

Adaptive Technology Roadmapping for Decision-Making Under Uncertainty in Hydrogen Import Infrastructure

Integrating Dynamic Adaptive Policy Pathways into Technology Roadmapping
and applying it to the Canada-Netherlands hydrogen import corridor

MSc Thesis

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Adaptive Technology Roadmapping for Decision-Making Under Uncertainty in Hydrogen Import Infrastructure

**Integrating Dynamic Adaptive Policy Pathways into Technology
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hydrogen import corridor**

by

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Cover: Green hydrogen production facility concept ("Green hydrogen factory concept", 2023)

Preface

In front of you lies my Master's thesis, which explores the role of adaptive technology roadmapping in the context of the hydrogen transition. The energy transition has long been close to my personal interests because of its urgency, scale, and complexity, an interest that only deepened through this work. This research also introduced me to something new: the world of roadmapping and adaptive decision-making. I came to appreciate approaches that do not assume the future can be predicted, but instead help structure action under uncertainty. Looking back, that perspective also shaped how I learned to navigate the thesis process itself. Developing a new method meant accepting that not everything would be clear from the start, and trusting that clarity would emerge through sustained work and refinement. That lesson extends beyond research to the energy and hydrogen transitions, where political volatility, infrastructure delays, and slow market formation can make it easy to lose hope. Yet uncertainty is part of the process, and it is precisely for that reason that we must continue turning ambition into action, learning as we go, and adapting as the context evolves.

I am very grateful to my supervisor, Shubham, who consistently took the time to engage with my questions in depth. Beyond his guidance on the content, he showed me how to approach academic research, and his encouragement made the thesis process far more manageable, especially when I struggled to see the way forward. I also thank Martijn and Daan for their constructive feedback and motivating words throughout the thesis meetings. Lastly, I would like to thank Robin and Peter for giving me the opportunity to conduct this thesis at Haskoning. Their support added significant value to this work, not only by sharing insights into how complex infrastructure and transition projects are executed in practice, but also by connecting me with relevant professionals who were willing to be interviewed.

This thesis marks the end of my Master's degree in Construction Management & Engineering, and with that, the end of my time as a student at TU Delft. I am excited for what comes next, taking the lesson to engage with uncertainty rather than avoid it with me. I enjoyed writing this thesis, and I hope you enjoy reading it too.

Julia Brink
Delft, February 2026

Executive Summary

Under the EU's 2050 climate-neutrality goal, green hydrogen is central to decarbonising hard-to-abate sectors. Connecting low-cost green hydrogen supply to demand is therefore crucial. However, across national plans worldwide, around 45 MT of hydrogen production capacity is targeted for 2030, and only 6 MT has advanced to final investment commitments, showing the gap between ambition and implementation. The province of Newfoundland and Labrador in Canada offers strong wind resources and export potential, while the port of Rotterdam in the Netherlands is a logical import hub given its existing terminals, repurposable pipelines, and connections to Northwest European industry. Building a hydrogen import corridor between Canada and the Netherlands requires coordinated action across the value chain under substantial technological, market, and policy uncertainty.

In this setting, Technology Roadmapping helps map what needs to happen, when, and under which conditions, to move a corridor from plans to implementation. In practice, however, roadmaps are often used in a relatively static manner: they describe a preferred sequence of steps, but do not specify how commitments should change when dependencies do not co-evolve or when assumptions no longer hold. This study addresses that gap by integrating an approach explicitly designed for planning under uncertainty, Dynamic Adaptive Policy Pathways, into Technology Roadmapping to support adaptive, system-level decision-making for hydrogen import infrastructure. This leads to the following main research question:

"How can Dynamic Adaptive Policy Pathways be used to make Technology Roadmapping adaptive and systemic, and what insights does this provide for the development of hydrogen import infrastructure?"

Drawing on the literature on decision-making under uncertainty, Dynamic Adaptive Policy Pathways was selected as a complement to system-level Technology Roadmapping because it adds concepts that make a roadmap adaptive:

Key concepts

- **Pathways:** Possible routes across different futures. A roadmap can show these options and fill each route with actionlines and milestones to show how it would be implemented.
- **Decision points:** Moments when a choice must be made to continue or switch route. A roadmap can place these at milestones, when major commitments are due.
- **Adaptation tipping points:** Moments when a route can no longer meet success. A roadmap can show where a route stops working under certain conditions.
- **Signposts:** Conditions to monitor to see whether they are improving or worsening. This keeps the roadmap connected to how conditions evolve over time.
- **Triggers:** Thresholds for signposts linked to decision points that guide the choice whether to continue or adjust the route. This makes adaptation in the roadmap concrete.
- **Contingency actions:** Actions prepared in advance for what to do if conditions develop differently. This avoids ad hoc decision-making when using the roadmap.
- **Sell-by dates:** The latest moment when an actionline or decision still makes sense for a route. This makes timing limits explicit in the roadmap.

Integrating Dynamic Adaptive Policy Pathways with Technology Roadmapping results in a new approach, termed Adaptive Technology Roadmapping in this study. Technology Roadmapping provides

the roadmap structure by sequencing actionlines and milestones over time across key parts of the system. Dynamic Adaptive Policy Pathways adds explicit adaptivity by mapping multiple routes, defining decision points, and linking those decisions to signposts and triggers, so commitments can be adjusted as conditions evolve.

The resulting Adaptive Technology Roadmapping approach consists of four steps, which are illustrated through a case study of the Canada-Netherlands hydrogen import corridor. Data collection combined interviews with key actor groups to identify vulnerabilities and opportunities for corridor development, supported by desk research to contextualise and substantiate interview insights. The full dataset was analysed in ATLAS.ti using the Gioia method to derive themes and higher-level dimensions that capture the corridor's system dynamics. These empirical findings were then used to apply and illustrate each of the four Adaptive Technology Roadmapping steps:

- 1. Define system scope:** Defines the wider set of connected systems that together shape outcomes, as well as the operational system, meaning the part where the roadmap focuses interventions and decisions. It also determines the planning horizon, the actor for whom the roadmap is developed and what "success" means. The corridor can be structured as four interconnected systems: production and export in Newfoundland and Labrador, transatlantic shipping, import infrastructure around Rotterdam and the hinterland, and demand in Northwest Europe. The roadmap focused on a project developer in Newfoundland and Labrador, producing green hydrogen and converting it into ammonia for export. Success meant being able to justify continued commitment through to 2060 by keeping the project safe, compliant, financeable, and market-eligible.
- 2. Develop evidence base & default plan:** Develops an evidence base of opportunities and vulnerabilities across the wider set of systems and translates them into what the actor can control, influence (through coordination), or is exposed to. From this, a basic plan and adaptation tipping points are developed: the actions the actor should keep doing across different possible futures and limits for when the plan no longer makes sense. In the Canada-Netherlands corridor, the developer mainly controls upstream design and execution, while most corridor-critical conditions depend on other actors, notably offtake, permitting, certification, and import-side infrastructure. It also defined two adaptation tipping points: one before the final investment decision, when enabling conditions do not converge, and the project cannot move into construction, and one after the final investment decision, when the project can no longer operate safely, compliantly, or commercially, making continued operation unjustifiable.
- 3. Construct roadmap:** Turns the basic plan into a visual step-by-step plan over time. It organises the work into actionlines and milestones, and combines these into pathways that show different routes, mainly varying by scale and the pace of scale-up. It also adds decision points at milestones, so the roadmap shows when the project can continue, slow down, scale up, scale down, or stop by switching pathways. In the Canada-Netherlands corridor, the roadmap shows several phased scale-up pathways, from smaller early phases to faster expansion, and also includes pathways for downscaling or project run-off. It marks the main decision points at milestones where choices become hard to reverse, notably the initial project configuration, major investment commitments, and expansion decisions after start-up, and it adds sell-by dates to show when these choices remain realistic.
- 4. Enable adaptation plan:** Adds the adaptive layer that keeps the roadmap usable as conditions change. It defines signposts to track conditions, translates these into triggers with IF-THEN thresholds, and links them to decision points to guide decision-making. It also specifies contingency actions in advance, including when to reassess the underlying plan if core assumptions no longer hold. In the Canada-Netherlands corridor, this produced an adaptation plan that monitors corridor dependencies, notably offtake, permitting and social acceptance, certification eligibility, financeability, deliverability, and import-chain accessibility, with thresholds tied to decision points and linked to pathways, showing when phased expansion is justified and when delaying, downscaling, or switching is the better option. It also included two reassessment options: revisiting the hydrogen carrier choice and revisiting the market focus if enabling conditions do not align.

Applying Adaptive Technology Roadmapping shows why hydrogen import infrastructure needs systemic and adaptive planning. Progress is often delayed by mutual dependencies: projects only become

financeable with long-term offtake, while offtake depends on uncertain policy support; fragmented certification and regulation create uncertainty about eligibility and market access, which affects upstream design choices; and European backbone and hinterland infrastructure can come later than upstream projects, reinforcing wait-and-see behaviour. Therefore, the challenge is not choosing one best end-state, but staging commitments so they stay feasible as technologies, markets, and policies evolve, using decision points guided by signposts and triggers to avoid building too early, too large, or in the wrong configuration. Phased and modular scaling then enables adaptivity as it allows smaller, partly reversible steps before committing to full scale, while some enabling choices must be settled early and can later restrict expansion, notably the permitting scope and port design. As hydrogen corridors are largely policy-driven, many decision points depend on whether policy conditions are in place. Adaptive Technology Roadmapping makes this visible by showing what policy needs to deliver to unlock progress: stronger demand through mandates and incentives, clear and consistent certification, import infrastructure with investable early tariffs, faster and more predictable permitting where possible, and public risk-sharing to make first projects financeable.

An evaluation of the Adaptive Technology Roadmapping approach highlights its limitations. Adaptation is based on an initial set of vulnerabilities and opportunities; if these shift, Adaptive Technology Roadmapping needs an explicit update loop to remain relevant. In addition, Adaptive Technology Roadmapping can produce many signposts at once, but would benefit from showing which ones matter most or how to handle conflicting signals, so choices can remain clear. Lastly, a single roadmap graphic can appear more schedule-like and complete than corridor processes really are, which can create unrealistic expectations, needing coordination rounds.

With the limitations acknowledged, comparing Adaptive Technology Roadmapping with traditional Technology Roadmapping also makes its added value clear: it supports decision-making under uncertainty by not only showing what to do, but also when and how to adapt when conditions change. It does so by laying out alternative pathways and linking commitments to monitored triggers, so actors can decide to adjust the pathway based on how conditions evolve. This is useful for planning hydrogen import infrastructure because it addresses a highly interdependent value chain where different parts progress at different speeds: it shows which steps the infrastructure project can move forward with now, which steps should wait until the main dependencies are in place, and how the project can scale up over time through modular expansion. In this way, Adaptive Technology Roadmapping makes a roadmap usable as a decision guide for long-lead, high-commitment hydrogen infrastructure projects where timing, interdependence, and uncertainty determine whether the next step is justified, helping to close the gap between the large ambitions for hydrogen corridors and implementation.

Managementsamenvatting

Onder de klimaatneutraliteitsdoelstelling van de Europese Unie voor 2050 is groene waterstof cruciaal voor het verduurzamen van sectoren die moeilijk te decarboniseren zijn. Het verbinden van aanbod van goedkope groene waterstof met vraag is daarom essentieel. Wereldwijd in nationale plannen is ongeveer 45 Mt aan waterstofproductiecapaciteit voorzien voor 2030, terwijl slechts 6 Mt is doorgegaan tot definitieve investeringsbesluiten, wat de kloof tussen ambitie en uitvoering laat zien. De Canadese provincie Newfoundland and Labrador beschikt over sterke windbronnen en exportpotentieel, terwijl de haven van Rotterdam in Nederland een logisch importknooppunt is gezien de bestaande terminals, herbruikbare pijpleidingen en verbindingen met industrie in Noordwest-Europa. Het opbouwen van een waterstofimportcorridor tussen Canada en Nederland vraagt om gecoördineerde actie over de hele waardeketen, onder aanzienlijke technologische, markt- en beleidsonzekerheid.

In deze context helpt Technology Roadmapping om in kaart te brengen wat er moet gebeuren, wanneer en onder welke voorwaarden om een corridor van plannen naar uitvoering te brengen. In de praktijk worden roadmaps echter vaak relatief statisch gebruikt: ze beschrijven een voorkeursvolgorde van stappen, maar maken niet expliciet hoe commitments moeten veranderen wanneer afhankelijkheden niet samen ontwikkelen of wanneer aannames niet langer standhouden. Deze studie adresseert dat hi-aat door een aanpak die expliciet is ontworpen voor plannen onder onzekerheid, Dynamic Adaptive Policy Pathways, te integreren in Technology Roadmapping om adaptieve, systeembrede besluitvorming voor waterstofimportinfrastructuur te ondersteunen. Dit leidt tot de volgende hoofdonderzoeksvraag:

“Hoe kan Dynamic Adaptive Policy Pathways worden gebruikt om Technology Roadmapping adaptief en systeembreed te maken, en welke inzichten levert dit op voor de ontwikkeling van waterstofimportinfrastructuur?”

Gebaseerd op de literatuur over besluitvorming onder onzekerheid is Dynamic Adaptive Policy Pathways gekozen als aanvulling op Technology Roadmapping, omdat het concepten toevoegt die een roadmap adaptiever en besluitgericht maken:

Kernbegrippen

- **Adaptatiepaden:** Mogelijke routes richting succes onder verschillende toekomsten. Een roadmap kan deze opties tonen en elke route invullen met actielijnen en mijlpalen om te laten zien hoe de uitvoering eruitziet.
- **Beslismomenten:** Momenten waarop een keuze nodig is om door te gaan of van route te wisselen. Een roadmap kan deze koppelen aan mijlpalen wanneer grote commitments aan de orde zijn.
- **Adaptatie-kantelpunten:** Momenten waarop een route niet langer aan het succescriterium kan voldoen. Een roadmap kan laten zien onder welke omstandigheden een route niet werkt.
- **Signalen:** Conditie die worden gevolgd om te zien of zij verbeteren of verslechteren. Dit houdt de roadmap verbonden met hoe omstandigheden zich in de tijd ontwikkelen.
- **Drempels:** Concrete grenswaarden voor signalen, gekoppeld aan beslismomenten, die bepalen of de route moet worden aangepast. Dit maakt adaptatie in de roadmap concreet.
- **Uitwijkacties:** Acties die klaarstaan voor wat te doen als omstandigheden anders uitpakken. Dit voorkomt het improviseren bij het gebruik van de roadmap.
- **Uiterste data:** Het laatste moment waarop een actielijn of beslissing nog zinvol is binnen een route. Dit maakt tijdslijnen in de roadmap expliciet.

Het integreren van Dynamic Adaptive Policy Pathways met Technology Roadmapping resulteert in een nieuwe aanpak, die in deze studie Adaptive Technology Roadmapping wordt genoemd. Technology Roadmapping levert de roadmapstructuur door actielijnen en mijlpalen in de tijd te ordenen over alle delen van het systeem. Dynamic Adaptive Policy Pathways voegt expliciete adaptiviteit toe door meerdere routes te beschrijven, beslismomenten te definiëren en die beslissingen te koppelen aan signalen en drempels, zodat commitments kunnen worden aangepast naarmate omstandigheden veranderen.

De resulterende Adaptive Technology Roadmapping-aanpak bestaat uit vier stappen, die in deze studie worden geïllustreerd aan de hand van een casestudy van de Canada-Nederland waterstofimportcorridor. De dataverzameling combineerde interviews met belangrijke actorgroepen om kwetsbaarheden en kansen voor corridorontwikkeling te identificeren, aangevuld met desk research om interviewinzichten te contextualiseren en te onderbouwen. De volledige dataset is in ATLAS.ti geanalyseerd met de Gioia-methode om thema's en hogere-orde-dimensies af te leiden die de systeemdynamiek van de corridor weergeven. Deze empirische bevindingen zijn vervolgens gebruikt om elk van de vier stappen van Adaptive Technology Roadmapping toe te passen en te illustreren:

1. **Systeemaafbakening:** Bepaalt de bredere set verbonden systemen die samen de uitkomsten vormen en definieert ook het operationele systeem: het deel waarop de roadmap de interventies en beslissingen richt. Daarnaast worden de planninghorizon, de actor voor wie de roadmap is ontwikkeld en de definitie van "succes" vastgelegd. De corridor kan worden gezien als vier onderling verbonden systemen: productie en export in Newfoundland and Labrador, transatlantische scheepvaart, importinfrastructuur rond Rotterdam en het achterland, en vraag in Noordwest-Europa. De roadmap richtte zich op een projectontwikkelaar in Newfoundland and Labrador die groene waterstof produceert en deze omzet in ammoniak voor export. Succes betekent dat een voortgezette commitment tot en met 2060 verdedigbaar blijft door het project veilig, regelconform, financieerbaar en markttoelaatbaar te houden.
2. **Kennisbasis & basisplan:** Bouwt een kennisbasis op van kansen en kwetsbaarheden in de bredere set systemen en vertaalt die naar wat de actor kan controleren, kan beïnvloeden (via coördinatie) en waar de actor geen invloed op heeft. Daaruit worden een basisplan en adaptatiekantelpunten afgeleid: acties die de actor in verschillende mogelijke toekomst moet blijven uitvoeren en grenzen waarboven het plan niet langer zinvol is. In de Canada-Nederland corridor controleert de ontwikkelaar vooral het ontwerp en de uitvoering van de productie, terwijl de meeste corridor-kritieke condities afhangen van andere actoren, met name afname, vergunningen, certificering en importinfrastructuur. Ook werden twee adaptatie-kantelpunten gedefinieerd: één vóór het definitieve investeringsbesluit, wanneer randvoorwaarden niet samenkomen en het project niet naar de bouwfase kan, en één ná het definitieve investeringsbesluit, wanneer het project niet langer veilig, regelconform of commercieel kan opereren, waardoor voortzetting niet langer te rechtvaardigen is.
3. **Roadmap opstellen:** Zet het basisplan om in een visuele stap-voor-stap planning in de tijd. Het organiseert het werk in actielijnen en mijlpalen en combineert die tot routes die verschillende adaptatiepaden laten zien, vooral variërend in schaal en tempo van opschaling. Het voegt ook beslismomenten gerelateerd aan mijlpalen toe, zodat de roadmap laat zien wanneer het project kan doorgaan, vertragen, opschalen, afschalen of kan stoppen door van adaptatiepad te wisselen. In de Canada-Nederland corridor toont de roadmap meerdere gefaseerde opschalingsroutes, van kleinere vroege fases tot snellere expansie, en bevat ook routes voor afschalen of gecontroleerde uitfasering. Het markeert de belangrijkste beslismomenten op mijlpalen waar keuzes moeilijk terug te draaien zijn, met name de initiële projectconfiguratie, grote investeringscommitments en uitbreidingsbeslissingen na start-up, en het voegt uiterste data toe om te laten zien tot wanneer deze keuzes mogelijk blijven.
4. **Adaptatieplan inrichten:** Voegt de adaptatieve laag toe die de roadmap bruikbaar houdt als omstandigheden veranderen. Het definieert signalen om condities te volgen, vertaalt deze naar drempels met ALS-DAN-regels en koppelt ze aan beslismomenten om keuzes te ondersteunen. Het specificeert ook uitwijkacties, inclusief wanneer het onderliggende plan opnieuw moet worden beoordeeld als kernveronderstellingen niet langer gelden. In de Canada-Nederland corri-

dor leverde dit een adaptatieplan op dat corridorafhankelijkheden volgt, met name afname, vergunningen en maatschappelijke acceptatie, certificeringsgeschiktheid, financierbaarheid, leverbaarheid en toegankelijkheid van de importketen, met drempels die zijn gekoppeld aan beslismomenten en verbonden aan adaptatiepaden. Dit laat zien wanneer gefaseerde expansie gerechtvaardigd is en wanneer uitstellen of afschalen de betere optie is. Daarnaast bevatte het twee resetopties: het heroverwegen van de waterstofdrager en het heroverwegen van de marktoriëntatie als randvoorwaarden niet op elkaar aansluiten.

Het toepassen van Adaptive Technology Roadmapping laat zien waarom waterstofimportinfrastructuur systeembrede en adaptieve planning nodig heeft. Vooruitgang wordt vaak vertraagd door wederzijdse afhankelijkheden: projecten worden pas financierbaar met langlopende afname, terwijl afname afhankelijk is van onzekere beleidssteun; gefragmenteerde certificering en regelgeving creëren onzekerheid over geschiktheid en markttoegang, wat productieontwerpkeuzes beïnvloedt; en aansluitende infrastructuur in het achterland kan later komen dan productieprojecten, waardoor afwachtgedrag wordt versterkt. Daarom is de uitdaging niet het kiezen van één beste eindbeeld, maar het faseren van commitments zodat zij haalbaar blijven naarmate technologieën, markten en beleid veranderen, met beslismomenten die worden gestuurd door signalen en drempels om te voorkomen dat er te vroeg, te groot of in de verkeerde configuratie wordt gebouwd. Gefaseerde en modulaire opschaling maakt adaptiviteit mogelijk doordat het kleinere, deels aanpasbare stappen toestaat voordat op volledige schaal wordt vastgelegd, terwijl sommige randkeuzes vroeg moeten worden vastgelegd en later uitbreiding kunnen beperken, met name de vergunningsscope en het havenontwerp. Aangezien waterstofcorridors grotendeels beleidsgedreven zijn, hangen veel beslismomenten af van het beschikbaar komen van beleidscondities. Adaptive Technology Roadmapping maakt dit zichtbaar door te tonen wat beleid moet leveren om vooruitgang te ontgrendelen: sterkere vraag via verplichtingen en prikkels, duidelijke en consistente certificering, importinfrastructuur met betaalbare tarieven in de beginfase, snellere en voorspelbaardere vergunningverlening waar mogelijk, en publieke risicodeling om eerste projecten financieel te maken.

Een evaluatie van de Adaptive Technology Roadmapping-aanpak laat ook beperkingen zien. Adaptatie is gebaseerd op een initiële set kansen en kwetsbaarheden; als deze verschuiven, heeft Adaptive Technology Roadmapping een expliciete updatecyclus nodig om relevant te blijven. Daarnaast kan Adaptive Technology Roadmapping veel signalen tegelijk opleveren, maar het zou helpen als duidelijker wordt welke het zwaarst wegen of hoe met conflicterende signalen om te gaan, zodat keuzes helder blijven. Tot slot kan één roadmapfiguur meer lijken op een vast tijdschema en completer ogen dan corridorprocessen in werkelijkheid zijn, wat onrealistische verwachtingen kan wekken en daarom periodieke afstemming en herijking vraagt.

De vergelijking tussen Adaptive Technology Roadmapping en traditionele Technology Roadmapping maakt echter de toegevoegde waarde duidelijk: het ondersteunt besluitvorming onder onzekerheid door niet alleen te laten zien wat te doen, maar ook wanneer en hoe bij te sturen als omstandigheden veranderen. Dit gebeurt door alternatieve routes te tonen en commitments te koppelen aan gemonitorde drempels, zodat actoren de route kunnen bijstellen op basis van hoe condities zich ontwikkelen. Dit is belangrijk voor het plannen van waterstofimportinfrastructuur omdat het gaat om een sterk onderling afhankelijke waardeketen waarin verschillende delen met verschillende snelheid vooruitgaan: het laat zien welke stappen een infrastructuurproject nu al kan zetten, welke stappen moeten wachten totdat de belangrijkste afhankelijkheden op orde zijn, en hoe het project in de tijd kan opschalen via modulaire uitbreiding. Daarmee maakt Adaptive Technology Roadmapping een roadmap bruikbaar voor waterstofinfrastructuurprojecten met lange doorlooptijden en grote commitments, waarbij timing, afhankelijkheden en onzekerheid bepalen of de volgende stap gerechtvaardigd is, en helpt het de kloof te overbruggen tussen grote ambities voor waterstofcorridors en uitvoering.

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Nomenclature

Abbreviation	Meaning
AEM	Anion Exchange Membrane
ATP	Adaptation Tipping Point
ATR	Adaptive Technology Roadmapping
CAPEX	Capital Expenditures
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CfD	Contract for Difference
CHITC	Clean Hydrogen Investment Tax Credit
COD	Commercial Operation Date
DAP	Dynamic Adaptive Planning
DAPP	Dynamic Adaptive Policy Pathways
DP	Decision Point
DRC	Delta Rhine Corridor
EA	Environmental Assessment
EPC	Engineering, Procurement and Construction
ETS	Emissions Trading System
EU	European Union
FEED	Front-End Engineering Design
FID	Final Investment Decision
FO	First-Order Term
GHG	Greenhouse Gas
IA	Impact Assessment
IMO	International Maritime Organisation
ISO	International Organisation for Standardisation
LCOE	Levelised Cost of Electricity
LCOH	Levelised Cost of Hydrogen
MoU	Memorandum of Understanding
NLFFA	Newfoundland and Labrador Fisheries, Forestry and Agriculture
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditures
PEM	Proton Exchange Membrane
PGS	Hazardous Substances Publication
PV	Photovoltaic
RDM	Robust Decision Making
RED	Renewable Energy Directive
RFNBO	Renewable Fuels of Non-Biological Origin
R&D	Research and Development
SME	Small and Medium Enterprises
SO	Second-Order Term
SOEC	Solid Oxide Electrolysis
TRL	Technology Readiness Level

Continued on next page

Abbreviation	Meaning
TRM	Technology Roadmapping
WACC	Weighted Average Cost of Capital

Unit	Meaning
DWT	Deadweight Tonnage
GW	Gigawatt
MT	Million Tonnes
MTPA	Million Tonnes Per Annum
MWh	Megawatt-hour
TPD	Tonnes Per Day

1

Introduction

The European Union (EU) aims to achieve climate neutrality by 2050, as outlined in the European Green Deal (European Commission, 2019). To support this goal, green hydrogen offers a solution to decarbonise industrial processes and sectors where reducing carbon emissions is urgent and difficult, such as steel production and long-distance freight transport. The European Commission (2022) emphasises the need to develop both domestic production and import capabilities.

Many countries have announced national hydrogen strategies, with over fifty governments planning or already committed to hydrogen development (Alsulaiman, 2023). In 2023, these strategies represented more than 45 MT of hydrogen production capacity aimed for 2030 (Alsulaiman, 2023). However, progress remains limited, as only a small share of announced capacity has progressed into committed projects. Globally, roughly 1 MT of clean hydrogen capacity is operational, and around 5 MT has reached final investment decision (FID) or is under construction (Hydrogen Council, 2025). This gap between ambition and implementation presents both uncertainty and opportunity for countries aiming to position themselves as future hydrogen producers and exporters.

New low-carbon technologies show strong potential to transform the global energy system, but a key challenge remains: what steps do the industry and governments need to take to ensure their effective development and deployment? Technology roadmapping (TRM) is a useful tool to guide the development of complex energy systems. By translating targets into concrete actions, technology roadmaps can help clarify the steps needed to support the timely deployment of hydrogen infrastructure, markets, and supply chains. Against this background, this chapter introduces the motivation for studying hydrogen import infrastructure and Technology Roadmapping as the study's central planning approach, formulates the research gap and questions, and outlines the research design, scope, and thesis structure.

1.1. Motivation

This section motivates the study by situating hydrogen import corridors in the broader challenge of connecting supply and demand regions under uncertainty. It then positions Technology Roadmapping as a relevant planning approach for coordinating these multi-actor transitions, while highlighting why greater adaptability is needed in current roadmap practice.

1.1.1. Connecting Hydrogen Supply and Demand Regions

Hydrogen is not bound by the same geographical constraints as, for example, fossil fuels. Countries with abundant solar or wind resources have the potential to produce hydrogen at lower cost. According to Breitschopf et al. (2022), the cost of hydrogen production in non-EU countries can be as low as 32-46 €/MWh, compared to 88 €/MWh in the EU. Based on the analysis by Ansari and Maria Pepe (2023), Canada and Norway are the most suitable and realistic partner countries for future hydrogen exports

to the EU. Both have extensive experience as energy exporters, established hydrogen industries, access to infrastructure and financing, and strong institutional stability. Due to their wind resources, both countries are well-positioned to produce green hydrogen. In addition, Breitschopf et al. (2022) have identified Canada as one of the top ten countries with the largest potential areas for renewable hydrogen and its derivatives. This makes Canada a strategically important partner for meeting the EU's hydrogen import goals. Canada aims to position itself as a leading global exporter of hydrogen (Government of Canada, 2020).

Northwest Europe, particularly the Netherlands, Belgium, and Germany, is home to major industrial clusters with high hydrogen demand (Buijs et al., 2025), making it central to the EU's hydrogen strategy. Within this context, the Netherlands stands out as an entry point for hydrogen imports, as it has repurposable port and pipeline infrastructure, and offers substantial storage capacity (de Vries et al., 2022). In combination with its long-standing role as a natural gas hub, it is strategically located to be a gateway for hydrogen imports into the EU.

Realising these ambitions requires reliable global hydrogen supply chains, which in turn depend on aligned infrastructure investments and cross-border coordination (Alsulaiman, 2023; de Vries et al., 2022). The development of the Canada-Netherlands corridor illustrates both the opportunity and the complexity of international hydrogen trade: progress relies on simultaneous advances in production, transport, import infrastructure, regulation, and demand creation. Despite commitments, the uncertainties in technology, markets, and policy make effective coordination challenging, creating the need for decision-making approaches that provide strategic direction while allowing for adaptation as conditions evolve. Technology Roadmapping is a widely used tool to organise such long-term transition planning across complex value chains, further elaborated in Subsection 1.1.2.

1.1.2. Technology Roadmaps in Energy Transitions

Technology Roadmapping is a strategic planning tool that aligns stakeholders around a shared vision and identifies milestones and enabling conditions that guide long-term technological development. Originally developed in industrial contexts, technology roadmaps have evolved into instruments for coordinating socio-technical transitions, including the energy transition towards climate neutrality (McDowall, 2012). Roadmaps help visualise potential futures, prioritise investments, and identify enabling conditions such as infrastructure, standards, and regulation.

In the hydrogen sector, technology roadmaps are useful for governments, consortia and companies to coordinate innovation, infrastructure development, and market entry strategies across value chains. For example, the IEA (2021) roadmap outlines how to reach net-zero emissions by 2050, including key milestones for hydrogen production, transport, and end-use. These applications illustrate the potential of Technology Roadmapping to structure long-term development under uncertainty. However, existing roadmaps are often static and provide limited guidance on how plans should evolve as conditions change. This limitation motivates the focus of this research on making system-level Technology Roadmapping more adaptive for hydrogen transitions.

1.2. Research Gap

As outlined in Section 1.1, planning emerging hydrogen infrastructure and supply chains involves long-term commitments made under significant technological, market, and policy uncertainty. At the same time, Technology Roadmapping is used to guide strategic development in such complex systems. This combination raises questions about how roadmapping approaches address uncertainty in theory, and how well they support decision-making in practice, as discussed in this section.

1.2.1. Academic Gap

System-level applications of Technology Roadmapping struggle to address uncertainty, as their largely static structure offers limited capacity to support adaptation when underlying conditions change (O'sullivan

et al., 2021). Consequently, system-level roadmaps often remain fixed and risk losing relevance as dynamics evolve.

In parallel, the literature offers approaches that are explicitly designed to keep long-term plans decision-relevant under uncertainty. Marchau et al. (2019) discuss several such approaches, including Dynamic Adaptive Planning, Dynamic Adaptive Policy Pathways, and Robust Decision Making. Dynamic Adaptive Planning adds a monitoring-and-response logic, but primarily supports adapting a single plan over time. Robust Decision Making tests strategies across many plausible futures, but it does not provide a roadmap-style structure for implementation. Dynamic Adaptive Policy Pathways (DAPP) combines multiple pathways with explicit decision points and monitoring rules, making it a suitable complement to Technology Roadmapping when plans must remain adjustable as conditions evolve. Bringing the logic of Dynamic Adaptive Policy Pathways into Technology Roadmapping is therefore a promising way to address the identified limitation.

1.2.2. Practical Problem

In practice, governments and industry are advancing hydrogen import corridor infrastructure under substantial uncertainty. The Canada-Netherlands hydrogen import corridor illustrates the broader ambition to establish hydrogen supply chains while technological, regulatory, and market conditions remain uncertain. Progress is often constrained by coordination challenges, as actors may delay commitments while waiting for complementary investments, clearer regulation, or stronger market signals. Consequently, actors could benefit from decision-support approaches that help them deal with uncertainty by structuring choices over time, clarifying when commitments should be advanced, adjusted, or reconsidered, and preserving flexibility as the global hydrogen trade system matures.

1.3. Research Objective and Questions

The objective of this study is to strengthen Technology Roadmapping for adaptive, system-level decision-making under uncertainty and to use it to generate decision-relevant insights for hydrogen import infrastructure development. To this end, the study reviews adaptive planning approaches and identifies Dynamic Adaptive Policy Pathways as the most suitable approach to integrate with Technology Roadmapping, so that it becomes adaptive and systemic. This objective follows from the identified gap that roadmaps often provide direction but limited guidance on how to remain decision-relevant at the system level as conditions change, a challenge that is particularly important for hydrogen import infrastructure, which is developing under high uncertainty. The main research question is formulated as follows:

"How can Dynamic Adaptive Policy Pathways be used to make Technology Roadmapping adaptive and systemic, and what insights does this provide for the development of hydrogen import infrastructure?"

To address this question, the research is structured around the following subquestions, each supported by objectives:

1. How do current Technology Roadmapping approaches address adaptability?
 - (a) To define Technology Roadmapping and identify its building blocks.
 - (b) To review whether and how Technology Roadmapping addresses adaptability for dealing with uncertainty.
2. Why is Dynamic Adaptive Policy Pathways a suitable approach to make Technology Roadmapping adaptive and systemic?
 - (a) To compare existing approaches aimed at making Technology Roadmapping adaptive at a systemic level to justify the selection of Dynamic Adaptive Policy Pathways.
 - (b) To identify the Dynamic Adaptive Policy Pathways' building blocks.

3. How can Dynamic Adaptive Policy Pathways be integrated into Technology Roadmapping?
 - (a) To translate the building blocks of Dynamic Adaptive Policy Pathways and Technology Roadmapping into an integrated conceptual model.
4. What insights does an empirical illustration of the integrated Dynamic Adaptive Policy Pathways and Technology Roadmapping model provide?
 - (a) To empirically apply the integrated Dynamic Adaptive Policy Pathways and Technology Roadmapping model to the development of the Canada-Netherlands hydrogen import corridor.

1.4. Research Design

This section outlines the study's research design, shown in Figure 1.1. First, SQ1-SQ3 are addressed through a literature review, which is integrated into a conceptual DAPP-TRM model. Second, SQ4 applies and illustrates this model through a case study using a Gioia analysis of semi-structured interviews complemented by document analysis, further elaborated in Chapter 3. This provides decision-relevant insights for the Canada-Netherlands hydrogen import corridor.

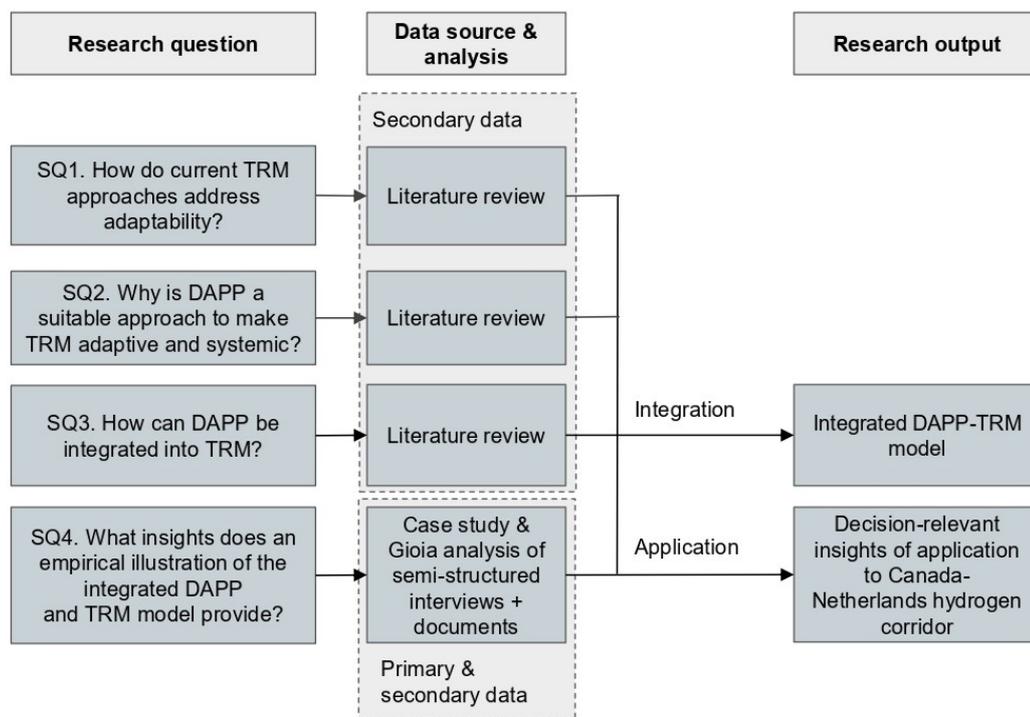


Figure 1.1: Research design

1.5. Scope

This thesis is scoped to the development of an adaptive, system-level technology roadmapping approach for hydrogen import systems that evolve under uncertainty, as outlined in this section. It focuses on making explicit how choices can be revised when external conditions change. The thesis, therefore, concentrates on the structure, content, and steps of roadmapping, so that long-term plans remain decision-relevant over time. The aim is methodological: strengthening Technology Roadmapping with Dynamic Adaptive Policy Pathways for complex hydrogen import systems where progress depends on many interacting developments and where timing and feasibility are uncertain.

The thesis, therefore, does not attempt to solve the full engineering or economic design problem of hydrogen systems. It does not deliver detailed plant design, permitting strategies, or a full techno-economic optimisation of investment timing. Instead, it stays at the level of strategic planning: what

needs to be monitored, which conditions must hold to proceed, and how alternative development pathways can be sequenced without assuming one future. While hydrogen import infrastructure and the Canada–Netherlands corridor are used to demonstrate and test the approach, the thesis contributes in two ways: it develops an adaptive roadmapping approach for hydrogen import systems that must evolve stepwise under uncertainty, and it generates case-based, decision-relevant insights into the conditions, timing sensitivities, and switching logic that shape the development of hydrogen infrastructure in the Canada-Netherlands corridor. The case boundaries are specified in Chapter 3.

1.6. Thesis Outline

This section provides a brief overview of the thesis structure. Chapter 1 motivates the study by introducing the research gap, objectives, questions, and scope. Chapter 2 reviews the literature on Technology Roadmapping and adaptive planning, focusing on Dynamic Adaptive Policy Pathways and other approaches that aim to keep long-term plans decision-relevant. It concludes with a synthesis that translates shared and complementary building blocks of DAPP and TRM into an integrated conceptual model. Chapter 3 presents the methodology, including a motivation for the use of a single case study to apply the conceptual model, data sources, and the Gioia-based coding and analysis procedure. Chapter 4 describes the context of the Canada-Netherlands hydrogen import corridor, defining the system-of-systems, actors, and uncertainties that frame the analysis. Chapter 5 applies and tests the integrated DAPP-TRM model in the case study, using the data analysis and empirical results. Chapter 6 presents the findings, structuring the results into system-level coordination dynamics in the Canada-Netherlands hydrogen import corridor and the resulting project-level decisions for import infrastructure development. Chapter 7 discusses what the findings imply for theory and practice, including how the integrated approach advances system-level roadmapping under uncertainty and what it recommends for hydrogen import infrastructure development. Chapter 8 concludes by answering the research question and summarising contributions.

2

Literature Review

A literature review is performed to build the foundation for the conceptual model developed in this chapter, by connecting insights from technology roadmapping and adaptive planning. Section 2.1 reviews Technology Roadmapping (TRM) and clarifies how it structures and coordinates long-term development in innovation systems, while also identifying the limitations that arise when conditions change. Section 2.2 then reviews adaptive planning approaches and explains why Dynamic Adaptive Policy Pathways (DAPP) offers the most relevant complement for addressing those limitations. Finally, Section 2.3 synthesises TRM and DAPP into an integrated model that specifies what is planned, how alternatives are represented, and how adjustment is organised as conditions evolve.

2.1. Technology Roadmapping

Technology roadmapping (TRM) was first developed in the 1970s as a planning approach for synchronising technology and product development, thereby aligning research and development (R&D) priorities with market needs in a firm-level context. Over the next decades, TRM expanded to sectoral and national contexts and was also used for policy development (Hart, 2019; Phaal et al., 2003). This evolution to the system level transformed TRM from a tool for internal alignment into a mechanism for coordinating innovation activities, integrating diverse knowledge sources, and linking technological capabilities with long-term strategic objectives.

While TRM at the firm level is relatively straightforward, as objectives, responsibilities, and information flows are concentrated within one organisation, its application at the system level is considerably more demanding. System-level roadmaps must consider longer time horizons, accommodate multiple and sometimes competing stakeholder priorities, and respond to high uncertainty (O’Sullivan et al., 2021). This level of planning makes the interdependencies between policy, markets, products, and technologies visible and highlights where coordination between stakeholders is necessary. Understanding TRM in this setting provides insight into how TRM can guide not just individual technologies or firms, but the transformation of entire innovation systems.

This increasing complexity has led to extensive research on how TRM is conceptualised and implemented. Consequently, the literature offers multiple definitions, with some broadening TRM beyond technology planning to encompass business, strategic, and innovation roadmapping (Kostoff & Schaller, 2001; Phaal et al., 2003). To provide clarity, this study characterises TRM in terms of its features: framework, content, and process, summarised in Table 2.1. Together, these features address the three fundamental questions that guide TRM: “Where are we going?”, “Where are we now?”, and “How can we get there?” (Phaal et al., 2005). Based on Table 2.1, this study defines TRM as an approach to strategic planning that uses a time-based, multi-layered framework, co-produced content, and a participatory process to map technology pathways from current capabilities to future objectives.

Table 2.1: Technology Roadmapping features

Feature	Description	References
Framework	The architecture or format that specifies how roadmap content is organised, typically as a time-based, multi-layered structure. The roadmap emerges once the framework is populated with content describing innovation and system evolution.	Park et al., 2020; Phaal and Muller, 2009; Phaal et al., 2001, 2004
Content	The knowledge captured within the framework, including system requirements, performance targets, technology alternatives, actions, milestones, and relevant external drivers.	Garcia and Bray, 1997; Phaal and Muller, 2009; Phaal et al., 2005
Process	The set of activities through which the framework is applied and content is generated, including preparation, actor engagement, synthesis, and follow-up.	Garcia and Bray, 1997; Kostoff and Schaller, 2001; Phaal et al., 2003, 2005

This section examines TRM by discussing how its framework, content, and process have evolved as its use has expanded from firm-level product planning to innovation systems, and how these elements enable TRM to deal with the greater complexity, longer time horizons, and stakeholder diversity found at the system level. It concludes by addressing a key gap: the absence of mechanisms to determine when and how roadmaps should be adapted. It proposes embedding explicit decision points and triggers into TRM to ensure that roadmaps remain relevant and actionable in rapidly changing contexts.

2.1.1. The Technology Roadmapping Framework

The TRM framework translates diverse knowledge into a shared, visual structure that links foresight insights with strategy. By positioning information along a time axis and across multiple layers, it creates a common language for decision-makers and makes connections between drivers and enabling technologies explicit (O'sullivan et al., 2021; Phaal et al., 2005). This common language acts as an integrative function that allows TRM to be both exploratory and normative, combining forward-looking evidence with prescriptive planning elements in a single instrument (Saritas & Oner, 2004).

Originally developed to synchronise technology and product planning within firms, TRM frameworks have since diversified and been adapted to a wide range of purposes (Phaal et al., 2001). One of the earliest comparative analyses by Phaal et al. (2004) categorised roadmaps by their purpose and format, a typology that has become central to TRM's conceptual foundations and widely adopted in the literature (Carvalho et al., 2013), shown in Figure 2.1. The variation in frameworks reflects differences in planning aims and visual and structural formats, following from the need to customise the framework to specific contexts, issues, and communication goals.

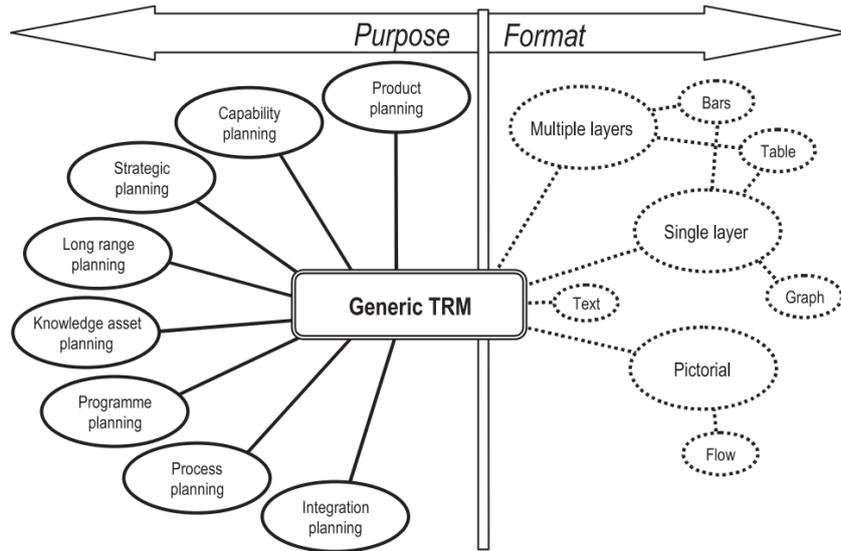


Figure 2.1: Types of Technology Roadmapping frameworks (Phaal et al., 2004)

Phaal et al. (2001) identify general characteristics that most frameworks share: it is graphically represented to support communication, multi-layered to integrate technological, product, and commercial perspectives, explicitly time-based to align developments across domains, and flexible enough to reflect the relevant knowledge dimensions. The three-layer, time-based roadmap form, proposed by Phaal and Muller (2009) and shown in Figure 2.2, is widely recognised as the generic or reference framework for TRM, forming the conceptual basis for many subsequent applications and customisations (Carvalho et al., 2013; Park et al., 2020). In this framework, the top layer focuses on purpose and external drivers ('know-why'), the middle layer addresses delivery mechanisms like products and services ('know-what'), and the bottom layer details the resources and capabilities required, including technology ('know-how') (Phaal & Muller, 2009; Phaal et al., 2005). These layers are aligned along a time axis ('know-when') and often embed additional dimensions such as 'know-who' and 'know-where' (Phaal et al., 2005).

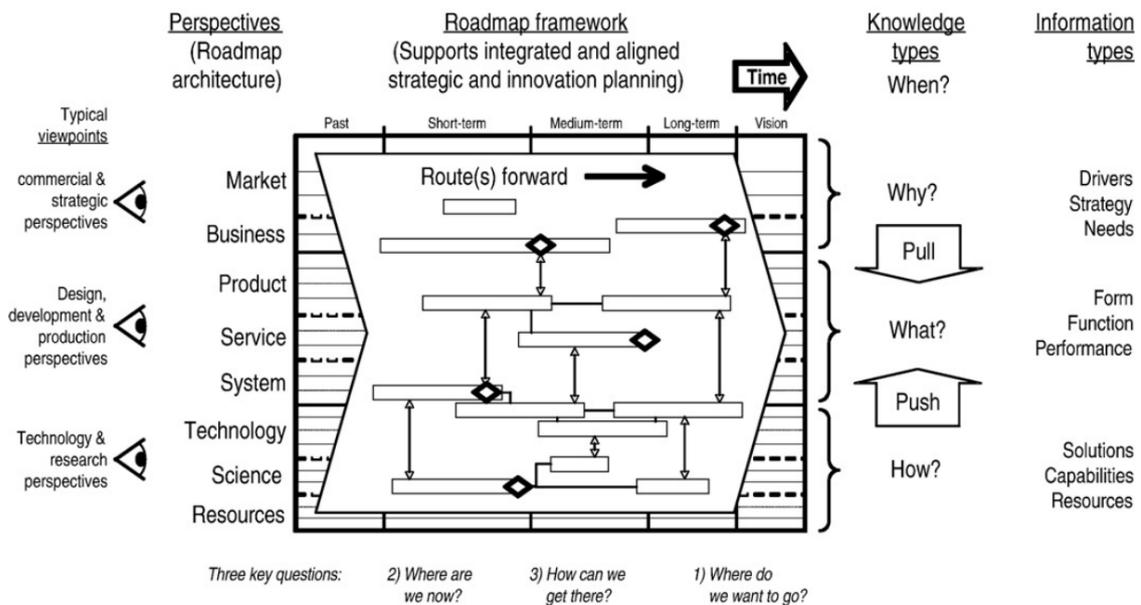


Figure 2.2: Generalised technology roadmap form (Phaal & Muller, 2009)

Figure 2.2 illustrates how TRM balances technology-push and market-pull logics. Technology-push roadmaps begin with existing or emerging capabilities and trace forward to potential applications, whereas market-pull roadmaps start from desired outcomes and work backwards to identify enabling technologies (Kostoff & Schaller, 2001). Most roadmaps combine both, linking technological feasibility to market demand for decision-making (Phaal et al., 2003). In the layered format, the bottom layer captures capabilities (push), the top layer captures drivers and needs (pull), and the middle layer connects them through products, services, and delivery mechanisms. Thus, TRM frames technologies within the co-evolution of supply and demand. This layered, time-based architecture creates value by positioning knowledge, revealing dependencies, and providing a shared canvas for dialogue. In innovation systems, where knowledge is distributed across organisations and disciplines, such a structure helps build a shared understanding of system dynamics and supports coordination of actions across decision-making levels (Saritas & Oner, 2004).

The framework's visual clarity and structured format can, however, mask the underlying uncertainty present in highly complex and contested environments (Phaal et al., 2005; Saritas & Oner, 2004). As roadmaps are often produced as static outputs, they can quickly become outdated as technologies, markets, and policies change, reducing their strategic value and causing emerging opportunities or risks to be overlooked. O'sullivan et al. (2021) conclude that roadmapping frameworks have the potential to offer a more flexible, scalable framework for studying innovation system dynamics. To maintain relevance, the framework must therefore be treated as dynamic rather than static, with explicit decision points for when to reconfigure layers, shift time horizons, or expand the scope of analysis. This insight provides a foundation for rethinking how the TRM framework can be updated to remain aligned with the evolving innovation landscape.

2.1.2. The Technology Roadmapping Content

The value of TRM ultimately depends on the quality and relevance of its content. As conceptualised by Phaal and Muller (2009), the framework described in Section 2.1.1 is populated with three types of content that represent the dimensions of innovation: the top purpose layer specifies external and internal drivers, trends, milestones, objectives, and constraints that shape the roadmap's overall purpose; the middle delivery layer describes the systems to be developed in response to these drivers, often including services, infrastructure, or other integration mechanisms in system-level roadmaps; and the bottom resources layer identifies the capabilities and inputs required to realise these systems, including technologies, skills, and competences.

Populating the roadmap layers requires combining diverse forms of evidence, empirical data, foresight analyses, and expert insights. TRM typically draws on complementary tools, such as SWOT, PESTLE, and scenario planning, to frame context, drivers, and uncertainty (Phaal et al., 2005; Saritas & Oner, 2004). As the roadmap is meant to inform commitments and coordination, TRM practice also makes explicit who sponsors or owns the roadmap effort and which stakeholder groups contribute and validate the content (Garcia & Bray, 1997). Expert and stakeholder input is essential to ensure that the content reflects diverse perspectives, validates evidence, and builds shared ownership of the resulting roadmap (Hart, 2019). As evidence and priorities change, TRM must be updated regularly by revisiting drivers, assumptions, targets, and stakeholder inputs to avoid becoming outdated and to remain useful for decision-making.

2.1.3. The Technology Roadmapping Process

Across the literature, TRM process activities are commonly grouped into three high-level phases: scoping and preparation, data collection and roadmap construction, and implementation and follow-up (Carvalho et al., 2013; Garcia & Bray, 1997; Gerdri et al., 2009; Phaal et al., 2005). Although the three-phase model reflects an early, more linear view of TRM, it remains widely used and is applied iteratively in practice today: insights from construction often reshape the initial scope, and implementation feeds back into successive roadmapping cycles (Hart, 2019). According to Lee and Park (2005), the process should be adapted to the specific context and changing conditions, balancing standardisation for coherence with customisation for relevance. Gerdri et al. (2009) emphasises that producing a roadmap

is insufficient on its own; sustained value requires integrating roadmapping into ongoing practice and continuously reviewing and updating the roadmap as drivers and technologies evolve. However, Carvalho et al. (2013) note that empirical evidence on how roadmaps are maintained and embedded in decision-making remains scarce.

At the system level, the implementation and follow-up phase is particularly important because early-stage TRM can rarely specify the required level of detail or stakeholder consensus (O'sullivan et al., 2021). The need for continuous revision also puts pressure on the other two features of TRM: the framework and content. A static framework and outdated content can quickly reduce a roadmap's relevance as conditions change. The process is meant to keep both the framework and content alive, but current implementation practices do not provide much clarity on how to ensure this happens. To ensure that TRM remains useful for decision-making, Subsection 2.1.4 identifies the key gaps that must be addressed to enable more adaptive roadmapping.

2.1.4. The Need for More Adaptive Technology Roadmapping

As shown in this section, TRM already contains features that could support adaptation. Its layered framework can be reconfigured to reflect new drivers or shifts in time horizons, its content can be updated as evidence and stakeholder priorities change, and its process is described as iterative, allowing feedback from implementation to inform and update the roadmap. However, this adaptive potential is often not realised because TRM typically lacks explicit decision points and trigger conditions that indicate when the roadmap, or the current course of action, should be reconsidered. Especially at the system level with high uncertainties and rapidly changing conditions, this risks the framework remaining fixed and the content becoming outdated, leading to limited clarity on what should be monitored and which thresholds would initiate roadmap updates and action revisions during its implementation.

Therefore, this study argues that TRM should include explicit decision points and trigger conditions, tied to evidence, stakeholder needs, and external signals, so that roadmaps and, thereby, the course of action can be updated systematically. Triggers can be defined in advance and activated by events such as market and policy shifts. O'sullivan et al. (2021) highlight this need by calling for "reflection points", and by proposing five preliminary principles for adaptive roadmapping: (1) aligning scope with user evidence needs, (2) revisiting time and resource allocations, (3) adopting adaptive and iterative scoping, (4) systematically checking evidence for gaps, and (5) applying adequacy tests to ensure evidence is precise and relevant. O'sullivan et al. (2021) recommend future research to focus on testing and refining these principles in practice, developing methods to detect evidence patterns that signal when adaptation is required. While these principles provide a valuable conceptual foundation, they do not specify how reflection points should be triggered or how triggers should translate into changes in the course of action.

This study addresses this gap by proposing an adaptive extension to TRM in which decision points and trigger conditions are explicitly built into the roadmap and its content and process, shifting TRM from a largely static plan toward a dynamic roadmap that can be updated across multiple plausible futures as evidence, stakeholders, and external conditions evolve.

2.2. Approaches to Adaptive Technology Roadmapping

Section 2.1 showed that TRM has evolved into a system-level planning tool for coordinating long-term innovation planning. However, innovation systems are dynamic and uncertain, so TRM also needs mechanisms that guide what to do when conditions change. Several adaptive planning approaches exist that can complement TRM. Marchau et al. (2019) present five approaches for supporting decision-making under uncertainty and distinguish between computational decision-support tools that generate quantitative insight and approaches that guide the design of adaptive strategies. In this typology, Info-Gap Decision Theory and Engineering Options Analysis are positioned as tool-like methods, whereas Dynamic Adaptive Policy Pathways (DAPP), Dynamic Adaptive Planning (DAP), and Robust Decision Making (RDM) are presented as approaches for creating adaptive strategies. These three are there-

fore the most suitable complements for extending TRM with an adaptive planning architecture and are compared with TRM in Table 2.2.

Table 2.2: Feature comparison of Technology Roadmapping and adaptive planning approaches

Feature	TRM	DAPP (Haasnoot et al., 2013)	DAP (Walker et al., 2019)	RDM (Lempert, 2019)
Frame-work	A time-based, multi-layered visual framework linking purpose/drivers (top), delivery (middle), and resources/technology (bottom), connecting market-pull needs and technology-push capabilities.	Maps alternative action sequences in a metro-map/decision-tree style; adaptation tipping points mark when success is no longer met, and decision points show where switching is possible.	Does not rely on a distinctive visual framework; it provides a planning architecture linking an initial plan to pre-specified adaptation (detailed in the content).	Does not rely on a distinctive visual framework; it structures the problem as XLRM (eXogenous uncertainties, policy Levers, Relationships, and performance Measures) so strategies can be represented consistently and compared on robustness rather than optimality (detailed in the content).
Content	Populates layers with drivers/objectives, system requirements, and actions/milestones linking current capabilities to future targets. Co-produced from evidence and foresight and revised as assumptions shift.	Starts from objectives, vulnerabilities and opportunities, defining actions and viability conditions. Specifies signposts and triggers for continuation, adjustment, switching, or reassessment, and links actions into alternative pathways.	Starts from objectives, vulnerabilities and opportunities, defining actions and viability conditions. Specifies signposts and trigger values for contingent actions, continuation, adjustment, or reassessment, so the plan can be defended, corrected, or redesigned.	Defines objectives, candidate strategies, and uncertainties, then runs simulation experiments to create a database of strategy performance across many plausible futures. The database is analysed to reveal when strategies succeed or fail and what trade-offs they imply (often using robustness/regret), and to support refining strategies, including near-term actions, signposts, and contingent actions.
Process	Typically follows three phases: scoping and preparation, roadmap construction, and implementation/follow-up, iterated over time. Participatory, integrating stakeholder input and periodic updates.	Follows an iterative cycle: define success and uncertainties; identify vulnerabilities/opportunities; generate and assess actions; assemble and compare pathways; select preferred pathways; specify monitoring and responses; implement, monitor, and revise.	Follows a design-and-implementation cycle: stage setting, initial plan, robustness actions, monitoring setup, and trigger-response preparation, followed by implementation with monitoring and triggered adaptation.	Follows "deliberation with analysis": frame the decision with stakeholders, run strategies across many futures, analyse vulnerabilities, compare trade-offs, refine more robust strategies, and iterate.

Table 2.2 shows that TRM, DAP, DAPP, and RDM all organise evidence into guidance for decision-making, but they differ in how they represent progress and how they respond when conditions change. TRM provides the roadmap backbone by linking objectives, delivery mechanisms, and enabling resources into a coherent set of actions and milestones. DAP builds on an initial plan by adding signposts, trigger values, and pre-specified contingent responses, so the plan can be defended, adjusted, or reassessed as conditions evolve, but it does not inherently show alternative routes in a single representation. RDM contributes most strongly on the analytical side: it stress-tests strategies with simulation across many plausible futures, identifies vulnerability conditions and trade-offs, and iterates these insights with stakeholders, but it does not naturally translate into a roadmap-style plan for staged de-

livery. DAPP aligns most directly with TRM because it retains a visual pathways map while making adaptation explicit in the same representation: it lays out alternative pathways and indicates when a switch to another option may be needed through adaptation tipping points and decision points, supported by monitoring. This makes DAPP the best fit for extending TRM when the roadmap needs to stay implementation-oriented while also specifying when and how the course should change. This section further analyses DAPP in terms of its framework, content, and process.

2.2.1. The Dynamic Adaptive Policy Pathways Framework

The DAPP framework builds on the Adaptation Pathways approach, which is structured around three concepts: adaptation tipping points, adaptation pathways, and decision points (Haasnoot et al., 2012, 2013). An adaptation tipping point marks the moment when a current strategy no longer meets its objectives due to changing external conditions, such as technological shifts, market disruptions, or evolving stakeholder needs. An adaptation pathway is a sequence of actions that can be followed over time to meet long-term goals, with decision points marking opportunities to continue or switch to an alternative (Haasnoot et al., 2012, 2013). This logic is visualised in an Adaptation Pathways map resembling a metro map or decision tree: each line represents a pathway, transfer stations indicate decision points, and terminals show adaptation tipping points where the current action no longer delivers the desired performance. Figure 2.3 illustrates a typical example, showing which options remain open, where transitions between actions may be required, and how long actions remain effective (Haasnoot et al., 2013, 2019).

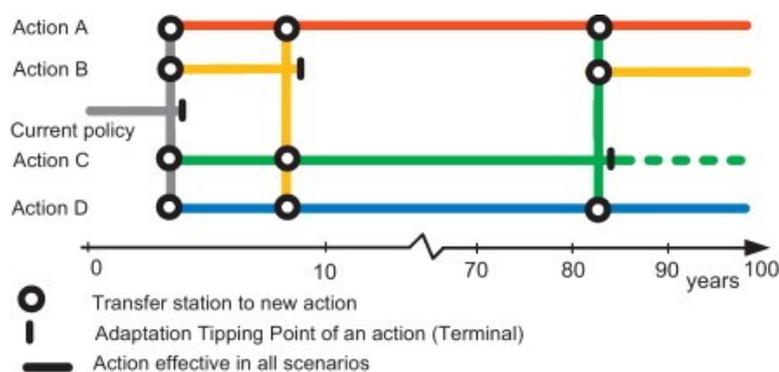


Figure 2.3: An Adaptation Pathways map (Haasnoot et al., 2013)

The adaptation pathways in Figure 2.3 can be developed in multiple ways. Haasnoot et al. (2012) use simulation-based methods to systematically identify adaptation tipping points and explore subsequent options across scenarios. Haasnoot et al. (2013) develop pathways through expert judgement on tipping points, while Kwakkel et al. (2015) apply a multiobjective robust optimisation approach. The pathways can be evaluated using tools such as cost–benefit analysis or multi-criteria scorecards, which surface no-regret actions, lock-ins, and critical intervention points (Haasnoot et al., 2013). This translation from map to plan involves selecting preferred pathways, specifying which options should be kept open and what preparatory steps are required.

Unlike traditional TRM representations, which are often presented as a single dominant trajectory, more advanced roadmap frameworks, such as the generic TRM form proposed by Phaal and Muller (2009) in Figure 2.2, can represent multiple trajectories and alternative sequences of actions. The DAPP framework goes further by making alternative development routes central: it links time-staged sequences of actions to decision points and adaptation tipping points, enabling systematic switching as conditions evolve. This makes DAPP suitable for complex innovation systems, where long-term strategies must remain robust while retaining the ability to adjust when assumptions no longer hold.

2.2.2. The Dynamic Adaptive Policy Pathways Content

DAPP starts by framing the decision context with stakeholders, using available evidence (e.g., data, model results, expert judgement, and scenario information) to describe the system, objectives, and relevant constraints in both the current situation and plausible future conditions (Haasnoot et al., 2013). This produces a shared definition of success, expressed in indicators and targets, that provides a basis for assessing the current situation and identifying uncertainties, opportunities, and vulnerabilities (Haasnoot et al., 2013).

DAPP embeds adaptivity in its content by linking evidence to monitoring and decisions. The decision points introduced in Subsection 2.2.1 are grounded in signposts and triggers: signposts are variables monitored to track relevant trends, and triggers are threshold values that indicate when adjustment or switching should be considered (Haasnoot et al., 2013; Walker et al., 2019). Two further concepts connect monitoring to timing: the sell-by date is the estimated time window in which an action is expected to stop meeting the definition of success (i.e., when the adaptation tipping point condition is reached), while lead time is the advance time required to prepare the next action so that switching is feasible when that tipping point occurs (Haasnoot et al., 2013, 2019).

DAPP content is built by first assembling a broad set of candidate actions, the basic action plan, and then sequencing them into pathways. Candidate actions can be described using the action types adopted from Adaptive Policymaking: mitigating actions reduce likely adverse effects, hedging actions reduce or spread risks from uncertain vulnerabilities, seizing actions capture likely opportunities, and shaping actions aim to influence external conditions to reduce the chance of failure or improve outcomes (Haasnoot et al., 2013). These actions provide the building blocks for the Adaptation Pathways map (the action options labelled “A”, “B”, “C”, and “D” in Figure 2.3); a pathway is formed by sequencing these actions over time, moving from one action to the next at a decision point.

Alongside this, DAPP specifies a contingency action plan that explains how the basic action plan is monitored and adjusted in implementation. This contingency action plan links signposts and triggers to predefined responses: defensive actions protect the current course of action without changing it, corrective actions modify it, capitalising actions exploit emerging opportunities, and reassessment is initiated when underlying assumptions or objectives no longer hold (Haasnoot et al., 2013).

Together, the basic action plan and the contingency action plan define DAPP’s content as a structured plan for both what to do now and how to change course as conditions evolve. As new evidence emerges or priorities shift, actions, pathways, and targets can be adjusted accordingly, and stakeholder input can reveal alternative preferences and trade-offs that affect pathway choice (Haasnoot et al., 2013). Similar to TRM, the DAPP content combines evidence-based analysis with stakeholder input. However, where content updates in TRM are dependent on internal review cycles, DAPP embeds continuous monitoring into the content itself, by specifying what is monitored, which thresholds matter, and which responses follow when those thresholds are reached.

2.2.3. The Dynamic Adaptive Policy Pathways Process

The DAPP process integrates the Adaptive Policymaking and Adaptation Pathways approaches into a sequence of steps that support decision-making under uncertainty (Haasnoot et al., 2013). This process is shown in Figure 2.4, and described by Haasnoot et al. (2013, 2019). It starts with describing the system and defining objectives and success indicators, followed by comparing the current situation with plausible future scenarios to identify vulnerabilities and opportunities. A wide range of possible actions is then generated, assessed for effectiveness and timing, and sequenced into adaptation pathways. These pathways are visualised in an Adaptation Pathways map, from which stakeholders select preferred routes. Contingency planning is then added to account for unexpected developments, linking actions to specific triggers and signposts that are monitored. The result is a dynamic adaptive plan that specifies near-term actions, preparatory steps to keep future options open, and a monitoring system that signals when decisions need to be revisited (Haasnoot et al., 2013, 2019). Once implemented, the plan enters a monitoring phase, where signposts are monitored, and triggers indicate when to act (Haasnoot et al., 2013, 2019). This ensures that adjustments are made at the right time, rather than

on a fixed schedule.

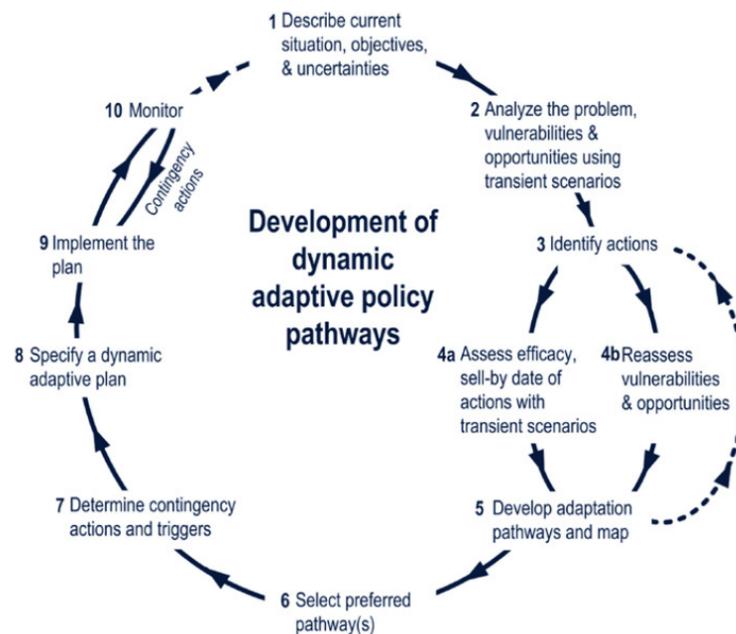


Figure 2.4: The Dynamic Adaptive Policy Pathways process (Haasnoot et al., 2013)

This process shows DAPP as an iterative, decision-oriented approach that builds adaptation into the plan. As Haasnoot et al. (2013) emphasise, DAPP encourages planners to think explicitly about which actions must be taken now to keep options open and which decisions have to be taken to enable switching between actions, making change part of the process. DAPP connects short-term actions with long-term goals while preserving flexibility to switch pathways based on defined triggers and signposts that are continuously monitored. By aligning framework, content, and process around this adaptive logic, it directly addresses the TRM limitations noted in Section 2.1. Section 2.3 therefore examines how DAPP can be integrated into a more adaptive TRM approach.

2.3. A Conceptual Model for Adaptive Technology Roadmapping

The review of TRM and DAPP in Sections 2.1 and 2.2 shows that both inform long-term planning in complex innovation contexts, but in different ways. TRM has evolved into a system-level coordination tool, whereas DAPP was designed to manage changing conditions through explicit adaptation logic. TRM provides a layered, time-based roadmap that links drivers, delivery mechanisms, and enabling resources and supports coordination across organisational boundaries. DAPP adds pathways and decision points, supported by signposts, triggers, and pre-specified responses, indicating when the current course should be adjusted and how alternatives can be kept available. This section conceptually integrates DAPP into TRM to develop an approach referred to in this study as Adaptive Technology Roadmapping (ATR).

The comparison in Table 2.2 points to the need for an integrated architecture that retains TRM's roadmap clarity while adding DAPP's explicit adaptive logic. Table 2.3 turns this into design choices by showing what TRM and DAPP provide (and where each falls short) for each feature, and how ATR combines these elements. The synthesis makes three moves: it keeps a visual roadmap but shows multiple plausible development routes and the transition moments between them; it makes the basis explicit by defining system dynamics and translating evidence into a default course with adaptation tipping points; and it replaces periodic updates with monitored signposts and trigger values linked to predefined responses that specify how the roadmap is adjusted when thresholds are reached.

Table 2.3: Synthesis of Technology Roadmapping and Dynamic Adaptive Policy Pathways into Adaptive Technology Roadmapping

Feature Aspect	TRM	DAPP	ATR	
Frame-work	Representation of system dynamics and flexible responses	Multi-layered canvas clarifies system structure and dependencies, but alternative routes and branching often remain implicit.	Metro-map makes flexibility explicit by showing alternative routes as pathways and where switching becomes feasible as conditions change at decision points; less emphasis on layered system depiction.	Trades TRM's layered canvas for navigability: uses pathways to show alternative ways the plan can unfold, and decision points to indicate when a shift can be made, using the metro-map visualisation to navigate changing system dynamics.
	Representation of action sequencing over time	Shows executable actions & milestones staged over time across roadmap layers to support implementation planning and coordination.	Pathways are composed of actions, using scenario-dependent timing (sell-by dates) to indicate how long an option remains viable; does not detail the implementation of an action or milestones within an action.	Combines TRM's execution with DAPP's timing logic: organising the roadmap into pathways containing action-lines & milestones with sell-by dates , keeping routes implementable while showing when options expire.
Content	Scope and objectives	Frames drivers, objectives, constraints, and a planning horizon across layers, often at the system level with multiple actors; captures the wider setting and decision ownership.	Starts from a study-area description, objectives/constraints and a success definition, but is policy-framed and less explicit about innovation-system dynamics and multi-actor decision ownership.	Distinguishes the wider system-of-systems , the system being planned, and the responsible actor , and defines a success definition and planning horizon , combining TRM's system scoping with DAPP's success framing to make context and agency explicit.
	Evidence collection under uncertainty	Integrates foresight, analyses and expert input to identify external/internal drivers, uncertainties, constraints, solution concepts, and enabling resources.	Builds reference cases and plausible futures with transient scenarios spanning key uncertainties; models and expert judgement compare performance against the success definition to identify vulnerabilities and opportunities.	Produces vulnerabilities & opportunities from the mix of evidence available (e.g. data, models, expert/stakeholder input), linked to the success definition and the defined system-of-systems, creating an evidence base.
	Translation of evidence to the default course of action	Synthesises drivers, needs and capabilities into staged actions and milestones, but typically without specifying the conditions under which that plan would fail or needs change.	Tests options against the success definition, identifies adaptation tipping points, and builds a basic action plan using mitigating, hedging, seizing and shaping actions.	Establishes a basic action plan (the default staged course) by translating the identified vulnerabilities & opportunities into DAPP's four action types, and specifies adaptation tipping points for when the success definition is no longer met.
Process	Monitoring & adaptation	Updates tend to be periodic and informal, rather than driven by monitored signals and decision rules.	Defines signposts and trigger values, plus a contingency action plan: defensive actions protect the plan, corrective actions adjust it, capitalising actions seize opportunities, and reassessment is triggered when objectives or core assumptions no longer hold.	Adds decision rules to execution: signposts and triggers guide when to keep, adjust or switch at decision points, and the contingency action plan specifies DAPP's four response types.
	Process stages & iteration	Starts with scoping, develops a roadmap, and then manages follow-up; iteration exists but is frequently periodic.	Uses a stepwise approach that frames the problem, explores actions across futures, sequences them into pathways, and prepares monitoring and responses.	Reconfigures TRM process with DAPP's adaptive cycle: it first defines the system scope , then develops an evidence base & default plan , uses this to construct the roadmap , and finally enables the adaptation plan for adjustments when conditions shift.

Across the aspects in Table 2.3, the ATR column highlights the specific elements that emerge from synthesising TRM and DAPP (shown in bold). Grouping these elements leads to four building blocks that together form the ATR model. Together, these four blocks align with the process stages highlighted in the last row of Table 2.3: define the system scope, develop an evidence base and default plan, construct the roadmap, and enable the adaptation plan. Figure 2.5 summarises the ATR building blocks and their elements, and shows how they connect.

System Scope

ATR makes the planning boundary and decision ownership explicit by distinguishing the wider system-of-systems, the system being planned, and the responsible actor, together with an agreed success definition and planning horizon. Here, a system-of-systems refers to the broader configuration of interacting systems that jointly shape outcomes in the domain of interest. Outcomes emerge from interactions across these systems rather than from any single party, even though actors can still influence trajectories through their own decisions. TRM already supports scoping by structuring drivers, objectives, constraints, and responsibilities in a shared roadmap across interdependencies and multiple actors, grounded in a system-level situation analysis of the relevant technology, market, and policy conditions (“where the system is now”). DAPP complements this by starting from a definition of success that clarifies objectives and constraints (“where to go”) and is used to evaluate alternatives and identify when change is needed. ATR builds on these strengths by making the system-of-systems level explicit to capture dynamics beyond the roadmap owner’s control, and by stating the agency logic, who has the mandate and capability to decide and implement, so the default course and later adjustments are tied to actors who can actually carry them out within the innovation system.

Evidence Base & Default Plan

ATR brings together diverse evidence into a set of vulnerabilities and opportunities and uses these to shape both a basic action plan and adaptation tipping points. This block draws on complementary strengths: TRM is strong at combining foresight, analysis, and stakeholder input into a shared knowledge base of system dynamics, but it often does not specify the conditions under which that course would stop being effective; DAPP addresses this by evaluating options against the success definition and identifying the conditions and expected timing under which an option no longer meets it. ATR combines these by treating vulnerabilities and opportunities as the bridge from evidence to a basic action plan that sets out commitments that should be pursued regardless of which development route is later preferred, and adaptation tipping points that state when the plan is no longer expected to meet the success definition. The basic action plan is constructed using DAPP’s four action types to handle uncertainty: mitigating actions reduce likely adverse effects, hedging actions spread or reduce exposure to uncertain developments, seizing actions capture likely opportunities, and shaping actions seek to influence external conditions to lower failure risks or improve outcomes, helping distinguish what can be done now from what needs to be prepared or kept flexible.

Roadmap

ATR takes the pathway logic and metro-map format from DAPP and specifies each route using TRM’s execution. The roadmap is shown as pathways, with decision points marking where a move to a different pathway may become relevant, but each pathway is shown as a sequence of TRM actionlines and milestones. Milestones act as commitment and information gates and are linked to decision points, because switching is often only feasible once preceding actionlines are completed and enabling milestones are reached, for example, when evidence is produced, approvals are secured, or capacity is in place. This reflects system-level dynamics, as switching can depend on progress by other actors, not only the roadmap owner. Milestones can also be linked to sell-by dates, indicating the latest feasible timing for key steps before an option expires or downstream moves become infeasible. TRM thus provides the planning logic within each route, while DAPP provides the adaptive form that keeps multiple routes visible and connects transitions to changing conditions; ATR adopts the metro-map visualisation while retaining TRM’s actionlines and milestones for follow-through. The basic action plan remains separate, capturing commitments that hold regardless of which pathway is followed.

Adaptation Plan

ATR makes adaptation explicit through signposts, triggers, and a contingency action plan. This block

emerges because TRM updates are often handled through periodic reviews, whereas DAPP ties adjustment directly to what is monitored and which threshold values are reached. In ATR, signposts specify what is tracked, and triggers specify when a decision or action is required. The contingency action plan then sets out in advance what happens next. Defensive responses protect the current course without changing it, corrective responses modify it, capitalising responses take advantage of emerging opportunities, and reassessment restarts the plan when objectives or core assumptions no longer hold. In this way, ATR clarifies what needs to be watched and what should happen when conditions change, instead of relying mainly on scheduled roadmap updates.

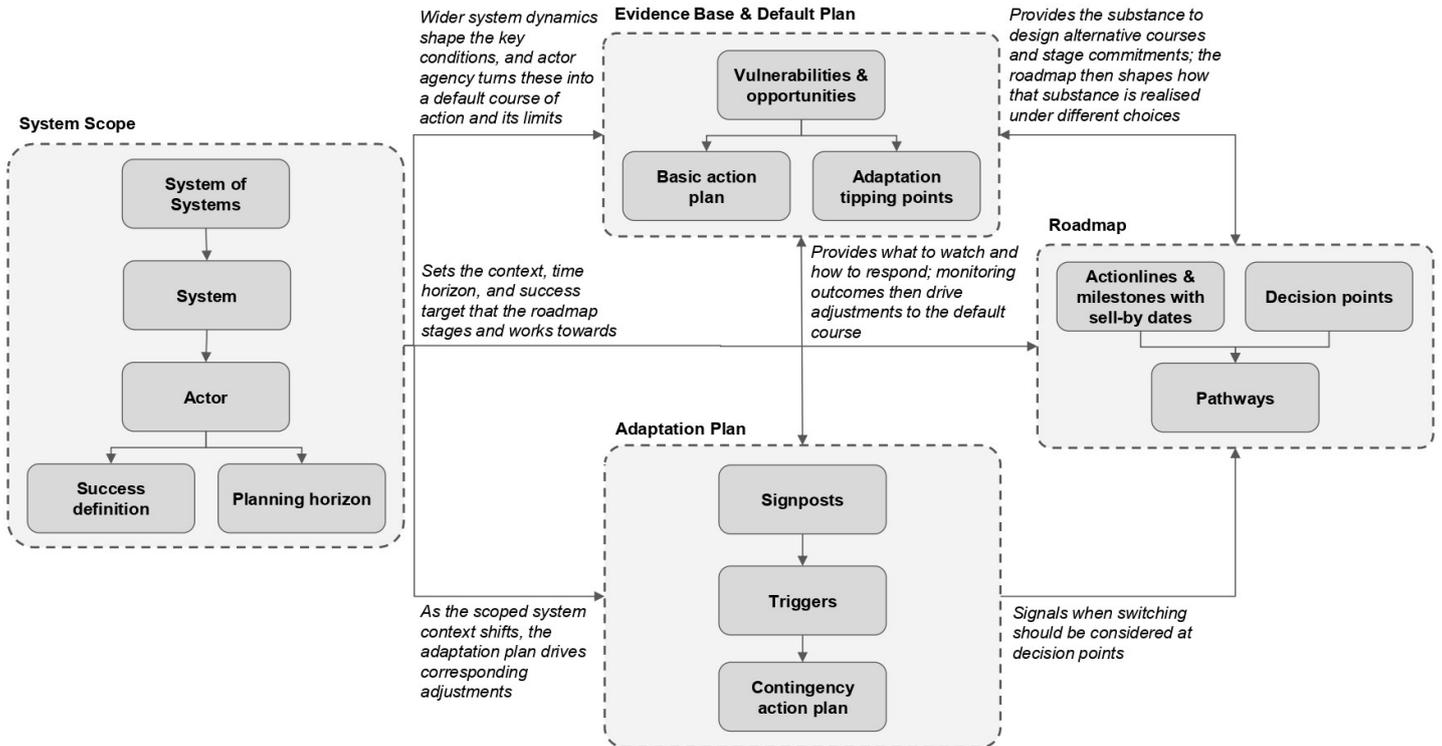


Figure 2.5: Adaptive Technology Roadmapping building blocks

The model shown in Figure 2.5 shows how ATR addresses TRM's main gap, limited guidance on when and how to adapt the roadmap under changing conditions, by embedding DAPP's monitoring, thresholds, and pre-specified responses into a roadmap that retains TRM's strengths in structuring and coordinating long-term development. System scope sets the boundary conditions; evidence and the default plan translate system dynamics into a baseline course and its limits; the roadmap stages commitments into alternative pathways; and the adaptation plan connects monitoring and responses to decision points so adjustments happen when needed. Chapter 5 applies this conceptual model to the Canada–Netherlands hydrogen import corridor to examine whether ATR can be applied to real-world system dynamics and uncertainty.

3

Research Methodology

This chapter explains how the conceptual ATR model from Section 2.3 is applied in an exploratory qualitative case study of the Canada-Netherlands hydrogen import corridor. The research follows an abductive logic, iterating between empirical insights and further refinement of the ATR model. Data collection combines semi-structured interviews with desk research. Interviews with actors across the hydrogen value chain identify vulnerabilities and opportunities affecting the development of the corridor, while desk research provides contextual grounding and background information. The combined dataset is analysed using the Gioia method to identify patterns and overarching themes that capture the dynamics of the system. These empirically derived dimensions form the basis for constructing and evaluating ATR. In this way, the case study tests ATR in practice, showing where the model provides value or encounters limitations under real-world uncertainty.

3.1. Case Study

This section introduces the Canada-Netherlands hydrogen import corridor as the case study context for ATR. It defines the scope and boundaries of the analysis, focusing on the upstream ammonia production and export segment and its interfaces with import infrastructure.

3.1.1. Single Case Study Selection

This study uses a single-case design to examine how ATR performs in a socio-technical system. The aim is not broad generalisation but to produce context-dependent knowledge that stays close to real-world complexity (Flyvbjerg, 2006). The hydrogen import corridor is shaped by interdependent infrastructures, shifting policy and market conditions, and coordination across many actors; understanding these dynamics requires the depth and contextual sensitivity a single case can provide. This also fits an abductive logic: ATR is confronted with empirical feedback from the case, and the analysis is used to demonstrate and refine the model rather than to verify its general application through cross-case comparison. This design exposes ATR to real decision conditions and shows where its assumptions hold or fail and how its adaptive mechanisms work in practice. The resulting insights can then be assessed in other system-level infrastructure contexts.

The Canada–Netherlands hydrogen corridor is selected as a critical case for ATR, because hydrogen import infrastructure functions as a system-of-systems and depends on alignment across jurisdictions and actors. Uncertainty is high because key conditions are still developing, and the corridor evolves as technologies, markets, regulations, and policies mature. In this setting, roadmapping must be systemic and adaptive: it must link decisions across interdependent system levels and specify when and how to adjust course as conditions change. Chapter 4 describes this system-of-systems context more in depth by detailing the actors, system dynamics, and uncertainties that shape corridor development.

3.1.2. Case Boundaries

The Canada-Netherlands hydrogen import corridor aims to develop a supply chain that exports green hydrogen from Canada to the Netherlands, where it can be distributed onward into Northwest Europe. The case focuses on Newfoundland and Labrador, which is one of Canada's most promising emerging regions for large-scale wind-to-hydrogen and ammonia export projects. The port of Rotterdam is treated as the point of entry because it is the primary import hub in Northwest Europe, with ongoing development of terminal capacity and connections for onward distribution of hydrogen carriers. The analysis centres on ammonia as the carrier, given its expected role in near-term imports. Other carriers and downstream infrastructure are treated as external conditions that may create constraints, opportunities, or switching points, rather than as part of the roadmap scope.

Figure 3.1 shows the full green ammonia value chain. The boundary in this study is the upstream production and export segment in Newfoundland and Labrador. The upstream segment is chosen because it is where large investments and design commitments are made under high uncertainty. Projects must lock in technology choices, scale, permitting, and offtake structures before demand, regulation, and European infrastructure are fully developed. The roadmap is therefore constructed from the perspective of a project developer responsible for green ammonia production and export, and it focuses on the choices, sequencing, and dependencies that shape project configuration, phasing, and export readiness, rather than mapping the full corridor across all actors. The time horizon is 2026-2060, consistent with infrastructure lifetimes and with the expected evolution of markets, technologies, and policy frameworks.

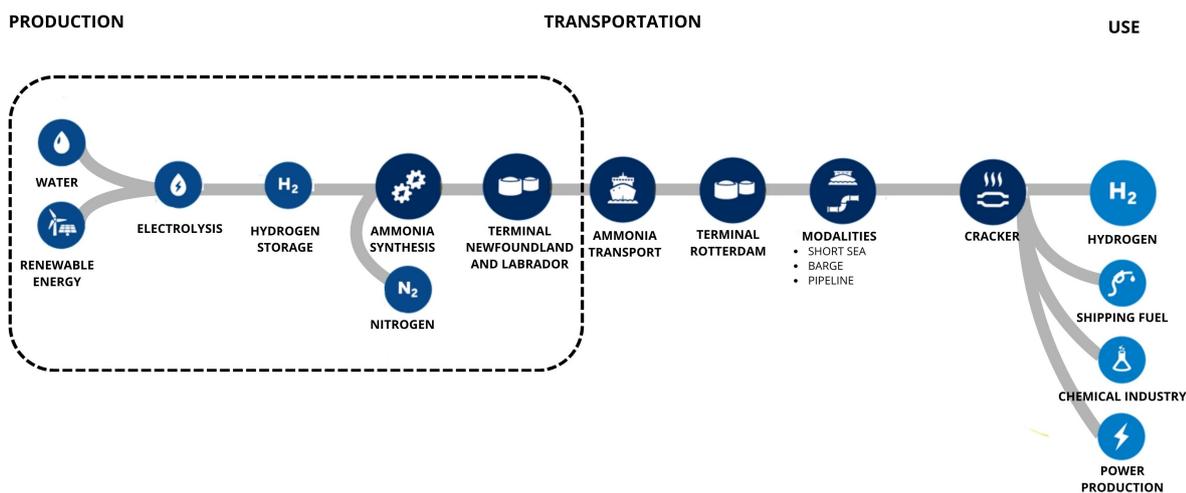


Figure 3.1: Focus in green ammonia value chain, adapted from Fluor (2023)

3.2. Data Collection: Interviews & Desk Research

This study combines semi-structured interviews with desk research, as detailed in this section. First, a preliminary review of publicly available documents was used to build a baseline understanding of the corridor, as outlined in Chapter 4, and to shape the interview guide. Interviews were then conducted, after which a more systematic document review was used mainly to contextualise, validate, and interpret interview insights and to fill remaining gaps.

3.2.1. Semi-Structured Interviews

Semi-structured interviews cover the same core topics with each respondent, while allowing follow-up questions when new issues come up. They are used to identify vulnerabilities and opportunities, and to capture stakeholder views on the main uncertainties, drivers, interdependencies, and coordination

challenges shaping the Canada-Netherlands hydrogen corridor.

Participants were selected through purposive sampling, targeting actors positioned across the Canada-Netherlands hydrogen import chain to capture their views on the most decision-relevant uncertainties and interdependencies across the system-of-systems segments. A full overview of the actor set is provided in Chapter 4 and summarised in Table 4.1. From this set, priority was given to energy producers and project developers and integrated value-chain actors (PD&IA), as they face the core project-level configuration decisions. These interviews also covered relevant shipping and logistics considerations and the technology choices and considerations. Interviews were further conducted with government and public authorities (GOV), one in the Netherlands, one at the Canadian federal level, and one in Newfoundland and Labrador, with the latter also addressing local community and workforce issues. In addition, three interviews were conducted with semi-public port and infrastructure operators (PIO) and one with a financial institution (FIN). Ideally, dedicated offtakers and an additional finance interview would also have been included, but access could not be secured. These gaps were addressed through two expert interviews, one focused on finance and one on offtake and demand contracting.

Table 3.1 provides an overview of the interviews, including their timing and duration. Interviews were initially designed to last between 45 and 60 minutes. In practice, interviews ranged from approximately 35 to 65 minutes. Shorter interviews generally occurred where responses were highly focused or where constraints existed on the respondents' availability, whereas longer interviews occurred when respondents offered elaboration, examples, or detailed narratives.

Table 3.1: Overview of interviews

Stakeholder group	Code	Interview date	Duration
Financial Institutions	FIN 1	Oct 2025	64 min
Energy Producers, Project Developers & Integrated Value Chain Actors	PD&IA 1	Oct 2025	51 min
	PD&IA 2	Oct 2025	64 min
	PD&IA 3	Oct 2025	38 min
Port Authorities & Infrastructure Operators	PIO 1	Oct 2025	47 min
	PIO 2	Oct 2025	41 min
	PIO 3	Nov 2025	35 min
Government & Public Authorities	GOV 1	Oct 2025	35 min
	GOV 2	Nov 2025	40 min
	GOV 3	Nov 2025	54 min
Experts	EXP 1	Nov 2025	59 min
	EXP 2	Dec 2025	45 min
Total	12		

The interview protocol was informed by exploratory desk research, outlined in Chapter 4. Core questions were structured around PESTLE themes (political, economic, social, technological, legal, environmental), but applied with some flexibility. For interviewees with broad system oversight and sufficient time, the interview explicitly walked through the full PESTLE, shown in Appendix A, to ensure systematic coverage of influences on the corridor. For respondents with a more specialised role, or where time was more limited, the discussion focused on those PESTLE dimensions most relevant to their expertise, while still ensuring that key topics such as major uncertainties, constraints, and drivers were addressed. In all cases, the same underlying thematic areas guided the conversation. In addition, each interview included a short set of role-specific questions tailored to the respondent's position in the corridor. The full interview protocol is provided in Appendix B.

All interviews were conducted online, with the exception of one in-person meeting. Prior to each interview, participants received an information sheet and informed consent form outlining the purpose of the study, the voluntary nature of participation, and data handling procedures. With explicit consent, interviews were video-recorded and subsequently transcribed. Transcripts were anonymised, with organisations and individuals referenced through stakeholder group codes, and stored on a secure drive accessible only to the researcher. Participants were offered the opportunity to review their transcripts and request corrections or redactions. The anonymised transcripts form the primary qualitative dataset for subsequent coding and analysis.

In line with the Gioia methodology, saturation in this study is understood as the point where additional interviews no longer add new first-order concepts or second-order themes, but instead reinforce already identified patterns (Gioia et al., 2013). This corresponds to what Saunders et al. (2018) call inductive thematic saturation (new interviews no longer add new codes or themes) and theoretical saturation (the main categories are developed enough for this study). Therefore, the saturation point is taken as the stage where additional data would add little conceptual insight. In this study, saturation was reached at approximately the tenth interview. At that point, the Gioia-style data structure had stabilised: new material consistently mapped onto the existing set of first-order concepts and second-order themes.

3.2.2. Desk Research

Desk research complements the interviews by providing an evidence base that contextualises and substantiates issues raised by respondents. Rather than being used to generate a parallel set of first- and second-order concepts, documents were primarily used to add detail, triangulate claims, and ground interview themes in concrete information (e.g. targets, capacities, cost ranges, and regulatory requirements). The documents cover policy strategies, intergovernmental and sector reports, project documentation, and academic studies. The policy and project documentation focus on Canada and Newfoundland and Labrador, given the upstream project perspective. Table 3.2 shows an overview of the documents. The documents were read selectively, so only sections relevant to the interview themes and the corridor's main uncertainties and dependencies were extracted and used, rather than conducting a full systematic content analysis of each source.

Table 3.2: Source overview for desk research

Source type	Description of source	#
Policy documents	The Hydrogen Strategy for Canada: Progress Report by Government of Canada (2024) outlines national hydrogen policy priorities and implementation progress. The Hydrogen Development Action Plan by Government of Newfoundland & Labrador (2024) details regional measures and targets for scaling hydrogen production and use in Newfoundland and Labrador.	2
Intergovernmental & sector reports	The Global Hydrogen Review by IEA (2025) provides an overview of global hydrogen policies, market trends, investments, and technological developments. The Energy Transition Outlook by DNV (2025) provides projections of global energy system developments, including hydrogen demand, infrastructure needs, and decarbonisation pathways. The Ammonia Innovation Outlook by IRENA and AEA (2022) analyses the prospects of ammonia as an energy carrier, with a focus on innovation pathways and global deployment potential. Scaling Hydrogen Financing for Development by ESMAP et al. (2024) explores financial and policy instruments to support hydrogen investments. Ason (2025) examines contractual structures and risk allocation in hydrogen offtake agreements. Enabling and Balancing the Hydrogen Infrastructure in North Western Europe by Buijs et al. (2025) assesses regional infrastructure needs and system integration challenges for hydrogen deployment.	6
Project documentation	The Environmental Assessment Registration Document by Strum (2024) provides project-specific information of a green ammonia export project in Newfoundland and Labrador.	1
Academic literature	Peacock et al. (2024) present a techno-economic analysis of hydrogen carrier options for intercontinental shipping from Atlantic Canada to Rotterdam, assessing their cost, efficiency, and feasibility. Trattner et al. (2021) examine modular hydrogen system designs, emphasising flexibility and scalability across the value chain.	2
Total		11

3.3. Data Analysis: Gioia Methodology

This section explains how the empirical data were analysed and transformed into a set of concepts that subsequently inform ATR. The analysis follows the Gioia methodology, which combines systematic inductive coding that can be organised into higher-order concepts (Gioia et al., 2013). Interviews and documents were analysed jointly in ATLAS.ti, using a single coding structure, so that the resulting themes capture both actor perspectives and documentary evidence.

The Gioia approach is suited to this study for three reasons. First, it assumes that actors are "knowledgeable agents" who can meaningfully explain their intentions, perceptions, and actions (Gioia et al., 2013). This aligns with the aim of understanding how stakeholders perceive uncertainties, drivers, and constraints in the Canada-Netherlands hydrogen corridor. Second, it offers a transparent data structure, from detailed codes to higher-order concepts, which shows traceability from raw material to system-level insights. Third, it is compatible with an abductive research logic: emerging themes are developed inductively from the data, while being iteratively applied in and used to refine the ATR model.

3.3.1. Gioia Coding Structure

Following Gioia et al. (2013), the analysis distinguishes three levels of abstraction. First-order concepts capture respondents' terms and phrases, staying as close as possible to the language used in interviews. At this level, the aim is to preserve respondents' meanings without imposing prior theoretical labels. Second-order themes are researcher-centric interpretations: related first-order concepts are grouped into more abstract categories that begin to reflect patterns in how actors talk about uncertainties, drivers, constraints, opportunities, and decision logics. Aggregate dimensions synthesise sets of second-order themes into broader system-level constructs. Each aggregate dimension can be traced back via second-order themes to specific quotations from interviews and documents.

Interviews and documents were coded within a single ATLAS.ti project to allow direct comparison and triangulation. Document evidence was assigned to the same codes and themes when it substantiated or contextualised interview insights. This ensured that the final coding structure integrated both actor perceptions and documentation. During and after the interviews, the targeted document review was performed to validate and contextualise claims made by respondents. Given the length of the documents, a selective reading strategy was adopted. As Bowen (2009) notes, document analysis often involves "skimming (superficial examination), reading (thorough examination), and interpretation", with depth of engagement determined by analytic relevance rather than completeness. Therefore, instead of conducting an exhaustive, line-by-line analysis of every source, only sections that directly addressed topics raised in the interviews were coded.

3.3.2. Coding Procedure in ATLAS.ti

All interviews were recorded (with prior consent), transcribed, anonymised, and imported into ATLAS.ti. Relevant documents selected through the desk research were likewise imported. The coding proceeded in three steps that mirror the Gioia structure.

First-order coding

The first-order terms are the vulnerabilities and opportunities to the development of the hydrogen corridor, as expressed by the respondents. The first coding cycle focused on generating first-order concepts. Transcript passages were coded line-by-line and relevant document sections paragraph-by-paragraph, assigning short, descriptive labels that reflected close paraphrases of the respondents. New codes were created whenever a segment expressed a meaning not yet captured by existing labels, leading to an initially large list of first-order concepts. Coding progressed iteratively: insights from later interviews led to re-reading and, where necessary, re-coding of earlier material to maintain consistency and comparability across the dataset.

Second-order themes

Once several interviews and documents had been coded at the first-order level, the focus shifted to identifying patterns across codes. The goal was to move beyond respondent-centric descriptions and develop more abstract themes that captured recurring patterns, such as shared sources of uncertainty, common system drivers, and repeated coordination challenges. In ATLAS.ti, related first-order concepts were grouped into preliminary categories, with iterative adjustments as the analysis progressed. Codes were merged, split, or renamed to improve conceptual clarity and reduce redundancy.

Aggregate dimensions

Second-order themes were subsequently clustered into broader aggregate dimensions that represent system-level dynamics. Themes relating to different types of uncertainty, structural drivers and constraints, and coordination challenges were grouped to form higher-level constructs. The underlying coded excerpts were revisited to ensure that the abstractions remained empirically grounded. This process produced a set of system-level elements that capture how interviewees and documents characterise the hydrogen corridor, forming the empirical basis for the demonstration of ATR.

4

Case Study

This chapter describes the Canada-Netherlands hydrogen corridor. It frames the corridor as a system-of-systems that links upstream production in Newfoundland and Labrador with transatlantic logistics, European import infrastructure, and downstream demand in Northwest Europe. The chapter then establishes the baseline conditions that shape corridor feasibility by outlining the relevant technology set, the market context, and the policy and regulatory landscape on both sides. Together, these elements define the actors, interfaces, and uncertainties that the empirical analysis and ATR application build on.

4.1. System-of-Systems Context

This section places the Canada-Netherlands hydrogen corridor in its system-of-systems context. It outlines the strategic and geopolitical framing and then describes the corridor's configuration across upstream production, transatlantic logistics, European import infrastructure, and downstream demand.

4.1.1. Strategic and Geopolitical Corridor Framing

The development of a Canada-Netherlands hydrogen corridor takes place within a strategic and geopolitical context shaped by European import targets, Canada's export ambitions, and the Netherlands' role as a gateway for hydrogen flows into Northwest Europe. The EU policy framework, notably the European Green Deal and the Fit for 55 package, is reinforced by the REPowerEU plan, which sets a target of importing 10 Mt of renewable hydrogen by 2030 (European Commission, 2022). IEA (2024) notes that the EU's growing reliance on hydrogen imports is driven not only by decarbonisation objectives, but also by concerns over energy security and supply diversification.

The increasing global demand for hydrogen has led to export market opportunities for Canada. Canada's Hydrogen Strategy recognises that developing a clean energy industry for both domestic use and export will increase jobs, develop supply chains, support innovation and create an opportunity for economic growth (Government of Canada, 2020). The Strategy also identifies Europe as the priority export market, and the Canada-Netherlands Memorandum of Understanding (MoU) formalises cooperation on standards, trade rules, infrastructure and investment in clean hydrogen (Natural Resources Canada, 2025). Newfoundland and Labrador is explicitly presented as a first-mover export region, based on its combination of strong wind resources, deep-water ports and proximity to European markets (Government of Newfoundland & Labrador, 2024).

For the Netherlands, hydrogen imports are not only an energy transition objective, but a strategic industrial and logistical role, with national strategies emphasising early import infrastructure, ammonia carrier choices and cracking capacity, and backbone network integration to supply Northwest European industry (Ministerie van Klimaat en Groene Groei, 2024). The port of Rotterdam plays a central role in this strategy, with port and national infrastructure plans focused on linking maritime hydrogen and

ammonia imports to the developing hydrogen backbone and to industrial clusters in the Netherlands and neighbouring countries (Notermans et al., 2020).

4.1.2. Corridor Configuration and Regional Setting

The Canada-Netherlands hydrogen corridor is defined as the value chain linking renewable-based hydrogen production in Newfoundland and Labrador to import, handling, distribution, and end-use pathways centred on the port of Rotterdam and its Northwest European hinterland. In system-of-systems terms, the corridor spans four interconnected systems. First, the upstream supply segment in Newfoundland and Labrador, covering renewable electricity generation and conversion into exportable energy carriers, namely ammonia, as well as associated storage and port export operations. Second, the Atlantic logistics segment comprises maritime shipping that enables cross-border transport between the supply and demand regions. Third, the European entry segment in and around the port of Rotterdam, including import terminals, storage, and onward distribution into regional networks and industrial clusters. Fourth, the downstream demand segment across Northwest Europe, where imported molecules are allocated to end-use markets such as industrial feedstock, with reconversion to hydrogen treated as a possibility.

The projects that have advanced through the first competitive round of Crown land bidding in Newfoundland and Labrador for the upstream supply segment are shown in Figure 4.1. These projects represent approximately 380,000 hectares of allocated land across the island and include multi-phase wind-to-ammonia production facilities, export terminals, and associated storage and infrastructure (Government of Newfoundland and Labrador, n.d.-b). The four awarded projects represent a prospective export capacity of more than 3 MTPA of green ammonia in their initial phases, with the potential for significantly higher volumes as development progresses and additional phases reach FID. Together, these initiatives show the push to convert resource potential into export capacity.

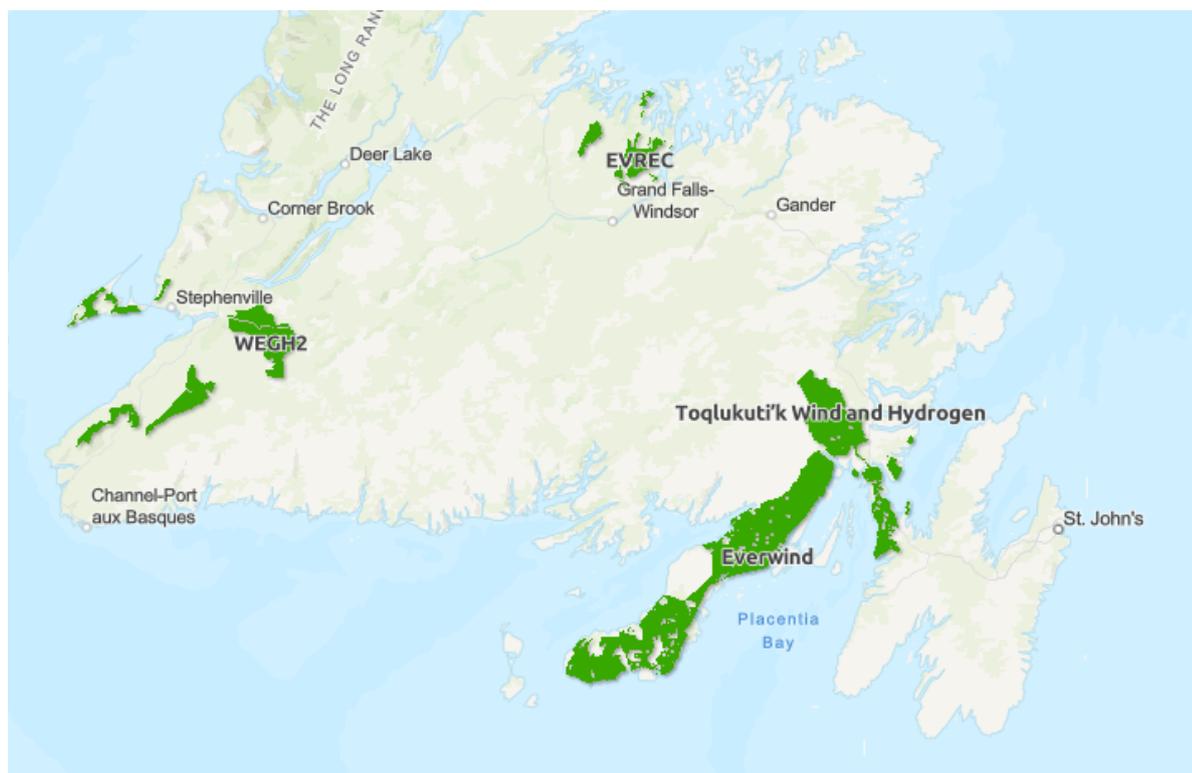


Figure 4.1: Map of green hydrogen projects in Newfoundland and Labrador (Government of Newfoundland and Labrador, n.d.-b)

On the import side, port authorities, network operators and national government actors are jointly plan-

ning import terminals, storage facilities and a hydrogen backbone. However, hydrogen import infrastructure in Northwest Europe is still at an early stage of development, and most large-scale public hydrogen networks are not expected to be fully operational before the early 2030s. Current rollout plans indicate delays in network connectivity between major industrial clusters, which constrains the ability to distribute imported hydrogen beyond port areas and creates uncertainty around the timing, scale, and system integration of large-scale imports (Buijs et al., 2025). At the same time, upstream project development in Newfoundland and Labrador is progressing in parallel, showing interdependence between the corridor's system components. The corridor can be understood as a co-evolving system-of-systems, with its eventual configuration depending on how production in Newfoundland and Labrador, transatlantic shipping, infrastructure development in Northwest Europe, and offtake interact over time.

4.2. Green Hydrogen and Ammonia Technologies

This section provides an overview of the technologies across the full green hydrogen and ammonia corridor. It distinguishes mature technologies from those that still limit scale-up, and covers the integrated set of production, conversion, storage, shipping, import, distribution, and end-use technologies needed to turn renewable electricity into exportable ammonia and enable its delivery and use in Northwest Europe, either as ammonia or as hydrogen after cracking.

4.2.1. Upstream Supply and Atlantic Logistics Technologies

The technologies described in this subsection follow the set-up of a large-scale hydrogen and ammonia production project in Newfoundland and Labrador, shown in Figure 4.2, as described by Strum (2024). The facility is planned to be operational from approximately 2030 until 2060. The project has completed feasibility studies and is currently in the front-end engineering design (FEED) phase. The project is based on a 3.5 GW onshore wind plant and a 150 MW solar PV plant, which together supply electricity to the hydrogen production facility. This facility includes up to 2.6 GW of installed electrolyser capacity, consisting of alkaline and PEM electrolysers, and is supported by above-ground hydrogen storage with a forecasted volume of 85,000 to 125,000 m³. To achieve a green ammonia production of approximately 1 MTPA, the project applies three parallel ammonia synthesis trains with a combined nameplate capacity of around 5,000 TPD. Ammonia is stored at the industrial facility in cryogenic double-walled tanks with an anticipated volume of 75,000 to 125,000 m³. The ammonia is piped from the industrial facility to the port via an underground ammonia line. The project has entered into a lease arrangement with an existing deep-water port nearby that can accommodate ammonia vessels. The project assumes a representative ammonia carrier of 50,000 DWT, using a standard industry practice ratio of 1.5 between terminal storage capacity and vessel capacity. These technologies are further elaborated in this subsection, alongside other possible technology options.

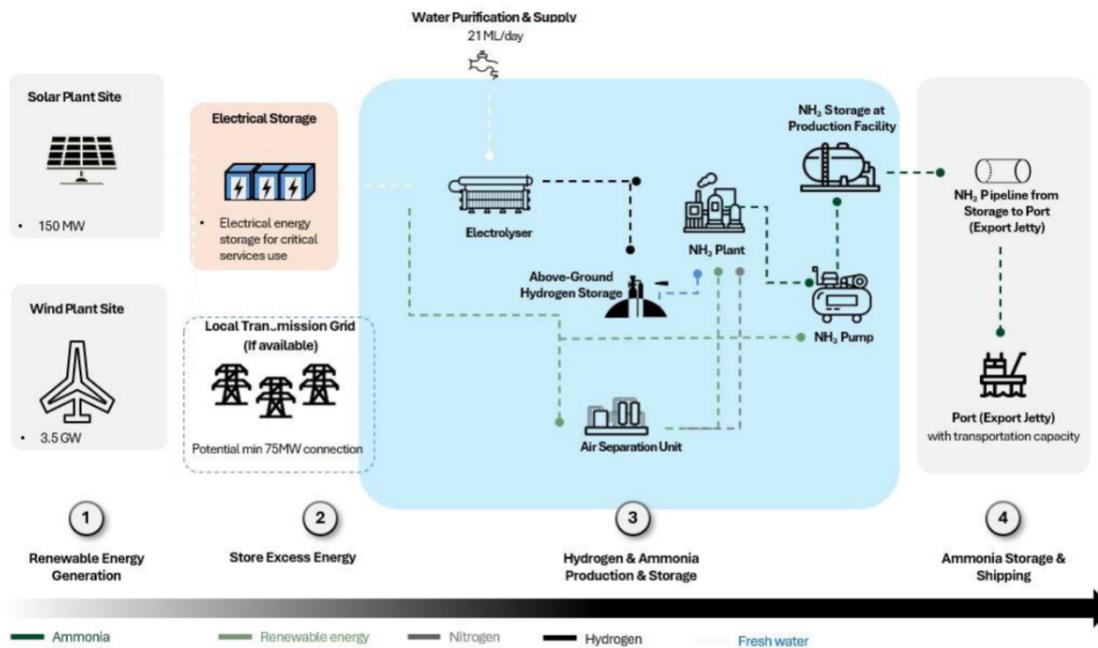


Figure 4.2: Green hydrogen and ammonia production process flow diagram (Strum, 2024)

Renewable Power Generation and Storage

Renewable electricity for large-scale hydrogen and ammonia production in Newfoundland and Labrador is primarily supplied by onshore wind farms, supported by solar photovoltaic (PV) systems and battery storage to stabilise power output (Strum, 2024). While wind provides most of the electricity, the solar PV can be used to provide power to the batteries when excess wind power is not available. Hydrogen- or biodiesel-fired turbines, ammonia-fired generators, and steam turbine systems can also be integrated into the system to provide additional flexibility and long-duration backup power (Strum, 2024). The electricity is transmitted through dedicated power lines to the hydrogen and ammonia production facilities (Strum, 2024). This configuration enables off-grid operation, allowing the production facilities to function independently from the provincial electricity network. A limited grid connection can be used for construction power, critical loads, and emergency supply. Renewable power generation and storage technologies are largely commercially available.

Electrolysis and Hydrogen Storage

Electrolysis is currently the main technology for producing renewable hydrogen, and several electrolyser types are commercially available or under development. Alkaline electrolysers remain the dominant technology, accounting for around 60% of global installed capacity (IEA, 2025). Alkaline electrolysers are fully mature with Technology Readiness Level (TRL) 9, and the advantage of this cost-efficient technology lies in the long lifetime and the absence of expensive and rare catalyst materials (Trattner et al., 2021). They operate with a liquid alkaline electrolyte and are suitable for large industrial installations. Proton exchange membrane (PEM) electrolysers are also fully mature with TRL 9 and offer faster response times and higher current densities than alkaline systems, making them suitable for operation with variable renewable electricity. PEM electrolysers can also produce high-purity hydrogen at higher pressures. However, PEM electrolysers rely on expensive and scarce platinum-group metal catalysts (Trattner et al., 2021).

Other electrolyser technologies are less mature but show strong innovation activity, based on IEA (2025) patent data. Anion exchange membrane (AEM) electrolysers (TRL 7) aim to combine the low-cost materials of alkaline systems with the compact design of PEM, but currently operate at a smaller scale and with shorter lifetimes (Trattner et al., 2021). Solid oxide electrolysis (SOEC) systems (TRL 8) work at high temperatures and can reach very high electrical efficiencies when heat is available, potentially from ammonia synthesis, but they have long start-up times and limited flexibility, making

them less suitable for variable renewable power supply (Trattner et al., 2021).

Electrolyser operation requires filtered, purified and demineralised water, which necessitates the installation of a water treatment system as part of the facility (Strum, 2024). Hydrogen produced by the electrolysers can first be stored in tanks near the production units to buffer short-term fluctuations and ensure a stable supply to the ammonia synthesis process. In addition, a centralised hydrogen storage system provides longer-term buffering capacity (Strum, 2024). Compressed gaseous hydrogen is the most common storage method for large-scale applications. Storage pressure involves a trade-off between space and energy use: lower pressures require larger storage volumes and higher capital costs, while higher pressures reduce space requirements but increase compression energy and operating costs. For very large capacities, underground storage in salt caverns or depleted gas fields is the most promising option, although its feasibility depends on local geological conditions (Trattner et al., 2021).

Ammonia Synthesis and Storage

Ammonia is produced by reacting nitrogen and hydrogen in the Haber-Bosch process. This reaction requires high temperature and pressure due to the strong bond in nitrogen, and iron-based catalysts are used to achieve practical conversion rates. This thermochemical synthesis route has been continuously optimised for more than a century and remains the dominant technology (Rouwenhorst et al., 2021). For green ammonia production, the same synthesis loop is combined with renewable hydrogen from electrolysis and nitrogen from an air separation plant. Conventional Haber-Bosch plants are designed for steady, continuous operation. Therefore, renewable-based systems typically rely on hydrogen and electricity storage to manage supply fluctuations (Tully et al., 2025). Recent research focuses on improving the operational flexibility and scalability of the Haber-Bosch reactor and associated units, allowing ammonia synthesis to follow variations in renewable energy supply more closely (Gu et al., 2026; Tully et al., 2025). In parallel, alternative ammonia synthesis routes, including electrochemical and plasma-based pathways, are being explored, but they remain at very early development stages (TRL 1-3) (Gu et al., 2026).

Ammonia is typically stored as a liquid in either refrigerated or pressurised tanks. Large-scale storage usually relies on cryogenic tanks, where ammonia is kept at atmospheric pressure and around $-33\text{ }^{\circ}\text{C}$, using insulated, double-walled vessels that are widely applied in the fertiliser and chemical industries (IRENA & AEA, 2022). Ammonia is a hazardous substance that is toxic in gaseous form. As pressurised liquid storage increases the risk of rapid large-scale release, ammonia is often preferentially stored as a refrigerated liquid at near-atmospheric pressure (IRENA & AEA, 2022).

Ammonia Export and Shipping

The export chain relies on mature technologies that are widely applied in the global ammonia and shipping industries, as ammonia is already an internationally traded commodity. Green ammonia is exported using specialised ammonia carriers that are loaded at a dedicated jetty terminal. The jetty is equipped with a loading arm or hoses, associated piping, venting and isolation systems, and control infrastructure to enable safe and efficient transfer (Strum, 2024). Ammonia carriers are typically double-hulled chemical tankers designed to transport liquefied ammonia either under refrigerated conditions at atmospheric pressure or under moderate pressure at ambient temperature (Royal HaskoningDHV, n.d.).

4.2.2. European Entry and Downstream Demand Technologies

This subsection outlines the technologies and infrastructure on the European import and demand side, focusing on ammonia handling and cracking in ports and the distribution pathways that connect imports to end users.

Ammonia Import, Storage and Cracking

The port of Rotterdam expects 10 MTPA of ammonia in 2030, and approximately 8 MTPA will be transported to the hinterland (Royal HaskoningDHV, n.d.). However, just over 8 MT ammonia import capacity is announced in the Netherlands, Belgium and Germany together in 2030, where only the existing OCI terminal expansion in the port of Rotterdam reached FID (Buijs et al., 2025). The announced hydrogen

import capacity is far behind the combined port ambitions and is also insufficient for the 2030 reference case if all projects are realised. Therefore, there is a need for additional ammonia import terminals equipped with large-scale refrigerated storage, dedicated unloading jetties, safety systems, and integrated ammonia cracking units to convert ammonia into hydrogen for onward distribution.

In addition, pilots are ongoing to confirm the potential to store hydrogen at large capacities in salt caverns in Northwest Europe. Six underground hydrogen storage sites have been selected, including one in the Netherlands and five in Germany, all based on salt caverns, with a combined working capacity of approximately 1.15 TWh by 2030 (Buijs et al., 2025). However, Buijs et al. (2025) show that the currently planned underground hydrogen storage capacity does not provide sufficient flexibility to ensure a reliable balance between hydrogen supply and demand, even with an optimised cross-border storage strategy. Additional flexibility at ports, such as local storage of hydrogen or hydrogen carriers, combined with flexible operation of facilities like ammonia crackers, can help reduce curtailment when underground storage is unable to meet system needs.

Ammonia cracking converts ammonia into hydrogen and nitrogen through catalytic thermal decomposition. The process requires high temperatures and a suitable metal catalyst. Current research focuses on improving catalysts and reactor designs to reduce costs, increase efficiency, and improve flexibility (Trangwachirachai et al., 2024). Despite these advances, further optimisation is needed to make ammonia cracking commercially viable at scale. VTTI is developing Project Amplify, which includes a proposed ammonia import terminal and ammonia cracking facilities at VTTI's terminal in Rotterdam (IEA, 2025). In parallel, a consortium led by the Port of Rotterdam Authority together with industrial partners has conducted a study on a large-scale central ammonia cracker in the port, aimed at producing approximately 1 MTPA hydrogen from imported ammonia (Fluor, 2023). This would require a multi-train facility, with the individual cracking units potentially located at a centralised plant or distributed across several sites.

Ammonia and Hydrogen Distribution

Ammonia that is not cracked can be transported by barge, rail, and road, which are already established transport modes in Northwest Europe, with a combined current capacity of approximately 1.7 MTPA (Royal HaskoningDHV, n.d.). Therefore, accommodating higher future volumes requires an expansion of fleets. Pipeline transport would be the most cost-efficient option, followed by rail, barge, and road transport. The Delta Rhine Corridor (DRC) is a major cross-border infrastructure initiative intended to connect industrial clusters in the Netherlands, including the port of Rotterdam and Chemelot, with demand regions in North Rhine-Westphalia in Germany (Buijs et al., 2025). Originally conceived to transport hydrogen and ammonia through a network of underground pipelines, the project has since been revised, and ammonia has been removed from the scope, even though WSP et al. (2024) has demonstrated in Zeeland that ammonia pipelines are technically feasible and can be operated safely. Inland shipping is expected to remain the preferred transport mode in the near term (Royal HaskoningDHV, n.d.).

The hydrogen backbone developed in the Netherlands relies on a combination of repurposed natural gas pipelines and newly built hydrogen infrastructure. The development is facing delays, however, and rollout remains uncertain. Simulations of Buijs et al. (2025) show that safe operation depends on maintaining pressure within strict limits, and that hydrogen's higher flow velocities and pressure fluctuations compared to natural gas can increase friction losses and mechanical stress in pipelines.

4.3. Green Hydrogen and Ammonia Markets

This section sets out the market baseline for green hydrogen and ammonia in Northwest Europe by summarising the main end-uses and why demand remains constrained.

Northwest Europe is an energy-intensive region that hosts large industrial clusters, including steel factories, refineries, ammonia plants, steam crackers, and chemical production facilities, all of which are hard to abate and rely on molecule-based energy carriers and feedstocks (Buijs et al., 2025). Imported

hydrogen carriers, particularly ammonia, are therefore expected to play a central role in the region's energy transition. Once imported, ammonia can follow two main end-uses. First, ammonia can be used directly as an industrial feedstock, especially in the chemical sector, where it replaces fossil-based ammonia in the production of fertilisers and other chemical products. Second, ammonia can serve as a transport carrier for hydrogen and be cracked back into hydrogen at dedicated facilities. The resulting hydrogen can then be used as a fuel for high-temperature industrial heat, electricity generation, or transport applications, and as a feedstock for steelmaking, synthetic fuels, and chemical processes (Buijs et al., 2025).

Green hydrogen and ammonia markets remain constrained by a persistent economic viability gap. This gap is defined as the difference between the value that end-users are willing to pay for green hydrogen and hydrogen-based carriers and the actual cost of producing and delivering it, which is estimated at 10-40% of total financing needs (ESMAP et al., 2024). The gap is driven by the large upfront investments required for renewable hydrogen projects and by the high perceived risks associated with new technologies, which increase the cost of capital (ESMAP et al., 2024). The policy instruments aimed to bridge the cost gap and establish demand are described in Section 4.4.

4.4. Green Hydrogen and Ammonia Policies and Regulation

This section outlines the policy and regulatory baseline that shapes corridor feasibility on both ends of the value chain. It summarises the main Canadian support and permitting framework for upstream production and export logistics, and the European rules for import infrastructure, certification and eligibility, demand mandates, carbon pricing, and revenue support mechanisms.

4.4.1. Policy and Regulatory Landscape for Upstream Supply and Atlantic Logistics

Hydrogen development in Canada takes place within a regulatory framework where federal and provincial authorities have complementary roles in investment support, permitting, and environmental regulation. At the federal level, Canada has introduced several financial mechanisms to support clean hydrogen production and related infrastructure. The Clean Hydrogen Investment Tax Credit (CHITC) provides a refundable tax credit for hydrogen projects based on their lifecycle carbon intensity and applies to both electrolysis and natural gas reforming with carbon capture, as well as to equipment for converting hydrogen into ammonia (Government of Canada, 2024). In addition, the Canada Growth Fund aims to reduce investment risk and accelerate the deployment of low-carbon hydrogen by supporting projects beyond the pilot phase, while the Canada Infrastructure Bank provides financing for decarbonisation projects and early-stage development activities (Government of Canada, 2024).

At the provincial level, Newfoundland and Labrador offers a Green Technology Tax Credit for capital investments in green activities, and has established a Wind-Hydrogen Fiscal Framework to provide fiscal clarity for wind-hydrogen projects (Government of Newfoundland & Labrador, 2024). The province also operates a Green Transition Fund to support businesses and institutions in greening existing operations and developing new opportunities linked to the growth of the green economy, including hydrogen-related activities (Government of Newfoundland & Labrador, 2024).

Large-scale hydrogen and wind-hydrogen projects in Canada may be subject to federal Impact Assessment (IA), depending on their potential adverse effects within federal jurisdiction. Project proponents must describe non-negligible impacts on areas such as aquatic ecosystems, migratory birds, federal lands, transboundary and marine environments, and Indigenous rights (Government of Canada, 2025b). Where relevant, federal assessments can also trigger additional authorisations under legislation such as the Fisheries Act, the Species at Risk Act and the Canadian Navigable Waters Act (Government of Canada, 2025a). At the same time, provincial governments retain authority over land use and electricity regulation, meaning that projects must also comply with provincial permitting and Environmental Assessment (EA) procedures. In Newfoundland and Labrador, proponents are required to submit an EA document outlining project impacts, mitigation measures, accident risks, cumulative effects, and public and Indigenous consultation before development approval is granted (Government

of Newfoundland and Labrador, n.d.-a, 2023).

In Canada, the maritime transport and port handling of ammonia are regulated under the Canada Shipping Act (Government of Canada, 2001) and the Transportation of Dangerous Goods Act (Government of Canada, 1992), which set safety and operational requirements for the transport of hazardous substances by sea. At the international level, ammonia carrier vessels must comply with the International Maritime Organisation's (IMO) International Gas Carrier Code, which establishes mandatory safety standards for the design, construction, and operation of ships transporting hazardous gases. In addition to regulation, the IMO (2023) Greenhouse Gas Strategy commits international shipping to net-zero emissions by around 2050 and promotes the uptake of low- and zero-emission fuels.

4.4.2. Policy and Regulatory Landscape for European Entry and Downstream Demand Segment

In the port of Rotterdam, the handling, storage and processing of hazardous substances, such as ammonia and hydrogen, are regulated by safety frameworks. The Seveso III Directive aims to prevent major industrial accidents involving dangerous substances and limit their impacts on human health and the environment (European Parliament & The Council, 2012). In the Netherlands, this is complemented by the Hazardous Substances Publication Series (PGS), which provides technical guidelines for the safe storage, handling and transport of substances such as ammonia and hydrogen (IEA, 2024). The EU hydrogen and gas decarbonisation package (European Parliament and Council, 2024a, 2024b), introduces a regulatory framework for hydrogen infrastructure, defining rules for network access, market organisation, and system operation to support the uptake of renewable and low-carbon gases.

EU legislation introduces several binding policy instruments that stimulate demand and define the eligibility criteria for renewable hydrogen and its derivatives. Under the revised Renewable Energy Directive (RED) III, Member States are required to increase the use of renewable fuels of non-biological origin (RFNBOs), including renewable hydrogen, particularly in industry and transport (European Parliament and Council, 2023a). The Delegated Acts on additionality, temporal correlation and greenhouse gas (GHG) accounting specify how renewable hydrogen must be produced and certified to qualify for compliance and support mechanisms (European Commission, 2023b, 2023c). While RED III sets the overarching renewable energy and RFNBO targets, ReFuelEU Aviation and FuelEU Maritime translate these objectives into binding, sector-specific fuel requirements for aviation and maritime transport (European Union, 2023).

The EU Emissions Trading System (ETS) puts a price on GHG emissions within the EU, and the Carbon Border Adjustment Mechanism (CBAM) under European Parliament and Council (2023b) complements this system by applying similar carbon costs to imported goods, preventing carbon leakage and maintaining a level playing field. Increasing the cost of fossil-based fuels and feedstocks improves the relative competitiveness of renewable hydrogen and ammonia in industrial and energy applications. To address the remaining cost gap between renewable hydrogen and fossil alternatives, the European Hydrogen Bank uses Contract for Difference (CfD)-type of competitive auctions to reduce uncertainty by guaranteeing a fixed revenue level and helping to bridge the gap between production costs and market prices (European Commission, 2023a). While the primary focus is on scaling up hydrogen production within the EU, the Hydrogen Bank also includes mechanisms to facilitate imports by linking non-EU suppliers with European offtakers.

4.5. Case Study Summary

This section summarises the case study context and its main uncertainties. As shown in Table 4.1, the emerging Canada-Netherlands hydrogen corridor is shaped by the interplay of multiple system segments and a set of public and private actors, each operating under substantial uncertainty. The corridor functions as a coupled socio-technical system in which technology readiness, infrastructure build-out, investment conditions, and policy and demand signals co-evolve. This configuration means that progress in one part of the value chain is highly contingent on developments elsewhere, and success will depend on synchronising investment decisions across multiple technologies, markets, and

policy regimes, none of which are yet fully stabilised.

The PESTLE analysis in Appendix A provides a full overview of the key political, economic, social, technological, legal, and environmental drivers shaping corridor development. These drivers function as the baseline context for the subsequent empirical analysis in Chapter 5.

Table 4.1: Case study summary of system-of-systems segments, actors, and main uncertainties (no relationship across rows)

System-of-Systems Segments	Actors	Main Uncertainties
<p><i>1. Upstream supply</i> Renewable electricity is converted into exportable ammonia in Newfoundland and Labrador, including storage and port export facilities.</p> <p><i>2. Atlantic logistics</i> Maritime shipping transports ammonia from Canada to the EU.</p> <p><i>3. European entry</i> The port of Rotterdam receives, stores, and distributes ammonia (and potentially cracked hydrogen).</p> <p><i>4. Downstream demand</i> Ammonia (or hydrogen) is distributed to and used by industrial end-users in Northwest Europe.</p>	<p><i>1. Government and Public Authorities (GOV)</i> Set policy frameworks, provide permits, and support infrastructure development.</p> <p><i>2. Financial Institutions (FIN)</i> Provide capital, risk instruments, and investment support.</p> <p><i>3. Energy Producers & Project Developers (PD)</i> Develop renewable power, hydrogen, and ammonia production projects.</p> <p><i>4. Port Authorities & Infrastructure Operators (PIO)</i> Develop and operate terminals, cracking, storage, pipelines, and grids.</p> <p><i>5. Shipping and Logistics Companies (SLC)</i> Transport hydrogen carriers across maritime and inland routes.</p> <p><i>6. Technology Researchers & Providers (TRP)</i> Research, develop, and supply electrolyser, cracking, storage, and conversion technologies.</p> <p><i>7. Offtakers (OFF)</i> Consume hydrogen or ammonia for industrial and energy applications.</p> <p><i>8. Local Communities & Workforce (COM)</i> Local residents, workers, and communities affected by siting, construction, and operations.</p>	<p><i>1. Technology scale-up in hydrogen and ammonia production</i> Wind, electrolysis, and Haber-Bosch are fully mature, but it is unclear how quickly integrated wind-to-ammonia systems can scale.</p> <p><i>2. Costs and investment risk</i> High capital costs combined with uncertain revenues create financial uncertainty for investors.</p> <p><i>3. Policy stability and regulatory frameworks</i> Despite policy ambitions, the long-term stability of EU and national support schemes, certification rules, and import criteria remains uncertain.</p> <p><i>4. Timeline of European hydrogen infrastructure</i> Delays in the rollout of the hydrogen backbone make the timing of large-scale distribution uncertain.</p> <p><i>5. Demand development and offtake security</i> Future demand for green hydrogen and ammonia remains policy-driven and economically uncertain, slowing investment decisions.</p>

In addition to the actors in Table 4.1, there are Integrated Value Chain Actors (IA) that operate across multiple segments of the hydrogen and ammonia value chain, for example, companies that develop and operate production and infrastructure while also acting as their own offtaker.

5

Data Analysis and Results

This chapter applies the ATR model as set out in the literature review in Chapter 2. Where Chapter 2 outlined ATR's building blocks, system scope, evidence base and default plan, roadmap, and adaptation plan, this chapter puts the first two into practice by using the Gioia methodology detailed in Chapter 3 to structure how actors describe the system dynamics shaping the Canada-Netherlands hydrogen corridor. The analysis brings these perspectives together into first-order terms (FOs), second-order terms (SOs), and aggregate dimensions that characterise the corridor's underlying mechanisms. These are interpreted from the perspective of the Newfoundland and Labrador project developer, who operates in the upstream supply system that is the focus of the ATR application. Together, these steps refine the system scope introduced in Chapter 4, defining success for the developer. These empirical elements form the foundation from which the default plan, roadmap, and adaptation plan are constructed in the remainder of the chapter, completing the application of ATR's building blocks.

5.1. Gioia Analysis: Defining the System Scope and Developing the Evidence Base

Building on the system-of-systems context established in the case study in Chapter 4, this section uses the Gioia methodology to code interview and document evidence and translate actors' perspectives into the concepts needed for ATR. It thereby refines the system scope for the Canada-Netherlands hydrogen corridor and defines success for the Newfoundland and Labrador project developer.

5.1.1. First- and Second-Order Terms

This subsection describes the first- and second-order terms that form the empirical foundation of the Gioia analysis. During the interviews, actors described factors shaping the development of the Canada-Netherlands hydrogen corridor, including uncertainties, drivers, enabling conditions, and constraints; these were subsequently coded into first-order terms and framed as opportunities and vulnerabilities. The document analysis was used to contextualise and deepen interview statements and to interpret the first-order terms from a project developer's perspective. The full list of first-order terms, illustrative quotes, and the supporting document-based context is provided in Appendix C. Across the interviews, 40 first-order terms were identified.

Example box: Gioia analysis first-order term with illustrative quote and description

First-order term (vulnerabilities & opportunities)

Low-cost renewable power is the primary driver of the levelised cost of hydrogen (LCOH) and makes Canada a competitive production country.

Illustrative quote

PD&IA 2: "When you look at the LCOH, that is a key factor. You can break it down into two components: the cost of hydrogen production (the facility) and the cost of power. And you'll see that the cost of power is actually the main driver for going to Canada: they have a very strong renewable energy base, with many full-load hours per year. ... As a result, you get relatively low electricity costs. ... Behind the LCOH, in my view, are primarily the LCOE and the cost of hydrogen production. And those vary depending on the technology and the location."

Description/interpretation for actor based on documents

The dominant driver behind LCOH is the cost and availability of renewable electricity. Newfoundland and Labrador offers an attractive proposition due to a clean grid, high renewable potential, and high full-load hours, which reduce electricity costs. Peacock et al. (2024) analyse a similar scale hydrogen export from Atlantic-Canada to the port of Rotterdam, concluding a LCOH delivered via ammonia of approximately \$6.75/kg H₂, which is cost-competitive with IEA forecast green hydrogen market prices.

While many concepts were shared among the actors interviewed, a few issues revealed divergences. First, respondents differed on which end uses of ammonia are most suitable, reflecting contrasting assessments of feasibility and acceptability (FO 28). Second, expectations about infrastructure readiness in the EU varied, indicating different levels of confidence in current plans and institutions (FO 30-33). Third, views diverged on Canada's long-term export orientation, balancing domestic priorities against strategic trade ambitions (FO 12). These disagreements are captured in the first-order terms.

The first-order terms provide the empirical grounding for the second-order themes. Taken together, they show that system development is shaped by conditions and uncertainties that can materialise as both vulnerabilities and opportunities, depending on how actors anticipate them and adapt their choices over time. The second-order themes represent the categories that emerged from the iterative coding process. Each theme clusters first-order terms into an underlying mechanism relevant for the functioning of the Canada-Netherlands hydrogen corridor. Table 5.1 summarises these 15 themes. SO 15 is an exception, as it does not describe the corridor itself but instead captures how actors plan for uncertainty and use roadmaps within their roles.

Table 5.1: Second-order terms and descriptions

#	Second-order term	Description
1	Technology Integration & Operational Flexibility	System integration choices (e.g. storage, turndown) determine whether variable renewables can be converted into stable hydrogen/ammonia output without major efficiency losses.
2	Technology Maturity & Production-Conversion Performance	Technology selection and maturity (e.g. electrolyzers, synthesis design) drive conversion efficiency, capital expenditures (CAPEX) and performance risk.
3	Supply Cost & Project Development	Project viability is shaped by the cost structure and scale dynamics (especially power cost, CAPEX intensity and utilisation), which determine whether phased investments are economic under uncertainty.
4	Industrial & Supply-Chain Capacity	Workforce availability and equipment manufacturing/logistics constraints can delay delivery and raise costs.
5	Demand Formation & Offtake	The ability to secure long-term offtake under commercially acceptable terms determines whether projects can reach FID and sustain operations beyond early phases.
6	Sectoral Application & Carrier / Fuel Choice	Uncertainty about end-use adoption and carrier preference (ammonia vs alternatives) shapes infrastructure needs, product specifications and the durability of demand.
7	Safety & Environment	Ammonia toxicity and lifecycle environmental impacts translate into design, operating and monitoring requirements.
8	Social Acceptance	Project continuity depends on sustained support among Indigenous communities, local stakeholders and affected land/sea users.
9	(Public) Infra Alignment & Spatial Planning	Export feasibility depends on alignment with power grids, storage options and siting constraints, as well as with downstream network and terminal connectivity.
10	Regulation, Standards & Certification	Eligibility, market access and value depend on evolving certification and regulatory rules (e.g. RED/RFNBO), which require measurable compliance and cross-jurisdictional alignment.
11	Permitting & Legal Procedures	Multi-level approvals and legal thresholds (e.g. provincial/federal) create timing and design risk and can constrain feasible project configurations.
12	Public Finance & Risk-sharing Instruments	Public capital, tax credits and revenue-support mechanisms reduce financing cost and market risk, enabling earlier investment despite the cost gap.
13	Policy Stability, Geopolitics & International Commitment	Market formation depends on stable, credible policy commitments and international rules, while geopolitical shifts can accelerate or undermine demand and project development.
14	Collaborative Public-Private Market Coordination	As the value chain is interdependent, coordination across firms and public actors is required to align timelines, share infrastructure and reduce mutual hold-up risk.
15	Planning Under Uncertainty	Actors use roadmaps, base cases and scenario sets to structure decisions and update plans as policy, technology and demand evolve.

5.1.2. Aggregates

The second-order terms shown in Table 5.1 interact with one another. These interactions reveal higher-level patterns across the corridor's underlying mechanisms, forming the aggregate dimensions. The aggregates represent the most abstract level of the Gioia structure, grouping multiple themes into a set of overarching dynamics that shape how the corridor develops, as described in this subsection.

Technology choices are described by the actors as decisive for project efficiency and cost, both on the production, import, and end-use side, while integration challenges, especially managing variable renewables, create operational trade-offs that must be engineered. Pilots and demonstrations are presented to de-risk these choices before scaling. The aggregate 'Technology & R&D' therefore defines the

technical space within which the rest of the system operates (SO 1-2). It captures how efficiency limits, carrier pathways, conversion performance, and system-integration requirements set what is technically feasible. These conditions shape risk perceptions and design choices that feed into cost structures on the supply side, viable end-use options on the demand side.

Actors describe supply scale-up as constrained by capital and execution capacity. As investment is typically only committed once offtake is secured, projects tend to progress in sequenced phases rather than being built ahead of demand. At the same time, workforce mobilisation and equipment lead times limit the achievable construction pace. The aggregate 'Supply Development' reflects the conditions under which ammonia can actually be produced and exported at scale (SO 3-4). It combines resource and labour conditions, supply-chain capacity, and exposure to macro-financial risk. Whereas the technology space addresses what could be built in principle, supply captures whether projects can be delivered competitively in practice. These dynamics are closely linked to policy coordination. Public finance tools and infrastructure decisions can reduce perceived risk and make projects economically viable.

The actors consistently treat demand commitments as the key condition for FID and sustained operation. They also highlight uncertainty about which end uses will absorb volumes and whether carrier preferences remain aligned with infrastructure and specifications. The aggregate 'Demand Development' captures how demand is shaped through offtake structures, willingness-to-pay, sector-specific applications, and competition with conventional alternatives (SO 5-6), as well as how policy ambitions are translated into demand commitments. The data show that demand does not follow from supply but is created through instruments such as mandates, standards, and support mechanisms. Interactions between supply conditions and demand formation are therefore modelled as mediated by policy.

Across the interviews, several issues are consistently described as non-negotiable boundary conditions that determine what is feasible. The aggregate 'Systemic Constraints' represent limits that bound what is possible in terms of both supply and demand development (SO 7-11). Environmental and safety norms, permitting and certification requirements, land-use and spatial planning, social acceptance processes, and public infrastructure roll-out restrict where, how, and how fast projects can move.

Actors describe corridor development as policy-driven and therefore exposed to shifts in policy priorities and geopolitics. Projects are capital-intensive and highly sensitive to financing conditions, so public finance tools and risk-sharing instruments are used to lower perceived risk and bring projects to FID. The value chain is highly interdependent, which makes coordination and shared infrastructure planning critical. The 'Policy & Governance' aggregate captures how policy can accelerate progress through stable targets and implementation, public finance tools, innovation support, and coordinated market-building. However, it can also slow progress when commitments weaken, or rules change (SO 12-14), thereby impacting investor confidence.

Together, the aggregates describe how the Canada-Netherlands corridor functions as a system-of-systems. They capture interdependent dynamics that jointly shape how the corridor evolves under uncertainty (SO 15). The five aggregate dimensions in Figure 5.1 group the second-order themes into a set of higher-level system aggregates that structure this socio-technical development.

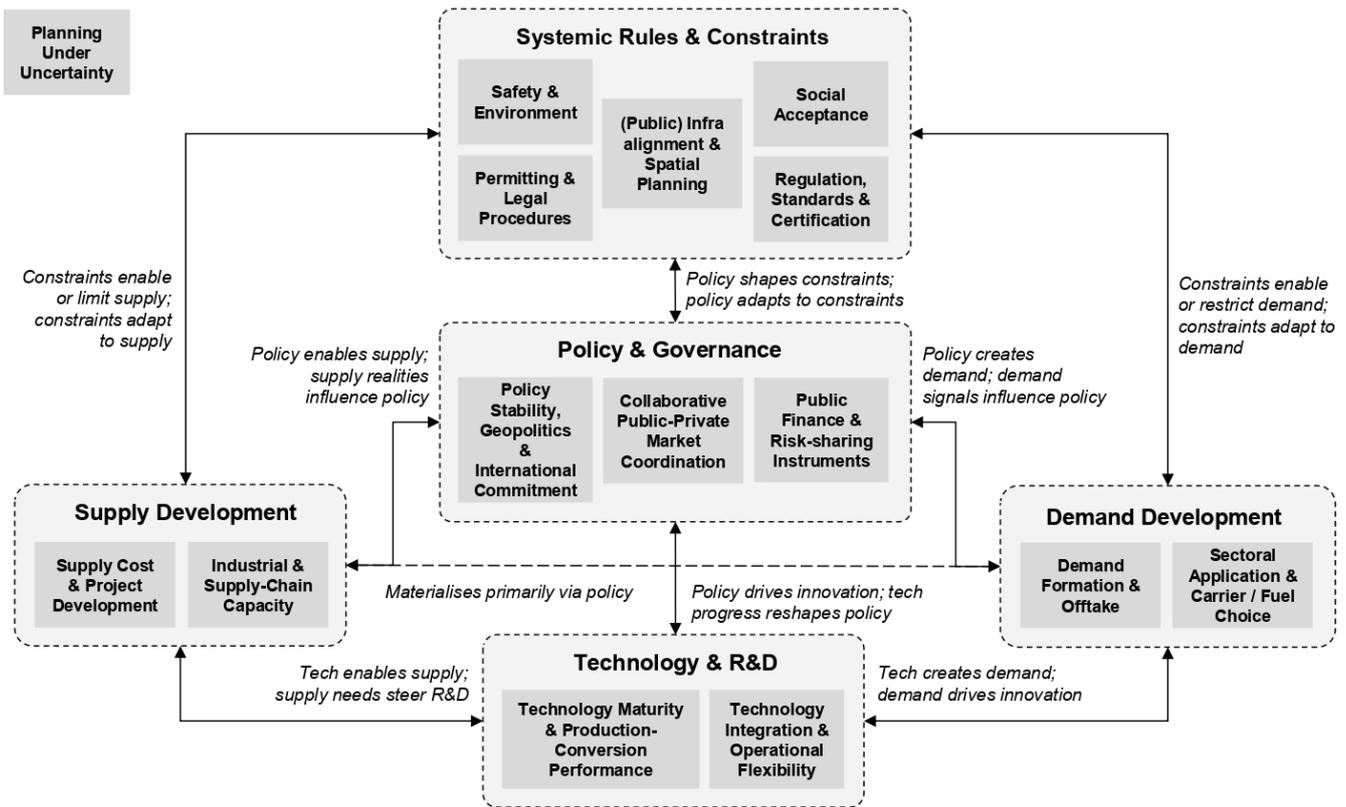


Figure 5.1: Overview of second-order themes grouped into aggregates

5.1.3. Definition of Success

This subsection derives a definition for success, based on the empirical structure of the Gioia analysis. The horizon extends to 2060, reflecting the project’s real planning horizon, long-term decarbonisation objectives, and typical infrastructure operating life.

Success for the Newfoundland and Labrador project developer in the Canada-Netherlands corridor is defined as delivering a safe, compliant and investable green ammonia export project. This means securing binding, financeable offtake for each major investment step (FO 7-8), maintaining social acceptance (FO 14-15), maintaining continuous compliance with permits, ammonia safety standards, environmental performance and certification requirements (FO 5-6, 13, 26), and maintaining the capability to operate commercially and technically as external conditions evolve, such as demand formation (FO 23-25), policy support and implementation (FO 34-37), EU infrastructure readiness (FO 30-33), and financing conditions (FO 17-19). As these drivers are partly outside the developer’s control, success is best expressed as meeting commitments and maintaining operability under uncertainty, rather than as achieving a single fixed production volume all the way to 2060.

The Gioia results show that the ultimate scale is largely dependent on external systems. A lower-scale operation or stopping the project before 2060 is therefore not automatically a failure. It can still be successful if the project delivers contracted volumes for the agreed period, avoids major safety/environmental breaches (FO 5-6), remains certification-compliant (FO 13, 26), and winds down when market or policy conditions no longer support continued operation (FO 23-25, 34-37). Early run-off before 2060 indicates non-success when it results from avoidable breakdowns in the developer’s controllable responsibilities, most clearly committing to major construction without sufficiently financeable offtake (FO 7-8), losing permit, safety, environmental, or certification compliance due to inadequate design or operational control (FO 5-6, 13, 26), or triggering shutdown through preventable stakeholder conflict and failures in social acceptance (FO 14-15). Secondly, early run-off indicates non-success when it results from failure to anticipate adverse external shifts that structurally remove the basis for continued operation, so the developer cannot recover its investment, such as when regulatory changes

make the product ineligible (FO 13, 26), infrastructure delays prevent access to buyers (FO 30-33), or financing conditions worsen to the point that continued operation is no longer viable (FO 17-19).

5.2. Developing the Default Plan

Building on the system scope, success definition, and evidence base established in Section 5.1, this section develops the default plan for the Newfoundland and Labrador project developer by translating the empirically identified first-order terms, expressed as vulnerabilities and opportunities, into basic plan actions and identifying the adaptation tipping points that mark when the default course can no longer meet the success definition.

5.2.1. Basic Plan Actions

To derive basic plan actions based on the Gioia analysis, each first-order term was first linked to its main actor(s). This actor mapping enabled the first-order terms to be sorted by the degree to which they fall within a project developer's direct control, can be influenced only partially through coordination with other actors, or represent conditions to which the developer is primarily exposed:

- Direct control (FO 1-6): Terms that relate to internal design and configuration choices, such as modular and phased scale-up, system integration for operational flexibility, and embedding safety and environmental performance in the project design.
- Partial control/influence (FO 7-16): Terms that require alignment with other actors across the value chain, most notably securing bankable offtake and shaping contractual structures (FO 7-8), coordinating innovation and export readiness (FO 9-10), matching project development with domestic and cross-border infrastructure readiness (FO 11-12), navigating certification and regulatory requirements (FO 13), and maintaining social acceptance and permitting progress (FO 14-16).
- Exposure (FO 17-40): Terms reflecting boundary conditions set by external systems. These include financing conditions and macro-financial volatility (FO 17-19), policy stability and geopolitics (FO 34-38), regulatory and certification evolution (FO 26-27), demand formation and sectoral uptake (FO 22-25, 29), EU infrastructure timing and logistics constraints (FO 30-33), and workforce or equipment supply-chain limitations (FO 20-21).

The first-order terms are grouped according to their associated second-order terms and aggregate dimensions, which revealed clusters of related issues that translate into courses of action for a project developer. The full mapping, from actors and the control/influence/exposure categorisation to the second-order and aggregate groupings and the resulting basic plan actions, is provided in Appendix C. Each basic plan action was then elaborated, drawing on the content of the underlying first-order terms and their document-based contextualisation. These actions were formulated as combinations of mitigating, hedging, seizing, and shaping actions, with each action typically comprising one to three of these action types. The full description of the resulting action set is provided in Appendix D, and an overview is provided in Table 5.2.

Table 5.2: Overview of basic plan actions and action types

#	Basic plan action	Action type	Description
1	Phased and modular by design	Shaping; Hedging	Built in phased scale-up and modular capacity so the project can start at a financeable scale and expand stepwise as demand, policy support, and infrastructure readiness evolve, while using each scale-up phase as an opportunity to (re)select and integrate the most suitable technologies available at that time.
2	Safe and sustainable by design	Shaping; Mitigating; Defensive	Embed safety and environmental performance into ammonia design and operations, supported by monitoring, procedures, and emergency response planning to maintain compliance with permits, safety standards, and environmental and certification requirements.
3	Secure bankable off-take contracts	Shaping; Hedging	Secure binding, financeable offtake before committing to construction, focusing first on established markets with existing ammonia and hydrogen demand (e.g., fertilisers, chemicals, and refining) to realise volumes and revenues while the newer end-use markets mature.
4	Coordinate innovation and export	Shaping; Hedging	Align with innovation programmes and value-chain partners to de-risk technology and enable export readiness, including coordination with governments, ports, and shared infrastructure where relevant.
5	Domestic infrastructure-aligned development	Shaping; Hedging; Seizing	Configure production and phasing to match domestic grid/storage realities.
6	Secure social acceptance	Shaping	Maintain social acceptance through sustained engagement and alignment with Indigenous communities and other local stakeholders across the full project lifecycle.
7	Secure full-scope permitting and land control	Shaping; Mitigating; Hedging	Secure permits and land rights for the full project scope early, while managing regulatory triggers (including federal processes) through design, siting, and phasing choices.
8	Secure public capital and demand-side support	Seizing	Combine Canadian capital support with European demand-side mechanisms to enable investment (e.g., tax credits, concessional loans/guarantees; CfDs, H2Global-style tenders).
9	Workforce and supply-chain alignment	Shaping; Hedging	Align the scaling pace with realistic workforce mobilisation in a tight regional labour market and OEM capacity (e.g. long lead times for electrolysers and turbines can delay delivery), and use standardisation and phasing to keep execution feasible.
10	Certification aligned project design	Shaping; Hedging	Design metering, accounting, and contracting so regulatory eligibility and lifecycle performance can be proven and verified, enabling market access through certification alignment.
11	End-use-flexible ammonia design	Shaping; Hedging	Design for certified, high-purity ammonia and flexible product conditioning (e.g., impurity control/spec adjustments), while reserving space and interfaces for future add-ons, such as for bunkering if the dominant end use shifts.
12	EU infrastructure-aligned export design	Shaping; Hedging	Align export assumptions with European backbone rollout by prioritising port-based pathways early and preserving the option to connect to pipelines/cracking/storage as infrastructure becomes available.
13	Policy alignment and dialogue	Shaping; Hedging	Maintain active policy and technical dialogue (including under the Canada-Netherlands MoU) so evolving targets, standards, and support schemes are translated into project design.

5.2.2. Adaptation Tipping Points

This subsection identifies the adaptation tipping points (ATPs) that follow from the vulnerabilities and opportunities revealed in the Gioia analysis. Adaptation tipping points mark the conditions under which

the current course of action is no longer expected to meet the success definition derived in Section 5.1.3.

For the Newfoundland and Labrador project developer, two types of adaptation tipping points emerge: one that occurs before FID, when the project has not yet materialised (ATP1), and one after FID, when ongoing operation can no longer be sustained under the required conditions (ATP2). Together, these adaptation tipping points reflect the boundary conditions that determine whether the project can be initiated and whether it can remain viable throughout its lifetime up to 2060. They arise from clusters of first-order terms across multiple Gioia dimensions.

The project reaches ATP1 when it cannot meet the conditions for taking FID within the decision window. This outcome arises when one or more of the following conditions persist:

- No bankable long-term offtake can be secured (FO 7-8, 23, 25). Offtake is repeatedly identified as the primary precondition for financeability. Without contracted volumes under acceptable terms, the project cannot be financed, regardless of its technical feasibility.
- Permitting, land control or legal certainty cannot be obtained (FO 14-16). Multi-level Canadian permitting introduces timing and scope risk; inability to secure full-scope approvals, provincial and federal, prevents FID.
- Certification or regulatory requirements remove eligibility (FO 13, 26). If evolving RFNBO, GHG accounting or grid-integration rules make the project non-eligible for green markets, the project cannot access demand or revenue-support instruments.
- Social acceptance cannot be secured (FO 14-15). Loss of Indigenous support or unresolved community concerns can block development.
- Financing conditions deteriorate beyond viability (FO 17-19). Excessively high Weighted Average Cost of Capital (WACC), macro-financial instability, or weakened public capital support can make the project unfinanceable.
- Infrastructure readiness does not materialise in time (FO 11-12, 30-33). Inability to align domestic storage/grid constraints or EU import/backbone timing with the investment schedule undermines the economic basis.

If these enabling conditions do not converge, the project cannot meet the success definition: a safe, compliant, investable, financeable export project. In this situation, the only feasible response is pre-construction early run-off. Importantly, this adaptation tipping point reflects structural constraints, not a failure in project execution.

The project reaches ATP2 when the conditions needed to justify continued operation and reinvestment no longer hold. The Gioia evidence shows that post-start adaptation tipping points arise under two mechanisms:

- Structural loss of commercial viability occurs when the project can technically operate but cannot secure new long-term revenue streams:
 - Failure to (re)contract volumes at acceptable terms after initial offtake expiry (FO 7-8, 22-23).
 - Persistent EU infrastructure delays preventing market access (FO 30-33).
 - Policy reversals, regulatory erosion or weakening demand mandates (FO 24-25, 34-37).
 - Loss of access to revenue-support schemes (CfDs, H2Global, hydrogen bank) (FO 18-19).
- Structural loss of compliance or operability occurs when the project can no longer satisfy minimum requirements for legal, safe, or certified operation:
 - Loss of certification eligibility (GHG intensity, additionality, temporal matching) (FO 13, 26).
 - Safety or environmental non-compliance (FO 5-6, 15).
 - Critical permitting changes or inability to maintain required permits (FO 14-16).

- Inability to maintain or replace key components due to supply-chain collapse (FO 20-21).

In these cases, the project no longer meets the success definition, and an early run-off becomes the only viable path. Importantly, not all early run-off is an adaptation tipping point. In line with the success definition, if the project meets contractual commitments, remains permit- and certification-compliant, and winds down only because market conditions weaken after value recovery, then early run-off does not constitute an adaptation tipping point.

5.3. Constructing the Roadmap

This section constructs the adaptive roadmap by translating the default plan and adaptation tipping points developed in Section 5.2 into time-sequenced pathways with corresponding actionlines, milestones, and decision points. Together, these elements show how the project can progress, adjust, or switch course as conditions evolve.

5.3.1. Adaptive Pathways

This subsection develops adaptive pathways that translate the definition of success into development trajectories for the Newfoundland and Labrador project. Building on the Gioia analysis, the pathways show how the developer can adapt the project configuration as external conditions change over time. The pathways mainly differ in the chosen build scale. Most parts of the production system can be scaled in steps by adding capacity over time (renewable generation, electrolysers, storage, and ammonia synthesis). The port connection, however, is treated as a one-off requirement that is built for the full-scale (e.g., berth/quay works and loading arms), so scale changes are mostly implemented on the production side rather than through port expansions. An overview of the pathways and their capacities is shown in Table 5.3.

In the full-scale pathway, the developer implements the reference configuration as planned, described in Section 4.2. This pathway represents the case in which demand materialises sufficiently through long-term offtake, policy support becomes implementable and durable, and the export route and certification conditions evolve in a way that preserves market access. The mid-scale and low-scale pathways represent outcomes when external conditions support an initial project but do not yet justify full-scale commitment. In both cases, the developer builds the same type of system but at a smaller scale. These pathways capture the uncertainty that demand formation and policy implementation can lag, and that infrastructure readiness and financing conditions can constrain near-term feasibility. Starting at a smaller scale allows the developer to meet initial commitments, begin operation, and demonstrate performance while retaining the option to expand later. Consistent with the basic plan actions, these pathways assume that the initial FEED and permitting approach anticipates later scale-up, even if the first construction scope is smaller, by securing land and obtaining permits for the full-scale project footprint and maximum intended capacity upfront.

Once the initial scale has been built and commissioned, further expansion becomes possible. Therefore, a scale-up pathway is included that enables transitions to a larger scale by adding the required upstream capacity alongside the existing operation. Each expansion pathway is treated as a new investment package, as it requires its own engineering finalisation, contracting and financing work, and a renewed FID based on updated technology, market, and policy conditions. To allow the full-scale configuration to grow when conditions are favourable, an expanded-scale pathway is added in which the developer installs one or two additional ammonia synthesis trains beyond the full-scale design. Unlike scaling within the originally permitted site area, this pathway may require securing additional land access and obtaining new or amended permits, and it may place higher demands on the port interface. It therefore represents a different pathway, not only extending capacity but expanding the project scope.

To reflect the possibility that the corridor does not mature as expected, the pathway set also includes outcomes in which the project does not reach, or cannot sustain, operation through 2060. In the early run-off pathway (pre-construction), the project does not proceed to construction because the basis for investment cannot be established, for example, because offtake, enabling policy support, permitting

certainty, or workable financing conditions fail to materialise. This pathway represents an adaptation tipping point; if the preconditions are not met, the only viable response is to stop rather than lock in major capital exposure. In addition, for each build scale (small, mid, full, and expanded), an early run-off pathway is included in which operations stop before 2060. A typical reason is that initial long-term offtake contracts expire and cannot be replaced on terms that sustain continued operation. In line with Section 5.2, early run-off is not necessarily an adaptation tipping point if the project has met its contractual commitments and recovered its investment during operation, remained compliant with permits, ammonia safety standards, environmental requirements and certification, and winds down only once market or policy conditions no longer support viable operation.

Lastly, a downscaled operation pathway is included for each build scale. In this pathway, the developer keeps the project running below nameplate capacity for a sustained period, for example, by lowering utilisation or operating fewer trains. Unlike a shutdown, operations remain in place, so output can be increased again if, for example, demand or policy support improves. Downscaled operation, therefore, reduces losses while preserving operational continuity under prolonged uncertainty.

Table 5.3: Overview of pathways

Pathway	Description
Early run-off pathway (pre-construction)	When the basis for investment cannot be established, the project does not proceed to construction.
Low-scale pathway	Commits to operating a facility consisting of: 1.2 GW wind and 50 MW solar PV; 1.2 GW electrolysers; hydrogen storage ~28,000-42,000 m ³ ; 1 ammonia synthesis train producing 0.3 MTPA ammonia; ammonia storage ~25,000-42,000 m ³ . A full-scale ammonia export berth is developed and equipped with loading arms.
Mid-scale pathway	Commits to operating a facility consisting of: 2.3 GW wind and 100 MW solar PV; 1.7 GW electrolysers; hydrogen storage ~57,000-83,000 m ³ ; 2 ammonia synthesis trains producing 0.7 MTPA ammonia; ammonia storage ~50,000-83,000 m ³ . A full-scale ammonia export berth is developed and equipped with loading arms.
Full-scale pathway	Commits to operating a facility consisting of: 3.5 GW wind and 150 MW solar PV; 2.6 GW electrolysers; hydrogen storage 85,000-125,000 m ³ ; 3 ammonia synthesis trains producing 1.0 MTPA ammonia; ammonia storage 75,000-125,000 m ³ . A full-scale ammonia export berth is developed and equipped with loading arms.
Expanded-scale pathway	Commits to operating a facility consisting of: 4.7-5.8 GW wind and 200-250 MW solar PV; 3.5-4.3 GW electrolysers; hydrogen storage ~113,000-208,000 m ³ ; 4-5 ammonia synthesis trains producing 1.3-1.7 MTPA ammonia; ammonia storage ~100,000-208,000 m ³ . Port facilities must be expanded, including additional berth capacity and loading arms, to accommodate the higher export volumes.
Intermediate scale-up pathway	Enables transitions to mid-scale, full-scale, or expanded scale by adding the associated upstream capacity on top of the assets already in place and in operation.
Early run-off pathway (post-start of operation)	Operations are stopped early when conditions shift in ways that remove the commercial basis for operation.
Downscaled operation	Assets are operated below their nameplate capacity for a sustained period, because full utilisation may not be possible under weaker conditions for the commercial basis of operation.

5.3.2. Actionlines, Milestones and Decision Points

The pathways defined in Subsection 5.3.1 describe alternative development trajectories for the Newfoundland and Labrador project. This subsection translates these trajectories into implementable project sequences, through a common set of actionlines, with a milestone marking the completion of each actionline and the transition to the next, and corresponding decision points indicating where the developer

assesses conditions and chooses whether to continue, adjust scale, or switch pathway.

The project is currently at the early engineering/FEED preparation stage, while the intended next step is committing to a first construction scope that can be financed and permitted. A pilot actionline is introduced as a bridging step between these stages. The pilot's purpose is to test, in real operating conditions, whether the chosen renewable power-electrolysis-buffer set-up can run safely and reliably. It reduces full-scale risk by generating evidence on performance, operability under variability, and control measures before committing to major construction. This can be demonstrated with a small-scale PEM & alkaline electrolyser block, equipped with an emulator that can simulate different electrical load profiles, in particular, the hybridisation of PV and wind energy. Here, an emulator is a test setup (hardware and/or software) that reproduces the power fluctuations the plant would experience in reality, without needing the full wind and solar system to be built first. Hybridisation refers to combining wind and solar generation, so their different production patterns complement each other, creating a more stable overall power supply for the electrolysers. A small battery and a small hydrogen buffer can be added to test how short-term power fluctuations are managed and how stable operation can be maintained when supply ramps up or down. The pilot should be equipped with full safety and emergency provisions (detection and response procedures), to demonstrate controlled and safe operation. A monitoring and data-logging system can be installed to capture operating profiles, electricity inputs, and key performance and environmental metrics, providing the evidence for permits and future certification. Ammonia synthesis dynamics and product quality can also be validated by adding a small ammonia synthesis unit. Otherwise, the pilot can focus on hydrogen production, buffering, safety, and measurement as the learning objectives. This pilot actionline functions as an ATR early-stage commitment that reduces uncertainty before irreversible investments are taken. It strengthens the decision logic by producing evidence that feeds directly into the configuration selection and the first investment decision, while preserving the option to adjust scale or redesign the configuration if the expected performance and operability assumptions are not met. Therefore, the pilot and configuration-selection actionline applies across all pathways.

After the pilot, the project follows standard project development actionlines (FEED, EPC, and commissioning/ start-up) for the scale selected in the chosen pathway and, where relevant, for any subsequent expansion step included in that pathway. This means that these actionlines may occur once (single build scope) or repeat in later cycles (phased expansion), depending on the scale choice and scale-up sequence. The project then moves into operation, which also depends on the pathway: assets are run either at or below nameplate capacity. All pathways, including early run-off, converge toward a late-life actionline focused on wind-down and decommissioning preparation. In this way, the actionlines and milestones translate the pathways in Table 5.3 into an implementable sequence, while their repetition and operating mode are determined by the pathway's scale and continuation choices. An overview of the actionlines and milestones is shown in Table 5.4.

Table 5.4: Overview of actionlines and milestones

Actionline	Description	Milestone
Pilot & configuration selection	Test safe and reliable operation of the power-electrolyser-buffer set-up under realistic variability.	Configuration selection
Configuration FEED	Translate the selected pathway into a buildable and financeable design.	FID
EPC	Execute detailed engineering, procurement and construction to deliver the approved scope.	Construction completion
Commissioning & start of operations	Bring the facility into service, complete performance testing, and confirm compliance before entering routine operations.	COD
Operation	Run the assets, meet and renew offtake commitments, and maintain safety and environmental compliance.	Transition to late-life operation
Late-life operation & decommissioning preparation	Plan and execute wind-down: manage contract expiry, optimise end-of-life spending, and prepare decommissioning activities.	Start decommissioning / final shutdown

Decision points (DPs) are defined as project-specific moments where the developer can choose configuration, scale, and continuation. They are derived from the pathway structure and placed at milestones where new decision-relevant evidence becomes available and/or a commitment window opens in which changing course is feasible. Three decision points capture those moments (DP1, DP3, DP5). A configuration choice can be taken after the pilot, when evidence on the technical set-up is available. A scale-up choice can be taken after COD, when a new expansion step can be initiated. A continuation choice can be taken at the first major contract roll-off, when continuing at the same scale, downscaling, or running off the project becomes possible through (re)contracting. Around these decision points, additional decision points are added to maximise flexibility by defining the latest moment when scope or operating mode can still be adjusted (DP2, DP4, DP6). Before each FID, a decision point allows the scope to be reduced or reshaped if the FEED outputs or corridor conditions do not support the intended construction step (initial or scale-up). During downscaled operation, a decision point preserves the option to ramp back up if conditions improve, or to move into run-off if conditions deteriorate. An overview of the decision points is shown in Table 5.5.

Table 5.5: Overview of decision points

	Decision point	Description
DP1	Which project configuration?	Select the reference configuration after the pilot and configuration-selection FEED, when the evidence needed to choose the initial build scale and technical set-up is available.
DP2	Take FID or adjust scale?	After configuration FEED, decide whether the chosen build step is ready for an FID, or whether the scope should be reduced/increased to match offtake, permitting status, and other enabling conditions before committing to construction.
DP3	Scale up?	After COD of the current phase, decide whether to initiate a new build step (i.e., start an expansion) based on operational performance and updated external conditions.
DP4	Take expansion FID or adjust scale?	After the expansion configuration FEED, decide whether to take an FID for the next expansion step or adjust the expansion scope, based on updated conditions and the financeability of the expansion package.
DP5	Continue operation, down-scale, or enter early run-off?	At the first major contract roll-off window, decide whether to (re)contract and continue at current scale, shift into sustained lower utilisation, or stop if the commercial basis for continued operation is no longer in place.
DP6	Maintain downscaled operation, return to scale, or move to run-off?	During downscaled operation, decide whether conditions have improved enough to ramp back up, whether to remain in downscaled mode under renewed contracts, or whether to proceed toward early run-off.

5.3.3. Sell-By Dates

This subsection translates the actionlines and milestones defined in the Subsection 5.3.2 into a set of pathway-specific timings. It does so by assigning each actionline a minimum, expected, and maximum duration and then converting these assumptions into milestone dates for each pathway. Starting from a common start year (2026), the earliest and expected milestone timings are calculated as cumulative sums of, respectively, the minimum and expected durations along the relevant pathway sequence. The latest milestone timings are derived differently: they are calculated by working backwards from the binding sell-by dates, subtracting the maximum remaining durations of the subsequent actionlines to identify the latest point at which each preceding milestone can still occur without breaching the sell-by constraints.

These milestone timings also define the decision point and adaptation tipping point windows: a window opens once the required preceding milestone has been reached and the necessary information becomes available, and closes at the last point that still leaves enough time, under maximum-duration assumptions, to complete the remaining steps within the sell-by constraints. The full set of assumed actionline duration ranges, the resulting milestone timings per pathway, and the corresponding decision point and adaptation tipping point windows, including the underlying calculations and assumptions, are reported in Appendix E.

There are three main sell-by date rules. Firstly, the start of decommissioning is fixed at 2060, reflecting a fixed end-of-life assumption. Secondly, the commercial operation date (COD) for any initial build or expansion phase must occur no later than 2045 to preserve a minimum of 15 years of operation. The decision window to move to the downscaled operation or early run-off pathways is tied to contract roll-off and lock-in, meaning they open when offtake can realistically be renegotiated (typically 10-15 years after COD) and close when signing a new contract would extend operation beyond the remaining asset life (capped at 2050).

With the pathway set, actionlines, milestones, decision points, and adaptation tipping points defined,

these elements can be assembled into a time-based roadmap. This roadmap is shown in Appendix F. Each pathway is drawn as a sequence of actionlines placed on the timeline using the expected durations. Decision points are then positioned at the milestones or points where a choice becomes available, and each decision point is annotated with its decision window to show that the choice can be taken anywhere within that window, not only at the expected point. If a decision is delayed within its window, the downstream actionlines shift accordingly, and the remaining time buffers shrink, so postponing one decision can narrow or close later switching options because the next steps may no longer fit within the sell-by constraints.

5.4. Enabling the Adaptation Plan

This section translates the basic plan actions defined in Section 5.2 into signposts, triggers and contingency actions that make adaptation explicit. For each basic plan action, a set of signposts is defined: observable developments that indicate whether success conditions (e.g. bankable offtake, permitting and certification compliance, safety and environmental performance, social acceptance, infrastructure readiness, and financeability) are strengthening or weakening. These signposts are then linked to triggers, phrased as IF-THEN conditions. A trigger can be paired with a contingency action that describes the practical response if the trigger is met. Defensive contingency actions protect the basic plan, corrective actions adjust it, capitalising actions seize opportunities, and reassessment actions reset the basic plan when its core assumptions no longer hold.

Two reassessment contingency actions are identified: reconsider the hydrogen carrier (ammonia vs. alternatives) and reconsider the market focus (export vs. domestic/Atlantic-regional). These options revisit the project's core strategic assumptions rather than adjusting the existing pathway.

Example box: Signpost, trigger, and contingency action (EU infrastructure aligned export design)

Signpost (monitor)

Monitor whether the Northwest European hydrogen backbone evolves from fragmented clusters toward a connected system, including realised timelines for key east-west links (e.g., the DRC), availability of large-scale ammonia import terminals, storage and cracking capacity beyond pilot scale, and evidence that industrial offtakers can access hydrogen or ammonia imports.

Trigger (IF-THEN)

IF backbone rollout continues to slip beyond 2032 and access to European demand remains constrained, credibly indicating that ammonia offtake is unlikely to materialise, **THEN** consider selecting a lower-capacity configuration or early run-off at DP1, suspending FID at DP2/DP4, and/or suspending scale-up at DP3, and activate the contingency action.

Contingency action (reassessment)

Reassess the project's market orientation by shifting from an export-led strategy to a domestic or Atlantic-regional focus, adjusting scale, sequencing and commercial assumptions accordingly, and deferring export-oriented scale-up.

A signpost defines what is tracked because it affects pathway viability, and a trigger then defines how that information is used. The trigger sets a threshold that indicates when the signpost suggests conditions are strong enough or too weak, and links that assessment to the specific decision point where a pathway adjustment can be made by indicating which move should be considered. In this way, DP1 selects the initial project configuration, based on whether the core enabling conditions are credible at the intended scale: bankable offtake (basic plan action 3), evidence from the pilot and configuration actionline that the system can operate safely and reliably under renewable variability (basic plan actions 1-2), and feasibility of permitting, land control, and social acceptance for the intended scale (basic plan actions 6-7). DP1 is further bounded by external readiness conditions that shape what scale is realistic, including certification and regulatory requirements, EU-side infrastructure access, available

public support instruments, and deliverability given workforce and supply-chain constraints (basic plan actions 8-10, 12).

DP2 and DP4 are the lock-in decisions because they determine whether the selected scope receives FID and thus becomes a major capital commitment. While bankable offtake (or a credible revenue-support mechanism) is the primary precondition, FID ultimately depends on the financeability of the full package: contracted revenues combined with permit and land certainty, demonstrable certification compliance, acceptable safety and environmental risk, and an executable engineering, procurement, and construction (EPC) plan.

DP3 is the post-COD decision on whether to initiate a scale-up step. Scale-up is only considered when the current facility demonstrates stable and compliant performance, additional volumes can be secured through new offtake (potentially supported by demand-side mechanisms), and export-chain conditions, including EU infrastructure access, are progressing in a way that preserves market access (basic plan actions 1-3, 8, 10, 12).

Early run-off or downscaled operation occurs when the commercial and compliance basis for continuing the selected pathway cannot be established or maintained: pre-construction when bankable offtake, permitting and land control, social acceptance, or overall financeability fail to materialise (DP1/DP2), and post-start when contract renewal fails or market access/eligibility is structurally removed (e.g., persistent EU infrastructure delays or regulatory changes), such that continued operation is no longer defensible (DP5/DP6).

The full signposts, triggers and contingency actions are provided in Appendix D. It shows the link between basic plan actions that follow from empirical vulnerabilities and opportunities, to planned monitoring, to decision-relevant triggers, and to contingency actions that keep the project aligned with the success definition under changing external conditions.

6

Findings

This chapter interprets the results of the analysis and the resulting ATR outputs for the Canada-Netherlands hydrogen import corridor in Chapter 5. It first sets out the system-level findings by describing the coordination dynamics across the value chain that shape corridor timing and scale, and then connects these dynamics to the project developer's decision space by showing how commitments are staged and adjusted. Throughout the chapter, first-order terms (FOs), elaborated in Appendix C, are used as a label for the wider results chain they generated: each FO is embedded in the Gioia themes and aggregates and is carried through into the ATR outputs, continued in Appendix D and F.

6.1. System-level Coordination Dynamics for Hydrogen Import Infrastructure Development

The results show that hydrogen import corridor development is a coordination problem shaped by mutual dependencies across the value chain. Production projects, export and import terminals, off-takers, backbone and hinterland infrastructure, and policy frameworks evolve in parallel, but none can progress at scale without signals that the others will progress as well. This creates a self-reinforcing hold-up dynamic in which stalled commitments in one part of the corridor delay investment elsewhere. ATR makes this interdependence explicit by showing why there are many plans but few investment decisions: visions, announcements, and early studies can move forward, while projects still fail to reach FID if the enabling conditions captured in ATR do not come together within the same decision window. This section unpacks these system-level dynamics by structuring the findings across five aggregate dimensions. Together, these dimensions explain why corridor progress is conditional, time-sensitive, and often characterised by many plans but few final commitments.

6.1.1. Technology & R&D Determining Performance

This subsection shows that technology development in the corridor is less about inventing new components and more about proving that existing technologies can run reliably in large-scale renewable hydrogen-to-ammonia production and export. Operational readiness is a precondition for scaling because early commitments require demonstrated performance under variable renewable supply and strict safety and environmental requirements.

System integration under renewable variability remains a major technical constraint. Especially ammonia synthesis in conventional Haber-Bosch loops is typically designed to operate most efficiently at steady conditions. This creates a trade-off between smoothing variable renewable supply with storage, or operating the ammonia plant at a lower load more often. Both options have drawbacks: storage and other flexibility measures increase CAPEX, while sustained operation at lower load tends to reduce efficiency and raise unit costs (FO 2). Operational readiness, therefore, depends on whether the integrated power-to-ammonia system can operate stably under fluctuating renewable supply while still

benefiting from low-cost renewable electricity (FO 3).

This integration challenge interacts with technology and conversion choices that lock in long-term performance. Design decisions around electrolyser configuration, such as selecting PEM or pressurised systems to reduce downstream compression needs, and around process integration, such as coupling with SOEC where available heat flows can be used more effectively, can improve efficiency and safety, but also determine cost and operational constraints over the asset life (FO 4). At the same time, safety and environmental performance function as hard boundary conditions: ammonia toxicity and accident consequences require engineering, operating procedures, and emergency preparedness (FO 5), while broader environmental externalities, such as water use, chemical and brine management, and lifecycle emissions, must be designed for and continuously monitored to sustain compliance (FO 6). Finally, technology learning and demonstration remain important system enablers, with innovation programmes and pilot-oriented support helping to de-risk deployments (FO 9).

Quote box

PD&IA 2: *"For me, that's the main crux: which technology do you choose? You can see the market now shifting toward pressurised electrolysers, because they require less compression and therefore have a positive impact on both installation costs and safety contours. In addition, integration with SOEC plays a role, especially in a value chain involving ammonia, where a lot of heat is released or needs to be removed. That is a very interesting option, but there are still too few concrete projects, mostly pilot concepts so far. This is a differentiating factor: the choice of electrolyser technology and the rationale behind it. Scale also comes into play: do you apply one technology, or do you combine multiple technologies within one facility to spread risk?"*

For hydrogen import infrastructure development, this means that technology choices shape performance risk. They affect how stable the system can run under variable power, how sensitive costs are to flexibility measures, and how much demonstration is needed before commitments become acceptable. In ATR, the pilot actionline hedges performance risk by generating operational evidence under realistic conditions. In parallel, performance-relevant signposts (operational, safety, and environmental) are monitored to assess whether this risk is reducing or persisting, so that pilot outcomes and evolving conditions can be used at subsequent decision points to confirm or adjust commitments, thereby embedding performance risk explicitly in decision-making.

6.1.2. Supply Development under Capital and Delivery Constraints

This subsection shows that supply-side progress in the corridor depends on whether projects become investable and deliverable under capital market and execution conditions. Even when the production concept is technically feasible, large-scale build-out depends on financing terms that keep unit costs within a viable range, and on the capacity to procure equipment and deliver construction on schedule.

Financing conditions emerge as a primary determinant of whether projects can proceed at scale. As these projects are capital-intensive, the cost of capital and macro-financial volatility matter: changes in interest rates, required returns, and perceived risk can make a project unattractive even if renewable resources are strong (FO 17). Public capital and fiscal support therefore function as core enablers. Two mechanisms stand out. The first is instruments that reduce upfront costs and share risk, such as investment tax credits, grants, concessional loans, and guarantees (FO 18). The second is revenue stabilisation mechanisms that reduce market risk by making cashflows more predictable in early markets with high price uncertainty and limited willingness-to-pay, such as CfDs and H2Global-style tenders (FO 19). Together, these tools determine whether a financeable package can be put in place.

Quote box

FIN 1: *"The cost of capital and financing environment is the trickiest part in places like Morocco. Very often, these countries have excellent conditions for wind and solar. But today, it's more likely we'll build a hydrogen plant in Spain than in Morocco or Colombia. Not because Spain has better resources, but because financing costs are lower. The perceived risk of something going wrong is much lower in Spain than in Morocco or Colombia, which are considered more unstable politically, economically, and socially."*

Beyond capital conditions, delivery capacity also limits supply development. Workforce constraints matter because construction requires large labour inputs over short periods, and remote locations can face higher costs and schedule risk when labour must be brought in (FO 20). Supply chains can also delay projects, as long lead times and limited availability of equipment such as electrolysers and turbines can slow commissioning (FO 21). These constraints add to broader financeability challenges, as renewable hydrogen and ammonia projects face very large capital needs and price uncertainty (FO 22).

Quote box

PD&IA 2: *"The labour force also plays a major role in Canada, and probably in Newfoundland as well. ... Canada has a strongly organised labour market, with powerful unions. ... If a project suddenly needs 6,000 people for 4 years in Newfoundland, it's not as simple as it sounds. You have to deal with Canadian labour laws and the question of whether you can actually get those people there. Often, you have to pay a high premium on top of already relatively high labour costs. This puts projects in Canada at a disadvantage compared to, for example, Egypt."*

Therefore, upstream production and export infrastructure development depends on financing conditions and delivery capacity. ATR makes this explicit by treating these factors as monitored enabling conditions and translating them into triggers that guide pathway choices. When capital becomes expensive, support instruments weaken, or equipment and labour constraints intensify, triggers indicate delaying or downsizing commitments, which reduces near-term volumes and weakens visibility for the wider value chain. Conversely, when risk-sharing and revenue support strengthen, and developers can secure procurement and construction capacity, triggers support moving from planning into the execution actionlines, thereby increasing volume visibility and coordination certainty for downstream actors.

6.1.3. Demand Development under a Willingness-to-Pay Gap

This subsection shows that demand in the corridor is held back by a persistent willingness-to-pay gap and by uncertainty about where, how, and under which rules hydrogen-based molecules will actually be used. As a result, offtake and contracting become the main bottlenecks: without bankable buyers and workable contract structures, projects struggle to move from plans to commitments.

The results highlight the willingness-to-pay gap as the dominant demand-side hold-up. Even where there is interest, buyers hesitate when low-emissions hydrogen or ammonia remains structurally more expensive than fossil alternatives, leaving voluntary demand too weak and fragmented to support large-scale commitments (FO 23). This connects directly to the corridor's investment logic: without offtake, producers cannot secure financing and FIDs stall (FO 7). Contracts can handle some uncertainty by building in flexibility, such as volume tolerance bands, price adjustment clauses, and exit or review points, but only within limits that still keep the agreement financeable (FO8).

Quote box

FIN 1: *"Right now, we have many people who want to produce hydrogen and many willing to invest in ports and distribution infrastructure. But we have hardly anyone saying, 'I'm going to buy it at the price that is required to make it worthwhile, to make it financially attractive'."*

Demand formation is therefore largely policy-driven rather than market-driven. The results show two central policy mechanisms. First, regulatory mandates and compliance penalties can create offtake even when willingness-to-pay is low, but delays or uncertainty in implementation weaken this effect and prolong hesitation (FO 25). Second, carbon pricing and emissions trading are treated as mechanisms to narrow the cost gap by pricing environmental externalities, thereby strengthening the business case for switching away from fossil-based molecules (FO 24). Alongside these demand mechanisms, the results show that carrier and end-use uncertainty feeds back into offtake formation. Ammonia is widely expected to be the dominant long-distance import carrier because it builds on existing logistics and trade practices (FO 28), yet there is still debate over which sectors will absorb large volumes and how suitable ammonia is across end uses (FO 29). Shipping is often mentioned as a major potential end-use market, but its trajectory depends on international rules and timing. Uncertainty in IMO standards and their implementation can delay investment and keep demand expectations unstable (FO 27).

Quote box

GOV 3: *"Another issue is the effective implementation of the EU RED by Member States, which includes quotas for green hydrogen and penalties for non-compliance. When is that going to be transposed, and delays in transposing these rules create uncertainty, which makes it harder for Canadian projects to reach FID. The longer that uncertainty continues, the harder it is for the financing of Canadian projects to continue, because as soon as you get non-compliance penalties, that is going to initiate the industry to start securing offtake."*

For hydrogen import infrastructure development, this means that demand risk is a corridor-level coordination risk. ATR makes this explicit by linking infrastructure project progress to demand formation. If the willingness-to-pay gap remains and policy implementation is unclear, triggers indicate that commitments should not progress beyond the FID decision point, keeping projects pre-FID. Conversely, when mandates, carbon pricing, and clearer end-use trajectories translate into bankable offtake, triggers support taking the FID decision, enabling the corridor to progress from announcements toward committed investments.

6.1.4. Systemic Constraints Shaping Market Access and Siting

This subsection shows that corridor progress is bounded by systemic constraints that sit outside individual project control. Even where supply and demand intent exist, projects and infrastructure can only move forward when they remain eligible under certification rules, fit within spatial and safety constraints, and can be permitted and socially accepted. These constraints act as hard boundaries: they determine where trade is possible, where infrastructure can be built, and how quickly developments can be realised.

A first boundary is regulatory eligibility and certification as conditions for market access. The results show that compliance is a requirement that shapes project design and operational choices (FO 26). In particular, grid-connection and electricity sourcing become compliance risks: if production relies on grid power in a way that is not accepted under green hydrogen rules, exported molecules can lose eligibility and value (FO 13). This introduces corridor-level uncertainty because eligibility depends on evolving methodologies and cross-jurisdictional alignment, meaning a corridor can be logistically feasible but commercially blocked if the product cannot qualify as intended.

A second boundary concerns permitting and social licence. The results show that legitimacy and timing depend on early and sustained alignment with (Indigenous) local communities and other stakeholders, shaping scope, sequencing, and project stability (FO 14). At the same time, multi-layer permitting can create design and timing risk because federal requirements can be triggered by specific project configuration choices, especially around marine works and shipping interfaces (FO 16). Public risk perception is an additional constraint: limited familiarity with hydrogen and ammonia, and concern about accident consequences, can constrain siting, routing, and acceptance of large facilities and transport (FO 15).

A third boundary is spatial feasibility and infrastructure accessibility, where European constraints directly shape corridor outcomes. The results show that environmental rules (e.g. Natura 2000/NOx) can restrict the siting and permitting of ammonia and hydrogen infrastructure, potentially shifting where cracking, storage, and conversion can realistically be placed (FO 31). Demand and utilisation are also shaped by whether hinterland access is available: without timely rollout of the backbone and connections, import volumes cannot reliably reach industrial users, undermining business cases and delaying decisions (FO 30). In this context, infrastructure economics becomes part of the constraint set. The results point to the need for incentives and amortisation approaches that keep early transport tariffs manageable while volumes are still low, otherwise network costs can become self-blocking (FO 32). Finally, modal preferences and safety-driven transport choices can conflict with logistics needs. Policy preferences to keep ammonia in-port or to prioritise certain routes and modes can diverge from how volumes must move to serve hinterland demand, creating friction and uncertainty for infrastructure planning (FO 33).

Quote box

PIO 2: *"What you see is that delays in connections to the hinterland have a direct impact on projects that depend on that infrastructure. Those projects need those connections to make their business case work, to get green energy carriers to their facilities. If they can't recover their investment, they won't invest in the first place. That infrastructure is essentially the key to scaling things up."*

Quote box

EXP 2: *"With the current legislation, it's basically a complete showstopper. As long as nothing changes in the nitrogen regulations, it's open season for parties who don't want projects to go ahead. We really need better policy, both on safety and on nitrogen, to create space for development. That's a societal agreement: what do we, as a country, consider acceptable in terms of development? What should that look like? If we only follow the current rules, very little is possible."*

For hydrogen import infrastructure development, these systemic constraints mean that corridor feasibility is conditional. ATR incorporates this conditionality into its decision-making. Eligibility rules can redefine what counts as a sellable product; permitting and social licence can redefine what can be built and when; and spatial and infrastructure constraints can redefine where demand can actually be reached. Therefore, ATR keeps commitments contingent on regulatory eligibility, permitting feasibility, social acceptance, and import-chain accessibility signposts, linking them through triggers to configuration, FID, and post-COD scale-up decisions. As a result, corridor progress depends on aligning design, siting, and infrastructure choices with evolving regulatory boundaries and spatial realities across both ends of the corridor.

6.1.5. Policy & Governance as the Corridor Foundation

This subsection shows that corridor progress is highly sensitive to public governance and geopolitical context. As the market is largely policy-driven, shifts in political priorities, delays in implementation, or doubts about continuity quickly translate into hesitation across the value chain. At the same time, geopolitical dynamics can strengthen the case for cross-border corridors by elevating diversification, trusted partnerships, and energy security as strategic goals.

Policy stability and long-term commitment emerge as a decisive condition for investment and market formation. The results show that volatility in political priorities and uncertainty about whether rules and support will persist can stall decisions (FO 34). In this context, crises and price volatility can act as catalysts that change political attention and accelerate action, but they also make the corridor more sensitive to abrupt shifts in direction and risk perceptions (FO 38). The combined effect is that progress accelerates when commitment strengthens and slows when signals weaken.

Geopolitics also reshapes partner choice and corridor alignment. The results show that diversification

motives and energy security considerations strengthen interest in multiple supply regions and carriers (FO 37). Political and institutional stability shape supply-country selection. Where a country is seen as a reliable long-term partner, such as Canada, developers and policymakers expect cooperation and commitments to hold across multiple political cycles, reducing perceived risk and supporting corridor planning (FO 35). Alongside this, societal and ethical concerns also matter, as concerns about 'green colonialism' and ESG expectations can make some supply routes more acceptable than others and can shape what responsible development is expected to look like, and sometimes whether buyers are willing to pay a premium for that supply origin (FO 36).

Quote box

FIN 1: *"One thing we have to face is that the hydrogen market is politically or legally driven. There are so many areas: what Canada wants to do with its climate targets, what the Netherlands wants to do, what the IMO agrees on, ... All of this is political. If, in all these forums, people decide they don't care about climate anymore, then there will be no market for hydrogen-based fuels. It's that simple."*

Lastly, the results highlight that governance is not only about policy content, but also about whether coordination actually happens. Cross-value-chain public-private coordination is necessary to reduce the hold-up dynamics that keep projects in pre-FID stages (FO 10).

Quote box

PIO 3: *"The entire value chain is new. Everyone is therefore dependent on each other. Look, maybe someone in Canada says, 'I've found a customer.' But that customer will only sign if they are sure the terminal will be built. Then the terminal says, 'I will only build my terminal if I'm sure I'll get paid by that customer.' So everyone is, in a way, holding each other hostage. That's why I think it will be crucial for parties in the value chain to cooperate more and to actively reduce their mutual dependencies."*

Hydrogen import infrastructure development is conditional on whether policy creates stable market conditions. When policy instruments are unclear, or when implementation is delayed, revised, or politically contested, uncertainty increases, and corridor progress slows. Uncertainty can be reduced when coordination across the value chain helps parties align timelines and sequence commitments. This is precisely where ATR adds value: it allows actors to use the timelines and progress of other systems and actors as decision-relevant inputs, and to sequence their own commitments within their respective decision spaces accordingly. At the same time, ATR can provide a shared language for articulating interdependencies, expectations, and timing, and for interpreting common signals such as progress, delays, and readiness. Thereby, it supports alignment when decisions remain distributed across actors.

6.2. Project-Level Decision Space for Developers under Corridor Uncertainty

Section 6.1 showed that hydrogen import corridor development is shaped by system-level coordination dynamics and mutual dependencies across the value chain. For project developers, the central challenge is that many conditions are uncertain, and therefore the pathway forward as well, which makes it difficult to plan. This section, therefore, shifts from corridor-level dynamics to how project developers can translate these dynamics into project decisions: first, how developers can progress through staged development and specify what must be in place at key commitment moments, and second, how adaptation is primarily executed through phased scale decisions and modular expansion in ATR.

6.2.1. Staging Commitments in Project Development

This subsection shows that project developers can manage corridor uncertainty by structuring development as a staged process consisting of actionlines and milestones, where each new actionline is contingent on meeting a set of enabling conditions. Roadmaps are seen as direction-setting tools that remain provisional and require regular revision as conditions evolve (FO 39), while decisions are disciplined through a defined base case and a limited set of sensitivities to test when the project becomes viable or not (FO 40). In this context, milestones are moments where the next step, or actionline in ATR terms, becomes difficult to reverse and, therefore, requires sufficient information and alignment before proceeding. This is why decision point and adaptation tipping point windows matter in the roadmap: they formalise when information becomes available (the opening of a window) and when delaying would remove the remaining ability to act within constraints (the closing of a window).

Quote box

PD&IA 2: *"What you are essentially trying to do is define a clear base case for yourself based on what you know today. From that base case, you create a number of sensitivities with low and high cases in different variants. The goal is to link those scenarios to what is often called a realisation pathway: you try to make a number of assumptions more concrete and combine them into a few coherent scenarios. Importantly, you don't want more than three combined scenarios, otherwise it becomes too complex."*

The results show that developers must translate broad uncertainties into concrete commitments and approvals that make the next project step possible. This is most difficult before the FID decision point. At this stage, a project can look technically feasible but still stall because the enabling conditions do not come together at the same time (FO 10). Offtake is the clearest example, as without offtake, investors will not commit and FID cannot be taken (FO 7). If offtake interest does not translate into commitments, or if policy support, permitting certainty, or financing conditions remain insufficient, the results show that stopping before construction (early run-off pathway) is the rational outcome to avoid major capital exposure without an investment basis (ATP1; DP1/DP2).

Beyond offtake, the results show that several non-negotiable constraints must also be in place to take FID at its decision point (DP2). One is eligibility and certification. Regulatory and certification fragmentation creates uncertainty about whether hydrogen and ammonia qualify for intended market use (FO 26), and grid-related sourcing rules can make compliance and market access contingent on electricity configuration (FO 13). A second constraint is permitting and social license. Indigenous consultation and stakeholder alignment shape legitimacy and can delay or stop projects unexpectedly (FO 14), while public safety perceptions and spatial planning can constrain siting, routing, and acceptance of hydrogen and ammonia infrastructure (FO 15). Multi-layer permitting adds further design and timing risk, including the possibility that specific marine or project configuration thresholds trigger additional federal procedures (FO 16).

A further condition is financeability under capital-market and delivery constraints. The results show that WACC, country risk, and macro-financial volatility determine whether projects are investable at scale (FO 17), and that capital support instruments and revenue stabilisation mechanisms often function as enabling conditions (FO 18; FO 19). At the same time, deliverability constraints shape whether the project can be executed on schedule and within cost bounds: workforce and reskilling needs, labour market tightness, and the ability to mobilise large construction workforces can become limiting factors (FO 20), while manufacturing capacity and equipment lead times for electrolysers and turbines can delay delivery (FO 21). These execution constraints feed back into financeability because delays and cost escalation can reopen the financing gap that support mechanisms were intended to close (FO 22). In practice, FID is taken at its decision point only when the full package aligns: bankable revenues (or revenue support), permitting and land certainty, certification compliance, acceptable safety and environmental risk (FO 5; FO 6), and a deliverable EPC plan (DP2/DP4). To help get to that point, developers can introduce the pilot actionline as a bridging step between early engineering and a first construction commitment. The pilot reduces risk by testing whether the renewable power-electrolysis-

buffer configuration can be operated safely and reliably, and by generating monitored performance data that supports the compliance case, in line with Subsection 6.1.1.

The results further show that developers try to make progress possible by coordinating timelines and commitments across the value chain. This coordination work does not remove uncertainty, but reduces mutual hostage dynamics by clarifying dependencies. Import-side readiness is part of this pre-FID coordination problem: the business case depends on reaching inland demand, so developers must be able to point to a route via terminals, storage/cracking plans, and expected backbone or hinterland access, even if these assets are not yet operational (FO 30-FO 33; DP2).

After FID, the focus shifts from whether the project can be committed to whether it can be operated successfully and expanded later. Operational performance becomes decision-relevant because it shows whether variability management and integration choices hold up in practice (FO 2) and whether safety and environmental performance can be maintained under real conditions (FO 5; FO 6). This performance is a prerequisite for considering expansion after COD (DP3), but it is not sufficient by itself: expansion depends on whether additional volumes can realistically be absorbed in the import system. Delays in backbone and hinterland connections can constrain where demand can be reached (FO 30), spatial and regulatory constraints can affect where import-side infrastructure is feasible (FO 31), and tariff economics can become self-blocking if network costs rise while volumes remain low (FO 32). The results, therefore, indicate that post-COD expansion decisions depend on a combined signal: stable, compliant plant performance on the supply side and absorption capacity and market access on the import side (DP3). Finally, the results show a later milestone around contract roll-off and renewal (DP5/DP6; ATP2). As long-term offtake contracts are typically time-bound and may expire before asset end-of-life, the ability to recontract becomes a decisive condition for continued operation (FO 7; FO 8).

In this way, project development is structured around staged commitments that recur across the project lifecycle, and ATR makes these stages explicit by translating pathways into actionlines and milestones coupled to decision points. By linking these points to the adaptation plan, ATR also clarifies how developers can use monitored conditions to confirm, adjust, or defer commitments as market, infrastructure, and policy conditions evolve, including configuration and investment choices as well as later contract renewal moments.

6.2.2. Adaptation through Scale and Modular Expansion

This subsection shows that the primary adaptation mechanism available to developers is scaling through phased and modular development. Developers preserve flexibility by starting with a smaller configuration and expanding in modules as demand, infrastructure readiness, policy support, and delivery conditions strengthen. This approach is framed as a practical response to early-market conditions: initial hydrogen and ammonia infrastructure can suffer from low utilisation and high unit costs, making large upfront investments uneconomic until volumes and enabling conditions are clearer (FO 1). As a result, the pathway logic in ATR is not only a descriptive scenario set but an adaptation approach: expansion is an option that can be exercised when conditions are met, while downscaling and run-off remain available if conditions weaken.

Quote box

PIO 3: *"You build it up step by step. An import terminal can be modular: start with one ammonia tank, then add the first cracker. Next, a second tank and a second cracker. That way, you can grow along with the market."*

Scaling involves expanding upstream generation, conversion, storage, and export throughput in coordinated steps, but not all elements scale in the same way. On the production side, additional renewable capacity (wind and solar) and electrolyser capacity can be added in blocks, increasing hydrogen output (FO 2). Buffering and storage scale alongside production: hydrogen storage volumes and flexibility measures must expand to sustain stable ammonia synthesis and to manage short-term variability. On

the conversion side, capacity increases through additional ammonia synthesis trains, with ammonia storage and handling expanding accordingly to match committed volumes. Each scale step is typically delivered as its own development package, with configuration/FEED, an FID decision, and then EPC and commissioning for the added scope. By contrast, permitting and the export interface are often shaped by early design and approval choices that aim to cover a larger future scope, so later phases focus mainly on adding modular capacity within that scope.

Technology choice is embedded in this phasing logic because it shapes performance risk and the upgrade path. Early phases can prioritise proven configurations that reduce integration and delivery risk, while keeping options open for later upgrades. For example, an initial electrolyser configuration can combine technologies to balance risk and performance (e.g., a $\geq 50\%$ PEM / $\leq 50\%$ alkaline mix), while the ammonia synthesis train and storage are sized for the first committed offtake volumes. Later phases can preserve the option to add less mature modules, such as SOEC integration, only once performance, lifetime, and integration conditions are sufficiently demonstrated and supply chains are ready. This turns technology choice into a modular expansion (FO 4; FO 9).

The results also clarify that the ultimate scale is not determined by technical ambition alone but by a set of binding conditions that either enable or cap expansion. The first is offtake and willingness-to-pay, which remains limited when low-emissions ammonia is structurally more expensive than fossil alternatives (FO 23) and therefore depends on mandates, carbon pricing, and demand-side mechanisms that translate targets into bankable demand (FO 25; FO 24; FO 19). A related scale determinant is end-use and carrier trajectory: while ammonia is widely expected to dominate long-distance imports due to techno-economic and logistical advantages (FO 28), uncertainty over which sectors will absorb volumes and how suitable ammonia is across applications shapes both demand timing and product specification requirements (FO 29). In particular, shipping is often framed as a potential high-volume end use, but its demand signal depends on IMO rules and their implementation, making it volatile for expansion decisions (FO 27). If these end-use signals shift or if ammonia demand does not consolidate, the results point to a reassessment of the hydrogen carrier (ammonia versus alternatives) as a strategic project scope adjustment.

In addition, the results indicate that the ultimate scale is shaped by domestic infrastructure alignment and political feasibility on the supply side. Developers in Canada can face a tension between export ambitions and domestic energy priorities, especially as electrification increases pressure on clean electricity supply and political sensitivity rises around exporting green hydrogen and derivatives (FO 12). This tension, together with export-chain readiness and eligibility constraints, can trigger a second reassessment of the project scope: when export-oriented growth is politically difficult or commercially constrained, developers may need to stabilise earlier phases with domestic or Atlantic-regional demand and infrastructure alignment rather than proceeding directly to export-oriented scale-up. Future-proof and adaptive infrastructure planning is also a provincial task. Decisions on grid reinforcement, interties, and the development of large-scale storage options shape the operating space available to projects by affecting system flexibility and resilience (FO 11). For example, if the province advances underground storage options such as salt cavern storage, a developer could integrate this system-level storage into the project configuration to strengthen buffering and reduce variability constraints.

These findings show how adaptation is primarily executed by adjusting scale and sequencing to remain inside these constraints. When enabling conditions strengthen, modular expansion allows the developer to grow volumes. When conditions weaken, downscaled operation provides a reversible response that preserves continuity under prolonged uncertainty, while early run-off remains the option when the commercial and compliance basis cannot be established or maintained. This is why phased, modular development functions as the core adaptation mechanism in ATR at the project level: it converts corridor uncertainty into a structured set of scalable commitments that can be increased, paused, reduced, or terminated as conditions evolve.

7

Discussion

This chapter translates the findings of the study into implications, limitations, and recommendations for using ATR in early-stage hydrogen corridors. It first discusses what the case suggests about ATR's value and boundary conditions under system-of-systems uncertainty. It then clarifies the main limitations of the research design, the ATR approach, and the resulting ATR outputs. Finally, it provides recommendations: practical guidance for infrastructure and project developers, policy recommendations aimed at reducing the corridor hold-ups, and directions for future research to test ATR's transferability and usability.

7.1. Adaptive Technology Roadmapping Implications

This section evaluates what the application of the Canada-Netherlands hydrogen corridor case implies for using ATR in system-of-systems settings. Each subsection follows the same structure. It states a claim about one ATR building block, shows what the case reveals in practice, and explains what this implies for ATR relative to TRM and DAPP. It then relates the findings to literature on system-of-systems decision-making under uncertainty, highlighting where ATR is supported and where limits appear. Each subsection ends with the implication for applying ATR in corridor-type projects. The final subsection draws these implications together by stating the boundary conditions under which ATR is likely to be applicable and transferable to other actors and system-of-systems configurations.

7.1.1. System Scope: Boundary Conditions and Decision Ownership

This subsection argues that ATR captures system-of-systems interdependence by making dependencies explicit in the roadmap's decision logic, rather than relying mainly on a TRM-style layered representation.

Applying the ATR system-scope block to the Canada-Netherlands hydrogen import corridor shows that the corridor is a system-of-systems in which progress depends on co-evolving Technology & R&D, Supply Development, Demand Development, Systemic Constraints, and Policy & Governance. The scope boundary is therefore consequential, as it separates what the developer can decide and deliver from what it can only influence or must accommodate. The control-influence-exposure mapping makes this concrete. The Newfoundland and Labrador project developer controls only part of the success conditions, such as design and phasing choices, must co-produce enabling conditions through coordination, such as bankable offtake and cross-border interfaces, and remains exposed to external shifts, such as macroeconomic conditions, geopolitics, and regulatory and certification changes. The Gioia-based definition of success then turns long-term ambition into criteria that can be checked at each staged commitment, supporting consistent configuration and scale choices as conditions evolve.

These findings refine how ATR builds on TRM and DAPP. TRM communicates system-level scope through a multi-layer, time-based roadmap that aligns drivers, delivery mechanisms, and enabling

resources (Phaal et al., 2004). In this corridor, however, the challenge is not only to depict interdependence but to specify which dependencies are decision-relevant conditions for the roadmap owner, which require coordination, and which remain external constraints. DAPP addresses part of this gap by starting from a bounded decision context and a definition of success, expressed as indicators and targets used to assess actions and pathways over time (Haasnoot et al., 2013). ATR's added value is that the system-of-systems boundary and agency distinctions make that logic usable for innovation planning by clarifying who decides what, and which external dependencies should be treated as conditions for proceeding.

This is consistent with DeLaurentis and Callaway (2004), who argue that system-of-systems problems become unmanageable when addressed through isolated low-level changes, because the solution space is highly interwoven, which risks "designing the trees and not the forest". Their layered lexicon formalises the need to abstract from component-level interactions to higher-level outcomes and policy choices. Read through this lens, ATR performs a similar abstraction move. It starts from detailed system-of-systems vulnerabilities and opportunities, translates them into system-level enabling conditions, and then links these conditions to an explicit agency logic that structures decision points and contingencies. In this way, the roadmap becomes a guide for when and how to commit under changing system conditions, rather than treating the roadmap as a catalogue of component developments.

The main implication is that a corridor roadmap should start with an explicit scope statement that names the system-of-systems dynamics that condition viability, defines the planned system and interfaces, clarifies decision authority for major commitments, and fixes a success definition and horizon that match staged investment. This turns external dependencies into conditions that can later be tracked and linked to decision points. Consequently, ATR's main contribution is not necessarily a more comprehensive representation of the system, but a more actionable way to navigate a system-of-systems as it evolves.

7.1.2. Evidence Base & Default Plan: Accounting for Uncertainty

This subsection argues that ATR strengthens roadmapping under uncertainty by translating system dynamics into vulnerabilities and opportunities that shape a default plan and specify under which conditions adaptation tipping points are reached. At the same time, the case highlights a limitation. If unknown unknowns reshape the underlying vulnerabilities and opportunities, the default plan and its triggers can become outdated, so ATR needs a revision loop alongside trigger-based adaptation.

In the Canada-Netherlands hydrogen corridor case, uncertainty is formulated as interdependent vulnerabilities and opportunities across the system-of-systems domains. For the project developer, this provides an evidence base that links what is changing in the corridor to what the project should do. Basic plan actions capture commitments that remain relevant across routes, including modular phasing, safety and sustainability by design, early permitting and land control, and sustained work on bankable offtake and certification alignment. At the same time, the evidence base shows that these commitments depend on external enabling conditions, especially demand formation, policy implementation, infrastructure access, and financing, which can strengthen or weaken over time. Vulnerabilities and opportunities, therefore, both justify the default course of action and mark its limits by indicating when a staged commitment no longer meets the success definition, for instance when regulatory eligibility or bankable offtake cannot be secured for the next investment step.

These findings show where ATR adds decision structure to what TRM and DAPP already contribute. TRM is effective at combining foresight, analysis, and stakeholder input into a shared view of system dynamics and a staged course of action (Phaal et al., 2005), but it often leaves the conditions under which that course should be revised implicit. DAPP addresses this by building plans around a definition of success and by identifying vulnerabilities and opportunities that shape performance and the timing of adaptation (Haasnoot et al., 2013). The case shows the value of combining both, as the evidence base shows system dynamics and justifies which actions remain necessary regardless of route, and clarifies which developments would make further commitments inconsistent with success. This is where action types matter: mitigating and hedging actions reduce exposure, while seizing and shaping actions support acting on opportunities and influencing what can be steered through coordination.

The results clarify how far this evidence-to-plan logic can go under deep uncertainty and where its limits lie. Marchau et al. (2019) describe uncertainty as an inadequacy of knowledge that spans a spectrum from near-deterministic situations to total ignorance, and distinguish four intermediate levels. At Levels 1-2, uncertainty can be treated through sensitivity analysis or probabilistic descriptions; at Level 3, analysts can specify a limited set of plausible futures but cannot assign probabilities; and at Level 4, uncertainty is deepest because “we only know that we do not know” and surprises or black swans may occur (Levels 4a/4b) (Marchau et al., 2019). Read through this lens, ATR can incorporate Levels 1-2 uncertainty already at the system-description stage by drawing on diverse evidence inputs (data, analysis, and expert judgement). Its main added value is at Level 3 and parts of Level 4a, where probabilities cannot be assigned and staged commitments must remain conditional on how enabling conditions unfold. ATR is less suited to Level 4b uncertainty, where discontinuities are hard to anticipate and indicators may not exist. If surprises reorder what is binding (e.g., an unforeseen regulatory interpretation, disruptive technology shift, or geopolitical shock), then the vulnerability-opportunity framing, and the actions, signposts, and triggers derived from it, may no longer fit and will need revision. ATR therefore reduces the risk of committing to one expected future, but it does not remove the need to periodically revisit the framing itself when deep uncertainty changes the problem.

The main implication is that an ATR application should include an explicit revision loop for the evidence base and default plan. In practice, alongside pre-specified trigger-based adaptation, the roadmap owner periodically re-checks whether the vulnerabilities and opportunities still reflect the binding conditions, whether the basic plan action set remains sufficient, and whether the success definition still captures what the project must satisfy. This keeps the default plan aligned with changing system dynamics while recognising that some uncertainty will remain inherently unpredictable.

7.1.3. Roadmap: Flexible Coordination

This subsection argues that ATR's roadmap should be read less as a predictive schedule and more as a tool for flexible coordination. By linking milestones to decision points, ATR times commitments to moments when information and cross-actor alignment can realistically emerge through interaction. At the same time, any single roadmap visual simplifies network dynamics. The implication is that the roadmap must be embedded in an ongoing coordination and learning process.

In the Canada-Netherlands corridor case, the ATR roadmap adds structure by separating ongoing basic plan actions from pathways with actionlines and milestones, such as FEED, EPC, commissioning, and operation. This clarifies what can be done now, what must be prepared, and when changes in scale or route become feasible. Milestones such as FID and COD also serve as checkpoints for key external conditions, for example, offtake, stakeholder support, and regulatory clarity, before moving to the next step.

TRM contributes the execution-oriented logic by staging actions and milestones over time to support coordination and follow-through (Phaal et al., 2005). DAPP contributes explicit alternative routes and switching logic under uncertainty (Haasnoot et al., 2013). ATR links these by representing each pathway as a sequence of TRM-style actionlines and milestones, while using DAPP-style decision points to indicate where switching becomes feasible. The added value is that milestones are tied to decision points, anchoring choices about scale, sequencing, or switching in deliverables and evidence produced by prior actionlines.

This added value becomes clearer when read through De Bruijn et al. (2010). ATR's roadmap is strongest as a process-management framework rather than a project schedule. De Bruijn et al. (2010) argue that in networks there is no project-like development and that linear decision-making should be replaced by a process that takes place in rounds. In such round-based processes, the information needed for commitments is not fully available upfront but emerges as actors interact, negotiate, and learn, while new developments can trigger redefinitions of problems and solutions (De Bruijn et al., 2010). This validates ATR's choice to link milestones to decision points: rather than assuming a plan-driven schedule, ATR ties major commitments to moments when preceding actionlines can realistically

have produced the deliverables, evidence, and alignment needed to defend the next step.

De Bruijn et al. (2010) also warn against imposing a “project-type template” that assumes stable goals, fixed schedules, and predefined end products, and they note that agendas are dynamic and substantive insights are often introduced at the wrong moment, too early or, more often, too late. Read through this lens, a static roadmap graphic can easily be read as a fixed schedule and as an exhaustive map of options, even though corridor feasibility depends on when multi-actor conditions mature across rounds and on how issues and linkages shift during the process (De Bruijn et al., 2010). In the corridor case, this matters because feasibility shifts with developments such as changing certification, infrastructure delays, and evolving demand, so switching is not only a pathway choice but also a negotiated outcome that depends on whether actors can align in the next round. The same process logic also explains why the graphic can make timelines look more reliable than they are. De Bruijn et al. (2010) warn that phased, sequential models are misleading in networks because decision-making is irregular and does not follow a neat plan-execute logic. In early-stage corridors, durations and milestone dates are therefore provisional, and even when ranges are shown, the visual roadmap can still understate delay and re-timing in a system-of-systems.

The main implication is that ATR roadmaps should be used within recurring coordination rounds. Sustained interaction supports learning and makes cooperation more likely over time (De Bruijn et al., 2010). Milestones can structure when evidence is reviewed and commitments are tested, while decision points enable adjustments and the pathway timeline is updated as feasibility conditions evolve. This keeps the roadmap implementable without implying project-like certainty in a system-of-systems.

7.1.4. Adaptation Plan: Responding to System Dynamics

This subsection discusses how ATR’s adaptation plan builds adjustment into implementation and supports responses without assuming change follows a fixed timetable. The case also shows a limitation: the output can list many signals and responses in parallel, but it does not indicate which signals should dominate, how to handle conflicting triggers, or how basic plan actions interact. The implication is that ATR benefits from an added decision routine to interpret mixed signals and manage trade-offs at decision points.

In the Canada-Netherlands corridor case, ATR translates uncertainty into a monitoring-and-response logic. It specifies which developments should be tracked, such as bankable offtake, certification rules, infrastructure access, permitting progress, and financing conditions, when changes are large enough to signal reconsideration, and which prepared responses are available, such as proceed, delay, rescope, switch scale, or move into run-off. This makes adaptation explicit because the plan already states the conditions under which choices should change.

This aligns with adaptive planning as defined by Marchau et al. (2019): plans are designed to be adjusted across time, and the adjustment logic is stated together with the plan. It also reflects the shift from planning on a fixed timeline to planning conditional on what is observed, since the timing of adaptation is not known in advance (Marchau et al., 2019). ATR fits this logic by using pathways to cover different future developments and by linking future commitments to observable developments.

The case also makes clear what ATR does not solve by itself. The adaptation plan can list many parallel signals and triggers, but it does not prioritise them or specify what to do when signals conflict, for example, offtake improving while infrastructure access deteriorates. This is partly inherited from DAPP-style monitoring. Haasnoot et al. (2013) combine pathways with signposts and triggers to activate contingency actions, but they do not provide a rule for weighing multiple signals when several move at once. In addition, dependencies between basic plan actions remain mostly implicit: the roadmap links actions to decision points, but not how progress on one action tightens or eases others. Taken together, ATR makes conditionality explicit, but still leaves decision-makers to combine multiple moving conditions into one judgement at each decision point.

Practically, this suggests complementing ATR with prioritisation layers, for example by distinguishing

between must-have triggers, such as offtake, and supporting triggers, such as tax instruments. In addition, the basic plan actions dependencies can be made explicit by mapping whether an action is an enabler, constraint, or pacing factor for another. This does not replace the adaptation plan, but it makes it easier to use when several conditions shift at once.

7.1.5. Boundary Conditions for Applicability

This subsection outlines when ATR is likely to be applicable. ATR provides decision logic for an actor operating in a system-of-systems. It starts by defining the system boundary and the actor's role, and then builds the roadmap within that frame. Transferability is therefore mainly a question of whether the same logic can be re-applied to other actors and other system-of-systems configurations, even though the specific content must be rebuilt each time. Drawing on the Canada-Netherlands corridor case and the discussions in this section, three boundary conditions stand out for when ATR is likely to be applicable:

1. **The decision problem must involve staged commitments that are costly to reverse:** ATR adds value when investments have long lead times and high sunk costs. This requires clear decision moments where the next commitment follows only after specific deliverables are achieved. If decisions are small, easily reversible, or updated continuously, there is less need for staging commitments or for defining decision and adaptation tipping points. There must also be real room to adapt, meaning that delaying, rescoping, scaling, or switching route is actually possible.
2. **The uncertainties must be mainly observable developments:** ATR works best when uncertainty can be framed as enabling conditions that can be monitored over time, even if probabilities and timing are unknown. These developments must be clear enough to translate into practical thresholds that indicate whether the next step is still feasible and still meets the success definition. If uncertainty is mainly driven by shocks that cannot be tracked in this way, or by a small set of input variables that can be handled with standard sensitivity or risk analysis, ATR's monitoring-and-trigger logic becomes less useful.
3. **There must be clear decision ownership and a coordination process:** ATR assumes that someone can define success, commit resources, and change course when conditions shift. It also assumes a repeated process in which information is gathered and shared, and trade-offs are revisited at decision points. This is essential in corridors because outcomes depend on progress elsewhere in technology, markets, and policy, not only on the project's own execution. Without decision ownership and an active interaction process, the roadmap may still describe options, but it will not work as an approach for conditional commitment and adaptation.

Under these conditions, ATR is expected to work well in other hydrogen import corridors, and it can transfer to similar infrastructure transitions such as electricity grid expansion and congestion management, or CO₂ transport and storage networks. In contrast, ATR fits less well in settings where change is fast and decisions are updated continuously instead of through investment gates. Examples include digital platforms and software-driven systems, where strategy can be adjusted frequently and investments are easier to reverse, and mature commodity supply chains with stable standards and contracting practices, where conditionality is already built in and the main challenge is, for example, cost efficiency rather than sequencing.

Within these systems, ATR fits best for actors who make staged, high-CAPEX commitments with clear go/no-go moments, such as project developers, (semi-)public infrastructure developers/operators, and consortium leads. For policy-makers the fit is more mixed. DAPP was developed for public actors who can choose policy pathways and activate instruments they control. ATR, as applied here, supports a project actor that depends on many enabling conditions outside its authority. As a result, many conditions are external, and many responses involve pausing, rescoping, or scaling rather than deploying policy instruments. Policy actors can still use ATR outputs to make dependencies, timing risks, and bottlenecks explicit, but a policy-focused version would need to start from public objectives as success criteria and treat policy instruments as the main pathways.

7.2. Limitations

This section outlines the main limitations of the study and its outputs. It separates limitations of the research design, limitations of ATR as an approach, and limitations of the ATR-based plan for the Newfoundland and Labrador green ammonia project. The aim is to clarify the boundaries of validity and the conditions under which the results should be interpreted.

7.2.1. Limitations of the Research

This subsection summarises the main limits of the study's empirical basis and analytic approach. The case offers depth and lets the ATR logic be tested in a realistic corridor setting, but data access, method choices, and the time-bound nature of the corridor context constrain how far the results can be generalised or treated as stable over time:

- **Uneven actor coverage:** Interviews cover several key stakeholder groups, but access to dedicated off-takers and additional finance actors could not be secured. Expert interviews partly compensate, but this still limits how well the study captures buyer procurement logic, lender requirements, and bankability thresholds as they are applied in practice.
- **Interview-document balance:** The study combines semi-structured interviews with a selective document review. Interviews reflect perceptions and incentives at the time of interviewing, and respondents may emphasise what fits their organisational position. The document review was mainly used for context and triangulation rather than a systematic content analysis, which limits independent validation of interview claims.
- **Gioia aggregation trade-off:** Gioia coding improves transparency by compressing rich accounts into concepts and themes, but this can smooth over nuance, disagreement, and conditional statements. Minority views and actor-specific interpretations can become less visible, even though these differences may matter in a system-of-systems context.
- **Single-case design:** The depth of one corridor case supports explanation and method testing, but it limits generalisation. The results, therefore, support analytical claims about how ATR can be used, rather than predictive claims about what will happen in other corridors.
- **Time- and perspective-bounded evidence:** The technology, market, and policy context is evolving, so the relative importance of constraints can shift over time. This is a limitation for ATR, as elaborated in Subsection 7.1.2, and it is also a limitation of this research because the findings reflect the conditions and perceptions observed during the study period. In addition, the corridor is analysed broadly, but the roadmap logic is developed from an upstream ammonia project perspective. Midstream and downstream dynamics are identified, but they are less detailed and less tightly validated in the ATR outputs than the upstream decision space.

These limitations show that the study demonstrates the usefulness and plausibility of ATR's logic in this corridor setting, but the specific vulnerabilities, opportunities, and thresholds should be treated as time-bound and actor-perspective dependent rather than as stable, complete corridor-wide facts.

7.2.2. Limitations of the ATR Approach

This subsection summarises the main limitations of ATR that follow from the implications discussed in Section 7.1. The case shows that ATR makes conditionality explicit and helps structure staged decisions, but it still requires additional routines and judgement to use the outputs well in a multi-actor corridor setting:

- **No rule for mixed signals:** ATR can specify many signposts, triggers, and responses, but it does not tell users how to weigh conflicting developments at a decision point.
- **Interactions between basic plan actions and actionlines remain partly implicit:** ATR distinguishes basic plan actions that apply across pathways from timing-specific actionlines, but it does not always make explicit how progress in one area changes what becomes feasible, urgent, or necessary in another.

- **Responses can be slower than the trigger logic assumes:** Even if a trigger is clear, acting on it may require renegotiation, redesign, permitting changes, or new counterpart commitments that do not fit neatly within the decision window.
- **Framing can become outdated:** ATR works best when uncertainties can be translated into observable conditions. If discontinuities change what matters, the trigger set may need revision, not just continued monitoring.
- **Roadmap visuals can be misread:** A single roadmap graphic can appear more schedule-like and complete than corridor processes really are, which can create unrealistic expectations.

These limitations do not undermine the value of ATR, but they clarify what ATR needs around it: a decision routine for prioritising signals, explicit handling of interactions between actions, periodic reframing, and coordination mechanisms that go beyond what any single roadmap can encode.

7.2.3. Limitations of the ATR Outputs and Findings

This subsection discusses limitations of the ATR-based plan developed for the green ammonia project developer in Newfoundland and Labrador. It highlights where the plan may still oversimplify how technology, markets, and policy translate into real project delivery. The limitations clarify which risks can be managed through adaptivity and which remain structural constraints on performance and execution:

- **The outputs can overstate modularity:** While the plan is adaptive and can scale in phases by adding capacity modules, such as additional wind turbines, electrolysers, and ammonia trains, it simplifies how modularity works in practice. Several enabling infrastructures, such as pipelines and high-voltage grid connections, are not modular in the same way and often require new routing, permits, tie-ins, or costly upfront oversizing, making later capacity additions less straightforward than implied. Moreover, “Safe and sustainable by design” and “Secure full-scope permitting and land control” force early lock-in decisions on, for example, emergency response design and land allocation, which can constrain how and where later tanks, trains, and utilities can be added. Finally, federal permitting can depend on the size and type of marine infrastructure and the vessel class, so even a small change, for example, a different berth design or a larger ship, can trigger a different permitting process, meaning export capacity cannot always be scaled easily and may sometimes be hard to scale at all.
- **The outputs can understate that flexibility creates extra work and cost:** The plan deliberately keeps options open by, for example, allowing different end uses, future bunkering, and off-grid operation with a limited grid back-up. This makes the plan flexible, but it also adds cost and work because flexibility has to be engineered into the project. In practice, it can mean redundancy and oversizing. That is especially problematic at low scale, for example, because the pathways already assume a full-scale export port interface early, so a small first phase can carry high fixed costs for design, permits, and port infrastructure that may only pay off at higher volumes. Flexibility tends to create follow-on work later: keeping options like bunkering available already shapes today’s layout and hazard zones, and moving to the next scale can require updated FEED and revised safety/permitting packages instead of simply adding another module.
- **Real flexibility can disappear before decision points:** The plan shows clear go/no-go moments at milestones like FEED, FID, and COD, but in practice, commitments are often made earlier because of long lead times, such as booking EPC capacity and ordering long-lead equipment. This means the roadmap can place decision points later than the point at which major cost and schedule commitments are already unavoidable.
- **The plan does not fully account for the cost of waiting and the risk of stranded work:** A strength of the plan is that it can defer FID or pause scale-up when signposts do not materialise, but deferral can generate losses even when the decision logic is correct. Each decision point still requires spending on, for example, FEED packages, environmental baseline work, consultation and stakeholder processes, and land control and permitting steps. If the plan later advises not to scale, early run-off, or prolonged downsizing, a significant share of this development effort

becomes unrecoverable. In addition, the plan does not fully build in the cost of waiting. Even if the plan correctly pauses scale-up, delays can still reduce total revenue by postponing sales and cash flow, missing early market opportunities, and incurring ongoing project costs.

- **Integration choices can create path dependency:** The plan keeps technology options open, but early design choices can still lock in the plant. For example, if the first phase is built around low-temperature electrolysis, adding SOEC later often requires a redesign to supply and integrate heat, update controls, and revise the safety case, rather than a simple upgrade.
- **Some triggers can stay too ambiguous to function as real decision rules:** The triggers assume that signposts can be translated into clear thresholds that indicate whether the next step remains feasible and meets the success definition. Some signposts are measurable, such as signed offtake coverage and permitting status. Others are harder to translate into clear decision thresholds, such as what counts as “credible” infrastructure readiness or “sufficient” policy stability. If thresholds remain vague or contested, triggers risk becoming interpretive discussion points rather than decision rules.

The limitations suggest that the plan simplifies how difficult execution can be in practice. It turns uncertainty into phases, triggers, and contingencies, but many real constraints show up as slow and expensive work in engineering, permitting, and contracting that cannot be solved by sequencing alone. In several places, the roadmap treats scaling and adaptation as if they mainly depend on making the right decision at the right moment, while in reality, the limiting factor is often whether changes can be implemented without major redesign, new approvals, or renegotiation. This means the roadmap is valuable for structuring choices and keeping the project from scaling too early, but it does not fully capture the practical effort, time, and cost involved in changing course, preserving options, and moving from one phase to the next.

7.3. Recommendations

This section translates the findings and discussion of the study into recommendations. It distinguishes between project-level recommendations for corridor and infrastructure developers on how to structure commitments and preserve adaptivity under system-of-systems dependencies, policy recommendations aimed at reducing the corridor hold-ups identified, and directions for future research to strengthen evidence on ATR’s transferability and usability across contexts.

7.3.1. Project-Level Recommendations

This subsection provides practical recommendations based on the insights on upstream green hydrogen and ammonia production and export infrastructure development. While formulated from an upstream developer perspective, they apply to hydrogen infrastructure development across the value chain, including import terminals, ports, storage and conversion assets, and backbone and hinterland networks.

In corridor settings, decisions tend to fail when they follow an internal project timeline while dependencies elsewhere are still immature. Structuring development around a number of decision moments helps keep commitments aligned with what the wider system-of-systems can support:

- **Plan corridor development as a sequence of commitments with explicit interfaces:** The corridor is best approached as a system-of-systems in which progress depends on multiple domains maturing together, including offtake, certification/compliance, access to import infrastructure, permitting and social licence, financeability, and delivery capacity (EPC, equipment, workforce). ATR shows that a practical way to manage this is to work with a limited set of milestones, such as FEED-ready, FID-ready, and COD/scale-up, and to define the minimum cross-actor package that must be in place, such as a contracting set-up and a defined route from port to end demand (storage/cracking/backbone or alternatives). This anchors commitments in corridor readiness rather than in an internal project timeline.
- **Build monitoring, coordination, and updating routines around the plan:** Progress depends on co-evolution across the wider system-of-systems, including not only infrastructure delivery

elsewhere in the chain (e.g., EU terminal readiness, cracking and storage capacity, and backbone/hinterland connections), but also policy implementation, certification and standards, market formation, financing conditions, and technology maturity. ATR shows that a plan can be kept usable by combining continuous monitoring of pre-defined signposts and thresholds with scanning for developments outside that set that may become decisive. Periodic coordination rounds can then be used to review what has changed across these domains, reassess which constraints are currently binding, and update sequencing and decision moments accordingly.

Adaptivity means keeping realistic options open as corridor conditions improve, stay uncertain, or deteriorate. This requires both scalable technical choices and an explicit set of alternative routes that remain feasible under different corridor trajectories:

- **Use modular scaling as the default adaptation mechanism, while anticipating non-modular enablers:** Phasing capacity in modules (e.g. generation-electrolysis-ammonia trains-storage-terminal throughput) allows growth to follow market formation and infrastructure readiness. At the same time, several enabling elements do not scale easily and benefit from early clarity, such as permitting scope, marine works/berth design, and pipeline/backbone access. If these are deferred, later expansion can trigger redesign, new permits, and renewed stakeholder processes. ATR shows that modular capacity can be treated as the flexible layer by using scale-based pathways, while addressing these enablers early with future phases in mind helps avoid expansion paths that later become infeasible.
- **Plan explicitly for multiple development pathways:** Corridor conditions can strengthen, stall, or weaken as demand, policy implementation, and import-side readiness evolve at different speeds. Practical planning, therefore, benefits from specifying more than one feasible route: ATR incorporates this by using scale-up pathways when enabling conditions improve, and downscaling or run-off pathways if conditions deteriorate. Making these pathways explicit reduces the risk that development follows a single expected growth path that later proves unrealistic under uncertainty.

In early corridors, investment readiness is not unlocked by one factor alone. Offtake is often the pacing constraint, but moving forward requires other conditions as well:

- **Treat offtake as the pacing condition:** Projects move beyond early development once there is sufficient offtake to support financing. Early progress is typically easier when offtake is concentrated in one or a few strong contracts and when what is sold aligns with what the first phase can deliver, specified in terms of volume coverage, contract length, buyer credit quality, and clear delivery and certification terms. Concentrated early offtake also reduces coordination complexity: it clarifies destination and delivery points, makes specifications and interfaces easier to fix, and allows the rest of the chain to be organised around a concrete buyer.
- **Build investability around a set of binding conditions:** Even with strong project fundamentals, investment typically depends on more than signed demand. FID readiness is shaped by (i) a permit and socially accepted scope, (ii) secured access to import-side infrastructure and a defined route to end demand, (iii) a financeable risk allocation and cost of capital, (iv) a deliverable EPC and supply-chain plan for long-lead equipment and workforce, and (v) evidence that the integrated system can perform reliably. ATR makes these dependencies explicit in its triggers. Within these triggers, certification and eligibility determine whether exports are actually sellable. Practical development, therefore, benefits from embedding monitoring, metering, data logging, and traceable mass-balance accounting in both plant design and contracts from the start, so compliance can be demonstrated at shipment or batch level. The pilot phase can be used to test the full compliance chain in practice (electricity sourcing logic, accounting, and emissions measurement and reporting), reducing late redesign risk and strengthening the case for subsequent investment decisions.

Together, the recommendations emphasise that early hydrogen infrastructure decisions are primarily coordination decisions under uncertainty. Progress is most reliable when commitments are tied to shared readiness across the chain, when flexibility is designed and managed as a capability, and when investment is treated as conditional on a set of binding conditions that can be monitored over time. This

is where ATR-based planning helps keep development viable not only in a best-case growth trajectory, but also under slower market formation, policy delay, and uneven infrastructure rollout.

7.3.2. Policy Recommendations

This subsection provides policy recommendations aimed at reducing the corridor hold-ups identified in the Canada-Netherlands hydrogen import corridor. The analysis shows that early corridor projects fail because demand, regulation, infrastructure, permitting, and finance mature at different speeds and remain mutually conditional. Policy, therefore, adds value when it reduces the gap between long-term ambitions and near-term investment decisions by lowering uncertainty, improving coordination across interdependent actors, and creating the conditions for staged commitments as mapped in ATR as the corridor evolves. The recommendations do not introduce new policy instruments for the hydrogen sector, but clarify which mechanisms must actually work to make a largely policy-driven hydrogen market move beyond announcements and become investable, including enabling projects to pass the FID decision point in ATR:

- **Turn targets into enforceable demand:** Offtake is the pacing condition for project finance, but offtake does not emerge at scale when willingness-to-pay remains below production cost. EU Member States should therefore focus on instruments that create and stabilise demand. First, EU demand mandates should be implemented consistently by prioritising the timely transposition of RED III industrial RFNBO targets into national law, including clear compliance obligations and penalties; uneven implementation sustains a wait-and-see offtake environment that undermines FID readiness. Second, price-stabilisation mechanisms for renewable ammonia and hydrogen should be scaled up and replicated, including H2Global-style double auctions and CfD-type instruments that bridge the cost gap and provide long-term revenue certainty; for corridor relevance, these mechanisms should explicitly support imported certified molecules where EU eligibility criteria are met. Third, carbon-cost exposure under ETS/CBAM needs to translate into a cost disadvantage that is large enough to affect contracting decisions within this decade, helping narrow the cost gap and enabling long-term RFNBO contracts. However, these measures can also raise level-playing-field concerns in globally traded sectors and increase relocation pressures. They do not resolve this concern, so it remains a key question mark for corridor demand formation: for firms to commit, the incentives and protections must make staying and investing in Europe the more attractive option than relocating. Still, without enforceable demand and gap-closing instruments, early offtake is unlikely to form, and ATR made clear that projects will continue to stall; in that sense, the transition requires first movers, and policy is the main way to make first-mover decisions feasible by shifting these key signposts beyond their ATR trigger thresholds.
- **Reduce certification ambiguity and align export-import eligibility pathways:** Certification policy adds value when rules are not only defined, but also applied in the same way in practice, so projects can design and contract from the start. A remaining challenge is consistent application across schemes and jurisdictions for export projects, including agreed documentation formats and data requirements at batch or shipment level. The Canada-Netherlands MoU and other platforms can be used to support practical interoperability between Canadian carbon-intensity approaches and recognised certification schemes, including clear verification requirements. ATR shows certification as a market-access condition: clearer alignment reduces eligibility risk at decision points and enables contracting and investment.
- **Enable backbone, terminal, storage and cracking investments ahead of demand while keeping early tariffs investable:** A classic chicken-and-egg dynamic in hydrogen corridors is that demand and signed contracts often depend on visible infrastructure access, while infrastructure investors need volume commitments to justify building. Early corridors make this especially difficult because utilisation is low in the first years and many costs are incurred upfront, so cost recovery through user tariffs can quickly become unattractive. Network regulators, infrastructure operators, port authorities, and governments can help break this loop by enabling early infrastructure while limiting the cost burden on first users. First, tariff and amortisation approaches can spread cost recovery over longer periods so early tariffs remain manageable under low utilisation and do not lock the system into a high-tariff/low-volume trap. Second, public risk-sharing

can support corridor-critical links and interfaces (e.g., port-to-hinterland connections, storage, and cracking interfaces), reducing reliance on immediate contracted throughput. Third, terminal development should be aligned with downstream infrastructure plans, so import capacity is developed together with a realistic route to storage, conversion, and end users, for example by linking port investments to backbone connection plans such as the DRC. Finally, where feasible, supported infrastructure should preserve flexibility (e.g., phased tankage and adaptable interfaces), given uncertainty about volumes, locations, and end uses. This recommendation follows from ATR because backbone and import-chain accessibility are binding enabling conditions: amortisation, risk-sharing, and phased flexible build-out can move these signposts across trigger thresholds, so scale-up becomes possible.

- **Make permitting pathways for corridor-critical assets workable:** ATR indicates that permitting constraints can become corridor showstoppers by closing otherwise viable pathways before key commitment moments. In the Netherlands, Natura 2000 and nitrogen rules can make import-chain assets difficult to site in Rotterdam without exemptions, adjustments, or alternative locations, which can reshape the feasible corridor configuration. In addition, disagreements over preferred ammonia transport modes (keep ammonia in-port versus move it to the hinterland; pipeline versus rail/barge and specific corridors) create uncertainty about routing and required permits, while routing itself requires coordination with many local stakeholders and is constrained by safety zones and limited public familiarity with ammonia and hydrogen risks. In Canada, permitting complexity is also a barrier: multi-layered provincial and federal processes create uncertainty about timelines and requirements, because additional federal review can be triggered by design thresholds such as the scope of marine works and vessel size. Dutch/EU authorities and Canadian federal and provincial authorities should therefore focus on making permitting pathways for corridor-critical assets more implementable and predictable, through better coordination across responsible authorities and transparent, decision-ready approaches to spatial, nitrogen, safety and routing trade-offs for terminals, cracking, storage and connected infrastructure, so projects can define feasible routes and configurations early enough to match investment decisions. This is difficult in practice because it involves contested trade-offs and multi-level decision-making, but making the trade-offs explicit and the permitting pathway predictable is itself a key enabler for corridor investment, as indicated by ATR.
- **Strengthen public risk-sharing to convert interest into investable projects:** Public finance policy adds value when it helps bridge the pre-FID-to-FID gap made explicit in ATR. The case suggests that shifts in interest rates and risk perceptions can quickly change whether large hydrogen projects still make economic sense, and that public involvement is often part of what makes the first projects financeable. Many instruments already exist, so the remaining issue is less the tool itself than whether public lenders, guarantee providers, and governments can apply support in a way that fits export corridors: at a scale that materially affects the cost of capital, and in a form that can be combined across jurisdictions. In practice, this means aligning Canadian supply-side support (e.g., tax credits and public loans) with European demand-side mechanisms (e.g., tenders and CfD-type support), so projects can combine CAPEX de-risking with revenue stabilisation and meet the financeability conditions required in ATR to take FID and sustain operation.

Across all of these points, coordination is the practical enabler: ATR makes explicit that corridor progress depends on whether timelines, interfaces and expectations across production, ports, regulation, infrastructure operators, and buyers can mature together. This can be seen as a core policy task because policy can provide the shared rules and decision frameworks that help align actors and cross-border interfaces and reduce repeated delays caused by unresolved dependencies. In ATR, these shared rules can support a common set of signposts and thresholds across actors, so that triggers shift from indicating that conditions are still too weak for investment and scale to indicating that construction and scale-up are possible.

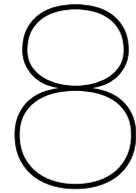
7.3.3. Recommendations for Future Research

This subsection outlines directions for future research that follow from this study's limitations and insights. Further work is needed to test ATR across contexts, validate it with intended users, and assess

how well it remains useful as corridor conditions evolve:

- **Broader empirical testing across cases, systems, and actors:** Future research could apply ATR in additional hydrogen corridors (e.g., different exporter-importer pairs) and in other socio-technical systems with similar timing and interdependence risks, while also varying the actor that the ATR effort focuses on (e.g., project developers, terminal/infrastructure operators, public actors). Comparing how the same building blocks perform under different regulatory regimes, infrastructure configurations, market maturity levels, and actor agencies would help evaluate ATR performance and distinguish which dynamics and trigger structures are context-specific and which are recurring patterns under system-of-systems uncertainty.
- **Actor-centred validation and usability testing:** Future research could test ATR with intended users in practice, for example through workshops. Such validation can assess whether signposts and triggers are interpreted consistently, whether decision points align with real decision-making and investment cycles, and whether contingency actions are operationally feasible within the time available. This would move evaluation beyond conceptual value toward demonstrated decision support.
- **Tracking how vulnerabilities and opportunities evolve over time:** Follow-up interviews and repeated coding rounds can track how vulnerabilities and opportunities shift as policies are implemented, infrastructure timelines change, and markets mature. This would also test whether a revision loop is practical over time and whether it improves plan relevance when new bottlenecks appear or earlier assumptions stop holding.
- **Dynamic updating and digital tooling:** A further research direction is to implement ATR as an updateable digital tool. In such a tool, milestones, duration ranges, and trigger statuses can be entered as data, after which the pathway map is generated automatically and updates whenever inputs change, with the affected decision points, actionlines, and contingency moves highlighted. Programming also makes it possible to link triggers to live data sources where available and provide a structured monitoring dashboard that supports regular decision reviews in long-term infrastructure development.

Together, these directions would strengthen evidence on where ATR transfers well and improve its practical usability for hydrogen infrastructure decisions under uncertainty.



Conclusion

The objective of this study was to strengthen TRM for adaptive, system-level decision-making under uncertainty and to use it to generate decision-relevant insights for hydrogen import infrastructure development. To achieve this, the study reviewed how current TRM approaches address adaptability, justified DAPP as a suitable approach to strengthen TRM, developed an integrated conceptual model by combining the building blocks of both approaches, and applied the model in an empirical illustration of the Canada-Netherlands hydrogen import corridor. This chapter concludes the study by addressing the main research question:

"How can Dynamic Adaptive Policy Pathways be used to make Technology Roadmapping adaptive and systemic, and what insights does this provide for the development of hydrogen import infrastructure?"

Current TRM approaches address adaptability mainly implicitly through three features, but they rarely make adaptation operational in the roadmap logic:

- TRM frameworks are flexible in principle. Their time-based, multi-layered structure can be reconfigured when drivers, scope, or time horizons change, and the layered format helps surface interdependencies across market/policy pull, delivery mechanisms, and technology/capability push. In system-level settings, this creates a shared representation that can be updated as a socio-technical system evolves. However, because the roadmap is often produced as static, the visual clarity of the framework can mask uncertainty and give the impression of a stable pathway even when conditions are shifting.
- TRM content can be revised as new evidence emerges. Roadmaps commonly integrate foresight and context tools and rely on stakeholder and expert input to revise assumptions, actions, milestones, and priorities. This enables TRM to incorporate new information over time, but it typically treats uncertainty as contextual background to be revisited in periodic updates, rather than specifying in advance what signals should be tracked and what thresholds would require a change in course.
- TRM processes are described as iterative and learning-oriented. This is especially relevant at the system level where implementation and follow-up are critical. The literature emphasises that roadmaps should be embedded in ongoing practice and revisited as drivers, technologies, and stakeholder priorities evolve. However, guidance on how roadmaps are maintained is limited, and most approaches do not define explicit reflection points with decision criteria. As a result, adaptability largely relies on informal review cycles and stakeholders' effort to notice system shifts, interpret their implications, and revise the roadmap accordingly.

Based on these points, TRM supports adaptability as an intention, through updateable frameworks, revisable content, and iterative processes, but it generally lacks explicit decision points and trigger conditions that indicate when to revisit the roadmap and how to adjust commitments. This gap is especially problematic in high-uncertainty, system-level contexts, motivating adaptive extensions that build

monitoring and triggers for when and how to change course directly into the roadmap.

Marchau et al. (2019) present five approaches for supporting decision-making under uncertainty, of which three explicitly support adaptive decision-making: Dynamic Adaptive Planning (DAP), Dynamic Adaptive Policy Pathways (DAPP), and Robust Decision Making (RDM). DAP adds a clear monitoring and response logic, yet it remains centred on adapting a single evolving plan and offers limited structure for long-horizon sequencing across alternative routes. RDM adds analytical stress tests by simulating candidate strategies across many plausible futures to identify where they break down and what trade-offs they imply, but it does not translate into a roadmap-style plan for implementation. DAPP combines a pathways framework that makes alternative development routes explicit, decision points and adaptation tipping points that clarify where and when switching becomes necessary, and signposts, triggers, and sell-by dates that connect changing system conditions to action. For these reasons, DAPP provides both the representation of multiple pathways and the decision logic to manage them, making it a suitable approach to complement TRM's system mapping with explicit mechanisms for adaptation.

Integrating DAPP into TRM can be understood as combining TRM's strengths in making long-term plans explicit and communicable with DAPP's explicit adaptation logic into one model. Integrating DAPP into TRM reshapes the framework from a single time-based route to a pathways representation, the content by adding signposts, triggers, and contingency actions to milestones and actionlines, and the process by embedding monitoring and trigger-based revision into implementation. This integrated approach is termed ATR. ATR is formalised into four steps, each demonstrated through an empirical illustration of the Canada-Netherlands hydrogen import corridor:

1. Define System Scope

ATR starts by defining the system-of-systems, as outcomes emerge from interactions between systems rather than from a single system in isolation. Within this wider context, the operational system is specified as the immediate socio-technical setting in which intervention is pursued. The actor for whom the roadmap is developed is then defined by clarifying which decisions it can make, what it can directly control within the system, and where it can only influence outcomes through interactions with other systems. Success is then defined as a set of criteria that determines whether continued commitment remains justified under uncertainty, rather than as a single optimal end-state, and the planning horizon is specified as the period over which decisions and consequences are considered. These elements together define the decision context: who decides, about what, within which system boundaries, over what time period, and according to which success criteria. TRM contributes a structured way to map the system context, as it helps articulate how goals, constraints, and interdependencies in the operational system and its surrounding environment shape what can realistically be pursued, and it provides a basis for later translating these insights into a time-phased roadmap. DAPP contributes the logic needed to judge plans under uncertainty: it requires that success is defined in a way that allows pathway viability to be assessed over time. ATR integrates both by turning the system-of-systems framing and actor agency into a unified decision frame: it makes explicit how interacting systems shape feasibility and clarifies what the actor can decide or control within that context, while evaluating choices against the success criteria that guide pathway design and switching.

Applying this step placed the Canada–Netherlands hydrogen import corridor in its system-of-systems structure consisting of four interacting systems: (1) upstream production and export (renewables-to-ammonia production, storage, and export in Newfoundland and Labrador), (2) transatlantic logistics (shipping to Northwest Europe), (3) import (terminals and cracking/storage in Rotterdam, and hinterland connectivity), and (4) downstream demand (buyers and offtake conditions). With this boundary in place, the operational system is defined as upstream production and export, and the actor as an export-oriented hydrogen/ammonia project developer in Newfoundland and Labrador who configures and delivers the production-and-export project, while relying on the other systems for its business case. Success is defined not as achieving a single optimal end-state or export target, but as maintaining a defensible commitment under uncertainty through to 2060. In practice, this means maintaining minimum conditions for safe, compliant, financeable,

and market-eligible operation, so that pathway choices and potential switching can be assessed over time as the systems co-evolve.

2. Develop Evidence Base & Default Plan

An evidence base is developed by identifying vulnerabilities and opportunities across the system-of-systems and translating them into an actor-centred logic by clarifying what the actor can control, what it can influence through coordination, and what remains external exposure. This agency translation converts system insights into decision-relevant implications. The evidence base establishes the default content of ATR in two parts, both derived directly from the identified vulnerabilities and opportunities. First, it develops a default action plan: a basic set of continuous actions that remains relevant across multiple plausible futures because it addresses vulnerabilities and leverages opportunities, thereby providing a stable backbone for implementation throughout the planning horizon. These basic actions can be characterised as mitigating actions (actions to reduce the likely adverse effects of a plan), hedging actions (actions to spread or reduce the uncertain adverse effects of a plan), seizing actions (actions taken to seize likely available opportunities), and shaping actions (actions taken to reduce failure or enhance success). Second, it defines baseline adaptation tipping points by specifying how changes in these vulnerabilities and opportunities could evolve to a point where the success criteria can no longer be met: when external developments shift project viability or when enabling interactions with other systems no longer hold. TRM contributes a structured way to build this evidence base by mapping the wider system context over time and across key layers, which helps to integrate dispersed insights and to identify where vulnerabilities and opportunities arise in the system-of-systems, while also creating a clear line of sight to later milestones and staged commitments in the roadmap. DAPP contributes the requirement that planning begins from a basic plan and that its viability limits are made explicit through adaptation tipping points, defined relative to the success criteria, as well as this basic plan action typology. ATR integrates both by linking system evidence to this default base, basic actions and adaptation tipping points, thereby turning system assessment into decision-relevant content.

A vulnerability-and-opportunity evidence base is developed for the Canada–Netherlands corridor. An agency translation then converts this evidence into the default basic plan actions, showing that the developer's leverage is concentrated in a small set of controllable upstream choices, while most corridor-critical conditions lie in the influence or exposure domains. Control is largely limited to the upstream configuration and operation: phased and modular by design and safe and sustainable by design. Influence covers outcomes that require coordination with other actors, including bankable offtake contracts, innovation and export coordination, domestic infrastructure-aligned development, social acceptance through Indigenous and community alignment, and full-scope permitting and land control; execution can also be strengthened through workforce and supply-chain alignment. Exposure captures conditions external to the developer, notably access to public capital and demand-side support and macro-financial conditions, as well as time-dependent rules and system factors that must be tracked and reflected in assumptions: certification-aligned project design, end-use-flexible ammonia design, EU infrastructure-aligned export design, and policy alignment and dialogue. In parallel, two baseline adaptation tipping points are identified that turn corridor uncertainty into explicit criteria for stopping the project. ATP1 captures a failure of enabling conditions to converge so that FID cannot be reached. After FID, ATP2 captures a structural loss of commercial viability and/or compliance and operability such that continued operation is no longer defensible.

3. Construct Roadmap

The roadmap is constructed by turning the default base into an execution structure over time. Actionlines are defined as the main workstreams that capture how the project is implemented in practice across its lifecycle. They describe what needs to be done and in which broad sequence, while the basic action plan sits behind them as overarching requirements that must be satisfied within and across these actionlines. Milestones are then defined to stage the actionlines in time. They mark moments where prerequisites must be in place, where commitments are made, or

where progress must be confirmed before moving on. Pathways are formed by combining the same actionlines and milestone structure in different time-based configurations that vary by controllable choices, most importantly, scale and the pace of scale-up. These pathway choices also shape how the basic action plan is implemented, because different configurations can change the level of requirements that must be met within the basic action plan. Sell-by dates set the latest feasible timing of the milestones and therefore bound the timing of the actionlines. Decision points are placed at selected milestones where pathway choices remain feasible, and adaptation tipping points are anchored to milestones so that pathway choice and timing can be evaluated against the success criteria as conditions evolve. TRM contributes the time-based structuring of actionlines and milestones, while DAPP contributes the pathway logic and the placement of decision points and adaptation tipping points. ATR integrates both by embedding DAPP's adaptive pathways and decision rules within TRM's actionline-and-milestone roadmap structure.

Applying this step converted the default plan into a time-sequenced roadmap for the project developer in the Canada-Netherlands hydrogen corridor. The roadmap is organised around a set of pathways that differ mainly in scale choices, low-, mid-, full-, and expanded-scale trajectories, while also keeping non-success outcomes inside the representation, including early run-off before construction, early run-off after start-up, and downscaled operation. To make these alternatives comparable and implementable, pathways are organised into actionlines that follow the same development logic: from early piloting and configuration selection through FEED, FID, EPC, COD, operation, and late-life/decommissioning. This structure then enabled the identification of decision points at moments when commitments become hard to reverse: the initial configuration choice, FID (and any later expansion FID), post-COD scale-up, and contract roll-off or renewal, thereby clarifying when switching between pathways is actually feasible. Finally, the roadmap added sell-by dates and decision windows that make timing constraints explicit, notably the latest feasible COD needed to preserve a minimum operating life, and the contract roll-off windows that indicate when continuation versus run-off becomes rational. In this roadmap, adaptation is mostly done through modular scaling and sequencing. By translating uncertainty into controllable options, it shows not only what could be done, but also when smaller commitments are needed under weak conditions and when faster expansion is justified as conditions strengthen, while marking the decision points at which pausing, downscaling, or exit becomes the rational response if enabling conditions fail to materialise.

4. Enable Adaptation Plan

The adaptation plan is specified to keep both the basic action plan and the roadmap relevant as conditions evolve. It defines signposts as monitored variables that follow from the basic action plan, focusing on developments that matter for delivering the success criteria. Triggers are then derived from these signposts as thresholds that inform roadmap decision points by indicating when continuation, adjustment, or pathway switching should be considered at the moments when such choices are feasible. These triggers are formulated as IF-THEN statements. In addition, contingency actions are defined in response to triggers to preserve the relevance of the basic action plan under changing conditions. They include defensive actions that preserve the benefits of the basic plan or address external challenges while leaving it unchanged; corrective actions that adjust the basic plan; capitalising actions that exploit opportunities to improve basic plan performance; and plan reassessment, initiated when the analysis and assumptions critical to success have clearly lost validity. DAPP contributes the adaptive logic that links monitoring to pre-defined responses, ensuring that signposts, triggers, and contingency actions are specified as part of the plan. ATR contributes by embedding this adaptive logic in roadmapping. Implementation then proceeds along the pathway selected by the actor, with adaptation applied as specified through the signposts, triggers, and contingency actions, while periodically revisiting the evidence base to capture shifts within the system scope and update the default base and roadmap accordingly.

Applying this step produced the corridor's adaptation plan for the developer by connecting the roadmap to a monitoring-and-response system. Signposts, triggers, and contingency actions are mapped to the basic plan actions, so that offtake, permitting and social licence, certification eligibil-

ity, safety and environmental performance, financeability, workforce and supply-chain deliverability, and EU import-chain accessibility are each tracked through concrete indicators and IF–THEN thresholds. These thresholds are explicitly tied to the roadmap’s decision points, meaning that continuation, pausing, downscaling, switching pathways, or run-off is justified by pre-defined evidence requirements at the moments when commitments can still be adjusted. In addition, two corridor-specific reassess contingencies are specified that reopen the project’s central assumptions when monitored conditions persistently fail to converge. The first contingency reassesses the carrier choice (ammonia versus alternative hydrogen carriers) if ammonia pathways are structurally unattractive. The second contingency reassesses market orientation (export-led versus domestic or Atlantic-regional focus) if EU-side infrastructure access and demand formation continue to lag. Therefore, the same roadmap remains usable under changing conditions because it specifies, in advance, what developments count as strengthening or weakening the business case and which concrete moves are needed when those developments occur.

Following these steps, ATR contributes a roadmap logic that makes adaptation explicit: it connects a system-of-systems framing to actor-specific commitments by specifying switchable pathways, decision windows, and observable thresholds that trigger adjustment. Applied to hydrogen import infrastructure, ATR makes explicit why progress often stalls even when individual subsystems move forward: commitments are interdependent but not synchronised. Upstream production and export development depends on offtake, while offtake stays limited as long as the willingness-to-pay gap persists and policy instruments and mandates are slow and uneven; certification and regulatory fragmentation keep eligibility and design choices uncertain; and uncertain EU backbone/hinterland timing, amplified by spatial/permitting limits and modal frictions, delays downstream investment, so actors keep postponing commitment because each waits for commitment by others. This creates wait-and-see behaviour across the value chain. ATR maps these interdependencies and timing windows, so actors can see what progress elsewhere is needed before they commit. It shows that offtake is typically the pacing condition for moving beyond early upstream development, but that reaching FID requires broader enabling conditions, including certification and eligibility, import-side infrastructure access and permitting feasibility, financeability, and deliverable EPC and supply-chain capacity, which ATR translates into monitorable thresholds that justify proceeding, pausing, rescoping, switching pathways, or terminating the project before irreversible commitments are made. In practice, this adaptivity is often delivered through modular, scalable design and phased expansion. In doing so, ATR provides a practical planning tool for staged commitment and coordinated investment in hydrogen import corridors where readiness evolves unevenly across the value chain.

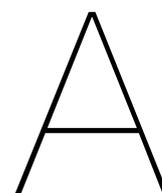
References

- Alsulaiman, A. (2023). *Renewable hydrogen import routes into the EU* (tech. rep.). Oxford Institute for Energy Studies. Oxford, Oxford Institute for Energy Studies.
- Ansari, D., & Maria Pepe, J. (2023, June). *Toward a hydrogen import strategy for Germany and the EU* (tech. rep.).
- Ason, A. (2025). Hydrogen Offtake Agreements. *The Oxford Institute for Energy Studies*.
- Bowen, G. A. (2009). Supporting a grounded theory with an audit trail: an illustration. *International Journal of Social Research Methodology*, 12(4), 305–316. <https://doi.org/10.1080/13645570802156196>
- Breitschopf, B., Zheng, L., Plaisir, M., Bard, J., Schröer, R., Kawale, D., Koornneef, J., Melese, Y., Gérard, F., Schaaphok, M., Gorenstein Dedecca, J., Bene, C., & Cerny, O. (2022, February). *The role of renewable H2 import & storage to scale up the EU deployment of renewable H2* (tech. rep.). <https://doi.org/10.2833/727785>
- Buijs, L. J., Wolleswinkel, G. J., Koornneef, J. M., Wijtzes, S., Octaviano, R., De Respinis, M., Gopalan Jayashankar, G., Van Gorp, E. F., Santiago, J., & Van Damme, P. R. (2025). *Enabling and balancing the hydrogen infrastructure in North Western Europe* (tech. rep.). TNO, ARCADIS. www.tno.nl
- Carvalho, M. M., Fleury, A., & Lopes, A. P. (2013). An overview of the literature on technology roadmapping (TRM): Contributions and trends. *Technological Forecasting and Social Change*, 80(7), 1418–1437. <https://doi.org/10.1016/J.TECHFORE.2012.11.008>
- de Vries, B., Mieog, J., Knoors, B., van der Slot, A., Albers, B., de Vries, M., Lanphen, S., & Tanis, A. (2022, October). *Making the hydrogen market: Requirements for the Netherlands to become a hydrogen hub* (tech. rep.). <https://www.rolandberger.com/en/Insights/Publications/Making-the-hydrogen-market.html>
- De Bruijn, H., Heuvelhof, E., & Veld, R. (2010). *Process management: Why project management fails in complex decision making processes*. Springer Berlin Heidelberg. <https://doi.org/10.1007/978-3-642-13941-3>
- DeLaurentis, D., & Callaway, R. K. (2004). A system-of-systems perspective for public policy decisions. *Review of Policy Research*, 21(6), 829–837. <https://doi.org/10.1111/j.1541-1338.2004.00111.x>
- DNV. (2025). *Energy Transition Outlook 2025* (tech. rep.).
- ESMAP, OECD, Global Infrastructure Facility, Hydrogen Council, & The World Bank. (2024, February). *Scaling Hydrogen Financing for Development* (tech. rep.). www.worldbank.org
- European Commission. (2019, December). *The European Green Deal* (tech. rep.).
- European Commission. (2022, May). *REPowerEU Plan* (tech. rep.). Brussels.
- European Commission. (2023a, March). *Communication on the European Hydrogen Bank* (tech. rep.).
- European Commission. (2023b, June). *Regulation (EU) 2023-1184* (tech. rep.).
- European Commission. (2023c, June). *Regulation (EU) 2023-1185* (tech. rep.).
- European Parliament and Council. (2023a). Directive (EU) 2023-2413. <http://data.europa.eu/eli/dir/2023/2413/oj>
- European Parliament and Council. (2023b, October). *Regulation (EU) 2023/956 establishing a carbon border adjustment mechanism* (tech. rep.). <http://data.europa.eu/eli/>
- European Parliament and Council. (2024a, July). *Directive (EU) 2024-1788* (tech. rep.). <http://data.europa.eu/eli/dir/2023/2413/oj>
- European Parliament and Council. (2024b, July). *Regulation (EU) 2024-1789* (tech. rep.). <http://data.europa.eu/eli/dir/2023/2413/oj>
- European Parliament & The Council. (2012, April). *Directive 2012/18/EU on the control of major-accident hazards involving dangerous substances* (tech. rep.).
- European Union. (2023). Fit for 55: increasing the uptake of greener fuels in the aviation and maritime sectors. <https://www.consilium.europa.eu/en/infographics/fit-for-55-refueu-and-fueu/>
- Fluor. (2023, April). *Large-scale industrial ammonia cracking plant* (tech. rep.).
- Flyvbjerg, B. (2006). Five misunderstandings about case-study research. *Qualitative Inquiry*, 12(2), 219–245. <https://doi.org/10.1177/1077800405284363>

- Garcia, M. L., & Bray, O. H. (1997). Fundamentals of technology roadmapping. *Sandia National Laboratories*.
- Gerdri, N., Vatananan, R. S., & Dansamasatid, S. (2009). Dealing with the dynamics of technology roadmapping implementation: A case study. *Technological Forecasting and Social Change*, 76(1), 50–60. <https://doi.org/10.1016/J.TECHFORE.2008.03.013>
- Gioia, D. A., Corley, K. G., & Hamilton, A. L. (2013). Seeking Qualitative Rigor in Inductive Research: Notes on the Gioia Methodology. *Organizational Research Methods*, 16(1), 15–31. <https://doi.org/10.1177/1094428112452151/FORMAT/EPUB>
- Government of Canada. (1992). Transportation of Dangerous Goods Act. <https://laws-lois.justice.gc.ca/eng/acts/t-19.01/page-1.html>
- Government of Canada. (2001). Canada Shipping Act. <https://laws-lois.justice.gc.ca/eng/acts/c-10.15/>
- Government of Canada. (2020, December). *Hydrogen strategy for Canada* (tech. rep.).
- Government of Canada. (2024, May). Hydrogen Strategy for Canada: Progress Report. <https://natural-resources.canada.ca/energy-sources/clean-fuels/hydrogen-strategy/hydrogen-strategy-canada-progress-report>
- Government of Canada. (2025a, August). Coordination of Federal Authorizations through the Impact Assessment Process. <https://www.canada.ca/en/impact-assessment-agency/services/policy-guidance/practitioners-guide-impact-assessment-act/coordination-federal-authorizations-impact-assessment-process.html>
- Government of Canada. (2025b, September). Designating a Project under the Impact Assessment Act. <https://www.canada.ca/en/impact-assessment-agency/services/policy-guidance/designating-project-impact-assessment-act.html#toc002>
- Government of Newfoundland and Labrador. (n.d.-a). Environmental Assessment. <https://www.gov.nl.ca/eccc/env-assessment/>
- Government of Newfoundland and Labrador. (n.d.-b). Wind Hydrogen Projects. <https://www.gov.nl.ca/em/wind-hydrogen-projects/>
- Government of Newfoundland and Labrador. (2023, April). *Environmental Assessment Guidance for Registration of Onshore Wind Energy Generation and Green Hydrogen Production Projects* (tech. rep.).
- Government of Newfoundland & Labrador. (2024). *Hydrogen Development Action Plan* (tech. rep.).
- Green hydrogen factory concept. (2023, April). <https://www.istockphoto.com/nl/foto/green-hydrogen-factory-concept-gm1478756113-506940440?searchscope=image%2Cfilm>
- Gu, T., Huš, M., Araya, S. S., Likožar, B., Gallucci, F., & Liso, V. (2026). Thermocatalytic ammonia synthesis beyond conventional Haber-Bosch: Principles, advances, challenges and opportunities. *Progress in Energy and Combustion Science*, 112. <https://doi.org/10.1016/j.pecs.2025.101262>
- Haasnoot, M., Kwakkel, J. H., Walker, W. E., & ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, 23(2), 485–498. <https://doi.org/10.1016/j.gloenvcha.2012.12.006>
- Haasnoot, M., Middelkoop, H., Offermans, A., van Beek, E., & van Deursen, W. P. (2012). Exploring pathways for sustainable water management in river deltas in a changing environment. *Climatic Change*, 115(3-4), 795–819. <https://doi.org/10.1007/S10584-012-0444-2/FIGURES/9>
- Haasnoot, M., Warren, A., & Kwakkel, J. H. (2019). Dynamic Adaptive Policy Pathways (DAPP). *Decision Making under Deep Uncertainty: From Theory to Practice*, 71–92. https://doi.org/10.1007/978-3-030-05252-2_4/TABLES/3
- Hart, D. (2019). Roadmapping. *Science and Engineering of Hydrogen-Based Energy Technologies: Hydrogen Production and Practical Applications in Energy Generation*, 357–382. <https://doi.org/10.1016/B978-0-12-814251-6.00007-1>
- Hydrogen Council. (2025). Global Hydrogen Compass.
- IEA. (2021). *Net Zero by 2050 - A Roadmap for the Global Energy Sector* (tech. rep.). www.iea.org/t&c/
- IEA. (2024, April). *Northwest European Hydrogen Monitor 2024* (tech. rep.). Paris. <https://www.iea.org/reports/northwest-european-hydrogen-monitor-2024>
- IEA. (2025). *Global Hydrogen Review 2025* (tech. rep.). www.iea.org
- IMO. (2023). Strategy on reduction of GHG emissions from ships.
- IRENA & AEA. (2022). *Innovation Outlook: Renewable ammonia*.
- Kostoff, R. N., & Schaller, R. R. (2001). Science and technology roadmaps. *IEEE Transactions on Engineering Management*, 48(2), 132–143. <https://doi.org/10.1109/17.922473>

- Kwakkel, J. H., Haasnoot, M., & Walker, W. E. (2015). Developing dynamic adaptive policy pathways: a computer-assisted approach for developing adaptive strategies for a deeply uncertain world. *Climatic Change*, 132(3), 373–386. <https://doi.org/10.1007/s10584-014-1210-4>
- Lee, S., & Park, Y. (2005). Customization of technology roadmaps according to roadmapping purposes: Overall process and detailed modules. *Technological Forecasting and Social Change*, 72(5), 567–583. <https://doi.org/10.1016/J.TECHFORE.2004.11.006>
- Lempert, R. J. (2019). Robust Decision Making (RDM). *Decision Making under Deep Uncertainty: From Theory to Practice*, 23–52. <https://doi.org/10.1007/978-3-030-05252-2\FIGURES/3>
- Marchau, V. A. W. J., Walker, W. E., Bloemen, P. J. T. M., & Popper Editors, S. W. (2019). *Decision Making under Deep Uncertainty*. Springer. <https://doi.org/10.1007/978-3-030-05252-2>
- McDowall, W. (2012). Technology roadmaps for transition management: The case of hydrogen energy. *Technological Forecasting and Social Change*, 79(3), 530–542. <https://doi.org/10.1016/j.techfore.2011.10.002>
- Ministerie van Klimaat en Groene Groei. (2024, November). *Kabinetsvisie waterstofdragers* (tech. rep.). www.rijksoverheid.nl/kgg
- Natural Resources Canada. (2025, January). Memorandum of Understanding between the Government of Canada and the Government of the Netherlands on cooperation in the field of hydrogen energy. <https://natural-resources.canada.ca/climate-change/memorandum-understanding-between-government-canada-government-netherlands-cooperation-field-hydrogen-energy>
- Notermans, I., van de Lindt, M., van der Have, C., van Raak, R., & Rotmans, J. (2020, June). *Hydrogen for the Port of Rotterdam in an International Context - a Plea for Leadership* (tech. rep.).
- O'sullivan, E., Phaal, R., & Charles, F. (2021). Agile Roadmapping: An Adaptive Approach to Technology Foresight. *Foresight and STI Governance*, 15(2), 65–81. <https://doi.org/10.17323/2500>
- Park, H., Phaal, R., Ho, J. Y., & O'Sullivan, E. (2020). Twenty years of technology and strategic roadmapping research: A school of thought perspective. *Technological Forecasting and Social Change*, 154. <https://doi.org/10.1016/J.TECHFORE.2020.119965>
- Peacock, A., Hull-Bailey, B., Hastings, A., Martinez-Felipe, A., & Wilcox, L. B. (2024). Techno-economic assessment of liquid carrier methods for intercontinental shipping of hydrogen: A case study. *International Journal of Hydrogen Energy*, 94, 971–983. <https://doi.org/10.1016/j.ijhydene.2024.11.205>
- Phaal, R., Farrukh, C. J. P., & Probert, D. R. (2001). Characterisation of Technology Roadmaps: Purpose and Format. In *Proceedings of picmet '01: Portland international conference on management of engineering and technology* (Vol. 1). IEEE.
- Phaal, R., Farrukh, C. J. P., & Probert, D. R. (2005). *Developing a Technology Roadmapping System* (tech. rep.). <http://mati.ncms.org>
- Phaal, R., Farrukh, C. J., Mills, J. F., & Probert, D. R. (2003). Customizing the Technology Roadmapping Approach. *Portland International Conference on Management of Engineering and Technology*, 361–369. <https://doi.org/10.1109/PICMET.2003.1222814>
- Phaal, R., Farrukh, C. J., & Probert, D. R. (2004). Technology roadmapping - A planning framework for evolution and revolution. *Technological Forecasting and Social Change*, 71(1-2), 5–26. [https://doi.org/10.1016/S0040-1625\(03\)00072-6](https://doi.org/10.1016/S0040-1625(03)00072-6)
- Phaal, R., & Muller, G. (2009). An architectural framework for roadmapping: Towards visual strategy. *Technological Forecasting and Social Change*, 76(1), 39–49. <https://doi.org/10.1016/J.TECHFORE.2008.03.018>
- Rouwenhorst, K. H., Krzywda, P. M., Benes, N. E., Mul, G., & Lefferts, L. (2021). Ammonia Production Technologies. In *Techno-economic challenges of green ammonia as an energy vector* (pp. 41–83). Elsevier. <https://doi.org/10.1016/B978-0-12-820560-0.00004-7>
- Royal HaskoningDHV. (n.d.). *Ammonia Transport Study* (tech. rep.).
- Saritas, O., & Oner, M. A. (2004). Systemic analysis of UK foresight results: Joint application of integrated management model and roadmapping. *Technological Forecasting and Social Change*, 71(1-2), 27–65. [https://doi.org/10.1016/S0040-1625\(03\)00067-2](https://doi.org/10.1016/S0040-1625(03)00067-2)
- Saunders, B., Sim, J., Kingstone, T., Baker, S., Waterfield, J., Bartlam, B., Burroughs, H., & Jinks, C. (2018). Saturation in qualitative research: exploring its conceptualization and operationalization. *Quality and Quantity*, 52(4), 1893–1907. <https://doi.org/10.1007/s11135-017-0574-8>
- Strum. (2024). EVREC Green Energy Hub Environmental Assessment Registration Document.

- Trangwachirachai, K., Rouwenhorst, K., Lefferts, L., & Faria Albanese, J. A. (2024, October). Recent progress on ammonia cracking technologies for scalable hydrogen production. <https://doi.org/10.1016/j.cogsc.2024.100945>
- Trattner, A., Höglinger, M., Macherhammer, M. G., & Sartory, M. (2021). Renewable Hydrogen: Modular Concepts from Production over Storage to the Consumer. *Chemie-Ingenieur-Technik*, 93(4), 706–716. <https://doi.org/10.1002/cite.202000197>
- Tully, Z., King, J., & Johnson, K. (2025). Hydrogen storage minimization under industrial flexibility constraints: A techno-economic analysis of off-grid green ammonia production. *International Journal of Hydrogen Energy*, 111, 12–21. <https://doi.org/10.1016/j.ijhydene.2025.02.109>
- Walker, W. E., Marchau, V. A., & Kwakkel, J. H. (2019). Dynamic Adaptive Planning (DAP). *Decision Making under Deep Uncertainty: From Theory to Practice*, 53–70. https://doi.org/10.1007/978-3-030-05252-2_{ }3/TABLES/3
- WSP, North Sea Port, Smart Delta Resources, & Provincie Zeeland. (2024). Haalbaarheidsstudie Ammoniakopleiding Publieke management samenvatting.



PESTLE Analysis

This appendix presents a PESTLE analysis of the political, economic, social, technological, legal, and environmental drivers that shape the feasibility and timing of renewable hydrogen imports from Newfoundland and Labrador to the Netherlands, used to guide the interviews.

Table A.1: PESTLE drivers relevant for hydrogen import from Canada to the Netherlands.

Dimension	ID	Driver	Relevance
Political	P1	EU import targets	The European Green Deal (2019) sets the 2050 climate-neutrality vision and positions renewable hydrogen as a key energy carrier. The Fit for 55 Package (2021) translates this into binding 2030 targets, while REPowerEU (2022) signals an ambition to import up to 10 MT of renewable hydrogen by 2030.
	P2	International maritime governance and IMO alignment	The IMO's GHG Strategy (2023) sets net-zero targets for shipping by 2050.
	P3	Transatlantic political alignment	The EU-Canada Green Alliance (2023) shows cooperation on clean energy and hydrogen. Canada prioritises European offtake.
	P4	Dutch national hydrogen framework and Rotterdam's import role	The National Hydrogen Programme (2022-2024) and National Hydrogen Strategy (2023) define the Netherlands' ambition to become a European hydrogen hub and prioritise large-scale import infrastructure. Within this framework, the port of Rotterdam is positioned as a key entry point.
	P5	EU and national funding support for early imports	Financial instruments such as the European Hydrogen Bank help bridge the green premium and de-risk early import and conversion projects. Price-stabilisation tools, including CfDs, are increasingly used to guarantee minimum revenues and reduce financing risk for first-mover projects.
	P6	Canadian policy and export framework	The Hydrogen Strategy for Canada (2020) sets the long-term vision for developing a domestic hydrogen economy and positioning Canada as a global exporter.

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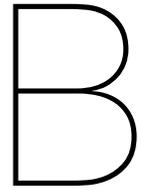
Dimension	ID	Driver	Relevance
Economic	Ec1	LCOH: power cost (LCOE)	Electricity costs and full-load hours dominate the hydrogen cost; location and system integration determine overall competitiveness.
	Ec2	LCOH: H ₂ plant, technology pathway & scale-up	Electrolyser/conversion CAPEX, efficiency, and utilisation levels drive hydrogen cost.
	Ec3	Cost of capital & financing environment	Financing costs capitalise policy, market, and technology risk; a higher WACC substantially increases LCOH.
	Ec4	Willingness to pay & offtake certainty	Customer price acceptance and offtake set the achievable price, revenue stability, and utilisation, defining bankability and project value. Market maturity remains limited, and willingness to pay for a green premium varies.
	Ec6	Regulatory credit value (RFNBO/low-carbon)	A substantial share of value is created through certificates/credits rather than molecule sales alone. Eligibility, verification, and monetisation of RFNBO/low-carbon certificates directly affect achievable revenues and bankability.
	Ec7	Price formation & benchmarks (grey/blue ammonia)	The existing global ammonia market shapes buyer expectations and effectively caps molecule sales prices for green hydrogen/ammonia; competitiveness depends on approaching cost parity with grey and blue ammonia.
	Ec8	Carbon pricing and cost parity	Rising EU ETS prices and prospective carbon adjustments improve the competitiveness of low-carbon hydrogen and ammonia relative to grey alternatives. Higher effective CO ₂ costs strengthen the business case for imports and accelerate convergence toward parity.
	Social	S1	Community acceptance
S2		Indigenous engagement and rights Canada	Projects must engage Indigenous groups in Newfoundland and Labrador as part of environmental and land-use approvals.
S3		Safety perception of hydrogen and ammonia	Production and handling hydrogen and ammonia raises concerns about health and environmental risks.
S4		Employment and regional development benefits	Projects can create construction jobs and stimulate local procurement.
S5		Labour force availability and skills	Projects and ports require trained personnel for ammonia handling, safety, and cracking operations.
Technological	T1	Hydrogen carrier pathway & end-to-end efficiency	Choice of carrier drives infrastructure, safety, and overall efficiency. Ammonia currently leads due to mature shipping and storage systems, but each conversion step adds irreducible energy losses.
	T2	Electrolyser technology selection & configuration	Technology choice affects CAPEX/OPEX and operability.
	T3	Grid integration, intermittency & dynamic operation	Wind-to-hydrogen systems must manage variability through buffering and plant turndown.

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Dimension	ID	Driver	Relevance
Legal	T4	Ammonia cracking & heat integration at import	Cracker efficiency and heat recovery determine terminal design, energy use, and carbon intensity. Improved catalysts and effective heat integration are necessary for large-scale imports into Rotterdam.
	T5	Hydrogen backbone readiness	Repurposing gas pipelines requires selective upgrades or possibly new-build segments.
	T6	Large-scale hydrogen storage & system buffering	Secure supply requires substantial H ₂ buffering (tanks or caverns) to manage outages and maintain pressure stability. Storage linked to crackers and backbone is essential.
	T7	Terminal engineering, safety & modular design	Safe large-scale ammonia handling depends on advanced berth, tank, and pumping design. Modular layouts enable phased expansion, and integrated safety systems and automation improve reliability.
	L1	Canada: permitting	Hydrogen export projects face provincial EAs (with public Project Registration) and potential federal Impact Assessment. Federal processes include Indigenous consultation.
	L2	EU/NL environmental permitting and major-hazard controls	In the Netherlands, the Environment and Planning Act (Omgevingswet, 2024) consolidates spatial and environmental permits. EU regimes and major-hazard law (Seveso III) apply to ammonia/hydrogen terminals, with Dutch PGS guidelines (e.g., PGS 12 for ammonia, PGS 35 for hydrogen) setting detailed design and operational requirements. Additionally, nitrogen deposition limits under Dutch nature law (Natura 2000) require modelling and mitigation of NO _x /NH ₃ emissions.
	L3	Certification, RFNBO and Guarantees of Origin	EU Delegated Acts define renewable (RFNBO) criteria and GoO rules that imports must meet.
Environmental	L4	Hydrogen market and network regulation (EU)	The Hydrogen and Gas Markets Decarbonisation Package establishes a framework for hydrogen networks (operatorship, unbundling, tariffs, and third-party access). Implementation will determine how import terminals interconnect with the European Hydrogen Backbone and the costs/terms of transmission.
	L5	EU demand-side obligations and sectoral mandates	RED III and related regulations create binding demand for renewable hydrogen (industry/transport sub-targets), while FuelEU Maritime and ReFuelEU Aviation impose legally enforceable GHG-intensity cuts and blending paths. These obligations support offtake certainty but introduce compliance requirements for producers, importers, and end-users.
	En1	Lifecycle GHG intensity, leakage and N ₂ O	The overall climate impact depends on the electricity mix, energy used for conversion and shipping, and emissions from cracking. Hydrogen leakage and ammonia slip can add indirect warming, while combustion or use may form N ₂ O.

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Dimension	ID	Driver	Relevance
	En2	Air quality, NOx and odour at ports	Emissions of NOx from operations are a permitting issue in ports. Ammonia vapours and odour can also raise local concerns. Using low-emission fuels, shore power, and good vapour and odour management helps meet air-quality standards.
	En3	Water, desalination and chemical management	Even where freshwater is available, water use and effluent discharge need careful management. Hydrogen and ammonia production also use large amounts of chemicals such as KOH, making safe storage, handling, and waste treatment essential.
	En4	Marine and coastal ecosystems	Jetty construction, dredging, and vessel movements can disturb marine habitats, fisheries, and wildlife.
	En5	Spill prevention and emergency response	Ammonia spills pose serious risks to workers, nearby residents, and aquatic life. Strong containment, leak detection, and emergency plans are essential for safety.
	En6	Cumulative effects and spatial/land-use integration	Multiple hydrogen and ammonia projects can together increase pressure on air, water, and ecosystems. Integrated spatial planning is needed.



Interview Protocol

This appendix provides the interview protocol used to obtain stakeholder insights on the key drivers, uncertainties, and constraints shaping the Canada-Netherlands hydrogen corridor.

Opening

Consent & Data Handling

- With your permission, I will record this interview for transcription only.
- The transcript will be anonymised (no names / identifiers).
- You may review and correct the transcript.
- Insights will be analysed thematically; quotes may be used but never traceable to you.

(Start recording after consent.)

Introduction & Research Context

- Introduce researcher and organisation.
- Thesis has two components:
 - Improving roadmap methods to make them more adaptive;
 - Applying that approach to the Canada-Netherlands hydrogen import corridor.
- Reference case: Newfoundland & Labrador → green ammonia → Rotterdam.
- Focus primarily on upstream (production and export Newfoundland & Labrador).

Purpose of Interview

- Gather stakeholder insights for grounding the roadmap in practice.
- Identify key uncertainties, drivers, risks and boundary conditions.

General Interview Structure

Introduction & Context Questions

- Can you describe your role and your organisation's involvement in hydrogen production, import, and/or transport?
- Have you (or your organisation) worked with roadmaps or scenario approaches before? If so, how did you handle uncertainty or multiple futures?

General Corridor Questions

- To what extent are you familiar with Canada as a potential export partner for Europe? Based on what you know, how do you assess Canada's prospects as a hydrogen supply corridor to Rotterdam?
- In your view, what determines whether a corridor like Canada–Rotterdam will truly reach scale?
- Which factors do you think are most likely to slow down or derail such a corridor in practice?

PESTLE Themes (general guiding questions)

These prompts guide the PESTLE discussion. Depending on time and relevance, either the full PESTLE is covered or only the most relevant dimensions. Questions are intentionally concise so they can be expanded or skipped as appropriate.

Political / Policy

- Which policy developments (national/EU/international) are currently most decisive for hydrogen import projects?

Economic / Market

- What do you see as the biggest economic bottleneck for large-scale imports (CAPEX, OPEX, offtake, financing, etc.)?

Social / Acceptance

- How important are societal aspects (safety, CSR, energy colonialism, reputation of supply countries) in choosing corridor partners?

Technological / System Integration

- Which technology choices (carrier, production/terminal concept, flexibility) are the most risky or decisive for success?

Legal / Regulatory

- Are there regulatory or permitting challenges you see as potential showstoppers or major sources of delay?

Environmental

- How are spatial constraints, ecology (Natura 2000, nitrogen), and CO₂ intensity considered in decision-making?

Stakeholder-Specific Questions

These questions are optional prompts to deepen the discussion during the PESTLE section. If not all PESTLE dimensions are covered, they can also be used instead to focus on the most relevant topics for this stakeholder.

Government & Public Authorities (GOV)

- How does your ministry/region balance demand certainty with industrial competitiveness (e.g. under the RED III 42% target)?
- What role do you expect imports to play compared to domestic production in national hydrogen strategies?
- How do you view the importance of CSR when selecting supply partners (e.g. Canada vs. MENA)?
- What do you see as the most important governance challenges around permitting and cross-border infrastructure?

Port Authorities & Infrastructure Operators (PIO)

- How do you deal with uncertainty around volumes and timing when planning pipelines and terminals?
- How do you choose terminal design and carrier choice (ammonia vs LOHC vs LH2)?
- How do you see the division of roles between public backbone infrastructure and private infrastructure?
- What is the impact of permitting pressure on project phasing and investment decisions?

Project Developers & Industry Actors (PD&IA)

- Where does the largest risk premium sit in the business case?
- What are the current dealbreakers for FID?
- What is crucial to make import bankable (e.g. subsidies, CfDs/ H2Global, CO₂ pricing)?
- How do you navigate the technology uncertainties in first markets (e.g. importance of pilots)?

Financiers (FIN)

- What are the most important requirements for bankability in hydrogen projects?
- Where do you see the greatest sensitivities in LCOH?
- How do you evaluate phased development versus megaprojects?
- How relevant are ESG criteria in country/corridor/carrier selection?

Offtakers (OFF)

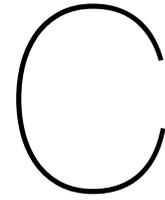
- What does your sector need in order to switch to RFNBO/low-carbon hydrogen?
- What price range or contract structure (term, flexibility) would make import hydrogen attractive?
- Which risk weighs most heavily on decision-making (e.g. price volatility, certification, or supply security)?
- What facility modifications and product specs would be required for process compatibility?

Closing**Future & Recommendations**

- Comparing all dimensions, where do you see the biggest uncertainties for this corridor to reach scale?
- What do you think needs to happen in the next 5–10 years to successfully align supply, demand, and infrastructure?

Ending

- Is there anything we have not discussed yet, or are there any final comments?
- Thank the interviewee and ask whether they would be willing to review the roadmap once drafted.



Gioia Analysis Results: Evidence Base

This appendix presents the results of the Gioia analysis, detailing the first-order terms, second-order themes, and associated basic plan actions. First-order terms are formulated as vulnerabilities and opportunities and form the empirical evidence base. For each first-order term, the main actors are mapped based on who can exert the strongest influence over that issue. It provides an overview of how actor insights and document evidence were coded and interpreted for the Canada-Netherlands hydrogen import corridor.

Table C.1: Overview of Gioia analysis results

#	First-order term (vulnerabilities & opportunities)	Illustrative quote(s)	Description/interpretation for actor based on documents	Second-order term	Main actors	Basic plan action
Control						
1	Phased and modular project scale-up enables capacity to grow in step with uncertain demand and infrastructure readiness	<p>PIO 1: "When you start with large GW-scale projects, a few will always drop out. But there are also always some that say, "I'll start a bit smaller after all." You can see that happening there now as well. You don't immediately build something large when the technology is not proven yet. But in the end, they all reach the same point. One starts big and realises "we still need to start smaller." Another starts small and thinks, "now I can scale up.""</p> <p>PIO 3: "You build it up step by step. An import terminal can be modular: start with one ammonia tank, then add the first cracker. Next, a second tank and a second cracker. That way, you can grow along with the market."</p>	Phased and modular scale-up is recognised as necessary because early hydrogen and ammonia infrastructure often suffers from low utilisation and high unit costs, making large, upfront investments uneconomic until demand, policy support, and infrastructure readiness are clearer (IEA, 2025; Trattner et al., 2021). By deploying capacity in steps, such as electrolyser blocks, projects can start at smaller, bankable scales and expand incrementally as volumes, market confidence, and system integration improve.	Technology Integration & Operational Flexibility Supply Cost & Project Development	PD	Phased & modular by design
2	Renewable variability can constrain output unless it is managed through storage or process flexibility	<p>PD&IA 1: "One thing that is a major challenge for green hydrogen or green ammonia is the intermittency or variability of the energy source. ... It's less of an issue for hydrogen production itself, but for the ammonia vessel, it does pose a challenge. ... There are two main approaches: one is energy storage, and the other is turning down the plant. That presents another technological challenge for the industry: the question of the turn-down ratio. ... Specifically, how much can the use of energy in the Haber-Bosch reactor be reduced when the energy supply drops? You can't simply switch it off; you can turn it down, but only to a certain extent. And when you do, you lose efficiency, which increases the overall production cost per delivered unit. ... So this remains a technological uncertainty: how will this actually work in practice?"</p>	A renewables-heavy system creates a basic trade-off between adding storage and accepting less efficient plant operation. Electrolysers can ramp with variable power, but ammonia synthesis works best at steady, high load and has limited turndown. Intermittency, therefore, needs to be managed through integration choices such as buffering, hydrogen or ammonia storage, and batteries (Strum, 2024).	Technology Integration & Operational Flexibility	PD	Phased & modular by design

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#	First-order term (vulnerabilities & opportunities)	Illustrative quote(s)	Description/interpretation for actor based on documents	Second-order term	Main actors	Basic plan action
3	Low-cost renewable power is the primary driver of LCOH and makes Canada a competitive production country	PD&IA 2: "When you look at the LCOH, that is a key factor. You can break it down into two components: the cost of hydrogen production (the facility) and the cost of power. And you'll see that the cost of power is actually the main driver for going to Canada: they have a very strong renewable energy base, with many full-load hours per year. ... As a result, you get relatively low electricity costs. ... Behind the LCOH, in my view, are primarily the LCOE and the cost of hydrogen production. And those vary depending on the technology and the location."	The dominant driver behind LCOH is the cost and availability of renewable electricity. Newfoundland and Labrador offers an attractive proposition due to a clean grid, high renewable potential, and high full-load hours, which reduce electricity costs. Peacock et al. (2024) analyse a similar scale hydrogen export from Atlantic-Canada to the port of Rotterdam, concluding a LCOH delivered via ammonia of approximately \$6.75/kg H ₂ , which is cost-competitive with IEA forecast green hydrogen market prices.	Technology Maturity & Production-Conversion Performance Supply Cost & Project Development	PD	Phased & modular design by
4	Technology and conversion choices can significantly improve power-to-ammonia efficiency, but they also largely determine CAPEX and lock in long-term performance	PD&IA 2: "... the cost of conversion, for example, to ammonia or other carriers. That requires the right technology choices. You have to make those choices together with different technology partners you believe in. For me, that's the main crux: which technology do you choose?" ... You can see the market now shifting toward pressurised electrolyzers, because they require less compression and therefore have a positive impact on both installation costs and safety contours. In addition, integration with SOEC plays a role, especially in a value chain involving ammonia, where a lot of heat is released or needs to be removed. That is a very interesting option, but there are still too few concrete projects, mostly pilot concepts so far. This is a differentiating factor: the choice of electrolyser technology and the rationale behind it. Scale also comes into play: do you apply one technology, or do you combine multiple technologies within one facility to spread risk? "	Once low-cost power is secured, the second critical uncertainty is how efficiently and reliably electricity is converted into hydrogen and ammonia. Technology choices such as electrolyser type and ammonia synthesis design directly affect efficiency, operating flexibility, cost, and scalability. Electrolyser technologies are evolving rapidly, and advanced options can reduce compression losses and improve system efficiency, but they introduce maturity, integration, and performance risk. According to IEA (2025), the capital cost of installing electrolysers manufactured outside China in 2024 typically ranged between \$2,000-2,600/kW, making conversion assets the dominant CAPEX component of green hydrogen projects. Modular and standardised electrolyser designs are increasingly deployed, with OEMs targeting 10% CAPEX reductions through replication and pre-fabrication rather than stack innovation alone (IEA, 2025).	Technology Maturity & Production-Conversion Performance Supply Cost & Project Development	PD	Phased & modular design by

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5	Ammonia's high toxicity and accident risk impose strict but manageable engineering and operational safety requirements for ammonia production and handling	FIN 1: "One is the toxicity of ammonia. That's the tricky part, what happens if something goes wrong? What are the effects on aquatic wildlife, on the people handling it, and on the local population living near the port?" PD&IA 1: "Of course, safety is always important, but I think it's manageable. It's not at a level where I would say we shouldn't pursue it. Safety can be designed for."	The inherent toxicity of ammonia and the potential severity of worst-case hydrogen/ammonia incidents translate into engineering design, operational procedures and emergency response requirements (Strum, 2024).	Safety & Environment	PD	Safe & sustainable by design
6	Environmental externalities of hydrogen production, water use, brine/chemical management, and secondary GHG emissions challenge sustainability claims	FIN 1: "Hydrogen itself is a greenhouse gas, which is a very important point. And ammonia, when burned, doesn't just produce emissions through slip; it also leads to N ₂ O emissions. You can address this with selective catalytic reduction, but it still needs to be managed. Otherwise, you end up with N ₂ O emissions, which are much worse than CO ₂ The second issue is desalinated water. ... You have to add chemicals, and then you need to discharge it somewhere, usually back into the sea. But what does that mean for marine life?"	Environmental impacts across the hydrogen–ammonia chain (chemical handling, lifecycle GHGs, hydrogen leakage effects, and N ₂ O from ammonia use) translate into requirements for plant design, operating procedures, monitoring, and emergency response (Strum, 2024). Compliance adds a hard lifecycle threshold (≤ 3.38 kg CO ₂ eq/kg H ₂ EU RFNBO (IEA, 2025)), making measurement and verification integral to design and operations.	Safety & Environment	PD	Safe & sustainable by design

Partial control / influence

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7	Without bankable long-term offtake, investment confidence is undermined, and FID cannot be taken	<p>FIN 1: "The real challenge for investment is offtake: finding buyers willing to purchase hydrogen at a reasonable price. Usually, as soon as someone says, I will buy X amount of green hydrogen at this price, you'll find a producer willing to supply it. Once that happens, port investments become simple because the port knows: there's a producer and a consumer, and the product needs to move from A to B through this port. Then they'll invest in infrastructure because it will be used."</p> <p>PD&IA 1: "Basically, if you don't have an offtaker, you don't have a project. Many projects fail at this stage, even large ones, including some under LNG side. To make a project viable, you need a long-term off-take agreement under commercially acceptable conditions. That's what makes the project real. Without it, there is no project."</p>	Large-scale hydrogen and ammonia projects only become financeable once a large share of production is secured under off-take agreements. The lack of firm offtake remains a binding constraint on project delivery: although more than 45% of announced low-emissions hydrogen projects target exports, only around one-quarter have identified an offtaker and less than 5% have secured committed investment (IEA, 2025). Firm offtake agreements account for only 2 MTPA, or roughly 5% of potential production by 2030, and their absence has contributed to delays, downsizing and cancellations of otherwise advanced projects (IEA, 2025). Securing offtake is therefore a necessary condition for achieving FID and scaling beyond intermediate development phases.	Demand Formation & Offtake Supply Cost & Project Development	OFF, PD	Secure bankable offtake contracts
8	Early offtake contracts can balance predictable revenues with flexibility to adapt over time	<p>PD&IA 1: "This is why LNG projects were structured around long-term contracts: both sides agreed on a fixed price, reducing market risk for sellers and buyers. The plant could run at full capacity, and both parties were locked into stable agreements." EXP 2: "Entering into a 10-15 year contract involves quite a bit of risk. That's why such contracts need to include clauses that offer flexibility, for example, the option to exit at a certain point. ... In addition, you could think about a price band within which the price can move, possibly linked to fluctuations in natural gas prices."</p>	Buyers are hesitant to commit to fixed volumes and prices, so hydrogen offtake agreements typically have a 10-15 year duration, but still rely on take-or-pay commitments of roughly 60–80% to support project finance (Ason, 2025). Contracts can include flexibility mechanisms, such as volume tolerance bands, allowing buyers to take lower volumes in a given year (typically 5-15%), make-up rights, enabling buyers to take previously paid-for but undelivered volumes in later periods, and specified price review clauses (Ason, 2025). Terminal access and delivery terms add another layer of uncertainty. According to Ason (2025), sellers often assume transport risk in early projects to simplify arrangements for buyers.	Demand Formation & Offtake Supply Cost & Project Development	OFF, PD	Secure bankable offtake contracts

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9	Innovation programmes and R&D support accelerate the development and de-risking of hydrogen technologies	<p>GOV 3: "There is a suite of tools that can be applied depending on the project. For example, innovation funding for technologies like methane pyrolysis has been supported. And now it is a practical solution. ... Now there are three vetted production pathways, because the innovation side is supported as well."</p> <p>GOV 2: "For example, an innovation mission is taking place in which a group of companies is travelling to Edmonton and Houston to explore technologies for liquid hydrogen, transport, and storage. This represents the more innovation-driven side of the work."</p>	IEA (2025) shows that government support for hydrogen R&D has quadrupled over the past five years to almost \$2.8 billion, with more technologies advancing at least one TRL in 2024 than in any previous year, particularly in end-use sectors such as steel, shipping and aviation. Government of Newfoundland & Labrador (2024) explicitly frames R&D, pilot and demonstration projects as essential to improving efficiency, scalability, storage, transport and verification of hydrogen and ammonia, leveraging local universities and applied research capacity. While this innovation push reduces long-term technology risk, developers may face timing risk as capital commitments may be made before technology development and standards stabilise.	Collaborative Public-Private Market Coordination Technology Maturity & Production-Conversion Performance	GOV, TRP, PD	Coordinate innovation & export
10	Cross-sector public-private coordination and value-chain integration align infrastructure, supply chains and market realities	<p>PIO 3: "The entire value chain is new. ... Everyone is therefore dependent on each other. Look, maybe someone in Canada says, "I've found a customer." But that customer will only sign if they are sure the terminal will be built. Then the terminal says, "I will only build my terminal if I'm sure I'll get paid by that customer." So everyone is, in a way, holding each other hostage. That's why I think it will be crucial for parties in the value chain to cooperate more and to actively reduce their mutual dependencies. ... What I also see as a problem in Canada is that there are five or six projects in the country that all have quite a lot of potential. But they don't work together. There is no shared infrastructure: no joint ports, no shared pipeline network, no shared ammonia plant. I think cooperation could really help them."</p>	IEA (2025) identifies coordination failures across the hydrogen value chain as a core barrier to scale-up, citing misaligned timelines between production, infrastructure and end use, slow progress on demand aggregation, and insufficient infrastructure readiness. Both supply and demand are expected to emerge in clusters rather than as isolated projects: IEA (2025) highlights industrial and port-based hubs as a key mechanism to pool supply, aggregate demand, share infrastructure and spread risk. Consistent with this, Government of Canada (2024) and Government of Newfoundland & Labrador (2024) emphasise public-private partnerships, hub development and international cooperation to align hydrogen production, ports, standards and workforce development with uncertain export demand.	Collaborative Public-Private Market Coordination	ALL	Coordinate innovation & export

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11	Future-proof and adaptive infrastructure planning enables scalable hydrogen deployment	<p>GOV 3: "We're actually working with our Dutch counterparts on this, which is long-term hydrogen storage using depleted wells and similar formations. In Newfoundland, ... which could potentially store up to 100 million tonnes of hydrogen. This is being positioned as a strategic reserve for future use, hypothetically, if there were ever an energy crisis in North America or Europe during the energy transition, and hydrogen was needed as a secure commodity."</p> <p>PIO 2: "A flexible system that can handle different energy carriers is a strong asset. It's not just about one type of carrier, but also about alternative molecules such as ammonia, methanol, and other options. By having diversity in the value chain, the system can adapt to market developments, which helps ensure long-term resilience."</p>	Federal policy emphasises grid reinforcement, storage and inter-provincial interties as key enablers of hydrogen scale-up (Government of Canada, 2024). This is particularly relevant for Newfoundland and Labrador, which combines clean energy with relatively limited and ageing transmission infrastructure. Hydrogen projects must be considered in parallel with grid readiness, the potential underground hydrogen storage via salt caverns (Government of Newfoundland & Labrador, 2024) and longer-term transmission development. As a result, project scalability is shaped by how hydrogen investments interact with evolving electricity infrastructure.	(Public) Alignment & Spatial Planning Technology Integration & Operational Flexibility	Infra &	PIO, PD	Domestic infrastructure-aligned development
12	Tension between Canadian domestic energy demand and hydrogen export can complicate hydrogen export projects	<p>PD&IA 2: "Why would Canada export its green electrons instead of using them itself? That is a crucial question, and also one of the reasons why projects in Canada are being stopped. Hydro-Québec has been very clear about this: "You are already asking for a lot of electricity, and that electricity is not going to Europe. It will stay in Canada." ... Although Newfoundland and Québec are very clean, provinces like Alberta and Ontario are still heavily polluted. ... Newfoundland, of course, is an island and more trade-driven, so export can be attractive there, but don't underestimate the political sensitivity of this issue."</p> <p>PIO 1: "It is important to first develop the local offtake market. If that is not your primary focus, you may start projects that eventually collapse because there is no market for the product. Demand in Europe has lagged far behind what we had hoped for. In reality, not enough has been done to create demand."</p>	Canada's decarbonisation could increase pressure to prioritise domestic hydrogen use over exports as electricity demand rises. Government of Newfoundland & Labrador (2024) explicitly addresses this trade-off by positioning the province primarily as an export-oriented supplier, reflecting its limited local industrial demand. At the same time, there are discussions about placing data centres and the plan emphasises regional coordination across Atlantic Canada, recognising that provinces such as Nova Scotia, with an industrial base, may provide domestic offtake opportunities. IEA (2025) also highlights the importance of domestic markets, noting that local use can stabilise revenues, reduce exposure to global price volatility and ease reliance on uncertain export demand.	(Public) Alignment & Spatial Planning Policy Stability, Geopolitics & International Commitment	Infra &	GOV, PD	Domestic infrastructure-aligned development

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13	Grid-connected production challenges compliance with green hydrogen certification rules	<p>FIN 1: "The question is: if you produce hydrogen using grid power, and the grid includes fossil fuel generation, which is the case almost everywhere, is that still allowed? Or is it only allowed with off-grid solutions where it's clear there is no fossil share? But that makes production more expensive again. This is the tricky part."</p> <p>PD&IA 1: "To receive credits, you would need to prove that only green energy is used, which is very difficult. As a result, you probably have to run the project as an island. So in my opinion, grid integration remains a major question mark."</p>	<p>According to DNV (2025), Europe is converging on stricter rules linking support and market access to lifecycle GHG intensity and renewable electricity sourcing. The EU requires RFNBOs to deliver at least 70% GHG savings versus fossil hydrogen and, from 2028, will enforce additionality (electricity from new renewable capacity) and temporal matching (hourly alignment between renewable generation and hydrogen production). This framework makes reliance on grid power increasingly risky for export-oriented projects, although Newfoundland and Labrador's grid is already >90% renewable (primarily hydro) and has surplus energy (Government of Newfoundland & Labrador, 2024).</p>	(Public) Alignment & Spatial Planning, Regulation, Standards & Certification	Infra &	GOV, PD	Domestic infrastructure-aligned development
14	Indigenous consultation and stakeholder alignment shape project legitimacy	<p>PD&IA 1: "For example, the Trans-Canada pipeline was already permitted, yet pipeline projects there have faced strong resistance from communities, including Indigenous groups. These situations can appear unexpectedly, are very difficult to predict, and can sometimes not only delay a project but also completely stop it."</p> <p>GOV 2: "I don't think permitting makes projects more difficult. On the contrary, I think Canada handles this very well, and it can even be seen as a best practice for other countries. ... Canada avoids that by actively involving Indigenous Peoples. In fact, they go further than just involving them: communities receive equity in projects and can decide for themselves how to invest it."</p>	<p>The legitimacy, timing and scalability of the project are linked to alignment with Indigenous communities, fisheries, and other local users of shared land and marine spaces. Government of Canada (2024) shows that early Indigenous partnerships are already shaping hydrogen project development across Canada, with formal partnership agreements or MoUs in place nationally. The report shows that early engagement, benefit-sharing and long-term collaboration reduce risk and enable projects to advance beyond early development stages.</p>	Social Permitting & Legal Procedures	Acceptance &	COM, PD	Secure social acceptance

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15	Public safety perceptions and spatial planning constrain hydrogen and ammonia projects and infrastructure	<p>PD&IA 1: "I would even say it's a potential minefield for these kinds of projects. Right now, I don't think the general public knows much about it. When people hear about hydrogen, they might picture the Hindenburg disaster. Ammonia is probably even less known.</p> <p>PIO 2: "If it's only about installing a pipeline underground, people more or less know by now what that should look like. The real challenge lies in the route, especially in coordinating with all the stakeholders along the way, from agricultural businesses whose land you cross to the cities and towns you pass through."</p>	Government of Canada (2024) highlights that public understanding of hydrogen and ammonia safety remains limited. Space constraints, routing complexity and safety zones can complicate siting decisions for hydrogen and ammonia infrastructure. The report emphasises that proactive engagement, transparent communication and consistent application of safety standards are essential to prevent opposition from becoming a bottleneck.	Social Acceptance Permitting & Legal Procedures (Public) Infrastructure Alignment & Spatial Planning Safety & Environment	COM, PD	Secure social acceptance
16	Complex, multi-layered Canadian permitting creates design and timing risk, but can be managed through project configuration choices	P&IA 1: "Well, permitting in Canada is definitely an important point. Just to add to that, it's a two-layered process: there's the provincial level and the federal level. It's not entirely clear whether the federal impact assessment is always required; it depends on certain criteria. Beyond that, there are other federal permits that may be needed, not just the impact assessment. For example, fisheries play a very important role in Canada, and there are specific requirements from fisheries, as well as Transport Canada."	In Canada, hydrogen and ammonia projects are subject to provincial and federal approval processes, involving multiple authorities (e.g. provincial environmental assessment, Fisheries and Oceans Canada, Transport Canada, and potential federal IA (Government of Canada, 2024)). Whether federal permitting is triggered depends on specific project design thresholds, such as marine infrastructure scope and vessel size, which introduces uncertainty for timelines, costs and final project configuration. Projects that leverage existing deep-water ports and limit new marine works can avoid triggering a federal IA altogether.	Permitting & Legal Procedures	GOV, PD	Secure full-scope permitting and land control

Exposed

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17	WACC, country risk and macro-financial volatility determine whether projects are investable at scale and make Canada a favourable location for project siting	<p>FIN 1: "The cost of capital and financing environment is the trickiest part in places like Morocco ... Very often, these countries have excellent conditions for wind and solar ... But today, it's more likely we'll build a hydrogen plant in Spain than in Morocco or Colombia. Not because Spain has better resources, but because financing costs are lower. The perceived risk of something going wrong is much lower in Spain than in Morocco or Colombia, which are considered more unstable politically, economically, and socially."</p> <p>PD&IA1: "Interest rates can change very quickly. We've seen in the renewables sector that certain projects were planned and budgeted with low interest rates, and then, years later, the interest rate was raised. As a result, those projects were no longer profitable or economically viable. I think that's another source of uncertainty."</p>	Green hydrogen and ammonia projects are highly capital-intensive and only become investable at scale when financing costs are sufficiently low. Advanced economies such as Canada typically enable project WACC in the range of 5-7%, whereas comparable projects in emerging hydrogen export regions often face required returns of 12-15%, increasing LCOH and constraining scale-up (ESMAP et al., 2024; IEA, 2025). Policy support and public financial participation have been decisive in allowing projects to reach FID by lowering perceived risk and WACC (IEA, 2025). In Canada, this advantage is reinforced by public financial institutions such as the Canada Infrastructure Bank, which provides debt financing and early-stage support, including funding for FEED for clean hydrogen and ammonia projects (Government of Canada, 2024).	Public Finance & Risk-sharing Instruments Supply Cost & Project Development	GOV, FIN	Secure public capital and demand-side support
18	Capital support and financing tools to reduce upfront costs and accelerate project deployment	<p>GOV 3: "There is the Clean Fuels Fund as well, a \$1.5 billion fund often used to support FEED and feasibility studies. On the production side, the Clean Hydrogen Investment Tax Credit is significant: projects can receive 15-40% credit on CAPEX, which is quite significant, and if the chosen carrier is ammonia, there's an additional 15%."</p> <p>PIO 1: "Subsidies are really necessary. If governments say, "We support this," then companies can also expect to receive some level of support."</p>	Governments play a central role by combining grants, tax credits, loans, guarantees and public equity to close the financing gap and de-risk first-of-a-kind projects (ESMAP et al., 2024; IEA, 2025). In Canada, this includes the CHITC, which provides a refundable 15-40% investment tax credit, and a 15% credit for hydrogen-to-ammonia conversion equipment (Government of Canada, 2024). The Canada Growth Fund is designed to accelerate the deployment of low-carbon hydrogen and to invest in the scale-up of projects that are beyond the pilot and demonstration phase (Government of Canada, 2024). Provincial instruments, such as Newfoundland and Labrador's 20% Green Technology Tax Credit and the Green Transition Fund, further reduce upfront capital exposure (Government of Newfoundland & Labrador, 2024).	Public Finance & Risk-sharing Instruments Supply Cost & Project Development	GOV, FIN	Secure public capital and demand-side support

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19	Revenue stabilisation mechanisms can reduce market risk for green ammonia	<p>GOV 3: "A strong policy and fiscal framework to support these projects is put together. Initiatives like H2Global are subscribed to to help kick-start the market. This is something my Dutch counterparts have done with Germany through joint tenders. Canada subscribed over a year ago."</p> <p>EXP 1: "You mentioned earlier the Hydrogen Bank, H2Global, and Contracts for Difference. That mechanism really needs to start working. The instruments are there, but they need to be scaled up significantly. Otherwise, the volumes will remain relatively small."</p>	Green hydrogen and ammonia projects face a gap between production costs and buyer willingness to pay. To bridge this gap and stabilise revenues, governments have introduced price-based support mechanisms. H2Global signs multi-year fixed-price supply contracts for RFNBO-compliant ammonia, while reselling the product to European buyers, with public funds covering the price difference (IEA, 2025). Ammonia has proven well suited to this model, and Germany has committed to bilateral H2Global tenders with Canada, co-funded by Natural Resources Canada (up to CAD 300 million), making Canadian export projects potentially eligible if EU RFNBO lifecycle emissions thresholds (≤ 3.38 kg CO ₂ eq/kg H ₂) are met (IEA, 2025).	Public Finance & Risk-sharing Instruments Demand Formation & Offtake	GOV, FIN	Secure public capital and demand-side support
20	The hydrogen transition can create new regional jobs in Canada, but it can also disrupt existing employment and require reskilling and workforce mobility	<p>GOV 1: "Newfoundland has a very active oil and gas industry. A lot of effort has gone into helping local Newfoundland companies build their expertise so they can directly support the oil and gas sector. We're now looking at doing something similar for wind and hydrogen. ... But there has already been some exploration into what transferable skills or capacity companies might have that they could apply to the wind and hydrogen sectors. For example, we explored what would be needed to establish an R&D hub so that individuals could be trained for that industry."</p> <p>PD&IA 2: "The labour force also plays a major role in Canada, and probably in Newfoundland as well. ... Canada has a strongly organised labour market, with powerful unions. ... If a project suddenly needs 6,000 people for 4 years in Newfoundland, it's not as simple as it sounds. You have to deal with Canadian labour laws and the question of whether you can actually get those people there. Often, you have to pay a high premium on top of already relatively high labour costs. This puts projects in Canada at a disadvantage compared to, for example, Egypt."</p>	The transition from oil and gas to hydrogen and renewables is reshaping labour markets in Canada, creating both opportunity and risk. Newfoundland and Labrador has a workforce with experience in offshore oil and gas, large-scale construction and industrial energy projects (Government of Newfoundland & Labrador, 2024). The project is expected to generate over 2,000 construction jobs and around 640 direct and indirect operational jobs (Strum, 2024). However, most labour demand concentrates in the construction phase, where multiple wind-hydrogen projects may compete for the same skilled profiles. While targeted reskilling and attraction instruments, including Labour Market Development Agreement funding and partnerships with training institutions, are in place (Government of Newfoundland & Labrador, 2024), workforce availability remains sensitive to timing, skills transfer and programme delivery. Government of Newfoundland & Labrador (2024) also positions hydrogen as an opportunity to expand Indigenous participation through training and employment pathways.	Industrial & Supply-Chain Capacity	COM	Workforce & supply-chain alignment

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21	Scale-up and equipment manufacturing constraints slow hydrogen project delivery	<p>GOV 1: "So, say a wind project goes ahead, and a local SME secures a contract, they might need support to purchase equipment or to train employees in specific skill sets. ... The turnaround time to scale up for these contracts can be very short. ... A small company can't justify purchasing all the equipment they might need in the future without a confirmed contract. ... So once they do secure one, they often have to move very fast."</p> <p>PD&IA 1: "It may be that scale-up and manufacturing, particularly for electrolysers, could become a supply chain issue. If you want to have 300 or even 500 turbines delivered to one location, the supply chain cannot easily handle that. It takes a lot of time to manufacture such components, and the same applies to electrolysers and other equipment."</p>	Large hydrogen projects are increasingly delayed by limits in equipment manufacturing and supply chains. IEA (2025) notes that electrolyser manufacturing capacity is highly concentrated in China, which accounts for nearly 60% of global capacity, while many manufacturers outside China have paused operations or consolidated due to weak order flows, creating uncertainty around delivery timelines and lead times for stacks and related equipment.	Industrial Supply-Chain Capacity	& TRP	Workforce & supply-chain alignment
22	High production costs, price volatility and large capital requirements undermine green hydrogen and ammonia bankability	<p>FIN 1: "The big uncertainty is really: what price can I achieve for my hydrogen product in the market, whether it's shipping, fertilisers, steel, it doesn't matter. Under current regulation, there's no way hydrogen-based fuel will be cheaper than coal or coke for steel, grey ammonia for fertilisers, or heavy fuel oil for shipping."</p> <p>PD&IA 1: "And then there's the issue of price fluctuations, especially with ammonia. Who is willing to commit to a long-term off-take agreement, and at what price? ... There is an existing ammonia market that is quite large, I believe around 180 MTPA, primarily used for fertilisers, and it has its own price dynamics. But almost all of that ammonia is produced using natural gas or other hydrocarbons, so it's not green. In some respects, green ammonia projects will have to compete with that. I don't think these green ammonia projects are truly competitive unless they're supported by the government."</p>	At best locations, renewable hydrogen production costs are around \$3/kg and can exceed \$10/kg under less favourable conditions, compared with roughly \$1/kg for conventional hydrogen and \$2/kg for low-carbon routes (ESMAP et al., 2024). This cost disadvantage exposes projects to commodity price volatility in power, gas and carbon markets, while revenues remain uncertain. At the same time, the capital intensity is high: producing 1 MT per year of renewable hydrogen requires on the order of 10 GW of electrolysers, 20 GW of renewables and around \$30 billion in investment (ESMAP et al., 2024). As a result, the global financing gap for clean hydrogen is estimated at \$10-40 billion per year to 2030, reflecting the scale of public and concessional support needed to reach economic viability.	Supply Project	Cost & Develop-ment	FIN Certification aligned project design

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23	Willingness-to-pay gap, unlevel-playing-field and weak demand creation block offtake	<p>FIN 1: "Right now, we have many people who want to produce hydrogen and many willing to invest in ports and distribution infrastructure. But we have hardly anyone saying, "I'm going to buy it at the price that is required to make it worthwhile, to make it financially attractive"."</p> <p>EXP 2: "A level playing field is important. Companies really look at whether the conditions in the Netherlands differ too much from those abroad. If the rules here are much stricter, you end up at a disadvantage. That plays a major role in their decision-making."</p>	IEA (2025) identifies the cost gap with unabated fossil hydrogen as a key barrier to project development, noting that support schemes remain necessary for longer, particularly in regions with low natural gas prices. Demand is largely policy-driven: binding instruments such as quotas, carbon pricing and CfD are required to create offtake and de-risk investment. At the same time, energy-intensive industries operate in highly competitive global markets and are reluctant to commit to higher-cost inputs unless competitors face comparable constraints. This concern over carbon leakage and loss of competitiveness reinforces the need for level-playing-field mechanisms such as ETS and CBAM, without which demand remains fragmented, uncertain and insufficient to support scale-up.	Demand Formation & Offtake	GOV, OFF, FIN	Certification aligned project design
24	Carbon pricing and emissions trading can internalise environmental costs and close the cost gap	<p>PD&IA 2: "In the end, the key question becomes: which route will be price-setting at a given moment? That is where emissions trading comes in. ... That underlying link between the CO₂ price and the cost difference between alternative routes is crucial for creating a financially robust framework."</p> <p>FIN 1: "The problem is that environmental benefits are externalities; they are not priced in today. Carbon pricing would change that, but until then, you need regulation to force adoption. Without it, companies won't switch because there's no commercial or operational sense, only environmental sense. To make that worthwhile, you need political will and regulatory power to reward the environmental advantage. That is why this is the key driver of the entire market."</p>	Carbon pricing and emissions trading are key drivers for making low-emissions ammonia competitive with fossil-based routes, as energy costs remain the dominant cost component across all production pathways (IEA, 2025). Historically, fertiliser producers received free allowances to safeguard international competitiveness, but these are being gradually phased out as the CBAM is introduced (IEA, 2025), reducing the risk of carbon leakage and creating fairer competition between EU and non-EU producers. Without carbon pricing, renewable ammonia remains structurally more expensive: IRENA (2022) estimates that a CO ₂ price of around USD 150/tCO ₂ is required for renewable ammonia to reach cost parity with conventional fossil-based ammonia, while USD 60-90/tCO ₂ is sufficient to close the gap between unabated fossil ammonia and fossil ammonia with CCS.	Demand Formation & Offtake Public Finance & Risk-sharing Instruments	GOV	Certification aligned project design

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#	First-order term (vulnerabilities & opportunities)	Illustrative quote(s)	Description/interpretation for actor based on documents	Second-order term	Main actors	Basic plan action
25	Regulatory demand mandates create offtake when market willingness-to-pay is low	GOV 3: "Another issue is the effective implementation of the EU RED by Member States, which includes quotas for green hydrogen and penalties for non-compliance. When is that going to be transposed, and delays in transposing these rules create uncertainty, which makes it harder for Canadian projects to reach FID. The longer that uncertainty continues, the harder it is for the financing of Canadian projects to continue, because as soon as you get non-compliance penalties, that is going to initiate the industry to start securing offtake."	When low-emissions hydrogen remains structurally more expensive than fossil alternatives, demand is primarily created by regulation rather than voluntary willingness-to-pay. In the EU, the RED sets a binding target to cover 42% of industrial hydrogen demand with RFNBOs by 2030, but implementation is slow and uneven: by mid-2025, only a few member states had fully transposed the industrial targets into national law (IEA, 2025). The Netherlands is considering rising industrial quotas (up to 4% by 2030 and 10% by 2035), supported by a mix of demand- and supply-side incentives, but final legislation is only expected in 2026, showing that near-term hydrogen demand remains policy-driven, fragmented and exposed to regulatory delay (IEA, 2025). Similar dynamics apply in aviation (ReFuelEU) and maritime transport (FuelEU Maritime), where compliance obligations can create offtake despite limited voluntary uptake.	Demand Formation & Offtake Public Finance & Risk-sharing Instruments	GOV	Certification aligned project design
26	Regulatory and certification fragmentation creates uncertainty over hydrogen eligibility, value, market access and unlocking demand	FIN 1: "One thing that is really important, is certification of hydrogen. Ideally, we need a global standard that clearly defines not just what hydrogen is (everyone knows that), but what counts as green hydrogen. The EU has established its rules, especially with the RFNBO regulation, but globally, this is critical. Countries need to agree on what qualifies as green hydrogen because there is a lot of room for interpretation, and it's not straightforward." GOV 2: "Yes, there are many of those discussions, especially in multilateral settings. ... They are working on an ISO standard for the methodology to calculate emissions. After all, you need to compare the same things and measure them using one common method; otherwise, you end up with different calculations."	Regulatory and certification frameworks for hydrogen and ammonia are maturing, strengthening the basis for market formation and cross-border trade. Several major jurisdictions, including the EU and Canada, now apply defined methodologies for lifecycle GHG quantification (IEA, 2025). In the EU, RED III provides a binding RFNBO framework supported by recognised voluntary schemes and accredited certifiers, while Canada has issued validation and verification guidance for estimating hydrogen carbon intensity. Internationally, ISO lifecycle standards for hydrogen production and transport are expected in 2025–2026, supporting greater methodological convergence. Nonetheless, detailed implementation rules under RED III continue to be refined, and the EU methodology for low-carbon hydrogen only recently entered into force, while discussions persist on alignment across jurisdictions and on how different production pathways will be treated.	Demand Formation & Offtake Regulation, Standards & Certification	GOV	Certification aligned project design

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#	First-order term (vulnerabilities & opportunities)	Illustrative quote(s)	Description/interpretation for actor based on documents	Second-order term	Main actors	Basic plan action
27	IMO standards can steer shipping fuel choices and speed decarbonisation, but delays or reversals add uncertainty and stall investment	FIN 1: "The IMO was supposed to adopt the so-called net-zero framework in October. This framework would have introduced policies, specifically a GHG emission fuel intensity standard ... It also included a relatively complex carbon pricing mechanism, requiring ships to pay for part of their GHG emissions. This framework had already been accepted in April. However, last week it was sabotaged by a small coalition ... This framework is essential because it underpins the regulations needed to achieve the IMO's political targets: full decarbonisation of the shipping sector by around 2050, with interim checkpoints of 20-30% GHG reductions by 2030 and 70-80% by 2040."	The decarbonisation of international shipping is a potential demand driver for green ammonia, but it remains sensitive to regulatory timing and political agreement. IEA (2025) notes that ammonia-powered shipping is expected to become cost-competitive in the long term, yet its technological maturity still lags behind methanol, particularly for large ocean-going vessels. The IMO's 2023 GHG Strategy sets net-zero targets for 2050 with interim reduction goals, yet implementation depends on the Net-Zero Framework introducing fuel-intensity standards and carbon pricing.	Sectoral Application & Carrier / Fuel Choice Policy Stability, Geopolitics & International Commitment	GOV	End-use-flexible ammonia design
28	Perceived technological advantages and existing supply chains make ammonia the expected primary hydrogen carrier in Northwest European import chains	PIO 2: "There is also a clear view on the regions from which the energy carriers are expected to come, and as a result, you see a clear preferred carrier emerging: ammonia. Most locations are already preparing for that. From a technical perspective, ammonia has a high energy density, which means you need relatively smaller ships to transport the same amount of energy. It is also a proven technology: ships are already transporting ammonia, perhaps not yet at the very largest scale, but they do exist and are in operation. In addition, ammonia is one of the most widely produced chemical substances in the world. That makes it a logical choice as an energy carrier."	Ammonia is expected to dominate long-distance hydrogen imports into Northwest Europe because it combines lower transport costs, higher technical maturity, and integration into existing global trade and port infrastructure. Around 85% of ammonia today is already traded for fertiliser use, and ammonia production accounts for 45% of global hydrogen consumption, making it the single largest existing hydrogen outlet outside refining (IRENA, 2022). Ports such as the port of Rotterdam have well-developed expertise in managing chemical products, indicating a strong readiness to also handle hydrogen-based fuels (IEA, 2025).	Sectoral Application & Carrier / Fuel Choice	ALL	End-use-flexible ammonia design

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#	First-order term (vulnerabilities & opportunities)	Illustrative quote(s)	Description/interpretation for actor based on documents	Second-order term	Main actors	Basic plan action
29	Sectoral suitability debates reveal uncertainty over where hydrogen-based options will be applied	<p>PD&IA 1: "From a technical perspective, the biggest realistic user of ammonia as fuel is shipping, particularly international shipping. This is where ammonia can make the biggest environmental impact. There's a huge amount of shipping happening globally, burning large quantities of fuel, much of it very dirty. For shipping, implementing ammonia as a fuel is easier compared to, say, road transport."</p> <p>PD&IA 2: "I see decarbonising shipping with hydrogen more as a long-term play, to be honest. I'm really not enthusiastic about using ammonia in ship engines. Where do we currently see problems with ammonia use in industry? Especially in small-scale operations, such as break-bulking and in the refrigeration sector. And if you then also bring that to very small operators and even introduce it into an engine room, I see that as a recipe for disasters."</p>	There remains uncertainty over which sectors will ultimately absorb large volumes of hydrogen, as hydrogen competes with electrification, CCS and other low-carbon options. IEA (2025) shows that demand growth remains concentrated in traditional uses, oil refining, chemicals and steel, while new applications account for less than 1% of global hydrogen demand.	Sectoral Application & Carrier / Fuel Choice	ALL	End-use-flexible ammonia design
30	Timely rollout of backbone infrastructure and hinterland connections in Northwest Europe is a critical enabler for unlocking demand and making projects bankable	<p>PIO 2: "What you see is that delays in connections to the hinterland have a direct impact on projects that depend on that infrastructure. Those projects need those connections to make their business case work, to get green energy carriers to their facilities. If they can't recover their investment, they won't invest in the first place. That infrastructure is essentially the key to scaling things up."</p> <p>PIO 3: "Last year, they [Canada] were present at the European Hydrogen Week and even asked: when will the Netherlands be ready? Canada is mainly targeting Germany as a sales market, and that route runs via Rotterdam. That is why it is important that the DRC is realised."</p>	An interconnected hydrogen backbone across Northwest Europe is essential for turning import and production potential into offtake (Buijs et al., 2025). Current plans, however, point to a delayed and fragmented rollout: the largest Dutch, Belgian and German clusters will not be fully connected by 2030 (Buijs et al., 2025). Large-scale terminals, storage and cracking capacity would need to be implemented rapidly and with high flexibility, which remains uncertain given current project maturity. As a result, uncertainty over backbone timing and flexibility is already delaying industrial FIDs, risks isolating clusters, and could shift demand geographically, meaning that without timely, connected and adaptable infrastructure, the hydrogen value chain may develop more slowly or at reduced scale (Buijs et al., 2025).	(Public) Infra Alignment & Spatial Planning	PIO, GOV	EU infrastructure aligned export design

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#	First-order term (vulnerabilities & opportunities)	Illustrative quote(s)	Description/interpretation for actor based on documents	Second-order term	Main actors	Basic plan action
31	Natura 2000 and NOx rules in the Netherlands can constrain the feasibility and siting of large ammonia and hydrogen infrastructure	<p>EXP 2: "With the current legislation, it's basically a complete showstopper. As long as nothing changes in the nitrogen regulations, it's open season for parties who don't want projects to go ahead. We really need better policy, both on safety and on nitrogen, to create space for development. That's a societal agreement: what do we, as a country, consider acceptable in terms of development? What should that look like? If we only follow the current rules, very little is possible."</p> <p>PD&IA 2: "In ammonia pathways, Natura 2000 and nitrogen regulations in the Netherlands play a crucial role. ... If there is no local exemption or adjustment, this makes most crackers in Rotterdam practically impossible. It is a major obstacle. That is why you see some parties considering placing crackers in Germany, where these issues are much less restrictive."</p>	Environmental and nitrogen rules can influence where, how, and even whether large ammonia and hydrogen facilities can be permitted in Dutch ports and industrial clusters.	(Public) Alignment & Spatial Planning Permitting & Legal Procedures Safety & Environment	Infra & GOV	EU infrastructure aligned export design
32	Infrastructure incentives and cost amortisation to enable backbone build-out and lower transport tariffs	<p>PIO 3: Right now, costs are rising while volumes are falling. That means you risk ending up with unaffordable transport tariffs. That's why work is being done on ways to keep those tariffs manageable in the future. In Germany, for example, they use an amortisation model. This means that you don't pass on all the costs of a pipeline to customers over the next 5 to 10 years, but instead spread part of those costs over a longer period, such as 20 years. That way, transport costs can be kept under control even when volumes are low."</p>	Public support schemes and long amortisation horizons for hydrogen networks and pipelines are needed so that backbone infrastructure can be built ahead of demand while keeping transport tariffs affordable during the early low-volume years. Germany has established a EUR 24 billion amortisation account, backed by a state loan, to enable early hydrogen network build-out while keeping user tariffs stable during the low-volume ramp-up phase, with repayment planned through 2055 (IEA, 2025).	(Public) Alignment & Spatial Planning Public Finance & Risk-sharing Instruments	Infra & GOV	EU infrastructure aligned export design

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# First-order term (vulnerabilities & opportunities)	Illustrative quote(s)	Description/interpretation for actor based on documents	Second-order term	Main actors	Basic plan action
33 Political preferences for ammonia transport modes can conflict with market logistics and hinterland demand	<p>PIO 2: "If ammonia is imported now, the first option considered is transporting it to the hinterland by rail and by barge. At the same time, you also hear voices saying: "We would rather use a pipeline than have ammonia trains running through the city centre." But there is still no official policy on how to deal with this."</p> <p>EXP 1: "The government's vision says "preferably keep ammonia in the port," while the market says: well, maybe half of it, a large share is actually destined for the hinterland. ... "Preferably by pipeline" ... The pipeline option has even been removed from the DRC, so it's not that simple. "Then preferably by inland shipping," according to the government vision, but the market says rail and inland shipping are complementary; you need both. Finally, if it has to go by rail, the government vision says "then via the Betuweroute." The market says: you may want that, but you cannot exclude other routes. Otherwise, you become fully dependent on the Betuweroute, and it doesn't connect everywhere."</p>	Governments' safety-based modal preferences for ammonia (e.g. no transport, keep it in port, pipeline first, then inland shipping or specific rail corridors) can clash with what is practically needed to move ammonia to the hinterland and serve industrial demand.	(Public) Infra Alignment & Spatial Planning Collaborative Public-Private Market Coordination	PIO, GOV	EU infrastructure aligned export design

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# First-order term (vulnerabilities & opportunities)	Illustrative quote(s)	Description/interpretation for actor based on documents	Second-order term	Main actors	Basic plan action
34 Policy volatility vs. long-term public commitment determines market formation and investment	<p>FIN 1: "One thing we have to face is that the hydrogen market is politically or legally driven. ... There are so many areas: what Canada wants to do with its climate targets, what the Netherlands wants to do, what the IMO agrees on, ... All of this is political. If, in all these forums, people decide they don't care about climate anymore, then there will be no market for hydrogen-based fuels. It's that simple."</p> <p>EXP 2: You can see that shifts are taking place. Over the past ten years, Europe has been very strict. We had the Paris Climate Agreement in 2015, and based on that, tight targets were set that everyone had to comply with. Now you notice that things are becoming more fluid. The European Commission and the European Parliament are asking themselves: should we really keep enforcing these rules so strictly? Can we even achieve them? ... That is a real issue for many industries right now. They are asking themselves, why should I invest now? I'd rather wait and see. We see that in our market as well, many projects are being put on hold. Companies are first watching how the political situation develops."</p>	<p>Shifting political priorities, delayed or weakened climate and hydrogen policies, and uncertain implementation timelines undermine investor confidence, while credible long-term targets backed by binding instruments and stable support schemes are essential to create hydrogen markets and unlock large-scale hydrogen investment. DNV (2025) states that hydrogen and its derivatives comprise the expensive side of decarbonisation, with uptake driven by policy rather than market forces.</p>	<p>Policy Stability, Geopolitics & International Commitment</p>	<p>GOV</p>	<p>Policy alignment and dialogue</p>

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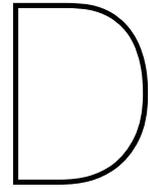
#	First-order term (vulnerabilities & opportunities)	Illustrative quote(s)	Description/interpretation for actor based on documents	Second-order term	Main actors	Basic plan action
35	Political support, institutional stability, and political alignment make Canada a credible long-term hydrogen partner for the Netherlands	<p>PIO 1: "A first step is to analyse potential projects and countries: where is there political stability? ... Canada is an attractive partner. It is an OECD country, with its own resources to invest, a lot of technology and knowledge, and political stability."</p> <p>GOV 3: "Because there is a dedicated MoU with the Netherlands on hydrogen, it's very focused. ... For example, at the World Hydrogen Summit last year, under this MoU, there was a joint technical workshop with our Dutch counterparts on hydrogen pipelines ... So through the Standards Council of Canada, we worked with the Netherlands to share lessons learned, explore interoperability, what has worked in the Dutch model, what has worked in the Canadian model, and compare what Canadian utilities are saying versus Dutch utilities. This exchange was very successful, and we're planning to do it again soon. That's the kind of work that advances under an MoU."</p>	<p>DNV (2025) notes that climate action is no longer a top priority for many governments, and clean energy still progresses unevenly across regions and sectors. Against this backdrop, Canada stands out for continuity in climate and low-carbon energy policy, and its political stability and explicit hydrogen cooperation with Europe and the Netherlands make it a trusted partner for building a Canada-EU hydrogen corridor. This is shown by bilateral agreements, such as the MoU between Newfoundland and Labrador and the port of Rotterdam on cooperation in the field of green hydrogen and market opportunities (Government of Newfoundland & Labrador, 2024).</p>	Policy Stability, Geopolitics & International Commitment	GOV	Policy alignment and dialogue
36	Concerns about green colonialism and ESG norms influence partner choice and ethical willingness-to-pay	<p>PIO 3: "A sensitive issue: the risk of a new form of energy colonialism. ... Canada itself often raises this point as well. They realise that their hydrogen production may be more expensive, but in terms of corporate social responsibility, they rank very highly worldwide. This raises the question: are we being hypocritical in Europe or not? If we don't want to be, we may have to be willing to pay a bit more for our hydrogen."</p> <p>GOV 3: "We see hydrogen as an opportunity to start the story right in Canada ... For us, this feels like working from a clean slate rather than constantly being reminded of past mistakes. Hydrogen offers a new opportunity for reconciliation."</p>	<p>DNV (2025) notes that both policy and private sector decision makers must prioritise recognition and assessment of societal impacts at the project level to achieve fair distribution of burdens and benefits and to help overcome delays in the project and overall energy transition. Concerns about, e.g. Indigenous rights and green colonialism make European actors favour partners like Canada with strong ESG records, and can justify paying a price premium for hydrogen from countries prioritising social and environmental responsibility.</p>	Policy Stability, Geopolitics & International Commitment	GOV	Policy alignment and dialogue

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#	First-order term (vulnerabilities & opportunities)	Illustrative quote(s)	Description/interpretation for actor based on documents	Second-order term	Main actors	Basic plan action
37	Geopolitics and EU import policy drive diversification of supply regions and hydrogen carriers and strengthen the Canada-EU partnership	<p>PIO 1: "Geopolitics also has an advantage in that respect. Canada is now looking much more closely at where it wants to strengthen its trade relations and how it can diversify them. Which buyers are there for Canadian products and services? The relationship with Europe has only grown stronger over the past year. There are downsides due to geopolitical tensions, but also benefits: it strengthens cooperation with reliable partners."</p> <p>GOV 2: "National production is crucial, but you can't produce everything yourself. You also need to import part of your energy, and make sure that the supply is sufficiently diversified in terms of suppliers, regions, and energy carriers. All of that contributes to energy security."</p>	The current geopolitical environment is a challenge for the transition, and energy and climate policies are now closely tied to strategies for future-proofing both energy sectors and regions against geopolitical risks (DNV, 2025). European energy security goals and geopolitical shifts lead to diversification of supplier countries and hydrogen carriers, positioning Canada as a long-term partner for the EU.	Policy Stability, Geopolitics & International Commitment	GOV	Policy alignment and dialogue
38	Crisis and price shocks catalyse deployment and policy action	PIO 1: "Maybe the crisis has to get worse first, electricity and gas becoming so expensive that everyone goes crazy, before we really start moving. As long as things remain somewhat affordable, everyone sticks to their own policies and interests. That's more or less where we are right now."	DNV (2025) stresses that while the direction of the energy transition is inevitable, its pace is highly sensitive to shocks. Energy crises, trade disruptions and extreme price volatility act as catalysts that break political inertia, re-prioritise energy, and accelerate support for low-carbon alternatives.	Policy Stability, Geopolitics & International Commitment	GOV	Policy alignment and dialogue
39	Roadmaps provide directional guidance, but are explicitly treated as provisional and regularly revised	FIN 1: "In roadmaps, we outline what should be done by when. ... In such a dynamic environment, you can still more or less plan what the next two to three years should look like. But then, afterwards, it becomes a little bit like crystal ball reading. We have roadmaps for the next 10, 15, even 20 years. Would I bet that everything in there will happen in 20 years? No, because it's just too uncertain. Still, I think it's very useful to have some idea of where to go. Then ask yourself every two or three years: is this still valid, or does it need to be revised?"	Strategic roadmaps are used to sketch a long-term direction for hydrogen corridors, but stakeholders consciously treat them as provisional tools: useful for orientation over the next few years, then revisited and updated every 2-3 years as policy, markets and technology evolve.	Planning Under Uncertainty		

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# First-order term (vulnerabilities & opportunities)	Illustrative quote(s)	Description/interpretation for actor based on documents	Second-order term	Main actors	Basic plan action
40 Scenario-based base cases and sensitivities are used to discipline decisions under demand and policy uncertainty	PD&IA 2: "What you are essentially trying to do is define a clear base case for yourself based on what you know today. From that base case, you create a number of sensitivities with low and high cases in different variants. The goal is to link those scenarios to what is often called a realisation pathway: you try to make a number of assumptions more concrete and combine them into a few coherent scenarios. Importantly, you don't want more than three combined scenarios, otherwise it becomes too complex."	Developers build a central base case and a limited set of policy-demand scenarios and sensitivities to test project economics, identify when they're "under water", and sequence infrastructure and offtake decisions under uncertainty.	Planning Under Uncertainty		



Action Library: Default and Adaptation Plan

This appendix translates the Gioia analysis results presented in Appendix C into an action library for the Canada-Netherlands hydrogen import corridor. It first specifies the default plan by describing how each basic plan action formed in Appendix C can be implemented in practice. It then develops the adaptation plan by defining, for each basic plan action, the associated signposts to monitor, the triggers that indicate when adjustment is required, and the contingency actions that can be activated to respond to uncertainties at decision points.

Table D.1: Action library: basic plan actions, signposts, triggers, and contingency actions

Basic plan action	Signpost	Trigger	Contingency action
1. Phased and modular by design			
<p>Shaping: Structure the project to start with a pilot that tests the chosen technologies and system integration, and then scale through modular phases rather than building full capacity in one step. Develop the FEED with future expansion in mind, so that once the chosen first configuration reaches COD, the project can add additional modules (e.g., electrolyser blocks, extra ammonia trains, storage and terminal units) when triggers emerge, allowing growth to follow market and system maturity while avoiding early low utilisation and overbuild risk.</p> <p>Hedging: Use each scale-up phase as an opportunity for both capacity expansion and technology evolution. Early phases can rely on the most bankable configuration, e.g. a $\geq 50\%$ PEM / $\leq 50\%$ alkaline electrolyser mix, above-ground hydrogen storage, and conventional Haber-Bosch synthesis. Later phases can hedge technological uncertainty by preserving optionality, e.g. adding SOEC modules once sufficiently high-grade waste heat from ammonia synthesis is available and performance and lifetime have been proven at scale.</p>	<p>Monitor technical performance and system stability of the current configuration.</p>	<p>IF persistent technical constraints emerge (e.g. hydrogen buffer depletion, excessive efficiency losses) THEN consider suspending FID at DP2/DP4 and/or suspending scale-up at DP3 and activate contingency action.</p> <p>IF persistent technical constraints emerge during pilot THEN consider selecting a lower-capacity configuration at DP1 and activate contingency action.</p>	<p>Corrective: Modify design (e.g. increased hydrogen storage, optimise control strategy and turndown operation).</p>
2. Safe and sustainable by design			
<p>Shaping: Design the hydrogen and ammonia facilities so that safety and environmental compliance are built in from the start. Use e.g. hazard zoning, automated isolation, and process integration to minimise water use, waste/effluents, and lifecycle emissions.</p> <p>Mitigating: Reduce operational risk with proven controls, e.g. continuous gas detection with automatic shutdown, loading-only pipeline pressurisation, predictive maintenance, hazardous materials management, and ongoing lifecycle GHG tracking.</p> <p>Defensive: Establish and maintain an Emergency Response Plan, Emergency Response Team, Environmental Protection Plan, Waste Management Plan, and Hazardous Materials Response and Training Plan, integrated with authorities.</p>	<p>Monitor safety and environmental performance and expectations, such as incidents, inspection results, compliance margins versus permit limits, lifecycle GHG intensity, and any tightening of rules.</p>	<p>IF safety or environmental requirements tighten substantially OR incidents, near-misses, or monitoring results show deteriorating performance OR measured lifecycle GHG intensity approaches or exceeds recognised market and regulatory benchmarks for green ammonia THEN consider suspending FID at DP2/DP4 and/or suspending scale-up at DP3 and activate contingency action.</p> <p>IF persistent safety or environmental constraints emerge during pilot THEN consider selecting a lower-capacity configuration at DP1 and activate contingency action.</p>	<p>Defensive: Add additional safety and environmental protections (e.g. larger buffers, extra containment and monitoring, upgraded treatment systems, enhanced training) until compliance and confidence is restored.</p>
3. Secure bankable offtake contracts			

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Basic plan action	Signpost	Trigger	Contingency action
<p>Shaping: Prioritise securing offtake agreements that cover a substantial share of initial production before committing to large-scale capital deployment (e.g. 70%). In 2024, the announced firm offtake agreements and most investment in committed low-emissions hydrogen projects were concentrated in established hydrogen users, refining and chemicals, while tender outcomes were mixed: steel tenders were delayed, but refining and fertiliser tenders led to FIDs in Europe and India (IEA, 2025). Offtake efforts should therefore prioritise sectors that already use hydrogen or ammonia today (fertilisers, chemicals, refining), where integration is straightforward and decarbonisation pressure is high. Projects that reach FID typically rely on a limited number of offtakers to reduce complexity. Contracts should be designed to meet financing requirements while recognising early-market uncertainty. As described by Ason (2025), this implies multi-year agreements (≈10-15 years) with take-or-pay commitments and flexibility mechanisms such as limited volume tolerance bands, make-up rights, price review clauses, and change-in-law provisions.</p> <p>Shaping & Hedging: Secure access to an import terminal in Rotterdam. This can be structured as described by Ason (2025) under Delivered Ex Ship or Cost, Insurance and Freight terms, with the seller arranging shipping and insurance and the offtaker taking title on arrival, reducing complexity and risk for early buyers and improving delivery certainty. As the market matures, contracts can shift to Free on Board terms, where buyers assume shipping after loading to gain greater flexibility and cost control.</p>	<p>Monitor whether demand converts into signed, bankable offtake, focusing on the share of capacity covered by binding contracts and contract duration, offtaker credit quality, and buyer acceptance of delivery structures.</p>	<p>IF offtake interest does not materialise or remains limited THEN consider selecting a lower-capacity configuration at DP1 or shifting towards early run-off at DP1/DP2.</p> <p>IF offtake interest exists that supports higher volumes THEN consider selecting a higher-capacity configuration at DP1 and/or scale-up at DP3.</p> <p>IF a capacity phase is largely covered by signed, long-term, bankable offtake from creditworthy customers THEN consider taking FID at DP2 and/or DP4.</p> <p>IF offtake contracts end, and new negotiations repeatedly stall and are insufficient to continue to support the current operation scale THEN consider downsizing or early run-off at DP5 and activate contingency action.</p> <p>IF offtake becomes sufficient to support the planned scale again THEN consider returning to the planned scale again at DP6.</p>	<p>Corrective: Redesign contracts to restore bankability by adjusting risk-sharing, such as introducing phased volume commitments, wider flexibility in early years, shorter initial contract tenors with extension options, while preserving sufficient contracted revenue.</p>
<h4>4. Coordinate innovation and export</h4>			
<p>Shaping & Hedging: Align project development with provincial and federal innovation programmes (including R&D support, pilot funding and demonstration schemes) and leverage partnerships with universities and applied research institutes to reduce first-of-a-kind and scale-up risk. Embed technological learning through phased development, including pilot and demonstration stages, before full commercial deployment. Consider a hub-and-spoke model, coordinating supply, infrastructure and export routes with other hydrogen and ammonia projects in Newfoundland and Labrador or across Atlantic Canada (e.g. Nova Scotia). Engage with the port of Rotterdam to enable the export route, potentially with the other projects, to coordinate supply.</p>	<p>Monitor progress of technologies from pilot to demonstration and higher TRL levels, performance of project pilots, and the effectiveness of coordination with other Atlantic hydrogen projects, including arrangements for shared infrastructure or export routes.</p>	<p>IF technologies fail to advance beyond pilot or demonstration stages, pilots underperform against expected benchmarks, or coordination with other projects and shared export infrastructure does not translate into concrete agreements THEN consider selecting a lower-capacity configuration at DP1, suspending FID at DP2/DP4 or suspending scale-up at DP3.</p>	
<h4>5. Domestic infrastructure-aligned development</h4>			

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Basic plan action	Signpost	Trigger	Contingency action
<p>Shaping & Hedging: Design the project around a predominantly off-grid renewable power system (dedicated wind and solar, supported by storage) to ensure compliance with tightening green hydrogen certification requirements in export markets (RED III / RFNBO), while maintaining a limited grid connection for critical loads, construction power and system resilience. Thereby reduce exposure to future EU rules, while retaining optionality to integrate with provincial grid upgrades, interties or large-scale storage if and when these materialise.</p> <p>Shaping & Seizing: Maintain flexibility in market orientation by sequencing development phases to allow early domestic or regional offtake where infrastructure, grid capacity or policy conditions favour local use, while preserving the ability to scale exports. Given Newfoundland and Labrador's limited local industrial demand, export remains the primary long-term pathway; however, regional coordination across Atlantic Canada and emerging uses can provide interim demand anchors that reduce exposure to uncertain export timing.</p>	<p>Monitor (i) progress on provincial and federal electricity grid reinforcement and intertie initiatives, (ii) development of large-scale provincial energy storage options (e.g. salt caverns), (iii) policy signals on the role of hydrogen in provincial electricity system balancing and energy security, and (iv) how EU and international hydrogen certification frameworks treat grid connections, and grid conditions that could enable additional system integration without jeopardising certification.</p>	<p>IF grid reinforcement, large-scale provincial storage (e.g. salt caverns) and/or interprovincial interties become available and green hydrogen certification rules allow compliant grid interaction THEN activate contingency action. IF policy, certification constraints and/or infrastructure conditions allow only domestic or regional hydrogen delivery (and not export-scale, certified production) for a sustained period THEN consider a lower-capacity configuration at DP1 and/or suspending scale-up at DP3, and activate contingency action.</p>	<p>Capitalising: Deepen integration with provincial and interprovincial infrastructure by linking operations to strengthened grid connections and emerging large-scale storage (e.g. salt cavern storage). Use these assets to improve system flexibility, manage variability and stabilise production, thereby expanding feasible operating modes while preserving certification compliance.</p> <p>Reassessment: Reassess the project's market orientation by shifting from an export-led strategy to a domestic or Atlantic-regional focus, adjusting scale, sequencing and commercial assumptions accordingly, and deferring export-oriented scale-up.</p>

6. Secure social acceptance

Shaping: To secure and maintain access to Crown land, the project must integrate formal land approvals with alignment with Indigenous communities, fisheries, municipalities and other local land and marine users throughout the project lifecycle. This requires continuous engagement with Indigenous communities, including formal support letters, MoUs and benefit arrangements, alongside coordination with Newfoundland and Labrador Fisheries, Forestry and Agriculture (NLFFA) as the lead authority responsible for Crown land administration (Strum, 2024). This coordination should identify, manage and resolve potential conflicts with fisheries, recreation groups and other Crown land users at an early stage. Strum (2024) identifies raising public awareness and managing risk perception by e.g. information sessions at schools, regular reporting to stakeholders, Indigenous Peoples, and the public, and drawing a public Participation Plan.

Monitor progress and continuity of Crown land approvals and agreements administered by NLFFA, the stability of Indigenous support (MOUs, letters of support, benefit agreements), the emergence of land-use conflicts with e.g. fisheries, recreation or infrastructure users or public acceptance conflicts, stakeholder feedback requiring design changes or additional mitigation measures, and compliance with environmental, safety and consultation commitments over time.

IF Crown land access is delayed, public or stakeholder support weakens, or unresolved conflicts with fisheries or other land users emerge THEN consider selecting a lower-capacity configuration or early run-off at DP1, suspending FID at DP2/DP4, and/or suspending scale-up at DP3, and activate contingency action.

Corrective: Re-engage NLFFA and affected stakeholders to redesign project layout, sequencing or operational plans to restore compatibility with Crown land uses. Reinforce Indigenous and community or public engagement and update mitigation, safety and environmental management commitments to preserve project acceptance.

7. Secure full-scope permitting and land control

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Basic plan action	Signpost	Trigger	Contingency action
<p>Shaping & mitigating: Secure full legal rights for the complete project upfront: land control (ownership/long-term lease), confirmed industrial zoning, and permits covering full-scale production, storage, utilities, marine export, and safety systems. Scope the Provincial Environmental Assessment to the whole project, including cumulative impacts (air, water, marine traffic, land use, regional effects) with clear mitigation, monitoring, and adaptive management. Secure grid connection, utility corridors, and port access for full-scale export. Indigenous consultation and accommodation must be done from the start (see 'Secure social acceptance').</p> <p>Hedging: Manage exposure to federal permitting through explicit design choices. Identify which technical thresholds trigger a federal IA under the Impact Assessment Act (e.g. new marine terminals, major berth construction, large vessel sizes). Where feasible, the project should be configured to remain below these thresholds by maximising use of existing deep-sea ports and facilities, shortening timelines and reducing permitting risk. Where a federal IA cannot be avoided, plan for it explicitly, to maintain design flexibility in vessel size, export volumes and berth layout, so future capacity can be reserved without being activated too early.</p>	<p>Monitor whether full-scope provincial, marine, industrial, energy and (if applicable) federal permits can be secured within timelines compatible with investment decisions, and whether federal IA scope and conditions become clearly defined.</p>	<p>IF permits for the full project cannot be secured THEN consider selecting a lower-capacity configuration or early run-off at DP1, suspending FID at DP2/DP4, and/or suspending scale-up at DP3, and activate contingency action.</p>	<p>Corrective: Reconfigure the project to improve permitting outcomes by adjusting scope, layout and phasing, and by adapting marine and industrial design choices (e.g. vessel size, berth configuration, use of existing terminals) to reduce regulatory triggers and prioritise a lower-risk initial configuration (e.g. smaller volumes, phased port works).</p>
8. Secure public capital and demand-side support			
<p>Seizing: Improve the project's financing conditions by combining Canadian public capital and tax support with emerging European demand-side support mechanisms for renewable ammonia. On the supply side, maximise eligibility for Canadian instruments that reduce upfront risk and capital intensity, including financing from the Canada Infrastructure Bank, participation by the Canada Growth Fund at the scale-up stage, and full access to the Clean Hydrogen Investment Tax Credit, complemented by Newfoundland and Labrador's Green Technology Tax Credit and selective provincial grants. In parallel, position the project to participate in European demand-side mechanisms such as H2Global and future European Hydrogen Bank auctions, including the Germany-Canada tender, to increase offtake certainty and reduce market risk for export volumes.</p>	<p>Monitor (i) the stability, eligibility and effective risk-reducing impact of Canadian capital support and public financing instruments, and their combined effect on achievable project cost of capital, and (ii) the evolution of European demand-side mechanisms relevant to renewable ammonia imports, in particular the design, scale and eligibility rules of H2Global tenders and joint Germany-Canada auctions linked instruments.</p>	<p>IF Canadian public capital and tax instruments remain stable and accessible at scale, resulting in a low and financeable project cost of capital AND European demand-side mechanisms (e.g. H2Global or Hydrogen Bank-linked tenders) credibly indicate that ammonia offtake is likely to materialise THEN consider selecting a higher-capacity configuration at DP1 and/or scale-up at DP3.</p>	
9. Workforce and supply-chain alignment			

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Basic plan action	Signpost	Trigger	Contingency action
<p>Shaping & Hedging: Phase construction and procurement in line with realistic OEM, EPC and workforce availability, aligning project scale and tempo with confirmed equipment delivery windows and locally trained labour supply. Leverage provincial and federal instruments, including Labour Market Development Agreement funded reskilling and partnerships with training institutions, to prioritise local and Indigenous participation. Standardise equipment specifications and construction approaches across phases to simplify procurement, ease EPC execution and limit exposure to manufacturing bottlenecks.</p>	<p>Monitor the availability of locally trained and reskilled labour and confirmed delivery schedules and lead times for equipment (e.g. electrolysers, turbines).</p>	<p>IF workforce bottlenecks emerge (e.g. insufficient trained workers, large reliance on external labour, or delays linked to labour availability) OR equipment delivery lead times extend beyond phase schedules THEN consider suspending scale-up at DP3 and activate contingency action.</p>	<p>Corrective: Re-sequence construction phases and installation windows to match available labour and confirmed equipment deliveries and mobilise external construction workforce from outside Newfoundland and Labrador to stabilise execution.</p>
<p>10. Certification aligned project design</p>			
<p>Shaping & Hedging: Design the production, metering, certification and contracting set-up so that regulatory eligibility is technically provable. This means configuring electrolyser operation, electricity sourcing and ammonia synthesis so that compliance with e.g. RFNBO rules and CBAM-relevant emissions can be demonstrated at the batch level (e.g. traceable power sourcing and lifecycle GHG accounting). It also requires installing metering, monitoring and data-logging systems that continuously capture electricity inputs, operating profiles and emissions, enabling third-party verification under EU RFNBO schemes, forthcoming ISO lifecycle standards and Canadian carbon-intensity guidance. Finally, Ason (2025) notes that where certification is legally required or contractually agreed, the relevant standard should be explicitly embedded in the contract specifications to avoid ambiguity and ensure the ammonia is valid for its intended use. As the hydrogen trade becomes more cross-border, contracts should also address how certification schemes across jurisdictions will be aligned for transport and delivery.</p>	<p>Monitor whether external conditions for green ammonia investment are improving, focusing on: (i) cost and financing realism, whether production costs move toward best-case levels (\approx USD 3/kg H₂) or remain structurally high (often > USD 10/kg H₂ (ESMAP et al., 2024)); (ii) the effective carbon cost on fossil ammonia in Europe via EU ETS and CBAM and whether it narrows the cost gap; (iii) whether mandates become enforceable demand (RED III transposition, Dutch RFNBO/GHG targets, penalties, certificate values) and translate into willingness to pay; and (iv) certification usability, whether contracts can specify required attributes (e.g., RFNBO status, carbon intensity) and whether certification rules align with actual plant operating constraints, including the value of compliance (e.g., certificate/penalty levels reported around USD 8-10/kg H₂ in some EU states) (IEA, 2025).</p>	<p>IF production costs converge toward stable, financeable levels AND carbon pricing, mandates or certificates credibly close the cost gap and translate into willingness-to-pay and credibly indicate that ammonia offtake is likely to materialise THEN consider selecting a higher-capacity configuration at DP1 and/or scale-up at DP3.</p>	
<p>11. End-use-flexible ammonia design</p>			

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Basic plan action	Signpost	Trigger	Contingency action
<p>Shaping: Design ammonia production and site layout to remain flexible across end uses, rather than optimised for one specific market. This means embedding the ability to deliver high-purity ammonia, with optional conditioning and specification adjustments depending on customer requirements, preserving the option to serve future marine-fuel or other regulated markets as requirements evolve. Specification in the offtake agreements defines the required quality, purity, and environmental attributes of the product, ensuring that it meets the buyer's intended use.</p> <p>Hedging: Preserve physical and technical space for future ammonia bunkering infrastructure (e.g. loading arms, pipelines, safety zones), without constructing these assets upfront.</p>	<p>Monitor the direction and timing of IMO shipping regulation (including adoption of the 2023 IMO Strategy that was planned for October 2025 and the outcomes of the planned 2028 strategy review), convergence or divergence in end-use demand signals, concrete customer requests for differentiated ammonia specifications, and whether ammonia remains the preferred hydrogen carrier at the global level.</p>	<p>IF one or more end uses begin to show sustained, bankable demand with specific technical requirements OR a globally significant shift away from ammonia as the preferred carrier emerges THEN activate contingency action.</p>	<p>Capitalising: Adapt production configuration, conditioning steps and on-site infrastructure to serve the dominant or contracted ammonia end use. If maritime fuel demand materialises, participate in ammonia bunkering pilots and, upon signed offtake, upgrade export facilities with dedicated fuel transfer and safety systems.</p> <p>Reassessment: Reassess the hydrogen carrier choice by assessing alternatives to ammonia (e.g., LH₂, methanol, LOHC), selecting a preferred option, and updating conversion technology, storage/terminal design, permitting scope, and scale-up sequencing accordingly and upon signed offtake.</p>

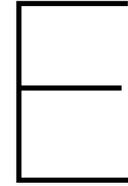
12. EU infrastructure-aligned export design

<p>Shaping & Hedging: Align the export system with European backbone rollout. Assume limited hinterland connectivity in the 2020s by prioritising port-based delivery, and offtake structures that do not rely on immediate access to inland pipelines or cracking capacity. Preserve optionality to connect into backbone infrastructure (pipelines, crackers, storage) once east-west corridors and large-scale storage become available, without committing upfront to assets whose viability depends on timely backbone completion.</p>	<p>Monitor whether the Northwest European hydrogen backbone evolves from fragmented clusters toward a connected system, including realised timelines for key east-west links such as the DRC, availability of large-scale ammonia import terminals, storage and cracking capacity beyond pilot scale, and evidence that industrial offtakers can access hydrogen or ammonia imports.</p>	<p>IF backbone rollout continues to slip beyond 2032 and access to European demand remains constrained, credibly indicating that ammonia offtake is unlikely to materialise THEN consider selecting a lower-capacity configuration or early run-off at DP1, suspending FID at DP2/DP4, and/or suspending scale-up at DP3, and activate contingency action.</p>	<p>Reassessment: Reassess the project's market orientation by shifting from an export-led strategy to a domestic or Atlantic-regional focus, adjusting scale, sequencing and commercial assumptions accordingly, and deferring export-oriented scale-up.</p>
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13. Policy alignment and dialogue

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Basic plan action	Signpost	Trigger	Contingency action
<p>Shaping & Hedging: Continue policy and technical dialogue under the Canada-Netherlands hydrogen MoU and related bilateral and EU-facing platforms, ensuring that evolving policy, certification and infrastructure requirements are translated early into project-relevant design and commercial assumptions. Maintain active communication with public authorities, ports and standard-setting bodies to track how Canadian, EU and Dutch political targets become binding rules.</p>	<p>Monitor whether long-term hydrogen and climate targets in the EU, the Netherlands and Canada are translating into binding legislation, funded programmes and implementable support mechanisms. This includes tracking whether Canada-Netherlands MoU dialogue delivers concrete regulatory clarity (e.g., standards, certification, infrastructure and shipping rules) and consistent alignment signals from ports, regulators and standard-setting bodies relevant to hydrogen exports.</p>	<p>IF hydrogen demand in the EU and import markets remains predominantly policy-driven and hydrogen and climate policies are repeatedly delayed, weakened, or remain non-binding visions without funding or implementation mechanisms THEN consider selecting a lower-capacity configuration or early run-off at DP1, suspending FID at DP2/DP4, and/or suspending scale-up at DP3.</p>	



Pathway Scheduling: Durations, Milestones, and Windows

This appendix translates the roadmap pathways into a schedule by outlining duration ranges for each actionline and the resulting milestone timings, including sell-by dates that constrain the latest feasible delivery of milestones. It also specifies the corresponding decision windows and adaptation tipping point windows that indicate when pathway choices remain feasible.

Table E.1 shows, per pathway, the assumed duration ranges for each action line (minimum, expected and maximum) and the resulting milestone dates. The roadmap starts in 2026, so the earliest and expected milestone timings are calculated as simple cumulative sums from that start date: “earliest” adds the minimum action durations up to each milestone, and “expected” adds the expected durations. Most milestone dates, therefore, represent calculated schedule outcomes rather than hard deadlines. Only a subset of milestones acts as true sell-by constraints. The start of decommissioning is fixed at 2060 (end-of-life is assumed to be fixed), and COD for the initial build and expansion pathways is capped at 2045 to preserve at least 15 years of operations before decommissioning starts. Accordingly, the latest milestone timings are derived by working backwards through the pre-COD sequence (maximum FEED + maximum EPC + maximum commissioning & start-up), while enforcing the boundary condition that the chain still reaches COD no later than 2045 Q1; subsequent end-of-life milestones then follow from the fixed 2060 date. The Operation actionline has no stated duration because it is defined as running until the transition to the late-life operation milestone.

Table E.1: Actionline durations and milestone timings

Actionline	Min dur. (years)	Exp. dur. (years)	Max dur. (years)	Milestone	Earliest timing	Expected timing	Latest timing
Pilot & configuration selection FEED	1	$1 \frac{1}{4}$	$1 \frac{3}{4}$	Configuration selection	2027 Q1	2027 Q2	2039 Q4
Pathway 1 Full-scale							
Configuration FEED	1	$1 \frac{1}{4}$	$1 \frac{3}{4}$	FID	2028 Q1	2028 Q3	2041 Q3
EPC	$3 \frac{1}{2}$	4	$5 \frac{1}{2}$	Construction completion	2031 Q3	2032 Q3	2043 Q2

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Actionline	Min dur. (years)	Exp. dur. (years)	Max dur. (years)	Milestone	Earliest timing	Expected timing	Latest timing
Commissioning & start-up	1	1 $\frac{1}{4}$	1 $\frac{3}{4}$	COD	2032 Q3	2033 Q4	2045 Q1
Operation	-	-	-	Transition to late-life operation	2054 Q1	2055 Q1	2056 Q1
Late life operation & decommissioning preparation	4	5	6	Start decommissioning	2060 Q1	2060 Q1	2060 Q1
Pathway 1E Expand to full-scale							
Configuration FEED	$\frac{3}{4}$	1	1 $\frac{1}{4}$	FID	2032 Q4	2034 Q4	2042 Q2
EPC	2	3	4	Construction completion	2034 Q4	2037 Q4	2043 Q3
Commissioning & start-up	$\frac{3}{4}$	1	1 $\frac{1}{2}$	COD	2035 Q3	2038 Q4	2045 Q1
Pathway 1D Downscaled operation of full-scale							
Operation	-	-	-	Transition to late-life operation	2054 Q1	2055 Q1	2056 Q1
Late life operation & decommissioning preparation	4	5	6	Start decommissioning	2060 Q1	2060 Q1	2060 Q1
Pathway 1R Early run-off of full-scale							
Late life operation & decommissioning preparation	4	5	6	ATP2	2046 Q3	2051 Q4	2056 Q1
Pathway 2 Mid-scale							
Configuration FEED	1	1 $\frac{1}{4}$	1 $\frac{3}{4}$	FID	2028 Q1	2028 Q3	2041 Q3
EPC	3	4	5	Construction completion	2031 Q1	2032 Q3	2043 Q2
Commissioning & start-up	1	1 $\frac{1}{4}$	1 $\frac{3}{4}$	COD	2032 Q1	2033 Q4	2045 Q1
Operation	-	-	-	Transition to late-life operation	2054 Q1	2055 Q1	2056 Q1
Late life operation & decommissioning preparation	4	5	6	Start decommissioning	2060 Q1	2060 Q1	2060 Q1
Pathway 2E Expand to mid-scale							
Configuration FEED	$\frac{3}{4}$	1	1 $\frac{1}{4}$	FID	2032 Q4	2034 Q4	2042 Q2

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Actionline	Min dur. (years)	Exp. dur. (years)	Max dur. (years)	Milestone	Earliest timing	Expected timing	Latest timing
EPC	2	3	3 $\frac{1}{2}$	Construction completion	2034 Q4	2037 Q4	2043 Q3
Commissioning & start-up	$\frac{3}{4}$	1	1 $\frac{1}{2}$	COD	2035 Q3	2038 Q4	2045 Q1
Pathway 2D Downscaled operation of mid-scale							
Operation	-	-	-	Transition to late-life operation	2054 Q1	2055 Q1	2056 Q1
Late life operation & decommissioning preparation	4	5	6	Start decommissioning	2060 Q1	2060 Q1	2060 Q1
Pathway 2R Early run-off of mid-scale							
Late life operation & decommissioning preparation	4	5	6	ATP2	2046 Q1	2051 Q4	2056 Q1
Pathway 3 Low-scale							
Configuration FEED	1	1 $\frac{1}{4}$	1 $\frac{3}{4}$	FID	2028 Q1	2028 Q3	2041 Q3
EPC	3	4	4 $\frac{1}{2}$	Construction completion	2031 Q1	2032 Q3	2043 Q2
Commissioning & start-up	1	1 $\frac{1}{4}$	1 $\frac{3}{4}$	COD	2032 Q1	2033 Q4	2045 Q1
Operation	-	-	-	Transition to late-life operation	2054 Q1	2055 Q1	2056 Q1
Late life operation & decommissioning preparation	4	5	6	Start decommissioning	2060 Q1	2060 Q1	2060 Q1
Pathway 3R Early run-off of low-scale							
Late life operation & decommissioning preparation	4	5	6	ATP2	2046 Q1	2051 Q4	2056 Q1
Pathway 4 Early run-off							
Run-off project	$\frac{3}{4}$	1 $\frac{1}{4}$	2	ATP1	2027 Q4	2029 Q4	2043 Q3
Pathway 5 Expand to expanded-scale							
Configuration FEED	1 $\frac{1}{4}$	1 $\frac{1}{2}$	2 $\frac{1}{4}$	FID	2033 Q4	2035 Q2	2041 Q1
EPC	2	3 $\frac{1}{2}$	4 $\frac{1}{2}$	Construction completion	2035 Q4	2038 Q4	2043 Q2
Commissioning & start-up	1	1 $\frac{1}{4}$	1 $\frac{3}{4}$	COD	2036 Q4	2040 Q1	2045 Q1

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Actionline	Min dur. (years)	Exp. dur. (years)	Max dur. (years)	Milestone	Earliest timing	Expected timing	Latest timing
Operation	-	-	-	Transition to late-life operation	2054 Q1	2055 Q1	2056 Q1
Late life operation & decommissioning preparation	4	5	6	Start decommissioning	2060 Q1	2060 Q1	2060 Q1
Pathway 5D Downscaled operation of expanded-scale							
Operation	-	-	-	Transition to late-life operation	2054 Q1	2055 Q1	2056 Q1
Late life operation & decommissioning preparation	4	5	6	Start decommissioning	2060 Q1	2060 Q1	2060 Q1
Pathway 5R Early run-off of expanded-scale							
Early run-off & decommissioning preparation	4	5	6	ATP2	2050 Q4	2055 Q1	2056 Q1

Table E.2 shows the opening and closing timings of the decision windows. DP1-DP4 define when the project can decide the next build step. Each of these decision points opens at the first moment when the required input information exists: DP1 opens after the pilot and configuration-selection FEED phase has been completed, because only then can a reference configuration be chosen; DP2 and DP4 open after the relevant (expansion) configuration FEED phase has been completed, so an informed take (expansion) FID or adjust scale decision can be taken; and DP3 opens after COD of the current phase, because only after COD can new works be initiated. In other words, for DP1-DP4, the opening and expected dates are the feasible availability of the decision, based on completion of the preceding phase. For DP1–DP4, the closing dates are calculated as the latest feasible decision moment under worst-case execution. Starting from the COD sell-by date (2045), the schedule is back-casted using the maximum durations of the remaining pre-COD action lines (FEED + EPC + commissioning & start-up, as applicable). The decision window closes when the remaining maximum-duration work can no longer fit before the COD sell-by date.

DP5-DP6 work differently: they govern the operational pathway, so their opening is tied to when hydrogen offtake can realistically be changed, which is when contracts can roll off (typically 10-15 years after COD, with an expected 13-year duration). Their closing is governed by contract lock-in: because any new hydrogen offtake agreement typically commits operations for at least 10 years, beyond 2050 signing a new contract would lock the project into continued (current or downscaled) operation beyond the remaining asset life; if not locked in in a contract at 2050 (current or downscaled), the only viable choice is to enter an early run-off pathway, and the window closes.

Table E.2: Decision windows

DP on pathway	Opening of decision window	Expected decision timing	Closing of decision window
DP1	Which project configuration?		

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DP on pathway	Opening of decision window	Expected timing	decision	Closing of decision window
	2027 Q1	2027 Q2		2039 Q4
DP2 Take FID or adjust scale?				
Pathway 1 Full-scale	2028 Q1	2028 Q3		<i>Switch option closes: 2039 Q4 Take FID option closes: 2041 Q3</i>
Pathway 2 Mid-scale	2028 Q1	2028 Q3		<i>Switch option closes: 2039 Q4 Take FID option closes: 2041 Q3</i>
Pathway 3 Low-scale	2028 Q1	2028 Q3		<i>Switch option closes: 2039 Q4 Take FID option closes: 2041 Q3</i>
DP3 Scale up?				
Pathway 1 Full-scale	2032 Q3	2033 Q4		<i>Scale to expanded-scale closes: 2038 Q4</i>
Pathway 2 Mid-scale	2032 Q1	2033 Q4		<i>Scale to expanded-scale closes: 2038 Q4 Scale to full-scale closes: 2041 Q1</i>
Pathway 3 Low-scale	2032 Q1	2033 Q4		<i>Scale to expanded-scale closes: 2038 Q4 Scale to mid/full-scale closes: 2041 Q1</i>
DP4 Take expansion FID or adjust scale?				
Pathway 1E Expand to full-scale	2032 Q4	2034 Q4		<i>Switch option to expanded-scale closes: 2038 Q4 Switch option to mid-scale closes: 2041 Q1 Take-expansion-FID option closes: 2042 Q2</i>
Pathway 2E Expand to mid-scale	2032 Q4	2034 Q4		<i>Switch option to expanded-scale closes: 2038 Q4 Switch option to full-scale closes: 2041 Q1 Take-expansion-FID option closes: 2042 Q2</i>
Pathway 5 Expanded-scale	2033 Q4	2035 Q1		<i>Switch option to mid/full-scale closes: 2041 Q1 Take-expansion-FID option closes: 2041 Q1</i>
DP5 Continue operation, downscale, or enter early run-off?				
Pathway 1 Full-scale	2042 Q3	2046 Q4		2050 Q1
Pathway 2 Mid-scale	2042 Q1	2046 Q4		2050 Q1
Pathway 3 Low-scale	2042 Q1	2046 Q4		2050 Q1
Pathway 5 Expanded-scale	2046 Q4	2050 Q1		2050 Q1
DP6 Maintain downscaled operation, return to scale, or move to run-off?				

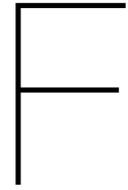
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DP on pathway	Opening of decision window	Expected decision timing	Closing of decision window
Pathway 1 Full-scale	2042 Q3	Not defined; timing is condition-dependent.	2050 Q1
Pathway 2 Mid-scale	2042 Q1	Not defined; timing is condition-dependent.	2050 Q1

Table E.3 shows the opening and closing timings of the adaptation tipping point windows. Adaptation tipping points are defined as the moment an early run-off decision is triggered, plus the time required to complete the run-off activities. ATP1 is linked to the early development stage: it opens when DP1 opens, because once the pilot and configuration-selection FEED outputs are available, the project can either proceed or decide not to progress, after which run-off activities can start. ATP1 closes when DP2 closes, because beyond that point the project can no longer take FID; the remaining viable choice is therefore binary: either FID has already been taken or the project must transition into run-off. ATP2 is linked to the operational stage: it opens when DP5 opens, when the first offtake contracts can roll off, and the project can choose between continued operation, downscaling, or early run-off. ATP2 closes at DP5 as well, when entering any new offtake would create an unacceptable lock-in for the final contract period, and run-off is the only viable pathway.

Table E.3: Adaptation tipping point windows

ATP on pathway	Opening of ATP window	Expected ATP timing	Closing of ATP window
ATP1			
Pathway 4 Early run-off	2027 Q4	2029 Q4	2043 Q3
ATP2			
Pathway 1 Full-scale	2046 Q3	2051 Q4	2056 Q1
Pathway 2 Mid-scale	2046 Q1	2051 Q4	2056 Q1
Pathway 3 Low-scale	2046 Q1	2051 Q4	2056 Q1
Pathway 5 Expanded-scale	2050 Q4	2055 Q1	2056 Q1



Roadmap

This appendix assembles the roadmap by placing the actionlines that form the pathways and the decision points at the milestone dates specified in Appendix E. It also positions the adaptation tipping points; together, these elements visualise the set of feasible pathway options and how the project can move between them, informed by the adaptation plan defined in Appendix D.

2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049 2050 2051 2052 2053 2054 2055 2056 2057 2058 2059 2060

