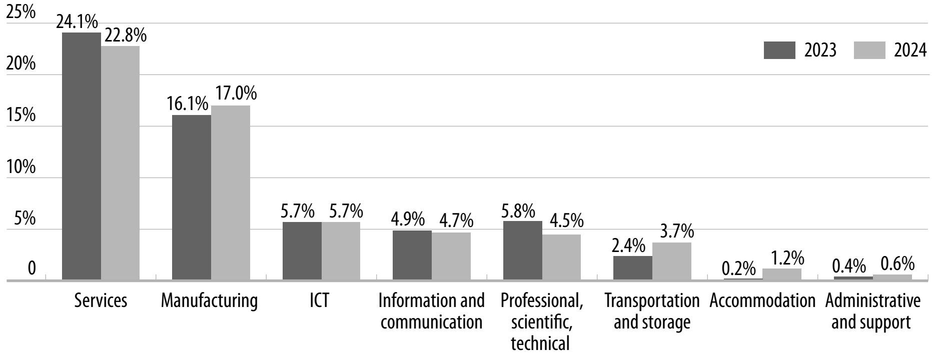
Source: Eurostat (2025a).

In AI adoption, Slovenia also stands above the EU average, with around 21 percent of companies using AI, up from 11 percent in 2023 (Statistical Office of the Republic of Slovenia, 2024; Figure 1). Adoption varies across sectors (Figure 3). Services account for the largest share at around 24 percent, followed by manufacturing at 17 percent (Statistical Office of the Republic of Slovenia, 2024). ICT, information and communication, and professional services each account for about 5 percent, while adoption remains marginal in transportation, accommodation, and administrative support. This reflects the fact that in many of these sectors, AI applications are either less relevant to core activities or adoption is constrained by limited resources and scale (OECD, 2024).

Between 2023 and 2024, AI adoption in Slovenian firms expanded rapidly across different areas of use (Figure 4). The highest adoption rates are found in business administration (80 percent of all AI users), accounting and finance (77 percent of all AI users), and marketing (75 percent of all AI users) (Statistical

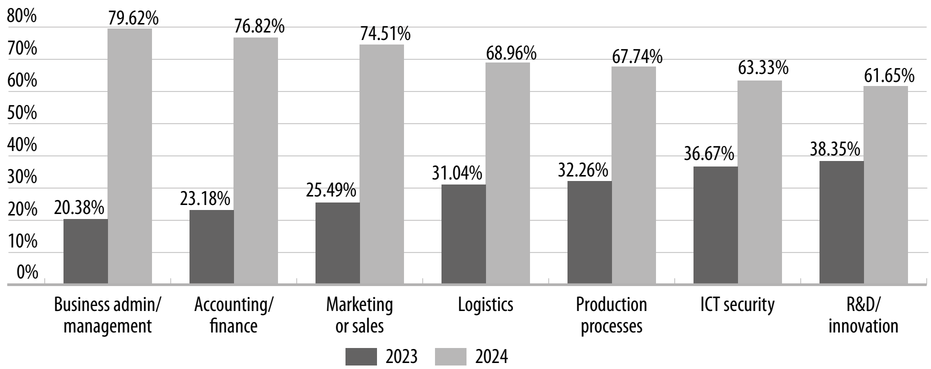
Office of the Republic of Slovenia, 2025). Other core areas, such as production, logistics, ICT security, and R&D, also show widespread use. This shows that AI is no longer implemented only for specific tasks but is becoming part of everyday business operations (Eurostat, 2025e).

Figure 3. Share of companies using AI, by sector (Slovenia, 2023–2024)



Source: Statistical Office of the Republic of Slovenia (2025).

Figure 4. Share of AI using companies, using AI for specific business functions (Slovenia, 2023-2024)



Source: Statistical Office of the Republic of Slovenia (2025).

Slovenia is generally quite strong in other digitalisation aspects as well. For example, in 2024, 80 percent of Slovenian firms reported using at least one advanced digital technology, compared to 74 percent in the EU (EIB, 2024). Firms demonstrate solid progress in digitalisation, with above-average adoption of advanced technologies, such as robotics (64 percent), the Internet of Things (59 percent), and big data/AI (45 percent), outperforming the EU average (EIB, 2024). At the same time, they significantly lag behind in areas like digital platforms, virtual or augmented reality, and 3D printing. Overall, this points to a digitalisation profile that is strong in industrial and data-driven technologies, but weaker in newer, platform-based solutions (OECD, 2024).

4 Methodology

Survey data were used to examine how the intensity of AI adoption influences business outcomes and labour transformation in Slovenia, as well as the key expectations and barriers to adoption, including labour shortages. The survey was distributed among middle and top managers of Slovenian companies, and a total of 175 responses were collected in August 2025.[1] The questionnaire comprised 48 questions, focusing on the following main topics: company characteristics, such as size, sector, and labour composition; the use of digital and AI technologies across business functions; perceived benefits and barriers to adoption; and labour-related impacts. The questionnaire was based on the Statistical Office of Slovenia (2023), OECD (2023), Redek et al. (2024) and Čater et al. (2021). In addition, the survey asked about firms' expectations for future investments, particularly in advanced tools, such as generative AI.

Out of 175 firms, large firms account for 28.6 percent, followed by medium-sized firms (24.6 percent), small firms (24.6 percent), and micro firms (22.3 percent). The distribution is relatively balanced, with a slight dominance of larger firms, although it does not fully reflect the structure of the firms' population. Manufacturing and professional (13.8 percent), scientific and technical activities (12.1 percent) dominate, followed by transportation and storage (8.6 percent), and other service activities (8.0 percent).

5 Results

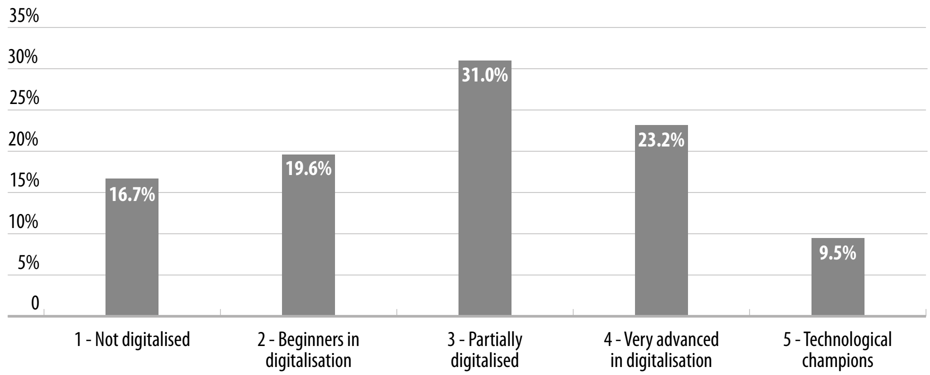
5.1 The current state of digital transformation

The use of AI represents a significant step in the digital transformation process within companies. Results show that companies differ strongly in their level of digitalisation (Figure 5). Around 16 percent are not digitalised at all, while 19.6 percent are beginners (with business processes largely non-digital and only mini-

1 Data was collected as part of the project V5-24020 *"Analiza pomanjkanja kadrov za potrebe slovenskega gospodarstva in družbe: Kadri za visoko-produktivno, inovativno gospodarstvo in dvojni prehod v digitalno iz zeleno družbo"*.

mal use of new technologies). Around 31 percent are partially digitalised, where some processes are supported digitally but without a comprehensive system. A further 23.2 percent are very advanced, with many processes digitalised and the use of tools such as ERP, CRM, cloud solutions, or selected AI applications. Finally, 9.5 percent are technological champions, with highly digitalised processes and a broad use of cutting-edge technologies, often tailored or developed in-house. This indicates that while many firms have joined the digital transformation, only a smaller share has reached the most advanced stage.

Figure 5. Distribution of companies by digitalisation level



Note: N = 168.

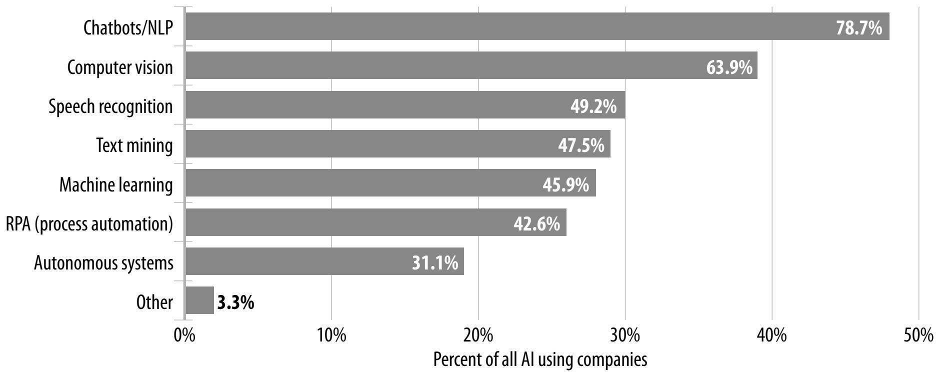
Source: Own work.

Besides AI, which is presented in detail later on, the most widely used are cloud computing (80.6 percent) and social media (79.4 percent), reflecting the relatively low costs and accessibility of these tools. More advanced business solutions are also available, such as CRM and e-commerce systems (56.0 and 55.4 percent), as well as ERP platforms (50.3 percent). In the mid-range, companies use business process management (39.4 percent) and cyber-physical systems (36.6 percent). By contrast, technologies like smart factories (17.7 percent), additive manufacturing (23.4 percent), or augmented/virtual reality (15.4 percent) remain far less common, as they require higher investments and specialised infrastructure. This pattern is consistent with previous findings that accessible, low-cost solutions can be broadly applied across business functions, whereas more complex technologies spread more slowly due to sector-specific infrastructure and expertise requirements (OECD, 2023c).

5.2 The current state of AI adoption

Currently, 34.9 percent of surveyed firms are using at least one form of AI, while 56 percent of users report using generative AI (the question allowed multiple answers and depended on respondents' understanding of individual technologies, so these figures should be interpreted with some caution). Among users, the most commonly used AI technologies are also Chatbots/NLP (78.7 percent), Computer vision (63.9 percent), and Speech recognition (49.2 percent). Autonomous systems remain the least adopted (31.1 percent), though their share is still notable (Figure 6). Only 10 companies (5.7 percent) rely solely on ChatGPT, showing that most adopters combine it with other AI applications rather than using it alone.

Figure 6. Types of AI technologies used by AI using firms



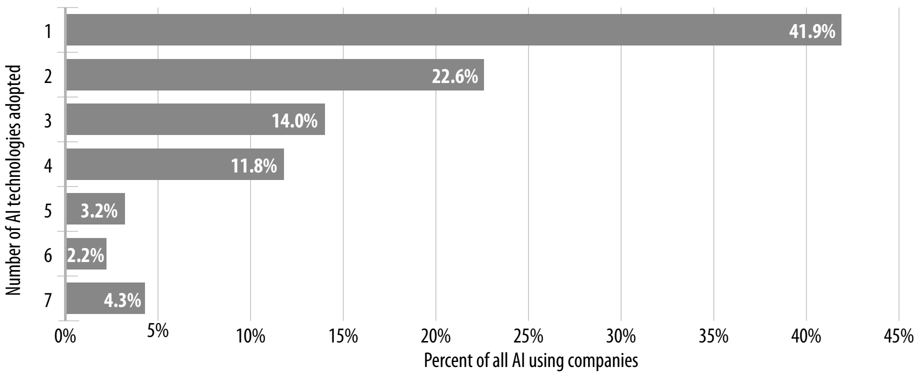
Note: N = 61. Multiple answers allowed.

Source: Own work.

Since many firms adopt several AI technologies simultaneously, adoption intensity was examined, measured by the number of different technologies used. Instead of only focusing on whether firms use AI, this analysis shows how broadly they apply it in practice.

A small share of adopters (21.5 percent) (Figure 7) use four or more technologies, while the majority (64.5 percent) are low-intensity users (1–2 technologies). In the latter category, the shares are 89.7 percent for micro firms, 83.7 percent for small firms, 72.1 percent for medium-sized firms, and 78 percent for large firms. Large companies are the only group with a notably high-intensity share (12 percent), while medium-sized companies are beginning to move up to high-intensity adoption. Clear differences also appear across industries: in information and communication, 28 percent of firms are medium- or high-intensity users, in financial services, 25 percent, and in professional, scientific, and technical activities, 21 percent, compared to only 5 to 8 percent in agriculture, manufacturing, and construction. A larger firm creates the potential for more intensive AI use (using more tools). However, this potential is mostly realised in industries with strong digital requirements, such as finance or ICT, rather than in agriculture, manufacturing, or construction.

Figure 7. Intensity of AI adoption measured by the number of different AI technologies used



Note: N = 93. Technologies adopted: 1–7 implies that the company uses 1 to 7 technologies.

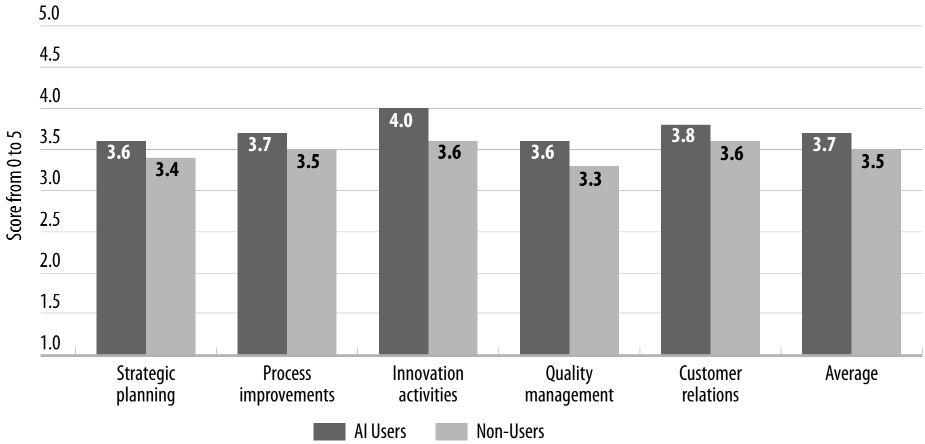
Source: Own work.

Results also show expected differences in the use of AI technologies depending on company size and sector. The results show that the same pattern observed in Figure 6 holds here as well: simpler tools, such as chatbots, natural language applications, and computer vision, are most commonly used, while more advanced systems, including machine learning, robotic process automation, and especially autonomous systems, are more rarely used. This suggests that adoption is shaped more by accessibility and ease of integration than by firm characteristics, and that without higher investment in skills and infrastructure, many firms may remain limited to basic applications (Lane et al., 2023). Current patterns show that AI is most often applied in advanced industrial areas. Almost half of firms use it for autonomous vehicles (48.8 percent), and 42.9 percent for digital twins and simulations. Robotics is somewhat less common, at 32.6 percent, while adoption in routine functions is limited, with only 21.4 percent using AI for quality control and 14.0 percent for employee support. This indicates that AI remains concentrated in specialised industrial tasks, while everyday business operations lag behind. For Slovenian firms, this suggests an opportunity to expand adoption into routine processes where productivity gains could be substantial.

5.3 Influence of AI adoption on business performance

Companies using AI tend to achieve better outcomes across several areas of business performance compared to non-users. The assessment was based on self-reported evaluations on a five-point scale (1 = poor performance, 5 = strong performance). AI users reported higher average scores in strategic planning, process improvements, innovation activities, quality management, and customer relations (Figure 8). On average, firms using AI reached a score of 3.72, compared to 3.47 among non-users. This means that AI users rated their business practices as being closer to “good” than “average”, while non-users remained slightly below that threshold. However, these differences are not statistically significant ($p > 0.05$), suggesting only a weak association at this stage. Still, the pattern suggests that AI adoption and effective management practices are positively related, contributing to gradual but measurable improvements in business performance. It is possible that these differences, while currently small, could become more pronounced as adoption deepens in the future.

Figure 8. Business performance of AI adopters vs. non-adopters



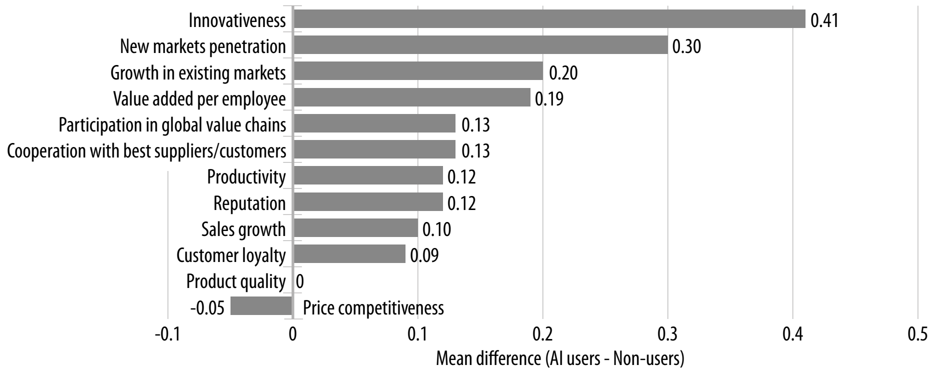
Note: N = 175. Score from 1 (poor performance) to 5 (strong performance).

Source: Own work.

The results show that AI adoption is also positively related to performance in specific areas, with the largest differences in innovativeness (+0.41 in rating by AI adopters compared to non-adopters), penetration into new markets (+0.30), and growth of market share in existing markets (+0.20) (Figure 9). These outcomes suggest that AI is especially valuable for creating new products and services, as well as supporting expansion into both new and existing markets.

This is consistent with evidence that AI adoption fosters firm growth through innovation and product development (Babina et al., 2024). At the same time, the impact is weaker or absent in more traditional areas, such as product quality or price competitiveness, which indicates that the benefits of AI are most visible where creativity and market opportunities play a central role (OECD, 2024).

Figure 9. Differences in self-evaluated performance between AI adopters and non-adopters



Note: N = 175. The chart shows the average differences in performance ratings between companies that use AI and those that do not, with positive values meaning AI users rated themselves higher and negative values meaning they rated themselves lower on a five-point scale (-2 to -1 refer to significantly less and less successful, 0 = equally successful, 1–2 refers to more and significantly more successful).

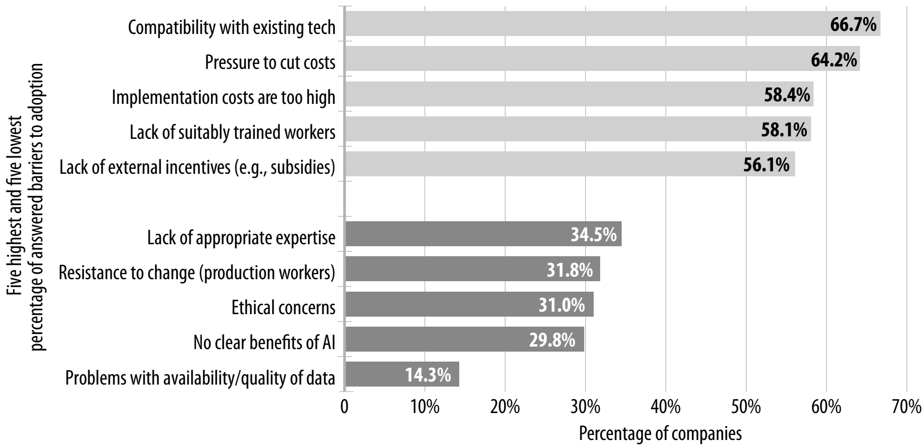
Source: Own work.

5.4 Barriers to AI adoption

The main barriers to AI adoption among firms are a combination of financial, technical, and organisational constraints (Figure 10). Compatibility with existing systems (67 percent) and pressure to cut costs (64 percent) are the most frequently reported obstacles, while high implementation costs (58 percent) and insufficient external incentives (56 percent) are also common. Similar patterns appear in OECD surveys, where system integration and high costs are repeatedly identified as central obstacles to adoption (Lane et al., 2023).

Regarding barriers to adoption connected to the labour force, skills shortages are another recurring challenge: 58 percent of Slovenian companies report a lack of suitably trained workers and 50 percent report insufficient technical knowledge. International evidence confirms this; both OECD (2023a) and more recent studies (Hoffman et al., 2025) underline that the absence of AI expertise is among the top barriers, often ranking even above ethical concerns.

Figure 10. Perceived barriers to digitalisation adoption (presenting the five most often/five least often selected barriers)



Note: N = 174. Multiple answers allowed.

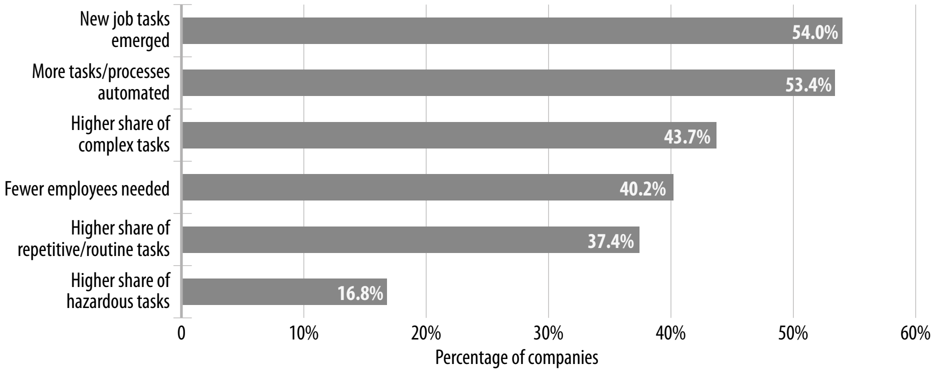
Source: Own work.

Organisational factors also play a significant role. In Slovenia, short-term management orientation (42 percent), low prioritisation of new technologies (41 percent), and resistance to change among staff are notable (Figure 10). While such issues are less systematically quantified in international datasets, qualitative research highlights the same tendencies: companies often struggle more with leadership commitment and organisational culture than with acceptance of AI's relevance (Madanchian & Taherdoost, 2025). By contrast, ethical concerns (31 percent) and doubts about the usefulness of AI (38 percent) are relatively rare, a finding consistent with OECD evidence that scepticism is a less important barrier compared to costs and skills (OECD, 2025). Slovenian firms are not reluctant to adopt AI because of mistrust in the technology, but are constrained by limited resources, skills, and management capacity, aligning closely with international trends.

5.5 Labour impacts of AI adoption

The survey results show several relevant impacts on workers. The most common impacts of AI on labour (Figure 11) are the creation of new job tasks (54 percent) and the automation of existing processes (53.4 percent). Forty-three percent of firms report a higher share of complex tasks, while 40.2 percent note that fewer employees are now needed. There are also increases in routine tasks. Overall, AI is reshaping the task mix more than it is reducing headcount.

Figure 11. Perceived effects of AI use on tasks and employment



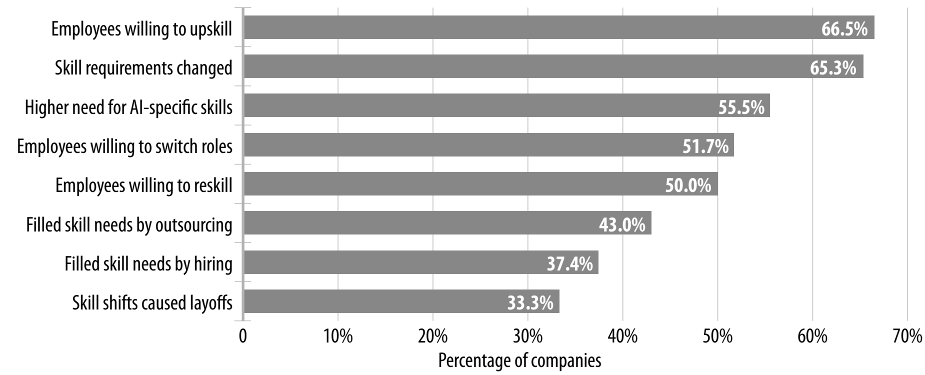
Note: N = 174. Multiple answers allowed.

Source: Own work.

The use of AI is associated with a shift towards higher productivity, safer workplaces, and more skilled employees. Almost 65 percent of companies highlight rising productivity and improvements in occupational safety, while the share of high-skilled employees is also growing. At the same time, physically demanding and health-threatening tasks, as well as the share of low-skilled workers, are declining. Expectations for the next decade are consistent with this picture: most companies foresee further productivity gains and improved safety, but only modest changes in total employment. The findings are consistent with earlier findings (Domadenik Muren et al., 2023) from OECD countries, which underline the role of AI in enhancing physical health and safety, with 65 percent of manufacturing workers reporting positive effects.

AI adoption also depends on worker involvement and accompanying training. However, our results show that companies with higher AI adoption do generally not invest more in training or involve employees more in decision-making. Generally the overall level of inclusion remains low: only 46 percent of firms inform employees about AI plans, while just over a third (35.5 percent) involve them in discussions about the skills or impacts on their tasks. Broader issues, such as wages, contracts, or long-term strategy, are rarely addressed. At the same time, 65 percent of firms report that skill requirements have changed, and 67 percent observe employees' willingness to upskill; yet, AI is still framed primarily as a technical rather than an organisational change (Lane et al., 2023). Regression analysis confirms that these labour effects are statistically significant, with firms adopting more AI technologies reporting stronger worker productivity ($p < 0.001$), even after controlling for firm size and sector. These quantitative findings are also consistent with qualitative evidence showing that Slovenian companies most often address skill gaps through informal learning methods, such as learning by doing and mentoring, while facing barriers including a lack of time, employee mindset, fear, and generational differences (Zupan et al., 2023). Similar patterns are observed internationally, where employees show readiness to reskill, but organisational initiatives remain limited (OECD, 2023a).

Figure 12. Perceived impact on employees' skills and mobility trends



Note: N = 174. Multiple answers allowed.

Source: Own work.

The growing importance of AI is clearly reflected in changing skill requirements. Around two-thirds of companies report substantial shifts in the types of skills they need, and most employees react positively: more than 65 percent are willing to upgrade their knowledge, about half are ready to retrain or switch roles, and over half highlight a need for AI-specific expertise (Figure 12). To respond to these pressures, many firms turn to outsourcing to fill gaps, while hiring new staff plays a smaller role. Layoffs related to changing skill needs are relatively rare, affecting only about one-third of firms, which indicates that most adaptation is managed through internal development and flexible mobility rather than labour reduction. This shows that while companies are investing in flexibility and training, gaps in AI-related expertise persist and are frequently bridged by external specialists.

6 Conclusion

The study reveals that Slovenian firms are progressing in their adoption of AI, yet the process is uneven across sectors and firm sizes. Adoption rates are relatively high compared to those in the EU, but most firms still use only one or two technologies, suggesting that real benefits will depend on deeper integration into core processes (Brynjolfsson et al., 2018; OECD, 2025b). Firms that invest strategically in AI already report better outcomes, especially in innovativeness, new market entry, and market share growth (Babina et al., 2024; OECD, 2024). However, barriers such as high costs, integration challenges, and skill shortages remain central, particularly for SMEs, while labour impacts are under-managed: most employees are willing to upskill, but few firms involve them in planning or training. Without stronger efforts in training and participation, there is a risk that AI will be used to replace rather than support workers (Acemoglu & Restrepo, 2019; Kochan, 2023).

The study has some limitations. The sample includes a proportionally higher number of large firms, while some sectors are underrepresented, and the data are based on firms' self-assessments rather than objective performance indicators. Cross-sectional design captures current associations but cannot fully trace how effects evolve over time. Adoption intensity was measured by the number of technologies used, which may not reflect the sophistication of their application. These suggest directions for future research: combining survey evidence with longitudinal data, exploring case studies that capture organisational dynamics in greater depth, and extending analysis across EU countries to better understand how policy and institutional settings shape adoption.

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SMART FACTORIES: THE CASE OF SILIKO

1 Introduction

Smart factories are a core element of Industry 4.0, the Fourth Industrial Revolution that links digital technologies with industrial production. The term Industry 4.0 was introduced in Germany in 2011 to describe the digitalisation of manufacturing, while other countries adopted different names for similar initiatives (Shi et al., 2020). A smart factory embodies this shift by merging physical and cyber systems into a connected environment where machines and processes exchange data, self-optimise, and adapt in real time. This enables manufacturers to handle shorter product lifecycles, rising demand for customisation, and cost-effective small-batch production, challenges where traditional mass production is less effective (Shi et al., 2020; Pametna tovarna, 2025)

The goal of this chapter is to investigate the smart factory paradigm by comparing its adoption in SMEs and large firms, and examining the role of the wider ecosystem. The Siliko case study aims to provide insights beyond aggregate data. Findings will help identify adoption gaps, highlight the role of external support structures, and extract firm-level lessons that inform both policy and practice. The first section introduces the concept, outlining its technologies, characteristics, benefits, and challenges. The second section examines global and Slovenian development trends, the third applies these insights in a case study of the company Siliko, and the fourth concludes with recommendations. The analysis draws on secondary research, including literature, statistics, and policy reports, as well as primary research through site visits and interviews with managers, technical staff, and external experts.

2 Industry 4.0 and a smart factory

2.1 The development, benefits and challenges of a smart factory

Smart factories, central to Industry 4.0, represent the shift from automated and digital setups to responsive, context-aware systems that integrate cyber-physical systems (CPS), Industrial IoT, artificial intelligence (AI), and advanced industrial software. These technologies enable interconnectivity, where machines, products, and people exchange data; distributed intelligence, as CPS and sensors make local adjustments; flexibility, with modular robotics and software-driven processes allowing fast product switches, even in single batches; and end-to-end integration, connecting design, production, logistics, and services across the value chain (Shi et al., 2020; Gao et al., 2025).

Industrial software plays a central role in this architecture, providing platforms for product lifecycle management (PLM), enterprise resource planning (ERP), manufacturing execution systems (MES), and digital twins that unify physical processes with virtual models. Together with cloud computing, big data analytics, and AI algorithms, these tools turn raw data into actionable insights, enabling predictive maintenance, optimised scheduling, and enhanced quality control (Gao et al., 2025). Table 1 presents the key characteristics of smart factories and their impact on production processes and efficiency.

Table 1. Smart factory characteristics and their impact on production efficiency

Smart factory characteristics	Impact
Interconnectivity (IoT, networks)	Real-time visibility, transparency, improved coordination
Distributed intelligence (CPS, AI)	Predictive maintenance, resilience, fewer breakdowns
Flexibility and adaptability	Rapid changeovers, mass customisation, responsiveness to demand
End-to-end integration (ERP, MES, PLM, digital twins)	Unified data flow, cost reduction, just-in-time production
Data-driven orientation (analytics, cloud, AI)	Faster decision-making, optimised processes, continuous improvement
Human-machine collaboration (robots, AR/VR)	Safer work environment, upskilled workforce
Sustainability focus	Energy savings, waste reduction, circular production models

Source: Shi et al. (2020); Gao et al. (2025); Červený et al. (2022).

Smart factory technologies generate a wide range of benefits that enhance both operational performance and strategic resilience. Real-time data flows improve efficiency, reducing downtime, waste, and inventory costs, with performance gains of up to 50 percent reported (Chong et al., 2020; Červený et al., 2022). Embedded sensors and AI-driven inspection enhance quality, instantly detecting defects and enabling automated traceability. Data-rich dashboards and analytics platforms support faster decision-making, while predictive models prevent breakdowns and extend equipment life. Robotics and automation not only provide flexibility but also reduce exposure to dangerous tasks, complemented by AR tools and wearables for safety. By lowering energy use, minimising scrap, and supporting circular practices, smart factories also advance sustainability goals (Červený et al., 2022).

At the same time, the path toward smart factories is constrained by significant barriers. The transition requires high upfront investment, which often deters small and medium-sized enterprises (SMEs). There is a persistent skills gap in data science, AI, and cybersecurity. Legacy equipment complicates integration, while rising connectivity increases cybersecurity risks. Organisational resistance also slows adoption, as employees fear job loss and managers hesitate to abandon familiar systems. Even when pilot projects succeed, scaling them into enterprise-wide operations demands sustained investment, strong leadership, and cultural adaptation – challenges many firms struggle to overcome (Jožef Stefan Institute, 2021; Won & Park, 2020).

2.2 Global trends driving the development of smart factories and manufacturing

The global spread of smart factories is driven by a mix of policy, technology, competition, and socio-economic change. Governments worldwide have launched strategies to secure leadership in advanced manufacturing, such as Germany's National Industrial Strategy 2030, China's 14th Five-Year Plan for Smart Manufacturing Development, the US Advanced Manufacturing Leadership Strategy, and the EU's Industry 5.0 framework, which all highlight digitalisation as a pillar of competitiveness (Gao et al., 2025). These programs not only channel public funding but also set standards that shape global adoption.

Reshoring has gained traction as recent crises exposed vulnerabilities in global supply chains. Smart factories make local production viable by combining automation with flexibility, supporting local-for-local strategies and enhancing resilience (Pametna tovarna, 2025). At the same time, technological convergence is accelerating the adoption of these technologies. Cheaper sensors, stronger AI, cloud platforms, robotics, digital twins, and industrial software make digital manufacturing more accessible, while its adoption spurs further innovation (Mabkhot et al., 2018).

Global market competition adds pressure, as emerging economies capture mass production, while advanced economies pursue smart manufacturing to compete through customisation and speed. Rising powers, such as China and South Korea, are also moving up the value chain, which in turn pushes efforts to establish international standards and interoperability for cross-border production networks (Shi et al., 2020; Gao et al., 2025). Large multinational companies are already building proprietary digital ecosystems. Siemens has invested over $10 billion in industrial software, while Boeing operates with thousands of proprietary tools, signalling that global competition now extends to control over industrial platforms (Gao et al., 2025).

Besides all mentioned, socio-economic trends reinforce this momentum. An ageing workforce, labour shortages, and rising wages increase pressure for automation, while environmental policies and consumer expectations for sustainability, personalisation, and rapid delivery strengthen the shift. These forces make smart factories a necessity for maintaining competitiveness in global manufacturing (Pametna tovarna, 2025; Červený et al., 2022).

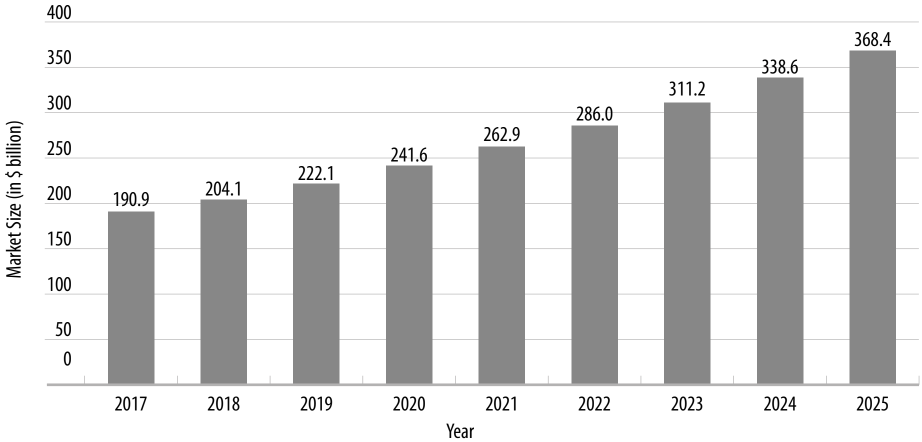
3 Market analysis of smart factories

The global market for factory automation has been expanding steadily, from $191 billion in 2017 to a forecast of almost $368 billion by 2025 (Figure 1) (Statista, 2025a). In this context, automation refers to the application of advanced control systems, industrial robots, sensors, and information technologies that allow machines and processes to operate with minimal human intervention (Chen et al., 2017; Evjemo et al., 2020).

Sectorally, smart manufacturing in Europe is strongest in the automotive, electronics, and pharmaceutical industries. These sectors are among the most important contributors to the EU's high performance in medium- and high-tech exports, which support its international competitiveness (European Commission, 2025).

The 2023 data on technology adoption in SMEs reveal significant differences across the EU. Overall, the most widely used technologies are ERP software and cloud computing services, with many countries achieving adoption rates of 60 to 70 percent. Northern European countries, particularly Denmark (66.4 percent ERP; 68.8 percent cloud) and Finland (55.7 percent ERP; 77.6 percent cloud), stand out as leaders. In contrast, adoption remains much lower in parts of Eastern Europe, such as Romania (21.4 percent ERP; 17.5 percent cloud) and Bulgaria (20.5 percent ERP; 16.6 percent cloud), highlighting a persistent digital divide (Figure 2).

Figure 1. Projected size of the global factory automation market

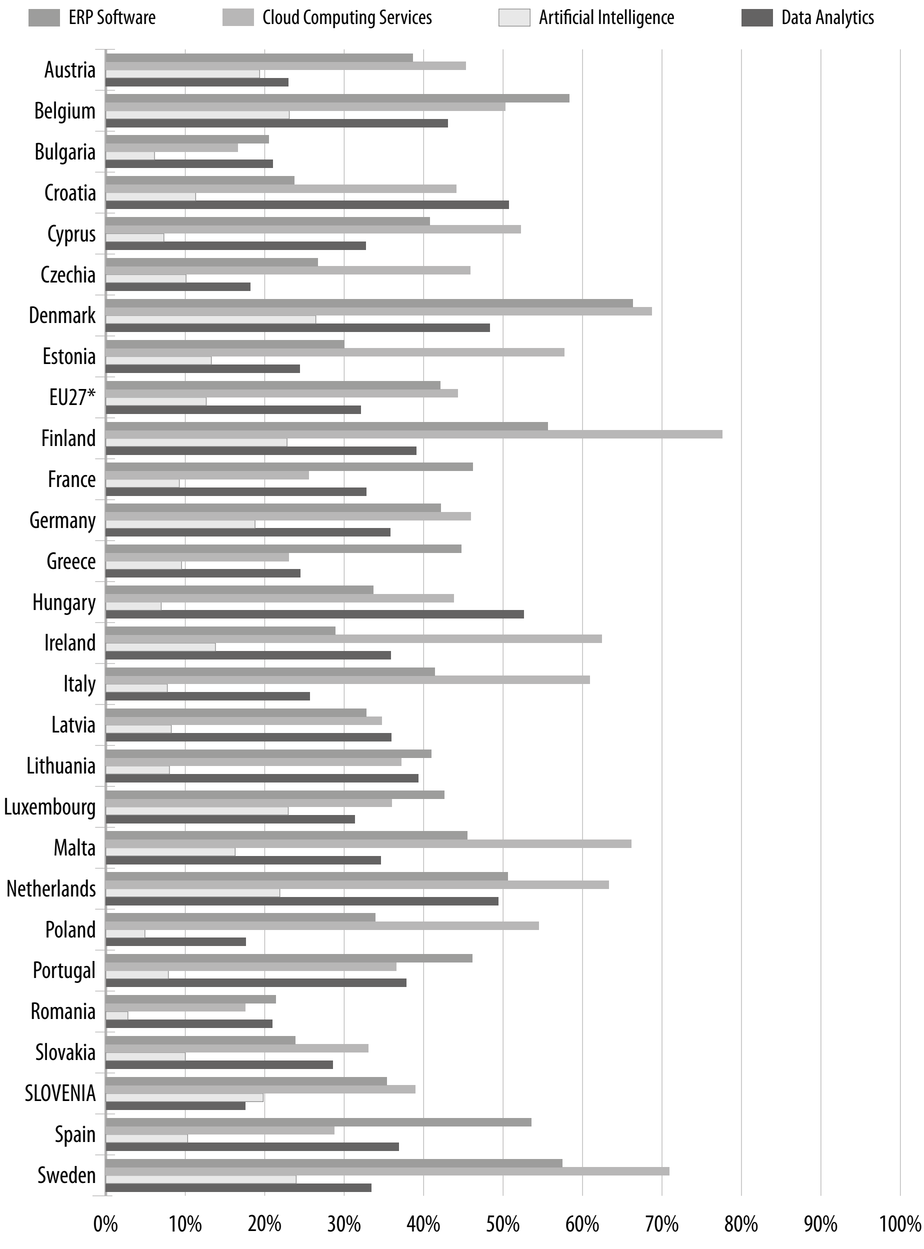


Source: Statista (2025a).

Artificial intelligence, while increasingly important, still lags other technologies. In most countries, its use is limited to single- or low double-digit percentages. Denmark (26.4 percent) and Belgium (23 percent) are among the frontrunners, whereas Romania (2.8 percent) has a very low adoption rate. Data analytics indicate a broader diffusion, with many economies reporting figures between 40 and 70 percent. The Netherlands (49.4 percent) and Croatia (50.7 percent) achieve particularly strong results, while Slovenia (17.5 percent) remains at the bottom (Figure 2).

When looking at large enterprises across the EU, the overall adoption of digital technologies is considerably higher than among SMEs. Most countries report near-universal use of ERP systems and cloud computing, while artificial intelligence and data analytics also achieve much stronger penetration. Northern and Western European economies remain leaders, but even in Southern and Eastern Europe, adoption levels among large firms are significantly above those of smaller companies (Figure 3).

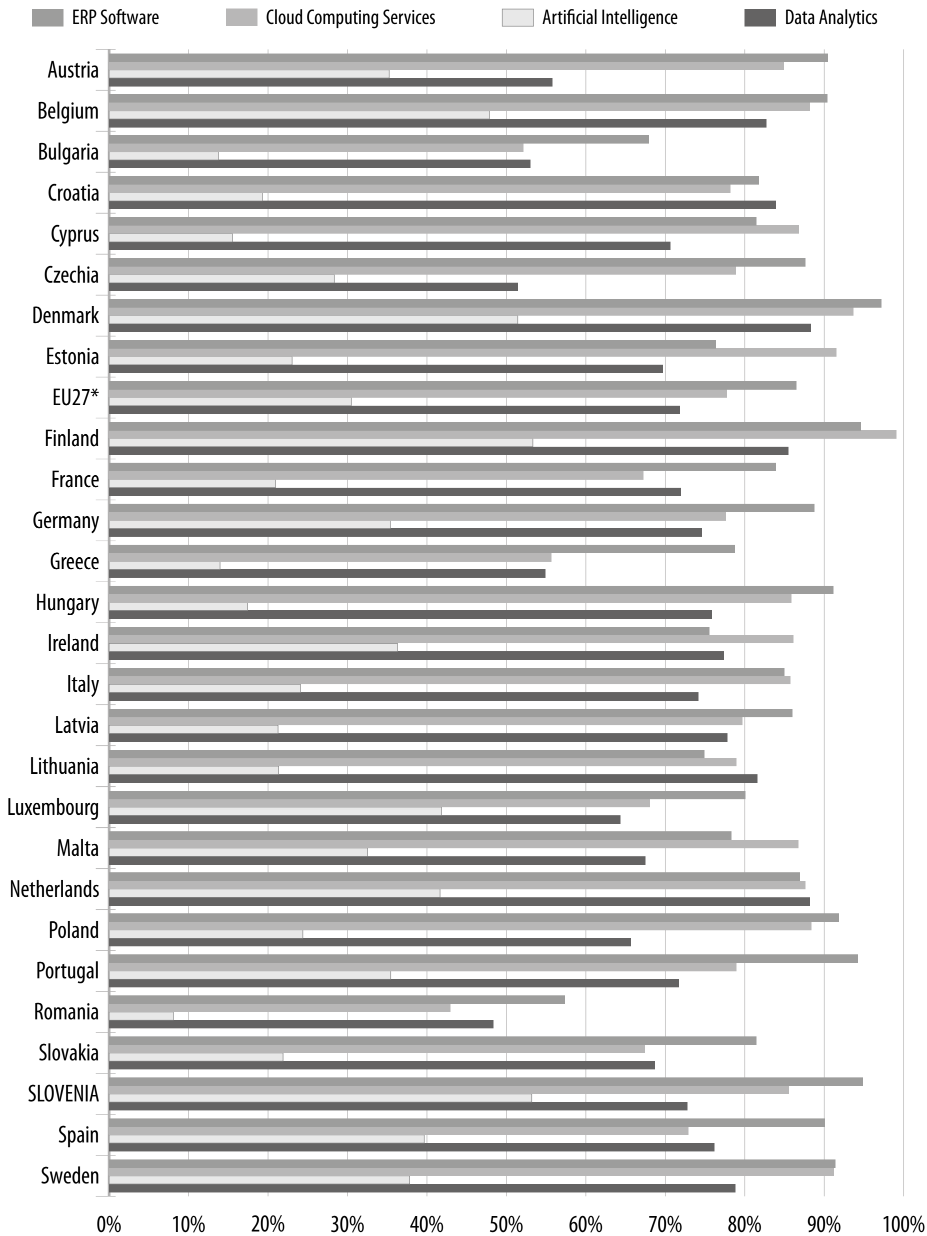
Figure 2. Adoption of selected digital technologies by SMEs in the EU, 2023



Note: *from 2020.

Source: Eurostat (2025a), Eurostat (2025b), Eurostat (2025c), Eurostat (2025d).

Figure 3. Adoption of selected digital technologies by large enterprises in the EU, 2023



Note: *from 2020.

Source: Eurostat (2025a), Eurostat (2025b), Eurostat (2025c), Eurostat (2025d).

Slovenia shows a particularly sharp contrast between SMEs and large enterprises. Among SMEs, ERP adoption (35.4 percent) and cloud uptake (38.9 percent) remain below the EU average (42.1 percent ERP; 44.3 percent cloud). However, Slovenian SMEs perform strongly in artificial intelligence, with 19.8 percent of firms using AI compared with the EU average of 12.6 percent, though they fall behind in data analytics (17.5 percent in Slovenia vs. 32.1 percent in the EU). By contrast, Slovenian large enterprises demonstrate near-universal adoption of ERP (94.9 percent) and cloud computing (85.5 percent). More than half (53.2 percent) already deploy artificial intelligence, which is far above the European mean (30.5 percent), and data analytics use (72.8 percent) is also well aligned with the EU average (71.8 percent). This positions Slovenia's large companies at the European frontier of digital transformation, while highlighting the gap that persists among its SMEs (Figure 2).

4 The case of Siliko

4.1 An overview of the company

Siliko d.o.o. is a Slovenian manufacturing company specialising in technical rubber and plastic components, with a history spanning more than three decades. The company traces its beginnings to 1984, when director Janko Koprivec built the first rubber injection-moulding machine and began operations as a craft business. It was formally incorporated as a limited liability company in 1993, during Slovenia's transition to a market economy. From these modest origins, Siliko has steadily grown into a major tier-1/2 supplier of elastomer and thermoplastic products, particularly for the automotive industry, while also diversifying into other industrial applications. The company's consistent growth and innovation were key factors in choosing Siliko as the subject of this case study. In 2024, Siliko was recognised with the factory of the year award, a testament to its advanced implementation of Industry 4.0 technologies and its leadership in smart manufacturing (Siliko, 2025).

The company's financial trajectory highlights its consistent growth, despite global supply chain disruptions and raw material cost pressures. Revenues rose from €81.79 million in 2021 to €90.46 million in 2022 and reached more than €106.22 million in 2023. In 2024, revenues stabilised at €101.67 million, reflecting both the cooling of global markets and Siliko's ability to maintain a high level of turnover. The stated numbers do not include Siliko GmbH, which was acquired in July 2024. Over the same period, employment numbers remained stable, ranging between 543 and 581 employees (Siliko, 2025). As group Siliko's turnover meanwhile already exceeds 150 mil EUR and employs more than 900 employees.

To provide a broader perspective, Table 2 presents Siliko's financial indicators for the period 2021–2024 alongside the Slovenian industry average for NACE C22.120 (Manufacture of other rubber products).

Table 2. Key financial and employment indicators of Siliko compared with the industry average (2021–2024)

	Siliko				Industry average (2024)
	2021	2022	2023	2024	
Revenue [in € million]	81.79	90.46	106.22	101.67	36.695
EBITDA [in € million]	9.91	11.40	15.22	15.78	3.816
Employees	553	543	557	581	204
Value added per employee [€]	51,307	56,605	68,479	66,346	58,949

Source: Ebonitete.si (2025).

The data (Table 2) show that Siliko consistently outperforms the industry average in both scale and efficiency. In 2024, its revenues were nearly three times the sectoral benchmark, while EBITDA was more than four times higher. With close to 600 employees, Siliko is also much larger than the average Slovenian rubber and plastics producer, which typically employs around 200 people. Value added per employee at Siliko exceeded the industry benchmark in every year.

Alongside its financial success, Siliko distinguishes itself through its vertically integrated operations. The company covers the entire production process from concept and product design to in-house mould manufacturing, elastomer formulation, and full-scale moulding and assembly. This capability allows Siliko to act as a development partner to clients, offering integrated solutions rather than isolated components. The product portfolio includes technical parts made of elastomers, thermoplastics, and liquid silicone rubber (LSR), manufactured to high precision standards for safety-critical applications. In addition, Siliko has developed strong expertise in multi-component injection moulding (2K/3K processes), which enables the combination of multiple materials or colours in a single part. These technologies are widely applied in automotive components, such as engine seals, gaskets, grommets, and shock absorbers, as well as in household appliances and industrial equipment (Siliko, 2025).

The automotive sector is by far Siliko's largest market, accounting for more than 90 percent of total sales. The company's client base includes major European car and truck manufacturers and their tier-1 suppliers, highlighting its position as a trusted partner in the international automotive supply chain. The remaining 10 percent of sales come from other industries, particularly home appliances and general industrial applications, which provide diversification while reinforcing Siliko's expertise in precision components. Historically, Siliko's international expansion was driven by exports to Germany, and Germany continues to play a central role in its customer base today (Siliko, 2025).

Geographically, the company is headquartered in Vrhnika and operates two production facilities in Slovenia (Vrhnika and Sevnica), along with subsidiaries in Serbia and Germany. This distribution enables Siliko to balance production costs with logistical efficiency, ensuring competitive delivery times across Europe. A key strength of this network is its integration: all facilities are connected under a single digital production management system. This system provides a unified "single source of truth" for operations across the company. Such digital integration positions Siliko not only as a reliable supplier but also as a frontrunner in Slovenia's ongoing transition toward smart factories (Siliko, 2025).

4.2 Insights from the interviews

A series of semi-structured, in-person interviews was conducted to capture the perspectives of different levels of Slovenia's smart factory ecosystem. Three groups of stakeholders were included: (1) academic experts from the Laboratory LASIM, Faculty of Mechanical Engineering, University of Ljubljana, representing the research and academic perspective; (2) company representatives from Siliko d.o.o., providing direct business insights; and (3) the Chamber of Commerce and Industry of Slovenia (GZS), offering the institutional and policy perspective (Table 3).

Table 3. Characteristics of interviewees

Organisation	Position	Code
University of Ljubljana, Faculty of Mechanical Engineering	Head of Laboratory	SMART1
	Researcher	SMART2
	Researcher	SMART3
SILIKO d.o.o.	Chief Executive Officer (CEO)	SMART4
	Chief Operating Officer (COO)	SMART5
	Head of Technology	SMART6
Chamber of Commerce and Industry of Slovenia	Director of the Electrical Industry Association	SMART7
	Senior Advisor	SMART8

Source: Own work.

This triangular approach makes it possible to examine the opportunities and barriers of smart factory adoption in Slovenia from complementary viewpoints: academic, business, and policymaking. While the LASIM researchers emphasised structural and cultural factors shaping digitalisation, the GZS representatives highlighted systemic support mechanisms and the role of state policy, and Siliko's case provided a concrete business example of digital transformation in practice.

The interviews with Siliko's leadership focused on how Industry 4.0 is integrated into the company's operations and strategy. The analysis addressed four main aspects: the drivers and leadership decisions that motivated Siliko's digitalisation; the specific technologies adopted and their impact on production efficiency; the organisational changes in roles, skills, and culture that accompanied the transformation; and the degree to which these initiatives are integrated into the company's long-term strategy and competitiveness in international markets.

4.2.1 Drivers and strategy

Siliko's journey toward becoming a smart factory was not accidental, but the result of a deliberate decision taken by its top management. The CEO recognised early on that remaining competitive in the automotive supply chain required not only efficiency improvements but also a long-term commitment to digital transformation. As he explained, *"Everything starts with what you see in the market and where the future is going. There is fear of missing the train"* (SMART4). This mindset shows a proactive rather than reactive orientation. Instead of waiting for customer pressure or regulatory demands, Siliko acted in anticipation of global industry trends. The automotive sector's growing demand for technological innovation also played a significant role in accelerating this transformation. Leadership explicitly linked digitalisation to competitiveness: *"If someone waits, they will fall behind and enter too late"* (SMART5).

This strategic vision reflects what LASIM researchers have consistently underlined: leadership engagement is a decisive factor in successful digitalisation (SMART1). They observed that projects fail when delegated to junior staff without top management support, while projects succeed when directors actively participate and align digital initiatives with broader business goals. In Siliko's case, the CEO's direct involvement echoes this principle and illustrates how leadership commitment translates into concrete outcomes.

At the same time, the company rejected the "big bang" model of transformation. A full greenfield investment was considered financially unrealistic:

"Greenfield is a different story. There you can set up ideally. We did a lot with retrofits" (SMART5). The decision to retrofit existing assets rather than build new facilities reflects a pragmatic strategy tailored to a mid-sized Slovenian firm with limited capital compared to global automotive giants. This incremental approach also made cultural adaptation easier and gave employees time to adjust, reducing resistance and avoiding disruption.

This incrementalism resonates with GZS's observations that for most Slovenian SMEs the complexity and cost of digitalisation are daunting, which is why step-by-step investments, supported by competence centres and best practice sharing, are more realistic. As one representative noted: *"Companies often do not know where to start, whether to start with equipment or with systems. Our role is to help them find the right entry point"* (SMART7). Siliko's choice to rely heavily on internal competence development further reinforces this SME-relevant lesson: *"We did a large part ourselves, with our IT and technology team"* (SMART4). By building in-house expertise, the company not only reduced dependence on external consultants but also created a knowledge base that strengthens long-term competitiveness.

4.2.2 Technological adoption

The technological backbone of Siliko's smart factory is a combination of industrial IoT, real-time data acquisition, and centralised process monitoring. Virtually every machine is connected to a central database. Older machines were retrofitted to capture at least basic signals, while new equipment integrated seamlessly. The system feeds into a manufacturing execution system (MES), the "digital nerve centre" of the company. MES enables continuous monitoring and transparency across operations. Supervisors and engineers no longer depend on manual reporting or phone calls to check machine status: *"This allows us to see the entire overview of the status of machines [from anywhere], without calling and guessing"* (SMART4). Manual routines were replaced with digital oversight: *"There is no need for manual stamping to prove presence. The system shows the real state"* (SMART4).

Among the most important metrics tracked is Overall Equipment Effectiveness (OEE). For the past five years, Siliko has measured OEE on every machine, producing a robust dataset. This has enabled the company to identify bottlenecks and inefficiencies systematically. As one manager highlighted: *"Distinguishing planned from unplanned downtime has allowed Siliko to find capacity without* *buying a new machine"* (SMART4). In practice, this means better utilisation of existing assets before committing to capital expenditure.

The same logic applies to maintenance and quality control. Traditionally, machine breakdowns led to reactive fixes. Now, Siliko is gradually moving toward predictive maintenance: *"Today, a failure leads to corrective action. We want prevention. AI, connected to our sensor data, constantly reviews signals and triggers warnings and schedules interventions before a breakdown" (SMART5). Quality control is also becoming data-driven: "Something is happening on this machine or product, go check there"* (SMART5).

This trajectory directly contrasts with patterns observed by LASIM researchers. They cautioned that many Slovenian firms invest in technology without first restructuring processes: *"If you go directly into digitalisation, you are basically informatising waste and doing yourself a disservice"* (SMART1). Siliko, by contrast, shows how systematically embedding MES and OEE ensures that digitalisation builds on a solid operational foundation. As LASIM further stressed, *"You cannot build a digital factory without knowing your elementary operations and thus exact cycle, task sequences, or product structure, meaning having high quality and reliable data first. Without this foundation, advanced solutions like digital twins are like building a house on sand"* (SMART2). Siliko's case illustrates how these pitfalls can be avoided by starting with data standardisation and gradually layering advanced tools.

4.2.3 Organisational change

Technological change reshaped Siliko's workforce and organisational structures. According to the CEO, *"The suppliers and customers are the same [as before], but inside the house the structure is changing: more automation, consequently less classic operator work, more development, more technological and IT support. Added value per employee is growing, and production is becoming more efficient. It is an evolution, not a revolution"* (SMART4).

This reflects a gradual shift from manual labour to higher-skilled tasks. Yet, as LASIM researchers stressed, such transitions demand cultural adaptation. They warned that without engaging employees, firms risk resistance and superficial adoption, as innovation often remains siloed within R&D rather than shared across the workforce (SMART1). Siliko faced similar challenges. Operators were initially sceptical and worried about surveillance. Management responded with communication and training: *"The purpose is not for people to get caught doing* *something wrong, but to uncover losses"* (SMART4). Over time, transparency turned resistance into participation. Work stations now allow operators to access data, input notes, and track performance: *"Once an operator realises that the system could provide useful insights, it pulls him in. Then he starts asking why something is deviating and suggesting improvements"* (SMART6).

To embed this cultural shift, Siliko tied performance indicators to transparent rewards: "Employee rewards are transparent and fair. You get rewarded not because you are likeable, but because you have results. And it works" (SMART4). This aligns with broader business concerns voiced by GZS, where representatives emphasised that *"the biggest challenge is staff. There are not enough people with the right knowledge"* (SMART7). Unlike many SMEs struggling with skills shortages and low engagement, Siliko demonstrates that linking digital tools with training and fair incentives can help close this gap.

4.2.4 Strategic integration

Siliko's transformation illustrates how digitalisation can move beyond isolated projects to become part of a broader strategic framework. Rather than treating Industry 4.0 initiatives as temporary or experimental, the company integrated them into its long-term vision for competitiveness in global supply chains.

Importantly, Siliko aligned subsidies and grants with internal priorities rather than chasing funding opportunities: *"We approach grants only if we know the projects make long-term sense. We never do it just because"* (SMART4). This principle reflects disciplined strategic governance, where external resources serve, rather than dictate, corporate direction. The same concern was echoed by GZS, whose representatives noted that *"calls are often inconsistent and delayed, which makes planning difficult for companies"* (SMART7).

Siliko's active engagement in industry associations, such as the Slovenian Automotive Cluster (GREMO), further illustrates this integration. Participation in collaborative platforms provides opportunities to exchange knowledge and benchmark progress, ensuring that digitalisation remains embedded in both corporate and sectoral strategy. Here again, company practice mirrors systemic needs: *"Companies need competence centres and pilot facilities where SMEs can safely test solutions before committing to investments"* (SMART8). LASIM experts similarly stressed that *"progress will accelerate once the state clearly supports competence centres that deliver results, demonstrations, and systematic training"* (SMART2).

4.2.5 Outlook

Looking ahead, Siliko plans to further integrate Industry 4.0 tools. The development of a digital twin is a priority: *"When a real digital twin is in place, we will be able to quickly simulate changes with lower cost and inventory... before touching the physical production"* (SMART5). Such a system would allow real-time simulation of layout changes, stock levels, and scheduling, thereby reducing the risks and costs associated with operational adjustments.

Artificial intelligence is also expected to expand further: *"When we implement it across the entire factory, it will spread to all areas and become our constant aid"* (SMART5). The plan to implement artificial intelligence refers to targeted applications where the company already sees tangible benefits. These include predictive, AI-supported quality management that is capable of detecting anomalies in real time, and process parameter analysis to reduce scrap and optimise operator performance. A digital twin of the factory is also envisioned, allowing simulations of layout changes, logistics flows, and inventory reductions before intervening physically. In addition, managers highlighted the potential for AI to improve safety through optimised emergency stop systems and anomaly detection. LASIM researchers noted: *"Younger engineers already experimenting with automation during their studies will drive adoption in the coming decade"* (SMART3). GZS added that speeding up the journey from idea to implementation is crucial, citing international examples of predictive maintenance and simulation centers as proof of what can be achieved.

Table 4. Key interview insights

Focus area	Key insights
Drivers and strategy	• Incremental retrofitting • Proactive investment
Technological adoption	• MES as digital nerve centre • OEE monitoring
Organisation and HR	• Cultural adaptation • Operator engagement • Incentive alignment
Strategic integration	• Management-led; subsidies aligned with long-term competitiveness
Outlook	• Digital twin and AI expansion

Source: Own work.

Finally, Siliko offers advice for other firms considering similar transformations: *"Never will there be an ideal moment. You just have to start. But the motivation must come from within, not due to outside pressure. Begin with a clear goal and go step by step"* (SMART4). This pragmatic message underlines the value of internal commitment and gradualism in achieving sustainable digital transformation. Table 4 summarises the core insights from the interviews, organised according to the research focus areas.

5. Conclusion

This chapter has shown how global and European trends in smart factory development set the framework for company-level transformations. Siliko illustrates this well. Strategic leadership, clear objectives, and incremental investment proved crucial for digitalisation. Instead of disruptive "big bang" changes, the company pursued a retrofitting strategy, making gradual adoption feasible for a mid-sized firm. Siliko achieved real-time monitoring and systematic OEE measurement, showing how data transparency can drive performance.

The case also highlights organisational and cultural aspects. Employee participation and incentives were crucial to the adoption. Initial resistance among operators was reduced, leading to stronger engagement and increased knowledge sharing. Looking ahead, Siliko plans to expand AI into predictive maintenance, quality management, and digital twin applications, showing how advanced analytics and simulation are finding practical use in the Slovenian context.

At the same time, the broader Slovenian ecosystem still faces challenges. A sharp divide remains between SMEs and large companies. To close this gap, stronger systemic support is required. Demonstration centres and pilot facilities are still scarce. Education reform and skills development must go hand in hand with digital investment, ensuring the workforce is prepared for new roles. Clearer regulation and faster, more predictable financing processes are also essential. Current calls for subsidies and grants are often delayed or overly complex, discouraging firms from participation.

Going forward, building stronger bridges between academia, business, and policy institutions will be key. Ultimately, Slovenia's competitiveness in the digital era will depend not only on individual pioneers like Siliko but also on an ecosystem where regulation, financing, and collaboration allow smaller firms to follow the same path.

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EMERGING QUANTUM TECHNOLOGIES AND THE SKILLS GAP: INSIGHTS FROM A SYSTEMATIC LITERATURE REVIEW

1 Introduction

Quantum technologies are emerging as a transformative force, driving innovation across computing, communication, sensing, and cryptography. Their potential impact is increasingly recognised not only in science and engineering but also in economics, business, and public policy (Dowling & Milburn, 2003; Feynman, 1982). The **"second quantum revolution"** marks a transition from theoretical research to practical applications with significant economic and societal implications. Governments and industries are competing to harness these opportunities, making the development of a skilled workforce a critical priority (National Science and Technology Council, 2022; Zhu et al., 2024).

The growing quantum skills gap has been widely acknowledged (Greinert et al., 2023). The demand for expertise in quantum computing, communication, and sensing is outpacing supply, and shortages are evident in research institutions, companies, and government agencies (Quantum Economic Development Consortium [QED-C], 2025). Misconceptions about quantum theory persist even among advanced students (Singh, 2001; Taber, 2005), and curricula often fail to link fundamental concepts with applied skills. Universities and training programs also struggle to balance disciplinary depth with the interdisciplinary knowledge required for emerging fields, such as quantum computing, where physics, computer science, and engineering converge.

To analyse these dynamics, the study combines bibliometric mapping and thematic analysis. Bibliometric methods identify the most influential works and research clusters. At the same time, thematic analysis highlights recurring issues, such as training needs, misconceptions, and models of collaboration between industry and education, as well as the implications for education, workforce planning, and innovation policy. Additionally, a comparative perspective was applied to explore how different countries are addressing these challenges, demonstrating the different strategies taken by the United States, European countries, and China. Europe's main challenges are reviewed: while strong in research output, it faces structural weaknesses due to fragmentation and limited integration between policy, education, and industry (Greinert et al., 2023). The chapter concludes with a summary and policy recommendations.

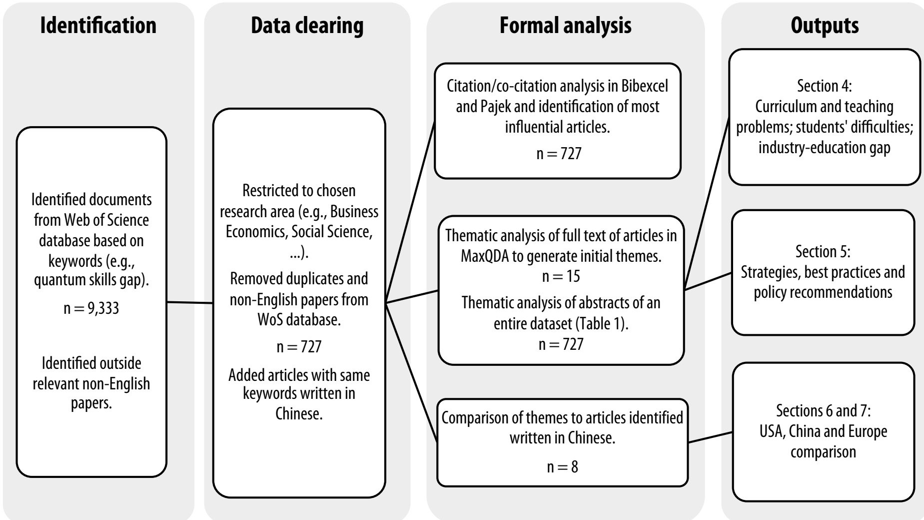
The findings contribute to current debates on how to close the skills gap and build a sustainable ecosystem for quantum technologies. The chapter provides recommendations for policymakers, companies, and education ministries, drawing on international best practices and considering how they can be adapted to different national contexts.

2 Methodology

This study relies on a combination of bibliometric analysis and qualitative thematic analysis. Bibliographic information retrieved from the Web of Science database was analysed using bibliometric mapping of the field. A qualitative thematic analysis of abstracts was performed in order to establish main themes, and an additional review of articles not written in English was used to compare gaps and strategies between the United States, Europe, and China. The methodological process is summarised in Figure 1, which illustrates the sequence of steps from data collection to analysis.

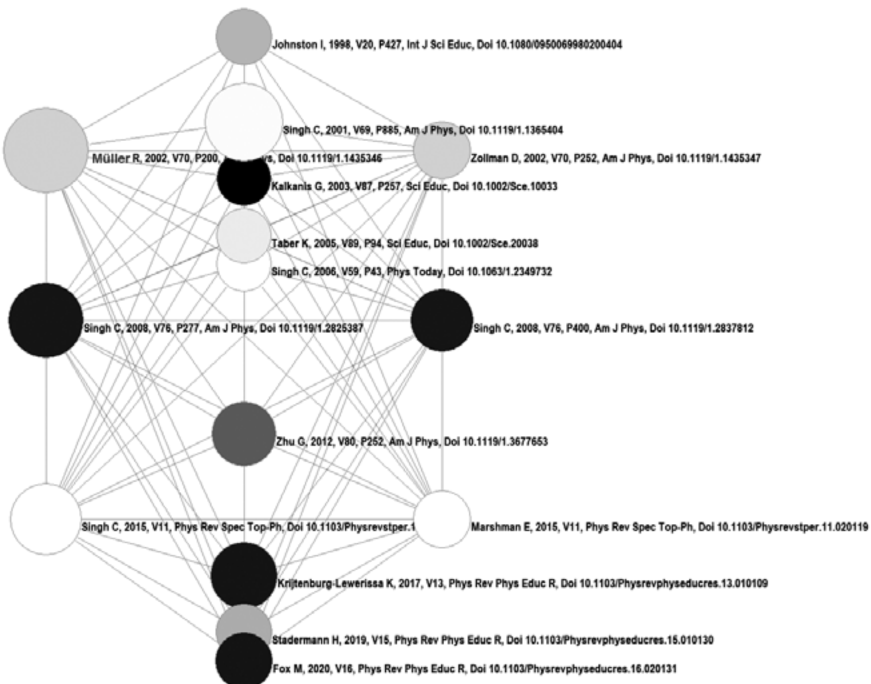
In the first step, bibliographic information was retrieved from the Web of Science (WoS), selected for its broad coverage of high-impact journals. The search strategy targeted concepts linked to the quantum technology skills gap, such as **quantum and deep tech education, quantum and deep tech training, and the quantum and deep tech skills gap**, as published in the business research area. The screening and filtering stages, as well as the final dataset of 727 records, are summarised in Figure 1. The dataset (n = 727) was processed in BibExcel to calculate citation counts and prepare files for network construction. Citation and co-citation analysis (Figure 2) was done in Pajek.

Figure 1. Methodological process applied in this study



Source: Own work, WoS (2025).

Figure 2. The most cited research papers in the field



Source: Own work, WoS (2025).

In the second step, the dataset was coded and thematically analysed (Braun & Clarke, 2021) in MaxQDA 12, using a combination of inductive and deductive coding of the entire text of the most influential articles, as well as the abstracts of the entire dataset (Table 1). This analysis forms the basis of sections 4 and 5, which summarise the main challenges to quantum skills education and provide an overview of strategies and solutions.

Table 1. List of final themes: Barriers and solutions to the quantum skills gap (n = 727)

	Barriers/challenges	Solutions/ strategies
Curriculum and teaching approaches	• Design of curricula focused on just a few core topics • Design of courses to emphasise algorithmic problem solving • Assessments reward procedural fluency rather than conceptual insight • Curricula do not balance theory and practice	• Innovative teaching methods (virtual labs, QuILT, games), interactive visualisations • Earlier introduction to quantum physics • Interactive, conceptual and epistemological engagement
Student difficulties	• Transition from classical to quantum thinking – disconnect between procedural skills and conceptual understanding • Different levels of preparation • A need for a paradigm shift from intuitive models to abstract mathematical frameworks • Persistence of incorrect mental models that actively distort reasoning	• Scaffolding strategies (triggering cognitive conflict, knowledge restructuring) • Diagnostic tools • Integrating qualitative and quantitative approaches • Assessments to inform design of effective teaching interventions (QMCS, QPS)
Industry-education gap	• Lack of graduates with the ability to apply knowledge to practical concepts • Skills shortages in frontier fields due to the slow adaptation of curricula • The capacity of organisations to keep training individuals	• Building stronger and more flexible bridges between academia, industry and government • Specialised certificates and training initiatives in collaboration with industry • University spin-offs partnering with private firms

Source: Own work.

In the third phase, in addition to the English-language dataset obtained from the Web of Science, relevant non-English papers were reviewed to widen the scope of the research. To include insights from the Chinese context, additional Chinese academic databases were searched (Wanfang Data, VIP Database, and Baidu Scholar). By incorporating insights from both international (WoS) and regional Chinese sources, the analysis provided a more comprehensive foundation for the comparative assessment, particularly for assessing the specific challenges faced by Europe's quantum education system, as discussed in sections 6 and 7.

3 An overview of the landscape of quantum technologies

In order to provide context for the literature review, the c**urrent state of quantum technologies and their applications** is outlined, showing how the principles of quantum mechanics are being transformed into practical innovations with major economic, industrial, and geopolitical implications.

Quantum mechanics has changed the way science sees the world. Instead of the predictable rules of classical physics, quantum mechanics introduces principles, such as probability, superposition (where systems exist in multiple states simultaneously), and entanglement (connections between particles across distances) (Johnston et al., 1998; Fox et al., 2020). These strange properties are now being harnessed to create a new wave of technologies, often referred to as the **second quantum revolution**. These include quantum computing, quantum cryptography, quantum sensing and quantum communication (Fox et al., 2020).

At its core, quantum technology utilises the laws of quantum physics to process information in a way that classical systems cannot. It can also have implications for communications, with quantum communication enabling new forms of highly secure information transmission, making it almost impossible for hackers to intercept data. Even in navigation, medical imaging, and underground resource detection, quantum sensor technology improves accuracy (Reuters, 2024). These examples show why countries and companies see quantum technology not just as another technology, but as a strategic advantage with global implications.

Practical applications of quantum technology are already emerging in various industries. In finance, banks are beginning to explore quantum algorithms for risk and credit scoring. Specifically, institutions like JPMorgan Chase and Goldman Sachs are developing these approaches to tackle risk analysis and fraud detection (JPMorgan Chase; Goldman Sachs blog). In healthcare, Roche and Google have teamed up to use quantum tools for modelling complex molecules, a move designed to speed up the discovery of new drugs (Nature, 2023). In logistics, companies such as Airbus and DHL are testing quantum computers to optimise flight schedules (Airbus, 2024; IonQ, 2023) and delivery routes to make supply chains faster and more efficient (Axidio, 2024; Masood, 2023). In the field of security, the Chinese satellite Micius has already demonstrated secure quantum communication over thousands of kilometres, providing a glimpse of a possible global quantum internet (Nature, 2020).

The quantum industry is still led by big tech players, such as IBM, Google, and Microsoft, since they are the only ones capable of handling the huge investment needed to scale these technologies (TSG Invest, 2025). At the same time, a fast-growing group of start-ups is bringing innovation to the market. Companies like IonQ (US), Pasqal (France) and Quantinuum (UK/US) are building the hardware, while firms such as Classiq (Israel) and Zapata (US) are focusing on software and applications (TechCrunch, 2023; Reuters, 2023). Global venture capital funding for quantum start-ups passed $2.3 billion in 2023 (TechCrunch, 2024), showing strong momentum.

Governments around the world are endeavouring to take the lead in quantum technology. The United States launched the National Quantum Initiative Act in 2018, investing over $1 billion annually and creating centres, such as Q-NEXT and the Quantum Economic Development Consortium, to connect research and industry (NQI, 2025). China has invested billions of dollars in quantum research and development, putting it at the forefront of quantum communication (Nature, 2020; Reuters, 2024). Meanwhile, in Europe, the Quantum Flagship, a 10-year, €1 billion program aimed at accelerating research and commercialisation, and the European Quantum Communication Infrastructure (EuroQCI) initiative, which aims to build a continent-wide secure quantum communications network, are underway (European Commission, 2024). These large-scale initiatives make it clear that quantum physics is no longer only an academic field of research; it has become both a geopolitical competition and a driver of industrial change. For businesses, early adoption of quantum physics offers a key competitive advantage in industries. For education, the message is even sharper. If schools and teachers do not quickly integrate quantum concepts into the curriculum, there is a risk of shaping a workforce that is unprepared for one of the most disruptive technological shifts of the century (Fox et al., 2020).

4 Findings: The quantum skills shortage and the challenge of education

In the literature, a clear conclusion is that quantum technologies are advancing rapidly. Yet, education has not kept pace: students often graduate without the conceptual foundation or practical skills needed for quantum computing, communication, or sensing (Fox et al., 2020), while fragmented curricula, traditional teaching methods, and persistent misconceptions contrast with industry's demand for graduates skilled in theory, programming, experimentation, and teamwork (Greinert et al., 2023; Mu et al., 2024). This section reviews the three main barriers identified in the literature: (1) **curriculum and teaching approaches**, (2) **student difficulties**, and (3) **the gap between education and industry needs**.

4.1 Curriculum and teaching approaches

One of the most obvious obstacles lies in the way the curricula are designed. International comparisons of secondary school curricula show a remarkable consistency in focusing on a few core topics (Stadermann et al., 2019); however, crucial aspects, such as the question of what quantum theory tells us about the nature of reality, are largely missing. Without these aspects, students find it difficult to build a solid conceptual framework.

At the university level, similar problems persist. Courses often emphasise algorithmic problem solving, particularly the time-independent Schrödinger equation[1], while neglecting the time-dependent formulation and dynamical aspects of quantum systems (Marshman & Singh, 2015). Assessments tend to reward procedural fluency rather than conceptual insight, making it difficult for teachers to recognise deeper thinking errors (Krijtenburg-Lewerissa et al., 2017). Even successful students can perform complex calculations, but they often have "structurally immature" mental models (Johnston et al., 1998).

This poses an immediate problem for employers. Start-ups like Pasqal (France) and IQM (Finland/Germany), which build quantum processors, often need engineers who not only understand equations but also know how to apply them to hardware development and testing. Without curricula that balance theory and practice, these companies face longer training periods and higher training costs (Kalkanis et al., 2003; Johnston et al., 1998).

To overcome these obstacles, innovative teaching methods have been developed. Müller and Wiesner (2002) demonstrated the benefits of a conceptualised pedagogy that uses virtual labs and allows students to engage directly with fault and measurement experiments. Singh (2016) developed interactive Quantum learning tutorials (QuILTs) that guide students through prediction-observation-reflection cycles to deepen their understanding of time evolution and uncertainty. Zollman and others (2002) argued for an earlier introduction to

1 The time-independent Schrödinger equation is like the "rulebook" of quantum mechanics that tells us which energy levels are possible for a particle. By solving it, scientists can find both the allowed energies and the shapes of the wavefunctions, for example, the fixed energy levels of electrons in an atom (Johnston et al., 1998).

quantum physics to build intuition even without advanced mathematics. These approaches emphasise that effective teaching requires not only revised curricula but also interactive, conceptual and epistemological engagement.

4.2 Student difficulties

The transition from classical to quantum thinking is one of the most persistent obstacles in teaching modern physics. Many students excel at formal calculations but struggle to interpret results qualitatively, highlighting a disconnect between procedural skills and conceptual understanding (Singh, 2001; Singh et al., 2006). This difficulty is compounded by structural challenges, including varying levels of preparation, fragmented motivations, and the need for a paradigm shift from intuitive models to abstract mathematical frameworks (Marshman & Singh, 2015). The coexistence of contradictory mental models, alternating between classical and quantum explanations, further complicates learning (Taber, 2005; Kalkanis et al., 2003).

These gaps have direct implications beyond academia. Companies such as Zapata Computing (USA), which develops quantum algorithms for finance and logistics, or Q-CTRL (Australia), which specialises in quantum navigation systems, need graduates who can move beyond rote calculation to model complex real-world problems in quantum frameworks. When this is not the case, organisations are forced to invest in lengthy retraining processes, which delay innovation cycles and increase costs (Johnston et al., 1998; Kalkanis et al., 2003). While similar dynamics can be observed in other technology-intensive industries, the quantum sector differs in two respects. First, the scientific foundations are still rapidly evolving, which creates greater uncertainty about the skills required (Greinert et al., 2024). Second, the translation of abstract quantum principles into practical engineering applications demands an unusually high level of interdisciplinary expertise, making skill gaps more disruptive than in more mature fields, such as information technology or mechanical engineering (European Commission, 2024).

Misunderstandings are also one of the biggest obstacles when discussing student learning. While the previous discussion referred to the gap between procedural skills and conceptual understanding, misconceptions go a step further: they involve the persistence of incorrect mental models that actively distort reasoning. For instance, a researcher who misunderstands the principle of uncertainty could misinterpret sensor data in a company developing quantum navigation technologies. In industries where mistakes carry high costs, conceptual clarity is not only an intellectual necessity but also a commercial imperative (Kalkanis et al., 2003; Johnston et al., 1998).

To address these challenges, researchers highlight the role of scaffolding strategies in fostering conceptual reorganisation. Taber (2005) and Kalkanis and others (2003) recommend the explicit juxtaposition of classical and quantum paradigms to trigger cognitive conflict and encourage knowledge restructuring. Singh and Marshman (2015) emphasise the importance of diagnostic tools that help teachers identify recurring reasoning errors, while Singh and others (2006) propose integrating qualitative and quantitative tasks to prevent reliance on purely mechanical approaches. Instruments such as the Quantum Mechanics Conceptual Survey (QMCS) and the Quantum Physics Conceptual Survey (QPCS) (Krijtenburg-Lewerissa et al., 2017), along with targeted tests on measurement and time evolution (Singh, 2001), provide valuable insights into students' thinking and inform the design of more effective teaching interventions. However, their adoption and validation remain limited.

4.3 The industry-education gap for emerging technologies

A critical obstacle for the development of emerging technologies is the gap between academic training and the skills demanded by industry. Companies working in fields such as quantum sensing, communications, and computing, but also in artificial intelligence, biotechnology, and advanced materials, require not only theoretical expertise but also programming skills, experimental know-how, teamwork, and interdisciplinary problem-solving (Fox et al., 2020). Graduates often leave university with insufficient ability to apply knowledge in practical contexts, resulting in a skills gap that hinders workforce readiness across multiple high-tech sectors. A recurring debate concerns whether universities should play this role at all, or rather if it is the task of polytechnic schools. While this view may have been relevant in the past, contemporary policy frameworks emphasise that universities are expected to equip individuals with practical knowledge, since employability is now one of the key outcome metrics used to evaluate higher education institutions (OECD, 2019; WEF, 2020).

The problem is not limited to quantum. The literature on innovation systems shows that skills shortages in frontier fields are structural and persistent, partly because universities are slow to adapt curricula, and partly because technology evolves faster than formal education cycles. As Cohen and Levinthal (1990) argue, the key challenge is not simply knowledge transfer at graduation but the absorptive capacity of organisations and individuals, their ability to keep learning and adapting as technologies advance. Without this capacity, even highly trained graduates risk becoming outdated within a few years.

Table 2. Classification of skills needed for the quantum workforce

Dimension	Key Skills	Examples/Relevance
Technical & domain-specific	• Quantum computing (algorithms, error correction, hardware); • Physics knowledge (superposition, entanglement, measurement); • Advanced mathematics (linear algebra, probability, complex systems); • Computer & information science (programming, data management); • Laboratory/experimental methods (optics, cryogenics, device calibration).	Required for building and operating quantum devices, running simulations, and supporting hardware/software development. Current curricula emphasise equations but neglect experimental know-how, forcing firms to retrain graduates (Fox et al., 2020).
Analytical & cognitive	• Problem solving (complex/non-routine); • Critical thinking (evaluating uncertainty, designing models); • Data analysis (interpreting simulations and experiments); • Metacognitive strategies (reflective learning, self-monitoring).	Enables graduates to translate theory into practice and avoid misconceptions (e.g., misinterpreting the uncertainty principle). A lack of emphasis in curricula leads to "structurally immature" mental models (Stadermann et al., 2019; Johnston et al., 1998).
Interdisciplinary & technological	• Integration of physics, computer science, and engineering. • Familiarity with innovation platforms (cloud-based access, hybrid computing); • Adaptability to rapidly evolving tools (quantum + AI, robotics).	Supports cross-disciplinary collaboration and alignment with fast-changing innovation cycles. Currently underdeveloped in formal education, making the skills gap more disruptive than in mature fields (Greinert et al., 2024; European Commission, 2024).
Professional & soft skills	• Communication (explaining complex concepts to non-experts); • Teamwork & collaboration; • Coaching/mentoring abilities; • Interpersonal networking.	Essential for industry–academia collaboration, start-up environments, and scaling innovations. Weakly addressed in curricula, forcing companies to invest in retraining (Fox et al., 2020).
Societal & structural competencies	• Awareness of equity, diversity, and inclusion; • Understanding the ethical, social, and economic implications of quantum technologies; • Capacity for responsible innovation.	Prepares graduates to contribute to sustainable workforce development. Still peripheral in most curricula, despite being emphasised in international frameworks (Greinert et al., 2023).

Source: Own work.

To mitigate this gap, universities and governments have begun creating specialised degrees, certificates, and training initiatives, often in collaboration with industry consortia. In the United States, the Quantum Economic Development Consortium (QED-C, 2025) brings together companies, research labs, and government agencies to align workforce development with industrial needs. It brings together more than 200 members, including federal agencies (NIST; Department of Energy), major technology companies (IBM, Google, Boeing, Zapata Computing), as well as universities (Purdue). Comparable initiatives exist in Europe, where university spin-offs in Paris, Delft, and Munich are partnering with private firms to translate research into talent pipelines. Although these efforts show promise, the literature underlines persistent challenges in scaling such programs, ensuring accessibility, and maintaining alignment with fast-changing industry demands (Fox et al., 2020).

The skills gap explained above thus involves five main categories of skills, which are summarised in Table 2: (1) technical skills, including laboratory experience, programming, and experimental design; (2) analytical and cognitive conceptual skills, such as understanding fundamental quantum principles like superposition and entanglement; (3) interdisciplinary skills, integrating physics, computer science, and engineering; (4) professional and soft skills, such as teamwork, problem-solving, and communication abilities; and (5) societal and structural competencies. Together, they illustrate not only what is missing but also why these skills are critical for bridging the gap between education and innovation.

5 Bridging the skills gap: Strategies, best practices and policy recommendations

Closing the quantum skills gap requires combining pedagogical innovation with **coordinated policy support**. The reviewed literature shows that four strategies are particularly effective in preparing students for the demands of the second quantum revolution: (1) collaboration between stakeholders; (2) the adoption of innovative teaching methods; (3) contextualised learning experiences; and (4) coordinated policy support.

Collaboration across universities, industry, and governments ensures that curricula remain aligned with evolving technological needs. Initiatives such as the US Quantum Economic Development Consortium demonstrate how structured partnerships can translate workforce demands into educational programs, while China's integration of quantum platforms into higher education illustrates the impact of linking research and industry with training (QED-C, 2025; Mu et al., 2024). Long-term cooperation is therefore essential to sustain a skilled pipeline (Fox et al., 2020).

Adoption of innovative teaching methods. The way quantum concepts are taught is equally important. Traditional approaches are often insufficient, and evidence suggests that hands-on learning, virtual laboratories, guided tutorials, and visualisation techniques improve conceptual understanding and professional readiness (Müller & Wiesner, 2002; Singh, 2016; Zollman et al., 2002). Such methods help overcome persistent misconceptions in quantum mechanics and link abstract concepts to practical problem-solving (Johnston et al., 1998; Kalkanis et al., 2003).

Contextualised learning experiences. Embedding learning in authentic contexts further strengthens knowledge transfer. Case studies from sectors such as healthcare, finance, or cybersecurity, combined with internships, micro-internships, and capstone projects, allow students to apply quantum principles beyond the classroom (Greinert et al., 2023; Stadermann et al., 2019). Diagnostic instruments like the QMCS and QPCS also help educators identify and address conceptual gaps, ensuring that learning outcomes are not only theoretical but also applicable in professional practice (Krijtenburg-Lewerissa et al., 2017).

Coordinated policy support. While these best practices are vital, they must be embedded in broader policy frameworks. Governments should provide funding, establish standards, and adopt competence frameworks, such as the CFQT, to align education with occupational profiles (Greinert et al., 2024). National initiatives, such as the US National Quantum Initiative and the EU's EuroQCI, show how infrastructure investments can also serve as training platforms (National Science and Technology Council, 2022; European Commission, 2024). Industry must complement these efforts by co-designing courses, signalling the skills required, and expanding experiential opportunities. Partnerships that provide access to cloud-based quantum computers, such as those developed by IBM and Google, are already familiarising students with industry tools (Fox et al., 2020), while apprenticeships and internships can further strengthen transitions to employment (QED-C, 2025). Finally, schools and universities need to introduce quantum concepts earlier and in more conceptual ways, while embedding work-based learning through collaborations with start-ups, such as Pasqal and IQM (Stadermann et al., 2019; TechCrunch, 2025).

Bridging the quantum skills gap requires an integrated approach. Collaboration, innovative pedagogy, and contextualisation from the educational foundation, while governments, firms, and schools provide the systemic support necessary to scale these practices. Only through the combination of these strategies and policy actions can a workforce be developed that is capable of sustaining the scientific and technological advances of the second quantum revolution (Fox et al., 2020; Greinert et al., 2024; QED-C, 2025; Stadermann et al., 2019).

6 The main differences in educational systems – USA, China and Europe

A cross-regional assessment shows that China, the United States and Europe all emphasise quantum education, but their approaches differ in structure and effectiveness.

China uses a top-down, nationally integrated strategy to promote quantum talent. In the 14th Five-Year Plan and Vision 2035, quantum information technology (QIT) is labelled a "pioneering and strategic technology" alongside artificial intelligence and biotechnology (Shi, 2025). This emphasises the importance that the leadership attaches to quantum information technology as crucial for national security and industrial independence. With major projects, such as the backbone network between Beijing and Shanghai and the Micius satellite, China has already demonstrated its global leadership in quantum communication (Mu et al., 2024). Building on this momentum, the country is also driving educational innovations that integrate an understanding of quantum physics at different levels of learning. At the secondary school level, the "Three-New" curriculum integrates quantum concepts into HPS (History and Philosophy of Science) classes, promoting inquiry-based learning and early exposure to complex scientific ideas (Liu & Li, 2023). At the university level, "new engineering" reforms combine quantum mechanics with engineering and computer science, promoting cross-disciplinary education that reflects the realities of quantum technology development (Shi, 2025). At the graduate level, elite institutions such as Tsinghua University and the University of Science and Technology of China (USTC) combine theoretical research with experimental practice, ensuring that future specialists acquire both conceptual depth and practical expertise (Mu et al., 2024).

Pedagogical innovations emphasise problem-based learning (e.g., Einstein-Bohr debates), cross-disciplinary applications in cryptography and sensing, and the development of creativity and critical thinking for the "quantum age" (Liu, 2020). As hardware remains expensive, companies such as Huawei, Baidu and Origin Quantum offer cloud platforms that provide students with access to simulators and processors, removing barriers to entry and increasing participation (Zhang et al., 2023). Despite this progress, China faces several challenges, including a mismatch between theory and practice, uneven adoption of teaching content in schools, weaker labour market integration than in the United States, and a persistent brain drain as many graduates seek opportunities abroad (Shi, 2025; Liu & Li, 2023; Zhu et al., 2024; Mu et al., 2024). Nonetheless, China's reforms have prioritised quantum talent and sought to improve both general education and elite knowledge.

The United States emphasises a workforce-focused strategy based on federal action. The Quantum Initiative Act of 2018 establishes a national framework that is complemented by the NSF's Quantum Leap Challenge Institutes, Q-12 outreach initiatives, and the Quantum Economic Development Consortium (QED-C, 2025). These initiatives link education directly to labour market needs, although scaling programs to meet demand remains a challenge (Zhu et al., 2024). Strong career pathways and competitive salaries retain talent (Fox et al., 2020).

Europe's strategy is distinguished by substantial top-down research financing and bottom-up, voluntary educational integration, which results in intrinsic fragmentation. It is mostly managed through EU-wide projects, such as the Quantum Flagship, which supports large-scale research, and QTEdu, which creates instructional tools. The European Competence Framework for Quantum Technologies (CF-QT) sets important benchmarks for knowledge and abilities (Greinert et al., 2023). Cross-border education is made possible by collaborative Master's programs, such as the Erasmus Mundus course in Quantum Science and Technology, as well as student mobility schemes like Erasmus+. However, member states can choose whether or not to use these frameworks and programs, which leads to inconsistent implementation and a lack of standards. This contrasts sharply with China's centralised national strategies and the United States' federated, industry-aligned strategy. As a result, although some nations, such as Germany and the Netherlands, have created advanced ecosystems, others lag behind, resulting in fragmented advancement in Europe (Li & Zhang, 2025).

Table 3 presents a comparative overview of quantum education and workforce strategies in the United States, China, and Europe, offering a concise reference point that highlights key differences and provides useful context for understanding the challenges discussed throughout this section. The results suggest that Europe's issues are both structural and pedagogical, raising broader questions about how educational institutions worldwide can better prepare for disruptive technologies. To address these gaps and ensure that the quantum revolution's speed is not delayed by a lack of talent, proven tactics and best practices must be considered to guide future reforms.

Table 3. Comparative summary of quantum education and workforce strategies in the United States, China, and Europe

Dimension	United States	China	Europe
Policy framework	National Quantum Initiative Act (2018): legally binding, workforce-oriented (U.S. Congress, 2018)	14th Five-Year Plan: top-down integration of quantum education into national priorities (Shi, 2025; Mu et al., 2024)	EU Flagship & QTEdu: voluntary, guidance-based, no binding enforcement (Greinert et al., 2023; European Commission, 2024)
Curriculum integration	Quantum modules in K-12 (Q-12 Initiative), university-industry alignment (Q-12 Education Partnership, n.d.)	"Three New" curriculum in secondary schools, integration with engineering and computer science (Liu & Li,2023)	Uneven across member states; limited K-12 integration (Stadermann et al., 2019)
Industry-education linkages	QED-C ensures coordination between academia, firms, and government (QED-C, 2025)	Companies (Huawei, Baidu, Origin Quantum) provide cloud access and training (Zhang et al., 2023)	National projects exist but are fragmented; weak continent-wide industry-academia integration (Greinert et al., 2024; Li & Zhang, 2025)
Mobility & retention	Strong career pathways and competitive salaries retain talent (Fox et al., 2020)	Growing career opportunities, but some brain drain abroad (Zhu et al., 2024)	High student mobility (Erasmus+), but weak retention; many graduates move to the US/China (Greinert et al., 2023)

Source: Own work.

7 Challenges in Europe's quantum education system

This section reviews the main challenges to Europe's quantum education system, as identified in the literature: a lack of coordinated integration, fragmentation across member states, a weak industry-education linkage, limited early education and insufficient teacher training, as well as struggles to retain talent.

A lack of coordinated integration. A frequently mentioned issue in Europe's quantum education system is the lack of binding, continent-wide structures for coordinating courses and training. While initiatives like the EU Quantum Flagship and QTEdu offer broad guidance, they do not require member states to incorporate quantum courses into their national education systems, making implementation highly dependent on individual government priorities (Greinert et al., 2023; Li & Zhang, 2025). This contrasts with the United States, where the National Quantum Initiative Act (2018) established a legally binding national framework, and China, where quantum education is integrated into top-down national programs, such as the 14th Five-Year Plan (Mu et al., 2024). Europe's reliance on voluntary coordination has thus been cited as an obstacle to systemic reform, causing uncertainty for universities and training institutions.

Fragmentation across member states. The European higher education system is decentralised, with each country having autonomy over its own universities and degree programs, leading to significant fragmentation in the adoption of quantum education across member states (Greinert et al., 2023; Li & Zhang, 2025). Decentralisation does not always lead to uneven development; for example, both the United States and China have various universities and independent institutions. The main difference is that in Europe, the lack of formal structures for cooperation has resulted in discrepancies in how rapidly member states adopt quantum-related activities. While Germany, the Netherlands, and France have created sophisticated Master's and doctoral programs in quantum technology, other member states have made less progress. Furthermore, the lack of uniform accreditation standards makes it impossible to compare qualifications across borders. Although the European Competence Framework for Quantum Technologies (CF-QT) sets benchmarks, its adoption has been limited due to a lack of institutional enforcement. As a result, Europe faces difficulties in developing a standardised talent pipeline, making it more challenging to compete with China and the United States, which employ more coordinated methods (Stadermann et al., 2019).

Weak industry and education linkages. Another frequently mentioned issue is the insufficient link between higher education and industry in Europe. In the United States, the Quantum Economic Development Consortium (QED-C, 2025) exemplifies coordinated cooperation by bringing together businesses, colleges, and federal agencies to ensure that training programs are aligned with the needs of the workforce. In contrast, Europe has fewer organised programs of this nature, and many quantum graduates believe that their education was more research-oriented than industry-ready (Fox et al., 2020; Greinert et al., 2023). Although various national projects promote collaboration between academia and businesses, these activities are scattered rather than continent-wide (Li & Zhang, 2025). This lesser integration reduces graduates' immediate employability and limits the industry's willingness to invest in European quantum talent (Greinert et al., 2024).

Limited early education and teacher training. Europe is also falling behind in incorporating quantum concepts into K-12 education. While China's "Three-New" curriculum incorporates quantum principles into high school physics (Liu & Li, 2023), and the United States' Q-12 Education Partnership actively promotes teacher training (Q-12 Education Partnership, n.d.), most European countries have yet to systematically integrate quantum science into pre-university education. Teacher training is noticeably lacking, with few programs that educate educators to teach quantum topics in a clear and intelligible manner (Stadermann et al., 2019). Without considerable early exposure and good educators, the pool of expertise decreases, leaving quantum instruction to universities or postgraduate programs. This lack of early preparation hinders Europe's capacity to lay a solid foundation for quantum understanding (Greinert et al., 2023; Stadermann et al., 2019).

The mobility vs. retention challenge. Europe promotes student mobility through initiatives, such as Erasmus+ and joint master's programs in quantum technologies, which foster the sharing of cross-border knowledge and experience. However, this mobility does not always lead to the retention of talent in Europe. Many highly qualified graduates relocate to the United States or China, where career opportunities in the quantum industry are more structured and provide greater wages (Greinert et al., 2024; Mu et al., 2024). This creates a paradox: Europe invests extensively in education and training, yet a large proportion of its human capital is lost abroad. Without greater incentives, such as competitive salaries, clearer career paths, and a dynamic industrial ecosystem, Europe risks becoming simply a talent training ground, thereby strengthening its global competitors.

8 Discussion and conclusion

This study shows that the rapid development of quantum technologies has created a structural skills gap that education systems, companies, and governments must address. While the scientific advances are clear, the capacity to translate them into economic and societal benefits depends on whether a workforce with the right knowledge and skills can be developed.

A comparative perspective reveals important lessons. The United States has advanced through initiatives, such as the National Quantum Initiative Act (U.S. Congress, 2018), which tied federal funding to training programs and supported interdisciplinary graduate schools. China has pursued a different but equally ambitious path, combining massive state investment with the creation of dedicated university centres and company-university partnerships (Zhu et al., 2024). Both cases highlight that talent development must be embedded in national strategies rather than treated as an afterthought. Europe, in contrast, has strong research capabilities but lacks the same degree of integration between policy, education, and industry (Greinert et al., 2023). Based on these insights, several recommendations can be drawn.

- **For policymakers:** Funding mechanisms should explicitly support workforce training alongside research. National programs should incentivise cross-disciplinary education and foster international collaborations, similar to those found in the US graduate schools and China's state-backed university hubs.
- **For companies:** Industry must play a more active role in building talent pipelines. Good practices include IBM and Google providing cloud-based quantum platforms for student use in the US, and Alibaba's partnerships with Chinese universities. European firms could follow by offering internships, joint labs, and co-designed curricula.
- **For education institutions:** Curricula should be modernised to combine physics, computer science, and entrepreneurship, while also addressing misconceptions that persist even among advanced students (Müller & Wiesner, 2002; Taber, 2005; Singh, 2001). Examples include US initiatives to integrate quantum modules into computer science and engineering programs (National Science and Technology Council, 2022) and China's creation of specialised Master's tracks in quantum communication and sensing (Zhu et al., 2024).

The key lesson is that no single actor can solve the skills gap alone. Only a coordinated ecosystem — where governments provide strategic direction, companies build bridges to practice, and schools and universities update their curricula — can ensure that investments in quantum technologies deliver their full potential. By adopting proven practices from global leaders while tailoring them to local contexts, policymakers and institutions can help secure the workforce required for the second quantum revolution.

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Published by
Časnik Finance d. o. o.

Editors:
Polona Domadenik Muren, Matjaž Koman, Tjaša Redek

Reviewers:
Uroš Godnov, Janez Prašnikar

Proofreader:
Meta Česnik

Technical Editor:
Ciril Hrovatin

Graphic Designer:
Ciril Hrovatin

Cover Designer:
Jera Jakše

Printed by
Aktiv PR d.o.o.

CEO of Časnik Finance:
Peter Frankl

Editor-in-Chief of Časnik Finance:
Simona Toplak

First printing

Ljubljana, November 2025

Circulation: 500 copies

In accordance with the amendment to the Value Added Tax Act (ZDDV-L Act, published in the Official Gazette of the Republic of Slovenia No. 72/19), the book belongs to products for which a special reduced VAT rate of 5% from 1 January 2020 is charged.

Editors:
Polona Domadenik Muren, Matjaž Koman, Tjaša Redek