Co-designing future pathways for a sustainable society: mapping systemic risks and opportunities in the green transition of the shipping sector

Three impact stories from the RRF project GYROSCOPE

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Introduction

The maritime sector is entering a period of profound transformation. Driven by global climate targets and advancing regulation from actors such as the EU and the International Maritime Organization (IMO), shipping is under growing pressure to reduce emissions and transition toward climate neutrality. At the same time, the sector is undergoing rapid technological change. Alternative fuels and other power sources, digital systems with AI, and increasingly autonomous vessels are reshaping how maritime transport operates – and how it may look in the decades to come.

Yet these developments are not unfolding in a vacuum.

Shipping is a capital-intensive and infrastructure-bound industry, shaped by long investment cycles, established practices, and tightly interconnected global value chains. Changes in fuel systems, operational technologies, labour structures, or digital capabilities rarely affect only one part of the system. Instead, they ripple across ports, fairways, service infrastructure, logistics networks, regulatory frameworks, workforce requirements, and environmental systems – often in ways that are difficult to anticipate in advance.

This makes the maritime sustainability transition not merely a technical challenge, but a systemic one.

History shows that well-intended technological solutions can unintentionally shift environmental burdens from one domain to another – from air to water, from local ecosystems to global supply chains, or from short-term gains to long-term risks. Today, the accelerating push for decarbonisation through alternative power sources, automation, and digital optimisation brings similar uncertainties (Altarriba et al., 2025; de Jong et al., 2025; Kauppi & Lehikoinen). How might new fuels affect marine environments across their lifecycle? What new vulnerabilities emerge as navigation and traffic management become increasingly data-dependent? How should regulatory systems respond when technological capabilities outpace international legal frameworks, as is already the case with autonomous vessels?

At the same time, decision-makers across industry and policy face a strategic fog: uncertainty about future regulation, infrastructure availability, technological standards, and market demand. Investments made today – in vessels, fuels, ports, or digital systems – may shape operational possibilities for decades to come.

Navigating this transition therefore requires more than incremental emission reductions or isolated technical innovations. It calls for improved collective capacity to anticipate long-term developments, understand interconnected risks and opportunities, and evaluate

transition pathways across environmental, social, economic, and technological dimensions.

The GYROSCOPE project set out to address this challenge.

By combining stakeholder-participatory foresight processes with systems-analytical risk assessment methods and scenario exploration, the project aimed to build a multidimensional understanding of the opportunities and risks associated with the green transition in maritime logistics. Beyond producing new knowledge, GYROSCOPE sought to strengthen the capacity of maritime stakeholders to engage in collective planning under uncertainty – recognising sustainability transition not as a sequence of isolated technical fixes, but as a complex socio-technical transformation unfolding over time.

The following impact storylines illustrate, through case examples, how the objectives were pursued and how they were achieved: what changed – and what may continue to change – as a result of our project.

Impact storyline 1: When fixing one problem creates another

In recent decades, reducing sulfur emissions from shipping became a global environmental priority. Engineers found a solution. Ships could install exhaust gas cleaning systems – scrubbers – that remove sulfur compounds from exhaust gases by washing them with seawater. The sulfur would no longer enter the atmosphere.

Problem solved.

Except it wasn't.

In many scrubber systems, the wash water is discharged back into the sea – now containing the very same sulfur compounds and other contaminants regulators originally sought to keep out of the environment. What began as a solution to air pollution quietly shifted the problem elsewhere, from the atmosphere into marine ecosystems.

Years later, regulators are still grappling with how to respond. Shipowners have made costly investments in technologies that may now be phased out. And the maritime sector has learned a difficult lesson: solving one sustainability challenge in isolation can create new risks somewhere else. To make matters even more complex and paradoxical, it was recently noticed that due to the reduced sulfur emissions, the planet briefly warmed faster – because the disappearance of reflective sulfur aerosols removed a masking effect that had earlier been preventing part of the incoming solar radiation reaching Earth's surface.

Today, global shipping stands at the threshold of another major transformation. Driven by climate targets, the sector is exploring alternative fuels, digital technologies, and new operational practices to reduce greenhouse gas emissions. Hydrogen, methanol, ammonia, electrification, automation – all promise cleaner futures.

But they also raise new questions:

What sustainability impacts might the production of alternative fuels have?

What safety risks emerge when storing or transporting them?

How will ports need to change?

What infrastructure investments are safe to make – and which might become stranded assets?

Ships, ports, and fuel infrastructures are built to last for decades. Investment decisions made today will shape operational possibilities far into the future. At the same time, the regulatory landscape is evolving, technologies are still maturing, and global energy markets remain uncertain. Many actors are navigating what could be described as a strategic fog: knowing that change is necessary, but unsure which pathways are genuinely sustainable – environmentally, economically, or socially.

This is where the GYROSCOPE project stepped in.

Rather than asking how to optimize individual technological solutions, the project asked a different question:

What needs to happen for the maritime green transition to be sustainable as a whole system?

In 2024, the GYROSCOPE consortium invited experts from industry, governance, and academia into a series of co-creation workshops to explore this question together. Initial hesitation among invitees revealed something important: understanding the sustainability implications of future maritime fuels is not possible for any single actor alone.

Once reassured that holistic prior knowledge was not required, participants joined the discussions. Together, they mapped the possible impacts of alternative fuels across their production, distribution, and use. They examined sustainability not only in terms of emissions, but also safety risks, infrastructure needs, workforce implications, and long-term investment uncertainty.

Risks that typically remain at the margins of strategic planning began to move into view.

- Environmental trade-offs between air and water impacts.
- Infrastructure bottlenecks in hydrogen distribution.
- Skill gaps related to digital vessel operations.

- Uncertainties regarding future regulation or fuel availability.

Participants reported that the greatest value of the workshops was not any single insight, but the opportunity to see how their own limited knowledge interacted with the insights of others and became connected to a broader socio-ecological-technological system through which sustainability is either achieved or put at risk.

Business cards were exchanged. Seeds of new potential partnerships were planted.

At this point, the project researchers took their next step. The joint insights of the stakeholders and experts were translated into different kinds of system representations. By structuring their thinking into visual maps of relationships, dependencies, and feedbacks, the project sought not to replace expert

judgement with models, but to make collective thinking visible and analyzable.

These system representations became tools for reflection and methodological development (Lehikoinen et al., 2025; Bahoo-Toroody et al.; Luoma et al.; Nikkanen et al.).

Structuring and modelling stakeholders' reflection on how investment decisions, infrastructure development, regulatory uncertainty, workforce capabilities, and fuel supply chains might interact over time, made new patterns to emerge. Some risks that had previously appeared isolated turned out to be structurally connected. Certain assumptions about transition pathways proved mutually reinforcing – or mutually constraining. In some cases, changes in one part of the system appeared capable of influencing developments elsewhere.

Through these processes, researchers were able to identify potential leverage points: areas where targeted interventions – technological, operational, or regulatory – might alleviate systemic bottlenecks or support more resilient transition pathways. Both collaborative knowledge construction among people and the systems analytical insights gained through modelling their thinking helped improve the shared situational picture among participants and analysts, enabling them to collectively reflect on where attention and resources might best be directed in order to support a sustainable maritime green transition.

In the short term, the workshops helped the participants strengthen their networks and allowed co-learning. The visualisation of interdependencies immediately supported collective sense-making and helped actors identify areas where additional knowledge, dialogue, investments, and regulation are needed. The systems analytical outputs – when published – will likely help all stakeholders better recognize system-level risks and opportunities associated with green transition – enabling more robust planning and decision-making.

In the medium term, new connections and shared understanding created may facilitate interdisciplinary RDI collaborations and more coordinated experimentation across organisational boundaries. The tested systems-analytical approaches for structuring and analysing stakeholder knowledge may also support the development of shared situational awareness in future transition-related planning processes.

In the long term, further development and application of such approaches may help decision-makers in maritime transport and beyond to collaboratively explore transition scenarios, anticipate unintended consequences, and identify interventions that improve safety, resilience, and sustainability at the system level. By making collective assumptions and dependencies explicit, these methods may support governance processes that are better equipped to navigate complex sustainability transformations across sectors.

Why does this matter?

Ensuring that green transition pathways are genuinely sustainable requires more than technological innovations; it requires the ability of diverse actors to build a shared understanding of complex transition systems and to coordinate action under uncertainty. By supporting knowledge co-production and by developing and testing methods for visualising and analysing collectively produced insights, the project contributed to new ways of navigating sustainability transitions. Without such shared situational awareness, well-intentioned investments risk reinforcing new forms of lock-in or shifting environmental and safety burdens elsewhere. Conversely, approaches that help stakeholders jointly identify leverage points within complex entities enable more resilient and cost-effective decision-making – not only in maritime transport, but also in other infrastructure-dependent sectors undergoing similarly profound sustainability transformations.

Impact storyline 2: Who moves first? The lock-in of the maritime green transition

Despite growing political commitment to decarbonization, the green transition and hydrogen-derived fuels is something that always seems to remain just out of reach. The conversations with maritime sector stakeholders during the interviews and workshops of the project started to reveal a tension between different actors. Shipping companies hesitate to invest in vessels capable of using alternative fuels without confidence that those fuels would be available on a scale. Energy producers and ports, in turn, are reluctant to invest in infrastructure without credible demand from vessel operators. Further, regulators are still in the process of defining future rules, leaving all sides uncertain

about which fuel pathways would ultimately prove viable. Finally, each actor appears to be waiting for someone else to move first.

We noticed that these individually sensible decisions form a paralysing dynamic, a catch-22 situation: the risk to transitioning to alternative fuels in maritime logistics is a lock-in involving overly cautious demand for alternative fuels leading to overly cautious investment in supply, which only secures the modest demand. In this Catch-22 situation uncertainty itself becomes the primary barrier to change. By analysing the emerging hydrogen hype, we were able to identify the systemic nature of this dilemma. The question was no longer simply which alternative fuel should be prioritised, but how the interdependencies between infrastructure, regulation, markets, and operational practices might be reshaped so that transition decisions could be made in the first place. Our analysis suggests the following two ways out of the systemic dilemma and for breaking the lock-in situation: large-scale technological innovations and global regulatory solutions.

One pathway lies in the large-scale technological solutions that can break the market logic of the loop. Large shipping companies investing in multi-fuel vessels and securing long-term fuel supply agreements can work as pioneers and show the direction to take in the maritime green transition. Such moves can alter perceived risks across the system by signalling commitment and creating early demand that enables infrastructure development. The other pathway lies in regulatory action at the international level, capable of reducing uncertainty by aligning incentives and redefining the conditions under which transition investments are made.

Neither of these approaches offers a guaranteed solution. Yet the absence of both would likely leave the sector locked into incremental change, a trajectory misaligned with the urgency of international climate targets. From a systems perspective, the greatest risk may therefore lie not in choosing the wrong technological pathway, but in postponing collective commitment until the opportunity for timely transition has passed.

What may change following the increased understanding and scientific documentation of this analysis (by Janasik et al. 2025)?

In the short term, the findings help shift attention from purely technological feasibility towards the systemic interdependencies that shape transition risks in maritime decarbonisation. By making visible the Catch-22 dynamic between fuel supply, vessel investments, and regulatory uncertainty, the analysis provides policymakers, infrastructure developers, and shipping companies with a more realistic understanding of why rational individual decisions may collectively delay sustainability transitions. This may support more informed policy preparation, investment strategies, and stakeholder dialogue by explicitly recognising transition risks that arise from coordination failures rather than technological limitations alone.

In the medium term, uptake of these insights may contribute to improved alignment between energy, transport, and regulatory planning processes. Recognising the lock-in dynamics embedded in infrastructure development and fuel adoption pathways can encourage anticipatory governance approaches, including risk-sharing mechanisms, coordinated pilot investments, or regulatory signals designed to reduce strategic waiting behaviour. This, in turn, may facilitate earlier experimentation with multi-fuel vessels, alternative fuel supply chains, and digitally enabled operational solutions that reduce uncertainty across maritime logistics systems.

In the long term, integrating systemic transition risks into governance frameworks may help avoid self-reinforcing investment gaps that would otherwise slow or stall the adoption of low-carbon fuels in maritime transport. By supporting collective commitment under conditions of uncertainty, such approaches can enable decarbonisation pathways that are not only technically feasible but institutionally robust and economically viable. Beyond the maritime sector, recognising similar coordination dilemmas may inform sustainability transitions in other complex socio-technical systems where infrastructure, markets, and regulation must evolve simultaneously.

Why does this matter?

Breaking the identified lock-in is critical for enabling the timely adoption of hydrogen-derived and other low-carbon fuels in maritime logistics, and thereby for achieving international climate targets. More broadly, the research highlights how transition risks emerge not only from technological uncertainty, but from the interdependence of decisions made by multiple actors operating under incomplete information.

Addressing such systemic dilemmas requires governance approaches capable of coordinating investments, aligning incentives, and managing uncertainty across sectors and scales. Without such coordination, rational short-term risk avoidance may lead to collectively suboptimal outcomes – delaying decarbonisation and increasing long-term societal risks associated with climate change. Conversely, embedding systems-level foresight into transition governance can strengthen resilience and support more timely sustainability transformations across infrastructure-dependent sectors of society.

Impact storyline 3: From research to action guidelines

Towards the end of the project, the GYROSCOPE consortium paused to ask a simple but crucial question: *What should be done differently now that we know what we know?*

Drawing on the project's interdisciplinary research and stakeholder engagement, the consortium consolidated its research-based policy and action recommendations under three key statements. These focused on the need for anticipatory and cross-sectoral governance of the maritime energy transition, the importance of recognising sustainability trade-offs in alternative fuel pathways, and the role of regulation not merely as a limiting force, but as a strategic enabler of innovation and long-term systemic change.

The resulting policy brief document was published in both Finnish and English (GYROSCOPE consortium, 2025) to support uptake among policymakers, industry actors, and international stakeholders navigating the uncertain terrain of maritime decarbonisation. Rather than offering prescriptive solutions for individual actors, the document translates GYROSCOPE's analytical insights into *guiding principles* for decision-making and strategic planning *across society as a whole*.

In the immediate future, these guidelines can help decision-makers see risks that might otherwise remain hidden in the margins of planning processes. For example, solutions that optimise emissions performance in the short term may introduce new environmental pressures elsewhere, or that create high-risk operational dependencies on data infrastructures whose vulnerabilities are only beginning to be understood. Paying attention to such trade-offs early on can support more informed regulatory preparation and investment decisions at a time when many actors are navigating technological options under considerable uncertainty.

In the medium term, as experimentation with new fuels, smart operational systems, and autonomous technologies progresses, the guidelines may also encourage closer coordination between policy domains that have traditionally evolved in parallel – such as transport, energy, and environmental governance. Viewing the maritime transition through a systemic lens can help ensure that advances in decarbonisation do not inadvertently introduce new safety risks, workforce challenges, or cybersecurity concerns, but instead contribute to innovation ecosystems in which technological development is aligned with broader sustainability objectives.

Over time, such an approach may gradually reshape how sustainability transitions in maritime transport – and beyond – are governed. Rather than responding to emerging challenges one by one, institutions may become better equipped to anticipate the interconnected effects of energy transition and digital transformation as they unfold together. In the long run, this can reduce the risk of repeating familiar transition pitfalls and support the emergence of decarbonisation pathways that are not only low-carbon, but also resilient, safe and secure, and socially legitimate in increasingly automated and data-intensive maritime systems.

To conclude

Ultimately, the GYROSCOPE project demonstrated that embedding systems-level foresight into maritime transition governance is not only about managing risks and opportunities in shipping, but about learning how to steer complex sustainability transformations more broadly. The lessons learned and recurring patterns identified throughout the project – related to uncertainty, cross-sectoral interdependencies, technological lock-ins, and unintended sustainability trade-offs – are not unique to maritime transport. Rather, they are characteristic of many ongoing green and digital transitions across society. As such, the approaches developed and insights gained within GYROSCOPE are relevant well beyond the maritime domain, offering transferable value for navigating systemic change in other sectors facing similarly complex socio-technical challenges.

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