

Design and Optimization of Renewable Energy Carrier Supply Chains: Global Logistics, Energy Storage, and Policy Frameworks

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Abstract

Achieving climate-neutrality goals requires a rapid transformation of energy and industrial systems. In this transition, Renewable Energy Carriers (RECs)—most prominently renewable hydrogen and its derivatives—are expected to play a central role in decarbonizing applications where direct electrification is limited. Scaling up REC supply chains is therefore not only a technology deployment challenge, but an integrated infrastructure-and-operations planning problem shaped by three interacting drivers: (i) spatial mismatches between regions with abundant renewable potential and demand centers, (ii) temporal variability and uncertainty in wind and solar availability, and (iii) evolving policy frameworks that steer adoption through incentives, targets, and mandates. Together, these drivers shape investment needs, operational feasibility, and the trade-offs between competing transition objectives.

Against this background, this cumulative dissertation develops and applies optimization-based decision support for the design and evaluation of REC supply chains. It focuses on global logistics, energy storage, and policy frameworks as key levers shaping transition performance. Going beyond cost minimization, it makes decision-relevant trade-offs explicit across economic performance, GHG emissions, and system robustness, including supply security and reliability requirements. The dissertation consists of three research papers (Papers I–III), each addressing a specific decision requirement while contributing to a coherent framework of transferable optimization modules.

Paper I addresses the strategic design of international REC trade and import portfolios. Spatial resource–demand mismatches necessitate long-distance transport and international partnerships. At the same time, import strategies must balance affordability, emissions, and security of supply. Paper I proposes a multi-period, multi-objective mixed-integer quadratic programming model that jointly minimizes net present cost, GHG emissions, and a supply-security risk index measured as a political-risk-weighted Herfindahl–Hirschman Index (HHI) capturing portfolio concentration. By generating Pareto-efficient solutions, Paper I shows how alternative import strategies trade cost and emissions against diversification and security objectives, and introduces a benchmark-compliant compromise selection concept to relate model outcomes to an interpretable reference level.

Paper II focuses on designing reliable renewable hydrogen supply chains under uncertainty in renewable electricity availability. Planning based on deterministic renewable-availability

profiles can underestimate the infrastructure and flexibility required to meet demand reliably. Paper II develops a two-stage, chance-constrained mixed-integer linear programming framework that jointly optimizes renewable electricity generation, hydrogen production and (re)conversion, hybrid energy storage, interregional transport within the modeled system boundary, and exogenous imports. Reliability is enforced through regional chance constraints at a predefined confidence level using wind and solar availability scenarios that capture temporal dependence and cross-regional correlations; a hierarchical time aggregation represents seasonal and diurnal patterns while keeping the optimization tractable. The results quantify how tightening reliability requirements translates into higher system costs and changes in the optimal flexibility and infrastructure portfolio needed to maintain reliable supply under uncertainty.

Paper III evaluates how policy instruments and their combinations shape the long-term development of renewable fuel supply chains. Rather than treating policy as an exogenous scenario setting, Paper III represents policy measures directly as incentives and constraints within a multi-period, bi-objective MILP. Using a structured assessment across policy combinations, Paper III quantifies both main effects and interaction effects and shows that interaction effects and policy timing can materially influence cost-effective transition pathways and cumulative GHG emissions outcomes.

Taken together, this dissertation contributes an integrated framework of optimization-based modules for designing REC supply chains under spatial constraints, temporal variability and uncertainty, and policy requirements. While the case studies emphasize the European context and specific carrier configurations, the modeling approaches are modular and transferable to other regions and REC contexts. The dissertation concludes by discussing limitations, including abstraction from detailed power-market coupling and additional socio-economic sustainability dimensions, and outlines directions for future research, including detailed representations of compound uncertainty and broader sustainability assessment beyond cost and GHG emissions.

Zusammenfassung

Das Erreichen der Klimaneutralität erfordert eine beschleunigte Transformation von Energie- und Industriesystemen. Dabei spielen erneuerbare Energieträger (Renewable Energy Carriers, RECs) – insbesondere erneuerbarer Wasserstoff und seine Derivate – eine zentrale Rolle bei der Dekarbonisierung von Anwendungen, in denen direkte Elektrifizierung nur begrenzt möglich ist. Der Ausbau von REC-Lieferketten ist nicht allein eine technologische Aufgabe, sondern eine integrierte Planungsherausforderung, die Infrastruktur- und Betriebsentscheidungen umfasst und durch drei miteinander verknüpfte Einflussfaktoren geprägt ist: (i) räumliche Ungleichgewichte zwischen Regionen mit hohem erneuerbarem Potenzial und Nachfragezentren, (ii) die zeitliche Variabilität und Unsicherheit der Wind- und Solarverfügbarkeit sowie (iii) dynamische politische Rahmenbedingungen, die die Diffusion erneuerbarer Energieträger über Anreize, Zielvorgaben und regulatorische Vorgaben steuern. Zusammen bestimmen diese Faktoren Investitionsbedarfe, operative Umsetzbarkeit und die Zielkonflikte zwischen zentralen Transformationszielen.

Vor diesem Hintergrund entwickelt und nutzt diese kumulative Dissertation eine optimierungsbasierte Entscheidungsunterstützung zur Gestaltung und Bewertung von REC-Lieferketten. Im Mittelpunkt stehen globale Transport- und Logistikstrukturen, Energiespeicher sowie politische Rahmenbedingungen als zentrale Einflussgrößen der Transformation. Über reine Kostenminimierung hinaus macht die Dissertation Zielkonflikte zwischen ökonomischer Leistungsfähigkeit, Umweltwirkung und Systemrobustheit explizit. Dabei werden Versorgungssicherheit (z. B. Robustheit von Importportfolios gegenüber Konzentration und Risikoexposition) und Versorgungszuverlässigkeit (verlässliche Deckung regionaler Nachfrage unter Unsicherheit) als komplementäre Anforderungen adressiert. Die Dissertation umfasst drei Forschungsbeiträge (Paper I–III), die jeweils unterschiedliche Dimensionen des REC-Entscheidungsproblems untersuchen und zugleich zu einem kohärenten, modular aufgebauten Rahmen übertragbarer Optimierungsmodule beitragen.

Paper I untersucht die strategische Ausgestaltung internationaler REC-Handels- und Importportfolios. Räumliche Unterschiede zwischen erneuerbaren Ressourcen und Nachfragezentren erzeugen den Bedarf an Ferntransport und internationalen Partnerschaften; zugleich müssen Importstrategien Bezahlbarkeit, Emissionswirkungen und Versorgungssicherheit miteinander in Einklang bringen. Paper I entwickelt hierfür ein

mehrperiodiges, multikriterielles Mixed-Integer Quadratic Programming (MIQP)-Modell zur Gestaltung von REC-Importlieferketten. Die Zielkonflikte werden erfasst, indem der Barwert der Gesamtsystemkosten, Treibhausgasemissionen und ein Versorgungssicherheits-Risikoindex minimiert werden, der als politisch risikogewichteter Herfindahl–Hirschman Index formuliert ist und sowohl die Konzentration des Importportfolios (Diversifizierung) als auch das Risikoprofil von Exportregionen erfasst. Die Pareto-effizienten Lösungen und ein benchmark-basiertes Auswahlkonzept ermöglichen eine transparente Einordnung der Portfolios anhand eines aus fossilen Importstrukturen abgeleiteten Referenzniveaus.

Paper II befasst sich mit der Auslegung zuverlässiger erneuerbarer Wasserstoff-Lieferketten unter Unsicherheit der erneuerbaren Stromverfügbarkeit. Deterministische Planungsansätze, die Variabilität und Unsicherheit nur unzureichend abbilden, können den Infrastruktur- und Flexibilitätsbedarf unterschätzen, der zur verlässlichen Nachfragedeckung erforderlich ist. Vor diesem Hintergrund entwickelt Paper II ein zweistufiges, chance-constrained Mixed-Integer Linear Programming (MILP)-Modell, das Investitionen und Betrieb von erneuerbarer Stromerzeugung, Wasserstoffproduktion und (Re-)Konversion, hybriden Speicherportfolios, interregionalem Transport innerhalb der Systemgrenze sowie exogenen Importen gemeinsam abbildet. Die Versorgungszuverlässigkeit wird über regionale Wahrscheinlichkeitsrestriktionen bei einem vorgegebenen Konfidenzniveau gewährleistet, basierend auf Szenarien zur Wind- und Solarverfügbarkeit, die zeitliche Abhängigkeiten und räumliche Korrelationen berücksichtigen; eine hierarchische Zeitaggregation hält das Optimierungsproblem rechnerisch durchführbar. Die Ergebnisse quantifizieren den Zielkonflikt zwischen Versorgungszuverlässigkeit und Kosten und zeigen, wie zeitliche und räumliche Flexibilität gemeinsam eine zuverlässige Versorgung unter Unsicherheit ermöglichen.

Paper III untersucht, wie politische Instrumente sowie deren Kombinationen die langfristige Entwicklung von Lieferketten für erneuerbare Kraftstoffe prägen. Anstatt politische Rahmenbedingungen lediglich als exogene Szenarioannahmen zu behandeln, bildet Paper III politische Maßnahmen direkt als Anreize und Restriktionen in einem mehrperiodigen, bi-objektiven MILP ab. Auf Basis einer strukturierten Bewertung über mehrere Politikkombinationen quantifiziert Paper III Haupteffekte und Interaktionseffekte und zeigt, dass Interaktionen und Timing die Systemresultate maßgeblich beeinflussen können.

Insgesamt liefert die Dissertation einen integrierten, optimierungsbasierten Rahmen zur Gestaltung von REC-Lieferketten unter räumlichen Restriktionen, zeitlicher Variabilität und

Unsicherheit sowie politisch geprägten Anforderungen. Während die Fallstudien den europäischen Kontext und spezifische Trägerkonfigurationen in den Vordergrund stellen, sind die entwickelten Modellansätze modular aufgebaut und auf andere Regionen und Anwendungskontexte übertragbar. Abschließend diskutiert die Dissertation einige Einschränkungen, darunter die abstrakte Abbildung der detaillierten Strommarkt- und Netzkopplung sowie weiterer sozioökonomischer Nachhaltigkeitsdimensionen. Darüber hinaus werden Perspektiven für zukünftige Forschung aufgezeigt, etwa detailliertere Darstellungen zusammengesetzter Unsicherheiten und eine breitere Nachhaltigkeitsbewertung jenseits von Kosten und Emissionen.

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Part I: Preface

Chapter 1

Introduction

This chapter motivates renewable energy carrier (REC) supply chains as an infrastructure and decision problem shaped by (i) spatial mismatches between renewable resource potentials and demand centers, (ii) temporal variability and uncertainty in renewable electricity availability, and (iii) policy frameworks that steer technology deployment and set requirements for sustainability (e.g., GHG emissions), security (e.g., security of supply, including import dependence and portfolio diversification), and reliability (e.g., demand satisfaction service levels). Chapter 1.1 provides the background and motivation for the research papers included in this cumulative dissertation, while Chapter 1.2 defines the dissertation aims, research questions, and overall structure.

1.1 Background

Achieving climate-neutrality goals requires a rapid transformation of energy and industrial systems, relying on several measures and technologies, including energy efficiency, direct electrification, carbon capture, and RECs (Agora Energiewende, 2019; Hydrogen Council, 2021; IEA, 2021; IRENA, 2024a). Among these, RECs such as renewable hydrogen and derived fuels play a key role in decarbonizing hard-to-abate sectors, functioning as both a feedstock and an energy carrier to substitute fossil-based inputs and fuels, thereby supporting long-term decarbonization strategies (Hydrogen Council, 2020; IEA, 2024; IRENA, 2022a; IRENA Coalition for Action, 2022). RECs are projected to supply a significant share of feedstock and fuel demand in steelmaking, non-ferrous metal processing, glass manufacturing, mineral processing, pulp and paper production, basic chemicals, refineries, aviation, maritime shipping, and other chemical industries (IRENA, 2020; Neuwirth et al., 2022).

This growing commitment to RECs is evident globally, with more than 2,500 REC projects having been announced to expand production capacity, build infrastructure, and integrate hydrogen into national and international energy strategies (IEA, 2025a, 2025b). The prospective scale of REC deployment implies not only a technology challenge but also a supply chain and infrastructure challenge (Taghavi et al., 2026). Substantial renewable electricity must be generated, converted into carriers, brought into suitable forms for storage and transport, and

delivered reliably to geographically dispersed demand centers (Hossain Bhuiyan and Siddique, 2025; IEA, 2019, 2024; IRENA, 2022b; World Energy Council, 2021a).

A core feature of REC systems is the spatiotemporal mismatch between renewable energy availability and energy consumption. Renewable energy potentials are unevenly distributed across regions due to variations in wind and solar resources, land availability, grid connectivity, water constraints, and infrastructure access (Jiang et al., 2025; Olabi et al., 2023). Major industrial and urban demand centers are frequently located in regions with limited low-cost renewable potential or land-use constraints (IEA, 2024; IRENA, 2022b). This spatial mismatch motivates international trade and interregional transport networks that connect supply-rich regions with demand centers and exploit comparative advantages (IRENA, 2024b; World Energy Council, 2021a).

In addition, renewable supply is intrinsically time-varying (Haas et al., 2017). Daily and seasonal patterns as well as interannual variability affect renewable availability and, consequently, the utilization of conversion units such as electrolyzers (Danish Energy Agency, 2018b; Taslimi and Khosravi, 2025). Temporal variability results in operational challenges and increases the need for flexibility options—especially storage—to ensure continuous supply to end users (Danish Energy Agency, 2018a). Therefore, REC systems are not merely a capacity expansion problem but a dynamic system planning problem in which long-term investments interact with short-term operations and flexibility needs (Danish Energy Agency, 2018a).

Taken together, these spatial and temporal aspects shape both feasibility and the ability to supply RECs reliably. Systems dominated by variable renewables require the ability to shift energy across time (temporal flexibility) and across space (spatial flexibility). Temporal flexibility is enabled primarily by storage (Khalili et al., 2025), whereas spatial flexibility is enabled by transport infrastructure and trade relationships (Guidehouse, 2021; IRENA, 2024b). Both are, in turn, shaped by policy frameworks that influence deployment conditions and define acceptable reliability, environmental performance, and import dependence (European Commission, 2022, 2025a; Qadir et al., 2021). Accordingly, this dissertation frames REC supply chain design as an integrated decision problem in which global logistics, energy storage and flexibility, and policy frameworks must be assessed jointly (Bamufleh et al., 2025).

These system characteristics make REC supply chain development a long-term infrastructure planning problem, not merely a technical deployment challenge. Establishing REC supply chains requires substantial upfront investments in renewable electricity generation, conversion

and reconversion facilities, storage, and transport infrastructure (IEA, 2019; IRENA, 2022b; World Energy Council, 2021a). Under current techno-economic conditions, many REC pathways remain more costly than fossil-based alternatives, largely because of technology costs and the cost of renewable electricity inputs (Hampp et al., 2023; Moritz et al., 2023). Although these costs are expected to decline through technological learning, economies of scale, and supportive policy, the pace and extent of such reductions remain uncertain and depend on deployment trajectories, supply constraints, and policy conditions (Hombach and Walther, 2015; Quarton and Samsatli, 2021). Taken together, this creates an inherently multi-period planning context in which early investment decisions shape future technology pathways, constrain future flexibility, and interact with evolving costs, demand, and system requirements. In addition, REC supply chain development requires coordinated decisions across generation, conversion, storage, transport, and end-use infrastructure, while alternative carriers differ in conversion losses, infrastructure requirements, handling characteristics, and emissions implications, creating non-trivial trade-offs (Danish Energy Agency, 2018b; Liebich et al., 2021; Oeko-Institut, 2023).

Accordingly, REC supply chains should be evaluated from multiple perspectives rather than from cost alone in order to support robust and sustainable long-term transition pathways (European Commission, 2026; Jaiswal et al., 2022; López et al., 2026; Suryawanshi and Dutta, 2022; Virah-Sawmy and Sturmberg, 2025). Affordability remains essential, since high system costs can slow deployment and limit feasibility (European Commission, 2025a, 2025b). However, environmental performance must also be assessed across the full supply chain, including production, conversion, storage, and transport (Liebich et al., 2021). In addition, supply chains must be robust against import dependence, supply concentration, and disruption risks, while also ensuring reliable demand satisfaction under variable and uncertain renewable availability (López et al., 2025; OECD, 2025). These requirements become even more important in systems that rely on temporal flexibility through storage and spatial flexibility through transport and trade (Abrell et al., 2022; Gorenstein Dedecca et al., 2025). Moreover, policy frameworks shape market demand, technology selection, infrastructure development, and the feasibility and cost-effectiveness of transition pathways (European Commission, 2021a, 2023). REC supply chain design therefore requires an integrated perspective that makes trade-offs transparent across economic, environmental, supply security, reliability, and policy dimensions.

This dissertation focuses on three levers that enable REC supply chains to bridge spatiotemporal mismatches.

(i) Global logistics and international trade connect supply-rich regions with demand centers and expand feasible decarbonization pathways. Global logistics design includes the selection of exporting regions, carrier choice, conversion technologies, and transport mode and route selection (ITF, 2016; Liebich et al., 2021). These decisions influence economic, environmental, and supply security dimensions, implying that international trade cannot be evaluated from a purely economic perspective (Aguirre-García et al., 2025; ITF, 2016; World Energy Council, 2024).

(ii) Energy storage options operate at different time scales, supporting intra-day balancing and bridging seasonal variability, thereby improving supply during prolonged low-renewable periods (Blanco and Faaij, 2018; Reuß et al., 2017). In REC systems, temporal flexibility may involve electricity storage, gaseous hydrogen storage, and storage of derivative carriers; thus, storage decisions are intertwined with conversion and reconversion portfolios (Danish Energy Agency, 2018a; Fasihi et al., 2021).

(iii) Policy frameworks steer the transition trajectory and the structural evolution of technology deployment (European Commission, 2021b; IEA, 2018). While clear, long-term policy targets and mandates reduce uncertainty for investors and other market participants and provide market visibility, mechanisms such as renewable supply requirements, GHG emission reduction targets, and carbon pricing directly influence investment incentives and the cost-competitiveness of renewable alternatives relative to fossil fuels (European Commission, 2021a, 2021b, 2021c; Taghavi et al., 2026). Policy frameworks also establish sustainability and security rules through eligibility criteria, certification schemes, import quotas, and reliability benchmarks, and they are increasingly embedded in national and regional hydrogen strategies and investment plans (European Commission, 2020; World Energy Council, 2021b).

REC supply chain design involves large-scale infrastructure choices with long-lived assets, multiple technology options, and interdependent decisions across space and time. Decision-makers must consider the system across multiple perspectives—economic, environmental, and supply security—while addressing uncertainty in renewable availability and policy conditions. To evaluate these impacts systematically, policy instruments need to be integrated explicitly within decision-support models, moving beyond their traditional treatment as exogenous assumptions (Balaban et al., 2025; Quarton and Samsatli, 2021). Mathematical optimization

models are well suited for this quantitative analysis: they represent system structure and operations consistently, enforce technical feasibility, and quantify trade-offs transparently. However, many existing approaches either emphasize a single perspective, simplify renewable variability, or do not integrate policy measures within the decision-support framework. This can underestimate the role of temporal and spatial flexibility, misrepresent reliability under uncertainty, and limit attribution of policy effects. Addressing these limitations motivates the models and analyses developed in Papers I–III.

1.2 Aims and Structure

Building on these three dimensions, this cumulative dissertation develops quantitative models and decision support for the design and evaluation of REC supply chains. It adopts an integrated perspective that makes trade-offs transparent and links qualitative targets such as security, reliability, and sustainability to explicit infrastructure and operational outcomes.

The aim of this dissertation is to develop quantitative models and decision support for the design and evaluation of REC supply chains, with particular attention to (i) spatial coordination through trade and logistics, (ii) temporal balancing through storage and flexibility options, and (iii) the role of policy frameworks in shaping transition pathways. This aim is operationalized through three aligned objectives. First, the dissertation examines spatial coordination through trade and logistics by developing supply chain design models for international REC planning that represent key infrastructure decisions across multiple regions and time periods and quantify trade-offs between economic, environmental, and supply-security performance. Second, it examines temporal balancing through storage and flexibility options by representing renewable variability, uncertainty, and reliability requirements, and by analyzing how storage portfolios, interregional transport, and exogenous imports shape system design. Third, it examines the role of policy frameworks by integrating policy measures explicitly within optimization models and evaluating how policy instruments and their combinations influence REC supply chain development and the cost-effectiveness of emission reductions. Figure 1.1 maps the dissertation structure and research questions to the three cumulative papers.

RQ (overarching): How can renewable energy carrier supply chains be designed and evaluated considering spatiotemporal mismatches between production and utilization, intermittent renewable availability, and policy frameworks?

Addressed through the combined insights of Papers I–III and synthesized in Chapter 4.

RQ a: How should international REC trade be shaped to jointly optimize economic and environmental objectives while considering supply security?

Addressed in Paper I, which develops a multi-period, multi-objective MIQP for Europe's REC import planning from an integrated economic, environmental, and supply-security perspective.

RQ b: How can a reliable REC supply be achieved by determining the capacities and technology portfolio of energy storage?

Addressed in Paper II, which develops a chance-constrained two-stage MILP for renewable hydrogen supply chain (RHSC) design under uncertain renewable electricity availability, optimizing generation, conversion, hybrid storage, interregional transport, and exogenous imports under a reliability confidence level.

RQ c: How can policy frameworks influence the development of REC supply chains and contribute to achieving climate-neutrality goals?

Addressed in Paper III, which employs a multi-period bi-objective MILP for renewable fuel supply chain (RFSC) design in transport sectors, integrating policy measures explicitly and evaluating their impacts through factorial and sensitivity analysis.

		Global Logistics	Energy Storage	Policy Frameworks
Part I: Preface	Chapter 1: Introduction	Motivation and related literature		
	Chapter 2: Literature Review			
	Chapter 3: Methodology	Sustainable and Secure International REC Supply Chains (RQ a)	Reliable REC Supply Chains under Uncertain Renewable Availability (RQ b)	Impacts of Policy Measures on REC Supply Chain Development (RQ c)
	Chapter 4: Key Findings	Designing and evaluating REC supply chains under spatiotemporal mismatches, uncertain renewable availability, and policy frameworks (RQ, overarching)		
	Chapter 5: Conclusion			
Part II: Cumulative papers	Chapter 6: Research Paper I	Multi-Objective Supply Chain Optimization of REC Imports for Europe	Designing Reliable RHSCs with Hybrid Storage under Uncertain Renewable Electricity Availability	Analyzing Policy Measures for RFSC Development in Transport Sectors
	Chapter 7: Research Paper II			
	Chapter 8: Research Paper III			

Figure 1.1. Structure of the dissertation and mapping of the research questions (RQs) to the three research papers. REC: renewable energy carrier; RHSC: renewable hydrogen supply chain; RFSC: renewable fuel supply chain.

The dissertation consists of two parts (Figure 1.1). Part I (Preface) provides dissertation framing and synthesis: Chapter 1 motivates the problem and defines the research questions; Chapter 2 synthesizes the relevant literature and develops the research gaps; Chapter 3 presents the

methodological foundations; Chapter 4 synthesizes key findings across Papers I–III; and Chapter 5 concludes with contributions, implications, limitations, and future research directions. Part II (Cumulative Part of the Dissertation) contains Papers I–III with full model formulations, data and case-study details, and extended results.

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Chapter 2

Literature Review

This chapter reviews literature relevant to the dissertation's three themes—global logistics, energy storage and flexibility, and policy frameworks—and consolidates research gaps that motivate the cumulative papers. The review first clarifies REC supply chain concepts and scope (Chapter 2.1), then summarizes sustainability-related perspectives and objectives as modeled in the literature (Chapter 2.2). Chapters 2.3–2.5 review the three theme-specific bodies of work and conclude with research gaps. Chapter 2.6 consolidates these gaps and links them to the research questions introduced in Chapter 1.

2.1 Renewable Energy Carrier Supply Chains: Concepts and Scope

In this dissertation, RECs refer to renewable hydrogen and its derivatives, as well as renewable fuels for transport, which may act as fuels, energy carriers, or industrial feedstocks. While technologies differ across carriers, REC supply chains share common structural stages: renewable energy is generated, converted into a carrier, prepared for storage and transport, and delivered to end-use sectors.

These stages can be structured as follows. First, renewable energy supply provides primary inputs, typically wind and solar electricity. Second, conversion and synthesis units transform energy into carriers (e.g., hydrogen, derivatives, fuels). Third, preparation and storage make carriers manageable across time and enable flexibility (e.g., compression, liquefaction, ammonia synthesis, Liquid Organic Hydrogen Carrier (LOHC) (de)hydrogenation). Fourth, transport and distribution move carriers across space through interregional transport and international trade. Fifth, (re)conversion and utilization provide carriers in usable form, including cracking or reconversion (Hampp et al., 2023; Wolff et al., 2023). Decision-making therefore includes both strategic investments (capacity and sizing) and operational decisions (production rates, inventories, and transport flows). Since strategic and operational decisions interact, REC supply chain analysis benefits from integrated planning models that link capacity choices and operations at a well-defined spatiotemporal resolution (Efthymiadou et al., 2025; Wolff et al., 2023).

REC supply chains are typically multi-regional due to spatial heterogeneity in renewable potentials and demand. This motivates both interregional transport (within a modeled system boundary) and international trade (across exporting and importing regions) (Weidenfeld et al., 2021). Spatial flexibility in a supply chain includes carrier choice, transport mode and route decisions, and infrastructure compatibility, which raise security and dependency challenges for importing regions (Galimova et al., 2023; World Energy Council, 2021). In the literature, spatial planning in REC supply chains is represented at different system boundaries, ranging from international trade planning to multi-regional system designs with interregional transport and exogenous imports.

Beyond spatial heterogeneity, REC systems are shaped by temporal variability and uncertainty in renewable supply. Renewable availability varies across intra-day, seasonal, and interannual time scales, affecting unit utilization and the feasibility of meeting demand (Hasan et al., 2025; Tong et al., 2021). Energy storage technologies therefore shape both operations and long-term investments (IEA, 2023; Khalili et al., 2025). REC supply chains balance supply and demand via storage of electricity, hydrogen, and derivatives, each with distinct efficiencies, losses, and infrastructure implications (Danish Energy Agency, 2018a; IRENA, 2024b). Reliability becomes particularly important when supply depends on uncertain renewable availability (Ghanbarzadeh et al., 2025; Tong et al., 2021). In the literature, temporal representation ranges from high-resolution formulations that capture intra-day and intra-year variability to yearly time steps used for long-term transition planning.

2.2 Sustainability Perspectives in REC Supply Chain Models

REC supply chain planning is increasingly evaluated across multiple perspectives, including economic, environmental, and additional dimensions such as security and reliability (Alanazi et al., 2025; Jansen et al., 2025; Kabeyi and Olanrewaju, 2022; Karbassi et al., 2023). In optimization models, these perspectives are represented as objective functions and constraints, enabling a systematic evaluation of trade-offs (Farajiamiri et al., 2023; Hombach and Walther, 2015).

From an economic perspective, affordability is central to widespread REC adoption (European Commission, 2025). Economic performance is commonly assessed through net present value (profit), net present cost, or annualized system cost, accounting for investments and operating costs across production, conversion, storage, and transport (Genge et al., 2023; Johnston et al., 2022; Samsatli and Samsatli, 2018). Key cost drivers include renewable electricity, electrolysis,

synthesis units, storage, and transport infrastructure capital expenditure (CAPEX) and operational expenditure (OPEX) (Wolff et al., 2023). These costs vary with renewable resource quality, geographic location, and logistical complexity, including transport requirements and the need for storage (Galimova et al., 2023; Hank et al., 2023; Wietschel et al., 2024). Sensitivity of CAPEX, OPEX, and operational parameters (e.g., efficiency) makes economic outcomes strongly dependent on assumptions about learning curves, technology improvements, and future market scale (Brändle et al., 2021; Bühler and Möst, 2025; GIZ, 2024; Pillai et al., 2026).

From an environmental perspective, RECs can significantly reduce GHG emissions relative to fossil-based counterparts (European Commission, 2023; Galimova et al., 2023; Terlouw et al., 2025), aligning with recent national and international climate regulations (Bube et al., 2025; Zahid et al., 2025). This perspective is typically implemented by representing GHG emissions either as an optimization objective (e.g., minimizing total emissions or maximizing emission savings) or as a system constraint (e.g., emission limits or intensity standards) (Samsatli and Samsatli, 2018; Solana et al., 2025; Thornley et al., 2015). However, studies differ substantially in system boundaries—particularly regarding infrastructure inclusion and material and energy balances—which can substantially affect pathway evaluations (Arrigoni et al., 2024; Balanza et al., 2025). Robust climate impact evaluation therefore requires assessment of the full REC supply chain, encompassing both installation and operation of resource utilization, production, storage, and transport infrastructure (Bube et al., 2025; Liebich et al., 2021).

While economic and environmental perspectives are central, the transition increasingly depends on supply security, since disruptions or shortages pose risks to economic stability (Abouelenein et al., 2026; Brodny and Tutak, 2023; Chalvatzis and Ioannidis, 2017; Rosa et al., 2022). Diversity and dependence are key metrics, commonly assessed through supply concentration and import dependency indicators (Abdullah et al., 2021; Chalvatzis and Ioannidis, 2017; Liu et al., 2021; Rosa et al., 2022), particularly under geopolitical uncertainty (Dalla Longa and van der Zwaan, 2024). Reducing supply concentration—or increasing diversification—can mitigate disruption impacts (e.g., extreme weather, geopolitical conflict, pandemics) by ensuring access to alternative sources of supply (Chalvatzis and Ioannidis, 2017; Dejonghe et al., 2023; Vivoda, 2019; Wang et al., 2024; Zhu et al., 2023). Accordingly, partnerships with low-cost and reliable suppliers are often discussed as a strategy to enhance supply security (Alpha et al., 2025; Ansari and Pepe, 2023; Breitschopf et al., 2022; Rosa et al., 2022; World Energy Council, 2022).

Alongside import metrics, the Herfindahl–Hirschman Index (HHI) is widely used as a benchmark for supply concentration (Lekavičius et al., 2024; Rosa et al., 2022; Triguero-Ruiz et al., 2023). In modeling, these metrics may be formulated as objective functions, represented as constraints, or embedded as implicit assumptions (Jansen et al., 2025).

Beyond GHG emissions, broader sustainability assessment can include additional environmental and social factors (IEA, 2024b; Virah-Sawmy and Sturmberg, 2025). Environmental criteria commonly considered in the literature include direct and indirect land-use change, water use, and biodiversity (Farajiamiri et al., 2023; Hofmann et al., 2025; Hombach et al., 2016; Tonelli et al., 2023). Social assessment can cover factors such as acceptance, labor and working conditions, local value creation, energy justice, and job creation (Becker et al., 2024; Bindi et al., 2025; Karbassi et al., 2023). These factors can be included directly as objectives or constraints, or indirectly through assumptions and input data (Becker et al., 2024; Hofmann et al., 2025; Hombach et al., 2016; Hombach and Walther, 2015).

2.3 Global Logistics in REC Supply Chains

Global logistics and international REC trade are critical for balancing the geographical mismatch between renewable energy supply and demand (Aguirre-García et al., 2025; IRENA and WTO, 2024). In global renewable energy trade, exporting regions are typically characterized by high resource abundance, whereas importing regions often have limited domestic potential relative to demand (Galimova et al., 2023; Kan et al., 2025; World Energy Council, 2022). Global trade can expand feasible decarbonization pathways and reduce system-wide costs by leveraging comparative advantages (IRENA and WTO, 2024; Moritz et al., 2021). Accordingly, analyses often characterize exporting regions through their cost and quantity of export potential after domestic demand is met (Kan et al., 2025). Beyond regional export potential and domestic demand, the economic and environmental impacts of global logistics infrastructure also shape international links (Galimova et al., 2023; Liebich et al., 2021). Planning global REC trade requires not only long-distance transport infrastructure but also carrier choices, conversion requirements, and infrastructure compatibility (Danish Energy Agency, 2018c; Hampp et al., 2023). Since global trade can increase exposure to disruptions, supply security must be examined alongside economic and environmental metrics (Kim et al., 2025; OECD, 2025).

Studies of global REC trade typically include renewable electricity generation, electrolysis, synthesis and reconversion facilities, storage, and transport infrastructure (Fakhreddine et al.,

2025; Hampp et al., 2023; Hank et al., 2023). Long-distance transport options include pipelines for regional links and shipping-based options (liquid hydrogen, ammonia, methanol, LOHC) for overseas supply (Karbassi et al., 2023). RECs differ in energy density, (re)conversion losses, and feasible transport technologies, requiring planning decisions that jointly consider carrier choice, transport technology, and infrastructure needs (Hampp et al., 2023; Kim, A. et al., 2023; Villalba-Herreros et al., 2023). Considering multiple carriers can also reveal synergies such as shared infrastructure or flexible pathways that single-commodity models may miss (Hampp et al., 2023; Karbassi et al., 2023; Wan et al., 2024). For long-term transition pathways, multi-period frameworks capture gradual demand growth, supply chain development, and technological advancement over time (Amjath et al., 2025; Linsel and Bertsch, 2024; Wan et al., 2024).

In global REC trade, optimization models typically decide the portfolio of exporting regions, technology pathways and capacities (renewable generation, REC production, transport, and reconversion), as well as trade quantities and routes (Fakhreddine et al., 2025; Riera et al., 2023). Economic objectives are commonly formulated as total system cost or delivered carrier cost (Amjath et al., 2025; Galimova et al., 2023; Linsel and Bertsch, 2024). Environmental performance is often represented through emission factors for construction and operation within the defined system boundary (e.g., cradle-to-gate or cradle-to-grave) (Liebich et al., 2021), resulting in objectives such as cumulative supply-chain emissions or emission costs that depend on assumptions including electricity sourcing and boundary definitions (Kim, A. et al., 2023; Makepeace et al., 2024). Supply security is frequently quantified by concentration metrics such as the Herfindahl–Hirschman Index (HHI) for export or import concentration (Cappelli and Carnazza, 2023; Lekavičius et al., 2024; OECD, 2025). Some studies integrate risk considerations by weighting concentration metrics with supplier-specific risk indicators (e.g., political instability) (Alpha et al., 2025; Cappelli and Carnazza, 2023; Jansen et al., 2025; Lekavičius et al., 2024; Wei et al., 2024; Xun et al., 2022). Environmental and security criteria may also be included as constraints rather than as objectives (Jansen et al., 2025).

Table 2.1 presents a selection of supply chain design studies considering global REC trade. Overall, the reviewed studies show that only a limited number jointly represent economic, environmental, and supply-security dimensions, relatively few analyze multiple REC carriers within a long-term (multi-period) planning framework, and political-risk-related diversification considerations are rarely represented explicitly in REC trade planning. Taken together, these

gaps indicate the need for REC trade planning models that jointly represent economic, environmental, and supply-security dimensions, incorporate multiple REC carriers in a multi-period setting, and explicitly represent political-risk-related diversification considerations within the supply-security dimension.

Table 2.1. Comparison of selected supply chain design studies considering global REC trade.

Author (Year)	Objective functions				Multiple RECs	Multi- period
	Economic	Environmental	Supply security	Others		
Zhuang et al. (2023)	min. total cost	—	—	—	—	—
Egerer et al. (2023)	min. total cost	—	—	—	—	—
Karbassi et al. (2023)	min. total cost	—	—	max. equity	✓	—
Hampp et al. (2023)	min. total cost	—	—	—	✓	—
Kim, A. et al. (2023)	min. total cost	min. emission cost	—	—	—	—
Makepeace et al. (2024)	min. total cost	min. emission cost	—	—	—	✓
Linsel and Bertsch (2024)	min. total cost	—	—	—	—	✓
Wan et al. (2024)	min. total cost	—	—	—	✓	✓
Amjath et al. (2025)	min. total cost	—	—	—	—	✓
Jansen et al. (2025)	min. total cost	min. emission cost	—	—	—	—
Alanazi et al. (2025)	max. profit	—	—	max. social welfare	—	—
Iseri et al. (2025)	min. total cost	min. emission	—	min. transportation risk	✓	✓

Note: ✓ indicates the feature is explicitly modeled in the study. — indicates not considered or not reported.

2.4 Energy Storage and Flexibility in REC Supply Chains

In addition to spatial flexibility via REC transport (global logistics), temporal flexibility via energy storage can address mismatches between renewable availability and demand (Suraparaju et al., 2025; Welder et al., 2018; Wolff et al., 2023). Producing RECs from variable renewable electricity (e.g., solar and wind) introduces time-varying availability across multiple time scales (IEA, 2024a), ranging from intra-day (hours within a day) to intra-year (weeks to seasons within a year) (IRENA, 2022; Jiang et al., 2025). Moreover, renewable electricity availability is uncertain and should be represented explicitly in REC supply chain design (Haas

et al., 2017). A robust REC supply chain design that includes appropriate energy storage portfolios can buffer variability and uncertainty in renewable inputs (Efthymiadou et al., 2025; Gorenstein Dedecca et al., 2025; Zhou et al., 2024). Storage portfolios may include technologies that differ in energy form, efficiency, charge/discharge limits, self-loss, capacity potential, and cost structure (Danish Energy Agency, 2018a; Guidehouse, 2021; Haas et al., 2017; Wolf et al., 2024; Zhang et al., 2025). For example, electricity storage (e.g., batteries) supports short-duration balancing; hydrogen storage (e.g., pressurized storage and underground storage) can cover large-scale, long-duration needs; and hydrogen-derivative storage (e.g., ammonia, LOHC) can leverage liquid infrastructures but introduces (re)conversion losses (Danish Energy Agency, 2018a; Reuß et al., 2017). System constraints, including geological and legal limitations on underground hydrogen storage, can also affect optimal storage choices (Guidehouse, 2021; Tarkowski and Uliasz-Misiak, 2022; Wietschel et al., 2024). Storage choices are therefore linked to carrier choice, conversion portfolios, and system constraints.

In supply chains with high shares of variable renewables, storage complements interregional transport and imports by enabling temporal balancing within the system. A flexible REC supply chain design therefore encompasses multiple interconnected stages: renewable electricity generation, hydrogen production, storage, transport, and delivery to end-use sectors (Almansoori and Shah, 2006; Li et al., 2019; Liu and Ma, 2024; Taghavi et al., 2026). While many models integrate a single storage technology or a small set of options (Fokkema et al., 2022; Li et al., 2024), several studies indicate that hybrid storage systems combining short-term and long-term technologies can overcome single-technology limitations and improve reliability and cost performance (Gabrielli et al., 2020; Khosravani et al., 2026; Wang et al., 2025).

Energy storage decisions in REC supply chains are often formulated using LP and MILP models to determine locations, capacities, and configurations of production, storage, and transport infrastructure while minimizing total system cost (Almansoori and Shah, 2006; Almaraz et al., 2024; Bozzolo Lueckel et al., 2025; Quarton and Samsatli, 2020; Yang et al., 2025). A prevailing approach assumes deterministic renewable availability profiles with coarse temporal resolution (e.g., seasonal or annual averages) (Wolff et al., 2023; Yu et al., 2025) or sizes storage using fixed days of autonomy assumptions (where storage covers a fixed number of days without renewable input) (Dayhim et al., 2014; Guerra et al., 2020). To represent variability while maintaining tractability, time decomposition is used in several studies (Wolff et al., 2023; Zhou et al., 2024). However, a robust design for optimal storage capacities,

locations, and operational strategies should also address uncertainty in renewable availability. A smaller body of work integrates uncertainty and its implications for storage sizing (Efthymiadou et al., 2025; Kim, S. et al., 2024; Yang et al., 2020), using approaches such as two-stage stochastic programming and chance-constrained programming (Efthymiadou et al., 2025; Yang et al., 2020).

Table 2.2 presents a selection of supply chain design studies considering energy storage in REC supply chain design. Overall, the reviewed studies show that existing models often either (i) rely on deterministic renewable availability representations with coarse temporal resolution or (ii) size storage using fixed autonomy assumptions or deterministic profiles. Only a small number of studies explicitly address uncertainty in renewable electricity availability and its implications for storage sizing, and these often rely on simplified temporal representations. Taken together, these gaps indicate the need for REC supply chain models that combine high temporal resolution, multiple hydrogen forms with compatible storage and transport options, and an explicit treatment of reliability under uncertain renewable electricity availability.

Table 2.2. Comparison of selected studies on supply chain design considering energy storage.

Reference	Multiple Storage Technologies	Hydrogen Storage Forms	Temporal Resolution	Spatial Resolution	Uncertainty Approach	Energy Storage Sizing Basis
Hassan et al. (2023)	—	G	I	—	—	DRA
Dautel et al. (2024)	✓	G	I	—	—	DRA
Li et al. (2024)	—	G	S	—	—	DRA
Sizaire et al. (2024)	✓	G	I	IRT	—	DRA
Vo et al. (2025)	✓	G, C	W	—	—	DRA
Gabrielli et al. (2020)	✓	G	I	—	—	DRA
Elberry et al. (2021)	—	G	I	—	—	DRA
Yu et al. (2025)	✓	G	D	IRT	—	DRA
Wolff et al. (2023)	✓	G	S	IRT	—	DRA
Guerra et al. (2020)	✓	G	I	—	—	DA
Le et al. (2023)	✓	G	I	—	—	DRA
Fokkema et al. (2022)	—	G	D	—	—	DRA
O'Neill et al. (2024)	✓	G	I	—	—	DRA
Kim, S. et al. (2024)	—	L	I	IMP	Stoch	SC
Efthymiadou et al. (2025)	—	G	I	IRT, IMP	Stoch	SC
Yang et al. (2020)	—	G	I	IRT	CC	SC

Note: ✓ indicates the feature is explicitly modeled in the study. — indicates not considered or not reported. G: gaseous; L: liquid; C: chemical; I: intra-day; D: daily; W: weekly; S: seasonal; Y: yearly; Stoch: stochastic; CC: chance-constrained; DRA: deterministic renewable availability profile(s); DA: days of autonomy; SC: scenario-based; IRT: interregional transport; IMP: import.

2.5 Policy Frameworks in REC Supply Chains

Achieving climate neutrality requires global coordination and ambitious measures that accelerate the transition to clean energy (IEA, 2021; IRENA, 2024a). Robust, binding policy frameworks at national and international levels are critical for moving from voluntary pledges to enforceable long-term strategies (Radtke and Renn, 2024). Policy frameworks are widely recognized as key drivers for accelerating REC deployment, directly addressing high upfront capital expenditures and bridging cost-competitiveness gaps relative to fossil fuels (Mamat et al., 2025; Montague et al., 2024; Olabi et al., 2023). Key aspects include sustainability criteria (e.g., GHG thresholds and land-use limits for biomass), certification (e.g., guarantees of origin), mandates (e.g., binding targets), and dependency-related constraints (e.g., import reliance) (Bube et al., 2025; European Commission, 2021b; Millinger et al., 2025; Zahid et al., 2025). As a result, policy measures shape market demand, guide technology selection, and foster infrastructure development (IRENA, 2024b; Taghipour et al., 2025).

Potential key policy measures influencing the development of REC supply chains include carbon pricing (by imposing the cost associated with emitting carbon dioxide), reducing GHG intensity (by obligations on maximum emissions permitted per unit of energy supplied), and REC share mandates (by obligations on a minimum fraction of the energy supplied to come from renewable sources) (European Commission, 2021a, 2021b, 2021c, 2021d; Taghavi et al., 2026). Effective policy combinations are therefore important for overcoming supply chain bottlenecks and reducing emissions (European Commission, 2021b; Hombach and Walther, 2015).

Integrating policy measures—such as carbon pricing, GHG-intensity targets, and renewable share mandates—into REC supply chain optimization can identify cost-effective pathways, accelerate technology deployment, and quantify emission reductions (Errendal et al., 2023; Esmaeili Aliabadi et al., 2023; Millinger et al., 2025; Wu et al., 2026). Modeling frameworks commonly represent a range of renewable resources, technology pathways (production, transport, and storage), and alternative RECs to evaluate system costs and emission savings (Millinger et al., 2019; Quarton and Samsatli, 2021; Solakivi et al., 2022). These supply chains interact with regulatory frameworks such as RED III, where GHG emissions accounting influences compliance and pathway attractiveness (European Commission, 2023). Multi-period long-term planning is therefore used to capture policy trajectories and the gradual tightening of targets and constraints (Hombach et al., 2016). In addition, technological change in costs,

efficiencies, and availability of production, transport, storage, and renewable generation technologies is often included to reflect learning and innovation over time (Dai et al., 2024; Danish Energy Agency, 2018b).

Integrating evolving policy frameworks into REC supply chain optimization provides a structured approach to capturing interactions between regulatory, economic, and environmental factors (Hombach et al., 2016; Teng et al., 2025). Policy-integrated REC supply chain designs are frequently modeled using LP and MILP to optimize network structure, including facility location, capacity planning, and multi-echelon flows under policy constraints (Ahmed and Sarkar, 2019; Quarton and Samsatli, 2021). These models typically optimize economic objectives (e.g., minimizing total system cost or maximizing profit) (Haji Esmaeili et al., 2020; Hombach and Walther, 2015). Policy measures can enter either the objective function (e.g., carbon pricing) or constraints (e.g., GHG thresholds) (Alizadeh et al., 2019; Gonela et al., 2015). Some studies adopt multi-objective optimization to investigate their trade-offs and evaluate the efficiency of different policy measures (Hombach et al., 2018; Hombach and Walther, 2015). Studies on policy timing generally indicate that early, consistent, and gradually tightening regulations support a more cost-effective transition (Hombach and Walther, 2015; Quarton and Samsatli, 2021; Wu and Lee, 2024). While studies frequently investigate a single policy measure in REC supply chain designs, some studies address a broad range of legal frameworks (Quarton and Samsatli, 2021) and large regions such as Europe (Solakivi et al., 2022). This is consistent with EU-wide policies that set binding targets and strengthen cross-border coordination requirements (European Commission, 2023; Hombach et al., 2016).

Table 2.3 presents a selection of studies assessing policy interventions in fuel supply chain development. Overall, the reviewed studies show that many focus on single policies (e.g., carbon pricing or renewable energy shares) and do not sufficiently capture broader policy frameworks and interdependencies. In addition, comprehensive studies covering diverse RECs supplied through multiple technology pathways and legal frameworks—particularly for large-scale case studies such as Europe—remain limited. Quantifying the effects of individual policy measures and their interactions on optimal REC supply chain design, including the relative efficiency of different policy combinations, is rarely addressed. Finally, only a small number of studies examine policy trajectory changes and technological advancement within long-term multi-period models. Taken together, these gaps indicate the need for multi-period REC supply

chain models that evaluate policy combinations, their interactions, and their timing effects in order to assess effective long-term transition pathways.

Table 2.3. Comparison of selected studies on assessing policy interventions in fuel supply chain development.

Authors	Multiple Policy measures	Multiple RECs	Multiple technology pathways	Multi-period	Technological advancement	Policy measures interaction
Gonela et al. (2015)	—	—	✓	—	—	—
Hombach and Walther (2015)	✓	—	✓	✓	—	SCA
Hombach et al. (2016)	✓	—	✓	✓	—	SCA
Najmi et al. (2016)	✓	✓	—	✓	—	—
Millinger et al. (2019)	—	✓	✓	✓	✓	—
Ahmed and Sarkar (2019)	✓	—	—	—	—	—
Alizadeh et al. (2019)	—	—	—	—	—	—
Hosseinalizadeh et al. (2019)	—	—	—	✓	—	—
Haji Esmaeili et al. (2020)	✓	—	✓	—	—	—
Quarton and Samsatli (2021)	✓	✓	✓	✓	—	—
Khalifa et al. (2022)	✓	—	✓	—	—	—
Solakivi et al. (2022)	✓	✓	✓	✓	✓	—
Ahmadvand and Sowlati (2023)	—	—	—	✓	—	—
Memari et al. (2023)	—	—	—	—	—	—
Munir et al. (2023)	—	—	—	—	—	—
Esmaeili Aliabadi et al. (2023)	✓	✓	✓	✓	—	SCA

Note: ✓ indicates the feature is explicitly modeled in the study. — indicates not considered or not reported. SCA: scenario analysis.

2.6 Research Gaps

Across the three themes reviewed in Chapters 2.3–2.5, the literature indicates that REC supply chain planning requires integrated models that jointly capture (i) spatial decisions for global trade and transport, (ii) temporal flexibility through storage under variable and uncertain renewable inputs, and (iii) policy-driven constraints and incentives that shape feasible

pathways. However, the corresponding modeling streams remain fragmented: many studies develop detailed insights for one decision lever while treating the others in a simplified way or as exogenous assumptions—for example, optimizing trade or infrastructure without representing risk and diversification objectives, sizing storage under deterministic renewable profiles with coarse temporal resolution, or analyzing policy measures without quantifying interaction and timing effects in long-term transition pathways. As a result, existing approaches provide only a partial representation of trade-offs between cost, environmental performance, security, and reliability, and offer limited guidance on how these targets translate into coordinated investment and operational decisions across space, time, and policy settings.

Building on these gaps, the dissertation focuses on three modeling requirements. First, REC trade models need to capture spatial coordination across exporting and importing regions while jointly evaluating economic, environmental, and supply-security dimensions. Second, REC supply chain models need to represent temporal flexibility through storage under variable and uncertain renewable availability, with sufficient temporal detail to assess reliability. Third, policy-oriented REC supply chain models need to represent policy measures explicitly in order to evaluate individual instruments, their interactions, and their timing in long-term transition pathways. These requirements motivate the research questions introduced in Chapter 1.2 and addressed in Papers I–III.

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Chapter 3

Research Methods

This chapter consolidates the methodological foundations used across this dissertation to answer the research questions introduced in Chapter 1.2. First, it outlines the common optimization-based strategic–tactical network design framework used to represent renewable energy carrier (REC) supply chains. Second, it introduces multi-objective optimization for cases in which economic, environmental, and supply-security perspectives must be considered jointly and motivates the use of the ϵ -constraint method with AUGMECON in Papers I and III. Third, it discusses optimization under uncertainty and explains why Paper II adopts a scenario-based, two-stage chance-constrained MILP to represent uncertain renewable availability and explicit reliability requirements. Methods not used are discussed only insofar as they clarify these methodological choices. Full mathematical formulations and implementation details are provided in Part II within each paper.

3.1 Strategic–Tactical Supply Chain Design Optimization

Across Papers I–III, REC supply chains are modeled as multi-regional networks that convert region-specific renewable resources into carriers and deliver them to region-specific demands. The network representation captures multiple echelons, including renewable electricity supply, production and synthesis, (re)conversion, storage, interregional transport, and exogenous imports (i.e., supply from outside the modeled system boundary). Technology portfolios may include multiple RECs and carrier-specific conditioning, storage, and transport options.

In order to represent long-term infrastructure planning and short-term system operation consistently, the models include both strategic and tactical decisions. Strategic decisions are associated with the long-term planning level and determine the fundamental structure of the supply chain. Because these decisions are difficult and costly to change once implemented, they have a lasting influence on system performance (Balaman, 2019; Pishvaei et al., 2021a). In the REC supply chain context, strategic decisions include the number, type, capacity, and location of production, (re)conversion, storage, and transport infrastructure and, where relevant, long-term exogenous import capacities or contracted quantities. Tactical decisions specify system operation given the installed infrastructure and therefore describe shorter-term adjustments

within the selected network structure (Balaman, 2019; Pishvae et al., 2021a). Tactical decisions include production levels, storage charging and discharging, inventory levels, and interregional transport flows.

Feasibility of the resulting network design is enforced through several classes of constraints. Mass and energy balances ensure accounting consistency by tracking inflows, outflows, conversions, and inventory changes across regions and time periods. Capacity constraints link operations to installed infrastructure so that tactical decisions remain feasible within the limits set by strategic choices. Resource availability constraints restrict the use of feedstock or renewable energy to region-specific potentials and, where relevant, time-specific availability. Technology availability constraints may limit adoption to feasible time periods in order to reflect technological advancement. Depending on the research question, additional constraints can represent policy requirements, sustainability criteria, security-related restrictions, or reliability targets.

Depending on the decision problem, the optimization framework may be formulated with a single objective or with several explicit objectives. In this dissertation, single-objective formulations are used when one performance dimension is primary, whereas multi-objective formulations are used when trade-offs between perspectives are themselves part of the problem scope. The corresponding methodological choices are described in Chapters 3.2 and 3.3.

3.2 Multi-Objective Optimization

Several planning problems addressed in this dissertation involve more than one relevant performance criterion. When these criteria are represented as separate quantitative objectives, the problem belongs to multi-objective decision-making; in mathematical programming terms, the relevant setting here is multi-objective optimization (MOO) (Ehrgott et al., 2026; Hwang and Masud, 1979). This is the case in Paper I, where economic, environmental, and supply-security perspectives must be considered jointly, and in Paper III, where economic and environmental outcomes are evaluated under different policy frameworks.

A feasible solution to a multi-objective problem is Pareto-efficient, or non-dominated, if no other feasible solution can improve one objective without worsening at least one other objective. The set of such solutions forms the Pareto frontier and represents the feasible trade-off structure of the problem (Ehrgott et al., 2026). For REC supply chains, this frontier is decision-relevant because it shows how improvements in one dimension, such as lower

emissions or higher supply security, are associated with changes in cost and infrastructure configuration.

Multi-objective methods are commonly distinguished by when decision-maker preferences are introduced (Hwang and Masud, 1979; Mavrotas, 2009). A priori methods require preferences to be specified before optimization, for example through weights, aspiration levels, or a strict priority order. A posteriori methods first generate efficient solutions and then allow the decision-maker to examine the trade-offs before selecting a preferred solution. Interactive methods alternate between optimization and preference elicitation during the solution process. For this dissertation, an a posteriori approach is most appropriate because the aim is not to impose preferences *ex ante*, but to make the trade-offs transparent and interpretable for strategic planning.

This choice also explains why several other MOO approaches were not adopted as the main framework. A priori methods such as weighted-sum, goal programming, and lexicographic optimization require weights, target levels, or a strict ranking of objectives before the feasible trade-off structure is known. In the context of this dissertation, this would require value judgments about the relative importance of cost, emissions, and supply security precisely in situations where the analysis is intended to reveal those trade-offs rather than presuppose them. Weighted-sum methods are also sensitive to objective scaling, while lexicographic optimization suppresses marginal trade-offs through strict priority ordering (Gass and Saaty, 1955; Jones and Tamiz, 2010; Vergara Rodríguez et al., 2025). Evolutionary algorithms such as NSGA-II and MOPSO can approximate Pareto frontiers for complex non-linear problems, but as heuristics they do not guarantee mathematically exact efficient solutions and are therefore less suitable for mixed-integer optimization models for strategic infrastructure planning where exact feasibility and transparent trade-off interpretation are required (Deb et al., 2002; Kadziński et al., 2017; Reyes-Sierra and Coello, 2006).

Among a posteriori methods, this dissertation adopts the ϵ -constraint method. In this approach, one objective is optimized while the remaining objectives are converted into constraints bounded by threshold values, denoted by ϵ (Ehrgott et al., 2026; Ehrgott and Ruzika, 2008). By varying these ϵ -levels across their feasible ranges, the method can be used to construct a representation of the Pareto frontier. For REC supply chain planning, this is particularly useful because environmental ambition, security requirements, or policy stringency can be expressed as explicit bounds, which is close to how real-world targets and regulatory requirements are

often formulated. In its classical form, however, it may also return weakly efficient solutions, which motivates the AUGMECON refinement.

To strengthen the classical ε -constraint method, Papers I and III use AUGMECON logic following Mavrotas (2009). The purpose of this augmentation is to reduce weakly efficient solutions. It does so by introducing slack variables for the constrained objectives and adding a very small augmentation term to the primary objective. As a result, the procedure supports a more reliable generation of efficient solutions and a clearer representation of the frontier. Recent reviews continue to identify AUGMECON as a robust and transparent benchmark for exact multi-objective optimization in mathematical programming (Böðvarsdóttir and Stidsen, 2025; Ehrgott et al., 2026).

Accordingly, Papers I and III use an ε -constraint framework with AUGMECON logic for three reasons. First, it avoids the need to specify a priori weights and is less sensitive to objective scaling than weighted-sum approaches. Second, it expresses environmental or supply-security ambition through explicit ε -levels, which are directly interpretable in planning and policy contexts. Third, the AUGMECON augmentation discourages weakly efficient solutions and supports a reliable representation of the Pareto frontier for the mixed-integer optimization models considered here. Stepwise variation of ε -levels therefore provides a transparent mapping from ambition levels to costs and infrastructure implications.

3.3 Optimization under Uncertainty

In REC supply chains, uncertainty is a structural driver of system design: ignoring variability and uncertainty in renewable inputs and broader system conditions (e.g., supply availability, demand, and operational constraints) can lead to solutions that perform poorly or violate feasibility under realistic operating conditions (Fan et al., 2022; Shabani and Sowlati, 2016). Uncertainty is treated explicitly in this dissertation when it is central to the research question. In Papers I and III, the primary aim is to analyze long-term transition pathways and trade-offs under deterministic assumptions, complemented by scenario and sensitivity analysis. In Paper II, by contrast, uncertain renewable electricity availability directly affects storage requirements, system design, and the cost of reliability. For this reason, uncertainty is modeled explicitly in Paper II.

Building on supply chain risk taxonomies, uncertainty in REC systems can be grouped into internal, network-related, and external risks (Pishvaei et al., 2021b). Internal risks include

uncertainty in technology performance and capital and operating costs. Network-related risks include demand uncertainty and supply-side resource uncertainty. External risks include environmental variability (weather), economic shifts (e.g., inflation), and socio-political factors (e.g., policy changes).

The mathematical representation of these risks depends on data availability and the type of uncertainty, commonly distinguished as randomness uncertainty, epistemic uncertainty, and deep uncertainty (Klibi et al., 2010; Pishvaei et al., 2021b). Under randomness uncertainty, historical data supports estimating probability distributions (e.g., wind speeds or solar irradiation). Epistemic uncertainty arises from limited knowledge, often requiring expert judgment (e.g., performance of emerging technologies). Under deep uncertainty, neither objective nor subjective distributions can be obtained, so uncertainty is represented through parameter bounds.

In this dissertation, the uncertain input considered explicitly is renewable electricity availability. Because long historical weather records are available, this source of uncertainty is treated as randomness uncertainty rather than as deep uncertainty. It is therefore represented through a finite set of scenarios derived from meteorological data, so that system design reflects not only average conditions but also the variability of renewable supply across the scenario set.

Several optimization frameworks can be used to address such uncertainty, balancing computational tractability and protection against risk (Habibi et al., 2023). Risk-neutral stochastic programming optimizes expected performance over a set of scenarios and is well suited to settings in which average performance is the primary concern (Birge and Louveaux, 2011). To capture the sequential nature of decision-making, two-stage stochastic programming with recourse is often employed. In this context, recourse refers to the model's ability to take corrective actions after the uncertainty has been realized: here-and-now decisions (e.g., investments) are fixed before the uncertainty is known, while wait-and-see decisions (e.g., operations) adapt to a specific scenario realization. Scenario set size and temporal resolution strongly affect computational effort, so practical implementations require a balance between uncertainty detail and model tractability (Nemirovski and Shapiro, 2004). The two-stage logic is relevant for REC planning because infrastructure investments must be decided before actual renewable availability is known, whereas dispatch and storage operation can respond to realized conditions (Pishvaei et al., 2021b).

However, expected-value stochastic programming does not by itself guarantee a required level of demand satisfaction. Robust optimization offers a stronger protection by requiring feasibility for all realizations within a predefined uncertainty set (Ben-Tal et al., 2009; Ben-Tal and Nemirovski, 1999). This can be attractive when absolute protection is required, but in renewable-driven planning it can also be overly conservative and may lead to oversized and economically inefficient systems (Fan et al., 2022; Nemirovski and Shapiro, 2004; Yuliu et al., 2026).

For Paper II, chance-constrained programming is the most appropriate framework because the research question is explicitly concerned with reliability. Chance-constrained programming (CCP), introduced by Charnes and Cooper (1959), allows constraints to be satisfied with a predefined confidence level. This framework acknowledges that enforcing absolute feasibility for every possible realization may be prohibitively expensive, allowing instead for a bounded probability of shortfall (Yang et al., 2020; Zhang et al., 2023). This is well aligned with supply planning under uncertainty, where absolute feasibility in all scenarios may be prohibitively expensive, but a defined service level is decision-relevant. In a scenario-based MILP formulation, the probabilistic requirement is approximated through a finite set of scenarios, which keeps the problem tractable for large-scale supply chain analysis (Nemirovski and Shapiro, 2004).

Paper II therefore adopts a scenario-based, two-stage chance-constrained MILP. This choice is justified by the randomness of renewable availability and by the need to represent reliability explicitly (Birge and Louveaux, 2011). Long-term infrastructure decisions are taken before renewable availability is known, while operational decisions adapt across scenarios after uncertainty is revealed. Compared with robust optimization, this approach avoids excessive conservatism, while compared with risk-neutral stochastic programming, it provides an explicit reliability guarantee. Reliability is represented through regional chance constraints requiring demand satisfaction in a subset of scenarios whose cumulative probability reaches at least the chosen confidence level. This formulation was selected because it directly matches the methodological requirement of Paper II: not to guarantee feasibility under every conceivable realization, but to quantify how stricter reliability requirements affect infrastructure design and cost under uncertain renewable availability. In this way, the model makes the cost of reliability explicit and allows the analysis of how storage, transport, and exogenous imports contribute to meeting higher service levels (Da Huo et al., 2021; Zare et al., 2024; Zhang et al., 2023).

Together, Chapters 3.1–3.3 provide the methodological backbone of the dissertation: a common strategic–tactical network design framework, an exact multi-objective approach for transparent trade-off analysis, and an uncertainty treatment that links renewable variability to explicit reliability requirements.

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Chapter 4

Key Findings

This chapter presents the key findings and methodological contributions of the three research papers that constitute the core of this cumulative dissertation. Taken together, Papers I–III develop and apply an integrated optimization-based framework for the design and evaluation of REC supply chains under (i) spatial resource–demand mismatches, (ii) variable and uncertain renewable availability, and (iii) evolving policy frameworks. Across all three papers, the models support strategic planning by jointly representing infrastructure investment and technology choice, operations consistent with technical constraints, and decision-relevant performance metrics (cost, GHG emissions, supply security and/or reliability, and policy outcomes).

Within this shared backbone, each paper extends the framework to address a distinct decision requirement: supply security in trade and import planning (Paper I), reliability under renewable-availability uncertainty (Paper II), and policy-driven transition pathways (Paper III). Paper I establishes the multi-objective foundation by introducing a mixed-integer quadratic programming (MIQP) model to evaluate trade-offs between cost, GHG emissions, and supply security in international trade. Paper II extends this perspective to account for operational reliability under uncertainty, utilizing a two-stage chance-constrained mixed-integer linear programming (MILP) framework. Paper III assesses the influence of evolving policy environments on supply chain development through a bi-objective MILP model combined with a comprehensive factorial analysis.

Across Papers I–III, this shared modeling backbone enables an integrated interpretation of how import portfolio choices (Paper I), flexibility portfolios (Paper II), and policy packages (Paper III) shape feasibility and performance in REC systems. While the case studies are mainly rooted in European contexts, the developed framework is modular and transferable to other regions, carriers, and planning contexts through adapted technology sets, boundary conditions, and decision metrics.

Figure 4.1 provides a structured overview of the three research papers and their interconnections within the dissertation’s overarching framework for REC supply chain planning. It summarizes,

for each paper, the specific research question, methodological approach, case-study scope, and key contribution in relation to the pillars of the energy transition (economic efficiency, environmental sustainability, supply security, and reliability). Chapters 4.1 to 4.3 then discuss the papers in detail with respect to their research questions, methodological approaches, and key findings.

Research Papers I–III Design and Optimization of Renewable Energy Carrier Supply Chains: Global Logistics, Energy Storage, and Policy Frameworks			
Designing and evaluating REC supply chains under spatiotemporal mismatches, uncertain renewable availability, and policy frameworks (RQ, overarching)			
	Research Paper I	Research Paper II	Research Paper III
Aim	Sustainable and Secure International REC Supply Chains (RQ a)	Reliable REC Supply Chains under Uncertain Renewable Availability (RQ b)	Impacts of Policy Measures on REC Supply Chain Development (RQ c)
Methodology	Optimization-based network design framework & Multi-objective optimization	Optimization-based network design framework & Optimization under uncertainty	Optimization-based network design framework & Multi-objective optimization
Case Study	REC imports from regions with high potential for renewable resources to Europe	Reliable RHSC design in a multi-country European case study	RFSC development in European transport sector
Key Findings	Compromise solutions provide transparent import portfolios balancing cost, emissions, and supply security.	Hybrid storage and spatial flexibility support reliable RHSC designs under uncertain renewable availability.	Policy-explicit optimization allows ex ante assessment of policy packages, revealing dominant effects and interactions.

Figure 4.1. Overview of the research papers constituting this dissertation. REC: renewable energy carrier; RHSC: renewable hydrogen supply chain; RFSC: renewable fuel supply chain; RQ: research question.

4.1 Research Paper I

Paper I addresses the strategic design of international REC import supply chains by responding to the research question: How should international renewable energy carrier trade be shaped to jointly optimize economic and environmental objectives while considering supply security? In other words, Paper I examines how optimal import portfolios change when supply security is treated as a decision objective alongside cost and GHG emissions, and how transparent compromise solutions can be selected from the resulting trade-off set.

This question matters because import strategies that are optimal under a single perspective can be systematically vulnerable under others. In practice, decision makers rarely seek a single optimal point; they require portfolios that remain defensible given competing constraints (affordability, climate targets, diversification requirements, and geopolitical exposure). To address this, Paper I develops a multi-period, multi-objective MIQP model that simultaneously minimizes total net present cost, cumulative GHG emissions, and supply-security risk. The MIQP formulation is used because the supply-security metric (HHI and its political-risk-weighted variant) is quadratic in import shares, while discrete technology and routing choices are represented with integer variables.

A key methodological innovation of Paper I is the integration of supply security as an optimization objective through a political-risk weighted HHI. Unlike traditional cost-minimizing models that assess risk *ex post*, the proposed formulation penalizes supply concentration and exposure to politically unstable regions directly within the optimization. It endogenously determines (i) export origins and trade quantities, (ii) supply chain routes and technology options, and (iii) the resulting system costs and emissions. The model covers the full supply chain from resource utilization in 23 potential exporting regions to Europe and includes 16 production and 8 transport technologies. Using the augmented ε -constraint method (AUGMECON), the study generates a Pareto frontier that makes the trade-offs between cost, sustainability, and supply security explicit. Paper I provides two key methodological contributions:

- Security objective integrated into optimization. Supply security is not only evaluated after optimization; it becomes a planning objective, enabling explicit trade-off exploration between cost, emissions, and security.
- Benchmark-compliant compromise selection. The Pareto set is mapped to an interpretable benchmark risk level derived from observed fossil import portfolios. Solutions meeting this reference level (within a numerical tolerance) form the benchmark-compliant set, from which a transparent compromise portfolio is selected.

The case-study results reveal that single-objective optimization induces extreme and often unattractive trade-offs. Cost-optimal designs tend to establish networks with concentrated supply and result in avoidable security exposure. In the cost-minimal solution, imports concentrate in a small subset of exporting regions, because low system costs dominate the objective. The result is a portfolio with high dependence on few exporting origins and thus high

exposure to geopolitical or disruption risks. In the cost-optimal solution (5.92 trillion €), imports concentrate on a few regions (e.g., Saudi Arabia and Chile), with hydrogen transported predominantly via pipelines ($\approx 87\%$) and complemented by Liquid Organic Hydrogen Carrier (LOHC) shipping for longer distances ($\approx 13\%$).

GHG-optimal designs can shift costs and still not guarantee robust supply security. The GHG-optimal solution prioritizes the lowest total GHG emission pathways. Depending on the geography of low-carbon potential and techno-economic assumptions, this can either diversify the portfolio or lead to dependence on few exporting regions. In this case study, the GHG-optimal solution is more concentrated (HHI 0.11 vs 0.07) and more exposed to political risk (political-risk weighted HHI 0.18 vs 0.10) than the cost-optimal solution. Shifting to the GHG-optimal solution reduces total GHG emissions by 12% but increases costs by over 230% and worsens security risk by 80% compared to the cost-optimal solution. This shift is due to a decision change toward distant, wind-rich regions (e.g., Peru and Nigeria).

Risk-optimal designs diversify export portfolios with substantial cost and GHG emissions consequences. When supply security becomes the explicit objective (minimizing the political-risk weighted HHI), the model substitutes part of low-cost but concentrated supply with diversified alternative exporting regions. The supply risk-optimal solution reduces the political-risk weighted HHI by about 90% (political-risk weighted HHI 0.01 vs 0.10) and also lowers concentration (HHI 0.02) but increases net present cost by about 190% and GHG emissions by about 63% relative to the cost-optimal solution. As priorities shift from cost to supply security, the optimal network structure evolves from concentrated pipeline routes to diversified LOHC and liquid hydrogen shipping networks.

Benchmark-compliant solutions provide interpretable policy options. Using the benchmark risk level—computed as the political-risk weighted HHI of a reference fossil import portfolio—Paper I highlights the subset of Pareto solutions that keep supply-security risk at this reference level. Within the benchmark-compliant set, the selected compromise portfolio lies about 5% above the minimal environmental objective. For this benchmark-compliant compromise portfolio, the total net present cost is 6.05 trillion € and total GHG emissions are 3.44 GtCO₂eq. Relative to the cost-optimal solution, it achieves substantially lower emissions at only a marginal cost increase while keeping supply-security risk within the benchmark risk level. The benchmark-compliant set and the compromise portfolio translate the Pareto frontier into policy-relevant candidate portfolios under an explicitly stated benchmark risk level. This compromise

portfolio offers a reproducible rationale for why a specific portfolio is recommended rather than selected subjectively. Overall, the compromise solution shows that meeting a benchmark-compliant security level while reducing GHG emissions relative to the cost-optimal case is feasible without moving to the most expensive extremes on the Pareto frontier. In the compromise solution, Peru and Chile together supply more than half of total REC imports, followed by Nigeria and Saudi Arabia, with political-risk weighting moderating the reliance on higher-instability exporters.

Paper I's contribution is transferable in three respects. First, the same framework can be used for other importing regions, renewable carriers, and time horizons because it relies on an explicit representation of (i) trade portfolios and (ii) comparable performance metrics. Second, the security objective can be extended by incorporating additional risk factors, such as geopolitical and technological disruptions, natural hazards, and corridor risks. Third, the benchmark-compliant compromise selection generalizes to other multi-objective planning problems where decision makers need transparent justification rather than a single optimal point. In such settings, the benchmark provides a practical reference level for risk that turns a Pareto set into an interpretable subset and a traceable recommended portfolio.

In summary, Paper I contributes a multi-period MIQP framework that enables the transition from single-perspective cost minimization to a multi-perspective trade strategy. The results highlight that while affordability (the cost-minimal solution) remains a prerequisite, significant improvements in security and sustainability are achievable through benchmark-compliant compromise portfolios.

4.2 Research Paper II

Paper II focuses on the operational and structural challenges of renewable hydrogen supply chains (RHSCs) under uncertainty, addressing the research question: How can a reliable renewable energy carrier supply be achieved by determining the capacities and technology mix of energy storage? Paper II examines how reliability targets (defined through a confidence level for demand satisfaction) translate into infrastructure capacities and operating strategies, and how temporal flexibility (hybrid storage) and spatial flexibility (interregional transport and exogenous imports) jointly support reliable supply.

This question goes beyond cost-optimal supply chain planning. A hydrogen system can be cost-efficient but fail under adverse renewable resource availability. Paper II therefore frames

hydrogen supply chain planning as a reliability-constrained design problem. The paper introduces a two-stage chance-constrained MILP framework that minimizes expected total annualized cost while enforcing regional supply reliability.

The primary contribution of Paper II is the explicit representation of uncertainty in renewable electricity availability (wind and solar) within a strategic network design model. The model employs a hierarchical time aggregation that captures both intra-day (diurnal) patterns and intra-year (seasonal) variability, ensuring that storage sizing reflects real-world operational needs. Paper II develops a chance-constrained, two-stage mixed-integer linear programming framework. The two-stage structure distinguishes between "here-and-now" investment decisions (capacities of production, transport, and storage technologies) and "wait-and-see" operational decisions (production and transport rates as well as inventory levels) that adapt to specific scenarios. Reliability is enforced through regional chance constraints, ensuring that demand is satisfied at a predefined confidence level. Reliability links a policy-meaningful requirement to concrete design outcomes. Paper II provides three key methodological contributions:

- Reliability as a binding requirement. Reliability is enforced within the optimization model rather than assessed only after a cost-optimal design is computed.
- Hybrid storage portfolios. The model endogenously selects storage technologies that serve complementary time scales (short-term buffering and seasonal balancing) across relevant energy forms and carriers.
- Joint quantification of temporal and spatial flexibility. Spatial flexibility is modeled as a distinct lever that, alongside temporal flexibility, mitigates geographic supply-demand imbalances across the network. The system responds to uncertainty by coordinating three key mechanisms: (i) interregional transport inside the modeled system boundary, (ii) bounded exogenous imports, and (iii) hybrid storage. The study quantifies the functional interdependencies between these levers, demonstrating how constraints on one mechanism alter the economic value—and in some cases, the technical necessity—of the others.

The application to a nine-country European case study for 2050 demonstrates that under predefined reliability requirements ($\pi=0.95$), renewable electricity generation and electrolysis dominate total system costs (75%), while storage and transport act as critical flexibility mechanisms.

Reliability targets impact both investment and operating decisions. The model aims to design the optimal supply chain so that demand is satisfied in scenarios whose cumulative probability mass is at least π in each region; unmet demand in the remaining scenarios is penalized. Therefore, increasing π tightens the demand-satisfaction requirement and leads to higher capacity deployment across the supply chain. Increasing the reliability target from 85% to 100% leads to a modest cost increase (from 54.1 to 56.8 bn €/year), reflecting higher capacity deployment and stronger use of external supply (i.e., interregional inflows and exogenous imports); in the extreme case ($\pi=1.00$), exogenous import flows are 92% higher than at the base case ($\pi=0.95$).

Integrating multiple storage technologies with distinct economic and technical characteristics leads to lower system reliance on exogenous imports. In the base case, LOHC and underground hydrogen storage (UHS) manage seasonal imbalances, while batteries provide short-term intra-day buffering. Restricting the storage portfolio significantly impacts the system; for example, excluding UHS increases exogenous imports by approximately 45% and raises total costs. In extreme scenarios with only one storage technology (e.g., only ammonia storage), the system shows higher total cost and stronger reliance on conversion and exogenous imports. These findings highlight the importance of representing multiple hydrogen carriers together with the associated (re)conversion steps and technologies as well as import flows.

Spatial flexibility and external supply significantly impact the optimal supply chain and can lead to infeasible solutions at very tight thresholds. A key insight is that high reliability targets can become infeasible if external supply is tightly limited. In particular, external-supply limits of 30% were infeasible at $\pi=0.95$, while an external-supply upper bound of 33% remains feasible but reduces external supply by 21% and increases total annualized cost by about 4% relative to the base case. This study also shows the complementary roles of interregional transport and exogenous imports. For example, tightening the exogenous import upper bound from 50% (base case) to 30% decreases exogenous imports by 39% and increases interregional transport by 18%, while total annualized cost changes by less than 1%.

Paper II contributes a reliability-explicit RHSC design framework that is transferable to other regional case studies. The chance-constrained approach proves superior to deterministic planning by capturing the "reliability-cost" trade-offs. It reveals that spatial flexibility (interregional transport and exogenous imports) and temporal flexibility (storage) are substitutes within certain thresholds. This framework can be extended along two directions: (i)

stronger coupling with power-system constraints and cross-border electricity interactions, and (ii) broader uncertainty sources (technology costs, demand, policy) in addition to renewable electricity availability. Importantly, the paper's decision-support contribution is not restricted to "hydrogen": the chance-constrained investment–operation logic is applicable to other infrastructure systems where reliability is politically mandated and uncertainty is structural.

In summary, Paper II shows that reliability is a key system element that requires coordinated planning of renewable generation, conversion, hybrid storage, interregional transport, and exogenous imports. The methodological integration of hybrid storage and interregional transport provides a robust basis for designing resilient energy systems that can withstand the inherent volatility of weather-driven resources. It provides a transparent mapping from reliability targets to design and cost outcomes. Paper II thus provides a reliability-explicit framework that links policy-driven confidence levels directly to infrastructure rollout.

4.3 Research Paper III

Paper III focuses on policy frameworks as a key driver of REC supply chain development and addresses the question: How can policy frameworks influence the development of REC supply chains and contribute to achieving climate-neutrality goals? Paper III investigates how policy instruments—individually and in combination—shape renewable fuel supply chain (RFSC) development over time, and how policy timing and instrument interactions influence cost-effectiveness and cumulative GHG emissions outcomes.

This question is critical because renewable fuel transitions are policy-driven. Policy instruments, including mandates, carbon prices, and infrastructure support, interact with each other across time and across supply chain stages. Paper III utilizes a multi-period bi-objective MILP model to balance net present cost against cumulative GHG emission savings over the 2025–2050 horizon.

A key methodological contribution of Paper III is the explicit embedding of multiple policy instruments—carbon pricing, GHG intensity reduction targets, and renewable fuel share mandates—directly into the optimization model. To understand the individual and combined effects of these measures, the study applies a factorial analysis with 64 distinct policy instances across four levels of ambition. This methodology enables the quantification of interaction effects, moving beyond single-instrument assessments. The case study encompasses the entire European transport sector (rail, road, aviation, and maritime) and includes diverse production

pathways and transportation technologies. Paper III provides three key methodological contributions:

- Policy-explicit modeling. Policy instruments are represented explicitly in the optimization problem as parameters and constraints, thereby endogenously shaping technology choice, capacity expansion, flows, and investment timing across the planning horizon.
- Attribution of main and interaction effects. Factorial design allows separation of dominant drivers from interaction effects. This is crucial because policy is typically deployed as a package rather than a single instrument.
- Evaluation of policy combinations against the Pareto frontier. Comparing policy measure combinations with the Pareto frontier reveals their relative performance and efficiency. In addition, the analysis of optimal policy trajectories highlights the importance of long-term policy design and collective policy effects.

The analysis demonstrates that policy is a prerequisite for renewable fuel deployment. In a purely cost-optimal scenario without integrating any policy measures, the rollout of renewable fuels is negligible. However, the CO₂-optimal solution shows that savings exceeding 16 GtCO₂eq are technically possible at a notably high total system cost. A delayed renewable fuel deployment in compromise solutions may lead to an additional 10 GtCO₂eq in cumulative GHG emissions compared to the CO₂-optimal solution. This result shows that earlier implementation of renewable fuels achieves higher cumulative GHG savings. Therefore, policymakers should introduce and escalate policy measures in a timely manner, ensuring that renewable fuel supply ramps up sufficiently to meet long-term climate goals (Quarton and Samsatli, 2021).

Furthermore, considering flexibility in RFSC design without mandating specific technologies or fuels allows multiple technology pathways for production and transmission of renewable fuels and helps explain why different policy combinations can yield similar objective values while implying different network configurations. The study identifies that policy-integrated solutions often are located near the Pareto frontier (average gap of 8%).

The factorial results identify carbon pricing as the dominant driver, explaining approximately 43% of cost variability and 40% of GHG emission savings variability. Crucially, policy interactions account for roughly 20% of the variance, particularly for GHG intensity reduction measures, suggesting that instruments must be co-designed to be effective. This analysis shows that policy measure combinations (e.g., medium levels of GHG intensity reduction goals, combined with medium levels of carbon pricing and renewable fuel share mandates) can lead

to moderate GHG emission savings. Therefore, combining policy measures avoids extreme scenarios, such as very high carbon prices without accompanying regulatory measures leading to burdensome energy costs for consumers, or overly stringent, inflexible energy policies (like very high renewable fuel obligations) that may be rejected by Member States due to their high costs for economic operators and consumers (European Commission, 2021).

The analysis of different policy trajectories identifies efficient policy combinations. A combination of a low increase in GHG intensity reduction and moderate increases in renewable fuel share and carbon pricing leads to a balanced economic and environmental solution with a small gap to the Pareto frontier (5%).

Paper III provides a general framework for policy evaluation in supply chain planning: (i) represent policy instruments as explicit model levers, (ii) evaluate policy measure combinations through factorial design to separate main and interaction effects, and (iii) report time-sensitive outcomes when cumulative GHG emissions matter. This approach is transferable across renewable energy carrier supply and across decision-making strategies where policy measures differ but the logic of interaction remains.

In summary, Paper III contributes a policy-informed MILP framework that quantifies the systemic impact of regulatory ambition. Paper III shows that renewable fuel supply chains must be evaluated under combinations of policy measures rather than isolated instruments. It contributes a policy-explicit optimization framework paired with factorial attribution, demonstrates that carbon pricing is typically a dominant lever, and shows that interactions and timing can materially shape cost-effective transition trajectories. The findings highlight that a moderate combined trajectory, integrating medium levels of multiple policy instruments, can deliver balanced economic and environmental outcomes while avoiding the disproportionate costs of an individual extreme policy measure.

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Chapter 5

Conclusion

This concluding chapter consolidates the dissertation's contributions and provides implications for planning and policy in renewable energy carrier supply chains. It returns to the overarching motivation: achieving climate-neutrality targets requires large-scale deployment of RECs, yet their deployment is constrained by (i) spatial resource–demand mismatches, (ii) temporal intermittency and uncertainty in renewable availability, and (iii) policy boundary conditions. Against this background, the dissertation develops optimization-based decision-support frameworks that (a) make trade-offs explicit, (b) link qualitative targets to quantitative infrastructure and operational outcomes, and (c) enable transparent evaluation of portfolios and policy packages.

The chapter is structured as follows. Chapter 5.1 summarizes contributions, emphasizing both transferable methodological advances and case-study insights. Chapter 5.2 discusses implications for system planning and policy design. Chapter 5.3 outlines limitations and future research directions.

5.1 Contributions

This dissertation advances REC supply chain planning by combining three complementary lenses into a coherent decision-support program: (i) international trade under economic, environmental, and supply security trade-offs (Paper I), (ii) reliable hydrogen supply chain design under renewable availability uncertainty (Paper II), and (iii) policy integration for renewable fuel supply chain development under economic and environmental trade-offs (Paper III). The core contribution is not only analytical breadth, but a consistent framing: each paper turns a policy-relevant requirement (security, reliability, policy) into an explicit model driver that can be traced to infrastructure and operational decisions.

Paper I contributes a framework that incorporates supply security through system design rather than descriptive *ex post* analysis. It demonstrates that reliance on single-objective cost optimization for international trade leads to extreme risks in supply security and emissions. It establishes that security must be an endogenous optimization goal to identify stable import portfolios. By integrating a supply-security objective and introducing a benchmark risk level,

Paper I identifies a benchmark-compliant subset of Pareto-efficient portfolios and selects a compromise portfolio within that subset. This enables justification against a real-world reference level rather than a subjective choice among Pareto points. It provides a methodological framework for selecting trade partners under explicitly stated policy preferences.

Paper II contributes a chance-constrained, two-stage planning framework that links a reliability confidence level directly to infrastructure and operations. The paper shows that reliability is achieved through coordinated investment in renewable generation, conversion, hybrid storage portfolios, interregional transport, and exogenous imports, rather than through any single lever. Paper II identifies feasibility thresholds that emerge when high reliability targets are combined with tight external supply dependency limits and restricted flexibility options. These thresholds are decision-relevant and help clarify when policy constraints are compatible and when they imply the need to relax certain limits, expand infrastructure options, or re-define reliability targets.

Paper III contributes a policy-explicit optimization framework combined with factorial design to quantify both main effects and interactions of policy instruments. The results show that carbon pricing is a dominant driver in many settings, but that interactions among instruments are central, and timing affects cumulative GHG emissions outcomes. Consequently, policy packages must be evaluated as combinations and trajectories rather than as isolated instruments. This contribution is methodological and practical, providing a structured framework to compare policy bundles and to explain which levers drive outcomes, which interactions matter, and where time-consistency is most important.

While each paper is founded in a specific application, the dissertation advances the state of the art by developing a transferable framework of optimization modules that can be adapted across carriers, regions, and planning contexts. Paper I provides benchmark-compliant compromise selection for multi-objective trade planning by translating the Pareto set into a benchmark-compliant set (defined at a benchmark risk level of the political-risk weighted HHI computed from observed fossil import patterns), supported by political-risk weighted diversification metrics for strategic sourcing. Paper II provides a chance-constrained investment–operation structure with hierarchical time aggregation to translate reliability targets into infrastructure and operational outcomes under renewable uncertainty. Paper III provides policy-explicit optimization combined with factorial attribution to quantify the main and interaction effects of

policy packages when timing matters. Therefore, these three modules translate the dissertation's overarching research question into traceable network-design outcomes by linking qualitative targets (security, reliability, and policy objectives) to explicit infrastructure and operational decisions.

Overall, the dissertation shows that REC supply chains are most informative when spatial and temporal flexibility are planned jointly under explicit security, reliability, and policy constraints. The resulting decision-support framework (i) quantifies trade-offs, (ii) identifies binding constraints and feasibility thresholds, and (iii) translates model outputs into actionable options for planners and policymakers.

5.2 Implications

The combined findings offer three primary implications for policy design and strategic infrastructure planning in REC supply chains.

First, import strategies should move beyond purely cost-optimal partnerships and be designed as balanced trade-offs among cost, GHG emissions, and supply security. In practice, this means identifying diversified portfolios that satisfy a clearly stated benchmark risk level (implemented as the political-risk weighted HHI) and then selecting a compromise portfolio from the benchmark-compliant set. The practical shift is from *ex post* screening ("is the cost-optimal solution too risky?") to transparent target-based design ("which portfolio meets the benchmark risk level with marginal cost and GHG emissions increase?"). In institutional settings, this enables clearer communication: recommended portfolios can be justified as consistent with the benchmark risk level rather than as a subjective choice among Pareto points.

Second, reliable renewable hydrogen supply requires joint planning of generation, storage portfolios, and spatial flexibility. Under renewable uncertainty, storage is not a standalone lever. Reliability emerges from coordinated investment and operation across renewable generation, conversion, hybrid storage, interregional transport, and exogenous imports. Restricting one lever increases the value of others and can create feasibility thresholds under high reliability targets. Therefore, reliability targets should be defined with constraints on exogenous imports and infrastructure options. Practically, this implies that reliability policy (e.g., reliability standards for hydrogen supply) should be paired with an infrastructure feasibility assessment. The same reliability target can imply very different costs and infrastructure needs depending on import limits, storage availability, and transport options.

Third, policy packages should be evaluated jointly and designed as time-consistent trajectories. Policy instruments interact, and timing affects cumulative GHG emissions outcomes. Policy design should therefore be evaluated as combined trajectories rather than as isolated measures and should aim to induce earlier deployment where cumulative savings are sensitive to rollout delay. A direct operational implication is that policy evaluation frameworks should report not only endpoint outcomes but also time-dependent metrics (e.g., cumulative GHG emissions), and they should make interaction effects visible so that package design does not rely on misleading single-instrument attribution.

For planning practice, the dissertation implies a three-step workflow: (1) state targets and benchmarks explicitly (cost tolerance, emission target, benchmark risk level, reliability level, import limits), (2) compute portfolio options using the appropriate model layer (trade, infrastructure flexibility, policy package), and (3) justify choices transparently using benchmarks, thresholds, and attributed policy effects. For policymakers, the actionable message is to specify clear tolerances and constraints, assess feasibility and trade-offs before setting binding limits, and evaluate policy measures as interacting packages with time-consistent trajectories.

5.3 Limitations and Future Research

While this work provides a robust foundation, certain limitations remain. First, security is quantified through stylized risk metrics and does not explicitly represent geopolitical regime shifts, endogenous disruption dynamics, or contract structures that could mitigate or exacerbate risk (e.g., long-term offtake contracts, diversification mandates, corridor-specific disruptions). As a result, the security objective should be interpreted as a structured proxy for exposure rather than a full model of geopolitical dynamics. Second, the temporal representation is intentionally kept tractable, and uncertainty is represented explicitly for renewable availability. The framework abstracts from full power-system interactions, including detailed grid constraints, dispatch coupling with other electricity demand, and cross-border electricity interactions. Additional uncertainty sources—technology cost distributions, demand uncertainty, and policy uncertainty—are not jointly represented in the core formulation, which may understate compound-risk effects. Third, it abstracts from distributional impacts and broader sustainability dimensions beyond GHG emissions (e.g., land or water use), and endogenous bottlenecks (e.g., permitting delays, supply chain constraints for critical materials) are not represented explicitly.

Hence, the results should be interpreted as decision-support insights on policy levers and interactions under modeled constraints, not as a complete socio-economic assessment.

Five research directions follow directly from these limitations and from the dissertation's cross-paper synthesis.

(i) Stronger coupling with electricity systems and cross-border electricity interactions to refine the valuation of spatial–temporal flexibility and to assess how grid constraints and market coupling shape reliable hydrogen supply chains.

(ii) Broader uncertainty modeling (technology, demand, policy, disruption dynamics) enabling combined robust–stochastic reliability analysis and stress testing of import portfolios and infrastructure designs under compound uncertainty.

(iii) Higher spatial and temporal resolution where feasible to represent binding capacity limits in grids or transport links, operational constraints, and localized bottlenecks more explicitly, while maintaining tractability through decomposition or advanced scenario reduction.

(iv) Extension of sustainability assessment beyond GHG emissions to land, water, biodiversity, critical materials, and distributional and social dimensions—particularly relevant for both import portfolios and renewable fuel policy packages.

(v) Integration of implementation constraints—permitting, financing, contracting, and institutional feasibility—so that benchmark-compliant compromise portfolios can be translated into actionable roadmaps with realistic deployment dynamics.

Part II: Cumulative Part of the Dissertation

Chapter 6

Multi-Objective Supply Chain Optimization of Renewable Energy Carrier Imports for Europe

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Abstract

The transition toward climate neutrality requires the adoption of renewable energy carriers (RECs). Spatial disconnects between renewable energy production in resource-rich regions and its utilization in resource-deficit regions create the need for supply chains that enable long-distance transport of RECs. To ensure sustainable REC supply chains, we must prioritize affordability, low environmental impact, and supply security. We propose a multi-period, multi-objective, mixed-integer quadratic programming model to design supply chains for importing RECs, including strategic decisions on exporting regions, resource allocation, and infrastructure for production and transportation. We evaluate economic, environmental, and supply-security aspects by minimizing net present cost, greenhouse gas (GHG) emissions, and a supply-security risk approximation measured as a political-risk-weighted Herfindahl–Hirschman index. A European case study shows that, compared with a cost-optimal solution, a supply risk-optimal approach reduces the supply-security risk index by 90% but increases cost by 190%, while a GHG-optimal solution reduces emissions by 12% at an additional cost of 232%. Hence, balancing cost, emissions, and supply-security remains essential for REC import planning. Our findings inform Europe's future REC imports, supporting decision-makers in shaping robust REC partnerships and facilitating Europe's transition to climate neutrality.

6.1 Introduction

Achieving climate neutrality aligned with the Paris Agreement requires global coordination and ambitious measures that accelerate the transition to clean energy (IEA, 2021; IRENA, 2024a). Several measures and technologies, including the use of renewable energy carriers (RECs), direct electrification, energy efficiency improvements, and carbon capture and storage, play significant roles in this transition (IRENA, 2024a). In particular, RECs (such as hydrogen, ammonia, and methane) are increasingly recognized as a promising pathway toward climate neutrality (European Clean Hydrogen Alliance, 2023; IRENA, 2020a; World Energy Council, 2021, 2022) in hard-to-abate industries such as heavy-duty transport, industrial processes, and high-temperature heat, where other solutions may be impractical or less cost-effective (IEA, 2019; IRENA, 2022b).

To meet growing projections for REC demand over the coming decades, international trade aimed at matching potential supply with demand is beginning to shape new global supply chains (IRENA, 2018, 2024c). Some regions with abundant solar irradiation and wind potential have a distinct advantage for producing RECs, making them potential exporters (DFF and DFR, 2021). As shown in Figure 6.1, regions such as South America, the Middle East, and Africa may become major exporters because of their resource potential (Galimova, Ram et al., 2023). Conversely, regions with limited renewable resource availability and REC production potential below domestic demand, such as Europe, will likely import RECs. These emerging international trading relationships necessitate establishing robust supply chains among regions (World Energy Council, 2021). Moreover, ensuring the long-term sustainability and reliability of REC supply necessitates a multifaceted perspective encompassing economic, environmental, and supply-security aspects (Rosa et al., 2022; World Energy Council, 2024).

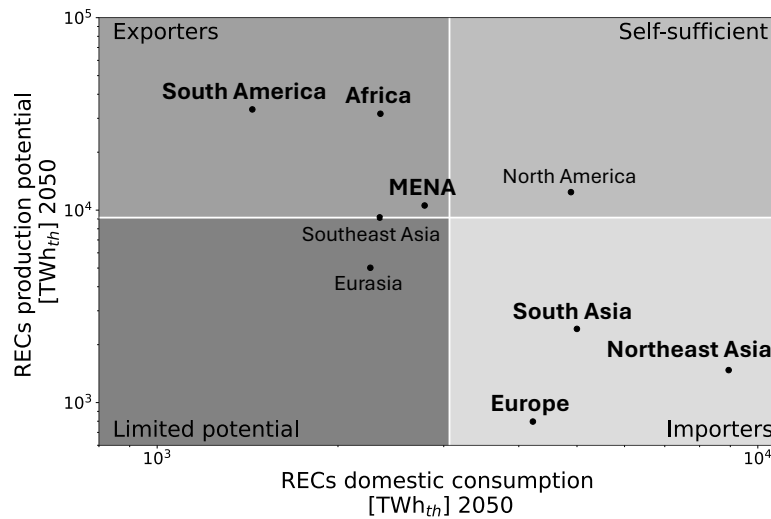


Figure 6.1. Comparison of selected regions based on REC consumption and production potential. Own illustration adapted from Galimova, Ram et al. (2023).

From an economic perspective, one of the key factors influencing the widespread adoption of RECs is their affordability (European Commission, 2025a). Affordability is typically assessed by lowering the overall system cost of the energy transition (Genge et al., 2023; Olabi et al., 2023), including the cost of production (The Danish Energy Agency, 2018a), transportation (Chen et al., 2023; Johnston et al., 2022; Schuler et al., 2024), and conversion infrastructure (Weichenhain, 2021). These costs vary depending on factors such as renewable resource quality, geographic location, and the logistical complexity of transporting RECs to import regions (Galimova, Ram et al., 2023). Although the supply of RECs requires significant upfront capital expenditure (IRENA, 2022d; World Energy Council, 2021), it is projected to become increasingly cost-competitive compared to fossil-based energy sources (IEA, 2019; Martin et al., 2023) as a result of technology improvements (IRENA, 2020b; Seymour et al., 2024), economies of scale (Breitschopf et al., 2022; IRENA, 2022c), and supportive policies (European Commission, 2021a; IEA, 2024).

From an environmental perspective, RECs offer significant advantages in reducing greenhouse gas (GHG) emissions compared to their fossil-based counterparts (European Commission, 2023; Galimova, Ram et al., 2023). Nevertheless, evaluating the overall climate impacts requires accounting for GHG emissions stemming from all stages of REC supply chains, including resource utilization, production processes, storage, and transportation (Bube et al., 2025; Liebich et al., 2021). Therefore, the design of REC supply chains should consider not only GHG emissions from infrastructure in exporting regions but also those arising from long-distance REC transportation as well as infrastructure in the importing region (Arrigoni et al., 2024; Cava et al., 2024; Zhao et al., 2024).

Beyond economic and environmental considerations, supply security also stands out as a critical factor for future REC development (Braun et al., 2023; Breitschopf et al., 2022; Carlson et al., 2023; Hank et al., 2023), particularly in light of recent geopolitical issues (Dalla Longa and van der Zwaan, 2024). Supply concentration (i.e., limited diversification) (Rosa et al., 2022) plays a crucial role in shaping supply security (Abdullah et al., 2021; Chalvatzis and Ioannidis, 2017; Liu et al., 2021). Reducing supply concentration can mitigate adverse effects stemming from disruptions (Zhu et al., 2023) (e.g., extreme weather events, geopolitical conflicts, pandemics, and terrorism) by enabling access to alternative sources of supply (Dejonghe et al., 2023; Vivoda, 2019). Consequently, creating partnerships with low-cost, reliable suppliers (Ansari and Pepe, 2023; Breitschopf et al., 2022; World Energy Council, 2022) represents an effective strategy for boosting supply security (Rosa et al., 2022).

In this context, establishing REC supply chains from resource-rich regions to import destinations requires significant investment in production and transportation infrastructure. Beyond economic perspectives, these supply chains must also address environmental and supply-security perspectives (World Energy Council, 2024), since mitigating GHG emissions (Kolb et al., 2022; Scheffler et al., 2025) and avoiding supply disruptions (e.g., the 1970s oil crisis or Germany's reliance on Russian gas) are crucial (Berger et al., 2022; GIZ, 2023; Kosai and Unesaki, 2020; World Energy Council, 2021). Consequently, decision-makers must balance economic, environmental, and supply-security objectives in planning REC imports.

Against this background, the goal of this paper is to investigate REC imports from regions with high renewable energy potential. We examine trade-offs in designing these supply chains using a multi-period, multi-objective mixed-integer quadratic programming (MIQP) model that optimizes economic and environmental objectives as well as a supply-security risk proxy. The supply-security objective introduces a quadratic term, while the remaining parts of the model are linear. Our aim is to identify optimal exporting regions, production and transportation technologies, and required infrastructure under three key objectives: net present cost, GHG emissions, and supply-security risk. We illustrate our model with a case study focused on REC imports from regions with high potential for renewable fuel production to Europe. The main contributions are:

- A multi-period MIQP model specifically developed for long-term REC import decisions that integrates a supply-security proxy alongside economic and environmental objectives in a multi-carrier supply-chain design framework.

- A detailed analysis of the trade-offs among supply chain costs, cumulative GHG emissions, and supply-security risk, highlighting cost-optimal, GHG-optimal, supply risk-optimal, and compromise solutions.
- An applied case study identifying viable regions for importing RECs to Europe, along with the requisite production and transportation infrastructure, adaptable to diverse importing regions.

6.2 Literature review

Numerous studies have explored how RECs can address global energy needs and support sustainability (World Energy Council, 2021). Building on the perspectives introduced in Section 6.1, we review existing methods for evaluating REC trade, categorizing the literature into assessment-based analyses (Sections 6.2.1–6.2.3) and prescriptive supply chain design approaches (Section 6.2.4). Sections 6.2.1–6.2.3 cover studies that evaluate REC trade from techno-economic, environmental, and supply-security perspectives, providing insights into each individual aspect. In contrast, Section 6.2.4 reviews optimization models for REC supply chains. Together, these literature streams provide the foundation for identifying gaps in current REC trade evaluations and supply chain design models. Section 6.2.5 synthesizes these gaps and derives the modeling requirements for our study.

6.2.1 Techno-economic assessment

Techno-economic analyses examine the technical feasibility and economic viability of REC trade (Badgett et al., 2025; Fakhreddine et al., 2025). Many studies compare renewable resources, production processes, and transport technologies, covering route-level transport costing (Johnston et al., 2022; Makepeace et al., 2024), regional supply cost comparisons (Liebich et al., 2021; Rezaei et al., 2024; Seck et al., 2022), and global trade potential assessments (Kenny et al., 2024; Moritz et al., 2023; Pieton et al., 2023). For instance, Fasihi et al. (2017) evaluated the feasibility and cost-effectiveness of exporting renewable fuels from the Maghreb region to Europe. Villalba-Herreros et al. (2023) used a techno-economic model to assess large-scale hydrogen distribution, accounting for production, conversion, transportation, and reconversion steps. Galimova, Fasihi et al. (2023a, 2023b) compared the costs of importing RECs (e.g., ammonia or hydrogen) with those of local production in the importing region. Abdelshafy et al. (2024) investigated strategic cost drivers shaping global hydrogen markets.

Several studies emphasize future scenarios and technology comparisons. Using Monte Carlo simulations, Wolf et al. (2024) estimated future levelized hydrogen costs across regions,

identifying cost-effective green hydrogen import partners for Germany by 2050. Sterner et al. (2024) performed a technical comparison of 19 hydrogen import pathways, covering various carriers such as ammonia, methanol, and liquid organic hydrogen carriers (LOHCs), in terms of efficiency and technological readiness. Seeger et al. (2025) presented a detailed techno-economic evaluation of hydrogen import routes from Algeria, Chile, and Canada to Germany, examining costs and logistical challenges in different years. Egli et al. (2025) explored the economic feasibility of exporting hydrogen from Africa to Europe using geospatial cost models under different interest-rate and policy scenarios for 2030.

Overall, these techno-economic studies highlight the crucial role of cost drivers such as production technologies, resource availability, and transport technologies in shaping the competitiveness of REC trade. However, most of these works focus on technical feasibility and economic viability, often neglecting broader environmental impacts or supply-security considerations. This gap highlights the importance of evaluating environmental (Section 6.2.2) and supply security (Section 6.2.3) dimensions alongside economic factors.

6.2.2 Environmental assessment

Environmental assessments quantify the impacts of REC trade, most prominently life-cycle GHG emissions across production and transport chains (Fakhreddine et al., 2025). GHG emissions stand out as a key impact category in regulations such as the Green Hydrogen Standard (international), EU Taxonomy Directive (Europe), Clean Hydrogen Production Standard (USA), Low Carbon Hydrogen Standard (UK), Japan Hydrogen Society Promotion Act (Japan), and China Hydrogen Alliance's Standard (China) (Bube et al., 2025). Accordingly, many studies quantify the GHG emissions of REC production, transport, and use to estimate overall climate impact (Fakhreddine et al., 2025). For instance, Liebich et al. (2021) analyzed the environmental impacts of imported RECs to Germany, considering differences in regional renewable resources, production pathways, and transportation technologies. Kolb et al. (2022) compared the GHG emissions of liquefied hydrogen imports from Chile, Canada, and Morocco to Germany. Kockel et al. (2024) assessed GHG emissions for different hydrogen production processes and import routes (via ships and pipelines) to Germany, quantifying their global warming potential. Kwak et al. (2025) evaluated multiple hydrogen import supply chains, highlighting the influence of transport distance and electricity mix on total GHG emissions.

In addition, several studies evaluate REC supply chains from both techno-economic and environmental perspectives simultaneously. Lee et al. (2022) analyzed hydrogen supply chains from both economic and environmental perspectives and found that efficiency improvements

and renewable energy integration can reduce costs and emissions. Sayer et al. (2024) performed a comparative analysis of different hydrogen supply chains from North Africa to Europe, examining trade-offs between economics and environmental impacts. Similarly, Carels et al. (2024) analyzed hydrogen import scenarios, considering both techno-economic costs and the associated GHG emissions. Scheffler et al. (2025) quantified the emissions of shipping RECs from Tunisia and Australia to Germany in 2030, demonstrating that transportation modes and production processes can significantly influence net emissions. Al-Ghussain et al. (2025) conducted a global multi-objective assessment of renewable hydrogen production, jointly evaluating techno-economic performance and life-cycle GHG emissions.

Taken together, these environmental studies demonstrate the importance of integrating GHG emissions considerations into REC supply chain planning, showing that focusing only on costs may overlook important environmental implications.

6.2.3 Supply security

Beyond economic and environmental considerations, supply security—commonly framed as the likelihood of supply disruption—is a core concern in international energy trade (Chalvatzis and Ioannidis, 2017; Li, Ng et al., 2023; Xun et al., 2022) and is increasingly emphasized for REC trade (Rosa et al., 2022), especially in light of recent geopolitical energy crises (Dalla Longa and van der Zwaan, 2024). Supply security is often assessed using concentration indicators such as the Herfindahl–Hirschman Index (HHI) (Brezina et al., 2016; Chalvatzis and Ioannidis, 2017; Sun et al., 2021). HHI-based measures have been applied in energy-security contexts (Rosa et al., 2022) (e.g., liquefied natural gas trade (Zhu et al., 2024)) and in commodity-trade risk contexts (NSTC, 2016) (e.g., phosphorus (Li, Ng et al., 2023) and cobalt (Liu et al., 2022)). High concentration (low diversification) in supply, indicated by a high HHI, correlates with greater vulnerability to disruptions (Abdullah et al., 2021; Chalvatzis and Ioannidis, 2017; Rosa et al., 2022). For instance, Vivoda (2019) studied market concentration in liquefied natural gas (LNG) imports for major importers such as China, India, Japan, South Korea, and Taiwan. Li, Li et al. (2021) assessed trade risks for countries importing copper materials by calculating HHIs of supplier shares. Liu et al. (2021) combined network analysis with HHI to study global rare metal trade. Li, Ng et al. (2023) evaluated phosphorus import exposure using HHI, recommending diversification strategies to improve supply security.

Although the concentration of supply reflects source diversity, it can be complemented by qualitative factors like political stability and geopolitical risk (Carmon et al., 2025; Xun et al., 2022), consistent with broader multi-dimensional energy security and dependency index approaches (Cappelli and Carnazza, 2023; NSTC, 2016). Therefore, several studies apply

politically weighted versions of HHI that integrate geopolitical instability (Colucci et al., 2025; Vidal et al., 2020). For instance, Wei et al. (2024) analyzed long-term supply risks of several bulk commodities for China, Japan, and the U.S., using an HHI adjusted for the political risk of supplier countries. Lekavičius et al. (2024) evaluated European energy import diversification by integrating political stability indices into HHI calculations. Kim, J. et al. (2025) similarly assessed the supply security of green energy for countries including Canada, Germany, and Japan using an HHI adjusted for political risk.

However, while politically weighted diversification metrics are well established in assessment studies, their integration into prescriptive REC supply-chain optimization, particularly in multi-period, multi-carrier settings with endogenous infrastructure decisions, remains limited. This motivates optimization approaches that include a political-risk-weighted HHI proxy when designing long-term REC import portfolios.

6.2.4 Mathematical modeling approaches

In contrast to assessment-focused studies, supply chain optimization models have been employed to design REC trade networks and infrastructure, typically optimizing various objectives (e.g., economic and environmental) (Fakhreddine et al., 2025). However, most studies have focused on a single objective function, typically cost minimization, when designing REC trade supply chains (Fakhreddine et al., 2025). For instance, Zhuang et al. (2023) developed a cost minimization model to evaluate offshore wind-based hydrogen trade among 15 Asia-Pacific countries (a regional network). Egerer et al. (2023) developed a comprehensive optimization framework for green ammonia supply chains, integrating hydrogen production, ammonia synthesis, storage, and transport. Wang et al. (2023) constructed a MILP model to design a cost-effective global ammonia network for maritime fuel use. Linsel and Bertsch (2024) introduced a global hydrogen transport model emphasizing the integration of international hydrogen trade. Wan et al. (2024) applied an optimization model to study China's roles in future REC trade, minimizing total supply chain costs.

While most models emphasize economic efficiency, some recent studies have expanded their scope to include sustainability perspectives (Alanazi et al., 2025; Karbassi et al., 2023; Kim, A. et al., 2023). For instance, Alanazi et al. (2025) modeled the long-term evolution of hydrogen trade by introducing country-specific supply and demand curves, maximizing overall social welfare. Karbassi et al. (2023) proposed a bi-objective optimization model demonstrating trade-offs between economic efficiency and equitable distribution (via a Gini coefficient) for multiple RECs exported from Africa in a Pareto-efficient frontier, balancing these perspectives. Kim, A. et al. (2023) implemented a MILP model for REC trade, aiming to

minimize total cost including investment and operating costs as well as carbon taxes, reflecting environmental assessment. Similarly, Makepeace et al. (2024) incorporated carbon costs as a policy measure, thus evaluating both economic and environmental factors. Jansen et al. (2025) proposed an import supply model that minimized a combination of cost and transport-related emission costs, while enforcing supplier diversity via constraints (e.g., requiring a minimum number of supply partners and limiting each partner's share). These multi-objective approaches illustrate methods to account for environmental impacts and supply security within an optimization framework, but models that simultaneously optimize economic, environmental, and supply-security objectives remain scarce.

Many models use a single period representation for future REC trade (Egerer et al., 2023; Kim, A. et al., 2023). For instance, Egerer et al. (2023) studied ammonia trade between Australia and Germany in 2030, and Kim, A. et al. (2023) analyzed hydrogen trade for 2030, 2040, and 2050. However, multi-period frameworks are needed to capture changes in demand and supply chain developments over time (Amjath et al., 2025; Wan et al., 2024). Wan et al. (2024) proposed an optimization model of REC trade dynamics from 2024 to 2050 on an annual basis. Amjath et al. (2025) developed a multi-period model for Qatar's hydrogen export supply chain over two decades, capturing how optimal decisions shift as demand and costs evolve. By modeling multiple time steps, multi-period models can capture the gradual scaling of REC production capacity and infrastructure deployment, as well as technological improvements over decades.

Some studies examine only one REC type, such as ammonia-only trade (Egerer et al., 2023), or compare alternative hydrogen carrier chains in separate scenarios (e.g., liquefied hydrogen, ammonia, LOHC) (Zhuang et al., 2023). Some models include multiple energy carriers such as hydrogen, methane, and Fischer–Tropsch fuel (Karbassi et al., 2023; Wan et al., 2024), and different forms such as liquid and gaseous hydrogen (Amjath et al., 2025; Hampp et al., 2023), highlighting the role of integrated infrastructure. Multi-commodity modeling can reveal synergies such as shared infrastructure or flexible production pathways, which single-commodity models miss.

REC supply chain modeling ranges from regionally scoped network design studies to global trade models (Fakhreddine et al., 2025). Regional studies typically focus on a set of countries (or regions) and resolve carrier pathways and infrastructure choices under local techno-economic assumptions and region-specific constraints (Egerer et al., 2023; Heuser et al., 2019). For instance, Zhuang et al. (2023) analyzed offshore-wind-based hydrogen across the Regional Comprehensive Economic Partnership economies. Kim, S. et al. (2024) compared international

green hydrogen and ammonia supply chains using a high-resolution, multi-timescale optimization framework. Wan et al. (2024) considered China's subregional potential for hydrogen trade to investigate the intra-China REC trade patterns and required infrastructure. Gado et al. (2025) assessed REC production across multiple sites in Egypt, showing how location-specific renewable resource conditions and infrastructure requirements shape techno-economic performance. In contrast, global models expand the set of regions and routes across continents to capture intercontinental competition and matching of supply and demand (Alanazi et al., 2025; Wang et al., 2023). Runge et al. (2023) compared the economics of traded renewable e-fuels produced in low-cost supply regions and delivered to end-use markets, and Makepeace et al. (2024) quantified green hydrogen export costs, highlighting how location advantages and long-distance logistics shape delivered costs. Taken together, global supply chain models are well suited to identify robust import portfolios and cross-basin diversification options, because comparing exporters across continents under decarbonization pathways depends on worldwide resource heterogeneity, costs, and intercontinental logistics. At the same time, many global studies rely on aggregated regions and logistics and therefore overlook detailed regional constraints (e.g., inland transport and port access). In contrast, regionally scoped network design studies can represent local heterogeneity and infrastructure constraints in more detail, but they may miss cross-basin substitution opportunities and intercontinental competition effects that shape delivered costs and diversification options for international trade (Alanazi et al., 2025; Hampp et al., 2023).

International REC supply chains are assessed from both import-oriented and export-oriented perspectives. Import-oriented studies examine how an importing region can meet demand through alternative carriers, routes, and trading partners (Hampp et al., 2023; Kim, A. et al., 2023). For example, Hampp et al. (2023) compared multiple REC import chains to Germany based on delivered costs across carriers and exporting regions. Kim, A. et al. (2023) investigated overseas hydrogen supply chains for Korea, Japan, and Germany by jointly considering economic and environmental performance. In contrast, export-oriented studies take the exporter as the decision-maker and emphasize export planning, including supply chain infrastructure, shipping pathways, and capacity expansion over time (Amjath et al., 2025; Karbassi et al., 2023). For instance, Amjath et al. (2025) developed a multi-period optimization model for Qatar that designs alternative hydrogen export pathways (e.g., ammonia, liquefied hydrogen, compressed hydrogen) across the export supply chain. Karbassi et al. (2023) investigated exports from Africa and highlighted the continent's strong export potential. Overall, these perspectives motivate an import-oriented modeling choice for our study:

identifying robust import portfolios for Europe requires comparing delivered costs and sustainability and security trade-offs across exporters and routes, while still enforcing exporter-side constraints (resource potential, technology options, and logistics) to ensure feasible and comparable solutions.

These patterns motivate the integrated multi-objective, multi-period research gap synthesized in Section 6.2.5.

6.2.5 Research gap

Table 6.1 summarizes several studies that use supply chain optimization models to investigate REC trade, highlighting their objective functions and scopes. As shown, none of the reviewed studies comprehensively addresses economic, environmental, and supply-security objectives simultaneously, nor do they incorporate political-risk-weighting for supply diversification. Additionally, only a few studies consider multiple carrier types over a long-term planning horizon.

Table 6.1. A summarized comparison of selected supply chain design studies considering REC trade.

Author (Year)	Objective functions				Multiple RECs	Multi- period	Trade perspective
	Economic	Environmental	Supply security	Others			
Zhuang et al. (2023)	min. costs						Import-oriented
Egerer et al. (2023)	min. costs						Export-oriented
Karbassi et al. (2023)	min. costs			max. equity	✓		Export-oriented
Hampp et al. (2023)	min. costs				✓		Import-oriented
Kim, A. et al. (2023)	min. costs	min. emission costs					Import-oriented
Makepeace et al. (2024)	min. costs	min. emission costs				✓	Export-oriented
Linsel and Bertsch (2024)	min. costs					✓	Import- and export-oriented
Wan et al. (2024)	min. costs				✓	✓	Import-oriented
Amjath et al. (2025)	min. costs					✓	Export-oriented
Jansen et al. (2025)	min. costs	min. emission costs					Import-oriented
Alanazi et al. (2025)	max. revenues			max. social welfare			Import- and export-oriented
This study	min. costs	min. GHG emissions	min. supply security risk		✓	✓	Import-oriented

Note: ✓ indicates that the feature is explicitly modeled in the study.

Although these studies provide valuable insights into global REC trade, critical gaps remain. First, there is a lack of multi-objective approaches that combine economic, environmental, and supply-security aspects. Second, only a few studies examine multiple REC carriers within a long-term (multi-period) planning framework. Third, the explicit integration of political-risk metrics into REC supply chain design remains limited. To address these gaps, we develop a multi-objective optimization model that combines all three objectives in a single framework. Our model simultaneously minimizes total cost and GHG emissions and includes a political-risk-weighted HHI proxy as a third objective for supply-security risk. While weighted diversification metrics are used in assessment studies, their formulation as an endogenous objective in multi-period, multi-carrier REC supply-chain optimization with infrastructure decisions remains limited. This model encompasses a broad range of production processes and transportation technologies including both conversion in exporting regions and reconversion in the importing region, and can analyze supply chains for multiple RECs delivered to a specific importing region. It identifies REC exporting regions and the associated infrastructure needed to enable REC trade. We demonstrate this approach with a case study that explores the import of several RECs into Europe from diverse exporting regions, illustrating its practical relevance and applicability.

6.3 Methodology

To capture the economic dimension of the REC supply chain, we consider the net present cost of establishing and operating the supply chain, including resource utilization, production, and transportation. By including GHG emissions arising from the REC supply chain as a key environmental measure (Bube et al., 2025; Quarton and Samsatli, 2021), we account for environmental sustainability in REC supply. Moreover, integrating a supply-security objective based on a political-risk-weighted HHI proxy captures supply-security risk in a tractable way and enables its endogenous integration into the multi-period, multi-carrier REC import optimization problem. Hence, the model's objective functions aim to minimize (1) net present cost, (2) GHG emissions, and (3) supply-security risk. Consequently, Pareto-efficient solutions provide trade-offs among these goals and identify alternative REC import supply chains.

6.3.1 Supply chain for importing RECs

We consider a set of regions ($i \in I_0$), which includes an importing region (i_0) that seeks to meet part of its future energy needs through RECs supplied from various potential exporting regions ($i \in I$). Figure 6.2 illustrates a broad supply chain design for all regions ($i \in I_0$), including

potential renewable energy resources, production pathways, and transportation technologies to deliver RECs to the importing region.

Resource origins ($o \in O$) in exporting regions act as supply points in the REC supply chain. They include exogenous resources ($o \in O \setminus O^e$) (e.g., freshwater, point-source CO₂), which are treated as demand-driven, and endogenous renewable electricity resources ($o \in O^e \subset O$) (solar and wind), whose infrastructure can be expanded within the model. Resource origins enable the production of resources ($m \in M$), including intermediates (e.g., nitrogen) and RECs ($m \in M^r \subset M$). The efficiency of renewable electricity ($o \in O^e \subset O$) varies depending on regional wind and solar potential. Renewable electricity can be used in water treatment units, air separation units, CO₂ capture units (direct air capture (DAC)), electrolysis units, and production and (re)conversion units. We model the production and (re)conversion of resources, such as demineralized (DM) water, nitrogen, atmospheric CO₂, and LOHC-based hydrogen, through process decisions in each region (black arrows in Figure 6.2).

Various technological pathways apply to production processes ($p \in P$) in the exporting regions, as well as reconversion processes ($p \in P^c \subset P$) in the importing region. Imported RECs can either be directly consumed or be reconverted to meet specific demand requirements. Accordingly, the model determines optimal transportation infrastructure and import quantities of RECs (blue arrows in Figure 6.2). In addition, renewable electricity ($o \in O^e \subset O$) in the importing region can also be used for reconversion processes ($p \in P^c \subset P$).

Among all resources ($m \in M$), we consider the import of RECs ($m \in M^r \subset M$) via a range of plausible transportation technologies ($q \in Q$) compatible with material characteristics, distances, and routes, including ships ($q \in Q^s \subset Q$) and pipelines ($q \in Q^d \subset Q$). Ship types ($q \in Q^s$) and pipeline types ($q \in Q^d$) differ in capacity, cost, and transported REC quantity. Since we evaluate REC trade in this study, the import of non-REC resources ($m \in M \setminus M^r$) is not considered. Each transportation process consumes a fraction of the RECs, for example, as fuel for compression (pipelines) or propulsion (shipping). We incorporate demand for RECs of all regions ($i \in I_0$), including both exporting regions and the importing region. In exporting regions ($i \in I$), we ensure that these regions satisfy their own domestic REC demand first (trapezoid “Domestic REC Demand” in Figure 6.2), with only the remaining surplus available for export. In the importing region (i_0), the model aims to satisfy the demand for imported RECs from exporting regions (trapezoid “Import REC Demand” in Figure 6.2).

We adopt a multi-period (annual) planning horizon ($t \in T$), acknowledging the need for gradual scaling of REC production as well as potential technological improvements in cost, capacity, and efficiency over time. Within this framework, we make strategic decisions regarding infrastructure rollout in each exporting region (e.g., number, size, and types of facilities), the transportation technologies required for importing RECs, and reconversion units in the importing region.

The full notation (sets, parameters, and decision variables) is reported in the Supplementary Information (Table 6.B.1).

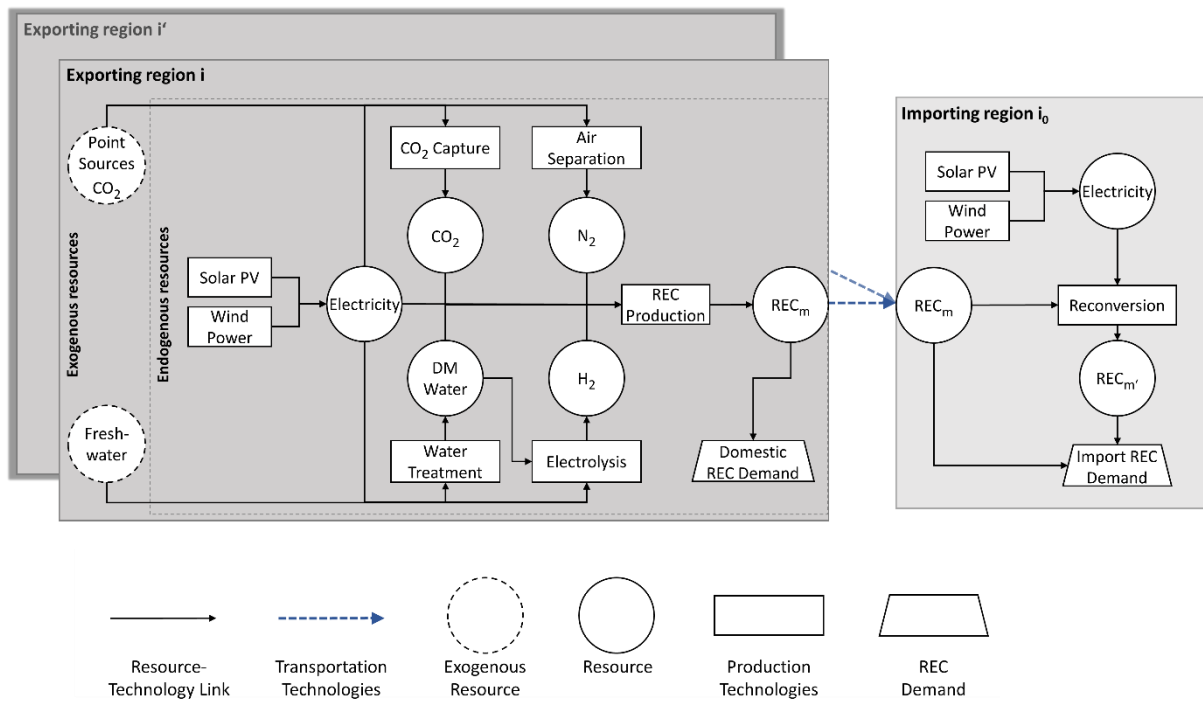


Figure 6.2. Schematic structure of the international REC supply chain.

6.3.2 Model formulation

We present a mathematical optimization model that encompasses economic, environmental, and supply-security aspects of a REC import supply chain, identifying promising exporting regions for multiple REC alternatives. By minimizing net present cost, cumulative GHG emissions, and supply-security risk over the long-term horizon, the model determines optimal designs for REC imports.

6.3.2.1 Total net present cost

As shown in Equation (1), net present cost includes investment and operating costs for production and transportation, as well as variable costs for resource utilization within the supply

chain. We apply a discounting factor τ to all cost terms throughout the planning horizon to make incurred costs at different planning periods comparable.

Equations (2) to (3) calculate the investment and operating costs for production technologies. The cost terms $C_t^{inv,p}$ and $C_t^{op,p}$ denote the investment and annual operating costs for production technologies (e.g., a methanation plant) in period t . These are auxiliary cost components that depend on the decision variable δ_{pit} , the number of installed plants of technology p in region i and period t .

Equations (4) to (8) address the investment and operating costs of transportation technologies, distinguishing pipelines from ships due to their distinct cost structures. The cost terms $C_t^{inv,d}$ and $C_t^{op,d}$ denote investment and annual operating costs for pipeline transportation technologies in period t , based on the number of pipelines κ_{qit} built from exporting regions. The cost terms for shipping transportation $C_t^{inv,s}$, $C_t^{op,s}$, and $C_t^{var,s}$ denote investment, annual operating, and variable costs for ship-based transportation technologies in period t , respectively. The variable shipping costs consist of a distance-independent cost $u_q z_{qmit}$ and a distance-dependent cost $u_q^{dist} l_i^{inland} z_{qmit}$ for inland transportation in exporting regions.

Equations (9) to (11) calculate the investment and operating costs for renewable electricity generation as well as the utilization cost of resource origins. The cost terms $C_t^{inv,o}$ and $C_t^{op,o}$ denote investment and annual operating costs for renewable electricity technologies in period t , based on the installed capacity σ_{oit} of technology o in region i . The cost of resource utilization (e.g., freshwater) in period t , $C_t^{var,o}$, is obtained by multiplying the resource utilization rate w_{oit} by the corresponding unit resource cost π_{oit} .

$$Z_1 = \sum_{t \in T} \frac{1}{(1 + \tau)^{(t-t_0)}} [C_t^{inv,p} + C_t^{op,p} + C_t^{inv,d} + C_t^{op,d} + C_t^{inv,s} + C_t^{op,s} \quad (1)$$

$$+ C_t^{var,s} + C_t^{inv,o} + C_t^{op,o} + C_t^{var,o}] \quad \forall t \in T \quad (2)$$

$$C_t^{inv,p} = \sum_{i \in I_0} \sum_{p \in P} f_p (\delta_{pit} - \delta_{pi(t-1)}) \quad \forall t \in T \quad (3)$$

$$C_t^{op,p} = \sum_{i \in I_0} \sum_{p \in P} v_p \delta_{pit} \quad \forall t \in T \quad (3)$$

$$C_t^{inv,d} = \sum_{i \in I} \sum_{q \in Q^d} f_q l_{qi} (\kappa_{qit} - \kappa_{qi(t-1)}) \quad \forall t \in T \quad (4)$$

$$C_t^{op,d} = \sum_{i \in I} \sum_{q \in Q^d} v_q l_{qi} \kappa_{qit} \quad \forall t \in T \quad (5)$$

$$C_t^{inv,s} = \sum_{i \in I} \sum_{q \in Q^s} f_q(\kappa_{qit} - \kappa_{qi(t-1)}) \quad \forall t \in T \quad (6)$$

$$C_t^{op,s} = \sum_{i \in I} \sum_{q \in Q^s} v_q \kappa_{qit} \quad \forall t \in T \quad (7)$$

$$C_t^{var,s} = \sum_{i \in I} \sum_{q \in Q^s} \sum_{m \in M^r} (u_q + u_q^{dist} l_i^{inland}) z_{qmit} \quad \forall t \in T \quad (8)$$

$$C_t^{inv,o} = \sum_{i \in I_0} \sum_{o \in O^e} f_o(\sigma_{oit} - \sigma_{oi(t-1)}) \quad \forall t \in T \quad (9)$$

$$C_t^{op,o} = \sum_{i \in I_0} \sum_{o \in O^e} v_o \sigma_{oit} \quad \forall t \in T \quad (10)$$

$$C_t^{var,o} = \sum_{i \in I_0} \sum_{o \in O \setminus O^e} \pi_{oit} w_{oit} \quad \forall t \in T \quad (11)$$

6.3.2.2 Cumulative GHG emissions

We adopt a cradle-to-gate perspective that comprises all processes along the supply chain, including resource utilization, REC production, and the REC transportation to the importing region (Liebich et al., 2021). This boundary includes any conversion and reconversion steps required within the modeled import chain (including reconversion in the importing region) but excludes emissions from the REC's final end use after delivery (e.g., combustion or industrial utilization). Therefore, we consider supply chain emissions resulting from resource utilization, production, and transportation in Equation (12). Equation (13) calculates the GHG emissions in various production and (re)conversion technologies (e.g., electrolysis, methanation, and ammonia cracking), denoted by G_t^p , including plant construction and operation. Equation (14) accounts for GHG emissions from transportation technologies (e.g., ships), denoted by G_t^q , which are proportional to the transported REC quantities. Equation (15) shows the calculation of GHG emissions related to resource origins (e.g., wind and photovoltaics), denoted by G_t^o , covering both construction and operation of the respective infrastructure (e.g., wind turbines and photovoltaic (PV) modules).

$$Z_2 = \sum_{t \in T} [G_t^p + G_t^q + G_t^o] \quad (12)$$

$$G_t^p = \sum_{i \in I_0} \sum_{p \in P} \eta_{pit} x_{pit} \quad \forall t \in T \quad (13)$$

$$G_t^q = \sum_{i \in I} \sum_{q \in Q} \sum_{m \in M^r} \eta_{qmit} z_{qmit} \quad \forall t \in T \quad (14)$$

$$G_t^o = \sum_{i \in I_0} \sum_{o \in O} \eta_{oit} w_{oit} \quad \forall t \in T \quad (15)$$

6.3.2.3 Supply security

Lower concentration (or higher diversification) of energy supplies can contribute to a more secure energy supply, since an importing region becomes less dependent on any single source of supply (Rosa et al., 2022; Zhu et al., 2023). The Herfindahl–Hirschman Index (HHI) is a common metric that assesses market or supply concentration (see Equation (16)). The HHI of the importing region is calculated by summing the squared shares of its imported RECs supplied by each exporting region over the planning horizon. The numerator of each share converts imported REC flows into energy units (using the lower heating value λ_m), and the denominator converts total REC demand in the importing region into the same energy units.

$$HHI = \sum_{t \in T} \sum_{i \in I} \left(\frac{\sum_{q \in Q} \sum_{m \in M^r} \lambda_m z_{qmit}}{\sum_{m \in M^r} \lambda_m d_{mi_0t}} \right)^2 \quad (16)$$

Lower HHI values indicate a more diversified import portfolio (more exporting regions with smaller shares), whereas higher values indicate greater concentration on a few exporting regions.

Moreover, an importing region's reliance on politically unstable exporters can also increase supply risk (Cappelli and Carnazza, 2023). Political stability and the absence of violence are closely linked to stable and reliable supply chains (Lekavičius et al., 2024). Thus, we adopt a political-risk-weighted HHI (Equation (17)) by integrating political instability into the concentration index (Lekavičius et al., 2024; Wei et al., 2024; Xun et al., 2022).

We represent the political instability of each exporting region i in period t by the parameter μ_{it} , ranging from 0 (lowest instability) to 1 (highest instability), i.e., higher values indicate greater potential instability. As shown in Equation (17), relying on politically unstable suppliers significantly increases this modified concentration (Z_3), indicating higher supply-security risks. Concretely, the political-risk-weighted HHI is obtained by multiplying each squared import share by the political instability factor μ_{it} , so that both high concentration (large import shares) and high political instability (μ_{it}) increase the risk measure. Following Lekavičius et al. (2024), the political instability parameter (μ_{it}) is multiplied by a factor of two to maintain nominal comparability between the political-risk-weighted HHI in Equation (17) and the standard HHI in Equation (16).

$$Z_3 = \sum_{t \in T} \sum_{i \in I} 2\mu_{it} \left(\frac{\sum_{q \in Q} \sum_{m \in M^r} \lambda_m z_{qmit}}{\sum_{m \in M^r} \lambda_m d_{mi_0t}} \right)^2 \quad (17)$$

Our third objective is to minimize supply-security risk via a measure that depends on supply concentration and political instability. This objective introduces a quadratic term because the political-risk-weighted HHI is quadratic in import shares. Accordingly, the political-risk-weighted HHI increases when imports rely on few exporting regions (high concentration) and when large import shares are sourced from politically unstable exporting regions. As a share-based concentration metric, it does not capture (i) correlated shocks affecting multiple exporting regions simultaneously, (ii) disruption risks along specific routes or infrastructure, or (iii) regulatory and trade impediments such as sanctions, tariffs, or export restrictions.

6.3.2.4 Constraints

The model enforces regional resource balances for all resources and time periods, including explicit accounting of REC exports and transport-related REC consumption. Capacity constraints link production, (re)conversion, transportation, and renewable electricity output to installed infrastructure, subject to regional resource availability. Additional constraints implement dynamic technology availability over the planning horizon, non-decreasing infrastructure (no deinstallation), and the variable domains. The complete constraint set is provided in the Supplementary Information (Constraints 6.B.1–6.B.21).

6.4 Case study

We apply the model to a European import case study. Section 6.4.1 describes the dataset and case-study assumptions, and Section 6.4.2 reports the single-objective benchmarks, the Pareto frontier, and the resulting trade patterns. Section 6.4.3 examines robustness through sensitivity analyses.

6.4.1 Case-study data and assumptions

To transition toward defossilization, Europe is expected to face an import dependency of around 50% (European Commission, 2021b). We apply the model to a European import case study for RECs over 2030–2055 with annual resolution.

Exporting-region set. We consider 23 candidate exporting regions with high techno-economic potential for REC supply. Regions are preselected based on global REC trade potential studies (Galimova, Ram et al., 2023; Hank et al., 2023; Pieton et al., 2023; World Energy Council, 2022) and consistency with European REC and hydrogen partnership strategies (GIZ, 2023; Hydrogen Council, 2023; IRENA, 2022b). We then apply transparent exclusion criteria on (i) water availability in regions without seawater access for large-scale desalination and (ii)

extreme political instability. The resulting exporting-region set, and screening indicators are reported in Appendix 6.A.3 and the Supplementary Information (Section 6.B.3).

Resources, technologies, and transport. The case study includes hydrogen, methane, methanol, ammonia, and Fischer–Tropsch fuels as RECs, with enabling technologies for renewable electricity supply, water treatment, CO₂ supply, and REC production and (re)conversion. Transport is modeled via REC pipelines and shipping options, with transport energy demand represented endogenously as carrier consumption during transportation. Detailed technology and route assumptions are provided in the Supplementary Information (Tables 6.B.2–6.B.13).

Key assumptions for the case study. All techno-economic and resource parameters in the case study are reported in the Supplementary Information. To represent parameter uncertainty, we perform sensitivity analyses with a variation range of $\pm 20\%$ around the base values for techno-economic parameters (Hampp et al., 2023). In this study, technological progress is represented by exogenous changes in costs and performance (FVV, 2021; Hampp et al., 2023; The Danish Energy Agency, 2018a). Particularly, investment costs for renewable electricity technologies follow declining investment and specific annual operating cost trajectories (see Table 6.B.2). To account for additional uncertainty in long-term technology development, we further analyze the impact of production technology improvements (in costs, efficiencies, and annual production capacities) on the optimal solutions, using the values reported in Table 6.B.7.

The discounting factor in the net present cost objective is derived from a weighted average cost of capital (WACC) of 8.5% per year, applied uniformly to all regions and technologies. This assumption follows recent REC studies that use a uniform WACC to retain comparability (Galimova, Ram et al., 2023; Hampp et al., 2023), and lies near the middle of the 4–13% WACC range reported in the review by Genge et al. (2023). Regional differences in investment risk are not reflected through region-specific WACC, but are approximated via the political instability-based risk indicator used in the supply-security objective.

REC demand in Europe and in each exporting region is exogenous, based on long-term scenario studies and independent of modeled costs. Exporting regions first satisfy their own REC demand and may export surplus volumes to Europe.

We do not include explicit policy instruments such as carbon taxes, subsidies, import tariffs or trade preferences. Greenhouse gas emissions are accounted for on a cradle-to-gate basis, covering resource utilization, REC production, conversion and reconversion steps included in

the model, and international transport to Europe, but excluding emissions from final end use after delivery (e.g., combustion or industrial utilization). Normalized political instability indicators are based on World Bank governance data, which are assumed constant over the modeling horizon. To consider the impact of political instability in addition to the regional 5-year averages (2019–2023), we examine cases using the minimum and maximum political instability values observed over the last 10 years, which capture the range of longer-term variability (see Table 6.B.10).

6.4.2 Results and discussion

We begin by separately optimizing each objective function (cost-optimal, GHG-optimal, and supply risk-optimal) to determine exporting regions and infrastructure needs. Next, we solve the multi-objective problem using the augmented ε -constraint method (AUGMECON) (Mavrotas, 2009; Mavrotas and Florios, 2013) to construct the Pareto frontier and examine trade-offs among these objectives. We also identify exporting regions that contribute to REC imports and, finally, conduct sensitivity analyses on regional configurations, political instability, REC demand levels, and key cost parameters.

Solution procedure. The formulation is a mixed-integer quadratic program (MIQP), where quadratic terms arise from the political-risk-weighted HHI objective (Equation (17)). The model is implemented in Python and solved with Gurobi 12.0.0 using its MIQP solver. All runs are executed on an AMD EPYC 9334 (32 cores, 2.70 GHz) with 64 GB RAM. To explore trade-offs among the three objectives, we adopt the augmented ε -constraint (AUGMECON) method (Mavrotas, 2009; Mavrotas and Florios, 2013). Net present cost is treated as the primary objective, while GHG emissions and supply-security risk are converted into ε -constraints. We first solve three single-objective problems and record the resulting objective values in a payoff table (see Table 6.2). Based on the payoff table, we compute the range of each constrained objective as the difference between its maximum and minimum values and use these ranges to define ε -intervals. We then discretize GHG emissions (Z_2) and supply-security risk (Z_3) into ε -levels ε_2 and ε_3 over their respective ranges and solve the resulting ε -grid to obtain a set of non-dominated Pareto solutions. The ε -constraints are expressed in the original units of each objective, and an augmentation term based on the normalized slacks, weighted by a small augmentation parameter, ϵ_{ps} , is included to avoid weakly efficient solutions. Each ε -subproblem solves

$$\begin{aligned} & \min(Z_1 - \text{eps}(s_2/R_2 + s_3/R_3)) \\ & \text{subject to} \\ & Z_2 + s_2 = \varepsilon_2, Z_3 + s_3 = \varepsilon_3, s_2, s_3 \in \mathbb{R}^+ \end{aligned} \tag{18}$$

where R_2 and R_3 denote the ranges of Z_2 and Z_3 obtained from the payoff table and $\text{eps} = 10^{-3}$ is the augmentation parameter. All ε -subproblems are solved with a maximum relative MIP gap of 1%. In our implementation, runtimes per Pareto point range from 1 to 56 hours.

We construct the Pareto set with an explicit ε -grid over the two constrained objectives. We discretize cumulative GHG emissions Z_2 into six ε -levels spanning 4.3–4.8 Gtonnes CO₂eq and supply-security risk Z_3 into six ε -levels spanning 0.045–0.095, yielding 36 ε -subproblems. In addition, we solve six benchmark-compliant subproblems along $Z_3 = 0.090$ over the same Z_2 levels. For transparency and reproducibility, the complete ε -grid specification and, for each ε -subproblem, the solver termination status, achieved MIP gap, and runtime are reported in the Supplementary Information (Table 6.B.20).

6.4.2.1 Pareto optimal solutions and network structures

This section presents results from the single-objective optimizations, the Pareto-efficient frontier, the compromise solution, and the network structures of the respective optimal solutions. Table 6.2 provides a payoff matrix for single-objective optimizations by minimizing the economic (Z_1), environmental (Z_2), and supply-security (Z_3) objectives separately.

In the cost-optimal solution, the net present cost is 5.92 trillion €, cumulative supply-chain emissions amount to 4.86 Gtonnes CO₂eq, and the political-risk-weighted HHI equals 0.10. Minimizing GHG emissions yields the GHG-optimal solution with about 12% lower emissions than in the cost-optimal case, but at a cost of 19.66 trillion € (+230%) and a higher supply-security risk index of 0.18 (+80%). In contrast, minimizing the political-risk-weighted HHI leads to the supply risk-optimal solution, where the risk index falls by about 90% relative to the cost-optimal solution. This strong reduction in risk is accompanied by a net present cost of 17.19 trillion € (+190% compared to the cost-optimal solution) and emissions of 7.90 Gtonnes CO₂eq ($\approx +63\%$).

In addition, Table 6.2 also reports the standard (unweighted) HHI for the three single objective solutions. The GHG-optimal solution is both more concentrated ($HHI = 0.11$ vs. 0.07 in the cost-optimal case) and more exposed to political risk ($Z_3 = 0.18$ vs. 0.10). The supply risk-optimal solution exhibits very low concentration ($HHI = 0.02$) and a correspondingly low political-risk-weighted index ($Z_3 = 0.01$). The parallel changes of HHI and Z_3 indicate that the

supply risk objective simultaneously promotes diversification and a shift toward politically more stable exporters, with the weighting by political-risk scores further penalizing portfolios that rely on high-risk partners.

Taken together, the payoff matrix confirms that improving any one objective substantially deteriorates at least one of the others. The robustness of these extreme and compromise solutions with respect to political instability and key techno-economic parameters is examined in Sections 6.4.3.4 and 6.4.3.6.

Table 6.2. Results for single objective optimization solutions (payoff matrix)

		Z_1 [trillion €]	Z_2 [Gtonnes CO ₂ eq]	Z_3 [-]	HHI [-]
$\min Z_1$	cost-optimal	5.92	4.86	0.10	0.07
$\min Z_2$	GHG-optimal	19.66	4.26	0.18	0.11
$\min Z_3$	supply risk-optimal	17.19	7.90	0.01	0.02

Non-dominated optimal solutions provide a Pareto-efficient frontier, where solutions above the frontier are suboptimal, while those below are infeasible. In posteriori methods, the efficient solutions of the problem (i.e., the Pareto set) are first generated, and then the decision maker selects among them according to their preferences (Mavrotas and Florios, 2013). Therefore, for this multi-objective problem, we generate the Pareto-efficient frontier to evaluate the trade-offs among the different objectives. Figure 6.3 illustrates a section of the Pareto frontier, spanning from 4.3 to 4.8 Gtonnes CO₂eq for emissions and 0.04 to 0.10 for supply-security risk. Figure 6.3 reveals that lowering GHG emissions raises the net present cost (due to different exporting regions and technologies). Similarly, reducing supply-security risk also increases costs, indicating that greater diversification may lead to additional costs, affecting economic feasibility.

Furthermore, we investigate trade-offs by examining a benchmark case in which supply-security risk is aligned with recent historical levels for fossil-based energy carriers. For this benchmark, we consider Europe's recent energy imports by calculating the average of supply-security risk values based on oil and petroleum imports from 2021 to 2023 (International Trade Centre, 2024) and political instability (World Bank, 2024). The calculated benchmark for supply-security risk is approximately 0.09 considering the normalized political instability of exporting regions and oil and petroleum imports to Europe using Equation (17). Figure 6.3 highlights Pareto solutions that satisfy this benchmark (red line), illustrating the cost–emission trade-off when supply security is held at a level comparable to recent fossil energy imports: along this benchmark, achieving lower GHG emissions requires higher costs.

Within this benchmark-compliant set, we identify a compromise solution (marked by a blue dot in Figure 6.3) that lies about 5% above the minimal environmental objective. This solution balances net present cost, GHG emissions, and supply security: it maintains the risk index at the benchmark level, reduces emissions compared with the cost-optimal solution, and avoids the very high costs associated with the GHG-optimal and supply risk-optimal solutions.

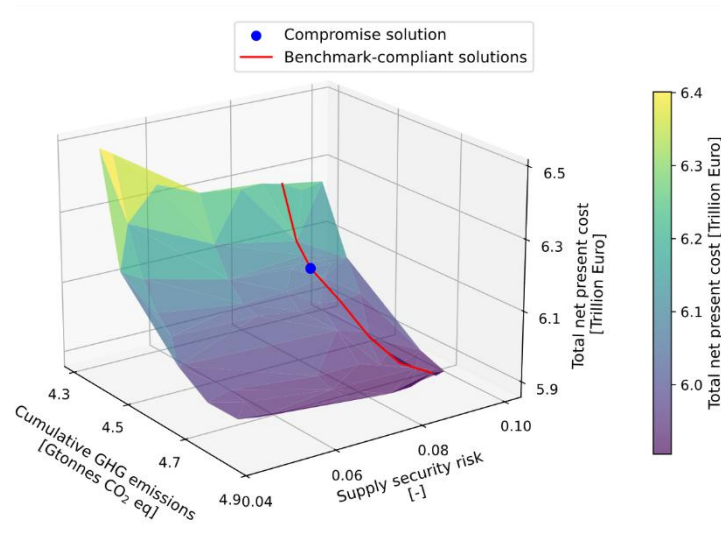


Figure 6.3. Pareto frontier of objectives for importing RECs to Europe. The benchmark-compliant solutions (red line) illustrate the trade-offs between economic and environmental objectives when the supply-security risk is 0.09. The compromise solution (blue dot) lies about 5% above the minimal environmental objective.

To clarify the cost and environmental details of each solution, Figure 6.4 shows the breakdown of total net present cost (TC) and total GHG emissions (TG) in the cost-optimal, GHG-optimal, supply risk-optimal, and compromise solutions. Figure 6.4 indicates that the largest share of costs comes from resource utilization and REC production (about 90-98%), with transportation contributing marginally. Comparing resource utilization costs of the cost-optimal versus GHG-optimal solutions highlights the trade-off in renewable electricity generation decisions. The cost-optimal solution deploys more PV, while the GHG-optimal solution favors wind power (the reasons are discussed in detail below). The cost increase in the supply risk-optimal outcome reflects additional investments for import diversification. Comparing these findings with the compromise solution shows that meeting the 0.09 supply-security benchmark in Europe, while raising emissions slightly beyond the GHG-optimal case, requires only a modest increase compared to the cost-optimal solution's total net present cost (Figure 6.4). Thus, a balanced approach can achieve environmental and security objectives without sharply increasing costs.

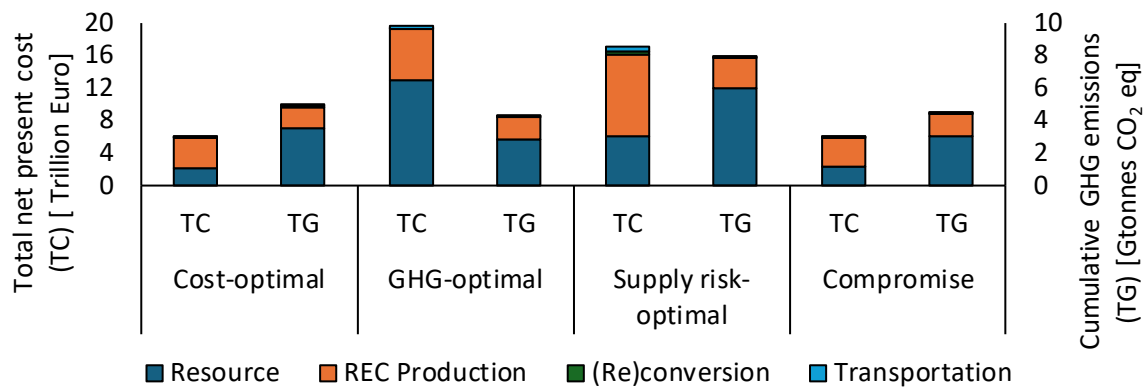


Figure 6.4. Total net present cost (TC) and cumulative GHG emissions (TG) structure for REC supply chains in the cost-optimal, GHG-optimal, supply risk-optimal, and compromise solutions.

To explain the large differences in net present cost and cumulative GHG emissions across the single-objective solutions, we decompose the change relative to the cost-optimal solution into four drivers consistent with Figure 6.4: resource utilization (including renewable electricity), production, (re)conversion, and transportation (Supplementary Figures 6.B.2 and 6.B.3; Table 6.B.14). This decomposition shows that the high cost increases in the extreme single-objective solutions arise from multiple upstream drivers, rather than from a single modeling assumption or a single technology choice.

Relative to the cost-optimal solution, the GHG-optimal solution increases net present cost by +13.74 trillion €, dominated by resource utilization (including renewable electricity) (+10.79 trillion €) and production (+2.70 trillion €), while (re)conversion and transportation have only minor contributions (+0.02 and +0.23 trillion €, respectively). In terms of GHG emissions, the GHG-optimal solution reduces cumulative emissions by −0.60 Gtonnes CO₂eq, primarily through lower emissions associated with resource utilization (Supplementary Figure 6.B.3), consistent with the shift in the PV–wind portfolio shown in Figure 6.5.

The supply risk-optimal solution increases net present cost by +11.26 trillion € relative to the cost-optimal solution. Here, the dominant driver is production (+6.42 trillion €), followed by resource utilization (including renewable electricity) (+3.93 trillion €), while transportation (+0.53 trillion €) and (re)conversion (+0.37 trillion €) contribute comparatively less. This pattern indicates that minimizing the political-risk-weighted HHI mainly requires a more distributed, multi-exporting-region production system (Figure 6.7), rather than being driven by transportation alone (Figure 6.6). In line with the more geographically dispersed sourcing,

average ship and pipeline transport distances increase substantially in the supply risk-optimal case (weighted by imported energy quantities; Table 6.B.15), while transportation remains a comparatively small cost driver in the decomposition.

The compromise solution increases net present cost only slightly (+0.13 trillion €) while reducing emissions by -0.46 Gtonnes CO_2eq relative to the cost-optimal solution; both changes are dominated by resource utilization. Overall, the decomposition attributes the cost penalties in the extreme solutions to broad upstream shifts across resource utilization and production, rather than to transportation and (re)conversion.

Because resource utilization dominates total cost and varies significantly among solutions, it is crucial to analyze decisions regarding regional renewable electricity capacity utilization. As shown in Figure 6.5, PV is most prominent in the cost-optimal solution, with about 94% PV and 6% wind over the planning horizon. Both PV and wind capacity expand in the GHG-optimal solution, but wind grows more strongly, reaching about 17% of total renewable capacity. The main reason is that wind typically yields lower GHG emissions than PV systems. Conversely, the supply risk-optimal solution prioritizes minimizing political-risk-weighted HHI, yielding installation decisions based on regional availability, so that around 63% of installed capacity is wind. Finally, in the compromise solution, a balance among objective functions leads to about one-fifth wind capacity, despite its higher cost relative to PV.

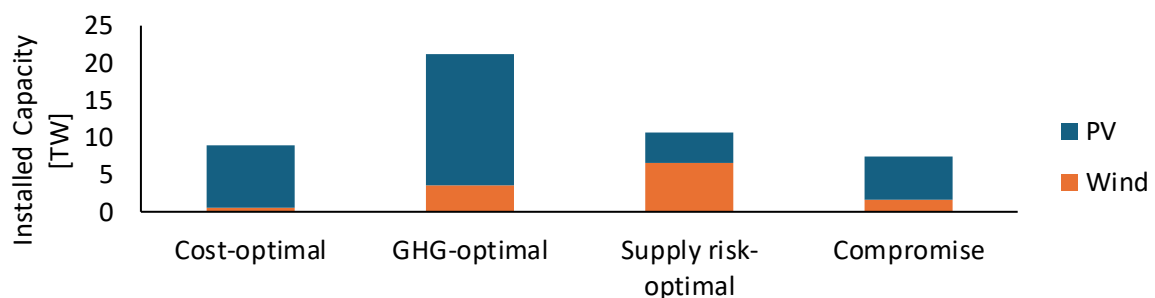


Figure 6.5. Installed capacity of PV and wind in exporting regions over the planning horizon in the cost-optimal, GHG-optimal, supply risk-optimal, and compromise solutions.

Figure 6.6 shows transportation structures for hydrogen (H_2) and methane (CH_4) import flows to Europe for the cost-optimal, GHG-optimal, supply risk-optimal, and compromise solutions. In the cost-optimal case, hydrogen is transported predominantly via pipelines (about 87%), with the remaining 13% transported as LOHC by ships, while methane is imported entirely by pipelines. Ammonia ships are not selected for hydrogen supply via ammonia due to the high investment costs for cracking ammonia back to hydrogen. Liquid-hydrogen ships are selected

to a limited extent, because transporting hydrogen (and required conversion processes) in liquid form is more expensive than transporting it as a LOHC (Hampp et al., 2023; Schuler et al., 2024). Consequently, LOHC ships are selected for the hydrogen import from distant regions (e.g., Chile), while hydrogen pipelines are selected for nearer regions (e.g., Saudi Arabia).

In the GHG-optimal solution, LOHC ships become more prominent for hydrogen imports (about 54% LOHC ships and 46% pipelines), reflecting the shift toward distant exporters (e.g., Peru, Argentina, Uruguay) with abundant renewable resources. Methane predominantly flows through pipelines (about 85%), complemented by a smaller share of LNG shipping (about 15%). In the supply risk-optimal solution, more exporters participate. In this solution, liquid-hydrogen ships carry about 11% and LOHC ships about 64% of hydrogen from distant regions, with pipelines covering nearer routes (25%). Methane relies mainly on pipelines (85%) with a small contribution from LNG ships ($\approx 15\%$). In the compromise solution, hydrogen imports to Europe are primarily via LOHC ships (86%), with a minor share via pipelines (14%), and methane is entirely transported via pipelines. Overall, these patterns highlight that transport choices depend on a combination of cost, environmental, and supply-security considerations, and they adapt as the decision maker's preferences shift across the Pareto frontier.

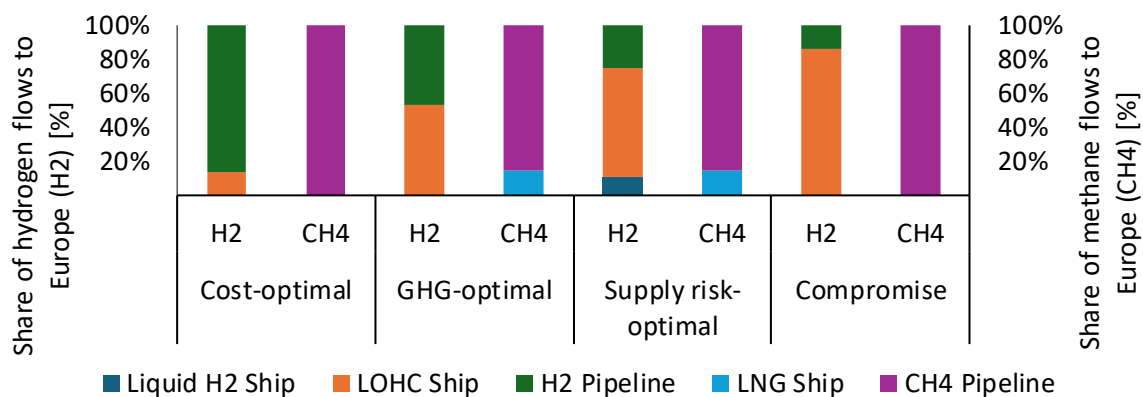


Figure 6.6. Transportation structures for hydrogen (H2) and methane (CH4) import flows to Europe.

6.4.2.2 Contribution of exporting regions

Figure 6.7 summarizes the spatial structure of REC exports to Europe. It shows, for the cost-optimal, GHG-optimal, supply risk-optimal, and compromise solutions, the main exporting regions and the dominant REC flows to Europe. Detailed results per REC and solution (hydrogen, ammonia, methane, methanol, and FT fuel) are reported in the Supplementary Information (Figures 6.B.4–6.B.8)

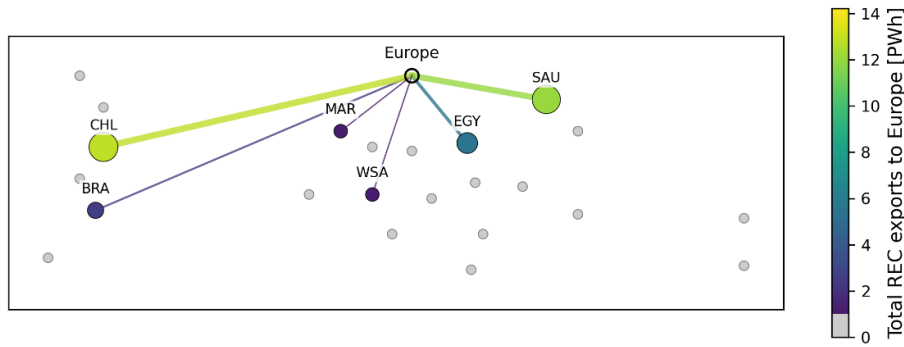
In the cost-optimal solution, Saudi Arabia and Chile emerge as top REC exporters to Europe. In this solution, Chile and Saudi Arabia together supply roughly two-thirds of total REC imports (each contributing about one-third), followed by Egypt (around 15%) and Brazil (around 7%). This pattern reflects Saudi Arabia's combination of high solar potential and short transport distance, and Chile's excellent full-load hours for both PV and wind. Most hydrogen and methane flows originate from Saudi Arabia, whereas FT fuels predominantly come from Chile, with Egypt and Brazil contributing mainly methanol.

By contrast, in the GHG-optimal solution, Peru, Nigeria, and Argentina & Uruguay (driven by abundant wind power and lower GHG emissions) are the main REC exporters. Peru and Nigeria together provide about 70% of REC imports, complemented by Argentina & Uruguay (around 17%), while Brazil and Chile play smaller roles. In this solution, hydrogen comes mainly from Peru and Nigeria, and methane exports are dominated by Nigeria.

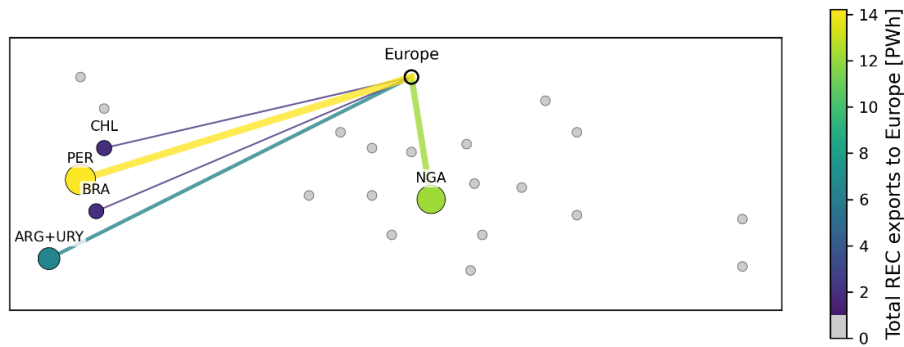
As shown in Figure 6.7, the supply risk-optimal solution involves more diverse regions exporting RECs to Europe, enhancing supply security at higher cost and emissions. This solution boosts exports from many politically more stable regions, including New Zealand, Australia, Oman, and Argentina & Uruguay, to reduce the political-risk-weighted HHI. New Zealand alone supplies almost 20% of total imports, and more than twenty regions contribute overall. Each REC (e.g., hydrogen and methanol) is supplied by several regions; for example, nearly all exporters contribute to hydrogen and methanol supply.

Finally, in the compromise solution, a balanced perspective among the objectives of our study leads to a solution in which regions with a better cost performance (e.g., Chile and Saudi Arabia) and lower GHG emissions (e.g., Peru and Nigeria) are selected as REC exporters. Peru and Chile together supply more than half of total REC imports (about 30% and 26%, respectively), followed by Nigeria (around 18%), Saudi Arabia (about 12%), and Argentina & Uruguay (around 6%). Compared with the cost-optimal solution, the share of REC imported from Saudi Arabia is reduced, and more hydrogen is imported from Chile. Relative to the GHG-optimal solution, the share of REC imported from Nigeria decreases, and Nigeria's exports shift from hydrogen and methane toward ammonia. Exports from politically less stable regions such as Nigeria, Saudi Arabia, and Egypt are moderated compared with their potential shares in the purely cost- or GHG-driven solutions.

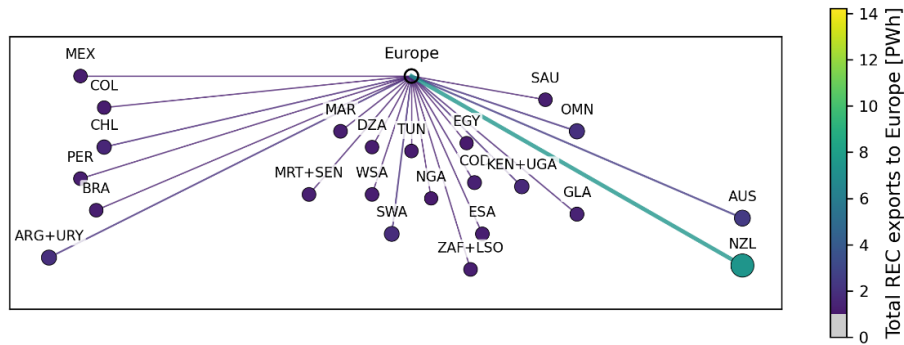
a) Cost-optimal solution



b) GHG-optimal solution



c) Supply risk-optimal solution



d) Compromise solution

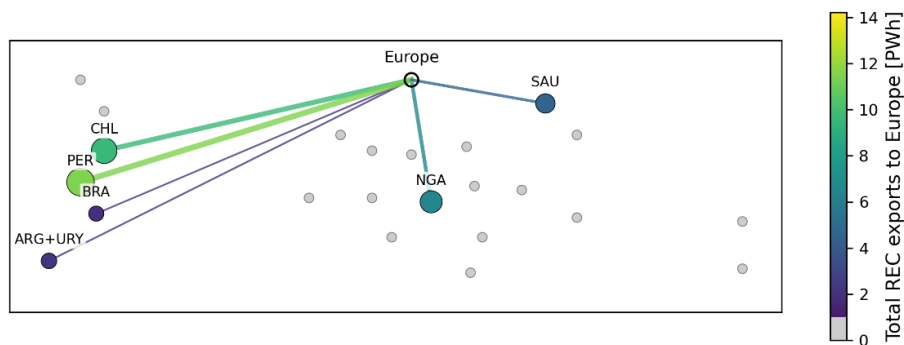


Figure 6.7. Trade patterns of REC imports to Europe in the a) cost-optimal, b) GHG-optimal, c) supply risk-optimal, and d) compromise solutions. Each panel shows the main exporting regions and the dominant REC flows to Europe. For readability, WSA, ESA, SWA, and GLA denote the aggregated regions GHA+CIV+BEN+BFA+TGO, MWI+MOZ+ZMB+ZWE, NAM+AGO+BWA, and TZA+RWA+BDI, respectively.

To analyze how REC imports change over time, Figure 6.8 shows the import flows to Europe over the planning horizon (in 2030, 2040, and 2050) by exporting region for each solution. In the cost-optimal solution, REC imports from Saudi Arabia dominate in the early years, while Chile's exports gradually increase and overtake Saudi Arabia toward the end of the horizon, confirming Chile's role as a key long-term supplier. In the GHG-optimal solution, REC imports are consistently dominated by Peru and Nigeria; contributions from Argentina & Uruguay rise toward the end of the horizon. In the supply risk-optimal solution, most exporting regions show a gradual increase in exports, but New Zealand exhibits a particularly high contribution, reflecting its prominent role in low-risk diversification. In the compromise solution, Peru and Chile expand their REC exports steadily, while Nigeria and Saudi Arabia gain importance in the later years, although their shares remain lower than in the cost-optimal and GHG-optimal solutions.

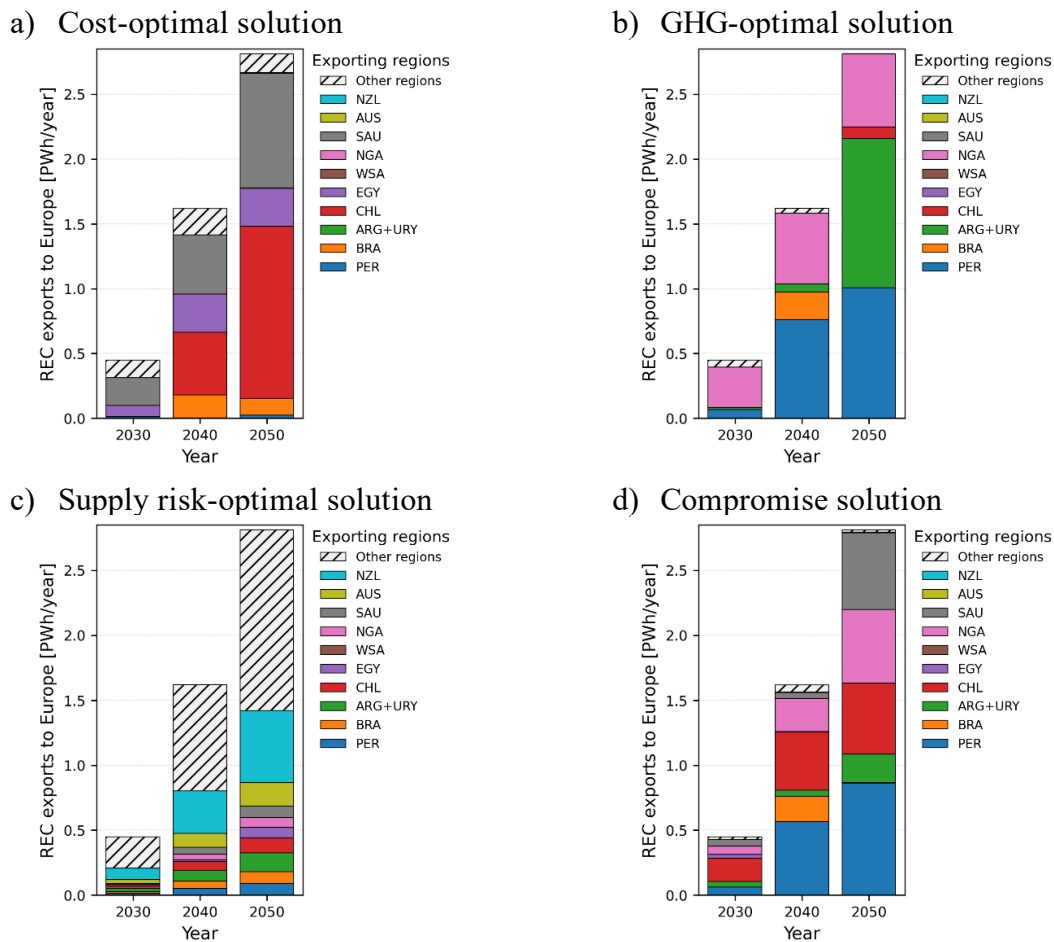


Figure 6.8. Import flows of RECs to Europe over the planning horizon (2030, 2040, and 2050) in the a) cost-optimal, b) GHG-optimal, c) supply risk-optimal, and d) compromise solutions, by exporting region. For readability, WSA denotes the aggregated region GHA+CIV+BEN+BFA+TGO.

These findings highlight how different decision-making priorities lead to varied supply chains for importing RECs to Europe. They also indicate that export regions may differ across scenarios and that the pattern of REC imports can change significantly over time.

6.4.3 Sensitivity analyses

In addition to the base-case results, we conduct a set of sensitivity analyses to assess the robustness of our findings. First, we test sensitivity to exporting-region screening thresholds, i.e., the exclusion criteria on water availability and extreme political instability that define the exporter set. Second, we examine regional sensitivities by varying the role of selected exporters (Australia and New Zealand) and by including China as a potential REC exporter to Europe. Third, we explore how alternative political-instability assumptions affect exporter selection in the supply risk-optimal and compromise solutions. Finally, we analyze sensitivity to REC demand levels, key cost parameters, and a technology-advancement case for production processes.

6.4.3.1 Sensitivity to exporting-region screening thresholds

To assess the robustness of our case-study findings to the data-driven exporting-region preselection, we test sensitivity to the two exclusion criteria used to define the exporting-region set: (i) extreme political instability and (ii) water availability without access to seawater for large-scale desalination. We consider three variants and recompute the cost-optimal, GHG-optimal, supply risk-optimal, and compromise solutions in each case: (a) tightening the political-instability threshold by excluding Nigeria, which is among the more politically unstable regions in the base exporting-region set; (b) relaxing the political-instability threshold by additionally including Libya, which is excluded in the base case due to extreme instability; and (c) relaxing the water-availability filter by additionally including Chad & Niger as a candidate exporting region despite lacking access to seawater for desalination. Supplementary Figures 6.B.9–6.B.11 show the resulting changes in exporting-region shares for the four representative solutions.

Including Libya illustrates why excluding extremely politically unstable regions matters when minimizing costs. In the cost-optimal solution, Libya's export share increases by about 49.5%, accompanied by reductions for Chile ($\approx -28.9\%$) and Egypt ($\approx -14.7\%$), yielding a more concentrated import portfolio. By contrast, Libya induces no meaningful change in the compromise portfolio and contributes only marginally in the supply risk-optimal solution,

consistent with the political-risk-weighted concentration objective penalizing portfolios with large shares from high-instability regions.

Excluding Nigeria leads to the expected redistribution of imports toward alternative exporting regions already present in the base case. In the compromise solution, excluding Nigeria ($\approx -17.6\%$) shifts imports mainly toward Saudi Arabia ($\approx +17.9\%$), with additional increases for other major suppliers, including Chile ($\approx +6.1\%$), while the set of dominant exporting regions remains unchanged. In the GHG-optimal solution, the reduction in Nigeria's share ($\approx -32.5\%$) is compensated primarily by Argentina & Uruguay ($\approx +25.6\%$), with smaller increases for Saudi Arabia and Peru. In the supply risk-optimal solution, Nigeria plays only a minor role in the base case; accordingly, excluding it induces only limited adjustments while maintaining a broad, diversified exporting-region portfolio.

Including Chad & Niger affects the cost-optimal solution more clearly, reflecting that cost minimization can respond strongly to the inclusion of additional candidate regions. Chad & Niger contributes about 5.1%, while Chile's share increases ($\approx +22.7\%$), mainly offset by lower shares from Egypt ($\approx -10.6\%$) and Saudi Arabia ($\approx -9.7\%$). In the compromise solution, Chad & Niger is not selected, and the set of major exporting regions remains unchanged.

Overall, these results confirm that the compromise portfolio is robust to exporting-region screening thresholds, whereas the cost-optimal extreme is more sensitive to the inclusion or exclusion of individual candidate regions. This robustness is consistent with the diversification incentive in the compromise (and supply risk-optimal) solutions, which avoids strong reliance on any single exporting region and therefore reduces sensitivity to marginal changes in the exporting-region set.

6.4.3.2 Regional sensitivity: inclusion of China

In the base case, China is not part of the exporting region set. To test whether this modeling choice affects our main findings, we perform a sensitivity analysis in which China is additionally included as a potential REC exporter to Europe and recompute the cost-optimal, GHG-optimal, supply risk-optimal, and compromise solutions. Figure 6.9 shows, for each solution, how the export shares of key regions change when China is considered as an exporting region.

In the cost-optimal and GHG-optimal solutions, China becomes a noticeable but non-dominant exporter. It primarily supplies FT fuel and methanol and takes over a small share of REC exports

previously sourced from other regions (e.g., Chile and Nigeria). However, the main exporters identified in the base case—such as Chile, Saudi Arabia, Peru, and Nigeria—continue to account for the largest shares of imports. China therefore enters as a complementary supplier rather than replacing the major exporting regions in the cost-optimal and GHG-optimal solutions.

In the supply risk-optimal and compromise solutions, the model limits China's share and maintains a broad portfolio of exporting regions. The same key regions as in the base case (notably Chile, Saudi Arabia, Peru, New Zealand, and several African regions) continue to dominate the exporting regions, with China providing only a small additional share of REC imports. In the compromise solution in particular, China's entry slightly reduces the shares of some existing exporters but does not change the set of major exporting regions.

Overall, including China as an exporter slightly redistributes REC flows among suppliers, but Europe's optimal import portfolios remain focused on promising exporting regions in Africa, the Middle East, and Latin America. The main patterns of cost, GHG, and supply-security trade-offs are preserved, indicating that our case-study conclusions are robust with respect to the treatment of China.

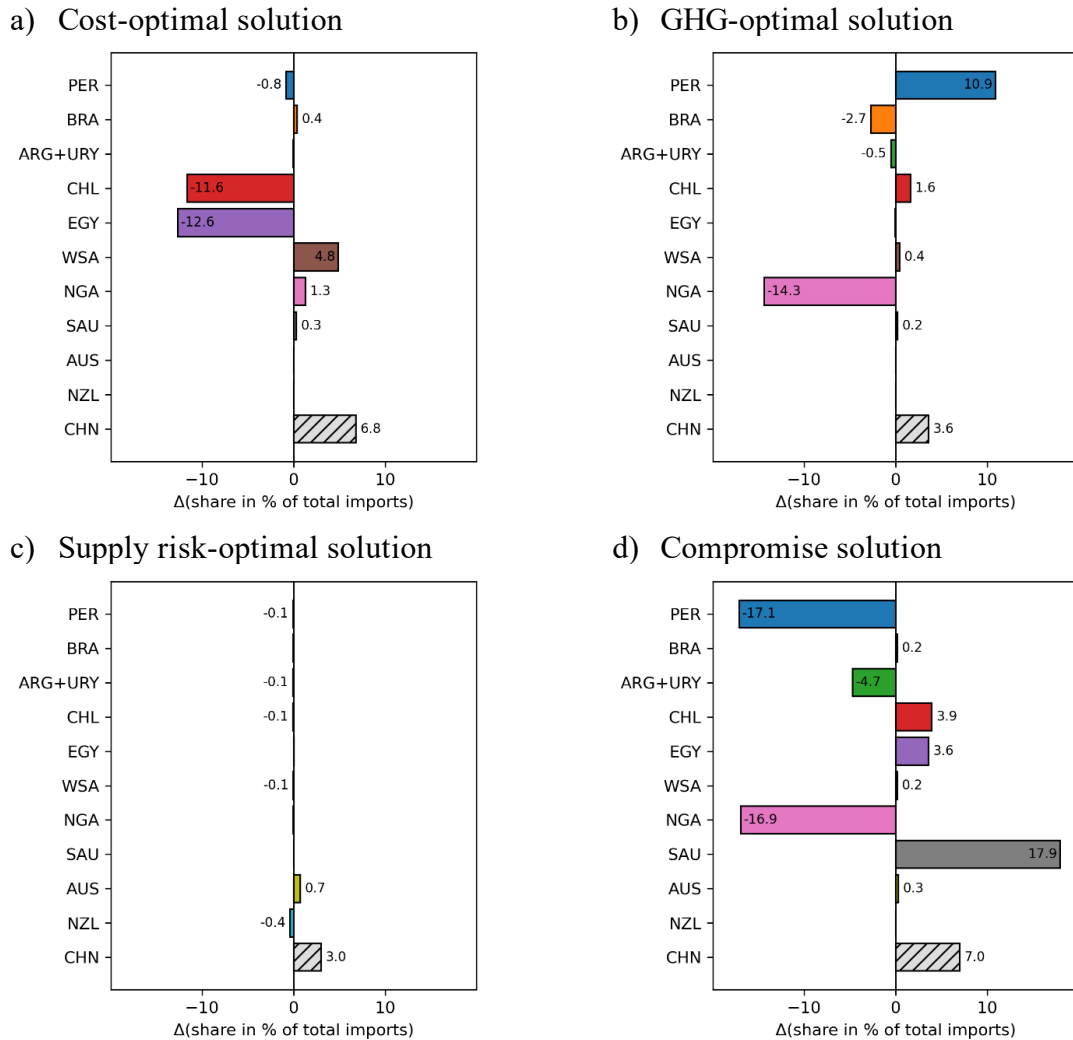


Figure 6.9. Change in REC export shares to Europe when China (CHN) is included as a potential exporter in the a) cost-optimal, b) GHG-optimal, c) supply risk-optimal, and d) compromise solutions. Bars show $\Delta(\text{share in \% of Europe's total REC imports})$ for each exporting region, i.e., the difference between the base case without China and the case with China included; positive values indicate a larger share, negative values a smaller share. For readability, WSA denotes the aggregated region GHA+CIV+BEN+BFA+TGO.

6.4.3.3 Regional sensitivity: Australia and New Zealand

To test the robustness of our findings on long-distance exporters, particularly the prominence of New Zealand in the supply risk-optimal solution, we perform a regional sensitivity analysis for Australia and New Zealand. We consider four alternative sea routes between these exporters and Europe (routes a-d in Table 6.B.13), which represent different realistic shipping paths and distances (Bertoli et al., 2016; Hank et al., 2023). For each route, we recompute the cost-optimal, GHG-optimal, supply risk-optimal, and compromise solutions and record the cumulative REC imports from Australia and New Zealand. Table 6.3 reports the resulting ranges across routes a-d.

For the cost-optimal and GHG-optimal solutions, imports from Australia and New Zealand remain small. In the cost-optimal solution, cumulative REC imports from each country are less than 0.1 PWh for all routes. In the GHG-optimal solution, imports from New Zealand are negligible (up to 0.01 PWh), while Australian exports range up to 0.22 PWh. In the supply risk-optimal solution, both countries contribute substantial volumes: across all routes, cumulative imports from Australia range between roughly 2.4–2.8 PWh, while imports from New Zealand lie between about 7.4–7.5 PWh. New Zealand therefore supplies approximately three times as much as Australia for every route considered. This indicates that the qualitative roles of New Zealand and Australia as low-risk suppliers are robust to variations in shipping paths and distances, even though total import volumes change slightly. In the compromise solution, imports from Australia and New Zealand are small: across routes a-d, imports from each country remain below about 0.1 PWh.

Taken together, this regional sensitivity analysis shows that Australia and New Zealand make only a marginal contribution to REC imports in the cost-optimal, GHG-optimal, and compromise solutions. By contrast, when supply security is prioritized, both countries become important diversification partners, with New Zealand consistently exporting around three times the energy supplied by Australia across all routes. Reporting import ranges across routes therefore confirms that New Zealand's strong role in the supply risk-optimal solution is robust.

Table 6.3. Ranges of REC imports from Australia and New Zealand across alternative shipping routes (a-d) to Europe, for the cost-optimal, GHG-optimal, supply risk-optimal, and compromise solutions.

Solution	Imports from Australia [PWh]	Imports from New Zealand [PWh]
Cost-optimal	<0.1	<0.1
GHG-optimal	<0.2	<0.1
Supply risk-optimal	2.4-2.8	7.4-7.5
Compromise	<0.1	<0.1

6.4.3.4 Sensitivity to political instability assumptions

To test how sensitive our results are to assumptions about political instability, we compare the base political instability case (5-year averages, 2019–2023) with low and high political instability scenarios, using the minimum and maximum political instability values observed over the last 10 years (Table 6.B.10). We focus on the supply risk-optimal and compromise solutions, where the political-risk term is most relevant. Figure 6.10 shows, for each exporter,

how the export shares of key regions change under the low and high political instability scenarios relative to the base case.

In the supply risk-optimal solution, the low political instability scenario shifts slightly away from more politically volatile exporters and toward regions with relatively higher stability. Shares of exporters such as New Zealand and Australia increase, while some politically less stable exporters experience modest reductions in their shares. In the high political instability scenario, these changes are partially reversed, but the adjustments remain moderate. In all cases, the model maintains a broad portfolio of exporting regions, and the same regions continue to dominate REC exports to Europe.

In the compromise solution, which also balances cost and GHG emissions, the low political instability scenario reduces the shares of exporters such as Saudi Arabia and Nigeria (which exhibit relatively high political instability), while other exporters show only minor changes. In the high political instability compromise solution, export shares change only slightly compared with the base case. The main exporters identified in the base case (notably Chile, Peru, Nigeria, Saudi Arabia, and selected African regions) remain central to the import portfolio.

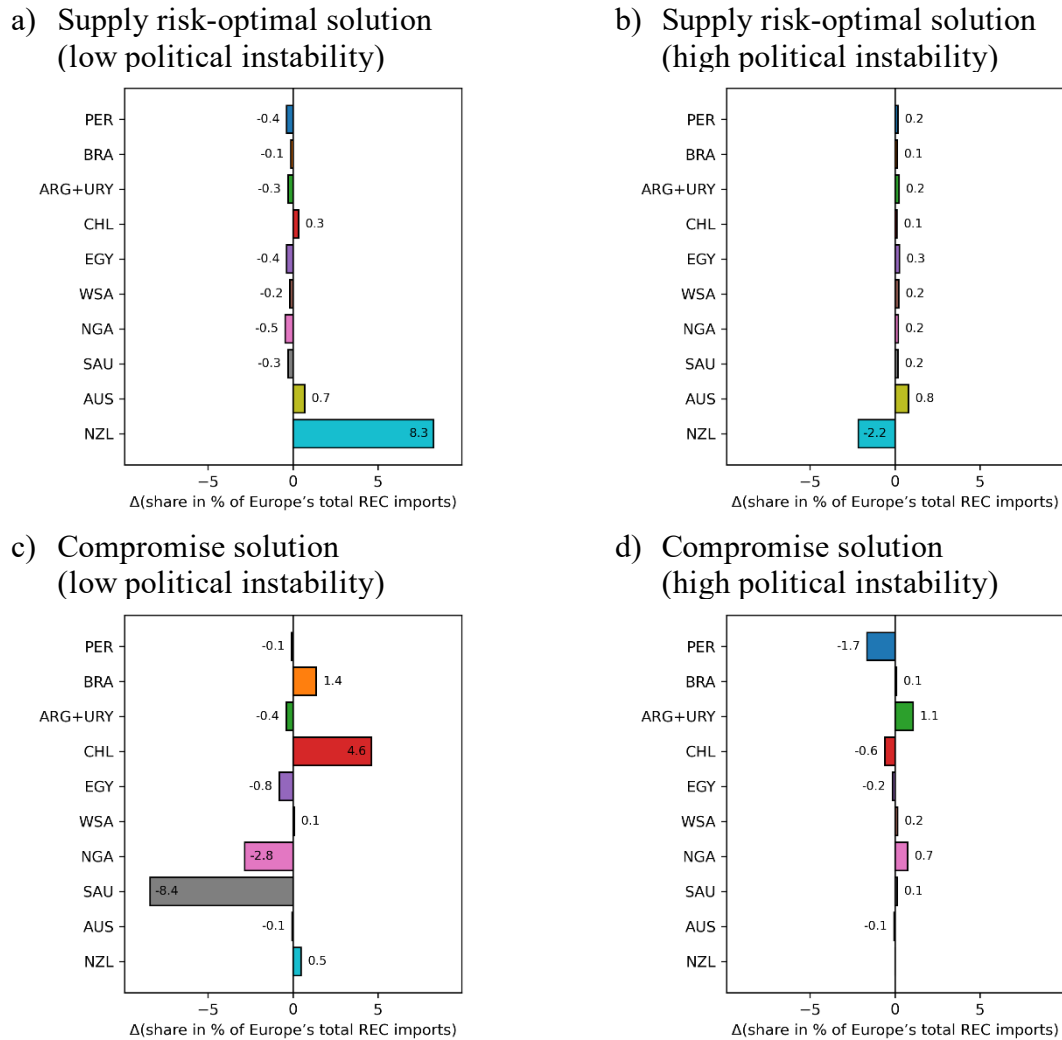


Figure 6.10. Change in export shares under alternative political instability scenarios: supply risk-optimal solutions for a) low political instability and b) high political instability cases, and compromise solutions for c) low political instability and d) high political instability cases relative to the base political instability case. Bars show $\Delta(\text{share in \% of Europe's total REC imports})$ for each exporting region; positive values indicate a larger share than in the base case, negative values a smaller share. For readability, WSA denotes the aggregated region GHA+CIV+BEN+BFA+TGO.

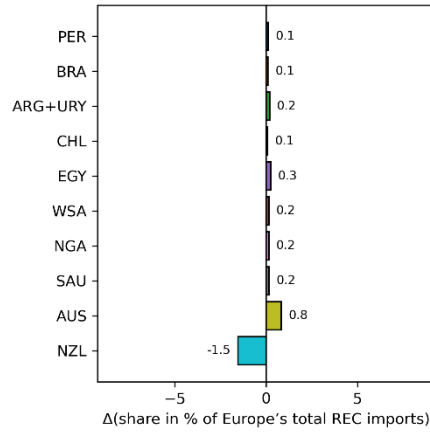
We also test stylized time-varying political instability trajectories over the planning horizon. For each exporting region, the normalized political instability parameter evolves linearly from the base value in 2030 toward exporter-specific 10-year bounds: a deterioration case reaching the historical maximum by 2055 and an improvement case reaching the historical minimum by 2055 (Table 6.B.10). Since long-run political stability is uncertain, we use bounded time-varying sensitivity trajectories rather than attempting political-risk forecasts (Lekavičius et al., 2024).

Figure 6.11 shows the resulting changes in exporter shares for the supply risk-optimal and compromise solutions. In the supply risk-optimal solution, the impact remains limited. Under deterioration, New Zealand's share decreases by 1.5%, while all other exporters change by less than 1.0%. Under improvement, the portfolio shifts toward New Zealand (+4.3%), with only minor changes for the remaining exporters (all below 1.0%). Overall, the risk-optimal portfolio remains broadly diversified and robust under time-varying political instability.

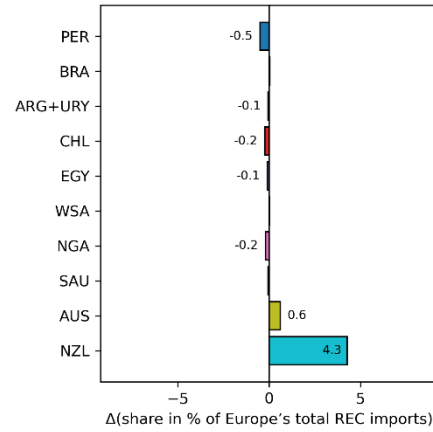
In the compromise solution, time-varying political instability leads to redistributions while preserving the set of key suppliers. Under deterioration, Nigeria (−4.0%) and Saudi Arabia (−1.8%) lose share, offset primarily by Argentina & Uruguay (+3.4%) and WSA (+2.0%). Under improvement, Nigeria's share decreases (−7.7%), with offsetting increases for Argentina & Uruguay (+3.7%), Chile (+2.8%), and Peru (+1.7%).

Overall, this political instability sensitivity analysis indicates that the set of main exporters remains stable within the historically observed range of political-risk variation. More extreme future shifts in political instability could, in principle, alter export-partner selection, but exploring such structural changes would require explicit political-risk forecasting.

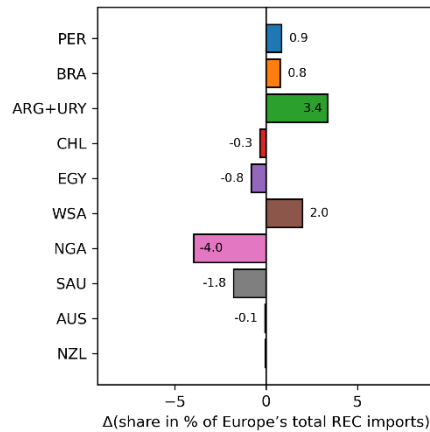
a) Supply risk-optimal solution
(deterioration trajectories)



b) Supply risk-optimal solution
(improvement trajectories)



c) Compromise solution
(deterioration trajectories)



d) Compromise solution
(improvement trajectories)

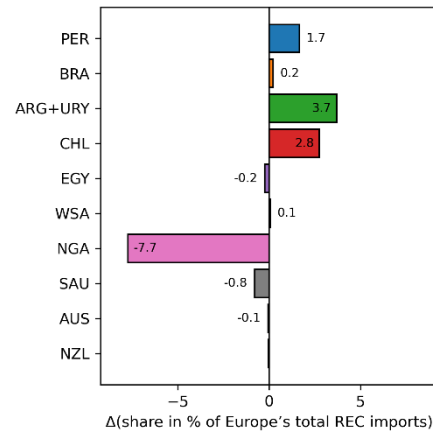


Figure 6.11. Change in export shares under time-varying political instability trajectories: supply risk-optimal solutions for (a) deterioration and (b) improvement trajectories, and compromise solutions for (c) deterioration and (d) improvement trajectories relative to the base political-instability case.

6.4.3.5 Sensitivity to REC demand

In a sensitivity analysis, we assess the impact of changing REC demand in both exporting regions and the importing region by $\pm 20\%$ and assess their impact on the design of optimal and compromise solutions. Similarly, we calculate compromise solutions for these scenarios according to the benchmark supply-security risk. Figure 6.12 shows that changing the REC demand primarily affects the cost and emissions associated with resource utilization and REC production. Compared with the base case, changing REC demand alters both the set and the shares of REC exporting regions. A 20% decrease in demand reduces REC imports from several regions, although imports from countries like Saudi Arabia slightly increase (more hydrogen export via pipelines). Decreased hydrogen and methane demand lead to fewer pipeline

installations from Saudi Arabia and Tunisia, respectively. In the high demand scenario, the optimal supply chain includes an additional pipeline from Egypt. In the low-demand scenario, about 50% of hydrogen imports are transported via pipelines and 50% via LOHC ships, while hydrogen import via liquid-hydrogen ships has less than 1% share. In the high-demand scenario, almost 30% of hydrogen import is transported via pipelines and 70% via LOHC ships.

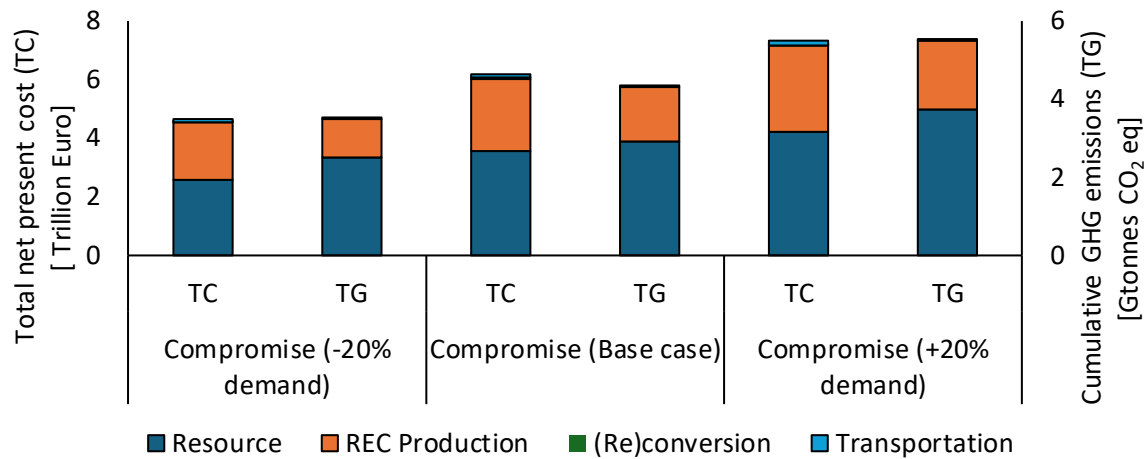


Figure 6.12. Total net present cost (TC) and Cumulative GHG emissions (TG) structure for the REC supply chain in low (-20%) and high (+20%) demand scenarios.

6.4.3.6 Sensitivity to cost parameters

We investigate changes of $\pm 5\%$, $\pm 10\%$, and $\pm 20\%$ in cost parameters to explore their impact on the optimal solutions. This analysis covers resource utilization, transportation, production, and renewable electricity costs. Figure 6.13 shows that variations in production and renewable electricity costs have by far the strongest effect: a $\pm 20\%$ change in production (renewable electricity) costs translates into roughly -12% to $+12\%$ (-7% to $+7\%$) changes in total net present costs, whereas equally large changes in resource utilization and transportation costs affect total net present costs by less than 1%.

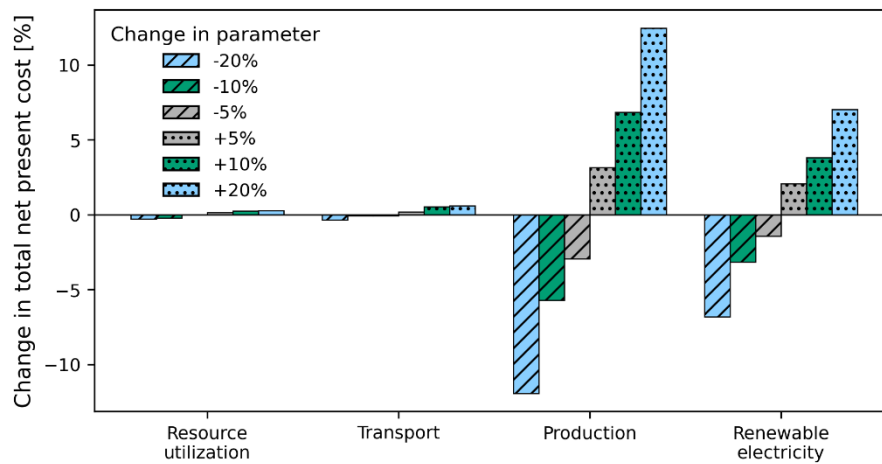


Figure 6.13. Sensitivity of total net present costs for the REC supply chain to Europe. Percentage change in total net present costs when varying resource utilization, transportation, production, and renewable electricity costs by -5% , -10% , -20% and $+5\%$, $+10\%$, $+20\%$ relative to the base case.

This sensitivity analysis confirms that, across all tested values, renewable electricity and production costs remain the dominant drivers of net present costs, highlighting the importance of scaling, technological progress, and learning effects (World Energy Council, 2022).

In an additional sensitivity case, we consider technological advancements for DAC, electrolysis, methanol synthesis, methanation, and Fischer–Tropsch fuel synthesis in terms of cost, capacity, and efficiency (see Table 6.B.7). These assumptions reduce total net present costs by roughly 22% compared with the base case. However, the set of main exporting regions remains essentially unchanged: Chile, Saudi Arabia, and Peru still supply most REC imports, with only moderate shifts in their relative shares. This indicates that techno-economic learning further improves the economic attractiveness of REC imports without qualitatively altering the geographic structure of optimal supply.

6.5 Implications: Partnerships for REC supply chains

Developing REC supply chains significantly supports climate neutrality targets and requires an expansion of REC infrastructure and enhanced REC trade (World Energy Council, 2022). Our findings are relevant for energy policy, providing a comprehensive analysis of REC imports to Europe. By identifying optimal export regions and transportation technologies, this research enables decision-makers to identify cost-effective regions for REC development while considering environmental impacts and supply security, thereby supporting strategic REC-import planning.

Evaluating the economic, environmental, and supply-security aspects of REC supply chains reveals that optimal solutions differ depending on stakeholder priorities. For instance, focusing exclusively on supply security approximately triples total costs compared to the cost-optimal solution, highlighting the value of compromise solutions for policymakers and investors. We identify a compromise solution that illustrates a balanced approach to REC supply without drastic trade-offs.

Furthermore, decision-makers' preferences regarding objective functions (cost, emissions, or supply-security risk) affect the choice of exporting regions and transportation methods. Thus, REC trade necessitates strategic agreements and partnerships that support long-term deployment of infrastructure. Our analysis suggests that, in addition to exporting regions and adequate renewable capacity, the quantity of RECs traded, and the chosen transport modes also depend on these preferences.

High potential for pipeline-based REC imports from several regions (e.g., Saudi Arabia, Nigeria, and Morocco) aligns with existing partnerships (BMWK, 2023; Braun et al., 2023; European Clean Hydrogen Alliance, 2023; Fasihi et al., 2017; Koshikwinja et al., 2025; van Wijk and Wouters, 2021). Moreover, studies on potential REC pipelines, such as the Saudi Arabia-Europe pipeline (100 TWh/year) or the Nigeria-Morocco gas pipeline (300 TWh/year) (Abdelshafy et al., 2024; AFRY, 2023; IRENA, 2022a; Koshikwinja et al., 2025; van Wijk and Wouters, 2021), are in line with our results. Similarly, shipping-based imports from Chile, Peru, Brazil, and Argentina also align with earlier findings (European Clean Hydrogen Alliance, 2023; Fasihi et al., 2016; Fasihi et al., 2021; Franzmann et al., 2023; Galimova, Ram et al., 2023; Hank et al., 2023; Moritz et al., 2023). Recent strategies in Chile, Argentina, and Brazil further emphasize the development of REC trade partnerships (Agora Energiewende, 2023; European Commission, 2024a, 2025b; IRENA, 2024b).

Finally, such developments and international collaborations may boost Europe's energy security while contributing to decarbonization efforts. Our analysis shows how a system designed for REC supply from renewable resource-rich regions can balance cost, GHG emissions, and supply security. Notably, Europe can benefit by broadening long-term REC trade partnerships beyond a small set of frequently considered countries, diversifying its future import dependencies (BMWK, 2023; CASSIS, EWI, 2025; IRENA, 2022b). Our analysis suggests that some regions less frequently mentioned in the literature, such as Peru and Nigeria, could be potential REC partners for Europe (Franzmann et al., 2023; Koshikwinja et al., 2025). By

informing policy and investment decisions, our study offers guidance for more comprehensive planning of sustainable REC development across Europe.

6.6 Conclusions and outlook

In this study, we present a multi-period, multi-objective mixed-integer quadratic programming (MIQP) model that integrates economic and environmental objectives with a supply-security risk proxy to identify optimal exporting regions, production pathways, and transportation technologies for multiple RECs.

Our case study examines REC imports to Europe from regions with high renewable energy potential. By assessing the Pareto-efficient frontier, we highlight trade-offs among these objectives. In the cost-optimal solution, hydrogen is primarily transported via pipelines, whereas in the GHG-optimal, supply risk-optimal, and compromise solutions, hydrogen is mainly transported as LOHC by ship. Methane relies on pipelines across all optimal and compromise solutions. Regions such as Chile and Saudi Arabia emerge as prominent exporters in the cost-optimal approach, whereas Argentina, Peru, and Nigeria also play significant roles in other optimal solutions.

These findings clearly show that optimizing a single objective can lead to suboptimal outcomes for other objectives, highlighting the need for a balanced approach to REC import planning. For instance, prioritizing cost minimization increases reliance on fewer exporting regions, potentially affecting supply security while raising emissions. Conversely, prioritizing only lower GHG emissions results in higher costs and less diversification of supply sources. Therefore, addressing multiple objectives simultaneously can yield compromise solutions that balance economic efficiency, environmental performance, and overall supply security for the REC-importing region. By incorporating multiple viable exporters, Europe can strengthen its security through greater supply diversity, mitigating risks linked to over-reliance on specific exporting regions.

Sensitivity analyses varying exporter configurations (Australia and New Zealand, inclusion of China), political instability assumptions, REC demand levels, key cost parameters, and technological advancements in production processes confirm that our main qualitative insights are robust. While total net present costs and individual exporter shares shift, the set of main exporting regions remains broadly unchanged across the economic, environmental, supply-security, and compromise perspectives.

In conclusion, our multi-objective model provides a comprehensive tool for designing REC import strategies, integrating economic and environmental objectives with a political-risk-weighted HHI proxy for supply-security risk. By highlighting regions with cost-effective export potential and emphasizing the importance of balancing these objectives, the model can support Europe in progressing toward sustainable energy goals while supporting a more diversified import portfolio and lower supply-security risk. The model can inform policymakers, enhance energy planning, and facilitate broader REC partnerships, ultimately accelerating the market ramp-up of RECs.

Although this study provides valuable insights into REC imports to Europe, some limitations should be acknowledged to guide future research developments. Future studies could include expanded geographic scope, higher-resolution spatial data, and more comprehensive modeling of risks beyond diversification proxies, particularly regarding geopolitical and technological disruptions, natural hazards, and changes in trade agreements. Incorporating other crucial factors, such as technical and economic risks, could further enhance supply-security evaluations. Moreover, a more detailed spatial resolution would improve accuracy in identifying optimal infrastructure locations and in generating more precise assessments. Addressing these limitations will enhance accuracy in the evaluation of global energy systems and foster more robust policy and investment decisions.

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6.A. Appendices

6.A.1. Abbreviations

Table 6.A.1. Abbreviations

Abbreviation	Description
AEL	Alkaline electrolysis
FT	Fischer-Tropsch
GHG	Greenhouse gas
HHI	Herfindahl–Hirschman Index
DAC	Direct air capture
LH ₂	Liquid hydrogen
LNG	Liquefied natural gas
LOHC	Liquid organic hydrogen carriers
MTG	Methanol-to-gasoline
PV	Photovoltaic
RE	Renewable energy
REC	Renewable energy carrier

6.A.2. List of European countries included in the case study

Table 6.A.2. List of European countries included in the case study (as the importing region)

Abbreviation	Countries
NOR	Norway
DNK	Denmark
SWE	Sweden
FIN	Finland
BLT	Estonia, Latvia, Lithuania
POL	Poland
IBE	Portugal, Spain, Gibraltar
FRA	France, Monaco, Andorra
BNL	Belgium, Netherlands, Luxembourg
BRI	Ireland, United Kingdom, Isle of Man, Guernsey, Jersey
DEU	Germany
CRS	Czech Republic, Slovakia
AUH	Austria, Hungary
BKN-W	Slovenia, Croatia, Bosnia and Herzegovina, Serbia, Montenegro, Macedonia, Albania
BKN-E	Romania, Bulgaria, Greece
ITA	Italy, San Marino, Vatican, Malta
CHE	Switzerland, Liechtenstein
TUR	Turkey, Cyprus

UKR	Ukraine, Moldova
ISL	Iceland

6.A.3. List of potential regions for exporting RECs in the case study

Table 6.A.3. List of potential regions for exporting RECs in the case study (as exporting regions).

Abbreviation	Countries
ARG+URY	Argentina, Uruguay
AUS	Australia
BRA	Brazil
CHL	Chile
COL	Colombia
COD	Democratic Republic of the Congo
DZA	Algeria
EGY	Egypt
KEN+UGA	Kenya, Uganda
MAR	Morocco
MEX	Mexico
NGA	Nigeria
NZL	New Zealand
OMN	Oman
PER	Peru
SAU	Saudi Arabia
MWI+MOZ+ZMB+ZWE	Malawi, Mozambique, Zambia, Zimbabwe
NAM+AGO+BWA	Namibia, Angola, Botswana
TUN	Tunisia
TZA+RWA+BDI	Tanzania, Rwanda, Burundi
GHA+CIV+BEN+BFA+TGO	Ghana, Côte d'Ivoire, Benin, Burkina Faso, Togo
MRT+SEN	Mauritania, Senegal
ZAF+LSO	South Africa, Lesotho
CHN	China (sensitivity analysis)
TCD+NER	Chad, Niger (sensitivity analysis)

Note: In Figures 6.7 and 6.B.4-6.B.8, aggregated regions are shown with short labels for readability: WSA = GHA+CIV+BEN+BFA+TGO, ESA = MWI+MOZ+ZMB+ZWE, SWA = NAM+AGO+BWA, GLA = TZA+RWA+BDI, and SAH = TCD+NER.

6.B. Supplementary Information

This Supplementary Information provides (i) full model notation and constraints, (ii) complete case-study input data and screening indicators, and (iii) additional results, sensitivity outputs, and Pareto-efficient solutions.

6.B.1. Model nomenclature

Table 6.B.1 presents the notation for the mathematical model.

Table 6.B.1. Notation.

Sets	Description
$t \in T$	Index set of yearly planning periods
$t \in T_0$	Index set of planning periods, including a start period t_0 , with $T_0 = T \cup \{t_0\}$
$i \in I$	Index set of regions with potential for exporting RECs
$i \in I_0$	Index set of regions, including exporting regions and the importing region i_0 , with $I_0 = I \cup \{i_0\}$
$p \in P$	Index set of production technologies
$p \in P^c \subset P$	Index set of reconversion technologies
$q \in Q$	Index set of transportation technologies
$q \in Q^s \subset Q$	Index set of ship types
$q \in Q^d \subset Q$	Index set of pipeline types
$m \in M$	Index set of resources
$m \in M^r \subset M$	Index set of RECs
$o \in O$	Index set of resource origins
$o \in O^e \subset O$	Index set of renewable electricity resources
Parameters	Description
τ	Discounting factor
f_o	Specific investment cost for renewable electricity technology o [€/MW]
f_p	Investment cost for production technology p [€]
f_q	Specific investment cost for transportation technology q [€/km] or [€/ship]
v_o	Specific annual operating cost for generating renewable electricity o [€/MW/year]
v_p	Annual operating cost for production technology p [€/year]
v_q	Specific annual operating cost for transportation technology q [€/km/year] or [€/ship/year]
u_q	Cost of unit transportation via technology q [€/tonne]
u_q^{dist}	Distance-related cost of unit transportation via technology q [€/tonne/km]
π_{oit}	Unit cost of utilizing resource origin o in region i in period t [€/tonne]

d_{mit}	Annual demand for resource m in region i in period t [tonne/year] or [MWh/year]
λ_m	Lower heating value of resource m [MWh/tonne]
η_{qmit}	Emission factor for transporting resource m via technology q from exporting region i to the importing region in period t [tonne CO ₂ eq/tonne]
η_{pit}	Emission factor for production technology p in region i in period t [tonne CO ₂ eq/tonne]
η_{oit}	Emission factor for resource origin o in region i in period t [tonne CO ₂ eq/tonne] or [tonne CO ₂ eq/MWh]
b_{qm}	1 if resource m can be transported via technology q ; 0 otherwise
b_{qi}	1 if export is possible via transportation technology q from exporting regions i to the importing region; 0 otherwise
β_{om}	1 if resource origin o can be converted to resource m ; 0 otherwise
α_{mp}	Conversion factor of resource m in production technology p [tonne/tonne] or [MWh/tonne]
l_{qi}	Distance for transportation technology q from exporting region i [km]
l_i^{inland}	Average distance for inland transportation in exporting region i [km]
H	Operating hours per year [hours/year]
k_p	Annual production capacity of technology p [tonne/year]
k_{qi}	Annual transportation capacity of technology q from exporting region i [tonne/year]
r_{oit}	Potential for resource origin o in region i in period t [tonne/year]
t'_o, t'_p, t'_q	First period in which renewable electricity technology o , production technology p , and transportation technology q are available
ϑ_{oi}	Annual average capacity factor for renewable electricity production o in region i [-]
θ_{oi}	Maximum installable capacity for generating renewable electricity o in region i [MW]
γ_{qmi}	Annual consumption of resource m per unit distance for transportation technology q from exporting region i [tonne/km/year]
μ_{it}	Normalized political instability of exporting region i in period t [-]
Decision variables	Description
δ_{pit}	Number of installed plants of production technology p in region i in period t [-]
κ_{qit}	Number of units transportation technology q for export from region i to the importing region in period t [-]
σ_{oit}	Installed capacity of renewable electricity technology o in region i in period t [MW]
x_{pit}	Production rate of technology p in region i in period t [tonne/year]
z_{qmit}	Import quantity of resource m via transportation technology q from region i to the importing region in period t [tonne/year]

w_{oit} Amount of resource origin o utilized in region i in period t [*tonne/year*]
or [*MWh/year*]

6.B.2. Constraints

Our model constraints cover resource balance, infrastructure capacity, resource utilization, technology availability, and variable domains.

Balance constraints

Constraints (6.B.1) state the balance for resource m in region i over the planning horizon $t \in T$. On the left-hand side, the terms represent the supply of resource m from resource origin o and the production ($\alpha_{mp} > 0$) or consumption ($\alpha_{mp} < 0$) of resource m by process p . On the right-hand side, the terms account for:

- non-RECs ($m \in M \setminus M^r$): Since we only import RECs, there is no transportation of non-RECs to the importing region.
- RECs ($m \in M^r$): It includes domestic REC demand (d_{mit}) within region i , quantity of RECs exported (z_{qmit}), and the consumption of RECs during transportation (ρ_{qmit}).

$$\begin{aligned} & \sum_{o \in O} \beta_{om} w_{oit} + \sum_{p \in P} \alpha_{mp} x_{pit} \\ & \geq \begin{cases} d_{mit} & \forall m \in M \setminus M^r \\ d_{mit} + \sum_{q \in Q \mid b_{qm}=1} z_{qmit} + \sum_{q \in Q} \rho_{qmit} & \forall m \in M^r \end{cases} \quad \forall i \in I, t \in T \quad (6.B.1) \end{aligned}$$

Constraints (6.B.2) describe REC consumption (ρ_{qmit}) caused by operating transportation technology q from region i in period t as a function of κ_{qit} . Here, γ_{qmi} denotes the annual consumption value of REC m required to operate transportation technology q (e.g., pipeline compressors, ship engines) (Hampp et al., 2023).

$$\rho_{qmit} = \gamma_{qmi} l_{qi} \kappa_{qit} \quad \forall q \in Q, m \in M^r, i \in I, t \in T \quad (6.B.2)$$

For the importing region (i_0), Constraints (6.B.3) ensure the balance for resource m in the importing region over the planning horizon $t \in T$. Similar to Constraints (6.B.1), there is no transportation of non-RECs ($m \in M \setminus M^r$) to the importing region. For RECs ($m \in M^r$), import needs can be met directly by imported RECs and possibly by converting other imported RECs.

$$\left\{ \begin{array}{l} \sum_{o \in O} \beta_{om} w_{oi_0t} + \sum_{p \in P^c} \alpha_{mp} x_{pi_0t} \quad \forall m \in M \setminus M^r \\ \sum_{q \in Q} \sum_{b_{qm}=1} \sum_{i \in I} z_{qmit} + \sum_{o \in O} \beta_{om} w_{oi_0t} + \sum_{p \in P^c} \alpha_{mp} x_{pi_0t} \quad \forall m \in M^r \end{array} \right. \geq d_{mi_0t} \quad \forall t \in T \quad (6.B.3)$$

Production and transportation constraints

According to Constraints (6.B.4), the upper bound for a production process p relates to installed capacity (δ_{pit}) and annual capacity (k_p) in both exporting and importing regions ($i \in I_0$).

$$x_{pit} \leq k_p \delta_{pit} \quad \forall p \in P, i \in I_0, t \in T \quad (6.B.4)$$

Constraints (6.B.5) specify the upper bound for the quantity of transported RECs based on the installed capacity (κ_{qit}) of the transportation technology q and the annual capacity (k_{qi}).

$$z_{qmit} \leq k_{qi} \kappa_{qit} \quad \forall q \in Q, m \in M^r, i \in I, t \in T \quad (6.B.5)$$

Constraints (6.B.6) and (6.B.7) prohibit the use of transportation technologies that are incompatible for the specific resource type or that cannot be deployed from a given exporting region. The binary parameter b_{qm} enforces that only feasible combinations of resources and technology are used (e.g., ammonia can be shipped but not transported via hydrogen pipelines), while b_{qi} restricts exports from regions that are not connected via a given technology (e.g., no pipeline connection).

$$z_{qmit} = 0 \quad \forall q \in Q, m \in M, i \in I, t \in T, | b_{qm} = 0 \vee b_{qi} = 0 \quad (6.B.6)$$

$$\rho_{qmit} = 0 \quad \forall q \in Q, m \in M, i \in I, t \in T, | b_{qm} = 0 \vee b_{qi} = 0 \quad (6.B.7)$$

According to Constraints (6.B.8) and (6.B.9), infrastructure installed over the planning horizon cannot be deinstalled. Therefore, the number of production and transportation facilities cannot decrease over time.

$$\delta_{pi(t-1)} \leq \delta_{pit} \quad \forall p \in P, i \in I_0, t \in T \quad (6.B.8)$$

$$\kappa_{qi(t-1)} \leq \kappa_{qit} \quad \forall q \in Q, i \in I, t \in T \quad (6.B.9)$$

Renewable electricity generation constraints

Constraints (6.B.10) determine the amount of electricity generated by renewable sources based on the installed capacity (σ_{oit}), the average regional capacity factor (ϑ_{oi}) and the operating hours (H).

$$w_{oit} \leq H \sigma_{oit} \vartheta_{oi} \quad \forall o \in O^e, i \in I_0, t \in T \quad (6.B.10)$$

Constraints (6.B.11) and (6.B.12) state that the installed capacity of renewable electricity cannot exceed the regional capacity and cannot decrease over time.

$$\sigma_{oit} \leq \theta_{oi} \quad \forall o \in O^e, i \in I_0, t \in T \quad (6.B.11)$$

$$\sigma_{oi(t-1)} \leq \sigma_{oit} \quad \forall o \in O^e, i \in I_0, t \in T \quad (6.B.12)$$

Resource utilization constraints

Constraints (6.B.13) specify that the utilization of each resource origin cannot exceed its regional availability r_{oit} .

$$w_{oit} \leq r_{oit} \quad \forall o \in O \setminus O^e, i \in I_0, t \in T \quad (6.B.13)$$

Technology availability constraints

We consider technological progress by introducing an availability year for each process (production, transportation, and renewable electricity generation). Over the long-term planning horizon, several technology variants with different costs, efficiencies, and capacities may become available. Constraints (6.B.14) to (6.B.16) reflect the availability of new technologies for production (p), transportation (q) and renewable electricity technology (o), as well as improvements in process yield and cost efficiency. Consequently, new technologies can only be installed after they become available. In Constraint (6.B.14), a production technology with availability year t'_p may only be installed for periods with $t \geq t'_p$. For $t < t'_p$, the number of installed units must be zero.

Constraint (6.B.15) applies the same logic to transportation technologies q , using their respective availability year t'_q . Before t'_q , the number of units of transportation technology q is forced to zero.

Constraint (6.B.16) restricts the installation of renewable electricity technologies to periods at or after their availability year t'_o . This can also be used to implement gradual improvements in efficiency or cost by introducing new generations of technologies with different parameters and availability years.

If Constraints (6.B.14)–(6.B.16) are not included, all technologies could in principle be installed from the first period, and technological progress over time could not be represented. Thus, these constraints are essential to link the dynamic availability of technologies (as specified in the data) with the timing of investment decisions in the model.

$$\delta_{pit} = 0 \quad \forall p \in P, i \in I_0, t \in T, | t < t'_p \quad (6.B.14)$$

$$\kappa_{qit} = 0 \quad \forall q \in Q, i \in I, t \in T, | t < t'_q \quad (6.B.15)$$

$$\sigma_{oit} = 0 \quad \forall o \in O^e, i \in I_0, t \in T, | t < t'_o \quad (6.B.16)$$

Variable domains

Lastly, Constraints (6.B.17) to (6.B.21) specify the domains of the decision variables.

$$\delta_{pit} \in \mathbb{N}_0 \quad \forall p \in P, i \in I_0, t \in T_0 \quad (6.B.17)$$

$$\kappa_{qit} \in \mathbb{N}_0 \quad \forall q \in Q, i \in I, t \in T_0 \quad (6.B.18)$$

$$\sigma_{oit} \geq 0 \quad \forall o \in O^e, i \in I_0, t \in T_0 \quad (6.B.19)$$

$$x_{pit} \geq 0, w_{oit} \geq 0 \quad \forall p \in P, o \in O, i \in I_0, t \in T \quad (6.B.20)$$

$$z_{qmit} \geq 0 \quad \forall q \in Q, m \in M, i \in I, t \in T \quad (6.B.21)$$

6.B.3. Case-study input data

This section reports the full numerical input dataset underlying the European import case study, including exporting-region screening indicators, renewable-electricity potentials, resource availability, techno-economic parameters, demand trajectories, and political-instability indicators.

Exporting-region screening and selection

To transition toward defossilization, Europe requires imports of renewable energy carriers and is expected to face an import dependency of around 50% (European Commission, 2021b).

Selection of exporting regions. We consider 23 exporting regions with high techno-economic potential for REC supply. Candidate regions are preselected based on (i) global REC trade potential studies identifying cost-competitive suppliers (Galimova, Ram et al., 2023; Hank et al., 2023; Pieton et al., 2023; World Energy Council, 2022), and (ii) consistency with European hydrogen and REC partnership strategies (Africa, Middle East, Latin America, Oceania) (GIZ, 2023; Hydrogen Council, 2023; IRENA, 2022b). Across these studies, the preselected exporters combine excellent potential for renewable electricity generation (solar PV and onshore wind) (Tables 6.B.5–6.B.6).

In the second step, we apply exclusion criteria based on water availability and extreme political instability. Regions located in areas of high water stress (Tonelli et al., 2023) and without access to seawater for large-scale desalination are not retained as exporting regions. Furthermore, we use the World Bank political instability indicator (World Bank, 2024) to construct a normalized political instability parameter for each preselected country (Table 6.B.10). Regions whose current political instability values lie at the extreme level of the global range are excluded from

the exporter set. With this assumption, we keep the case study focused on exporting regions with robust data and moderate-to-high, but not extreme, political instability.

Some large economies that are sometimes discussed as potential REC exporters, most notably China, India, and the United States, are not included in the exporter set in our case study. Recent REC trade and geopolitics studies increasingly classify these countries primarily as major importers with ambitious domestic decarbonization needs, rather than as structural long-term REC exporters to Europe (GIZ, 2023; IRENA, 2022e). In several scenarios, they are either close to self-sufficiency or focus on regional trade within Asia or the Americas, while Europe's main import partners are located in North Africa, the Middle East, Latin America and parts of Sub-Saharan Africa (GIZ, 2023; IRENA, 2022b, 2025). Against this background, our case study does not consider China, India and the United States as potential REC exporters to Europe (they are treated as outside the exporter set). In a sensitivity analysis, we additionally examine a variant where China is included as a potential exporter to assess the robustness of this assumption (Section 4.3.2 in the main manuscript). Taken together, the chosen exporter set therefore reflects (i) strong techno-economic export potential for RECs, (ii) alignment with current European REC and hydrogen partnership strategies, and (iii) transparent, data-driven filters on water availability and extreme political instability.

Resources and technologies. We collect data on regional resource availability for freshwater, CO₂, and renewable electricity. We derive wind and PV potentials based on work by Galimova, Ram et al. (2023). Water availability derives from freshwater sources (by subtracting agricultural, industrial, and municipal uses) (Tonelli et al., 2023). We determine CO₂ availability based on unavoidable industrial sources (e.g., cement, biogenic) (Global Carbon Project, 2022; Marconi and Rosa, 2023).

For each resource, we consider a range of enabling technologies, including desalination and DAC (Liebich et al., 2021), air separation (Hampp et al., 2023), and REC production as well as conversion, and reconversion processes (FVV, 2021; The Danish Energy Agency, 2018a). Seawater desalination units can supply the water needed in addition to the regionally available freshwater. Similarly, DAC modules can capture CO₂ to supplement the regional availability from unavoidable industrial sources. Nitrogen is produced via air separation units. We include hydrogen, methane, methanol, ammonia, and FT fuels as RECs. In this case study, ammonia serves a dual purpose: (1) meeting direct demand and (2) acting as a hydrogen carrier that can be cracked into hydrogen upon arrival. After the initial conversion for transportation (e.g.,

gaseous hydrogen into ammonia), these carriers are reconverted to their usable form upon arrival (Hampp et al., 2023).

Transport options. For transporting RECs, we consider specific ship and pipeline technologies aligned with each REC type. Hydrogen and methane are transported via pipelines in gaseous form, while liquid hydrogen, liquid methane, methanol, ammonia, and FT fuel are transported via ships (Hampp et al., 2023; The Danish Energy Agency, 2018b). We assume the transportation energy requirements come from the same REC being transported; for instance, methanol ships use methanol as fuel (Hampp et al., 2023; Oeko-Institut, 2023). Boil-off gas from RECs (e.g., liquid hydrogen) is also assumed to be used as an energy source for the transportation system (Bakkali and Ziomas, 2019; European Commission, 2024b; Schuler et al., 2024). In the model, these transport energy requirements are represented as endogenous REC consumption during transport, which reduces the delivered quantity and thereby increases upstream production requirements. Potential REC leakage during transportation is assumed to be negligible (The Danish Energy Agency, 2018b).

Demand, planning horizon and model size. We estimate REC demand in each exporting region as well as in the importing region (Galimova, Ram et al., 2023; Tonelli et al., 2023). We assume that half of RECs in Europe will be covered by imports (European Commission, 2021b). Exporting regions first satisfy their domestic REC demand, and can then export any surplus. Figure 6.B.1 visualizes 2050 REC demand for hydrogen, methane, methanol, ammonia, and FT fuels in each exporting region (domestic demand) and in Europe (import demand).

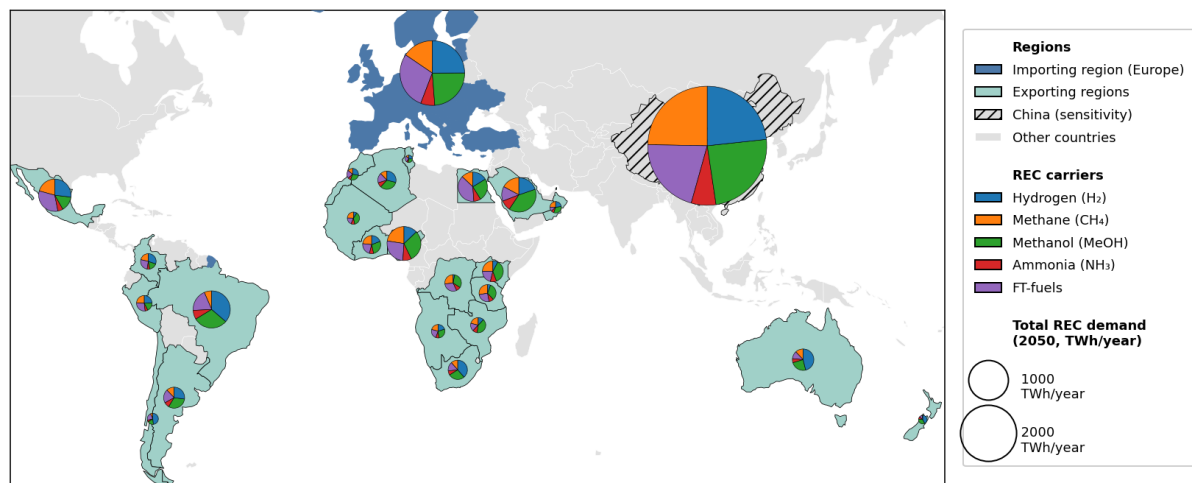


Figure 6.B.1. Case-study regions and REC demand in 2050. For each region, a pie chart is proportional to total REC demand in 2050 (TWh/year), and the slices indicate the demand shares of hydrogen, methane, methanol, ammonia, and FT fuels.

We set a planning horizon from 2030 to 2055 on an annual basis. We consider 23 regions for potential export of RECs to Europe. The case study includes 16 production technologies and 8 transportation technologies. The model comprises 81,218 continuous and 12,096 integer variables. Details of the solution procedure and solver settings are described in the Solution procedure subsection.

6.B.4. Numerical input tables

Tables 6.B.2–6.B.13 report the complete numerical inputs used in the case study.

Table 6.B.2. Costs related to renewable electricity modules in the case study (FVV, 2021).

Technology	f_o [M€/MW]	v_o [1000€/MW/yr]	t'_o
Wind turbine	1.2	39.6	2030
Wind turbine	1.15	37.9	2040*
Wind turbine	1.1	36.3	2050
Solar PV	0.68	10.1	2030
Solar PV	0.59	8.8	2040*
Solar PV	0.5	7.5	2050

* Estimated by interpolation.

Table 6.B.3. Availability of CO₂ from cement industry in the case study (Global Carbon Project, 2022; Marconi and Rosa, 2023).

Region	CO ₂ potential cement industry [Mtonnes/yr]	CO ₂ Potential biogenic [Mtonnes/yr]
ARG+URY	5.4	21.7
AUS	2.9	11.2
BRA	23.6	103.5
CHL	1.0	3.7
COL	6.2	11.4
COD	0.6	8.2
DZA	9.6	5.5
EGY	20.6	14.4
KEN+UGA	5.5	10.8
MAR	5.1	5.0
MEX	21.5	26.0
NGA	11.2	24.2
NZL	0.4	1.2
OMN	2.3	0.3
PER	5.5	5.6
SAU	30.0	3.6
MWI+MOZ+ZMB+ZWE	3.1	7.0
NAM+AGO+BWA	1.7	4.3
TUN	4.2	1.6
TZA+RWA+BDI	2.7	12.4
GHA+CIV+BEN+BFA+TGO	2.5	16.9
MRT+SEN	3.8	1.8
ZAF+LSO	5.3	11.8
CHN	763.4	230.2

Table 6.B.4. Availability of regional freshwater in the case study (Tonelli et al., 2023).

Region	Freshwater 2030 [Gtonnes/yr]	Freshwater 2050 [Gtonnes/yr]
ARG+URY	165	641
AUS	79	81
BRA	1661	1665
CHL	122	255
COL	12529	11113
COD	31	14
DZA	0	0
EGY	0	0
KEN+UGA	12	15
MAR	0	0
MEX	0	0
NGA	5	7
NZL	215	185
OMN	0	0
PER	78	81
SAU	0	0
MWI+MOZ+ZMB+ZWE	68	125
NAM+AGO+BWA	195	422
TUN	0	0
TZA+RWA+BDI	17	561
GHA+CIV+BEN+BFA+TGO	20	100
MRT+SEN	36	82
ZAF+LSO	0	0
CHN	0	0

Note: Water availability is derived from freshwater resources after subtracting agricultural, industrial, and municipal uses.

Table 6.B.5. Maximum installable capacity for renewable energy in the case study (Galimova, Ram et al., 2023).

Region	Solar PV capacity [GW]	Wind power capacity [GW]
ARG+URY	8790	897
AUS	22826	2547
BRA	24707	2857
CHL	2242	230
COL	3226	384
COD	6816	788
DZA	6986	787
EGY	2311	263
KEN+UGA	2286	229
MAR	1236	146
MEX	3878	481
NGA	4434	596
NZL	787	81
OMN	862	101
PER	3690	432
SAU	5756	634
MWI+MOZ+ZMB+ZWE	6115	699
NAM+AGO+BWA	9240	1044
TUN	443	52
TZA+RWA+BDI	2807	335
GHA+CIV+BEN+BFA+TGO	2780	338
MRT+SEN	9551	1071
ZAF+LSO	3538	392
CHN	15801	1140

Table 6.B.6. Capacity factor for renewable energy in the case study (Galimova, Ram et al., 2023).

Region	Solar PV [-]	Wind power [-]
ARG+URY	0.21	0.55
AUS	0.23	0.39
BRA	0.22	0.34
CHL	0.24	0.53
COL	0.21	0.00
COD	0.21	0.02
DZA	0.23	0.34
EGY	0.23	0.33
KEN+UGA	0.24	0.44
MAR	0.22	0.32
MEX	0.24	0.28
NGA	0.22	0.55
NZL	0.17	0.45
OMN	0.25	0.29
PER	0.25	0.61
SAU	0.24	0.30
MWI+MOZ+ZMB+ZWE	0.23	0.29
NAM+AGO+BWA	0.24	0.31
TUN	0.20	0.31
TZA+RWA+BDI	0.24	0.34
GHA+CIV+BEN+BFA+TGO	0.22	0.16
MRT+SEN	0.23	0.35
ZAF+LSO	0.23	0.36
CHN	0.20	0.50

Table 6.B.7. Techno-economic data of production technologies in the case (Caldera and Breyer, 2017; FVV, 2021, 2022; Hampp et al., 2023; Liebich et al., 2021; Linde, 2025; Reuß et al., 2017; The Danish Energy Agency, 2018a). Base-case values correspond mainly to 2030 assumptions; technologies marked with † are used only in the technology-advancement sensitivity case.

Technology	k_p [tonnes/day]	f_p [M€]	v_p [M€/yr]	t'_p
Desalination	133000	153	6.14	2030
Air separation unit	229	5.67	0.17	2030
DAC	0.14	0.11	0.004	2030
DAC [†]	0.14	0.01	0.0004	2050
AEL	0.74	0.99	0.02	2030
AEL [†]	0.74	0.11	0.002	2050
Hydrogen Liquefaction	10	10	0.25	2030
Hydrogen evaporation	10	1.7	0.04	2030
LOHC hydrogenation	300	40	1.20	2030
LOHC dehydrogenation	300	30	0.90	2030
Haber-Bosch	444	140	4.20	2030
Ammonia cracker	200	248	10.68	2030
Methanation	35	12	0.29	2030
Methanation [†]	867	53	1.31	2050
Methane liquefaction	1000	113	3.96	2030
Methane evaporation	1000	43	1.07	2030
Methanolisation	600	150	4.49	2030
Methanolisation [†]	900	198	5.93	2040
MTG	1300	98	2.45	2030
FT fuel synthesis	1125	1215	48.62	2030
FT fuel synthesis [†]	2964	2723	198.91	2050

Table 6.B.8. Costs of transportation for pipeline types (Cloete et al., 2021; Guidehouse, 2021).

Technology	k_q [tonnes/hour]	f_q [1000 €/km]	v_q [1000 €/km/yr]	u_q [€/tonne]
Hydrogen pipeline	157	2232	44.64	-
Methane pipeline	1484	2232	44.64	-

Table 6.B.9. Costs of transportation for ship types (Depken et al., 2022; Dieterich et al., 2020; Hampp et al., 2023; Runge et al., 2023; The Danish Energy Agency, 2018b).

Technology	Ship capacity [1000 tonnes/ship]	f_q [M€/ship]	v_q [M€/ship/yr]	u_q [€/tonne]	u_q^{dist} [€/tonne/km]
LH ₂ ship	11	361	14.45	47.85	1.01
LOHC ship	75	32	1.59	82.94	1.99
Ammonia ship	53	74	2.98	3.93	0.11
LNG ship	58.3	151	5.29	0.91	0.03
Methanol ship	75	32	1.59	2.92	0.09
FT fuel ship	75	32	1.22	2.98	0.10

Table 6.B.10. Normalized political instability of exporting region (World Bank, 2024).

Region	Normalized political instability [-] (Avg. 2019-2023)	Normalized political instability [-] (Min. 2014-2023)	Normalized political instability [-] (Max. 2014-2023)
ARG+URY	0.51	0.44	0.54
AUS	0.36	0.30	0.40
BRA	0.82	0.70	0.87
CHL	0.64	0.49	0.69
COL	0.88	0.86	0.92
COD	0.97	0.95	1.00
DZA	0.89	0.86	0.92
EGY	0.90	0.88	0.94
KEN+UGA	0.89	0.87	0.92
MAR	0.80	0.77	0.82
MEX	0.87	0.86	0.90
NGA	0.97	0.96	0.99
NZL	0.13	0.07	0.17
OMN	0.49	0.39	0.52
PER	0.80	0.74	0.84
SAU	0.82	0.75	0.87
MWI+MOZ+ZMB+ZWE	0.81	0.71	0.84
NAM+AGO+BWA	0.54	0.49	0.57
TUN	0.87	0.85	0.91
TZA+RWA+BDI	0.72	0.67	0.81
GHA+CIV+BEN+BFA+TGO	0.84	0.73	0.87
MRT+SEN	0.79	0.75	0.82
ZAF+LSO	0.83	0.71	0.88
CHN	0.81	0.74	0.83

Table 6.B.11. Demand of exporting regions in 2030, 2040, and 2050 (Galimova, Ram et al., 2023; Tonelli et al., 2023).

Region	Hydrogen [1000 tonnes/yr]	Methane [1000 tonnes/yr]	Ammonia [1000 tonnes/yr]
ARG+URY	347, 1377, 2407	151, 547, 2599	755, 3232, 4781
AUS	447, 2363, 4278	72, 180, 2678	619, 2536, 3677
BRA	604, 5357, 10109	79, 295, 4378	2168, 9290, 14207
CHL	293, 748, 1202	36, 94, 418	97, 503, 832
COL	664, 1069, 1473	14, 43, 2513	174, 948, 1684
COD	0, 79, 157	0, 58, 3578	97, 1006, 3136
DZA	10, 970, 1931	29, 842, 1966	523, 2323, 3677
EGY	18, 1413, 2808	22, 1886, 5364	948, 5032, 8671
KEN+UGA	2, 335, 668	29, 396, 5285	155, 1800, 5381
MAR	1, 374, 748	0, 252, 936	135, 735, 1355
MEX	210, 2927, 5644	43, 3845, 10462	929, 4316, 7084
NGA	95, 1552, 3009	0, 194, 12593	755, 5477, 12426
NZL	116, 376, 636	22, 14, 115	174, 619, 813
OMN	267, 433, 599	0, 259, 1562	271, 1026, 1355
PER	362, 761, 1161	14, 1188, 2858	174, 987, 1800
SAU	4, 2347, 4690	72, 5875, 9792	3310, 11671, 15020
MWI+MOZ+ZMB+ZWE	1, 278, 555	0, 14, 2354	97, 968, 3019
NAM+AGO+BWA	0, 362, 724	14, 22, 1836	135, 852, 1819
TUN	1, 138, 275	0, 108, 331	58, 310, 542
TZA+RWA+BDI	0, 162, 323	7, 101, 3938	97, 1103, 3368
GHA+CIV+BEN+BFA+TGO	158, 704, 1250	0, 7, 3686	155, 1219, 3174
MRT+SEN	0, 133, 265	7, 108, 1793	58, 561, 1877
ZAF+LSO	49, 1471, 2892	29, 727, 2110	503, 2148, 3426
CHN	3288, 34897, 66511	691, 17525, 169410	21678, 87446, 123756

Note: Values are reported as 2030, 2040, 2050.

Table 6.B.11 (continued). Demand of exporting regions in 2030, 2040, and 2050 (Galimova, Ram et al., 2023; Tonelli et al., 2023).

Region	Methanol [1000 tonnes/yr]	FT fuel [1000 tonnes/yr]
ARG+URY	3432, 12735, 16889	0, 2987, 5188
AUS	2818, 11127, 13547	8, 0, 2971
BRA	9935, 40606, 50360	0, 0, 14954
CHL	434, 1752, 2565	92, 912, 1540
COL	795, 3306, 5022	0, 1808, 3540
COD	434, 3631, 10404	0, 1741, 4619
DZA	2402, 9230, 13349	0, 2042, 3264
EGY	4353, 18370, 25758	0, 7967, 18377
KEN+UGA	723, 6918, 19346	17, 2134, 5138
MAR	614, 2728, 4642	0, 1021, 1715
MEX	4299, 14252, 18840	0, 10176, 19021
NGA	3432, 19942, 41816	0, 8728, 17096
NZL	759, 2529, 3107	0, 285, 460
OMN	1282, 4281, 5130	0, 452, 887
PER	759, 3631, 5383	0, 1481, 3682
SAU	15119, 48084, 56791	0, 6519, 9121
MWI+MOZ+ZMB+ZWE	452, 3920, 11217	0, 745, 2167
NAM+AGO+BWA	596, 3143, 6196	0, 1280, 2402
TUN	289, 1156, 1788	0, 494, 820
TZA+RWA+BDI	488, 4155, 11579	0, 1439, 4126
GHA+CIV+BEN+BFA+TGO	668, 4444, 10838	0, 1841, 4134
MRT+SEN	253, 2186, 6864	0, 611, 1607
ZAF+LSO	2294, 8562, 12391	0, 1900, 3163
CHN	79280, 340799, 418670	0, 91096, 166812

Note: Values are reported as 2030, 2040, 2050.

Table 6.B.12. Demand of the importing region in 2030, 2040, and 2050 (Galimova, Ram et al., 2023; Tonelli et al., 2023).

	Hydrogen [Mtonnes/yr]	Methane [Mtonnes/yr]	Ammonia [Mtonnes/yr]	Methanol [Mtonnes/yr]	FT fuel [Mtonnes/yr]
2030	12.9	2.0	14.3	65.6	0.1
2040	27.5	4.4	55.5	212.2	66.9
2050	42.1	62.8	76.6	242.1	135.0

Table 6.B.13. Inland and maritime distances for alternative export routes from Australia and New Zealand to Europe (Bertoli et al., 2016; Hampp et al., 2023; Hank et al., 2023).

Route	Inland distance- Australia [km]	Distance Australia- Europe [km]	Inland distance- New Zealand [km]	Distance New Zealand-Europe [km]
a	638	21212	597	19494
b	100	17761	100	19492
c	100	16372	100	19497
d	100	15221	100	18580

6.B.5. Additional results

Table 6.B.14. Driver decomposition of changes in cost and GHG emissions relative to the cost-optimal solution (cost in trillion €, emissions in Gtonnes CO₂eq).

Scenario (relative to cost-optimal)	GHG-optimal	Supply risk-optimal	Compromise
ΔCost total (trillion €)	+13.74	+11.26	+0.13
ΔCost: Resource (incl. RE)	+10.79	+3.93	+0.06
ΔCost: Production	+2.70	+6.42	+0.01
ΔCost: (Re)conversion	+0.02	+0.37	+0.01
ΔCost: Transportation	+0.23	+0.53	+0.05
ΔGHG total (Gtonnes CO₂eq)	−0.60	+3.04	−0.46
ΔGHG: Resource (incl. RE)	−0.63	−0.09	−0.47
ΔGHG: Production	+0.02	+3.05	−0.00
ΔGHG: (Re)conversion	+0.01	+0.05	+0.01
ΔGHG: Transportation	−0.00	+0.04	+0.00

Table 6.B.15. Diversification and distance indicators.

Solution	Cost-optimal	GHG-optimal	Supply risk-optimal	Compromise
HHI	0.0708	0.1051	0.0183	0.0603
Ship distance (km)*	7117	9617	12432	8497
Pipeline distance (km)*	1869	8084	7037	1864

* Weighted by imported energy quantities.

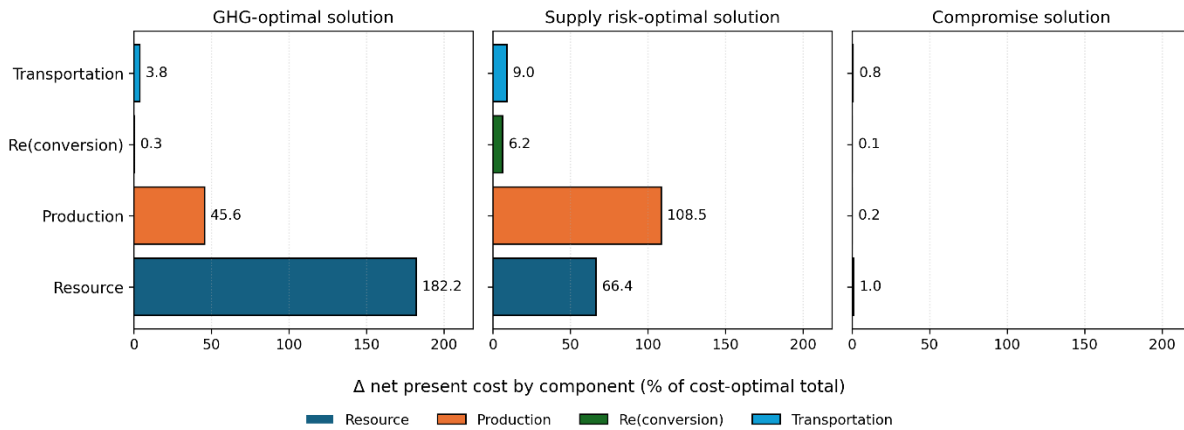


Figure 6.B.2. Cost driver decomposition relative to the cost-optimal solution for the GHG-optimal, the supply risk-optimal, and the compromise solution. Bars show changes expressed as a percentage of total net present cost in the cost-optimal solution, broken down by driver: resource utilization (incl. renewable electricity), production, (re)conversion, and transportation.

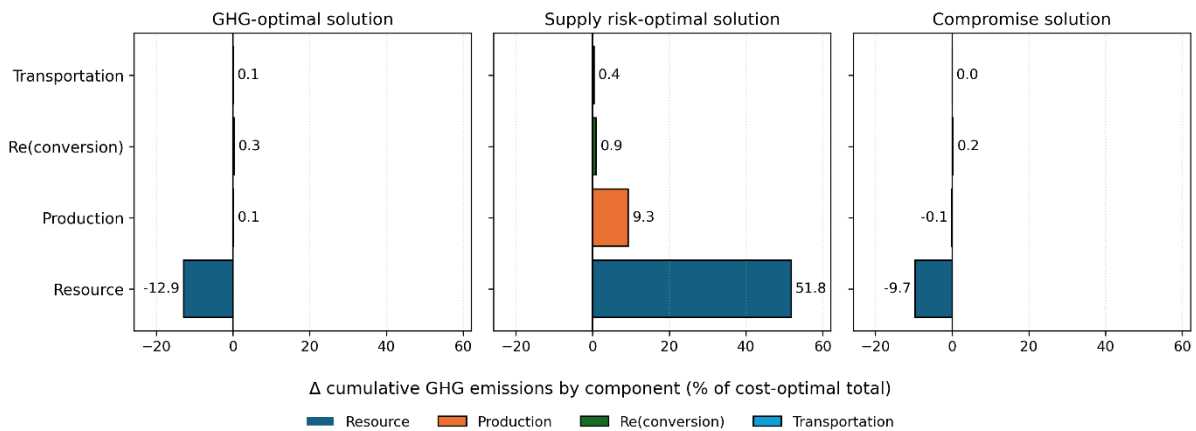


Figure 6.B.3. GHG-emission driver decomposition relative to the cost-optimal solution for the GHG-optimal, the supply risk-optimal, and the compromise solution. Bars show changes expressed as a percentage of total cumulative GHG emissions in the cost-optimal solution, broken down by driver: resource utilization (incl. renewable electricity), production, (re)conversion, and transportation.

Table 6.B.16. Import flow from regions in cost-optimal solution (base case). Values show import flows per period (TWh/yr).

Region	2030	2035	2040	2045	2050	2055
ARG+URY	0	0	0	0	1	1
AUS	0	0	0	0	3	3
BRA	0	0	175	175	129	129
CHL	0	0	485	485	1329	1329
EGY	85	85	293	293	291	291
NGA	0	0	0	0	3	3
NZL	0	0	0	0	3	3
PER	13	13	4	4	24	24
SAU	215	215	458	458	885	885
Other regions	135	135	203	203	145	145

Table 6.B.17. Import flow from regions in GHG-optimal solution (base case). Values show import flows per period (TWh/yr).

Region	2030	2035	2040	2045	2050	2055
ARG+URY	14	52	62	37	1153	852
AUS	0	0	0	0	0	0
BRA	0	0	211	174	0	0
CHL	0	0	0	0	90	482
EGY	3	0	0	0	0	0
NGA	308	308	547	551	563	563
NZL	0	0	0	0	0	0
PER	68	68	761	802	1006	915
SAU	0	0	0	0	1	0
Other regions	55	20	38	55	0	0

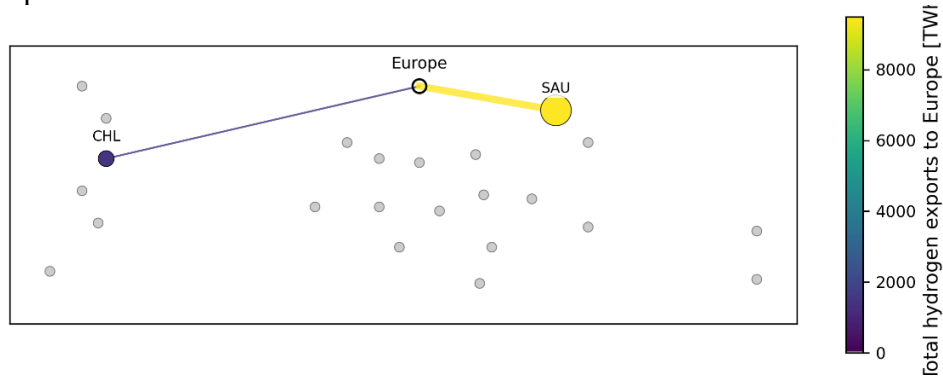
Table 6.B.18. Import flow from regions in supply risk-optimal solution (base case). Values show import flows per period (TWh/yr).

Region	2030	2035	2040	2045	2050	2055
ARG+URY	24	23	85	83	144	144
AUS	29	29	106	104	180	180
BRA	12	14	53	52	89	89
CHL	18	18	67	66	115	115
EGY	12	13	13	47	81	81
NGA	10	12	45	44	76	76
NZL	88	88	326	319	555	555
PER	14	15	54	53	91	91
SAU	0	14	53	51	89	89
Other regions	240	222	819	802	1392	1392

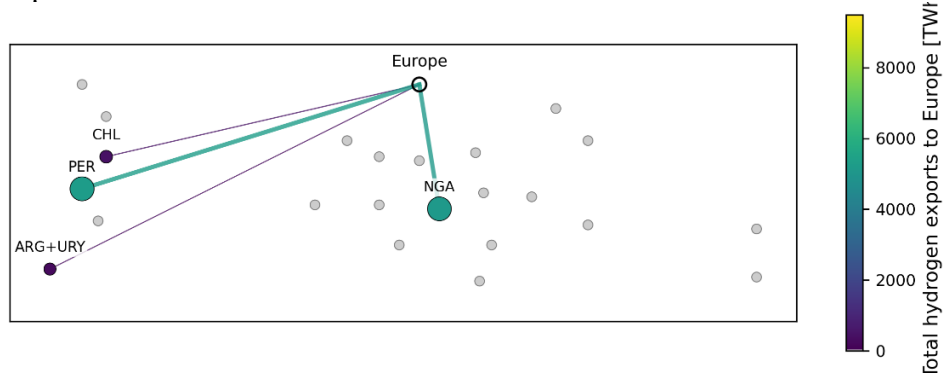
Table 6.B.19. Import flow from regions in Compromise solution (base case). Values show import flows per period (TWh/yr).

Region	2030	2035	2040	2045	2050	2055
ARG+URY	41	41	47	47	220	220
AUS	0	0	1	0	3	3
BRA	0	0	196	196	2	2
CHL	181	181	450	450	547	547
EGY	30	30	0	0	0	0
NGA	62	62	256	256	567	567
NZL	0	0	0	0	3	3
PER	62	62	565	565	863	863
SAU	52	52	48	48	590	590
Other regions	19	19	57	57	19	19

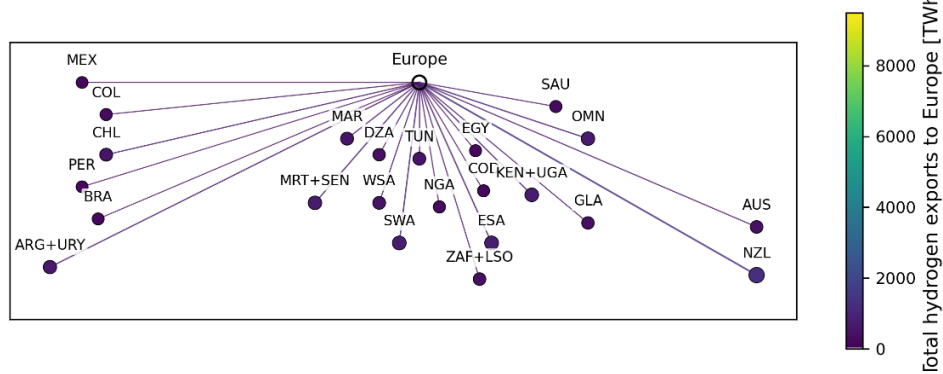
e) Cost-optimal solution



f) GHG-optimal solution



g) Supply risk-optimal solution



h) Compromise solution

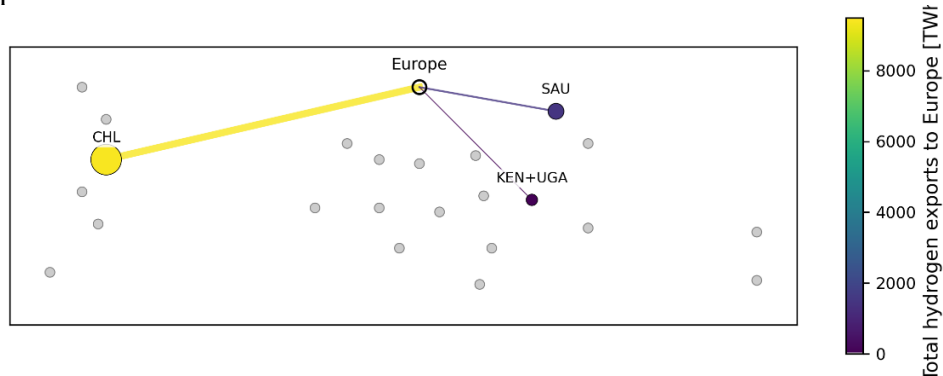
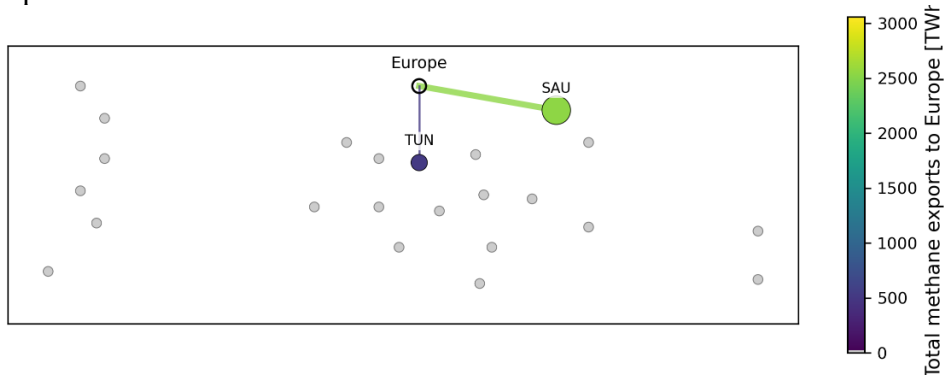
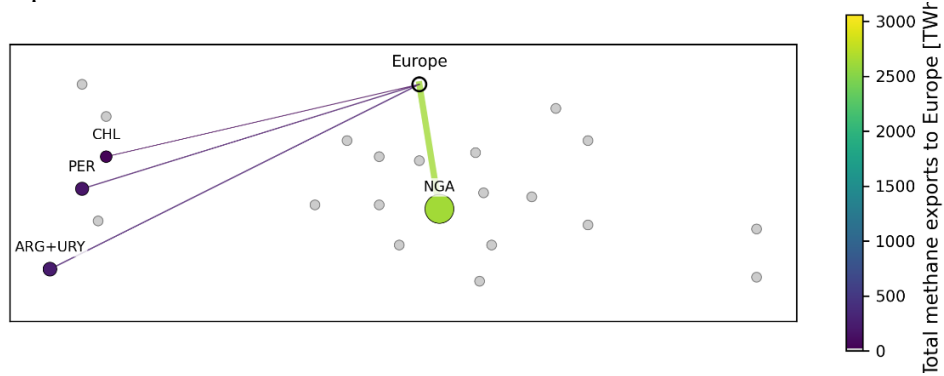


Figure 6.B.4. Trade patterns of hydrogen imports to Europe in the a) cost-optimal, b) GHG-optimal, c) supply risk-optimal, and d) compromise solutions. For readability, WSA, ESA, SWA, and GLA denote the aggregated regions GHA+CIV+BEN+BFA+TGO, MWI+MOZ+ZMB+ZWE, NAM+AGO+BWA, and TZA+RWA+BDI, respectively.

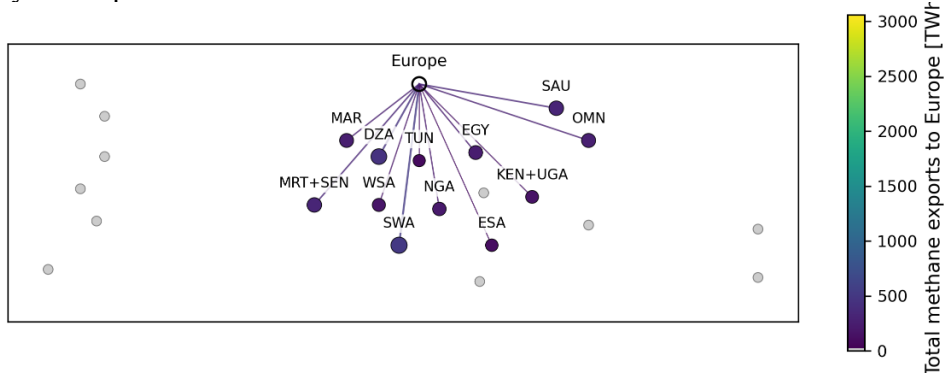
a) Cost-optimal solution



b) GHG-optimal solution



c) Supply risk-optimal solution



d) Compromise solution

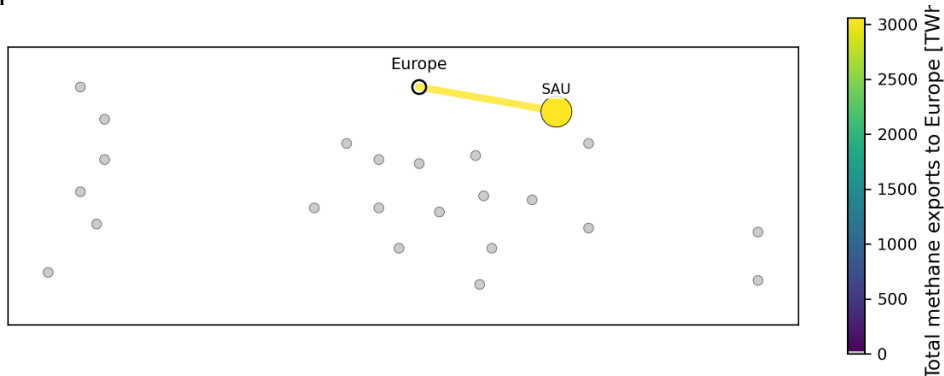
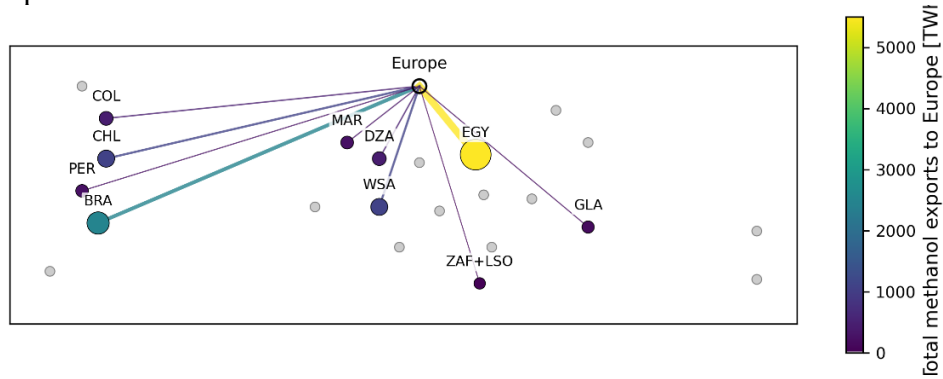
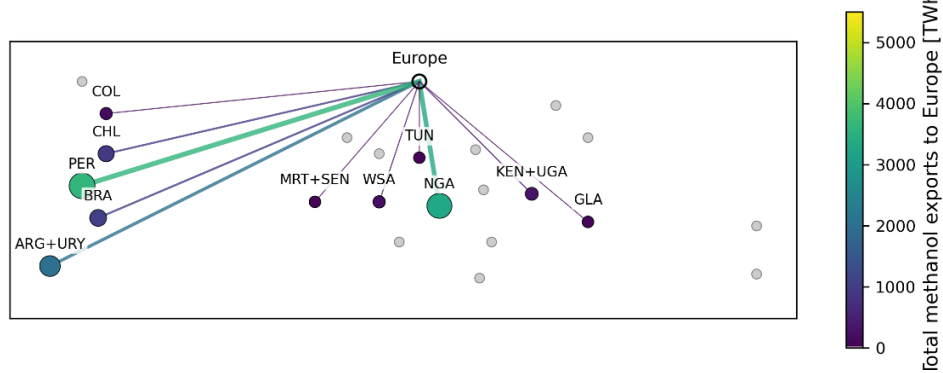


Figure 6.B.5. Trade patterns of methane imports to Europe in the a) cost-optimal, b) GHG-optimal, c) supply risk-optimal, and d) compromise solutions. For readability, WSA, ESA, SWA, and GLA denote the aggregated regions GHA+CIV+BEN+BFA+TGO, MWI+MOZ+ZMB+ZWE, NAM+AGO+BWA, and TZA+RWA+BDI, respectively.

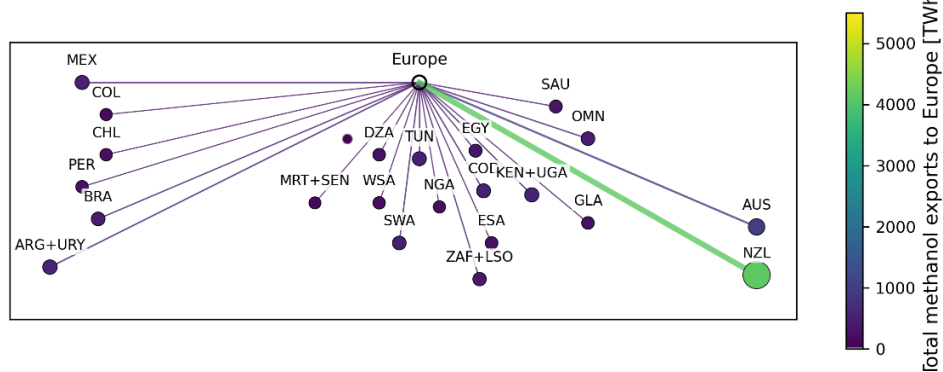
a) Cost-optimal solution



b) GHG-optimal solution



c) Supply risk-optimal solution



d) Compromise solution

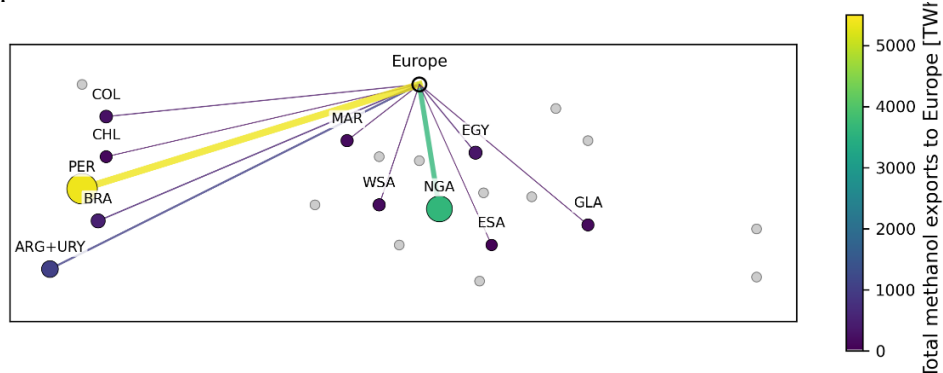
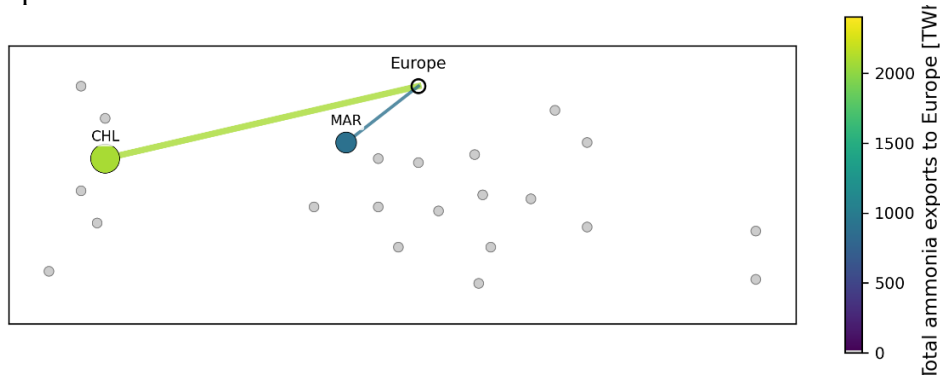
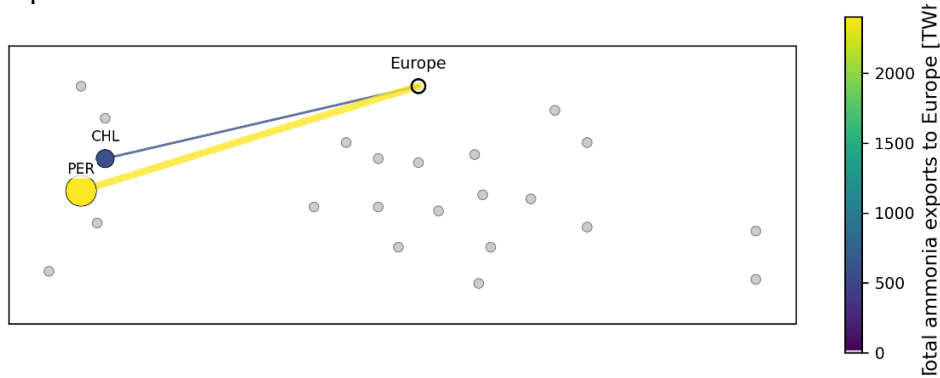


Figure 6.B.6. Trade patterns of methanol imports to Europe in the a) cost-optimal, b) GHG-optimal, c) supply risk-optimal, and d) compromise solutions. For readability, WSA, ESA, SWA, and GLA denote the aggregated regions GHA+CIV+BEN+BFA+TGO, MWI+MOZ+ZMB+ZWE, NAM+AGO+BWA, and TZA+RWA+BDI, respectively.

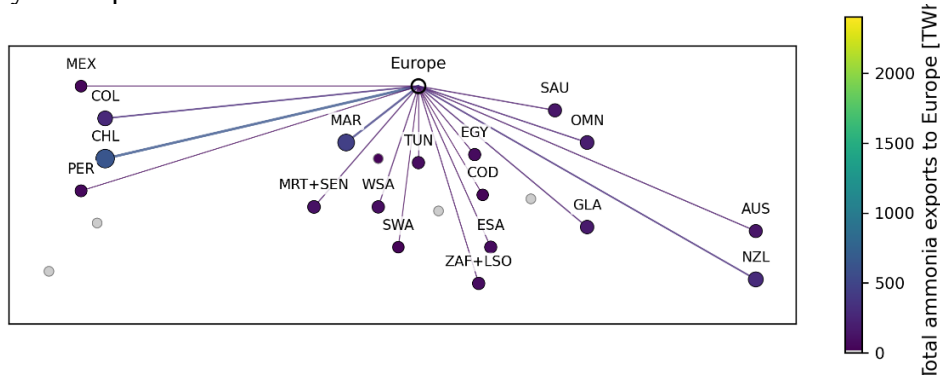
a) Cost-optimal solution



b) GHG-optimal solution



c) Supply risk-optimal solution



d) Compromise solution

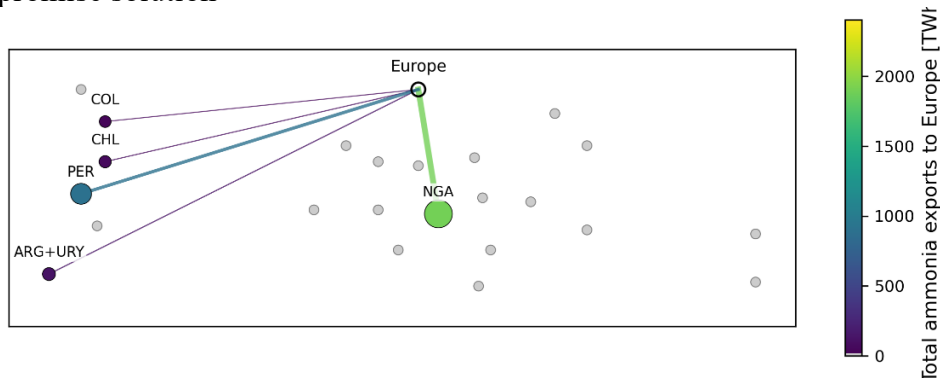
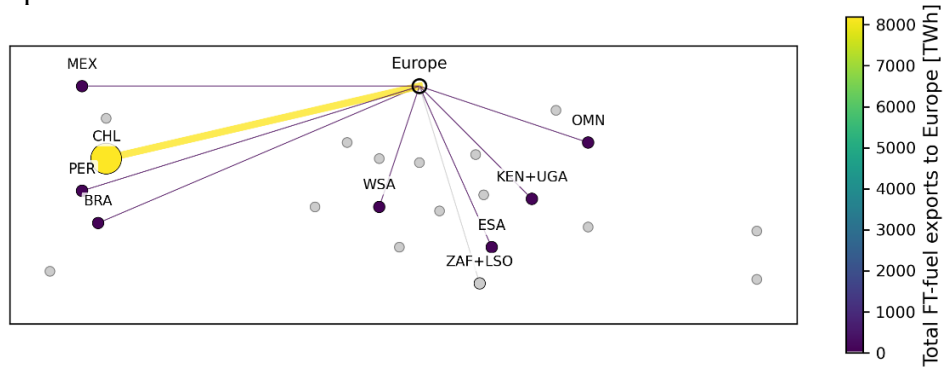
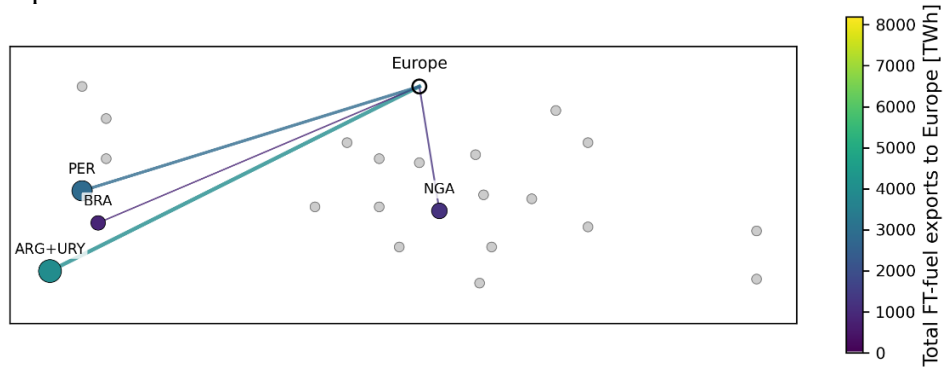


Figure 6.B.7. Trade patterns of ammonia imports to Europe in the a) cost-optimal, b) GHG-optimal, c) supply risk-optimal, and d) compromise solutions. For readability, WSA, ESA, SWA, and GLA denote the aggregated regions GHA+CIV+BEN+BFA+TGO, MWI+MOZ+ZMB+ZWE, NAM+AGO+BWA, and TZA+RWA+BDI, respectively.

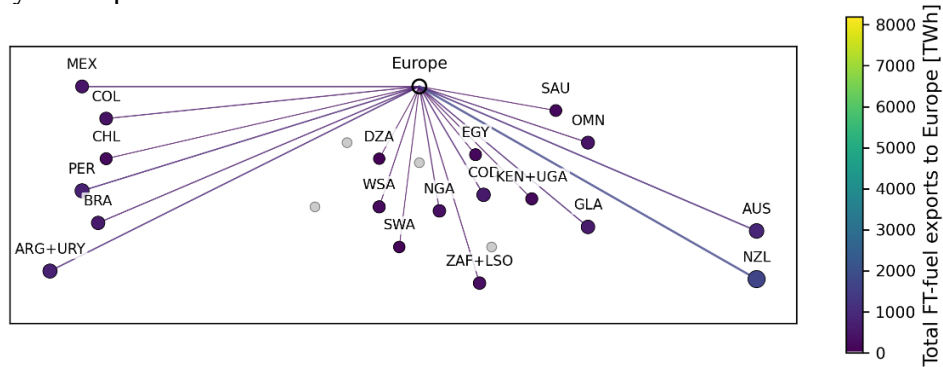
a) Cost-optimal solution



b) GHG-optimal solution



c) Supply risk-optimal solution



d) Compromise solution

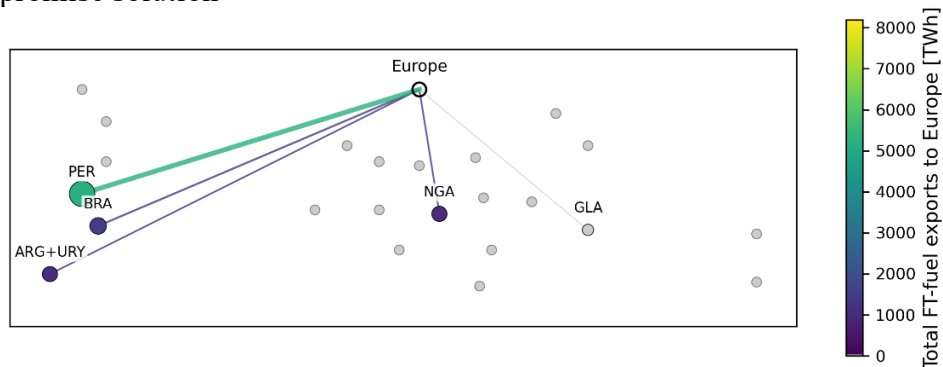


Figure 6.B.8. Trade patterns of FT-fuel imports to Europe in the a) cost-optimal, b) GHG-optimal, c) supply risk-optimal, and d) compromise solutions. For readability, WSA, ESA, SWA, and GLA denote the aggregated regions GHA+CIV+BEN+BFA+TGO, MWI+MOZ+ZMB+ZWE, NAM+AGO+BWA, and TZA+RWA+BDI, respectively.

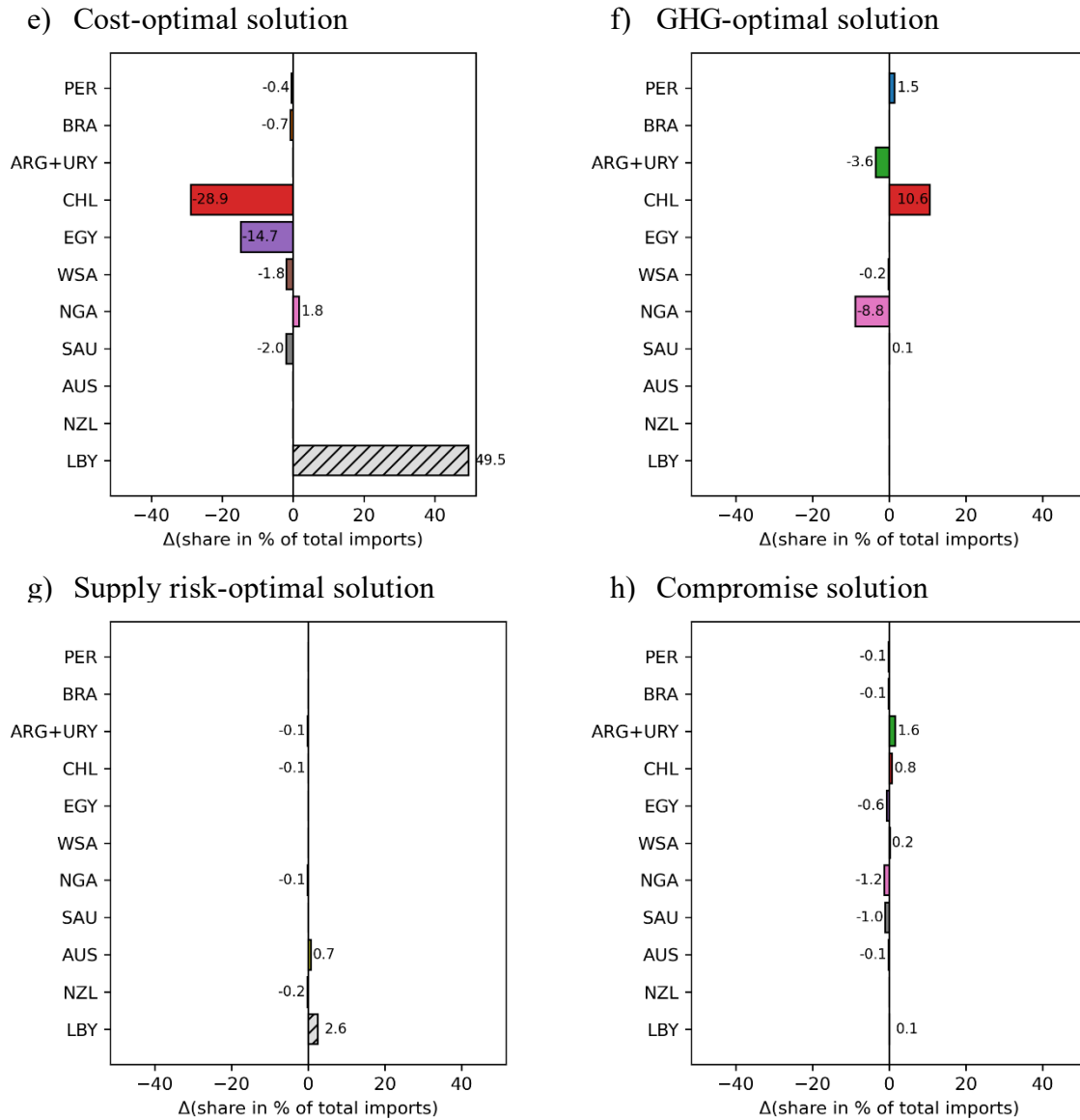


Figure 6.B.9. Change in REC export shares to Europe when Libya (LBY) is additionally included as a candidate exporting region (relaxing the extreme political-instability filter). (a) cost-optimal, (b) GHG-optimal, (c) supply risk-optimal, and (d) compromise solutions relative to the base case. Bars show $\Delta(\text{share in \% of Europe's total REC imports})$ for each exporting region; positive values indicate a larger share than in the base case, negative values a smaller share. For readability, WSA denotes GHA+CIV+BEN+BFA+TGO.

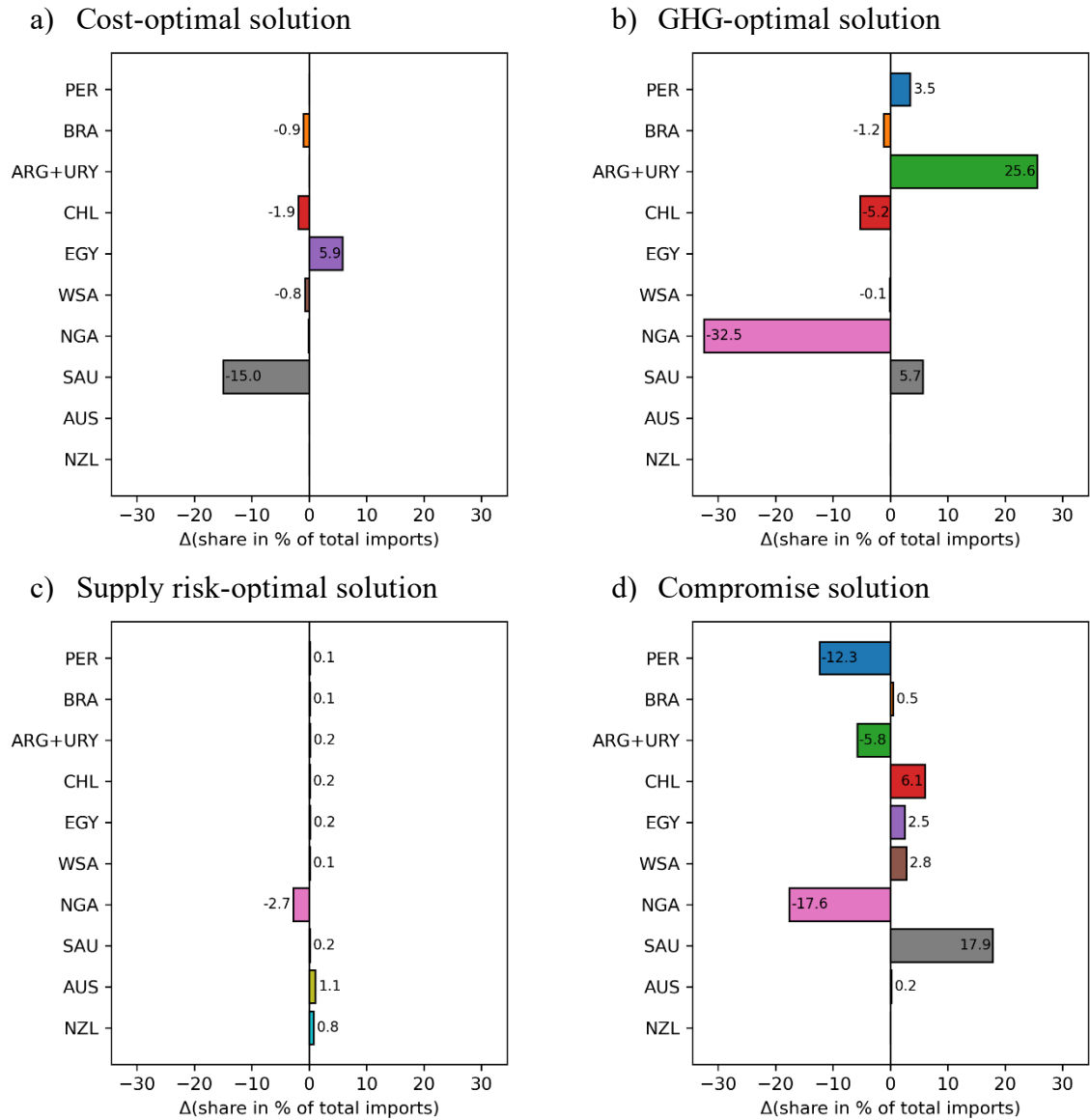


Figure 6.B.10. Change in REC export shares to Europe when Nigeria (NGA) is excluded from the exporting-region set. (a) cost-optimal, (b) GHG-optimal, (c) supply risk-optimal, and (d) compromise solutions relative to the base case. Bars show $\Delta(\text{share in \% of Europe's total REC imports})$ for each exporting region; positive values indicate a larger share than in the base case, negative values a smaller share. For readability, WSA denotes GHA+CIV+BEN+BFA+TGO.

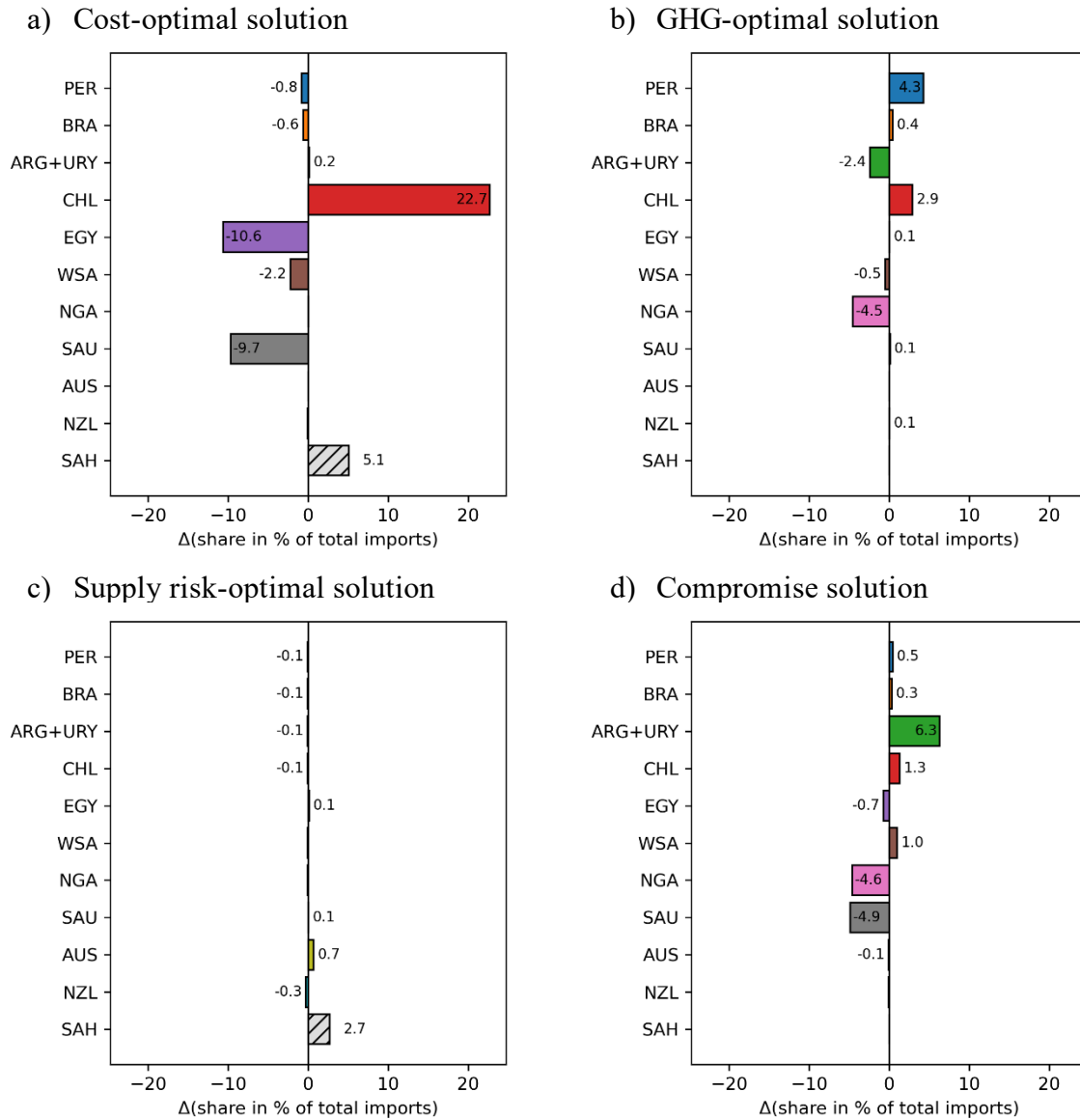


Figure 6.B.11. Change in REC export shares to Europe when Chad & Niger (SAH) is additionally included as a candidate exporting region (relaxing the water-availability filter despite no access to seawater for desalination). (a) cost-optimal, (b) GHG-optimal, (c) supply risk-optimal, and (d) compromise solutions relative to the base case. Bars show $\Delta(\text{share in \% of Europe's total REC imports})$ for each exporting region; positive values indicate a larger share than in the base case, negative values a smaller share. For readability, WSA and SAH denote GHA+CIV+BEN+BFA+TGO and TCD+NER, respectively.

Table 6.B.20. AUGMECON ε -grid subproblems and solver statistics.

Point	Total net present cost [trillion €]	Cumulative GHG emissions [Gtonnes CO ₂ eq]	Supply- security risk [-]	MIP gap [%]	Runtime [h]
1	6.54	4.3	0.045	0.9	56
2	6.17	4.4	0.045	1.0	17
3	6.01	4.5	0.045	0.4	51
4	6.00	4.6	0.045	1.0	39
5	5.94	4.7	0.045	0.5	42
6	5.94	4.8	0.045	0.8	31
7	6.45	4.3	0.050	0.9	33
8	6.14	4.4	0.050	0.9	17
9	6.02	4.5	0.050	0.8	14
10	5.99	4.6	0.050	0.9	42
11	5.96	4.7	0.050	0.9	38
12	5.93	4.8	0.050	0.7	13
13	6.29	4.3	0.070	0.5	7
14	6.08	4.4	0.070	0.9	17
15	6.02	4.5	0.070	0.6	7
16	5.94	4.6	0.070	0.2	28
17	5.93	4.7	0.070	0.7	20
18	5.92	4.8	0.070	0.6	25
19	6.27	4.3	0.080	0.8	12
20	6.06	4.4	0.080	1.0	8
21	6.00	4.5	0.080	0.9	20
22	5.97	4.6	0.080	1.0	21
23	5.94	4.7	0.080	0.7	16
24	5.90	4.8	0.080	0.2	20
25	6.28	4.3	0.085	1.0	35
26	6.07	4.4	0.085	1.0	22
27	6.00	4.5	0.085	1.0	9
28	5.98	4.6	0.085	0.7	17
29	5.92	4.7	0.085	0.5	34
30	5.90	4.8	0.085	0.3	32
31	6.26	4.3	0.090	1.0	10
32	6.05	4.4	0.090	0.7	13
33	6.00	4.5	0.090	0.9	7
34	5.94	4.6	0.090	0.5	32
35	5.91	4.7	0.090	0.3	10
36	5.92	4.8	0.090	0.7	14
37	6.23	4.3	0.095	1.0	4
38	6.05	4.4	0.095	1.0	4
39	6.01	4.5	0.095	1.0	32
40	5.96	4.6	0.095	0.7	40
41	5.95	4.7	0.095	1.0	9
42	5.91	4.8	0.095	0.6	25

Note: All ε -subproblems were feasible and terminated upon meeting the relative MIP-gap criterion (MIPGap $\leq 1\%$). Achieved MIP gaps and runtimes are reported.

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Chapter 7

Designing Reliable Renewable Hydrogen Supply Chains with Hybrid Storage under Uncertain Renewable Electricity Availability

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Abstract

Renewable hydrogen can decarbonize hard-to-abate sectors, but large-scale deployment requires renewable hydrogen supply chains (RHSCs) that cope with variability and uncertainty in renewable electricity availability. Reliable demand fulfillment requires planning temporal flexibility via hybrid storage and spatial flexibility via transport across regions. We develop a cost-minimizing chance-constrained mixed-integer linear programming framework that optimizes renewable electricity generation, hydrogen production and (re)conversion, hybrid storage, interregional transport within the modeled system boundary, and imports from exogenous sources. Reliability is enforced through regional chance constraints at a specified confidence level using wind and solar availability scenarios that capture temporal dependence and cross-regional correlations. A hierarchical time aggregation with intra-year and intra-day slices represents seasonal and diurnal patterns while keeping the model tractable.

We apply the framework to a European case study for 2050. At 95% supply reliability, renewable electricity investments dominate cost, and pipelines connect resource-rich countries to demand centers. The storage portfolio is dominated by long-duration options (liquid organic

hydrogen carriers and underground hydrogen storage) for seasonal balancing, while batteries mainly provide intra-day buffering. Sensitivity analyses show the system scales with hydrogen demand and that restricting storage options increases cost and reliance on imports from exogenous sources. Tightening the import share mainly shifts supply between exogenous imports and interregional transport with minor cost effects. A non-domestic supply limit (imports plus net interregional inflow) binds around one-third of demand in the case study, triggering additional domestic renewable capacity and seasonal storage. The framework quantifies reliability–cost trade-offs and the roles of temporal and spatial flexibility.

7.1 Introduction

Meeting global emission-reduction targets requires a rapid transition to low-carbon energy systems, including large-scale deployment of renewable energy (IRENA Coalition for Action, 2024). This transition relies on a broad portfolio of measures and technologies, including energy efficiency improvements, renewable power generation, and renewable fuel supply (Agora Energiewende, 2019; Hydrogen Council, 2021). Among these, renewable hydrogen and its derivatives play a key role in decarbonizing hard-to-abate sectors, where hydrogen functions as both a feedstock and an energy carrier (Hydrogen Council, 2020; IEA, 2024a; IRENA, 2022a; IRENA Coalition for Action, 2022). Renewable hydrogen is projected to supply a significant share of feedstock and fuel demand in steelmaking, non-ferrous metal processing, glass manufacturing, mineral processing, pulp and paper production, basic chemicals, refineries, aviation, maritime shipping, and other chemical industries (IRENA, 2020; Neuwirth et al., 2022).

This growing commitment to hydrogen is evident globally, with more than 1,500 renewable hydrogen projects announced to expand production capacity, build infrastructure, and integrate hydrogen into national energy strategies (IEA, 2024b). As a result, renewable hydrogen production and demand are expected to grow sharply, driven by accelerating decarbonization efforts and expanding applications across multiple sectors (IEA, 2021; IRENA, 2020). Supporting this scale-up, various national and regional hydrogen strategies and investment plans are being implemented worldwide, providing essential support for infrastructure development and market creation (European Commission, 2020; World Energy Council, 2021b).

Despite its strong potential, large-scale renewable hydrogen deployment faces several technical, economic, and logistical challenges. Widespread adoption is hindered by substantial

upfront capital requirements, high production costs, limited infrastructure, and an underdeveloped value chain for renewable hydrogen and its derivatives (Hossain Bhuiyan and Siddique, 2025; IEA, 2019, 2024a; IRENA, 2022b; World Energy Council, 2021a). In addition, renewable hydrogen supply chains (RHSCs) need to bridge a spatial disconnect between renewable resource-rich regions and major demand centers, which motivates interregional infrastructure planning and coordination (IEA, 2024a; IRENA, 2022b). Finally, when hydrogen is produced from variable renewable electricity (e.g., solar and wind), the supply chain inherits time-varying availability at multiple time scales, ranging from intra-day variability (e.g., hourly patterns) to intra-year variability (weeks to seasons) (IRENA, 2022b). These spatiotemporal challenges imply that RHSCs must adapt across time and regions while balancing reliability and cost. We distinguish two complementary levers of flexibility. Spatial flexibility is provided by interregional transport infrastructure and imports from exogenous sources, which enable balancing across regions (Guidehouse, 2021; Haas et al., 2017). Temporal flexibility is provided by energy storage that shifts electricity and hydrogen across time and buffers renewable variability (Taslimi and Khosravi, 2025). Together, these levers support a stable, year-round supply of renewable hydrogen that many industrial applications require (Li, Y. et al., 2024; O'Neill et al., 2024; Wang et al., 2020).

The first lever—spatial flexibility—arises from transport and infrastructure choices that connect regions and allow renewable hydrogen supply to be balanced across regions (Guidehouse, 2021; Haas et al., 2017; Hofmann et al., 2025). It includes interregional transport infrastructure as well as long-distance import pathways from exogenous sources (hereafter: exogenous imports) (Guidehouse, 2021; Hampp et al., 2023). However, current strategies also seek to lower energy import dependency, which should be considered in RHSC design (Hydrogen Europe, 2025). Therefore, investigating domestic production and non-domestic supply (via interregional transport and exogenous imports) is crucial. Consequently, jointly optimizing renewable generation, hydrogen production and (re)conversion, storage, and transport enhances flexibility through trade-offs between local production and interregional balancing.

The second lever—temporal flexibility—relies on energy storage and conversion/reconversion options that shift electricity and hydrogen across time and buffer renewable variability. In addition to variability, availability of renewable electricity is uncertain and must be represented explicitly when designing RHSC infrastructure (Haas et al., 2017). Figure 7.1 illustrates variability and uncertainty in solar photovoltaic (PV) and wind capacity factors in Germany

(2000–2019) based on data from Pfenninger and Staffell (2016) and Staffell and Pfenninger (2016). Panel (a) shows the seasonal pattern of daily capacity factors across the year, while panels (b) and (c) show the distribution of hourly profiles for typical summer and winter days. Shaded areas represent quantile ranges (10–90% and 25–75%), and the lines indicate the median for PV and wind. The quantile ranges highlight substantial uncertainty in renewable electricity availability, motivating an explicit uncertainty representation when sizing production, storage, and transport capacity.

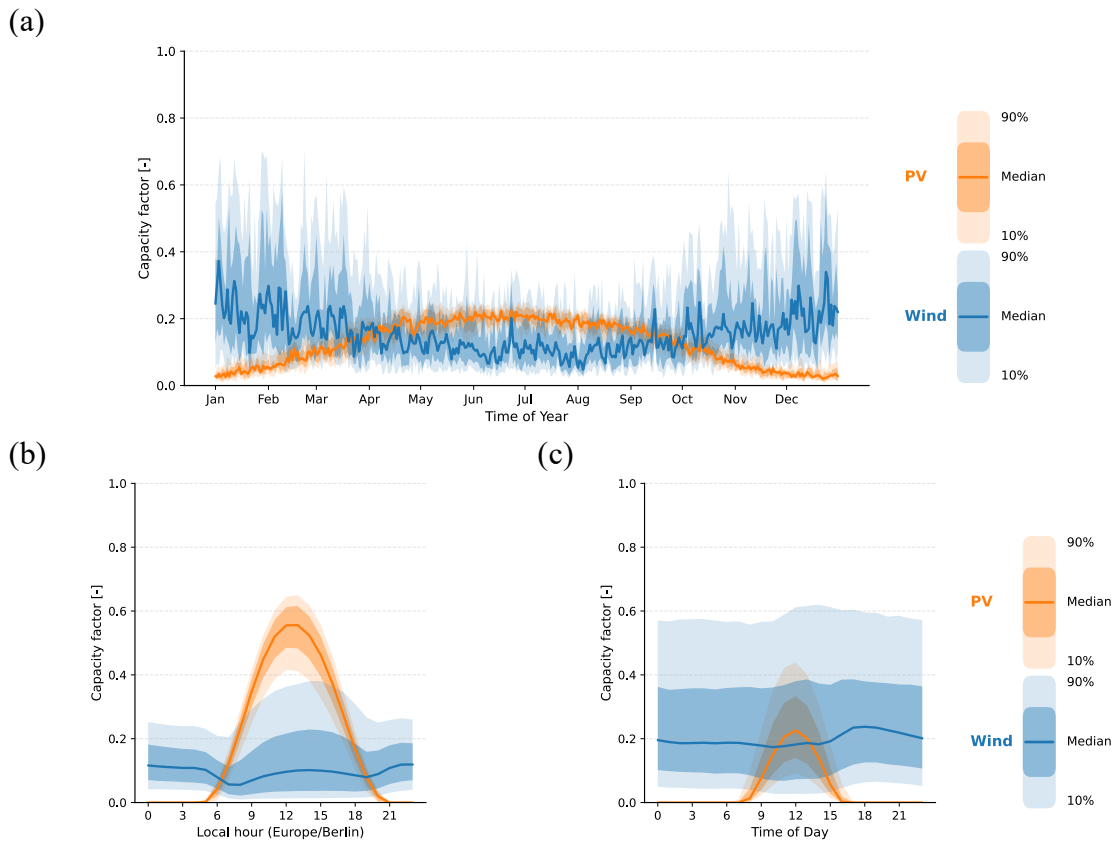


Figure 7.1. Variability and uncertainty in renewable electricity availability in Germany (2000–2019), shown as the median and quantile ranges (10–90% and 25–75%) of PV and wind capacity factors based on Pfenninger and Staffell (2016) and Staffell and Pfenninger (2016): (a) daily distributions across the year; (b) hourly distributions for a typical summer day; (c) hourly distributions for a typical winter day.

Temporal flexibility requires storage that can buffer variability in renewable input. In RHSCs, storage can be located at different stages of the chain: (i) electricity-side storage, where renewable electricity is stored upstream of hydrogen production (e.g., batteries), and (ii) hydrogen-side storage, where hydrogen is stored either directly or via carriers such as ammonia and liquid organic hydrogen carriers (LOHCs) (Danish Energy Agency, 2018a; Hydrogen Europe, 2025). Accordingly, we represent a set of storage options (Table 7.1), including electricity storage, multiple hydrogen storage options (gaseous, liquid, and underground

hydrogen storage), and hydrogen-derivative options (ammonia and LOHC). These technologies differ in efficiency, charge/discharge limits, self-loss, energy-capacity potential, and cost structure, making them suitable for different horizons from intra-day balancing to seasonal shifting (Danish Energy Agency, 2018a; Guidehouse, 2021; Haas et al., 2017; Wolf et al., 2024; Zhang et al., 2025). Some energy storage technologies also face additional barriers such as geological and legal constraints on underground hydrogen storage (Guidehouse, 2021; Tarkowski and Uliasz-Misiak, 2022; Wietschel et al., 2024). Given these differences, suitability depends on the use case, and no single technology is optimal in all cases (Haas et al., 2017; Hydrogen Europe, 2025; Møller et al., 2017). A detailed parameter table for storage and (re)conversion technologies is provided in the Supplementary Information (Table 7.B.6).

Table 7.1. Storage options represented in the model and case study and their main characteristics (Al Ghafri et al., 2022; Cloete et al., 2021; Danish Energy Agency, 2018a; Demirhan et al., 2020; Fasihi et al., 2021; Hampp et al., 2023; Kim, Park, Heo, and Lee, 2024; Reuß et al., 2017; Terlouw et al., 2022; Zhang et al., 2025).

Technology (stored carrier)	Advantages	Limitations
LiB (Electricity)	High charge/discharge efficiency; fast response; suitable for short-term balancing of variable renewable electricity.	High investment cost for large energy capacity; relatively high self-loss; typically not suitable for seasonal storage.
GHS (GH ₂)	Mature and modular option; low self-loss; suitable for short- to medium-duration buffering of hydrogen supply and demand.	Requires compression equipment and energy; low volumetric energy density compared with LH ₂ and hydrogen derivatives (e.g., NH ₃ , LOHC).
LHS (LH ₂)	Higher volumetric energy density than GH ₂ , enabling compact inventories.	Requires liquefaction and re-gasification units, adding efficiency losses and CAPEX/OPEX; cryogenic handling complexity; boil-off losses.
UHS (GH ₂)	Large energy-capacity potential and low self-loss; suitable for long-duration/seasonal balancing; low specific storage CAPEX at large scale.	Availability constrained by regional geology/permitting; charge/discharge rate limits can constrain fast cycling.
NH ₃ S (NH ₃)	Established large-scale storage; low self-loss; suitable for long-duration storage as a hydrogen carrier.	Requires conversion and reconversion, adding conversion losses and CAPEX/OPEX.
LOHCS (LOHC)	Liquid handling near ambient conditions; low self-loss; suitable for long-duration storage as a hydrogen carrier.	Requires hydrogenation and dehydrogenation units, adding conversion losses and CAPEX/OPEX; performance depends on carrier choice and process integration assumptions.

Note (abbreviations). LiB: lithium-ion battery, GHS: gaseous hydrogen storage, LHS: liquid hydrogen storage, UHS: underground hydrogen storage, NH₃S: ammonia storage, LOHCS: liquid organic hydrogen carrier storage. H₂: hydrogen, GH₂: gaseous hydrogen, LH₂: liquid hydrogen, NH₃: ammonia, LOHC: liquid organic hydrogen carrier, CAPEX: capital expenditure, OPEX: operating expenditure.

Operational constraints of production and (re)conversion units (e.g., minimum-load requirements and ramping limits) influence how effectively storage can buffer renewable variability under time-varying availability (Danish Energy Agency, 2018c; Kim, Park, Heo, and Lee, 2024; Taslimi and Khosravi, 2025).

Figure 7.2 provides an overview of the RHSC and illustrates the two flexibility levers considered in this study across intra-day and intra-year time scales. Temporal flexibility can be

enabled by electricity-side and/or hydrogen-side storage, which buffer short-term fluctuations and enable longer-term shifting of energy stored in hydrogen or derivative carriers. Spatial flexibility can be enabled by interregional transport and exogenous imports, which allow balancing of supply and demand across regions.

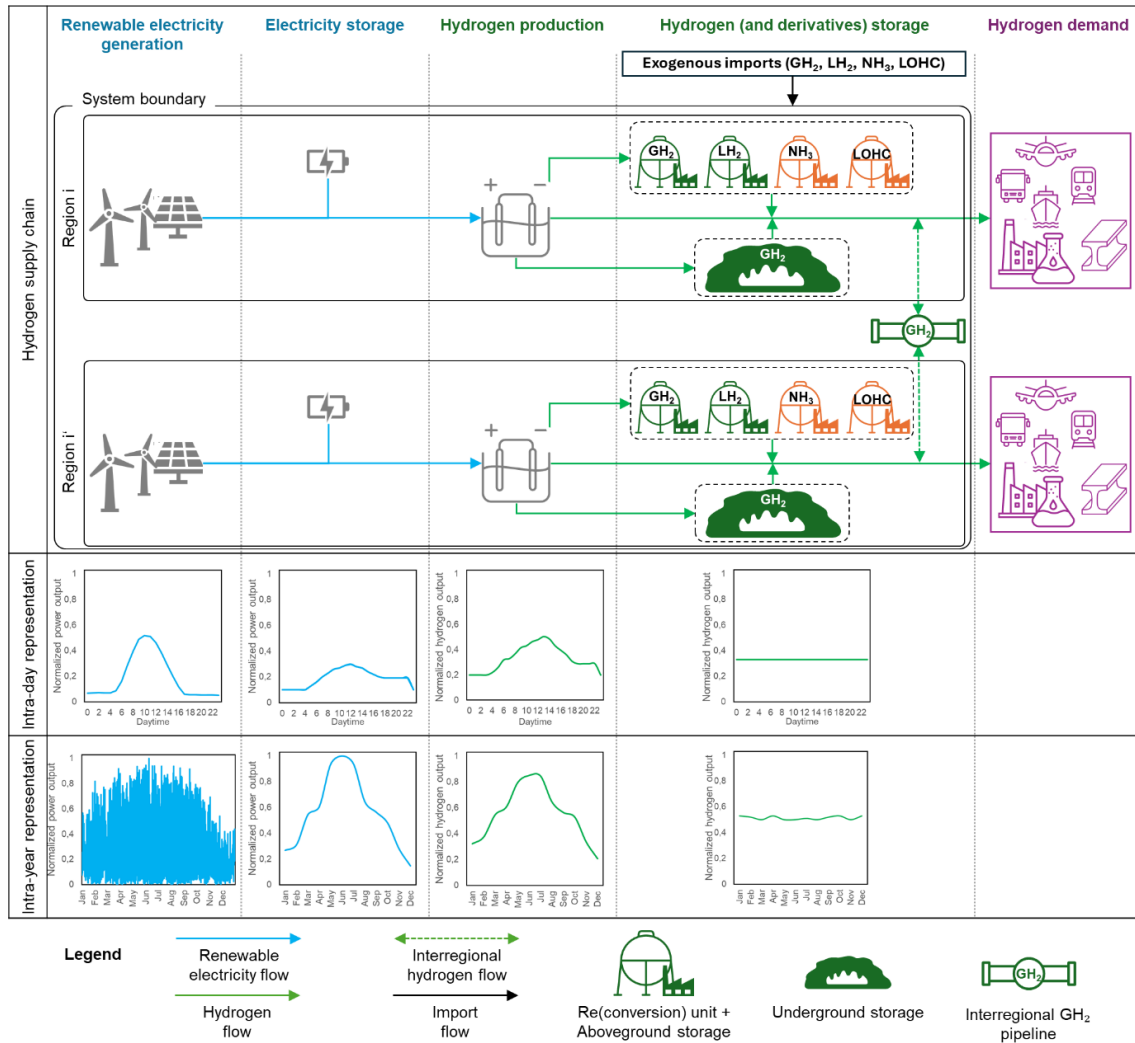


Figure 7.2. RHSC variability across intra-day and intra-year time scales and the two flexibility levers considered in this study: spatial flexibility via interregional transport and exogenous imports, and temporal flexibility via electricity-side and hydrogen-side storage. Blue arrows denote electricity flows; green arrows denote hydrogen flows; dashed green arrows indicate interregional flows; black arrows indicate exogenous import flows. H₂: hydrogen, GH₂: gaseous hydrogen, LH₂: liquid hydrogen, NH₃: ammonia, LOHC: liquid organic hydrogen carrier.

Taken together, these challenges highlight the need for RHSC models that (i) capture renewable variability at sufficiently high temporal resolution, (ii) explicitly represent uncertainty in renewable electricity availability, (iii) represent temporal flexibility through hybrid storage portfolios and the associated conversion/reconversion processes, and (iv)

represent infrastructure decisions that capture the spatial dimension, including interregional transport and exogenous imports. Against this background, we develop a modeling framework to design RHSCs that integrate hybrid storage while explicitly addressing uncertainty in renewable electricity availability. We formulate and solve a chance-constrained mixed-integer linear programming (MILP) model with an economic objective. The model accounts for multiple energy storage types and capacities, as well as the relevant transport technologies required for their integration into the supply chain. Our goal is to identify the type, capacity, and location of renewable electricity generation, hydrogen production and (re)conversion, storage, and interregional transport infrastructure, and to determine exogenous import quantities required to supply demand reliably under uncertainty in renewable electricity availability. We demonstrate the applicability of the proposed approach in a multi-country European case study for 2050. The main contributions of this work are as follows:

- Developing a chance-constrained MILP model for RHSC design that captures variability and uncertainty in renewable electricity availability (solar and wind).
- Analyzing how the reliability level (confidence level) of demand satisfaction affects the optimal RHSC design.
- Quantifying the value of hybrid storage portfolios for intra-day buffering and seasonal balancing, and their impact on system cost and reliance on interregional transport and exogenous imports.
- Assessing how hydrogen demand, temporal flexibility options (storage-technology portfolio), and spatial flexibility options (interregional transport and exogenous imports) shape optimal RHSC configurations through a systematic sensitivity analysis.
- Illustrating the practical implementation of the methodology in a multi-country European case study for 2050.

7.2 Literature review

The design of RHSCs encompasses multiple interconnected stages: renewable electricity generation, storage, hydrogen production, transport, and delivery to end-use sectors (Almansoori and Shah, 2006; Li et al., 2019; Liu and Ma, 2024). We review RHSC network design models with a focus on (i) temporal resolution and storage representation, (ii) uncertainty in renewable electricity availability, and (iii) spatial flexibility via interregional transport and exogenous imports. Optimization of RHSCs typically relies on network design approaches, often formulated as MILP models, to determine the optimal location, capacity, and

configuration of production, storage, and transport infrastructure while minimizing total system cost (Almansoori and Shah, 2006; Almaraz et al., 2024; Bozzolo Lueckel et al., 2025; Quarton and Samsatli, 2020; Yang et al., 2025). Recent works have expanded these approaches by increasing spatial and temporal detail and by representing a broader set of storage and transport options. For example, Feng et al. (2024) designed multi-period RHSC networks with centralized and decentralized storage configurations, while Sizaire et al. (2024) introduced an hourly resolution model covering multiple regions to capture the variability of renewable electricity supply and hydrogen demand. Dautel et al. (2024) optimized layouts under alternative demand scenarios, showing that design outcomes depend strongly on electricity availability and hydrogen demand.

Building on these RHSC design studies, hybrid storage portfolios play a critical role in addressing temporal mismatches between renewable hydrogen supply and demand (Agora Energiewende, 2021). Several studies show that hybrid storage systems combining short-term and long-term technologies can overcome single-technology limitations and improve reliability and cost performance (Gabrielli, Poluzzi et al., 2020; Wang et al., 2025). However, most RHSC studies analyze a single hydrogen form and a narrow set of storage and transport technologies. The literature concentrates on gaseous hydrogen (Elberry et al., 2021; Hassan et al., 2023), with fewer studies on liquid hydrogen (Almansoori and Shah, 2012; Nunes et al., 2015) and on carrier-based storage options (e.g., LOHC, ammonia) (Vo et al., 2025). Models often restrict storage and transport technologies to a single option or a small set of options (Fokkema et al., 2022; Li, L. et al., 2024). Recognizing this gap is crucial, as considering multiple hydrogen forms alongside a broader set of compatible storage and transport options, and allowing for hybrid short-term and long-term storage, can improve flexibility in the design of RHSCs (Bique and Zondervan, 2018; Dayhim et al., 2014; Kim, J. et al., 2008; Wang et al., 2025).

The prevailing modeling approach is deterministic network design. In deterministic optimization approaches, most commonly LP and MILP, hybrid storage is sized and located to balance seasonal variations, usually assuming deterministic seasonal or annual renewable availability profiles (Wolff et al., 2023; Yu et al., 2025) or fixed “days of autonomy” (where storage covers a fixed number of days without renewable input) (Dayhim et al., 2014; Guerra et al., 2020). These models determine optimal storage capacities, locations, and operational strategies (Elberry et al., 2021; Fokkema et al., 2022; Guerra et al., 2020; Moustapha Mai et al., 2025; Reuß et al., 2017; Wolff et al., 2023) but do not address uncertainties in renewable electricity availability.

For example, Reuß et al. (2017) examined seasonal hydrogen storage across multiple carrier pathways. Gabrielli, Gazzani et al. (2018) introduced a MILP model for the optimal design and operation of multi-energy systems, addressing the challenge of seasonal energy storage and showing the potential for cost reductions by integrating renewable energy and multiple storage technologies. O'Neill et al. (2024) quantified the levelized cost of hydrogen for industrial applications under renewable intermittency. Guerra et al. (2020) assessed multiple long-term storage technologies, concluding that hydrogen becomes competitive under projected cost reductions. Gabrielli, Poluzzi et al. (2020) showed the value of underground hydrogen storage combined with short-term batteries. Elberry et al. (2021) demonstrated that shifting summer surplus to winter demand via seasonal hydrogen storage can reduce infrastructure overcapacity and enhance supply security. Wolff et al. (2023) further emphasized that incorporating seasonal variability into renewable fuel supply chain design can lead to more robust long-term infrastructure strategies. Fokkema et al. (2022) demonstrated that hydrogen storage could be a viable long-term option to address mismatches between seasonal energy production and demand. Le et al. (2023) showed that hybrid systems combining batteries and hydrogen storage can outperform systems with only hydrogen storage. Li, L. et al. (2024) optimized seasonal hydrogen storage sizing in integrated energy systems under seasonal variability. Vo et al. (2025) expanded on hybrid approaches by integrating hydrogen and battery storage for renewable-based methanol production. Yu et al. (2025) optimized RHSCs focusing on storage and transport technologies. While these works demonstrate diverse seasonal hydrogen storage integration strategies, most deterministic models derive storage capacity from simplified assumptions, deterministic renewable availability profiles, or fixed days of autonomy, without capturing uncertainties in renewable electricity availability. These simplifications can yield storage and infrastructure designs that are cost-optimal for the assumed renewable-availability profile but less robust when renewable availability deviates from that profile.

Some studies extend beyond deterministic frameworks by incorporating uncertainty into RHSC design, primarily in hydrogen demand (Ge et al., 2022; Timalisina et al., 2025; Türkali Özbek and Güler, 2025). For instance, Kim, J. et al. (2008) presented a stochastic model to optimize RHSC configuration under uncertain hydrogen demand. Almansoori and Shah (2012) used stochastic optimization to reduce unmet demand risk while optimizing investments. Dayhim et al. (2014) designed RHSC infrastructure under uncertain demand, providing strategic facility sizing and location insights. Nunes et al. (2015) designed a RHSC, specifically addressing uncertainty in future hydrogen demand using two-stage stochastic mixed-integer programming.

Robles et al. (2020) applied a fuzzy approach for robust RHSC design. Xu et al. (2024) developed a robust optimization model to improve adaptability under demand and supply imbalances. Zhou et al. (2024) proposed large-scale, data-driven robust models for hydrogen infrastructure under demand uncertainty. However, even in these uncertainty-focused studies, uncertainty in renewable electricity availability, which is a key driver of energy storage requirements, is not addressed. Instead, storage capacities are commonly derived from fixed autonomy periods or deterministic seasonal averages, limiting the ability to capture uncertainty in renewable generation patterns.

A smaller body of work in the context of RHSC design considers uncertainty in renewable electricity availability and its implications for energy storage sizing. Yang et al. (2020) used chance-constrained programming to address wind intermittency in hydrogen network planning, showing significant effects on facility sizing and location. Kim, S., Park, J., Chung, W. et al. (2024) applied two-stage stochastic programming to international RHSCs under renewable electricity uncertainty. Efthymiadou et al. (2025) developed a two-stage stochastic model incorporating uncertainties in renewable and biomass resources across different penetration scenarios. Despite these advances, many scenario-based studies use only a few representative periods, which can overlook diurnal and within-season variation that is relevant for storage sizing.

Spatial flexibility in RHSCs is provided by interregional transport infrastructure and imports, which allow supply–demand balancing across regions and reduce reliance on strictly local production. Several RHSC studies represent interregional hydrogen supply via transport links that connect renewable resource-rich areas with major demand centers (Almansoori and Shah, 2012; Hofmann et al., 2025; Sizaire et al., 2024; Yang et al., 2020). A smaller set of contributions additionally considers exogenous imports as part of the supply portfolio, in combination with interregional transport and storage decisions (Efthymiadou et al., 2025; Quarton and Samsatli, 2020; Zhou et al., 2024). However, Table 7.2 indicates that only a small subset of models co-optimizes temporal flexibility (hybrid storage portfolios) and spatial flexibility (interregional transport and imports) under uncertain renewable electricity availability while capturing both intra-day and intra-year dynamics. It also summarizes the main characteristics of representative works that explicitly model energy storage within RHSC design, highlighting modeling approaches, storage considerations, temporal resolution, uncertainty approaches, and energy storage sizing basis.

Table 7.2. Selected RHSC optimization studies that explicitly model energy storage and hydrogen carriers, comparing temporal resolution, spatial representation, uncertainty treatment, and the inclusion of interregional transport and exogenous imports.

Reference	Model Type	Multiple Storage Technologies	Hydrogen Storage Forms	Temporal Resolution	Spatial Representation	Renewable electricity uncertainty	Uncertainty Approach	Energy Storage Sizing Basis
Hassan et al. (2023)	Sim	—	G	I	—	—	—	DRA
Dautel et al. (2024)	MILP	✓	G	I	—	—	—	DRA
Li, L. et al. (2024)	MILP	—	G	S	—	—	—	DRA
Sizaire et al. (2024)	LP	✓	G	I	IRT	—	—	DRA
Vo et al. (2025)	MINLP	✓	G, C	W	—	—	—	DRA
Gabrielli, Poluzzi et al. (2020)	MILP	✓	G	I	—	—	—	DRA
Elberry et al. (2021)	LP	—	G	I	—	—	—	DRA
Yu et al. (2025)	MILP	✓	G	D	IRT	—	—	DRA
Wolff et al. (2023)	MILP	✓	G	S	IRT	—	—	DRA
Guerra et al. (2020)	Sim	✓	G	I	—	—	—	DA (1-30 days)
Le et al. (2023)	MILP	✓	G	I	—	—	—	DRA
Fokkema et al. (2022)	MILP	—	G	D	—	—	—	DRA
O'Neill et al. (2024)	Sim	✓	G	I	—	—	—	DRA

Kim, J. et al. (2008)	MILP	✓	G, L	Y	IRT	—	Stoch*	DA (10 days)
Dayhim et al. (2014)	MILP	✓	G, L	Y	IRT	—	Stoch*	DA (5 days)
Nunes et al. (2015)	MILP	✓	L	Y	IRT	—	Stoch*	DA (10 days)
Xu et al. (2024)	MILP	—	G	I	IRT	—	Robust*	DRA
Almansoori and Shah (2012)	MILP	✓	L	Y	IRT	—	Stoch*	DA (10 days)
Zhou et al. (2024)	MILP	✓	G	I	IRT, IMP	—	Robust*	DRA
Robles et al. (2020)	MILP	✓	L	Y	IRT	—	Fuzzy*	DA (10 days)
Kim, S., Park, J., Chung, W. et al. (2024)	MINLP	—	L	I	IMP	✓	Stoch	SC (9 scenarios)
Efthymiadou et al. (2025)	MILP	—	G	I	IRT, IMP	✓	Stoch	SC (5 scenarios; representative day/season)
Yang et al. (2020)	MILP	—	G	I	IRT	✓	CC	SC (t-distribution for wind power)
This work	MILP	✓	G, L, C	I	IRT, IMP	✓	CC	SC (20 scenarios; representative day/month)

Notes. Sim: simulation, MILP: Mixed-Integer Linear Programming, MINLP: Mixed-Integer Nonlinear Programming, LP: Linear Programming, G: gaseous, L: liquid, C: chemical, I: intra-day, D: daily, W: weekly, S: seasonal, Y: yearly, Stoch: stochastic, CC: chance-constrained, DRA: deterministic renewable availability profile(s), DA: days of autonomy, SC: scenario-based, IRT: interregional transport representation, IMP: exogenous import.

* Uncertainty sources other than renewable electricity availability.

Taken together, Table 7.2 shows that most existing RHSC models either (i) employ deterministic representations of renewable electricity availability with coarse temporal resolution (e.g., seasonal or annual averages), or (ii) incorporate uncertainty mainly in hydrogen demand while sizing storage using fixed autonomy assumptions or deterministic profiles. Only a few studies explicitly address uncertainty in renewable electricity availability and its implications for storage sizing, and they often rely on simplified temporal representations. Moreover, Table 7.2 highlights how studies differ in temporal resolution, uncertainty approach, energy storage sizing basis, and technology portfolios, and the representation of interregional transport and imports, which can lead to different RHSC designs. This motivates integrated RHSC models that combine high temporal resolution, an explicit spatial network, multiple hydrogen forms with compatible storage and transport options, and a reliable supply of renewable hydrogen under renewable electricity uncertainty.

To address these gaps, this work proposes a chance-constrained MILP framework for RHSC design that jointly represents temporal flexibility through hybrid storage portfolios and spatial flexibility through interregional transport and exogenous imports under uncertainty in renewable electricity availability. Section 7.3 presents the model formulation and the sensitivity dimensions used in the case study.

7.3 Renewable hydrogen supply chain under uncertainty in renewable electricity availability

This work develops a chance-constrained MILP framework for the optimal design of the RHSC, including hybrid storage portfolios and interregional transport and exogenous import requirements, under uncertain renewable electricity availability. The model incorporates multiple hydrogen forms (gaseous, liquid, and carrier-based forms) together with compatible production, storage, and transport technologies. We structure the model as a two-stage program to separate long-term investment from short-term operations. First-stage decisions are strategic investments that are common across all scenarios and include the number, type, and location of production, storage, and transport infrastructure for multiple hydrogen forms as well as exogenous imports. Second-stage decisions are operational choices, including production rates, storage inventory levels, and interregional transport flows, which are scenario-dependent.

7.3.1 Supply chain representation

The aim is to design infrastructure for a stable, reliable, year-round supply of renewable hydrogen across multiple regions. The planning area comprises regions $i \in I$ to capture spatial differences in renewable electricity availability and hydrogen demand. The renewable hydrogen supply chain (RHSC) includes resource supply, energy storage (including storage of electricity, hydrogen, and derivatives), production, demand, and interregional transport (Figure 7.3). Two resource types are considered: regionally available inputs (e.g., water), which are assumed to be supplied locally, and endogenous resources (e.g., electricity) generated within each region (dashed lines in Figure 7.3). Resources $m \in M$ may be available in each region from different origins $o \in O$ based on their regional potential or may be produced within the supply chain.

The availability of renewable electricity $o \in O^e \subset O$ varies by region according to wind and solar potential under scenarios $k \in K$ and is represented by capacity factors. Capacity factors are aggregated and aligned to the intra-day time resolution (see Section 7.3.2 Temporal resolution). Generated renewable electricity can be stored to capture fluctuations or supplied to downstream production units. The model includes technology options for production $p \in P$, storage $l \in L$, and transport $t \in T$. Produced hydrogen (H_2 in Figure 7.3) can be stored to bridge mismatches between production and demand. Renewable hydrogen can be stored in multiple hydrogen carriers (H_2 forms in Figure 7.3; e.g., gaseous, liquid, LOHC, and ammonia) using storage technologies $l \in L$ that differ in characteristics (e.g., self-loss rate, charge/discharge rate, charge/discharge efficiency, and cost parameters). We consider underground hydrogen storage technologies $l \in L^u \subset L$, which have regional capacity limitations. Accordingly, conversion and reconversion units $p \in P^c \subset P$ are included to transform hydrogen into forms compatible with the selected storage technologies, as indicated by the binary parameter $b_{tm} = 1$. Interregional transport $t \in T$ is modeled through feasible transport technologies (captured by $b_{tm} = 1$) and routes (captured by $b_{tii'} = 1$). Finally, demand in each region can be supplied by (i) domestic production, (ii) net inflow via interregional transport from other modeled regions, and (iii) exogenous imports from outside the modeled system boundary. We refer to the combination of net interregional inflow and exogenous imports as non-domestic supply.

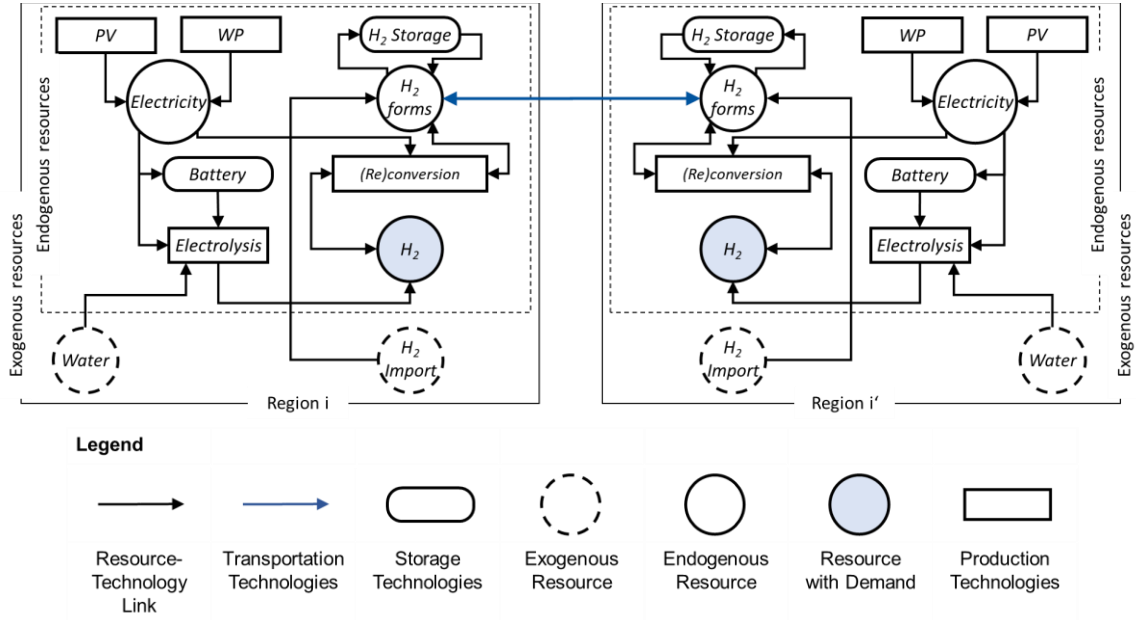


Figure 7.3. Overview of the RHSC model. H_2 : hydrogen; H_2 forms: gaseous hydrogen, liquid hydrogen and hydrogen derivatives; H_2 storage: storage of gaseous hydrogen, liquid hydrogen and hydrogen derivatives.

We consider the following assumptions for this problem:

- Interregional transport distances are computed as centroid-to-centroid distances between regions.
- Intra-regional distribution is not modeled (Efthymiadou et al., 2025; Wolff et al., 2023).
- Each transport technology is compatible with one resource ($\sum_{m \in M} b_{tm} = 1, t \in T$).
- Underground storage technologies $L^u \subseteq L$ are limited by regional capacity (Cihlar et al., 2021).
- Scenarios $k \in K$ occur with probabilities $\rho_k \geq 0$ and $\sum_{k \in K} \rho_k = 1$. Uncertainty enters through renewable capacity factors (ϑ_{oiwsk}) in each scenario k and all other parameters are deterministic.

7.3.2 Temporal resolution

To enable flexible energy storage portfolios, we consider hybrid storage comprising electricity storage and storage of hydrogen and its derivatives (Wang et al., 2025). We also account for the operational flexibility of production units via their ability to adjust to resource variability, represented through ramp-up and ramp-down limits (Elberry et al., 2021; Taslimi and Khosravi, 2025). Consequently, the model captures both diurnal (intra-day) and seasonal (intra-year) fluctuations to ensure the technological feasibility across the supply chain (Jiang et al., 2022).

To represent diurnal and seasonal variability while keeping the problem tractable, we adopt a cyclic year with hierarchical time aggregation (Efthymiadou et al., 2025). The year is decomposed into $|W|$ representative intra-year slices (e.g., monthly resolutions). Each intra-year slice is mapped to one typical day, which is then partitioned into $|S|$ intra-day slices (e.g., 6-hour blocks) to capture intra-day dynamics. Prior work uses $|W| \in [12, 52]$ and discusses the trade-off between temporal detail and computational tractability (Demirhan et al., 2020; Kakodkar et al., 2024; Zhou et al., 2024). In our hierarchical structure (Figure 7.4), each intra-year slice $w \in W$ represents n_w^d calendar days, with $\sum_{w \in W} n_w^d = 365$. Each representative day is partitioned into intra-day slices $s \in S$, where each slice s represents n_s^h hours and $\sum_{s \in S} n_s^h = 24$. Thus, the total number of hours represented over the year is $\sum_{w \in W} \sum_{s \in S} n_w^d n_s^h = n_y^h = 365 \times 24 = 8760$.

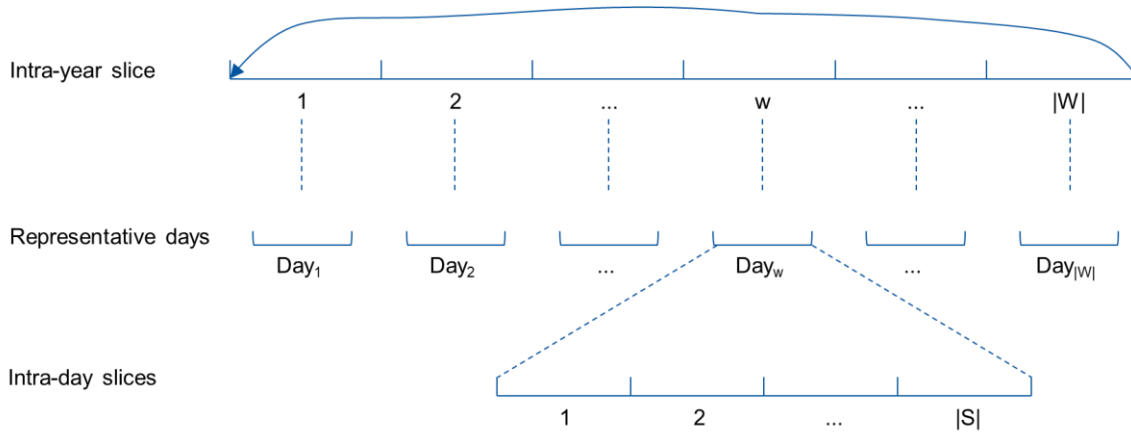


Figure 7.4. Hierarchical time aggregation showing the year divided into intra-year slices (e.g., weeks or months), each represented by a typical day, and the day partitioned into intra-day slices.

7.3.3 Mathematical formulation

In this section, we present the mathematical formulation for designing the RHSC. We formulate a chance-constrained MILP model that minimizes economic cost while ensuring supply reliability under uncertainty in renewable electricity availability. Investment costs are annualized based on expected lifetimes and depreciation rates.

7.3.3.1 Model nomenclature

Table 7.3 presents the notation employed in the mathematical model.

Table 7.3. Notation for sets, parameters, and decision variables.

Sets (indices)	Description
$i \in I$	regions
$p \in P$	production technologies ($P^c \subseteq P$ reconversion technologies)
$k \in K$	scenarios
$l \in L$	storage technologies ($L^u \subseteq L$ underground storage technologies)
$m \in M$	resources
$o \in O$	resource origins ($O^e \subseteq O$ renewable electricity resources)
$t \in T$	transport technologies ($T^{inv} \subseteq T$ transport technologies that require investment)
$s \in S$	intra-day slices per representative day
$w \in W$	intra-year slice
Parameters	Description
A_i^{imp}	Exogenous import upper bound in region i [-]
b_{lm}	1 if resource m can be stored in technology l ; 0 otherwise
b_{tm}	1 if resource m can be transported via technology t ; 0 otherwise
$b_{tii'}$	1 if a route i to i' is feasible for transport technology t ; 0 otherwise
$d_{ii'}$	Distance between regions i and i' [km]
D_{miws}	Demand of resource m in region i in intra-year slice w during intra-day slice s [tonne/intra-day slice] or [MWh/intra-day slice]
G_p	Capacity of production technology p [tonne/hour]
G_l	Capacity of storage technology l [tonne] or [MWh]
G_t	Capacity of transport technology t [tonne/hour]
n_w^d	Number of days per intra-year slice [day]
n_s^h, n_y^h	Hours per intra-day slice, hours per year [hours]
Q_l^{chg}, Q_l^{dch}	Maximum charge/discharge rate of storage technology l [tonne/hour] or [MWh/hour]
Q_p^{rdw}, Q_p^{rup}	Maximum ramp-up/ramp-down rate of production technology p [hour ⁻¹]
R_{oiws}	Potential for resource origin o in region i in intra-year slice w during intra-day slice s [tonne/intra-day slice]
α_{mp}	Conversion factor of resource m in production technology p [tonne/tonne] or [MWh/tonne]
β_{om}	1 if resource origin o can be converted to resource m ; 0 otherwise
Γ_{li}	Total available underground capacity for $l \in L^u$ in region i [tonne]
$\eta_l^{chg}, \eta_l^{dch}$	Efficiencies of the charging and discharging processes for storage technology l [-]
$\eta_{ti'i}^{tr}$	Transport efficiency (fraction delivered) for technology t from region i' to region i [-]
θ_{oi}	Maximum installable capacity for renewable electricity o in region i [MW]

λ_m	Lower heating value of resource m [$MWh/tonne$]
μ_p^{lb}	Minimum operating level for production technology p as a share of nameplate capacity [-]
π_i	Regional confidence level of demand satisfaction [-]
ρ_k	Probability of scenario k [-]
τ_l^{sl}	Self-loss rate for storage technology l [$hour^{-1}$]
ϑ_{oiwsk}	Capacity factor of renewable electricity o available in region i in intra-year slice w during intra-day slice s in scenario k [-]; scenario-dependent
Cost parameters	Description
v_p^{inv}	Annualized investment cost for production technology p [$€/year$]
v_l^{inv}	Annualized investment cost for storage technology l [$€/year$]
v_t^{inv}	Annualized investment cost for transport technology t [$€/km/year$]
v_o^{inv}	Annualized investment cost for renewable electricity technology o [$€/MW/year$]
v_m^{inv}	Unit exogenous import cost for resource m [$€/tonne$]
v_p^{op}	Unit operating cost for production technology p [$€/tonne$]
v_l^{op}	Unit operating cost for storage technology l per unit of inventory per hour [$€/tonne/hour$]
v_t^{op}	Specific operating cost for transport technology t [$€/tonne/km$]
v_t^{var}	Unit cost of transport via technology t [$€/tonne$]
v_o^{op}	Unit cost of utilizing resource origin o [$€/tonne$] or [$€/MWh$]
v_m^{plt}	Unit penalty cost of shortage in resource m [$€/tonne$]
Decision variables	Description
δ_{pi}	Number of installed plants of production technology p in region i [-]
γ_{li}	Number of installed storage technology l in region i [-]
$\kappa_{tii'}$	Number of established transport technology t from region i to i' [-]
σ_{oi}	Installed capacity of renewable electricity generation o in region i [MW]
ω_{mi}	Quantity of exogenous import of resource m to region i [$tonne$]
x_{piwsk}	Production rate of technology p in region i in intra-year slice w during intra-day slice s in scenario k [$tonne/intra-day slice$]
$q_{lmiwsk}^{chg}, q_{lmiwsk}^{dch}$	Charge/discharge rates of storage technology l of resource m in region i in intra-year slice w during intra-day slice s in scenario k [$tonne/intra-day slice$] or [$MWh/intra-day slice$]
y_{lmiwsk}	Intra-day inventory level for storage technology l of resource m in region i in intra-year slice w in intra-day slice s in scenario k [$tonne$] or [MWh]
y'_{lmiwk}	Intra-year inventory level for storage technology l of resource m in region i in intra-year slice w in scenario k [$tonne$] or [MWh]
$z_{tmii'wsk}$	Transport flow via technology t from region i to i' in intra-year slice w during intra-day slice s in scenario k [$tonne/intra-day slice$]

u_{oiwsk}	Amount of resource origin o utilized in region i in intra-year slice w during intra-day slice s in scenario k [tonne/intra-day slice] or [MWh/intra-day slice]
a_{miwsk}	Quantity of shortage in resource m in region i intra-year slice w during intra-day slice s in scenario k [tonne/intra-day slice]
φ_{ik}	Binary variable indicating reliability; 1 if demand in region i is met for scenario k ; 0 otherwise [-]

7.3.3.2 Objective function

To capture the economic dimension of the RHSC, we minimize the expected total annualized system cost. The objective function in Equation (1) is the sum of first-stage (here-and-now) investment and exogenous import costs and probability-weighted second-stage (wait-and-see) operating costs across scenarios $k \in K$ with probabilities ρ_k . The first stage sets strategic capacities and exogenous import levels before uncertainties are realized, based on a scenario set for renewable availability, so that decisions remain feasible across all scenarios. It includes annualized investment costs for production $C^{f,p}$, storage $C^{f,l}$, interregional transport $C^{f,t}$, and renewable generation $C^{f,o}$ technologies as well as the cost of exogenous import $C^{f,imp}$, as defined in Equations (2) to (6). The second stage adapts operations after uncertainties are realized (e.g., renewable availability), adjusting production, storage charge/discharge, interregional transport flows, and resource utilization. It includes operating costs for production $C_k^{s,p}$, storage $C_k^{s,l}$, and interregional transport $C_k^{s,t}$, and resource utilization $C_k^{s,o}$, as defined in Equations (7) to (10). We penalize unmet demand via a shortage cost $C_k^{s,plt}$ in Equation (11). The expectation operator $\sum_{k \in K} \rho_k (\cdot)$ reflects operating the integrated system under uncertainty.

$$\min obj^{cost} = [C^{f,p} + C^{f,l} + C^{f,t} + C^{f,o} + C^{f,imp}] + \sum_{k \in K} \rho_k [C_k^{s,p} \quad (1)$$

$$+ C_k^{s,l} + C_k^{s,t} + C_k^{s,o} + C_k^{s,plt}]$$

$$C^{f,p} = \sum_{i \in I} \sum_{p \in P} v_p^{inv} \delta_{pi} \quad (2)$$

$$C^{f,l} = \sum_{i \in I} \sum_{l \in L} v_l^{inv} \gamma_{li} \quad (3)$$

$$C^{f,t} = \sum_{i \in I} \sum_{i' \in I | i' \neq i} \sum_{t \in T^{inv}} v_t^{inv} d_{ii'}(\kappa_{tii'}) \quad (4)$$

$$C^{f,o} = \sum_{i \in I} \sum_{o \in O^e} v_o^{inv} \sigma_{oi} \quad (5)$$

$$C^{f,imp} = \sum_{i \in I} \sum_{m \in M} v_m^{inv} \omega_{mi} \quad (6)$$

$$C_k^{s,p} = \sum_{i \in I} \sum_{p \in P} \sum_{w \in W} \sum_{s \in S} n_w^d v_p^{op} x_{piwsk} \quad k \in K \quad (7)$$

$$C_k^{s,l} = \sum_{i \in I} \sum_{m \in M} \sum_{l \in L} \sum_{w \in W} \sum_{s \in S} (n_w^d n_s^h) v_l^{op} y_{lmiwsk} \quad k \in K \quad (8)$$

$$C_k^{s,t} = \sum_{i \in I} \sum_{i' \in I | i' \neq i} \sum_{m \in M} \sum_{t \in T} \sum_{w \in W} \sum_{s \in S} n_w^d (v_t^{var} + v_t^{op} d_{ii'}) z_{tmi'wsk} \quad k \in K \quad (9)$$

$$C_k^{s,o} = \sum_{i \in I} \sum_{o \in O} \sum_{w \in W} \sum_{s \in S} n_w^d v_o^{op} u_{oiwsk} \quad k \in K \quad (10)$$

$$C_k^{s,plt} = \sum_{i \in I} \sum_{m \in M} \sum_{w \in W} \sum_{s \in S} n_w^d v_m^{plt} a_{miwsk} \quad k \in K \quad (11)$$

7.3.3.3 Constraints

We consider several constraints in the model including chance-constrained resource balance, inventory balance, exogenous import limits, charging and discharging rate limits, infrastructure capacity, resource utilization, and variable domains.

7.3.3.3.1 Chance-constrained resource balance

To ensure a reliable supply, Constraints (12) enforce that, for each region i , demand must be fully met in scenarios whose cumulative probability is at least π_i . Demand is satisfied by resource utilization u_{oiwsk} , net production x_{piwsk} (with $\alpha_{mp} \geq 0$ resource m produced; $\alpha_{mp} < 0$ resource m consumed), net storage $q_{lmiwsk}^{dch} - q_{lmiwsk}^{chg}$, net interregional inflow $\eta_{ti'i}^{tr} z_{tmi'wsk} - z_{tmi'wsk}$, as well as exogenous import. Due to transport losses, the delivered quantity equals $\eta_{ti'i}^{tr} z_{tmi'wsk}$, where $\eta_{ti'i}^{tr}$ is the transport efficiency.

$$\Pr \left(\sum_{o \in O} \beta_{om} u_{oiwsk} + \sum_{p \in P} \alpha_{mp} x_{piwsk} + \sum_{l \in L | b_{lm}=1} (q_{lmiwsk}^{dch} - q_{lmiwsk}^{chg}) + \sum_{i' \in I} \sum_{t \in T | b_{tm}=1} (\eta_{ti'i}^{tr} z_{tmi'wsk} - z_{tmi'wsk}) + \omega_{mi} n_s^h / n_y^h \geq D_{miws} \right) \geq \pi_i \quad \begin{matrix} m \in M, i \in I, \\ w \in W, s \in S \end{matrix} \quad (12)$$

We linearize the probabilistic Constraints (12) using a binary indicator variable φ_{ik} . Constraints (13) apply when demand is fully met ($\varphi_{ik} = 1$). Otherwise, Constraints (14) apply when

demand is not met ($\varphi_{ik} = 0$) and allow shortage a_{miwsk} . The chance requirement ensures that at least a fraction π_i of scenarios meet demand.

$$\begin{aligned} \sum_{o \in O} \beta_{om} u_{oiwsk} + \sum_{p \in P} \alpha_{mp} x_{piwsk} \\ + \sum_{l \in L | b_{lm}=1} (q_{lmiwsk}^{dch} - q_{lmiwsk}^{chg}) \\ + \sum_{i' \in I} \sum_{t \in T | b_{tm}=1} (\eta_{ti'i}^{tr} z_{tmi'iwsk} - z_{tmi'i'wsk}) \\ + \omega_{mi} n_s^h / n_y^h \geq D_{miws} \varphi_{ik} \end{aligned} \quad \begin{array}{l} m \in M, i \in I, \\ w \in W, s \in S, k \\ \in K \end{array} \quad (13)$$

$$\begin{aligned} \sum_{o \in O} \beta_{om} u_{oiwsk} + \sum_{p \in P} \alpha_{mp} x_{piwsk} \\ + \sum_{l \in L | b_{lm}=1} (q_{lmiwsk}^{dch} - q_{lmiwsk}^{chg}) \\ + \sum_{i' \in I} \sum_{t \in T | b_{tm}=1} (\eta_{ti'i}^{tr} z_{tmi'iwsk} - z_{tmi'i'wsk}) \\ + \omega_{mi} n_s^h / n_y^h + a_{miwsk} \geq D_{miws} (1 - \varphi_{ik}) \end{aligned} \quad \begin{array}{l} m \in M, i \in I, \\ w \in W, s \in S, k \\ \in K \end{array} \quad (14)$$

Finally, Constraints (15) ensure that the desired regional confidence level π_i is met by forcing the sum of probabilities for reliable scenarios ($\varphi_{ik} = 1$) to be at least π_i .

$$\sum_{k \in K} \rho_k \varphi_{ik} \geq \pi_i \quad i \in I \quad (15)$$

7.3.3.3.2 Inventory balance

We employ a hierarchical time aggregation to reduce the problem size but retain high temporal resolution, Figure 7.5 (Efthymiadou et al., 2025; Wolff et al., 2023). Therefore, several time slices represent the intra-day storage profile. In addition, to represent year-round operation, we decompose the year into intra-year time slices which are specified by a representative day. Figure 7.5 shows the time steps representing intra-day and intra-year storage profile aligned with time decomposition presented in this study. To connect the inventory level of each intra-year slice with the intra-day slices we define decision variables y'_{lmiwk} and y_{lmiwsk} .

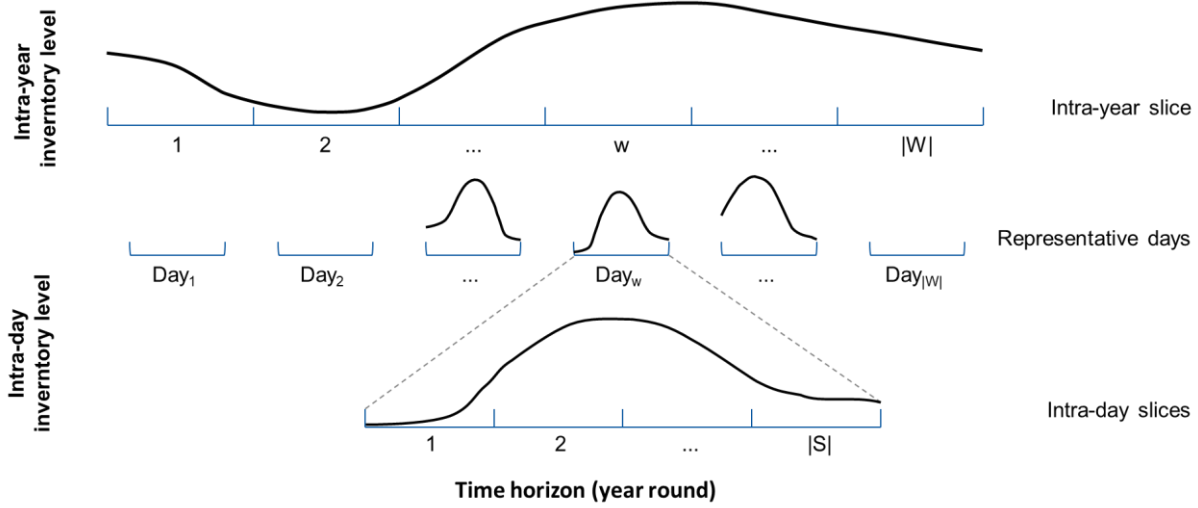


Figure 7.5. Storage modeling visualization aligned with time aggregation. The black curves show the inventory level of resources over a representative day and time slices in a year-round time horizon. Constraints (16) define the intra-day inventory balance, stating that the storage level at an intra-day slice equals the level from the previous slice plus net charges. Here we consider the self-loss rate as well as the charge and discharge efficiency for storage technologies in each intra-day slice.

$$y_{lmiwsk} = (1 - n_s^h \tau_l^{sl}) y_{lmiw(s-1)k} + (\eta_l^{chg} q_{lmiwsk}^{chg} - q_{lmiwsk}^{dch} / \eta_l^{dch}) \quad \begin{matrix} l \in L, m \in M, i \in I, \\ w \in W, s \in S \setminus \{1\}, k \in K \end{matrix} \quad (16)$$

Constraints (17) state that the intra-day inventory at the first slice equals the start-of-day inventory y'_{lmiwk} of the same intra-year slice plus net charge.

$$y_{lmiw1k} = (1 - n_s^h \tau_l^{sl}) y'_{lmiwk} + (\eta_l^{chg} q_{lmiw1k}^{chg} - q_{lmiw1k}^{dch} / \eta_l^{dch}) \quad \begin{matrix} l \in L, m \in M, i \in I, \\ w \in W, k \in K \end{matrix} \quad (17)$$

Constraints (18) model the intra-year inventory dynamics. The inventory at the start of the intra-year slice w equals the inventory at the start of the previous slice $w - 1$ plus the total net change over the representative day (difference between the end-of-day inventory $y_{lmi(w-1)Sk}$ and start-of-day inventory $y'_{lmi(w-1)k}$), scaled by the number of days in the intra-year slice n_w^d . This formulation creates a cyclic storage profile over the year (for $w = 1$; $w - 1 \equiv |W|$).

$$y'_{lmiwk} = y'_{lmi(w-1)k} + n_w^d (y_{lmi(w-1)Sk} - y'_{lmi(w-1)k}) \quad \begin{matrix} l \in L, m \in M, i \in I, \\ w \in W, k \in K \end{matrix} \quad (18)$$

7.3.3.3 Exogenous import limits

Constraints (19) ensure that exogenous imports (energy basis) do not exceed a share A_i^{imp} of the total annual demand in region i .

$$\sum_{m \in M} \lambda_m \omega_{mi} \leq A_i^{imp} \sum_{m \in M} \sum_{w \in W} \sum_{s \in S} \lambda_m n_w^d D_{miws} \quad i \in I \quad (19)$$

7.3.3.3.4 Charging and discharging rate limits

Constraints (20) and (21) limit the charge and discharge rates based on the installed storage capacity.

$$q_{lmiwsk}^{chg} \leq n_s^h Q_l^{chg} \gamma_{li} \quad l \in L, m \in M, i \in I, w \in W, s \in S, k \in K \quad (20)$$

$$q_{lmiwsk}^{dch} \leq n_s^h Q_l^{dch} \gamma_{li} \quad l \in L, m \in M, i \in I, w \in W, s \in S, k \in K \quad (21)$$

7.3.3.3.5 Production, storage and transport constraints

Constraints (22) ensure that the production rate does not exceed the total installed production capacity in each region. They also ensure that production does not fall below the minimum operating level associated with technology.

$$\mu_p^{lb} n_s^h G_p \delta_{pi} \leq x_{piwsk} \leq n_s^h G_p \delta_{pi} \quad p \in P, i \in I, w \in W, s \in S, k \in K \quad (22)$$

Constraints (23) ensure that the production rate cannot increase and decrease relative to the previous time slice than ramp-up and ramp-down rate, which technically limits how plants can adjust to fluctuations (Kim, Park, Heo, and Lee, 2024; Li, Y. et al., 2024).

$$\begin{aligned} -Q_p^{rdw} (n_s^h)^2 G_p \delta_{pi} &\leq x_{piwsk} - x_{piw(s-1)k} \\ &\leq Q_p^{rup} (n_s^h)^2 G_p \delta_{pi} \end{aligned} \quad \begin{aligned} p \in P, i \in I, w \in W, \\ s \in S \setminus \{1\}, k \in K \end{aligned} \quad (23)$$

Constraints (24) and (25) ensure that inventory levels do not exceed the installed storage capacity.

$$y_{lmiwsk} \leq G_l \gamma_{li} \quad l \in L, m \in M, i \in I, w \in W, s \in S, k \in K \quad (24)$$

$$y'_{lmiwk} \leq G_l \gamma_{li} \quad l \in L, m \in M, i \in I, w \in W, k \in K \quad (25)$$

Constraints (26) limit the total installed capacity for underground storage technologies ($l \in L^u$) based on regional geological potential.

$$G_l \gamma_{li} \leq \Gamma_{li} \quad l \in L^u, i \in I \quad (26)$$

Constraints (27) prohibit storing, charging, and discharging a resource in an incompatible technology.

$$y_{lmiwsk} = 0, q_{lmiwsk}^{chg} = 0, q_{lmiwsk}^{dch} = 0 \quad \begin{aligned} l \in L, m \in M, i \in I, w \in W, \\ s \in S, k \in K | b_{lm} = 0 \end{aligned} \quad (27)$$

Constraints (28)(6.B.5) limit the quantity of resource transported between two regions by the installed link capacity.

$$z_{tmii'wsk} \leq n_s^h G_t \kappa_{tii'} \quad t \in T^{inv}, m \in M, i \in I, i' \in I, w \in W, s \in S, k \in K | i \neq i' \quad (28)$$

Constraints (29) prevent transport via incompatible technologies or infeasible routes.

$$z_{tmii'wsk} = 0 \quad \begin{matrix} t \in T, m \in M, i \in I, i' \in I, w \in W, \\ s \in S, k \in K | b_{tm} = 0 \vee b_{tii'} = 0 \end{matrix} \quad (29)$$

7.3.3.3.6 Renewable electricity generation constraints

Constraints (30) limit renewable electricity generation ($o \in O^e$) based on the installed capacity and the renewable electricity availability (capacity factor) in each time slice.

$$u_{oiwsk} \leq n_s^h \sigma_{oi} \vartheta_{oiwsk} \quad o \in O^e, i \in I, w \in W, s \in S, k \in K \quad (30)$$

Constraints (31) ensure installed capacity does not exceed the maximum regional potential.

$$\sigma_{oi} \leq \theta_{oi} \quad o \in O^e, i \in I \quad (31)$$

7.3.3.3.7 Resource utilization constraints

Constraints (32) limit the use of resources (e.g., water) by their regional availability.

$$u_{oiwsk} \leq R_{oiws} \quad o \in O \setminus O^e, i \in I, w \in W, s \in S, k \in K \quad (32)$$

7.3.3.3.8 Variable domains

Finally, Constraints (33) to (44) define the domains for all decision variables.

$$\delta_{pi} \in \mathbb{N}_0 \quad p \in P, i \in I \quad (33)$$

$$\gamma_{li} \in \mathbb{N}_0 \quad l \in L, i \in I \quad (34)$$

$$\kappa_{tii'} \in \mathbb{N}_0 \quad t \in T^{inv}, i \in I, i' \in I \quad (35)$$

$$\varphi_{ik} \in \{0,1\} \quad i \in I, k \in K \quad (36)$$

$$\sigma_{oi} \geq 0 \quad o \in O^e, i \in I \quad (37)$$

$$\omega_{mi} \geq 0 \quad m \in M, i \in I \quad (38)$$

$$x_{piwsk} \geq 0 \quad p \in P, i \in I, w \in W, s \in S, k \in K \quad (39)$$

$$q_{lmiwsk}^{chg}, q_{lmiwsk}^{dch}, y_{lmiwsk} \geq 0 \quad l \in L, m \in M, i \in I, w \in W, s \in S, k \in K \quad (40)$$

$$y'_{lmiwk} \geq 0 \quad l \in L, m \in M, i \in I, w \in W, k \in K \quad (41)$$

$$z_{tmii'wsk} \geq 0 \quad t \in T, m \in M, i \in I, i' \in I, w \in W, s \in S, k \in K \quad (42)$$

$$u_{oiwsk} \geq 0 \quad o \in O, i \in I, w \in W, s \in S, k \in K \quad (43)$$

$$a_{miwsk} \geq 0 \quad m \in M, i \in I, w \in W, s \in S, k \in K \quad (44)$$

7.4 Case study, results, and discussion

We apply the proposed chance-constrained MILP framework to a case study illustrating RHSC design under variability and uncertainty in renewable electricity availability in Europe. Section 7.4.1 describes the case-study data and uncertainty representation, and Sections 7.4.2 and 7.4.3 report the results and sensitivity analyses.

7.4.1 Data

This case study applies the model to a European, country-level renewable hydrogen supply chain. The system includes Germany, France, Italy, Spain, Poland, the Netherlands, Belgium, Sweden, and Austria—countries that together represent 913 TWh/year of the reference hydrogen demand in 2050 ($\approx 80\%$ of EU-27), as detailed in Appendix 7.A.1. Sectoral demands are from Tonelli et al. (2023) for steel, transport, refineries, cement, light industry, chemical feedstock uses (ammonia and methanol), under reference, low, and high scenarios for 2050. All key techno-economic parameters, demand inputs, and renewable potential data are documented in the Supplementary Information.

Temporal structure. The planning horizon covers a full year. Seasonal (intra-year) variability is represented at monthly granularity, and diurnal (intra-day) variability is represented by four representative intra-day slices of 6 hours, consistent with the time aggregation in Section 7.3.2.

Resources. Renewable electricity availability is represented via capacity factors (i.e. actual energy output over maximum possible energy output) for wind and solar. We assume that approximately 15% of regional renewable electricity potential is available for hydrogen production (Hydrogen Council, 2021; Pathak et al., 2023). Water requirements for hydrogen production are tracked against local freshwater availability (by subtracting agricultural, industrial, and municipal uses) (Tonelli et al., 2023).

Production. Hydrogen is produced from renewable electricity via electrolysis, consistent with recent studies (Guo et al., 2025). Produced hydrogen can serve demand, be stored directly, or be converted into alternative storage carriers (liquid hydrogen, LOHC, or ammonia) through investments in the required conversion and reconversion units (e.g., liquefaction/evaporation for LH_2 and hydrogenation/dehydrogenation for LOHC). Conversion and reconversion processes incur associated losses. Operational limits include minimum/maximum operating capacity and ramp-up/ramp-down rates for production, conversion, and reconversion processes (Danish Energy Agency, 2018c).

Storage. Multiple energy storage technologies include lithium-ion batteries (electricity buffering), gaseous hydrogen tanks, underground hydrogen storage (salt caverns) where geologically available, and tanks for liquid hydrogen, LOHC, and ammonia. Each option is characterized by techno-economic parameters, efficiencies, and charging, discharging, and storage losses, as well as maximum charging and discharging rates based on Danish Energy Agency technology projections for 2050 (Danish Energy Agency, 2018a).

Exogenous import and interregional transport. Exogenous imports of hydrogen carriers (gaseous hydrogen, liquid hydrogen, LOHC, and ammonia) are restricted to a maximum of 50% of each country's demand (European Commission, 2021). We assume a uniform exogenous import upper bound across all countries in the case study, $A_i^{imp} = A^{imp}$.

Aligned with the European Hydrogen Backbone, which frames interregional hydrogen transport in Europe as a high-pressure gaseous pipeline network, our model case study represents inter-country transport via pipelines (Guidehouse, 2021). Road transport is treated as a short-distance, small-volume distribution mode and is therefore excluded from our country-level case study (Danish Energy Agency, 2018e; Zhou et al., 2024). Cross-border electricity transmission is not represented, as we assume electricity used for hydrogen production and (re)conversion to be sourced domestically within each country (European Commission, 2023; Hofmann et al., 2025).

System overview. Figure 7.6 shows the RHSC in the case study. Regional photovoltaics and wind turbines supply electricity that is either stored in batteries for later use or dispatched to hydrogen production. Gaseous hydrogen can satisfy demand directly or enter storage for later uses. When alternative hydrogen carriers are used for storage, the model includes the required conversion and reconversion steps and their losses. Hydrogen also moves across borders through pipelines and may be supplied via exogenous imports (from outside the system boundary) as gaseous hydrogen (GH₂), liquid hydrogen (LH₂), LOHC, or ammonia (NH₃). Unsatisfied hydrogen demand is penalized; in the base case, we set the penalty to 10× the unit cost of exogenous imports.

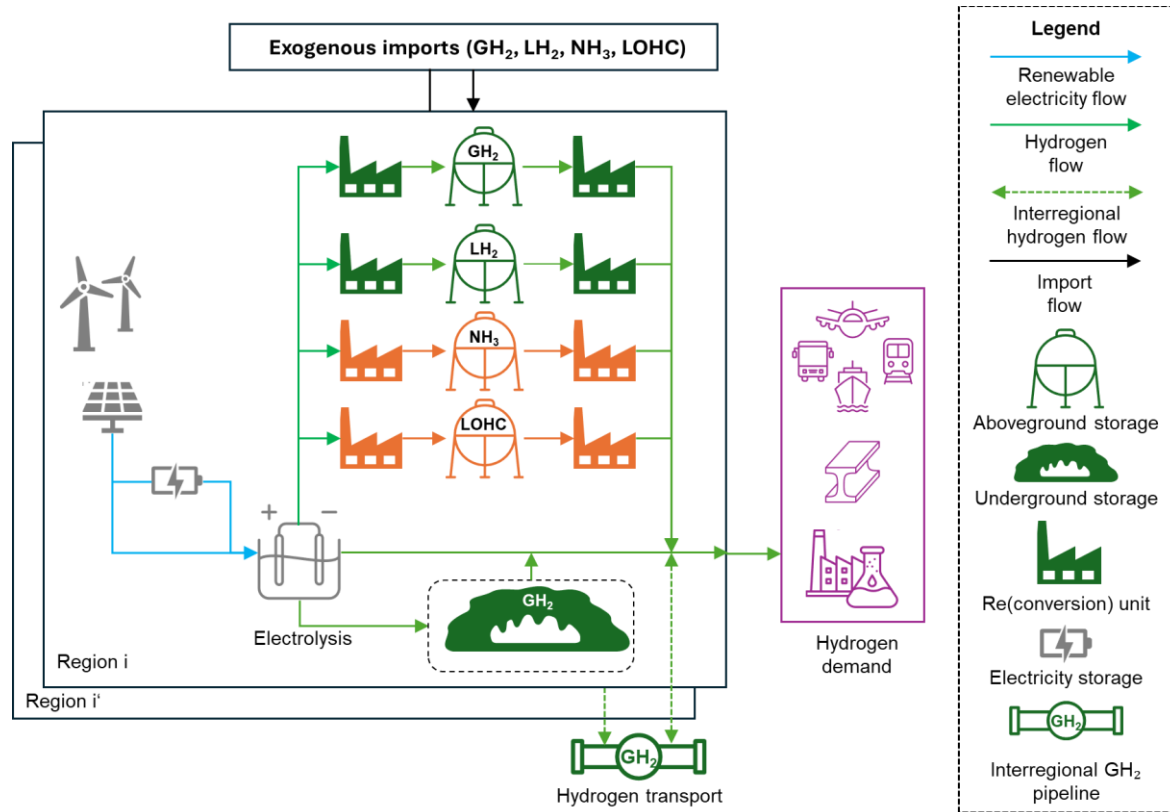


Figure 7.6. Case-study superstructure of the RHSC. GH₂: gaseous hydrogen; LH₂: liquid hydrogen; NH₃: ammonia; LOHC: liquid organic hydrogen carrier.

Overall, this case study illustrates the flexibility of renewable hydrogen supply across different supply chain elements and regions. Renewable hydrogen can be produced domestically (and stored), transported across borders within the modeled system boundary, or sourced via exogenous imports. We investigate the resulting optimal designs under uncertainty using a scenario-based representation of renewable availability.

Uncertainty and scenarios. Renewable electricity availability is treated as uncertain and represented through a scenario set constructed in four steps. First, we use historical hourly capacity factor data for wind and solar for all considered regions over 1980–2019 (Pfenninger and Staffell, 2016; Staffell and Pfenninger, 2016). Second, we fit a multivariate seasonal autoregressive model to capture temporal persistence and spatial correlations in these capacity-factor time series (Haider et al., 2021; Nuño Martinez et al., 2018; SAS Institute Inc., 2014; Yunus et al., 2017; Zhang et al., 2021). This approach captures diurnal and seasonal variation and accounts for spatial dependencies (Nuño Martinez et al., 2018; Yunus et al., 2017; Zhang et al., 2021). Third, we generate 1000 simulated time series for the included regions and map them to the representative intra-year and intra-day slices used in the optimization model. Finally, we apply fast-forward scenario reduction (Heitsch and Römisch, 2003) to obtain a

tractable set of 20 scenarios with associated probabilities. To check that this level of reduction does not bias the results, we compared reduced scenario sets with different numbers of scenarios (see Appendix 7.A.2). The resulting total annualized costs and capacity decisions change only marginally, so we use a reduced set of 20 scenarios in all subsequent analyses.

The model comprises 164,397 continuous variables and 147 integer variables (100 binary) and is solved with Gurobi 12.0.0 on a 32-core AMD EPYC 9334, 2.70 GHz machine with 64 GB RAM. Solution times range from 2 to 48 hours per instance, with a maximum MIP gap of 2%.

7.4.2 Base-case results

We first present the base-case design of the European RHSC under uncertainty in renewable electricity availability. The base case adopts the Tonelli et al. (2023) reference hydrogen demand, a monthly intra-year aggregation (12 slices) with four intra-day slices and a uniform regional reliability requirement across all countries. We impose $\pi_i = \pi$ (Equation (15)) and set $\pi = 0.95$, meaning that in each country demand must be fully satisfied in scenarios whose cumulative probability is at least 95% (Equation (13)–(15)). As base case assumptions, exogenous imports (from outside the modeled system boundary) are limited to 50% of demand, and underground hydrogen storage is available where geologically feasible.

In the base case, the model yields a total expected annualized system cost of 55.4 bn €/year and a levelized cost of hydrogen (LCOH) of 2.81 €/kg-H₂. Costs are dominated by renewable electricity generation ($\approx 59\%$), followed by hydrogen production ($\approx 16\%$) and exogenous imports ($\approx 15\%$). Interregional transport ($\approx 5\%$) and energy storage ($\approx 3\%$) contribute to smaller shares, while the shortage penalty ($\approx 1\%$) remains minor. Despite its smaller cost share, hybrid storage is pivotal for meeting 95% reliability target, with long-duration options (LOHC and underground hydrogen storage) enabling seasonal balancing. Figure 7.7 reports the annualized cost breakdown of the system, decomposed into investment and operating costs.

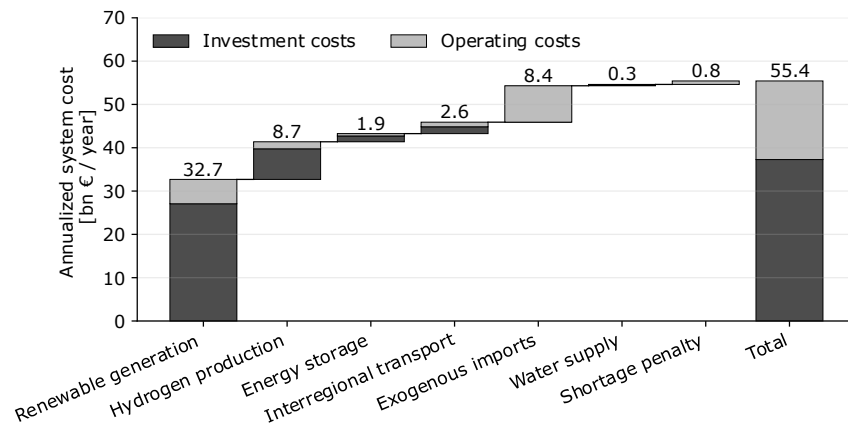


Figure 7.7. Base-case annualized system cost decomposition ($\pi = 0.95$).

Figure 7.8 summarizes the spatial structure of the base-case solution. Renewable hydrogen supply concentrates in regions with strong renewable potential (notably France and Spain), and the system forms a south-to-central corridor that supplies major demand regions. The largest interregional flows occur from Spain to France, from France to Germany, and from France to Belgium. These corridors form a backbone that transports surplus renewable hydrogen from resource-rich areas to demand centers. Exogenous imports primarily enter Germany (≈ 45 TWh/year), indicating that spatial flexibility (interregional transport and exogenous imports) complements domestic renewable supply and interregional balancing.

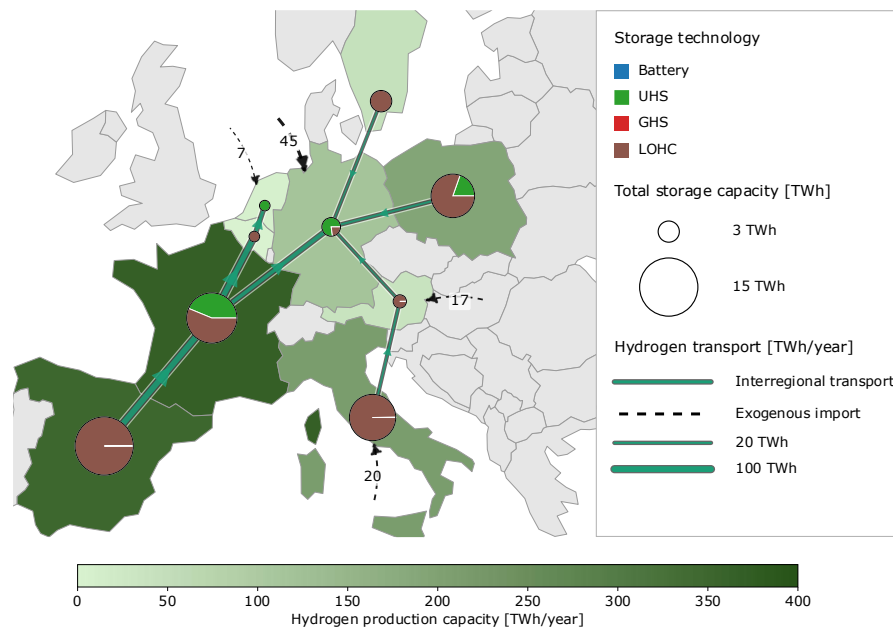


Figure 7.8. Base-case optimal RHSC in 2050 ($\pi = 0.95$). Country shading indicates renewable-based hydrogen production potential; solid links show interregional pipeline flows (TWh/year); dashed arrows denote exogenous imports; pie markers indicate installed storage capacities (TWh) by technology.

The installed storage portfolio is dominated by LOHC and underground hydrogen storage. Storage capacity is concentrated in regions with high hydrogen production capacity, consistent with its role in seasonal balancing.

7.4.3 Sensitivity analysis

Building on the base case, we examine the sensitivity of the optimal RHSC design with respect to (i) hydrogen demand, (ii) the storage-technology portfolio, (iii) spatial flexibility via interregional transport and exogenous imports, (iv) the shortage-penalty level, and (v) the reliability level. Sensitivities related to modeling choices (scenario-set size and temporal aggregation) are reported in Appendix 7.A.2–7.A.3, and additional network maps are provided in the Supplementary Information.

7.4.3.1 Sensitivity to hydrogen demand

To quantify how the optimal 2050 system changes with hydrogen demand, we conduct a sensitivity around the base case by decreasing and increasing final demand by $\pm 50\%$, while keeping all techno-economic assumptions and the reliability level ($\pi = 0.95$) unchanged. This range lies within the uncertainty range reported by Tonelli et al. (2023) for 2050, corresponding to approximately -77% to $+62\%$ relative to their reference scenario.

Total annualized cost decreases from 55.4 bn €/year in the base case to 26.6 bn €/year under -50% demand and increases to 86.6 bn €/year under $+50\%$ demand. Despite the substantial change in system scale, LCOH varies only moderately (2.67–2.89 €/kg-H₂). Across this range, the optimal design largely scales with demand, while higher demand levels increase reliance on storage, interregional transport, and exogenous imports. Figure 7.9 reports percentage changes in annualized cost components relative to the base case. Under -50% demand, imports are low and the system relies mainly on domestic renewable supply. Under $+50\%$ demand, interregional transport, storage, and exogenous imports expand more strongly, reflecting the higher value of spatial and temporal flexibility at larger system scale.

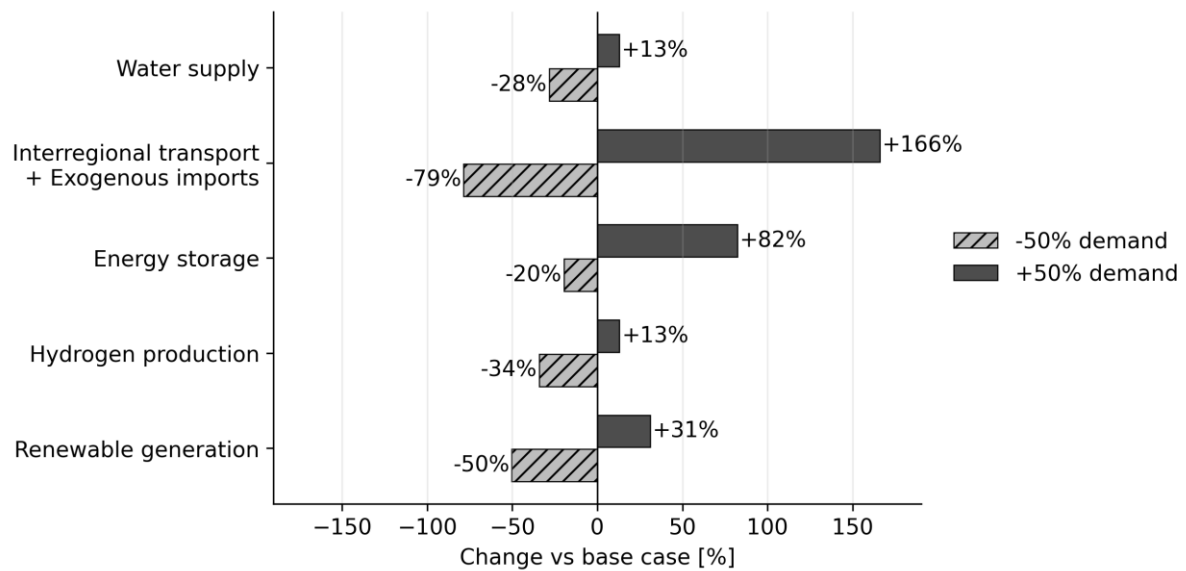


Figure 7.9. Demand sensitivity ($\pm 50\%$, $\pi = 0.95$). Percentage change in annualized system cost components relative to the base case.

7.4.3.2 Sensitivity to the energy-storage portfolio

This subsection evaluates how restricting the set of storage technologies affects the optimal RHSC design. In the base case, the storage portfolio includes lithium-ion batteries, gaseous hydrogen storage (GHS), liquid hydrogen storage (LHS), underground hydrogen storage (UHS), ammonia storage (NH_3S), and LOHC storage (LOHCS). We compare this benchmark to four variants: No-UHS (without underground storage), H_2 -only (hydrogen storage technologies without derivatives), LOHC-only (LOHC storages only), and NH_3 -only (NH_3 storages only).

Relative to the base case, restricting the storage portfolio increases reliance on exogenous imports and raises total cost. Excluding UHS increases exogenous imports by $\approx 45\%$, highlighting the role of underground storage in seasonal balancing. Forcing the system to use a single derivative storage medium (LOHC-only and NH_3 -only scenarios) leads to more reliance on exogenous import (+13% and +45% respectively). Overall, a broader storage portfolio reduces reliance on exogenous imports. Several restricted storage portfolios also show higher installed battery capacity, which is consistent with batteries serving intra-day balancing in our time-sliced operational model (ramp-up/ramp-down limits and minimum-load requirements) when alternative storage pathways are restricted. Table 7.4 summarizes the resulting storage capacities, exogenous imports, and interregional transport across scenarios. In the base case and

the No-UHS scenario, LOHC remains the dominant above-ground storage technology, whereas in the H₂-only case storage shifts toward underground hydrogen storage where feasible.

Table 7.4. Storage, exogenous imports, and interregional transport outcomes under alternative storage-portfolio assumption.

Scenario	Total installed electricity storage [GWh]	Total installed hydrogen storage [TWh]	Exogenous imports [TWh/year]	Interregional transport [TWh/year]
Base case	1.8	61.0	90.2	348.8
no-UHS	14.8	51.9	146.6	306.9
H ₂ -only	12.1	21.9	183.2	445.1
LOHC-only	17.1	48.4	164.2	333.8
NH ₃ -only	249.3	14.8	319.6	316.0

Figure 7.10 compares the annualized system cost across storage-portfolio variants. The base case exhibits the lowest cost, while all restricted portfolios lead to higher system costs, primarily driven by increased expenditures on exogenous imports. Restricting the storage portfolio increases total cost, mainly through higher exogenous import expenditures. The NH₃-only case yields the highest cost, driven by substantially higher imports.

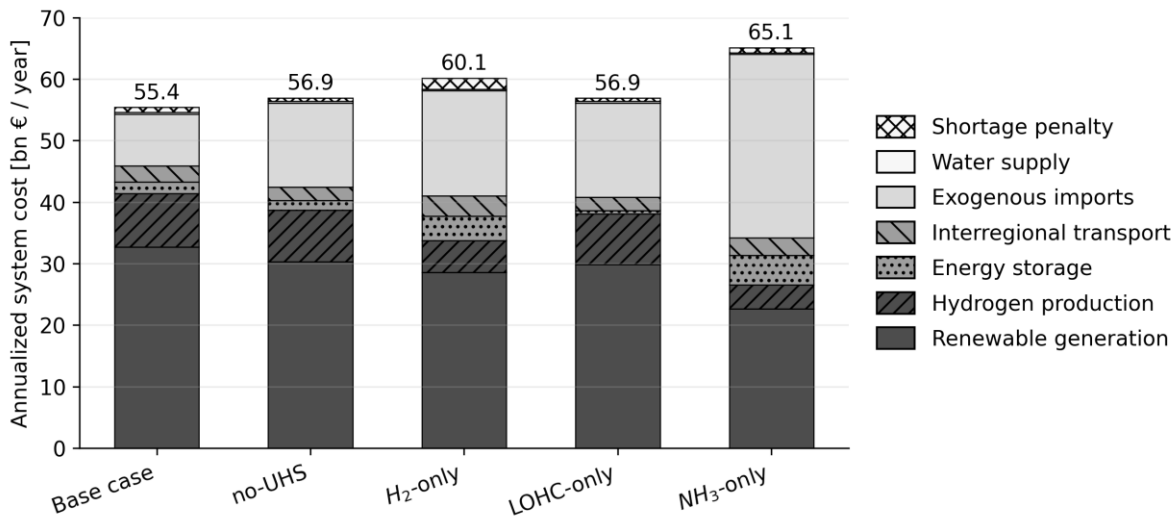


Figure 7.10. Annualized system cost breakdown for the base case and storage-portfolio variants (No-UHS, H₂-only, LOHC-only, NH₃-only).

7.4.3.3 Sensitivity to spatial flexibility

To assess how strongly the RHSC relies on spatial flexibility, we vary two case-study limits while keeping all other assumptions fixed. First, we adjust the exogenous import upper bound (share of demand supplied by exogenous imports). Second, we impose a non-domestic supply upper bound (share of demand supplied by exogenous imports plus net interregional inflow).

Exogenous import limits. Tightening the exogenous import upper bound from 50% (base case) to 30% reduces exogenous imports by 39% and increases interregional transport by 18%, Figure 7.11. The cost composition shifts toward domestic supply, with higher costs for renewable generation, production, and interregional transport, and lower exogenous import costs. Relaxing the limit to 70% produces the opposite trade-off: exogenous imports increase (+46%) and interregional transport declines (−20%). Across these cases, total annualized system cost changes by less than 1%, indicating that the system can substitute between imports and interregional transport with limited impact on total cost.

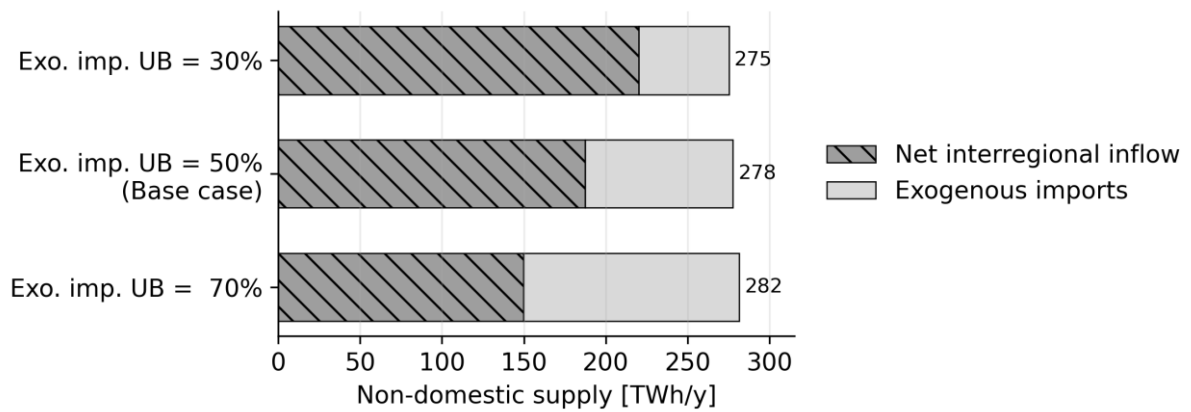


Figure 7.11. Sensitivity to the exogenous import upper bound (A^{imp}): changes in exogenous imports and interregional transport. Exo. imp. UB: exogenous import upper bound.

Non-domestic supply limits. We then restrict non-domestic supply to 33%, 50%, and 75% of total demand, Figure 7.12. The 50% and 75% cases remain close to the base case (less than 1% changes in non-domestic supply), whereas the tightest constraint (33%) reduces non-domestic supply substantially (−21%) and increases total annualized cost by +4%. This increase is driven mainly by higher investments and operating costs for renewable generation, hydrogen production, and storage, indicating a shift from spatial to temporal flexibility. Non-domestic supply limits below roughly one-third (e.g., 30%) were infeasible at $\pi = 0.95$ under the case-study assumptions, indicating that a minimum level of non-domestic supply is required to satisfy demand reliably.

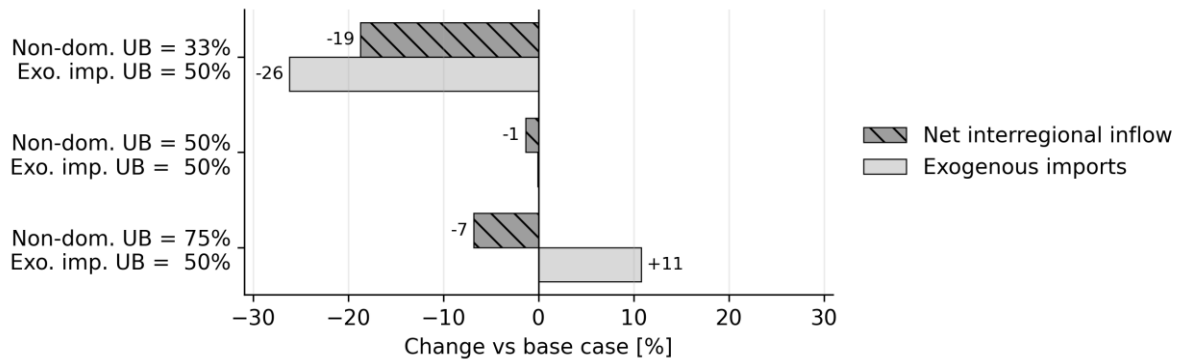


Figure 7.12. Sensitivity to the non-domestic supply upper bound (exogenous imports plus net interregional inflow): changes in exogenous imports and net interregional inflow relative to the base case. Non-dom. UB: non-domestic supply upper bound; Exo. imp. UB: exogenous import upper bound.

Figure 7.13 visualizes the network configuration under the strict non-domestic supply upper bound (33%). Relative to the base case, several corridors change, reflecting a reallocation of supply toward more domestic sourcing under the tighter limit on exogenous imports and net interregional inflow. The reduced spatial flexibility is accompanied by higher storage deployment ($\approx +13\%$), consistent with the observed cost changes.

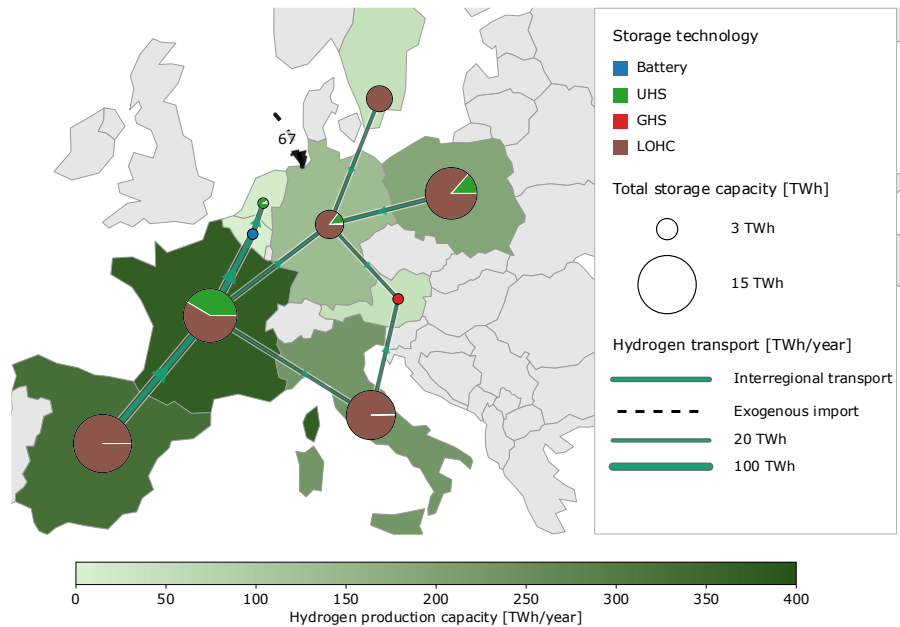


Figure 7.13. Optimal renewable hydrogen supply chain in 2050 under a strict non-domestic supply upper bound (non-domestic supply $\leq 33\%$ of total demand). Elements are defined as in Figure 7.8.

7.4.3.4 Sensitivity to the shortage-penalty level

In the base case, the shortage penalty is set to $10\times$ the unit cost of exogenous imports. To examine this assumption, we test penalty multipliers of $5\times$, $10\times$ (base), and $15\times$. As shown in Figure 7.14, increasing the penalty mainly reduces the expected shortage—from 5.70 TWh/year ($5\times$) to 2.92 TWh/year ($15\times$)—while changing the total annualized system cost only marginally. The penalty term remains small because shortages can occur only in the limited set of scenarios in which unmet demand is permitted by the chance-constraint formulation and therefore contribute only a minor share to the expected total cost.

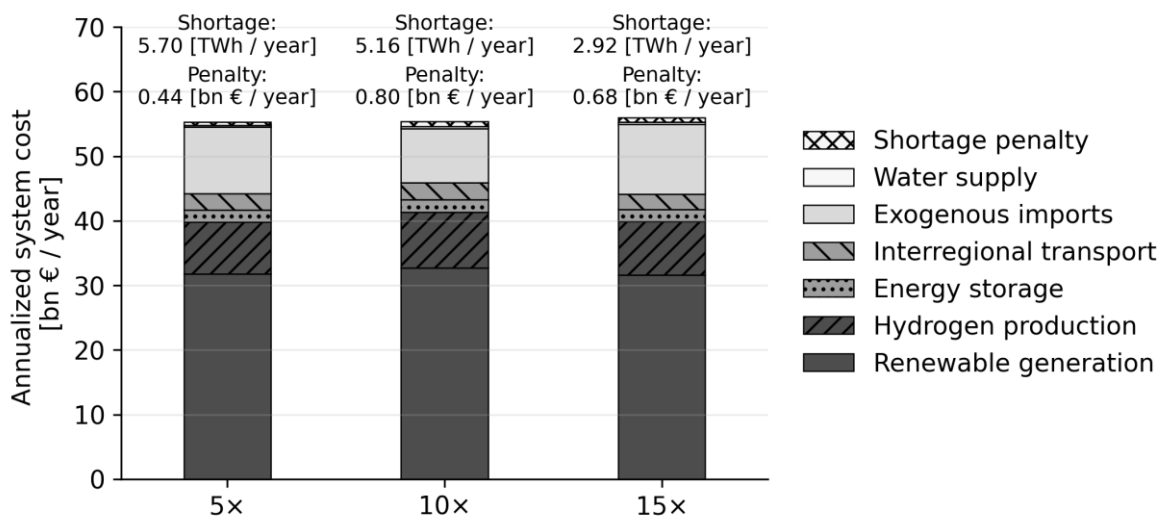


Figure 7.14. Penalty-cost sensitivity. Annualized system cost breakdown for shortage-penalty multipliers $5\times$, $10\times$ (base), and $15\times$, with the corresponding expected shortage (TWh/year).

7.4.3.5 Sensitivity to the confidence level of demand satisfaction

In this subsection, we examine how the chance-constraint reliability level π affects the optimal design. In Equation (13)–(15), π specifies the minimum cumulative probability of scenarios in which each region's demand must be fully satisfied; unmet demand in the remaining scenarios is penalized. Therefore, increasing π tightens the demand-satisfaction requirement and leads to higher capacity deployment across the supply chain.

Figure 7.15 reports total annualized system cost and its decomposition across reliability levels. Total annualized system cost increases from 54.1 bn €/year at $\pi = 0.85$ to 56.8 bn €/year at $\pi = 1.00$. Higher reliability reduces expected shortage and shifts the cost structure toward greater capacity deployment across the supply chain, including domestic infrastructure and non-domestic supply. In the extreme case ($\pi = 1.00$), exogenous import flows are 92% higher than in the base case ($\pi = 0.95$), indicating that satisfying demand in all scenarios requires a

combination of domestic supply, interregional balancing, and exogenous imports under the assumptions of this case study.

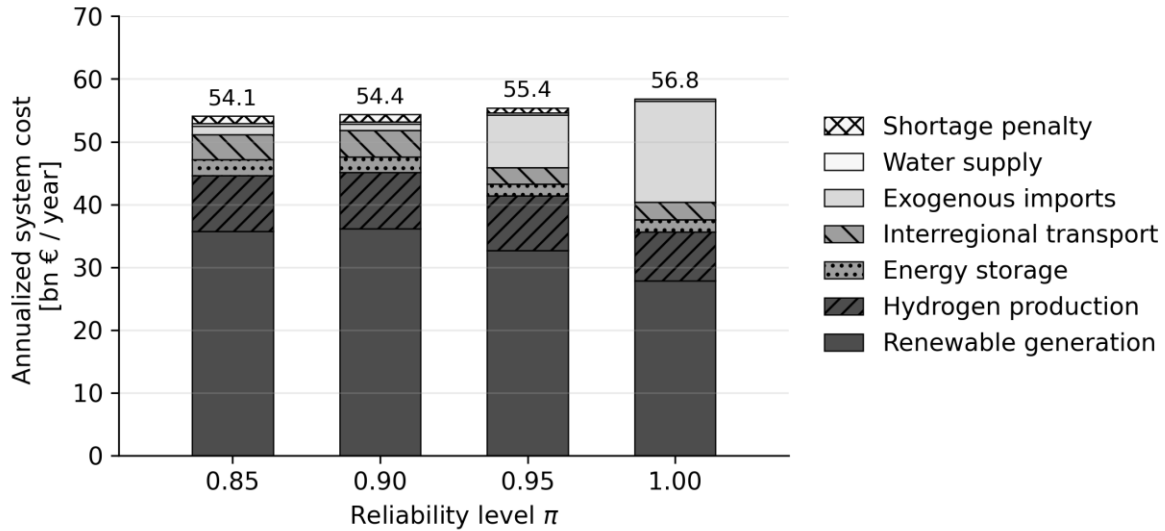


Figure 7.15. Reliability–cost trade-off under chance-constrained demand satisfaction. Annualized system cost is reported for discrete reliability levels π (Eq. (13)–(15)) and decomposed into the same cost components as the base case.

7.5 Conclusion

7.5.1 Implications from the case-study results

First, the case study highlights the need to jointly consider temporal and spatial flexibility. Across the base case and sensitivities, demand is balanced through hybrid storage, domestic supply, interregional transport (within the modeled system), and exogenous imports (from outside the system boundary). Planning studies should therefore evaluate these elements jointly.

Second, hybrid storage portfolios provide cost-effective flexibility. In the base case, LOHC and underground hydrogen storage contribute mainly to seasonal balancing, while batteries support intra-day balancing under the hierarchical time aggregation and operational constraints. When the storage-technology portfolio is restricted, the system relies more on exogenous imports and total cost increases. This highlights the importance of representing multiple hydrogen carriers and the associated (re)conversion steps needed to enable storage.

Third, interregional transport is a robust feature of the optimal RHSC design. Renewable hydrogen supply concentrates in regions with strong renewable potential and supplies major demand centers through cross-border pipeline corridors. This supports coordinated planning of interregional infrastructure.

Fourth, exogenous imports and interregional transport act as substitutes. Tightening the exogenous import upper bound shifts the solution toward higher interregional transport and higher domestic supply investments. Relaxing it shifts the solution toward higher exogenous imports and lower interregional transport. In this case study, these substitutions mainly change the allocation between domestic supply, interregional transport, and exogenous imports, while the total annualized cost changes only marginally. Lower import shares require additional domestic renewable generation, production, storage, and interregional transport, and very stringent limits may become infeasible at high reliability under the case-study assumptions.

Fifth, higher reliability requirements lead to clear capacity adjustments. Increasing the confidence level raises total annualized cost modestly, but it increases capacity deployment across the supply chain. It also strengthens the role of exogenous imports and interregional transport in satisfying demand across a larger set of renewable-availability scenarios.

7.5.2 Implications from the modeling framework

First, RHSC planning benefits from representing both intra-day and intra-year dynamics. Our hierarchical time aggregation maps renewable availability to diurnal and seasonal slices, allowing storage, conversion, and transport decisions to reflect both time scales within a tractable model size. This matters because batteries primarily support intra-day balancing under operational constraints, while hydrogen and derivative storage options contribute mainly to longer-duration shifting. Coarser temporal representations can therefore change implied buffering needs and shift storage choices.

Second, explicitly representing uncertainty in renewable electricity availability strengthens infrastructure assessment. Deterministic “average-year” designs can miss correlated low-availability conditions across regions and seasons. These are the conditions that increase requirements for storage, interregional transport, and exogenous imports. A scenario-based representation that preserves temporal persistence and spatial correlations provides a stronger basis for evaluating investment trade-offs.

Third, chance-constrained demand satisfaction links reliability targets directly to infrastructure outcomes. The confidence level π specifies the minimum cumulative probability of scenarios in which each region’s demand must be fully satisfied. Shortages are only permitted in the remaining scenarios and are penalized. This structure makes the reliability–cost trade-off explicit and supports consistent evaluation of policy-relevant constraints, such as tighter import limits or higher reliability.

Overall, the case study indicates that robust RHSC design under renewable variability and uncertainty requires jointly planning storage portfolios, interregional transport, and exogenous imports, and linking reliability targets explicitly to investment decisions.

7.6 Summary and outlook

This paper presented a chance-constrained MILP framework for designing renewable hydrogen supply chains (RHSCs) under uncertainty in renewable electricity availability. The model jointly represents domestic renewable supply, multiple hydrogen carriers and associated (re)conversion steps, hybrid storage, interregional transport within the modeled system boundary, and exogenous imports from outside the system boundary. Reliability is imposed through regional chance constraints with confidence level, linking demand-satisfaction requirements directly to capacity decisions and operational outcomes.

Methodologically, we combine a two-stage formulation—where infrastructure investments are common across renewable-availability scenarios and operations adapt by scenario—with a hierarchical time aggregation that captures both intra-day and intra-year dynamics. Uncertainty in renewable electricity availability is represented through a scenario set that preserves temporal persistence and spatial correlation across regions.

In the European 2050 case study, the base case ($\pi = 0.95$) yields a system in which renewable electricity investments dominate total annualized cost and cross-border pipeline corridors connect renewable resource-rich countries to major demand centers. The cost-optimal storage deployment is dominated by long-duration options (LOHC and underground hydrogen storage), consistent with seasonal balancing, while batteries primarily contribute to intra-day balancing under the modeled operational constraints. Sensitivity analyses show that the system design largely scales with hydrogen demand, while higher demand increases the value of flexibility provided by storage, interregional transport, and exogenous imports. Restricting the storage-technology portfolio increases reliance on exogenous imports and raises total cost, while varying import limits reveals substitution between interregional transport and exogenous imports with only marginal changes in total annualized cost. Increasing the reliability level raises total cost modestly but requires additional capacity deployment across the supply chain to satisfy demand in a larger share of renewable-availability scenarios.

Overall, the proposed framework provides a transparent and rigorous basis for evaluating RHSC investment strategies under renewable-availability uncertainty while explicitly accounting for reliability targets.

Future research can extend the framework in four directions. First, co-optimizing the RHSC with the electricity system—including alternative assumptions on cross-border electricity transmission—would enable a more integrated assessment of power-system and hydrogen-system interactions. Second, adding further sector coupling (e.g., heat and industrial demand response) would broaden the representation of flexibility options. Third, incorporating endogenous technology learning and policy instruments (e.g., carbon pricing or capacity mechanisms) would support transition-pathway analysis. Fourth, extending uncertainty beyond renewable availability to techno-economic parameters and policy constraints would allow a broader robustness assessment.

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7.A. Appendices

7.A.1. The list of countries in the case study

The list of countries in the case study is presented in Table 7.A.1 in part a and the remaining EU-27 countries in part b. The values for hydrogen demand (reference, low, and high scenarios) are based on Tonelli et al. (2023) for steel, transport, refineries, cement, light industry, ammonia, and methanol, for 2050. The selected 9 countries represent about 80% of the EU-27 hydrogen demand in 2050 (reference scenario), i.e. more than three quarters of the projected demand.

Table 7.A.1. Total hydrogen demand in 2050 for EU-27 countries for (a) the case-study countries, and (b) the remaining EU-27 countries. Values in the parentheses represent cumulative % of the EU-27 total for that scenario.

(a) Case-study countries

Country	2050 Reference	2050 Low	2050 High
Germany	241.9 (21.1%)	55.4 (21.1%)	390.7 (21.1%)
France	162.6 (35.2%)	37.2 (35.2%)	262.6 (35.2%)
Italy	124.5 (46.0%)	28.5 (46.0%)	201.1 (46.1%)
Spain	103.2 (55.0%)	23.6 (55.0%)	166.6 (55.0%)
Poland	81.6 (62.1%)	18.7 (62.1%)	131.8 (62.1%)
Netherlands	79.0 (69.0%)	18.1 (69.0%)	127.6 (69.0%)
Belgium	48.2 (73.2%)	11.0 (73.2%)	77.8 (73.2%)
Sweden	36.7 (76.4%)	8.4 (76.4%)	59.2 (76.4%)
Austria	35.4 (79.5%)	8.1 (79.4%)	57.2 (79.5%)

(b) Remaining EU-27 countries

Country	2050 Reference	2050 Low	2050 High
Czech Republic	28.6 (82.0%)	6.5 (81.9%)	46.2 (82.0%)
Greece	27.8 (84.4%)	6.4 (84.3%)	45.0 (84.4%)
Romania	24.9 (86.6%)	5.7 (86.5%)	40.2 (86.6%)
Finland	20.9 (88.4%)	4.8 (88.3%)	33.7 (88.4%)
Hungary	19.6 (90.1%)	4.5 (90.0%)	31.6 (90.1%)
Portugal	19.0 (91.7%)	4.3 (91.7%)	30.6 (91.7%)
Denmark	16.5 (93.2%)	3.8 (93.1%)	26.6 (93.2%)
Ireland	14.8 (94.5%)	3.4 (94.4%)	23.9 (94.5%)
Slovakia	14.0 (95.7%)	3.2 (95.6%)	22.7 (95.7%)
Lithuania	11.2 (96.6%)	2.6 (96.6%)	18.1 (96.7%)
Bulgaria	9.6 (97.5%)	2.2 (97.5%)	15.4 (97.5%)
Croatia	8.8 (98.3%)	2.0 (98.2%)	14.2 (98.2%)
Luxembourg	8.6 (99.0%)	2.0 (99.0%)	13.9 (99.0%)
Slovenia	5.9 (99.5%)	1.4 (99.5%)	9.6 (99.5%)
Latvia	3.3 (99.8%)	0.8 (99.8%)	5.3 (99.8%)
Estonia	2.3 (100.0%)	0.5 (100.0%)	3.7 (100.0%)

Note: Cyprus and Malta are not reported in the source dataset; therefore EU-27 totals refer to the sum across 25 Member States.

7.A.2. Sensitivity to the number of reduced scenarios

To assess robustness with respect to the size of the reduced scenario set, we resolve the model with 10 to 50 representative scenarios and compare results to the base case. Table 7.A.2 reports total annualized cost, and solver statistics (runtime and optimality gap). Overall, the results show only small differences in expected total annualized costs; increasing the number of retained scenarios primarily affects computational effort.

Table 7.A.2. Sensitivity of annualized total system cost to the number of reduced scenarios for the base case (regional confidence level 0.95, 12 intra-year slices and 4 intra-day slices).

Reduced scenarios [-]	Annualized total system cost [bn €/year]	Runtime [hours]	Optimality gap [%]
10	54.1	2	1.4
20	55.4	8	1.0
30	55.9	23	1.1
40	56.2	10	1.7
50	56.5	48	1.8

7.A.3. Temporal aggregation sensitivity

We test the robustness of the base-case results to temporal aggregation by varying (i) the intra-year representation (4 seasonal slices vs 12 monthly slices) and (ii) the number of intra-day slices (3/4/6). Table 7.A.3 reports total annualized system cost, solver runtime and optimality gap.

Table 7.A.3. Sensitivity to temporal aggregation. Annualized total system cost under alternative intra-year aggregation (4 seasons vs 12 months) and intra-day resolution (3/4/6 slices).

Intra-year aggregation [-]	Intra-day resolution [-]	Annualized total system cost [bn €/year]	Runtime [hours]	Optimality gap [%]
4 (seasonal)	3	57.5	1	2.0
4 (seasonal)	4	53.7	1	1.8
4 (seasonal)	6	55.1	1	1.2
12 (monthly)	3	59.9	3	1.3
12 (monthly)	4	55.4	8	1.0
12 (monthly)	6	57.8	20	1.3

7.B. Supplementary Information

This document provides case-study data and techno-economic parameters used in the European 2050 case study, and additional network maps for the base case and sensitivity analyses.

7.B.1. Case-study data and assumptions

Table 7.B.1. Techno-economic assumptions for renewable electricity generation technologies used in the case study (2050) (Danish Energy Agency, 2018b).

Technology	CAPEX [M€/MW]	OPEX [k€/MW/y]	Lifetime [y]
Wind turbine	1.1	15.6	30
Solar PV	0.3	7.4	40

Table 7.B.2. Regional input data for the European case study: available freshwater resources (after subtracting agricultural, industrial, and municipal uses), renewable electricity potential, and hydrogen demand for 2050 (Ruiz et al., 2019; Tonelli et al., 2023).

Country	Available freshwater [Gt/y]	PV potential [GW]	Wind potential [GW]	Hydrogen demand [TWh/y]
Germany	0.11	494	86	242
Netherlands	20.79	67	4	79
Belgium	0	149	88	48
France	46.17	822	296	163
Italy	0.43	443	212	125
Spain	0	658	838	103
Poland	8.98	447	121	82
Sweden	32.43	71	125	37
Austria	12.05	73	30	35

Table 7.B.3. Techno-economic parameters for production and (re)conversion technology modules included in the case study (2050) (Danish Energy Agency, 2018b; Hampp et al., 2023; Hank et al., 2023; Reuß et al., 2017).

Technology	Capacity [t/h]	CAPEX [M€/unit]	OPEX [M€/unit/y]	Lifetime [y]
Desalination	5542	218	17.0	30
PEM electrolysis	22	325	6.5	25
Hydrogen Liquefaction	2	105	8.4	20
Hydrogen evaporation	2	0.3	0.009	10
LOHC hydrogenation	13	40	1.2	20
LOHC dehydrogenation	13	30	0.9	20
Haber-Bosch	95	471	14.1	30
Ammonia cracker	18	310	13.3	25

Table 7.B.4. Techno-economic parameters for storage technology modules included in the case study (2050) (Cloete et al., 2021; Danish Energy Agency, 2018a; Erichsen et al., 2019; Fasihi et al., 2021; Hampp et al., 2023; Reuß et al., 2017).

Technology	Capacity [t]	CAPEX [k€/unit]	OPEX [k€/unit/y]	Lifetime [y]
Gaseous hydrogen	0.5	744	15	30
Liquid hydrogen	0.5	13	0.3	20
Underground hydrogen	4500	191412	6489	100
Ammonia	33000	20559	822	30
LOHC	3.4	3	0.2	20
Battery	4.8†	754	8.7	20

† Battery capacity unit in MWh

Table 7.B.5. Techno-economic parameters for interregional hydrogen pipeline transport used in the country-level case study (2050) (Danish Energy Agency, 2018d).

Technology	Flow rate [t/h]	CAPEX [M€/km]	OPEX [M€/km/y]	Lifetime [y]
Hydrogen pipeline	102	1.4	0.08	50

Table 7.B.6. Main storage-technology characteristics used for qualitative comparison in the paper (Al Ghafri et al., 2022; Cloete et al., 2021; Danish Energy Agency, 2018a; Demirhan et al., 2020; Fasihi et al., 2021; Hampp et al., 2023; Kim, Park, Heo, and Lee, 2024; Pan et al., 2020; Reuß et al., 2017; Terlouw et al., 2022; Wen et al., 2025; Yang et al., 2024; Zhang et al., 2025).

Technology	Stored carrier	Charge/discharge efficiency [%]	Self-loss [%/day]	Energy capacity [GWh]	CAPEX [€/kWh]	OPEX [% of CAPEX/y]
LiB	Electricity	95–99	0.01–0.36	<0.01	100–1000	≈1–3
GHS	GH ₂	88–90	0–0.10	<10	20–45	≈2
LHS	LH ₂	≈100	0–0.40	<10	0.75	≈2
UHS	GH ₂	98–100	0–0.001	≈150	1–3	≈2–4
NH₃S	NH ₃	≈100	0–0.02	scalable	0.10–0.20	≈2–4
LOHCS	LOHC	72–75	≈0	<10	1–2	≈6

Note: LiB: lithium-ion battery; GHS: gaseous hydrogen storage; LHS: liquid hydrogen storage; UHS: underground hydrogen storage; NH₃S: ammonia storage; LOHCS: liquid organic hydrogen carrier storage. H₂: hydrogen, GH₂: gaseous hydrogen, LH₂: liquid hydrogen, NH₃: ammonia.

7.B.2. Model results

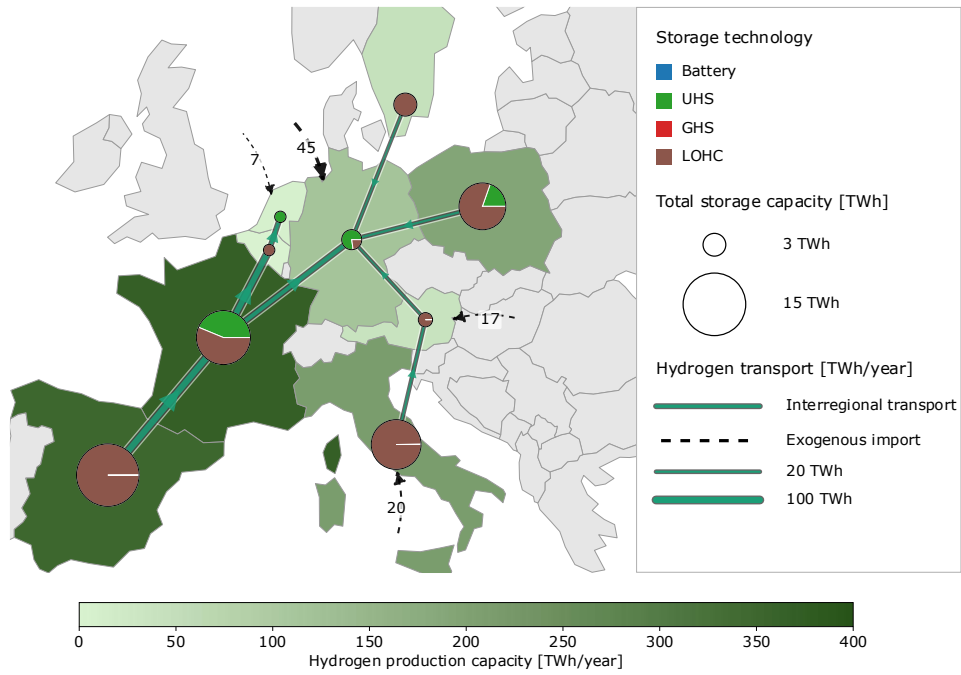


Figure 7.B.1. Base-case optimal RHSC in 2050 ($\pi = 0.95$). Country shading indicates renewable-based hydrogen production potential; solid links show interregional pipeline flows (TWh/year); dashed arrows denote exogenous imports; pie markers indicate installed storage capacities (TWh) by technology.

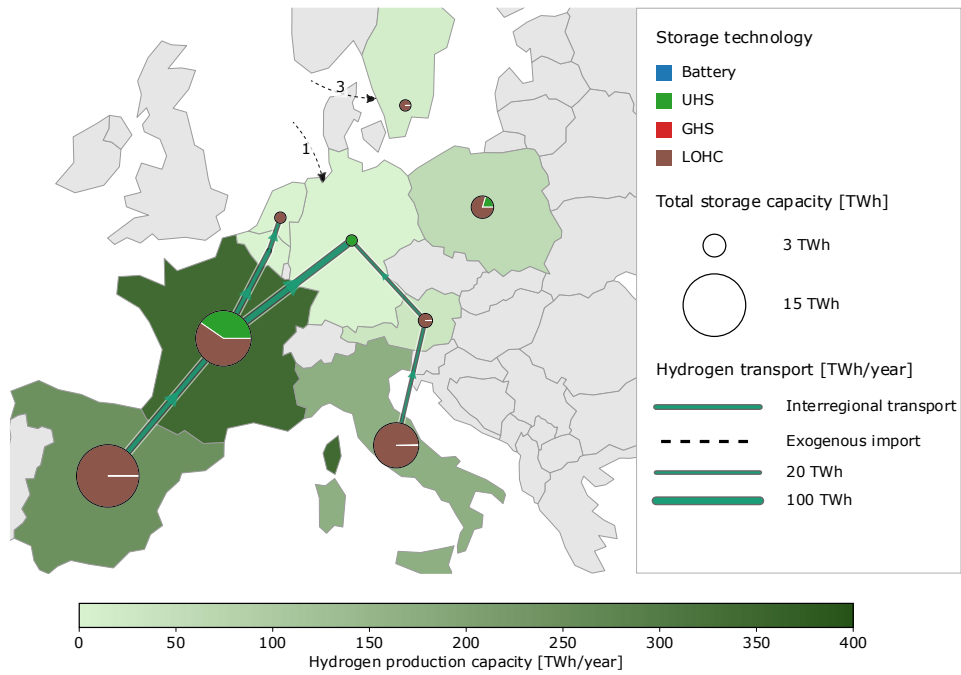


Figure 7.B.2. Optimal RHSC in 2050 for the low-demand scenario. Other elements are defined as in Figure 7.B.1.

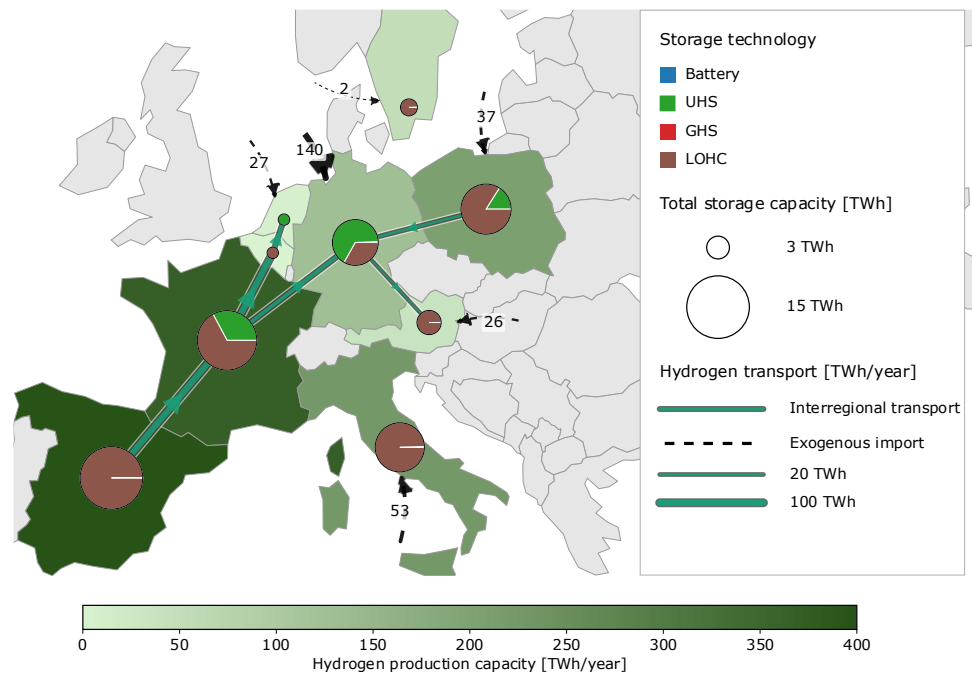


Figure 7.B.3. Optimal RHSC in 2050 for the high-demand scenario. Other elements are defined as in Figure 7.B.1.

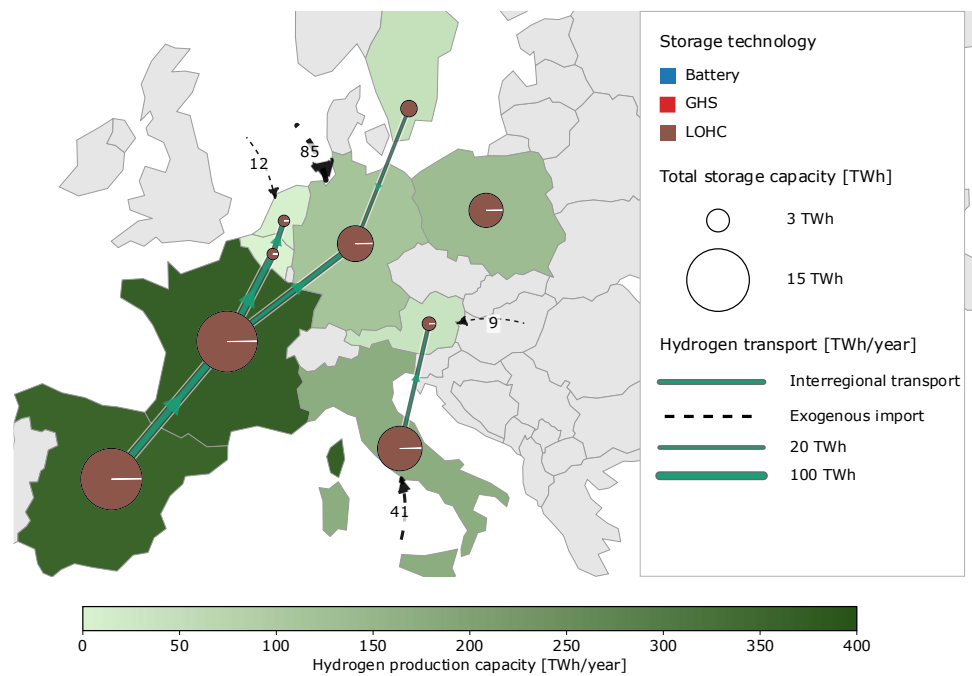


Figure 7.B.4. Optimal RHSC in 2050 for the No-UHS scenario (no underground hydrogen storage). Other elements are defined as in Figure 7.B.1.

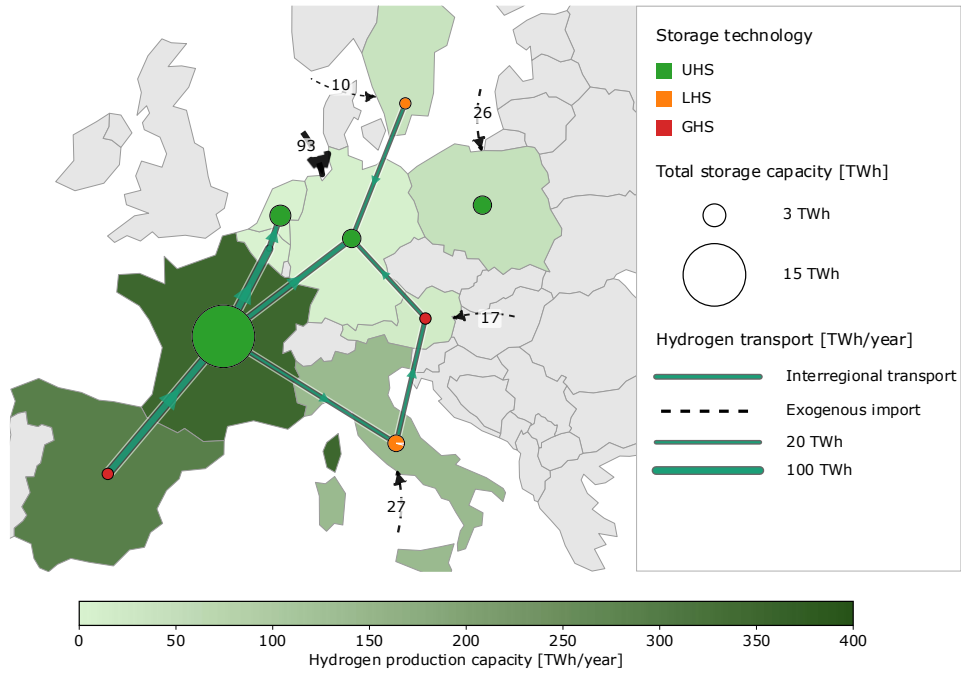


Figure 7.B.5. Optimal RHSC in 2050 for the H₂-only scenario (hydrogen storage technologies without derivatives). Other elements are defined as in Figure 7.B.1.

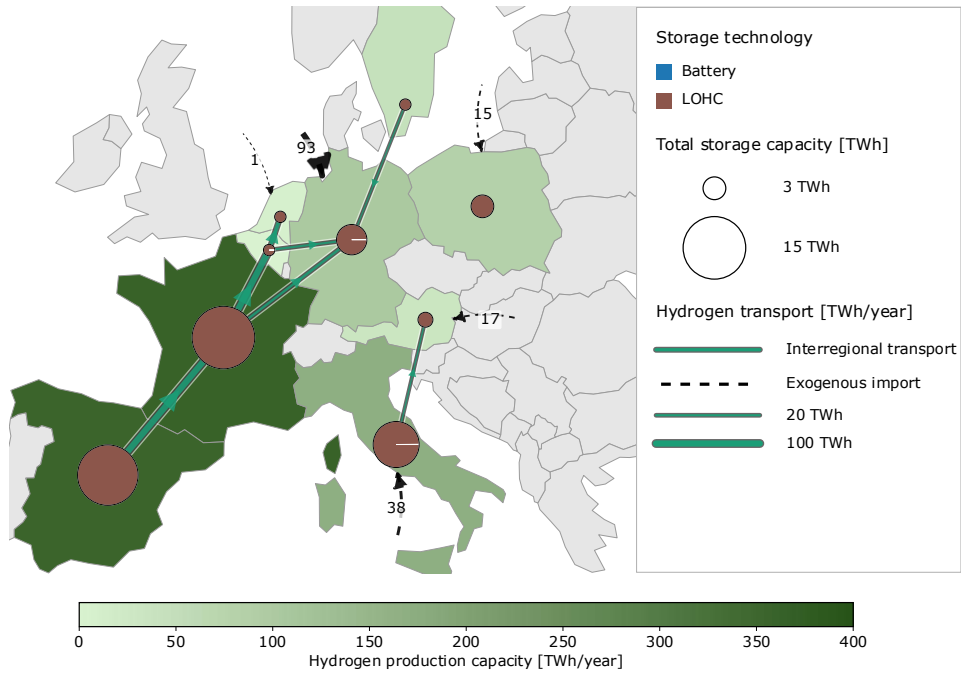


Figure 7.B.6. Optimal RHSC in 2050 for the LOHC-only scenario. Other elements are defined as in Figure 7.B.1.

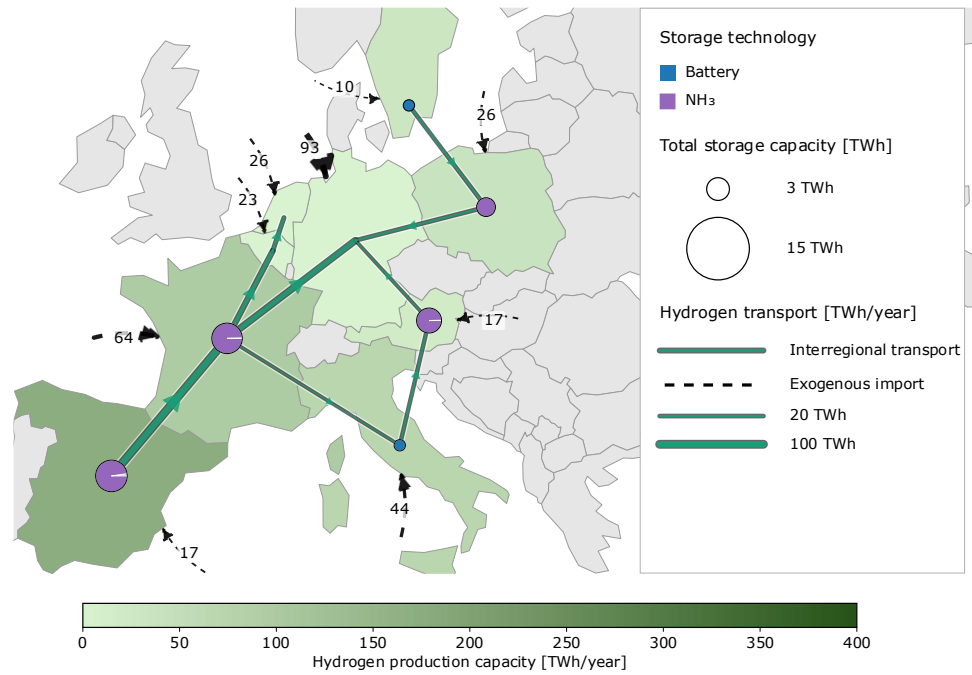


Figure 7.B.7. Optimal RHSC in 2050 for the NH₃-only scenario. Other elements are defined as in Figure 7.B.1.

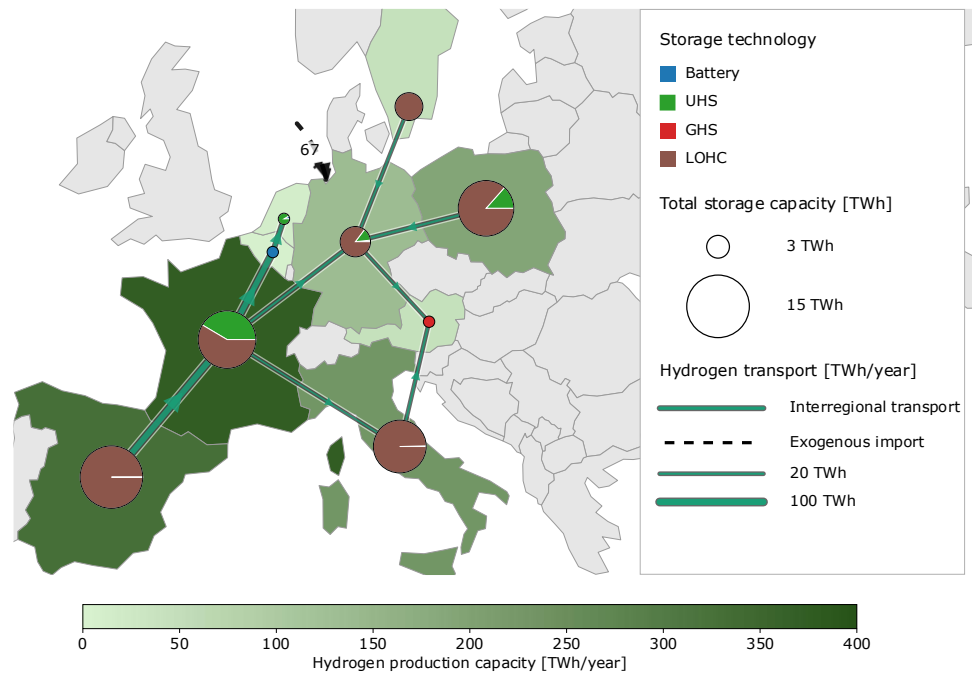


Figure 7.B.8. Optimal RHSC in 2050 under a strict non-domestic supply upper bound (non-domestic supply $\leq 33\%$ of total demand). Other elements are defined as in Figure 7.B.1.

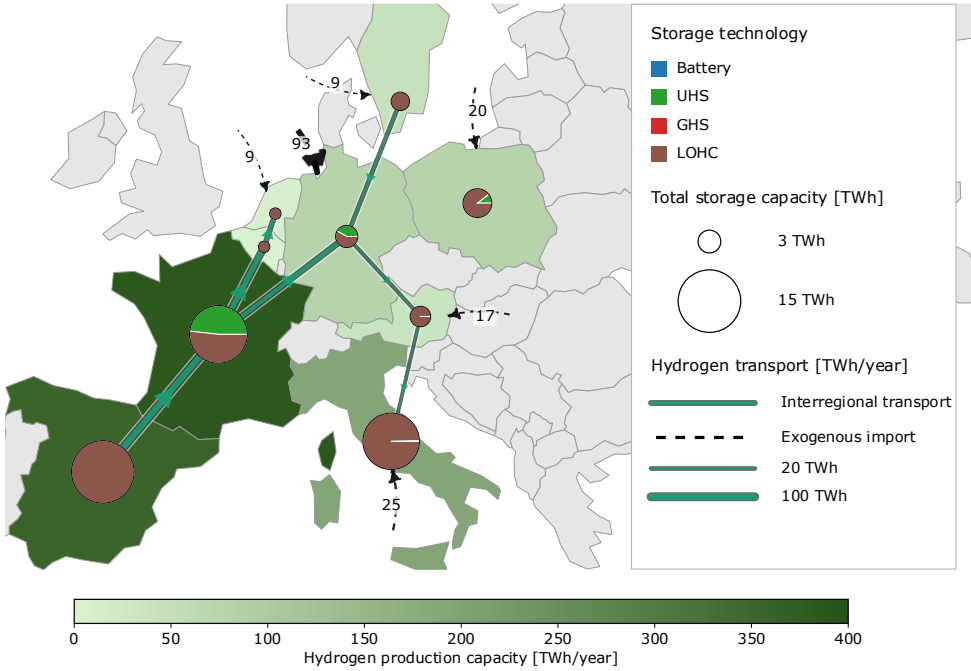


Figure 7.B.9. Optimal RHSC in 2050 under $\pi = 1.00$. Other elements are defined as in Figure 7.B.1.

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Chapter 8

Analyzing Policy Measures for Renewable Fuel Supply Chain Design in Transport Sectors

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Abstract

As a result of climate neutrality targets, renewable and low-carbon fuels are increasingly used, particularly in hard-to-abate sectors. A key factor in establishing renewable fuel supply chains (RFSC) is analyzing the impact of policy measures. To gain insights into the impacts of various policies on RFSC, we propose a mixed-integer linear programming model that incorporates factorial and sensitivity analyses of policy measures, such as carbon pricing, GHG intensity reduction, and renewable fuel share mandates. We analyze both economic and environmental aspects of RFSC through net present cost and cumulative GHG emission savings objective functions. Applied to the European transport sector, our model reveals that carbon pricing has the highest impact on cumulative GHG emission savings. Our findings demonstrate substantial trade-offs between economic and environmental objectives and show that integrating medium levels of policy measures can lead to balanced economic and environmental outcomes.

8.1 Introduction

To achieve climate neutrality by 2050, the European Commission has proposed a 55% reduction in greenhouse gas emissions by 2030, which would provide certainty to policymakers and investors (European Commission, 2020). The Commission outlined its plans to achieve climate neutrality,

including revisions to several EU climate legislations under the European Green Deal, such as the 2030 Climate Target Plan (European Commission, 2020), A Clean Planet for all (European Commission, 2018), and Clean Energy for all (European Commission, 2019). A significant challenge for decarbonizing the European Union (EU) is the transport sector, which accounted for 29% of EU's final energy consumption and has been increasing over the past decade (Eurostat, 2021, 2023).

The European Commission's targets to reduce CO₂ emissions in the transport sector by 15% by 2030 and 36% by 2050 necessitate a transition to renewable energy sources (European Commission, 2021d). Besides direct electrification, this shift involves using renewable and low-carbon fuels, particularly in hard-to-abate sectors like aviation, maritime and heavy-duty road transport, due to their specific standards and technical requirements (Christodoulou and Cullinane, 2022; Meisel et al., 2020; Patrick Plötz et al., 2021). Renewable fuels, such as biofuels and synthetic fuels, can substitute fossil fuels without drastic changes to existing infrastructure and vehicles, especially in aviation and long-distance transport (E3-Modelling, 2018). Therefore, the establishment of renewable fuel supply chains (RFSC) based on technologies that produce fuels from biomass or fuels from (recycled) CO₂ (European Commission, 2022) is essential.

At the same time, policies play a crucial role in establishing RFSC networks, due to their influence on demand, technology selection, and infrastructure (Siegemund et al., 2017; Zahraee et al., 2020). Key policy measures include implementing carbon pricing on supplied fuels to encourage innovative fuels and facilitate the transition towards lower GHG emissions, as well as decreasing the greenhouse gas (GHG) intensity of fuels, and mandates for a minimum share of renewable fuels to promote their use in transport sector (European Commission, 2021b, 2021c, 2021d, 2021g). However, current directives and legal proposals apply different variations and combinations of these measures across the transport sector, including rail and road, aviation, and maritime. The impact of these measures on reducing CO₂ emissions in the transport sector, including the impact on renewable fuel supply chains, and the interrelation between measures remain unknown.

Against this background, our research objective is to analyze policy measures that support climate neutrality in the transport sector, focusing on their impact on the design of RFSC. We utilize a multi-period Mixed-Integer Linear Programming (MILP) model to assess the effects of policy frameworks on RFSC, evaluating both the total net present costs and the GHG emission savings. This model is specifically tailored to long-term decision-making and provides a comprehensive ex-ante evaluation of the economic and environmental implications of various policy measures. Our findings aim to demonstrate how transport sector policies can facilitate progress towards climate neutrality by promoting the use of renewable fuels through different technologies and resources.

Our study employs bi-objective optimization to identify Pareto-efficient solutions for the transition of the RFSC, balancing the trade-offs between the total net present costs and cumulative GHG emission savings of supplying renewable fuels. Additionally, by employing factorial analysis, we examine the impacts of policy measures on these economic and environmental objectives within the RFSC. This approach allows us to assess the cost-effectiveness and GHG saving benefits of different levels of policy intervention across the transport sectors comprehensively. By implementing sensitivity analyses, we investigate the effect of variations in model parameters and policy measures on both economic and environmental objectives. We also evaluate different combinations of policy measures to determine optimal policy trajectories. This analysis offers valuable insights into how policy measures can influence the renewable fuel supply trajectory and contribute to achieving climate neutrality goals in the transport sector.

Overall, the contribution of this paper is as follows:

- The paper introduces a multi-period MILP model tailored for long-term decision-making in the transport sector. This model assesses the economic and environmental impacts of RFSC, focusing on total net present costs and cumulative GHG emission savings. It provides an in-depth analysis of the trade-offs between these economic and environmental objective functions in renewable fuel supply.
- Policy measures are intricately incorporated into the MILP model, enabling a detailed evaluation of their effects on the RFSC. This integration facilitates an analysis of the economic and GHG emission impacts of various policy frameworks and highlights the influence of these measures on the renewable fuel supply trajectory.
- The study employs factorial analysis to examine the impacts of individual policy measures on the total net present costs and cumulative GHG emission savings of the RFSC. This approach allows for a comprehensive assessment of the cost-effectiveness and GHG saving benefits of different levels of policy intervention across the transport sectors.
- We conduct sensitivity analyses to evaluate the effect of variations in model parameters and policy measures on the development of the RFSC, considering economic and environmental objective functions. In addition, we examine several policy measure trajectories over the long-term planning horizon to determine Pareto-efficient long-term policy measures that balance economic and environmental objectives.
- Our model is applied to a case study of renewable fuel supply within the European transport sector. This application considers various production pathways for renewable fuels, providing a focused examination of renewable fuel supply dynamics under different policy measures in the transport

sector. Over the long-term planning horizon of our model, we consider technological advancements in terms of cost, efficiency, and availability of new technologies for production, transmission, and renewable electricity generation.

8.2 Literature review

This section reviews existing literature on policy measures and their impact on RFSC. The literature review focuses on two main areas: (1) an analysis of policies aimed at reducing GHG emissions in the transport sector, and (2) the consideration of these policies in the design of RFSC models.

8.2.1 Policy analysis

The European Green Deal has led to the creation of the 'Fit for 55' package, which includes a range of amendments and fresh legislative initiatives aimed at aligning with the EU's climate goals (European Council, 2023). The EU has addressed significant measures to reduce greenhouse gas (GHG) emissions, especially in the transport sector, through the Renewable Energy Directive (RED) series and upcoming revised directives such as the EU ETS. Measures in the EU transport sector include mainly carbon pricing, reduction of GHG intensity, and mandates for renewable fuel share (European Commission, 2021b).

Carbon pricing is an instrument for reducing emissions and aiding the transition towards climate neutrality by imposing a penalty for each unit of CO₂ emitted (Fahimnia et al., 2013; Rezaee et al., 2017; Zakeri et al., 2015). Carbon pricing schemes increase costs for high GHG emitters, effectively giving an advantage to fuels with lower GHG emissions. As a result, traditional, high-emission technologies become more expensive, potentially opening the market to emerging technologies and encouraging investment in decarbonization. Currently, the EU Emissions Trading System (EU ETS) incentivizes GHG emission reductions in the maritime and aviation sectors and plans to extend it to road transport (European Commission, 2021h). This expansion aims to promote the use of alternative energy carriers through carbon pricing (Duwe et al., 2023). In addition to the EU-wide carbon pricing, countries like Germany and Austria have implemented their own schemes, though they support an EU-wide approach to eventually replace national schemes (Federal Ministry Republic of Austria Finance, 2022; Graichen and Ludig, 2024; World Bank, 2023).

Additionally, GHG intensity reduction targets of fuels directly address emissions per unit of fuel supplied (European Commission, 2023b). This strategy considers emission savings from utilizing various fuels and their production processes compared to a baseline fossil fuel GHG intensity. As a result, this measure requires fuel suppliers to provide fuels with lower GHG emissions (Searle, 2021). Consequently, fuel suppliers must invest in renewable fuel production to achieve the GHG intensity

reduction goals. In the EU, the revised RED II mandates a minimum GHG intensity reduction for fuels supplied in the transport sector (European Commission, 2021g). Moreover, the FuelEU Maritime regulation sets targets to lower GHG intensity for large ships from 2025 to 2050 (European Commission, 2021f).

For achieving a minimum share of renewable fuels in the final supply, fuel suppliers are obligated to gradually raise the share of renewable and low-carbon fuels (European Commission, 2021c, 2022). In the EU, the revised Renewable Energy Directive (RED II) sets targets for the minimum share of renewable fuels in total fuels supplied (European Commission, 2021g). Additionally, multipliers are considered to promote the use of renewable fuels in transport sectors, particularly in sectors that are hard to electrify (European Commission, 2021g). These multipliers amplify the contribution of supplied renewable fuels, but only those in aviation and maritime are retained in the latest revisions (European Commission, 2023b; Searle, 2021). Furthermore, the ReFuelEU Aviation Initiative requires fuel suppliers to introduce sustainable aviation fuels (SAF) and synthetic aviation fuels (SYN) into their fuel supplies, for instance through blending electrofuels into jet fuel mixtures (European Commission, 2021e; Searle, 2021; Skov and Schneider, 2022).

In summary, Table 8.1 outlines various policy measures directed at fuel suppliers in the transport sector across EU countries. These quotas and mandates are primarily set until 2030, with post-2030 regulations derived from scenarios outlined in the European Green Deal (European Commission, 2021b). Carbon pricing has been established up to 2030 for aviation and maritime sectors. While carbon pricing has not yet been specified for the road transport sector, the European Green Deal provided scenarios for possible values starting from 2025 (European Commission, 2021b). Projections for carbon pricing across all transport sectors after 2030 are also based on the European Green Deal scenarios (European Commission, 2021b).

Table 8.1 also details targets for GHG intensity reduction and renewable fuel share based on the RED II (European Commission, 2023b), along with supplementary regulations from ReFuelEU Aviation (European Commission, 2021e) and FuelEU Maritime (European Commission, 2021f). RED II's goals for reducing GHG intensity and mandating minimum renewable fuel shares are projected up to 2030, with future values based on the European Green Deal scenarios. While FuelEU Maritime focuses on measures related to fuel use in line with GHG intensity reduction, ReFuelEU Aviation emphasizes mandates for renewable fuel shares.

Table 8.1. Summary of policy measures affecting RFSC in the EU transport sector.

		Carbon pricing	GHG intensity reduction		Renewable fuel share	
Measures		[€/tonne CO ₂ eq]	Overall transport sector	Maritime sector [○]	Overall transport sector	Aviation sector ^{○○} (SAF/SYN)
			[%]	[%]	[%]	[%]
Revised RED II	2025			2	1	2/0
	2030		14.5	6	5.5	5/0.7
	2035			13		20/7
	2040			26		32/8
	2045			59		38/11
	2050		90 ⁺	75		63/28
EU ETS Maritime & Aviation	2025	<35				
	2030	<52 ⁺				
	2050	<430 ⁺				
EU ETS Road	2025	<53 ⁺				
	2030	<80 ⁺				
	2050	<430 ⁺				

Note: SAF and SYN represent sustainable aviation fuel and synthetic aviation fuel.

+ Based on the European Green Deal scenarios (European Commission, 2021b, 2024).

○ Based on the proposal for FuelEU Maritime regulation (European Commission, 2021f).

○○ Based on the proposal for ReFuelEU Aviation regulation (European Commission, 2021e).

8.2.2 Policy considerations in RFSC models

Evolving renewable energy policy frameworks aim to guide the RFSC towards climate neutrality. These frameworks significantly influence the RFSC, either as a whole or at specific stages of the supply chain (Daneshmandi et al., 2022; Quarton and Samsatli, 2021). This section examines the literature on the optimal design of RFSC networks, considering multiple policy measures.

The RFSC includes processes from resource utilization to renewable fuel synthesis, storage, distribution, and end use (Wolff et al., 2023). Making strategic decisions in supply chain network design, technology selection, and location, as well as tactical and operational decisions such as production, inventory management, and logistics, are crucial (Daneshmandi et al., 2022; Lan et al., 2020; Zahraee et al., 2020). Policy measures can impact the RFSC by penalizing existing technologies through emission pricing or by incentivizing emerging technologies and setting targets for specific renewable fuels or GHG intensity reduction (Daneshmandi et al., 2022; Quarton and Samsatli, 2021).

Several studies have assessed the impact of carbon pricing on supply chain management, influencing low-carbon technology choices, production planning, and transportation decisions (Zhou et al., 2021). Zakeri et al. (2015) provided an analytical perspective on the performance of supply chains under carbon pricing and emissions trading schemes, highlighting trends in emissions reduction under these policy instruments. Ahmed and Sarkar (2019) examined carbon taxes on emissions from biofuel supply chain activities, assessing their impacts on operational strategies. Alizadeh et al. (2019) explored the impacts of uncertain carbon tax rates on sustainable olefin supply networks using a stochastic programming model to generate robust investment decisions. Haji Esmaeili et al. (2020) considered four different carbon pricing policies to investigate the economic and environmental aspects of establishing first-generation and second-generation bioethanol supply chains in a MILP model. Malladi and Sowlati (2020) investigated the impact of different carbon pricing policies on the design of biomass supply chains for optimal feedstock mix in district heating plants. They extended a general optimization model by incorporating different carbon pricing policies by modifying the objective function and adding new constraints to the optimization model. However, according to Duwe et al. (2023), even substantial increases in carbon prices may lead to only slight reductions in emissions in the transport sector. As a result, carbon pricing should be implemented alongside other regulations and incentives.

The evolution of supply chain design, with a focus on GHG reduction, reflects a trend toward integrating environmental objectives. Hombach and Walther (2015) established the groundwork by discussing Pareto-efficient legal regulations to ensure effective integration of environmental and economic objectives. Applying their analysis to the German biodiesel market, they demonstrated that current and past European Union directives are not Pareto-efficient and may cause unintended side effects, highlighting the importance of carefully designed regulations. Gonela et al. (2015) developed a MILP model to maximize the profit of the bioethanol supply chain while meeting maximum allowable GHG emissions and land use constraints. Millinger et al. (2019) emphasized the need to incorporate GHG abatement strategies as key constraints and objectives in supply chain design, influencing both technological and logistical choices. Quarton and Samsatli (2021) analyzed carbon budgets and carbon pricing in a MILP model to support emerging energy technologies and to encourage system decarbonization. They used value chain optimization to assess the effectiveness of carbon budgets and carbon pricing in a system transitioning to net-zero emissions. They emphasized that policy intervention is needed for hydrogen technologies to become established, which can be effective in achieving net-zero emissions, but the details of the policy design can significantly influence overall costs and emissions. Solakivi et al. (2022) analyzed the cost competitiveness of

alternative maritime fuels compared with fossil fuels, considering carbon pricing and GHG intensity reduction targets. Khalifa et al. (2022) explored optimization in designing optimal biofuel supply chains, where GHG reduction and carbon pricing schemes are integrated into the objective function to promote the utilization of alternative fuels in the aviation sector.

Targets for the share of renewable fuels are also crucial in transitioning to sustainable fuel options. Hombach and Walther (2015) developed a MILP model aiming to maximize net present value and minimize GHG emissions by blending biofuels into fossil fuels while integrating quotas for biofuel market shares. Hombach et al. (2016) aimed to examine the optimal design of biofuel supply chains under variation in policy instruments, including biofuel market share quotas and GHG emission saving targets. Hosseinalizadeh et al. (2019) developed a multi-objective and multi-period MILP model for biodiesel supply chain design, considering different biodiesel blends and primary resources. By optimizing cost and GHG emissions of biodiesel supply chains, they identified the most appropriate blending options for several scenarios. Esmaeili Aliabadi et al. (2023) considered GHG intensity reduction quotas in the transport sector to meet the requirements of policy instruments in Germany. They developed a model maximizing GHG emission savings and minimizing costs, considering constraints related to RED II and GHG emission targets. However, these studies often focus solely on biofuels or are restricted to single countries.

Few studies address a diverse range of renewable fuels and legal frameworks in vast regions like the EU. Due to the focus on specific case studies, insights from these studies may not be generalizable. Since policies and regulations are commonly designed for a vast region such as the entire European Union, promoting the full range of alternative fuels (Hombach et al., 2016). In addition, there is an urgent need to explore the most effective policies and regulations supporting the development of renewable fuels, as their design and timing will have a significant impact on progress towards decarbonizing the transport sector (Cullinane and Chang, 2023). Table 8.2 shows a summary and comparison of selected studies that integrate policy measures into mathematical models for optimal design of renewable fuel supply chains.

Table 8.2. A summarized comparison of selected supply chain design studies considering assessing policy measures intervention on development of fuel supply chain. CP, GHG, and RF represent carbon pricing, GHG intensity reduction, and renewable fuel share.

Authors	Mathematical model	Policy measures			Multiple alternative fuels	Multiple technology pathways	Technology advancement	System dynamic	Policy measures interaction	Case study	Application
		CP	GHG	RF							
Gonela et al. (2015)	MILP	✗	✓	✗	✗	✓	✗	✗	✗	North Dakota	Bioethanol markets
Hombach and Walther (2015)	MILP	✗	✓	✓	✗	✓	✗	✓	Scenario analysis	Germany	Transport sectors
Hombach et al. (2016)	MILP	✗	✓	✓	✗	✓	✗	✓	Sensitivity analysis	Germany	Transport sectors
Najmi et al. (2016)	NLP	✓	✓	✗	✓	✗	✗	✓	✗	Iran	Biofuel markets
Millinger et al. (2019)	LP	✗	✓	✗	✓	✓	✓	✓	✗	Germany	transport sectors
Ahmed and Sarkar (2019)	LP	✓	✓	✗	✗	✗	✗	✗	✗	-	Biofuel markets
Alizadeh et al. (2019)	MILP	✓	✗	✗	✗	✗	✗	✗	✗	Mississippi	Olefin markets
Hosseinalizadeh et al. (2019)	MILP	✗	✗	✓	✗	✗	✗	✓	✗	-	Biodiesel markets
Haji Esmaeili et al. (2020)	MILP	✓	✓	✗	✗	✓	✗	✗	✗	North Dakota	Bioethanol markets
Quarton and Samsatli (2021)	MILP	✓	✓	✓	✓	✓	✗	✓	✗	Great Britain	Electricity, heat and industrial sectors
Khalifa et al. (2022)	LP	✓	✓	✗	✗	✓	✗	✗	✗	UK, Australia, Dubai	Aviation sector

Solakivi et al. (2022)	LP	✓	✓	✗	✓	✓	✓	✓	✗	Europe	Maritime sector
Ahmadvand and Sowlati (2023)	LP	✓	✗	✗	✗	✗	✗	✓	✗	British Columbia	Bio-based Syngas
Memari et al. (2023)	MILP	✓	✗	✗	✗	✗	✗	✗	✗	-	Biofuel markets
Munir et al. (2023)	LP	✓	✗	✗	✗	✗	✗	✗	✗	Pakistan	Biodiesel markets
Esmaeili Aliabadi et al. (2023)	LP	✗	✓	✓	✓	✓	✗	✓	Scenario analysis	Germany	Transport sector
This study	MILP	✓	✓	✓	✓	✓	✓	✓	Factorial analysis Scenario analysis	Europe	Transport sector

In summary, existing studies have several shortcomings. Many focus on single policies, such as carbon pricing or the share of renewable fuels, without adequately addressing the entire policy framework and interdependencies. Additionally, there is a noticeable absence of comprehensive studies covering a diverse range of renewable fuels and legal frameworks, especially for extensive case studies like the EU. To bridge this gap, we investigate the impacts of multiple policy measures on renewable fuel supply for the transport sector in the EU. Our study introduces a mathematical model that evaluates RFSC from both economic and environmental perspectives, including the contributions of policy measures. Additionally, we analyze the impacts of each policy measure and their interactions on the RFSC. This model is designed to facilitate the development of supply networks that align with dynamic policy environments, thereby contributing to a more sustainable fuel supply future.

8.2.3 Research questions

Based on the gaps identified in the literature review, we propose the following research questions:

1. What is the Pareto-efficient frontier for the transitioning of the RFSC, balancing the trade-offs between the total net present costs and cumulative GHG emission savings of supplying renewable fuels?
2. How do policy measures affect the development of renewable fuel supply?
3. What are the impacts of individual policy measures on the total net present costs and cumulative GHG emission savings of the RFSC? What are the interactions between policy measures regarding the economic and environmental objectives of the RFSC?
4. Which model parameters significantly impact both objective functions in developing the RFSC? How do variations in policy measures affect the development of the RFSC?
5. What are the optimal combinations of policy measures to promote the development of the RFSC when economic and environmental objectives are balanced?

To address these research questions, we developed a bi-objective mathematical model that optimizes both economic and environmental objectives for the development of the RFSC. We integrated policy measures into our model to evaluate their impact on the transition of the RFSC. Furthermore, we conducted factorial analysis to investigate the impact of individual policy measures as well as their interactions on RFSC development. By implementing sensitivity analyses, we explored the effects of variations in model parameters and policy measures on both economic and environmental objectives. Finally, to determine the optimal

combinations of policy measures, we examined different policy trajectories over the long-term planning horizon and compared them with a balanced Pareto-efficient solution that considers both objectives. This comprehensive approach allows us to provide valuable insights into how policy measures can effectively promote the development of the RFSC while balancing economic costs and environmental benefits.

8.3 Methodology

We have developed a multi-objective optimization model to analyze the impact of policy measures on RFSC. Our model focuses on analyzing both economic and environmental factors of optimal supply networks. This involves minimizing total net present costs while simultaneously maximizing cumulative GHG emission savings. By generating Pareto-efficient solutions, our study explores the trade-offs between economic and environmental objectives within current policy frameworks. We then compare these solutions to the proposed policy measures to evaluate their effectiveness and optimality.

8.3.1 Renewable fuel supply chain system

The model structure encompasses the entire RFSC for the transport sector considering various policy measures. The supply network encompasses elements including resource supply, renewable fuel production technologies, transmission technologies, and meeting demand requirements, Figure 8.1. Certain resources, like concentrated CO₂ from industries and biomass, are considered as supply (input into the network), based on demand-driven strategies. Conversely, resources like renewable electricity can be produced, or atmospheric CO₂ can be captured from the air within the network. We take into account resources from different origins (e.g., biomass, wind, and solar PV electricity) based on their regional potential. The model incorporates a variety of technologies for production and transmission. The system can utilize locally produced fuel, fuel transmitted within the system, or import fuel to meet renewable fuel demands. Renewable fuels produced from different resources are assigned to fuel types (e.g., liquid and gas fuels), as shown in Figure 8.1, by arrows. A particular type of fuel can also satisfy the fuel demands of a given transport sector such as aviation, shown by arrows between fuel types and transport sectors in Figure 8.1. The model determines the utilization levels of resources in the supply network for producing and importing renewable fuels to satisfy demands. This includes decisions about the type, number, capacity, and installation timing of infrastructure over the long-term planning horizon. The planning period is yearly, allowing for consideration of investment and operational costs for the required infrastructure over a strategic

planning horizon from 2025 to 2050. We account for learning effects, recognizing that technologies may evolve in terms of capacity, efficiency, and cost improvements over time. The model operates under the assumption that specific renewable fuels can replace fossil fuels without necessitating radical changes in the existing system (E3-Modelling, 2018).

Furthermore, policy measures impact the renewable fuel supply through model constraints and additional terms in the objective function. This also includes time-dependent policy measures such as carbon pricing, GHG intensity reduction, and renewable fuel share. Carbon pricing measures aim to reduce emissions by penalizing GHG emissions from the fuel supply. GHG intensity reduction levels obligate fuel suppliers to reduce fuel GHG intensity. In addition, renewable fuel share levels ensure that at least a portion of the fuel supplied is renewable.

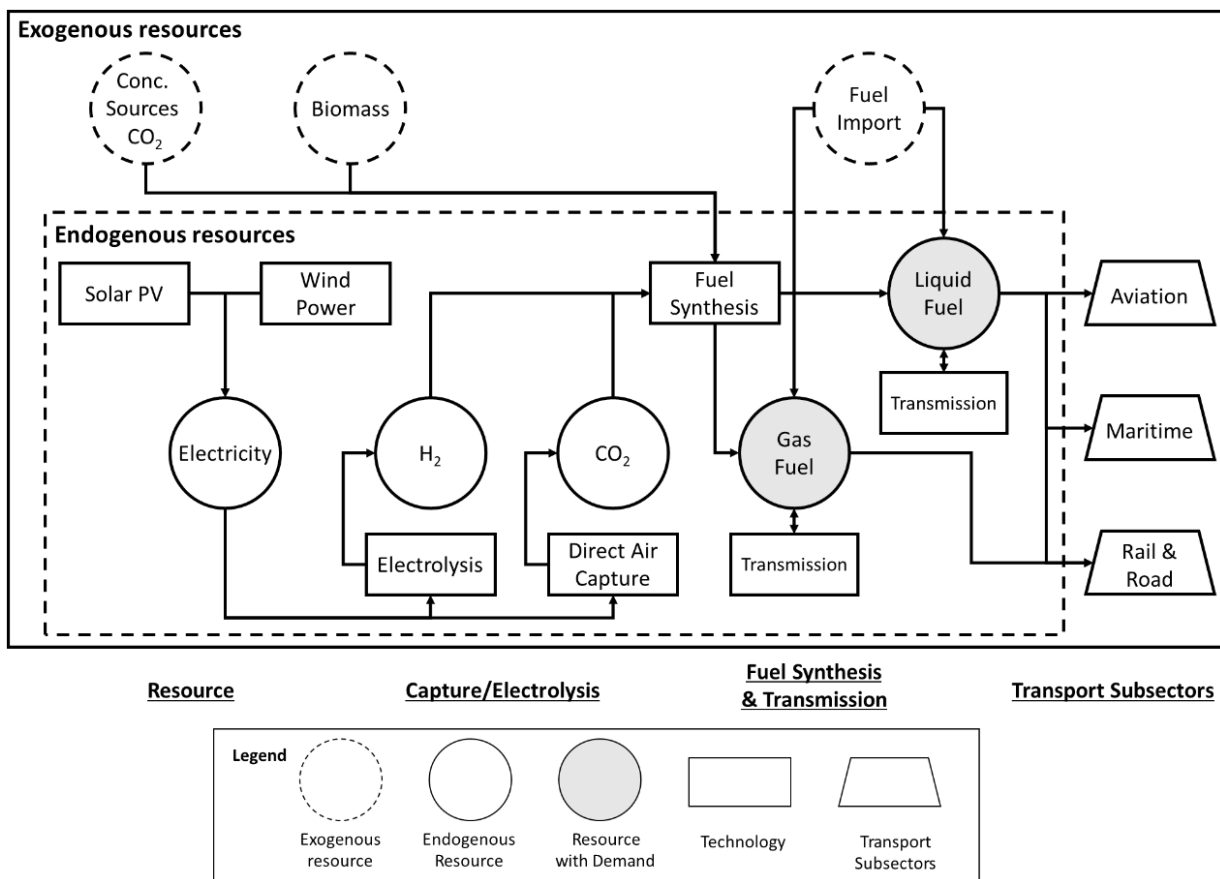


Figure 8.1. Schematic of the renewable fuel supply chain.

8.3.2 Model Nomenclature

The notation of our mathematical model is represented in Table 8.3.

Table 8.3. Notation table.

Sets	Description
$t \in T$	Index set of planning periods
$t \in T_0$	Index set of planning periods with start period
$i \in I$	Index set of regions
$e \in E$	Index set of renewable electricity generation technologies
$p \in P$	Index set of production technologies
$q \in Q$	Index set of transmission technologies
$m \in M$	Index set of resources
$o \in O$	Index set of resource origins
$v \in V$	Index set of transport sector (e.g., aviation)
$f \in F$	Index set of fuel types (e.g., liquid fuel and gas fuel)
Subsets	Description
$Q_{inv} \subset Q$	Sets of transmission technologies that require an investment
$R \subset M$	Set of renewable fuels
Parameters	Description
τ	Discount rate
f_e	Investment for renewable electricity generation technology e [€]
f_p	Investment for production technology p [€]
f_q	Investment for transmission technology q per distance [€/km]
c_e	Annual operational cost of renewable electricity generation technology e [€/year]
c_p	Annual operational cost of production technology p [€/year]
c_q	Annual operational cost of transmission technology q per distance [€/km/year]
u_q	Cost of unit transmission via technology q [€/tonnes]
v_{oit}	Unit cost of utilization resource origin o in region i in period t [€/tonnes]
v_{fit}	Unit cost of non-renewable fuels for fuel type f in region i in period t [€/tonnes]
v_{rt}^{imp}	Unit import cost of utilization renewable fuel r in period t [€/tonnes]
$v_{vit}^{CO_2}$	Carbon pricing for sector v in region i in period t [€/tonne CO ₂ eq]
D_{fvit}	Demand of fuel type f for transport sector v in region i in period t [tonnes/year]
e_f^c	Emission factor of fossil fuel comparator for fuel type f [tonne CO ₂ eq/tonnes fuel]
e_{rt}	Emission factor for renewable fuel r in period t [tonne CO ₂ eq/tonnes fuel]
B_{qm}	1 if Resources m that can be transmitted via technology q ; 0 otherwise
$B_{qii'}$	1 if transmission is possible via technology q between regions i and i' ; 0 otherwise

η_{fr}	1 if renewable fuel r is included in fuel type f ; 0 otherwise
ζ_{rv}	1 if renewable fuel r can be utilized in transport sector v ; 0 otherwise
β_{om}	1 if origin o can be converted to resource m ; 0 otherwise
α_{mp}	Conversion factor of resource m in production technology p [-]
$l_{ii'}$	Distance between region i and i' [km]
U^{imp}	Import upper bound [-]
H	Operational hours per year [hour/year]
K_p	Production capacity for technology p [tonnes/hour]
K_q	Transmission capacity for technology q [tonnes/hour]
R_{oit}	Potential for resource origin o in region i in period t [tonnes/year]
t'_e, t'_p, t'_q	Period in which renewable electricity generation technologies e , production technologies p , and transmission technologies q are available
ϑ_{ei}	Capacity factor for renewable electricity production e [-]
Θ_{ei}	Maximum installable capacity for generating renewable electricity e in region i [MW]
ρ_{vit}	Minimum required GHG intensity reduction for transport sector v in region i in period t [-]
π_{vit}	Minimum required share of renewable fuels for transport sector v in region i in period t [-]
γ_v	Multiplier for transport sector v
Decision variables	Description
δ_{pit}	Number of installed plants of production technology p in region i in period t
$\kappa_{qii't}$	Number of installed transmission technology q in region i in period t
σ_{eit}	Installed capacity of renewable electricity production e in region i in period t [MW]
x_{pit}	Production rate of technology p in region i in period t [tonnes/year]
$z_{qmii't}$	Transmission quantity via transmission technology q from region i to i' in period t [tonnes/year]
z_{rit}^{imp}	Import for renewable fuel r in region i in period t [tonnes/year]
ω_{oit}	Amount of utilization of resource origin o in region i in period t [tonnes/year] or [MWh/year]
d_{rvit}	Demand for renewable r in transport sector v in region i in period t [tonnes/year]

8.3.3 RFSC model formulation

In this section, we introduce a mathematical model describing the objective functions and constraints associated with our renewable fuel supply chain. Subsequently, we discuss the

constraints imposed by the policies (carbon pricing, GHG intensity reduction, and renewable fuel share).

8.3.3.1 Objective functions

We develop an optimization mathematical model to minimize the total net present costs and maximize the cumulative GHG emission savings for renewable fuel supply in the transport sector over a long-term horizon.

8.3.3.1.1 Total net present costs

Total net present costs include the costs associated with the generation of renewable electricity, the production of renewable resources, and the transmission of renewable energy. Moreover, it includes the variable costs associated with transmission, resource utilization and non-renewable fuel supply, and the costs associated with the import of renewable fuels. A discounting factor is applied to all expenses over the planning horizon in order to ensure a consistent comparison of costs over time. The appendix provides a more detailed explanation of total net present costs.

$$\begin{aligned}
 Z_1 = \sum_{t \in T} \frac{1}{(1 + \tau)^{(t-1)}} & \left[\sum_{i \in I} \sum_{e \in E} f_e (\sigma_{eit} - \sigma_{ei(t-1)}) + \sum_{i \in I} \sum_{e \in E} c_e \sigma_{eit} \right. \\
 & + \sum_{i \in I} \sum_{p \in P} f_p (\delta_{pit} - \delta_{pi(t-1)}) + \sum_{i \in I} \sum_{p \in P} c_p \delta_{pit} \\
 & + \sum_{i \in I} \sum_{i' \in I | i \neq i'} \sum_{q \in Q_{inv}} f_q l_{ii'} (\kappa_{qii't} - \kappa_{qii'(t-1)}) \\
 & + \sum_{i \in I} \sum_{i' \in I | i \neq i'} \sum_{q \in Q_{inv}} c_q l_{ii'} \kappa_{qii't} + \sum_{i \in I} \sum_{i' \in I | i \neq i'} \sum_{m \in M} \sum_{q \in Q} u_q z_{qmii't} \\
 & + \sum_{o \in O} \sum_{i \in I} v_{oit} \omega_{oit} + \sum_{i \in I} \sum_{v \in V} \sum_{f \in F} v_{fit} \left(D_{fvit} - \sum_{r \in R | \eta_{fr}=1 \wedge \zeta_{rv}=1} d_{rvit} \right) \\
 & \left. + \sum_{r \in R} \sum_{i \in I} v_{rt}^{imp} z_{rit}^{imp} \right]
 \end{aligned} \tag{1}$$

8.3.3.1.2 Cumulative GHG emission savings

This calculation includes the reduction in GHG emissions resulting from the use of renewable fuels in the transport sector over the planning periods, Equation (2). The GHG reductions are derived from the supply of renewable fuels in the transport sector $v \in V$ such as aviation in each region $i \in I$ during the planning period $t \in T$. To calculate the GHG emission savings for each fuel type, the resulting emission from renewable fuel utilization are compared to the GHG emission factor for fossil fuels provided in the RED II regulation guideline, e_f^c (European Commission, 2021g, 2023a).

$$Z_2 = \sum_{t \in T} \sum_{v \in V} \sum_{i \in I} \sum_{r \in R} (e_f^c - e_{rt}) d_{rvit} \quad (2)$$

8.3.3.2 Constraints

The general constraints pertaining to the renewable fuel supply network are presented in the following.

8.3.3.2.1 Balance constraints

Constraints (3) ensure the balance for resource m in region i during planning horizon $t \in T$. The first term in Constraints (3) indicates the supply of resource m from resource origin o in region i in period t (ω_{oit}) with the binary parameter β_{om} allocating resource origin o to resource m . The second term is the stoichiometric coefficient used to calculate resource consumption or production by process p , where α_{mp} stands for the production capacity of x_{pit} . Herein, negative coefficients are interpreted as resource consumption, while positive coefficients are interpreted as production. The next two terms take into account the shipment of the resource to and from region i via transmission mode q . Terms on the right-hand side of Constraints (3) indicate renewable fuel demand in region i in period t over all transport sectors (d_{mvit}), and the renewable fuels imported into region i from locations outside the system boundaries (z_{mit}^{imp}).

$$\begin{aligned} & \sum_{o \in O} \beta_{om} \omega_{oit} + \sum_{p \in P} \alpha_{mp} x_{pit} + \sum_{i' \in I} \sum_{q \in Q | B_{qm}=1} (z_{qmi'it} - z_{qmii't}) \\ & \geq \begin{cases} \sum_{v \in V} d_{mvit} - z_{mit}^{imp} & \forall m \in M \setminus R, i \in I, t \in T \\ 0 & \forall m \in R, i \in I, t \in T \end{cases} \quad (3) \end{aligned}$$

According to Constraints (4), the total demand for renewable fuels d_{rvit} should not exceed the overall demand for each fuel type f in transport sector v , region i , and time period t (D_{fvit}). A variety of renewable fuels $r \in R$ can be utilized for fuel type f , if $\eta_{fr} = 1$. Moreover, each renewable fuel r can be utilized in sector v , if $\zeta_{rv} = 1$.

$$\sum_{r \in R | \eta_{fr}=1 \wedge \zeta_{rv}=1} d_{rvit} \leq D_{fvit} \quad \forall f \in F, v \in V, i \in I, t \in T \quad (4)$$

According to Constraints (5), imports from outside the system boundary are only allowed to meet a specific share (U^{imp}) of renewable fuel demand. The import decisions z_{rit}^{imp} are calculated corresponding to this import upper bound for each renewable fuel $r \in R$.

$$z_{rit}^{imp} \leq U^{imp} \sum_{v \in V} d_{rvit} \quad \forall r \in R, i \in I, t \in T \quad (5)$$

8.3.3.2.2 Production and transmission constraints

Constraints (6) indicate the upper bound for production process p based on its full load hour H and installed capacity.

$$x_{pit} \leq H K_p \delta_{pit} \quad \forall p \in P, i \in I, t \in T \quad (6)$$

Constraints (7) specify that the quantity of resources transmitted must respect the maximum capacity of the specific mode of transmission and its installed capacity. Here, the constraints only apply to modes requiring infrastructure investment, $q \in Q_{inv}$.

$$z_{qmii't} \leq H K_q \kappa_{qii't} \quad \forall q \in Q_{inv}, m \in M, i \in I, i' \in I, t \in T, |i \neq i' \quad (7)$$

In accordance with Constraints (8) only compatible transport technologies should be used for the transportation of resources.

$$z_{qmii't} = 0 \quad \forall q \in Q, m \in M, i \in I, i' \in I, t \in T, | B_{qm} = 0 \wedge B_{qii'} = 0 \wedge i \neq i' \quad (8)$$

According to Constraints (9) and (10), the established infrastructure (production and transmission) cannot be deinstalled during the planning horizon. Thus, the number of installed production and transportation facilities cannot decrease over time.

$$\delta_{pi(t-1)} \leq \delta_{pit} \quad \forall p \in P, i \in I, t \in T \quad (9)$$

$$\kappa_{qii'(t-1)} \leq \kappa_{qii't} \quad \forall q \in Q_{inv}, i \in I, i' \in I, t \in T, | i \neq i' \quad (10)$$

8.3.3.2.3 Renewable electricity production constraints

The use of renewable electricity is modelled as an endogenous decision. Consequently, renewable electricity is provided from wind turbines (onshore and offshore) and solar panels. According to Constraints (11), the utilized electricity from renewable sources (ω_{eit}) is limited by the installed capacity decision (σ_{eit}) the average regional capacity factor (ϑ_{ei}) and the operational hours (H).

$$\omega_{eit} \leq H \sigma_{eit} \vartheta_{ei} \quad \forall e \in E, i \in I, t \in T \quad (11)$$

Further, renewable electricity generation (e.g., electricity from wind and solar PV) must not exceed maximum installable capacity for generating renewable electricity in each region (Ruiz et al., 2019), which is considered in Constraints (12).

$$\sigma_{eit} \leq \theta_{ei} \quad \forall e \in E, i \in I, t \in T \quad (12)$$

According to Constraints (13), the installed capacity of generating renewable electricity cannot be reduced over time and must remain constant until the end of the planning period.

$$\sigma_{ei(t-1)} \leq \sigma_{eit} \quad \forall e \in E, i \in I, t \in T \quad (13)$$

8.3.3.2.4 Technology availability constraints

Technology advancement in this paper is considered not only in terms of cost and process efficiency, but also in terms of availability of new technologies for production (t'_p), transmissions (t'_q) and renewable electricity generation (t'_e). Technologies can only be installed from a certain period on.

$$\delta_{pit} = 0 \quad \forall p \in P, i \in I, t \in T, | t < t'_p \quad (14)$$

$$\kappa_{qii't} = 0 \quad \forall q \in Q_{inv}, i, i' \in I, t \in T, | i \neq i' \wedge t < t'_q \quad (15)$$

$$\sigma_{eit} = 0 \quad \forall e \in E, i \in I, t \in T, | t < t'_e \quad (16)$$

8.3.3.2.5 Resource utilization constraints

In accordance with Constraints (17), it is important to consider the availability of resource origins (e.g., biomass and CO₂) when considering resource utilization.

$$\omega_{oit} \leq R_{oit} \quad \forall o \in O \setminus E, i \in I, t \in T \quad (17)$$

8.3.3.2.6 Variable domains

Finally, Constraints (18) to (20) define the domains of the decision variables.

$$\delta_{pit}, \kappa_{qii't} \in \mathbb{N}_0 \quad \forall p \in P, q \in Q_{inv}, i \in I, i' \in I, t \in T_0, | i \neq i' \quad (18)$$

$$\sigma_{eit} \geq 0 \quad \forall e \in E, i \in I, t \in T_0 \quad (19)$$

$$x_{pit}, z_{qmii't}, z_{rit}^{imp}, \omega_{oit}, d_{rvit} \geq 0 \quad \forall p \in P, q \in Q, m \in M, r \in R, o \in O, i \in I, i' \in I, t \in T, | i \neq i' \quad (20)$$

8.3.3.3 Integration of Policy Measures into the RFSC Model

In this subsection, we extend the mathematical formulations by equations representing the policy measures that have an impact on the renewable fuel supply chain. Additional constraints on renewable fuel supply are imposed by GHG intensity reduction levels and renewable fuel share levels. Additionally, carbon pricing is incorporated into the objective function as a cost term associated with GHG emissions.

8.3.3.3.1 Carbon pricing measure

Carbon pricing measures add an additional term to the total net present cost function. Constraints (21) reflect this additional cost of the policy measure based on the GHG emissions resulting from the renewable fuel supply chain.

$$Z'_1 = Z_1 + P^{CO_2} \quad (21)$$

In Constraints (22), the first term indicates the resulting GHG emissions from utilized renewable fuels (d_{rvit}) based on corresponding emission factors e_{rt} in tonnes of CO₂ equivalent. The second term refers to the GHG emissions associated with the use of non-renewable fuels and based on emission factors e_f^c . Multiplying the total resulting GHG emissions from all renewable and non-renewable fuels for each fuel type by the carbon price $v_{vit}^{CO_2}$ results in the total carbon price for the transport sector v in region i during period t . Carbon pricing is then calculated by summing the costs across all transport sectors and regions and then discounting these costs over the planning periods. Using the discounting factor results in a consistent comparison of costs over time, as well as penalizing earlier emissions that have been present in the atmosphere for an extended period of time (Quarton and Samsatli, 2021).

$$\begin{aligned}
p^{CO_2} = & \sum_{t \in T} \frac{1}{(1 + \tau)^{(t-1)}} \sum_{i \in I} \sum_{v \in V} \sum_{f \in F} v_{vit}^{CO_2} \left(\sum_{r \in R | \eta_{fr}=1 \wedge \zeta_{rv}=1} e_{rt} d_{rvit} \right. \\
& \left. + e_f^c \left(D_{fvit} - \sum_{r \in R | \eta_{fr}=1 \wedge \zeta_{rv}=1} d_{rvit} \right) \right)
\end{aligned} \quad (22)$$

8.3.3.3.2 GHG intensity reduction measure

In regulations such as RED II and FuelEU Maritime, setting GHG emission reduction obligations aims to force fuel suppliers to produce more renewable fuels (European Commission, 2021f, 2021g). Constraints (23) ensure that the GHG intensity reduction in the transport sector v in region i during period t should be higher than a specified level set by policy measures, ρ_{vit} . The numerator calculates the total GHG savings, considering the difference between the baseline emission factor e_f^c (GHG emission factor for fossil fuels) and renewable fuel emission factor e_{rt} , if renewable fuel r is utilized. The denominator represents the total baseline emissions for the respective fuel types, i.e. assuming comparable fossil fuels (European Commission, 2021g).

$$\begin{aligned}
& \sum_{f \in F} \sum_{r \in R | \eta_{fr}=1 \wedge \zeta_{rv}=1} (e_f^c - e_{rt}) d_{rvit} / \sum_{f \in F} e_f^c D_{fvit} \\
& \geq \rho_{vit} \quad \forall v \in V, i \in I, t \in T \quad (23)
\end{aligned}$$

8.3.3.3.3 Renewable fuel share measure

Another policy measure to obligate fuel suppliers for producing more renewable fuels is to mandate a minimum share of renewable fuels. Constraints (24) state that for the transport sector v in region i during period t the minimum share of renewable fuels, π_{vit} , should be met. For each transport sector a multiplier, γ_v , may be defined by policy makers. The numerator calculates the total renewable fuels in the transport sector v in region i during period t considering also multipliers. The denominator represents the total demand of fuel types for the transport sector v in region i during period t .

$$\sum_{f \in F} \sum_{r \in R | \eta_{fr}=1 \wedge \zeta_{rv}=1} \gamma_v d_{rvit} / \sum_{f \in F} D_{fvit} \geq \pi_{vit} \quad \forall v \in V, i \in I, t \in T \quad (24)$$

8.4 Case study

Our case study aims to evaluate the RFSC for the European-wide transport sector considering effective policy measures.

8.4.1 Data

As the forthcoming regulations pertain to the entire European Union, the study encompasses Europe at a country level, with a planning horizon spanning from 2025 to 2050, evaluated on an annual basis. Throughout this planning horizon, the availability and costs for resource supply are subject to change. The resource data include regional biomass availability and cost (Ruiz et al., 2019), regional availability of point sources of CO₂ from non-avoidable sources of CO₂, e.g., cement industry (Global Carbon Project, 2022), regional capacity factors and potentials for solar PV, wind onshore and wind offshore (Pfenninger and Staffell, 2016; Staffell and Pfenninger, 2016a, 2016b). We limit the utilization of regional potential for biomass and renewable electricity to a maximum of 50% for the transport sector (FVV, 2022). Fuel demand projections are aligned with the Climate Target Plan (CTP) of the European Commission (European Commission, 2021c). The transport sector is divided into three sectors: rail and road, aviation, and maritime. Demand disaggregation for each region and sector is based on the respective activities under CTP scenarios.

This case study considers both liquid and gas fuels for transport. Production and transmission technologies are key considerations for fuel supply. A number of production technologies are considered, including biomass to liquid fuels (BtL), electricity to gas or liquid fuels (PtG or PtL), and electricity and biomass to liquid fuels (PBtL). We consider their techno-economic data, including capacity, cost, and period of availability of technology (FVV, 2021b; Liebich et al., 2021). Transmission technologies considered include trucks and pipelines, which comprise both repurposed and new pipeline infrastructure (Guidehouse, 2021) and existing truck infrastructure (Wolff et al., 2023). In the model, it is assumed that up to 30% of the renewable fuel demand can be met through imports (European Commission, 2018; FVV, 2021b). The GHG emissions associated with renewable fuels have been estimated based on the work of Liebich et al. (2021).

8.4.2 Factorial analysis

By implementing factorial analysis, we aim to investigate the impact of multiple policy measures and their interactions on the RFSC design, focusing on their influence on the total net

present costs and cumulative GHG emission savings. Therefore, we consider each policy measure as factors at four levels to investigate their contribution to establishing the RFSC. Herein, we examine each factor individually, as well as their interactions. As shown in Table 8.4, factors including carbon pricing, GHG intensity reduction, and renewable fuel share are analyzed, resulting in $4^3 = 64$ instances. The first level represents current mandates, while the next three levels represent scenarios with low, medium, and high values (levels are represented by indices 1, 2, 3, and 4, respectively). The value in each instance represents the policy measures in periods 2030, 2040, and 2050. Based on the European Green Deal scenarios, carbon pricing values are considered in the range of 100 to 500 €/tonne CO₂ equivalent (European Commission, 2021b). At the low level, all transport sectors are assumed to have the same values for GHG intensity reductions and renewable fuel shares. At the medium and high levels, however, more ambitious targets are considered. For GHG intensity reductions and renewable fuel shares in 2050, ambitious target of 90% is considered according to the European Green Deal scenarios (European Commission, 2021c). For example, GHG intensity reductions at the low level for the aviation sector in 2030, 2040, and 2050 would equal 15%, 50%, and 90%, respectively. An instance is defined by the level of the factors. For example, instance 142 corresponds to carbon pricing at level 1, GHG intensity reduction at level 4, and renewable fuel share at level 2. When a single policy measure (e.g., at its highest level) is analyzed, we refer to it as “400”, “040”, and “004”, which shows only carbon pricing, GHG intensity reduction, and renewable fuel share measures.

Table 8.4. Factors (policy measures) and their levels for the factorial design in 2030, 2040, and 2050.

Level Index	Current regulations (1)	Low (2)	Medium (3)	High (4)
Factor 1: Carbon pricing [€/tonne CO₂ eq] per transport sector				
Rail and road	100, 100, 100	100, 200, 300	200, 300, 400	300, 400, 500
Aviation	100, 100, 100	100, 200, 300	200, 300, 400	300, 400, 500
Maritime	100, 100, 100	100, 200, 300	200, 300, 400	300, 400, 500
Factor 2: GHG intensity reduction [-] per transport sector				
Rail and road	15%, 50%, 90%	15%, 50%, 90%	25%, 55%, 90%	35%, 65%, 90%
Aviation	0%, 0%, 0%	15%, 50%, 90%	25%, 55%, 90%	35%, 65%, 90%
Maritime	5%, 25%, 75%	15%, 50%, 90%	25%, 55%, 90%	35%, 65%, 90%
Factor 3: Renewable fuel share [-] per transport sector				
Rail and road	5%, 5%, 5%	15%, 50%, 90%	25%, 55%, 90%	35%, 65%, 90%
Aviation	5%, 30%, 65%	15%, 50%, 90%	25%, 55%, 90%	35%, 65%, 90%
Maritime	0%, 0%, 0%	15%, 50%, 90%	25%, 55%, 90%	35%, 65%, 90%

8.4.3 Results and discussion

We first solve a bi-objective model to evaluate the Pareto frontier and identify trade-offs between the total net present costs and cumulative GHG emission savings. In addition, comparing the results of incorporating single policy measures into the model shows their effectiveness on RFSC development. The impact of policy measures and their interaction on the RFSC are then examined in a factorial analysis. As a result, we determine to what extent the policy measures contribute to the total net present costs and cumulative GHG emission savings of the RFSC.

8.4.3.1 Pareto-efficient frontier

In the Pareto-efficient frontier of the RFSC for the European case study, the trade-offs between the total net present costs and the cumulative GHG emission savings are depicted. This frontier highlights two ideal points: one where the total net present costs are minimized (the cost-effective solution), and the other where the cumulative GHG emission savings are at their maximum (the CO₂-optimal solution) considering no policy measures, as shown in Figure 8.2-a. Optimal solutions are situated on the Pareto-efficient frontier, while suboptimal ones are found above this line. The area below the frontier is considered infeasible.

The absence of policy measures results in a cost-effective solution that minimizes the total net present costs as there will be no incentive to use renewable fuels. Consequently, there will be no reduction in GHG emissions. However, the CO₂-optimal solution with maximum cumulative GHG emission savings (the extreme right point on the Pareto-frontier) indicates that savings of more than 16 Gtonnes of CO₂ equivalent are possible, though at a significant expense. Using the marginal abatement cost as a benchmark provides policymakers with a clear carbon price to incentivize optimal emission reduction measures (Longva et al., 2024). Estimates for the abatement costs of replacing fossil fuels with renewable fuels vary widely in the literature. For example replacing renewable fuels is estimated to cost between 200 and 700 euros per tonne of CO₂ equivalent (Martin et al., 2023). In our analysis, we consider two benchmark solutions to explore the trade-offs between economic and environmental objectives in relation to Pareto frontier solutions: (1) We use a value of 320 € per tonne of CO₂ equivalent (Albrecht and Nguyen, 2020; Longva et al., 2024; Martin et al., 2023; Millinger et al., 2021) as an Abatement Cost Benchmark Point (ACBP), assuming carbon pricing based on abatement cost. According to the ACBP solution, investing approximately 200 million € on the RFSC may save about 1.6 Gtonnes of CO₂ equivalent. Additionally, (2) we apply the weighted Tchebycheff distance

method to find a compromise solution (Karakaya and Köksalan, 2023; Ostovari et al., 2024; Ozbey and Karwan, 2014), referred to as the Balanced Objective Point (BOP), giving equal preference to both economic and environmental objectives. The BOP solution shows saving about 6.2 Gtonnes of CO₂ equivalent by balancing these objectives. Our research also examines the optimal design of RFSC by incorporating each policy measure at its highest level, compared to the Pareto-efficient frontier, to assess their pure impacts on RFSC design. Specifically, instances “400”, “040”, and “004” represent optimal solutions for scenarios where pure carbon pricing, GHG intensity reduction, and renewable fuel share are all incorporated into the optimization model. As can be seen in Figure 8.2-a, instances “004”, “040” and “004” are (nearly) on the Pareto-efficient frontier. Instance “400”, representing carbon pricing at a high level, shows the higher GHG emission savings compared to instance “004”, which represents renewable fuel share at a high level. Further, considering only the high level of GHG intensity reduction measure results in emission savings of approximately 7.1 Gtonnes of CO₂ equivalent with an investment in RFSC of approximately 1.1 trillion €.

In Figure 8.2-b, the optimal solutions for instances that integrate a combination of policy measures (represented by orange circles) are compared to the Pareto-efficient frontier. The integration of these policy measures results in near-optimal solutions, with average gaps of about 8% between these solutions and the Pareto-efficient frontier. For better visualization, a zoomed-in area highlights where integrating policy measures leads to emission savings between 5-7 Gtonnes of CO₂ equivalent.

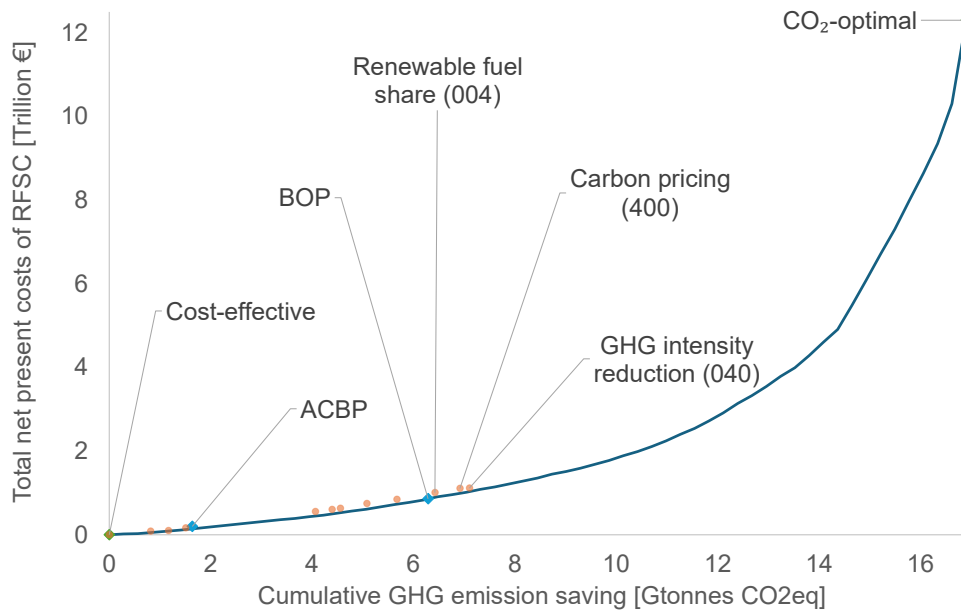
As shown in Figure 8.2-b, there is a marginal gap between policy-integrated solutions and Pareto-efficient solutions, which leads to different designed supply networks and renewable fuel supplies. This difference is due to significant flexibility without mandating specific technologies or renewable fuels, allowing policy measures to still result in near-optimal solutions. In our case study, this flexibility is evident as the network includes several technology pathways for production and transmission of renewable fuels without mandating any specific type.

According to the figure, changing the level of renewable fuel share leads to negligible changes in objective functions, as seen in instances “130”, “131”, “132”, and “133”. This indicates that setting a medium level of GHG intensity reduction causes the renewable fuel share constraints to become non-binding at both low and medium levels, resulting in nearly identical outcomes. Additionally, higher carbon pricing levels (e.g., instance “233”) show greater potential for

saving GHG emissions compared to lower levels (e.g., instance “133”). In instance “233”, about 1% more renewable fuels are supplied with a higher portion of PBtL compared to instance “133”. Comparing the efficiency of solutions for instances “133” and “233” with the Pareto frontier (the BOP solution) shows that for the same amount of net present cost, there is about 9% and 7% less reduction in GHG emissions, respectively.

These results demonstrate that while integrating policy measures can lead to similar economic and environmental objectives, the design of the RFSC may differ. Therefore, changes in policy measures mainly lead to confusion in RFSC design while having minimal impact on overall Pareto-efficiency. Consequently, policy measures should be designed, considering long-term and combinatorial aspects of the planning problem.

a)



b)

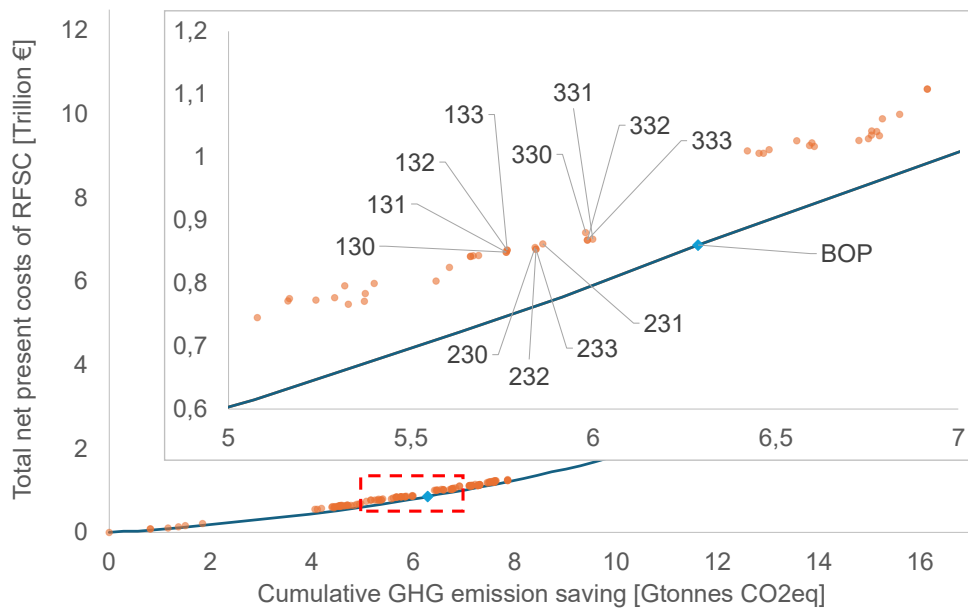


Figure 8.2. a) Pareto-efficient frontier of the renewable fuel supply chain. Also, solutions for scenarios with pure carbon pricing (400), GHG intensity reduction (040), and renewable fuel share (004) each at the highest level are presented. b) Optimal solutions integrating policy measures in the renewable fuel supply chain.

The cumulative GHG emission savings across the planning periods are shown in Figure 8.3 (solid lines). As a result of the trajectory of emission savings, compared to the CO₂-optimal solution, the other solutions are delayed, which indicates a delay in the supply of renewable

fuels. A comparison of net present costs over the planning periods is also shown in Figure 8.3 (dashed lines). According to Figure 8.3, comparing the CO₂-optimal with the BOP solution shows that postponing the production of renewable fuels could result in the additional release of more than 10 Gtonnes of CO₂. The total GHG emission savings for “400”, “040”, “004”, and the BOP solutions are about 6.9, 7.1, 6.4, and 6.3 Gtonnes of CO₂ equivalent. Figure 8.3 shows that renewable fuel supplies may begin from 2030 onward, with each policy measure having a different influence on the rate of supply.

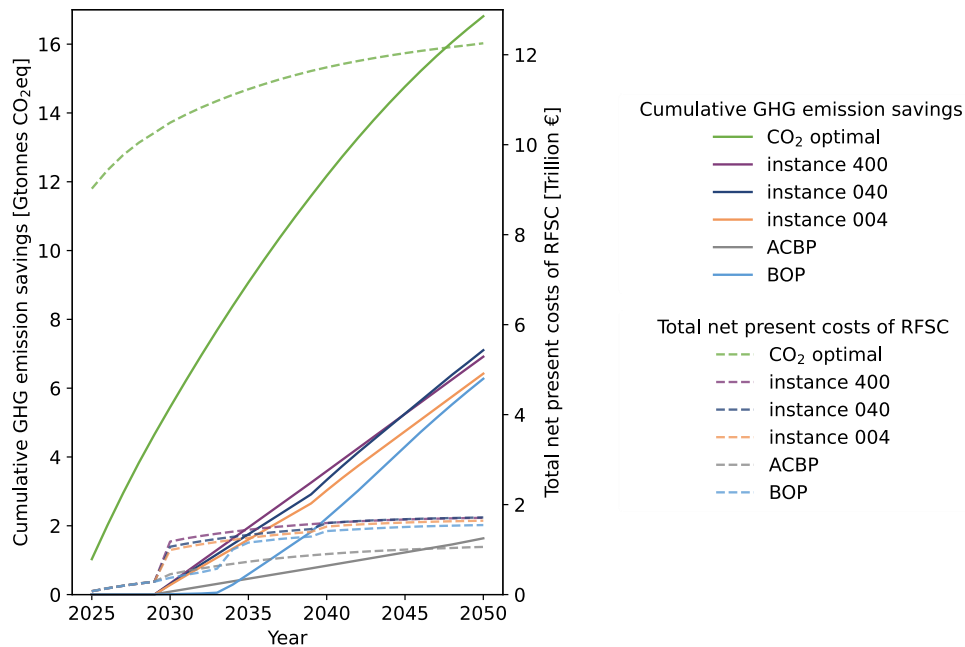


Figure 8.3. Cumulative GHG emission savings and total net present costs over planning periods.

8.4.3.2 Results of factor analysis

As part of the solution, we integrated carbon pricing, GHG intensity reduction levels, and renewable fuel shares into the model. A factorial analysis was used to assess the impact of each of these policy measures on renewable fuel production. Table 8.4 indicates that each policy measure is included in four levels, resulting in 64 instances in total. Two objectives are investigated, total net present costs and cumulative GHG emission savings.

Table 8.5 presents a summary of the main effects and their interactions. It provides the sum of squares, degree of freedom (df), contributions, and P-values for the main factors and their interactions on total net present costs and cumulative GHG emission savings. CP, GHG, and RF represent the main effects of carbon pricing, GHG emission intensity, and renewable fuel share, and CP×GHG, CP×RF, RF×GHG represent their interactions. Subtracting the sum of

squares for each main effect and interaction from the total sum of squares will yield the sum of squares for the residual and can be treated as the interaction of three factors $CP \times GHG \times RF$. The results indicate that carbon pricing is the primary contributor to net present costs and cumulative GHG emission savings, accounting for 43% and 40% of the variability in cost and environmental objectives, respectively. Furthermore, GHG intensity reduction and renewable fuel share measures together explain an additional 40% of the variability in net present costs and cumulative GHG emission savings. Notably, the interactions among policy measures contribute approximately 20% to the variation in both objectives. Table 8.5 highlights the significant contributions of interactions between GHG intensity reduction with carbon pricing and renewable fuel share measures.

Table 8.5. Summary of the effect of main factors and their interactions on total net present costs and cumulative GHG emission savings. CP, GHG, and RF represent the main effect of carbon pricing, GHG emission intensity, and renewable fuel share, and $CP \times GHG$, $CP \times RF$, $RF \times GHG$ represent their interactions.

Factors	Sum of squares	df	Contribution (%)	P-value
Total net present costs				
CP	1.257	3	43.11%	5.15e-19
GHG	0.784	3	26.89%	2.16e-16
RF	0.348	3	11.94%	4.38e-12
$CP \times GHG$	0.185	9	6.34%	7.68e-07
$CP \times RF$	0.112	9	3.85%	7.16e-05
$RF \times GHG$	0.178	9	6.09%	1.15e-06
Residual	0.052	27	1.78%	
Cumulative GHG emission savings				
CP	31.741	3	40.38%	7.24e-19
GHG	23.553	3	29.96%	3.34e-17
RF	9.348	3	11.89%	2.90e-12
$CP \times GHG$	4.901	9	6.24%	6.19-07
$CP \times RF$	2.863	9	3.64%	8.13-05
$RF \times GHG$	4.848	9	6.17%	6.89e-07
Residual	1.349	27	1.72%	

Figure 8.4 illustrates the main effects of each factor (policy measures) on the total net present costs and cumulative GHG energy savings. Levels 1, 2, 3, and 4 on the x-axis represent current regulations, low, medium, and high levels, respectively. According to the main effect plot, higher levels of policy measures result in a positive correlation with total net present costs (right y-axis) and cumulative GHG energy savings (left y-axis). This means that as the levels of policy measures increase, both the total net present costs and cumulative GHG energy savings tend to rise. Figure 8.4 shows that carbon pricing, GHG intensity reduction and renewable fuel share

measures lead to an increase in total net present costs and cumulative GHG emission savings at medium (3) and high (4) levels. The figure indicates that these policy measures at low (2) and medium (3) levels significantly impact mean cumulative GHG emission savings, while their effects on mean total net present costs are relatively minor. Specifically, increasing the level of carbon pricing, GHG intensity reduction, and renewable fuel share measures results in mean cumulative GHG emission savings increasing by 29%, 26% and 15%, respectively, while mean total net present costs increase by 38%, 31% and 19%.

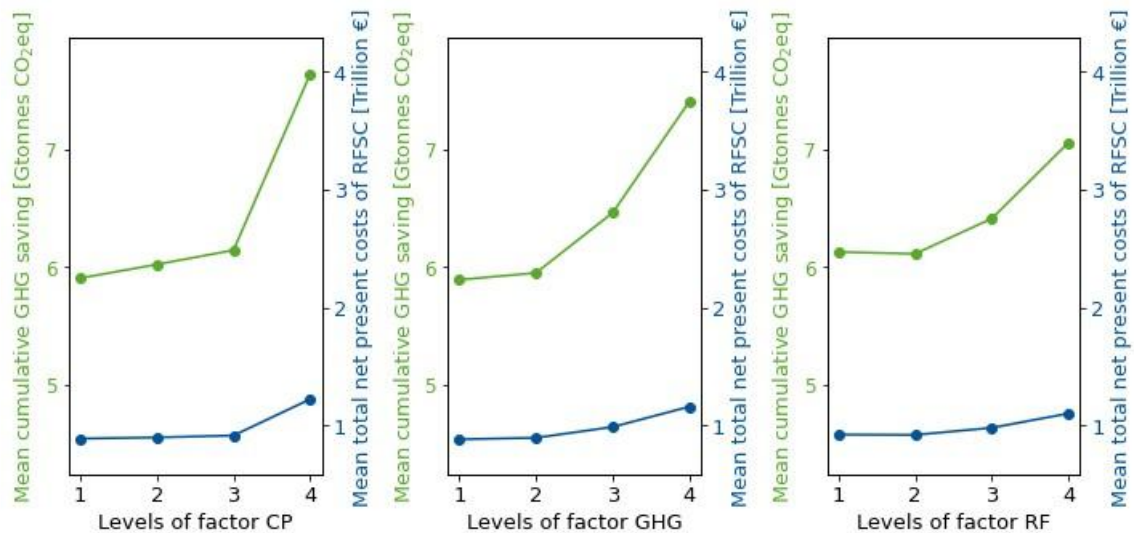
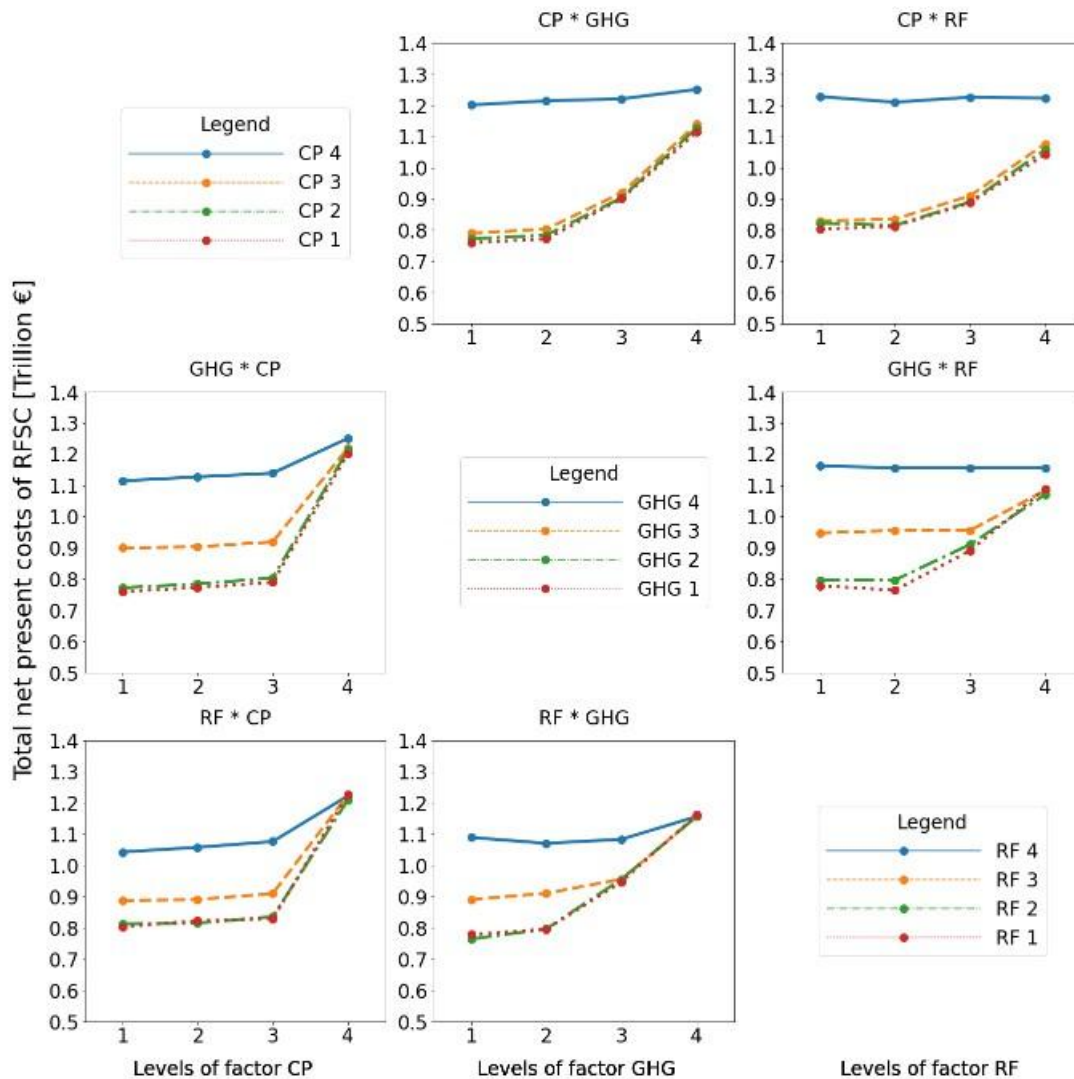


Figure 8.4. Main effect plot of three policy measures for cumulative GHG saving (green line) and total net present costs (blue line). Factors CP, GHG, and RF are abbreviations of policy measures carbon pricing, GHG intensity reduction, and renewable fuel share.

As depicted in Figure 8.5, interactions are represented by a series of variations resulting from the impact of one design factor on responses (i.e., net present costs or cumulative GHG emission savings). For each response, six subplots depict the interaction of factors. Each column in Figure 8.5 illustrates the level of a factor; for example, the left column shows the level of carbon pricing (CP). Each row in Figure 8.5 also depicts the level of another factor, as depicted by the lines described by legend. When lines in a subplot are not parallel, the effects of one factor on the responsive variable will vary based on variations in the other factor. In the GHG*CP subplot in Figure 8.5-a, the red dotted line (GHG1) represents the first level of GHG intensity reduction changes across its four levels of carbon pricing measures. As carbon pricing increases from low to high levels, the lines depicting GHG intensity reduction levels also rise, indicating that higher carbon pricing leads to an increase in total net present costs. Consequently, GHG intensity reduction would increase the interactive impact of carbon pricing measures. Based on Figure

8.5-a and Figure 8.5-b, it is evident that the GHG intensity reduction and the carbon pricing significantly interact with total net present costs and cumulative GHG emission savings. Additionally, the GHG intensity reduction and the renewable fuel share have a significant interaction. Nevertheless, parallel lines in a subplot indicate slight interaction, such as between carbon pricing and the renewable fuel share. According to subplot CP*RF in Figure 8.5-b, adopting higher renewable fuel shares will increase cumulative GHG emission savings at lower levels of carbon pricing (i.e., CP1 and CP2). Conversely, at higher carbon pricing (i.e., CP4), renewable fuel shares do not have a significant impact on net present costs or cumulative GHG emission reductions. This highlights a marginal interaction between these two measures at lower carbon pricing.

a)



b)

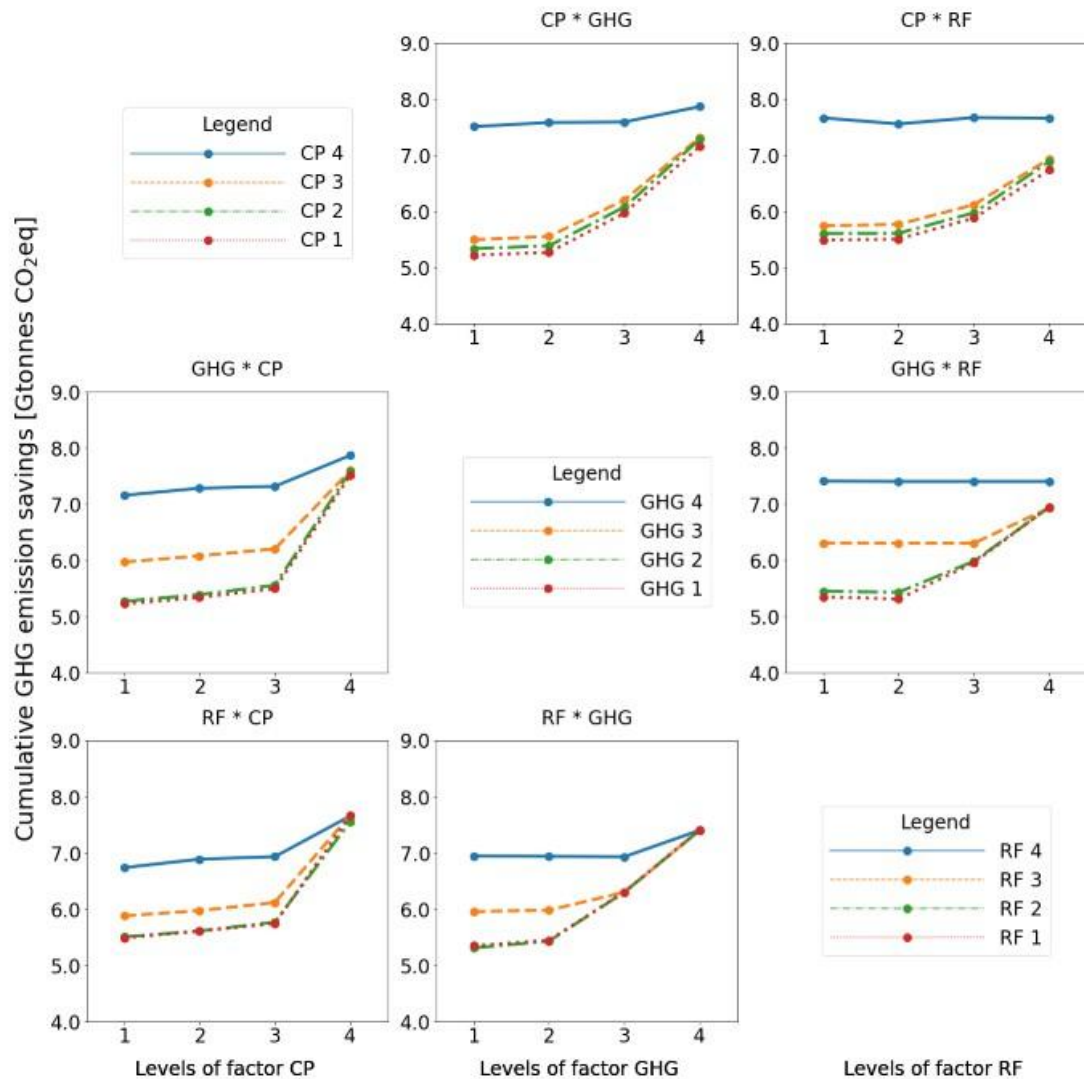


Figure 8.5. Interaction plot matrix for a) total net present costs and b) cumulative GHG saving. Factors CP, GHG, and RF are abbreviations of policy measures carbon pricing, GHG intensity reduction, and renewable fuel share.

Figure 8.6 shows the normalized responses of total net present costs (blue) and cumulative GHG emission savings (green) for various policy measures, for instances with different levels of each policy measure. Instance “443”, for example, represents a carbon pricing and GHG intensity reduction measure at level 4 and a renewable fuel share measure at level 3, showing high values for both objectives. As shown by instance “141”, high cumulative GHG emission savings with high total net present costs can be achieved by the highest level of GHG intensity reduction combined with the lowest levels of carbon pricing and renewable fuel share measures. Furthermore, integrating policy measures at the medium level (instance “333”) may result in moderate economic and environmental objectives. The normalized values of the cumulative

GHG emission savings and the total net present costs for instance “333” are 0.76 and 0.70, respectively.

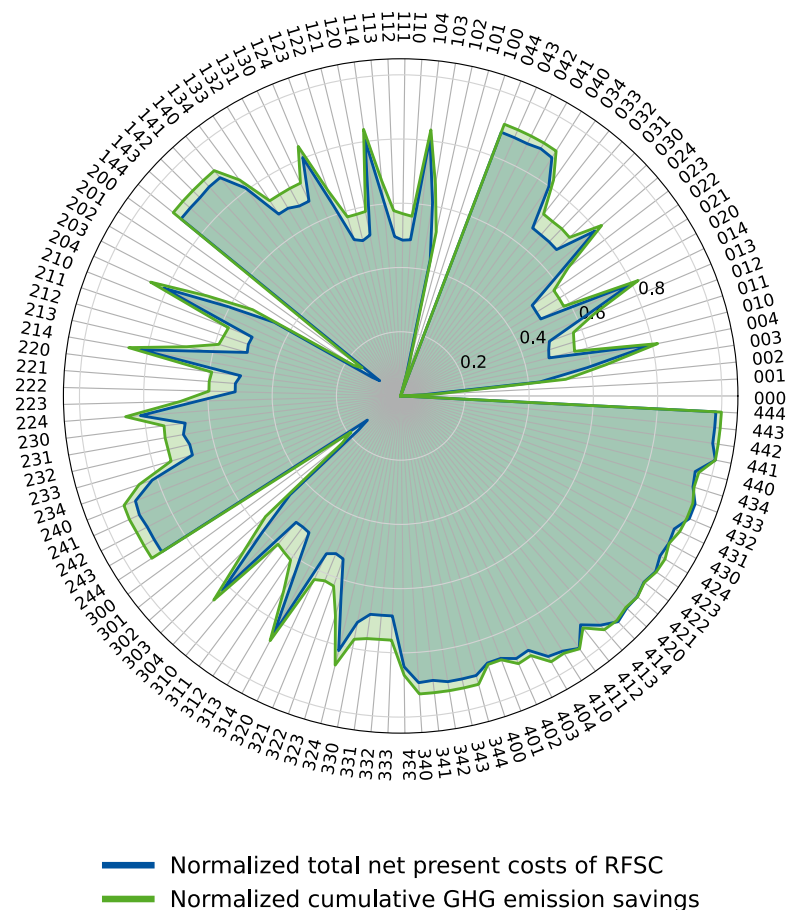


Figure 8.6. Comparing the total net present costs and cumulative GHG emission savings for instances with varying levels of policy measures.

Therefore, these findings show that defining trajectory goals for policy measures is essential for achieving moderate cumulative GHG emission reductions and total net present costs. According to Figure 8.6, moderate economic and environmental objectives can be achieved by integrating the medium level of carbon pricing combined with medium levels of GHG intensity reduction and renewable fuel share measures.

8.4.3.3 Sensitivity to cost parameters

To assess how changes in model parameters might impact optimal solutions, a sensitivity analysis was conducted. The parameters examined included the costs of (1) biomass, (2) renewable electricity generation, (3) renewable fuel import, (4) transmission, (5) production, and (6) fossil fuels. During this analysis, each parameter's value was adjusted by $\pm 20\%$ and compared with the instance having medium levels of carbon pricing, GHG intensity reduction,

and renewable fuel share (i.e., instance “333”). The outcomes of this sensitivity analysis are illustrated in Figure 8.7.

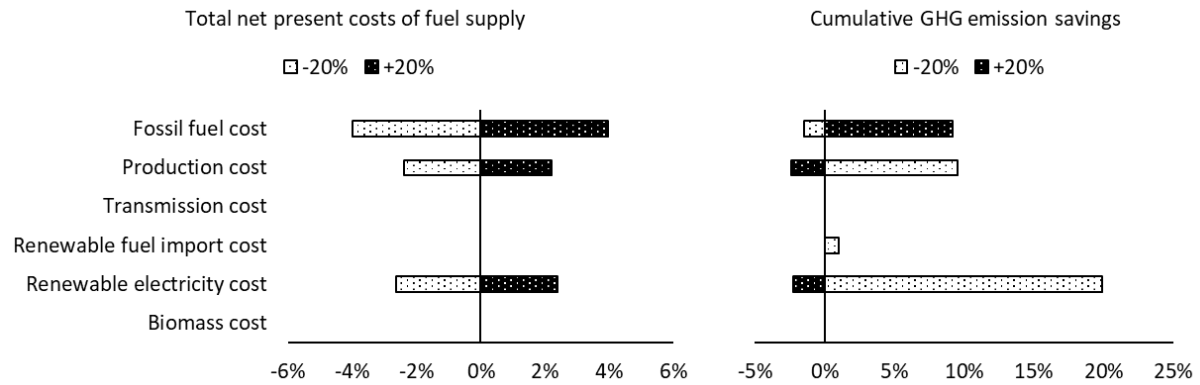


Figure 8.7. Sensitivity of Total net present costs and Cumulative GHG emission savings of fuel supply to selected parameters (compared with instance “333” with medium levels of policy measures).

The total net present costs of fuel supply are moderately sensitive to fossil fuel cost and costs associated with production technologies and renewable electricity generation. However, cumulative GHG emission savings are highly sensitive to variations in costs of fossil fuels, production technologies, and renewable electricity generation.

When the fossil fuel price increases or decreases by 20%, the total net present costs increase or decrease by less than 5%. However, by increasing the fossil fuel price by 20%, the cumulative GHG emission savings could increase by around 10%. The sensitivity of total net present costs to changing the production cost by $\pm 20\%$ is about 2%, while the cumulative GHG emission savings increase by about 10% when the production cost is decreased by 20%. While changing renewable electricity costs by 20% only impacts total net present costs by less than 3%, decreasing costs of renewable electricity generation by 20% may result in up to 20% more savings in GHG emissions (see Figure 8.7).

The findings from the sensitivity analysis show a slight impact of transmission, renewable fuel import, and biomass costs on both the economic and environmental objectives. Since the associated costs of transmission, renewable fuel import, and biomass utilization consist of a small portion of total net present cost (less than 10% for instance “333”), even 20% changes have a slight impact on the cost function. On the other hand, the emission savings for more expensive fossil fuels (+20% fossil fuel cost) and cheaper renewable fuels (-20% production

cost and -20% renewable electricity generation) indicate a significant opportunity for higher cumulative GHG emission savings.

8.4.3.4 Sensitivity to variation in policy measures

To evaluate the variation of policy measures on economic and environmental objectives, we compared the instance “333” (medium-level policy measures) with instances having low and high levels of policy measures. Sensitivity analysis was implemented for single policy measure changes, including high and low levels of carbon pricing, GHG intensity reduction, and renewable fuel share. In addition, we compared the combinations of policy measures at low and high levels with the medium level (i.e., instance “333”). Figure 8.8 shows the results of the sensitivity analysis of policy measures.

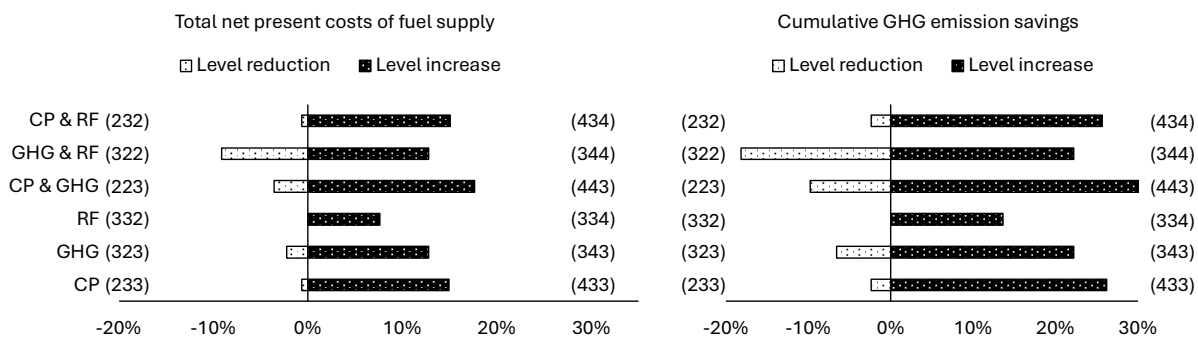


Figure 8.8. Sensitivity of total net present costs and Cumulative GHG emission savings of fuel supply to changes in policy measures. The levels of policy measures for each instance are represented in parentheses, corresponding to carbon pricing (CP), GHG intensity reduction (GHG), and renewable fuel share (RF).

The findings of this sensitivity analysis show that decreasing levels of policy measures (see low level in Table 8.4) lead to decreases in both economic and environmental objectives. Conversely, increasing levels of policy measures (see high level in Table 8.4) significantly increase both total net present costs and cumulative GHG emission savings.

When single policy measures (including carbon pricing, GHG intensity reduction, and renewable fuel share) increase from the medium level to high level (from instance “333” to instances “433”, “343”, and “334”, respectively), the net present costs increase by 15%, 13%, and 8%, respectively. Meanwhile, the cumulative GHG emission savings for the high levels of carbon pricing, GHG intensity reduction, and renewable fuel share increase by 26%, 22%, and 14% compared with the medium level of policy measures. These results show higher sensitivity

of cumulative GHG emission savings than total net present costs to changes in high and low levels of policy measures compared with the medium level.

Furthermore, comparing the variation in levels of two policy measures shows significant impacts on both economic and environmental objectives. When policy measure levels decrease (instances “223”, “322”, and “232”) compared to medium level (instance “333”), the cumulative GHG emissions decrease by up to 18%. On the other hand, increasing levels of two policy measures simultaneously leads to significant increases in both total net present cost and cumulative GHG emission savings. For instance, carbon pricing and GHG intensity reduction at high levels (instance “443”) result in an increase of the economic objective, since it leads to higher carbon pricing of GHG emissions from fuel supply and higher investment cost for supplying more renewable fuel. However, comparing instance “443” with “333” shows more than 31% higher cumulative GHG emission savings. This demonstrates that higher levels of policy measures implemented together have a more substantial impact on cumulative GHG emission savings than increasing individual measures alone. Therefore, increasing levels of policy measures simultaneously leads to greater benefits in environmental objectives but also higher economic costs.

8.4.3.5 Optimal combinations of policy measures

In this section, we aim to investigate the optimal combinations of policy measures that balance economic and environmental objectives. We implemented a comparison of scenarios with different trends for carbon pricing, GHG intensity reduction, and renewable fuel shares to examine the optimal combinations of policy measures. Then we compare the results with the balanced solution, which we chose as the BOP since it is a compromise solution with equal preference to both economic and environmental objectives. The carbon pricing trends include:

- An increasing trend with a moderate increase (A)
- A constant trend with a moderate value (B)
- An increasing trend with a high increase (C)
- A constant trend with a high value (D)

The GHG intensity reduction and renewable fuel shares are considered with low (A) and moderate increase (B) over the planning horizon.

Table 8.6. Details of scenarios for trajectories of policy measures including carbon pricing (CP), GHG intensity reduction (GHG), and renewable fuel shares (RF).

Policy measures		2030	2040	2050
CP [€/tonne CO ₂ eq]	A	100	200	300
	B	300	300	300
	C	100	300	500
	D	500	500	500
GHG [%]	A	5	25	75
	B	15	50	90
RF [%]	A	5	25	75
	B	15	50	90

Comparing the results of combining different trends of policy measures with the compromise solution (i.e., BOP) gives us the opportunity to investigate the optimal combinations of carbon pricing, GHG intensity reduction, and renewable fuel shares. In addition, comparing the results of scenarios for combining policy measures with the Pareto-efficient frontier shows how efficient implementing these policy measures is. The results of these comparisons are presented in Table 8.7. For each scenario, we calculated the relative values of the economic and environmental objectives compared to BOP as a balance solution for both objective functions. In addition, we investigated the efficiency of policy integration in each scenario by comparing its gap to the pareto-efficient frontier.

Table 8.7. Results of combinations of policy measures with different trajectories.

Scenario			Deviation from the compromise solution (BOP)		Deviation from Pareto-efficient
CP	GHG	RF	Total net present cost	Cumulative GHG emission saving	
A	A	A	-64,3%	-59,8%	16,4%
B	A	A	-49,0%	-50,0%	27,1%
C	A	A	-36,5%	-31,7%	8,6%
D	A	A	60,2%	32,1%	2,5%
A	A	B	19,2%	7,0%	5,2%
B	A	B	19,4%	7,3%	5,0%
C	A	B	19,4%	7,4%	4,9%
D	A	B	64,3%	34,0%	2,4%
A	B	A	30,8%	15,7%	3,3%
B	B	A	31,2%	16,0%	3,3%
C	B	A	31,8%	16,2%	3,5%
D	B	A	62,9%	34,2%	1,8%
A	B	B	30,8%	15,7%	3,3%
B	B	B	31,2%	16,0%	3,3%
C	B	B	31,8%	16,2%	3,5%
D	B	B	62,9%	34,2%	1,8%

The results show that the lowest GHG emission savings among the scenarios defined in this section occur when the carbon pricing trends are relatively moderate (A or B for carbon pricing) and GHG intensity reduction and renewable fuel shares both have a low increase. It is evident that selecting more ambitious trends for policy measures (D for carbon pricing and B for GHG intensity reduction and renewable fuel share) leads to high cumulative GHG emission savings but at a high expense.

To determine a scenario in which the combination of policy measures leads to a balanced solution for both economic and environmental objectives, we compare the objective functions of the scenarios with the BOP solution. In this analysis, the closest scenario to the BOP is when the trend of GHG intensity reduction shows a low increase (A) and the renewable fuel share shows a moderate increase (B), while carbon pricing has an increasing trend with a moderate increase (A). In this case, the deviation from BOP for total net present costs and cumulative GHG emission savings are about 19% and 7%, respectively, and the gap to the Pareto-efficient frontier is about 5%. In addition, the results show that changing the trajectory of carbon pricing to a constant trend with a moderate value (B) or an increasing trend with a high increase (C) may not significantly change the solution. Therefore, these combinations show that a balanced solution is possible by integrating policy measures to promote the development of the RFSC. In the scenarios with a moderate increase in trend of GHG intensity reduction (B) and renewable fuel share (B), the gap to the Pareto-efficient frontier is as low as 3%. However, by combining carbon pricing of constant trend with a high value (D), the lowest gap to the Pareto-efficient frontier (2%) is seen in these scenarios, but at a relatively high net present costs compared with the BOP (more than 60% increase in the economic objective).

8.4.3.6 Recommendations on policy measures design

Based on our findings from the Pareto-efficient frontier, factorial analysis, sensitivity analyses of model parameters and policy measures, and the evaluation of optimal combinations of policy measures, we provide the following recommendations for policymakers.

Our results demonstrate that the long-term supply of renewable fuels, considering both economic and environmental aspects, requires a stable and integrated policy plan (Hombach and Walther, 2015). Therefore, policy measures should be designed so that the economic and environmental objectives of the designed supply networks under policy measures are located close to the Pareto-efficient frontier (Esmaeili Aliabadi et al., 2023; Hombach and Walther, 2015).

Integrating policy measures into the mathematical model shows that the supply of renewable fuels is possible by implementing policy measures such as carbon pricing, GHG emission reduction, and renewable fuel shares. The results highlight the importance of early implementation of renewable fuels to achieve higher GHG emission savings. Delaying investments in the RFSC can lead to substantial additional CO₂ emissions. Therefore, policymakers should act promptly to introduce and escalate policy measures in a timely manner, ensuring that renewable fuel supply ramps up sufficiently to meet long-term climate goals (Quarton and Samsatli, 2021). Furthermore, given the flexibility in RFSC design without mandating specific technologies or fuels, policy measures should encourage innovation and allow the market to identify the most cost-effective solutions. This approach avoids potential confusion in supply chain design and leverages multiple technology pathways for production and transmission of renewable fuels (Esmaeili Aliabadi et al., 2023; European Commission, 2021g).

According to the results of the factorial analysis, the studied policy measures have high impacts on total net present costs and cumulative GHG emission savings, with moderate interactions between these policies. Our analysis shows that setting medium levels of GHG intensity reduction goals, combined with medium levels of carbon pricing and renewable fuel share mandates, can lead to moderate GHG emission savings. As noted by the European Commission (2021c), combining policy measures avoids extreme scenarios, such as very high carbon prices without accompanying regulatory measures leading to burdensome energy costs for consumers, or overly stringent, inflexible energy policies (like very high renewable fuel obligations) that may be rejected by Member States due to their high costs for economic operators and consumers. Therefore, policymakers could set long-term planning of targets that balance environmental impact with economic considerations, based on known impacts of policy measures and their interactions on promoting the supply of renewable fuels.

The sensitivity analysis of model parameters reveals that costs associated with production technologies and renewable electricity generation affect both economic and environmental objectives. To facilitate higher cumulative GHG emission savings, policymakers should consider providing economic support or incentives for investments in these areas, such as subsidies, tax credits, or research funding (Hombach et al., 2016). Moreover, technological advancement of production technologies and renewable electricity generation in terms of lower

associated costs, higher efficiency, and earlier availability, which we included in our study, leads to earlier development of the RFSC (Solakivi et al., 2022).

Additionally, the sensitivity analysis of policy measures indicates that combining policy measures leads to greater GHG emission savings than implementing single measures alone. Therefore, policymakers should design comprehensive policy packages to ensure that the policies reinforce each other and drive the desired transition in the RFSC. European Commission (2021c) also proposed policy packages including different combinations of policy measures shows that a possible extension of carbon pricing alone would not lead to promote the development of renewable fuels. Focusing only on one policy measure such as carbon pricing may not promote the development of RFSC (European Commission, 2021a; German Environment Agency, 2023) and in this case high values for carbon pricing are expected (German Environment Agency, 2024).

Our evaluation of optimal combinations of policy measures suggests that balanced economic and environmental objectives can be achieved with medium levels of carbon pricing, GHG intensity reduction and renewable fuel shares. These combinations showed small gaps to the Pareto-efficient frontier, indicating effective performance. Policymakers should consider adopting these moderate trajectories to maximize GHG emission savings while maintaining economic viability.

Moreover, introducing ambitious targets supporting climate neutrality may lead to higher costs for citizens and increase the cost burden for consumers, particularly low-income households and vulnerable consumers (European Commission, 2021c; German Environment Agency, 2024). Additionally, while utilizing renewable fuels in hard-to-decarbonize industry sectors such as steel, ammonia, and methanol production reduces environmental impact, it could increase the costs for these sectors (European Commission, 2021c). Therefore, future research should entail investigating early support mechanisms from these sectors and considering other stakeholders' perspectives, such as those of public authorities, industry, companies, and operators.

8.5 Conclusion

This study provides a framework for integrating policy measures into the design of renewable fuel supply. For the supply of renewable fuels in the transport sector, we designed a renewable fuel supply network over a long-term planning period in a case study for European countries.

The policy measures examined in our study include carbon pricing, GHG intensity reduction, and renewable fuel share. We investigated the trade-offs between net present costs and cumulative GHG emission savings using a bi-objective model. Additionally, we employed factorial and sensitivity analyses to determine the significance, interactions, and impacts of each policy measure on our economic and environmental objective functions. We also evaluated optimal combinations of policy measure trajectories and provided recommendations for policymakers.

According to the Pareto frontier, cumulative GHG emission savings can be achieved with higher net present costs. However, our findings indicate that moderate economic and environmental objectives can be achieved by integrating medium levels of carbon pricing combined with medium levels of GHG intensity reduction and renewable fuel share measures. Our sensitivity analysis reveals that costs associated with production technologies and renewable electricity generation significantly affect both economic and environmental objectives.

Comparing the impact of the different policy measures, carbon pricing is the most significant factor for the total net present costs and the cumulative GHG emission savings. In addition, Carbon pricing accounts for more than 40% of the variability in net present costs and cumulative GHG emission savings. The GHG intensity reduction measure shows a significant interaction with both carbon pricing and renewable fuel share measures. Our evaluation of optimal combinations of policy measures suggests that balanced economic and environmental objectives can be achieved by integrating medium levels of policy measures.

The results of instances integrating policy measures show a marginal gap to the Pareto-efficient frontier, suggesting potential improvements in economic and environmental objectives. Therefore, efficient policy measures should be designed with consideration for their long-term and combined impacts on the development of the RFSC.

Based on our findings, we recommend that policymakers design integrated policy measures, implement early and balanced policy actions, encourage flexibility in RFSC design, provide economic support for production technologies and renewable electricity generation, and consider optimal combinations of policy measure trajectories to effectively achieve significant GHG emission savings without imposing excessive economic burdens.

Future research should consider other aspects of sustainability, such as environmental impacts beyond GHG emissions and social aspects. Furthermore, it is important to consider the

perspectives of various stakeholders, such as public authorities, industry sectors, companies, operators, and consumers, to ensure that policy measures are practical, widely accepted, and effective. As part of the development of a renewable fuel supply chain, bottlenecks, such as the availability of critical raw materials like lithium and cobalt, should also be considered. It is also necessary to address uncertainties related to techno-economic, environmental, and political parameters.

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8.A. Supplementary Information

8.A.1. Model input data

Table 8.A.1. Techno-economic data of production technologies in the case study (FVV, 2021a; Liebich et al., 2021).

Technology	Product	Capacity [tonnes/hour]	f_p [M€]	c_p [M€/year]	t'_p
BtL	FT-fuels	8	529	21	2025
BtL	FT-fuels	44	2223	89	2030
BtL	FT-fuels	80	3365	135	2040*
BtL	FT-fuels	117	3898	156	2050
PtL	FT-fuels	8	396	16	2025
PtL	FT-fuels	44	1302	52	2030
PtL	FT-fuels	80	2190	88	2040*
PtL	FT-fuels	117	2917	117	2050
PtL-DAC	FT-fuels	8	369	15	2025
PtL-DAC	FT-fuels	44	1216	49	2030
PtL-DAC	FT-fuels	80	2044	82	2040*
PtL-DAC	FT-fuels	117	2723	109	2050
PBtL	FT-fuels	11	483	19	2025
PBtL	FT-fuels	44	1559	62	2030
PBtL	FT-fuels	80	2389	96	2040*
PBtL	FT-fuels	117	2817	113	2050
AEL	H ₂	0.03	1.4	0.03	2025
AEL	H ₂	0.03	1.0	0.02	2030
AEL	H ₂	0.03	0.7	0.01	2050
DAC	CO ₂	0.006	0,36	0.0146	2025
DAC	CO ₂	0.006	0,11	0.0043	2030
DAC	CO ₂	0.006	0,06	0.0024	2040*
DAC	CO ₂	0.006	0,01	0,0004	2050
PtG	CH ₄	1	12	290	2025
PtG	CH ₄	6	18	440	2030
PtG	CH ₄	21	47	1178	2040*
PtG	CH ₄	36	53	1313	2050

* Estimated by interpolation.

Table 8.A.2. Costs of transmission technologies of the case study (Cloete et al., 2021; Fasihi et al., 2019; FVV, 2021a; Guidehouse, 2021).

Technology	capacity [tonnes/hour]	f_q [1000 €/km]	c_q [1000 €/km/year]	u_q [€/tonne]
CO ₂ truck	—	—	—	13,0
CO ₂ pipeline	91	592	6	—
H ₂ pipeline	56	762	15	—
CH ₄ pipeline	537	762	15	—

Table 8.A.3. Costs related to renewable electricity modules in the case study (FVV, 2021a).

P	f_e [M€/MW]	c_e [1000€/MW/YR]	t'_e
Wind onshore	1.45	47.8	2025
Wind onshore	1.2	39.6	2030
Wind onshore	1.15	37.9	2040*
Wind onshore	1.1	36.3	2050
Wind offshore	3.3	115.5	2025
Wind offshore	2.6	91.0	2030
Wind offshore	2.38	83.1	2040*
Wind offshore	2.15	75.3	2050
Solar PV	1	15.0	2025
Solar PV	0.68	10.1	2030
Solar PV	0.59	8.8	2040*
Solar PV	0.5	7.5	2050

* Estimated by interpolation.

Table 8.A.4. Biomass price and availability in the case study (Ruiz et al., 2019).

Country	Period	Biomass average price [€]	Biomass availability [M tonnes/year]
Austria	2025	56.48	7.9
Austria	2030	51.47	8.6
Austria	2040	51.73	7.5
Austria	2050	49.89	7.1
Belgium	2025	51.75	4.7
Belgium	2030	49.84	5.6
Belgium	2040	46.72	4.7
Belgium	2050	34.88	3.5
Bulgaria	2025	43.42	10.91
Bulgaria	2030	41.58	10.43
Bulgaria	2040	40.12	10.57
Bulgaria	2050	37.59	11.40
Croatia	2025	40.21	1.66
Croatia	2030	36.80	1.79
Croatia	2040	34.05	1.86
Croatia	2050	31.90	1.95
Czech Republic	2025	47.15	9.64
Czech Republic	2030	41.81	10.90
Czech Republic	2040	41.34	10.52
Czech Republic	2050	40.39	11.06
Denmark	2025	85.18	3.3
Denmark	2030	78.59	3.3
Denmark	2040	75.42	3.2
Denmark	2050	72.57	3.0
Estonia	2025	49.55	1.54
Estonia	2030	47.30	1.58
Estonia	2040	58.11	0.97
Estonia	2050	48.59	0.79
Finland	2025	48.38	9.6
Finland	2030	44.50	10.5
Finland	2040	44.54	11.1
Finland	2050	45.07	11.8
France	2025	57.51	40.3

France	2030	53.48	49.5
France	2040	51.06	49.3
France	2050	48.91	48.9
Germany	2025	63.51	29.1
Germany	2030	59.42	38.6
Germany	2040	58.53	36.3
Germany	2050	56.32	36.9
Greece	2025	94.28	4.63
Greece	2030	99.54	3.93
Greece	2040	94.83	4.19
Greece	2050	92.30	4.48
Hungary	2025	46.15	15.03
Hungary	2030	42.77	15.99
Hungary	2040	40.83	17.06
Hungary	2050	39.84	18.13
Ireland	2025	86.55	2.2
Ireland	2030	81.75	2.3
Ireland	2040	80.77	1.9
Ireland	2050	69.48	1.4
Italy	2025	94.76	26.6
Italy	2030	90.44	26.1
Italy	2040	87.01	25.5
Italy	2050	84.53	24.4
Latvia	2025	37.93	3.71
Latvia	2030	33.31	4.44
Latvia	2040	32.89	4.20
Latvia	2050	30.35	3.77
Lithuania	2025	50.66	5.39
Lithuania	2030	44.12	6.03
Lithuania	2040	49.48	5.19
Lithuania	2050	44.03	4.15
Luxembourg	2025	50.00	0.2
Luxembourg	2030	45.79	0.2
Luxembourg	2040	44.08	0.2
Luxembourg	2050	41.66	0.2
Netherlands	2025	102.4	1.5
Netherlands	2030	93.82	2.8
Netherlands	2040	88.03	2.6
Netherlands	2050	82.39	2.4
Poland	2025	69.70	31.98
Poland	2030	62.95	37.09
Poland	2040	61.32	36.55
Poland	2050	60.51	35.69
Portugal	2025	62.94	4.0
Portugal	2030	54.56	4.7
Portugal	2040	56.26	4.6
Portugal	2050	59.54	4.5
Romania	2025	40.97	43.31
Romania	2030	37.53	47.74
Romania	2040	37.52	46.74
Romania	2050	37.90	45.06
Slovakia	2025	48.05	3.30
Slovakia	2030	40.79	3.89
Slovakia	2040	42.04	3.35

Slovakia	2050	39.16	2.70
Slovenia	2025	37.77	0.65
Slovenia	2030	35.92	1.18
Slovenia	2040	34.06	1.10
Slovenia	2050	31.54	0.98
Spain	2025	98.98	43.9
Spain	2030	87.17	52.2
Spain	2040	84.75	55.6
Spain	2050	83.25	59.1
Sweden	2025	42.70	19.3
Sweden	2030	39.98	20.7
Sweden	2040	37.09	20.7
Sweden	2050	34.47	20.6

Table 8.A.5. Availability of CO₂ from cement industry in the case study (Global Carbon Project, 2022).

I	CO₂ Potential Cement industry [M tonnes/year]
Austria	1,77
Belgium	2,82
Bulgaria	1,13
Croatia	1,18
Czech Republic	1,98
Denmark	1,13
Estonia	0,30
Finland	0,58
France	6,59
Germany	13,29
Greece	3,36
Hungary	1,02
Ireland	1,89
Italy	7,91
Latvia	0,56
Lithuania	0,58
Luxembourg	0,39
Netherlands	0,01
Poland	7,69
Portugal	2,23
Romania	3,83
Slovakia	1,40
Slovenia	0,48
Spain	9,06
Sweden	1,35

Table 8.A.6. Maximum installable capacity for renewable energy in the case study (Ruiz et al., 2019).

Country	Solar PV capacity [GW]	Wind onshore capacity [GW]	Wind offshore capacity [GW]
Austria	147	15	0
Belgium	104	18	2
Bulgaria	299	155	0
Croatia	99	54	5
Czech Republic	223	93	0
Denmark	152	55	27
Estonia	55	27	1
Finland	72	31	21
France	1644	906	16
Germany	988	144	28
Greece	314	264	0
Hungary	321	133	0
Ireland	227	147	1
Italy	886	292	6
Latvia	96	79	15
Lithuania	187	128	3
Luxembourg	6	2	0
Netherlands	135	49	48
Poland	893	105	12
Portugal	184	102	0
Romania	761	387	9
Slovakia	120	45	0
Slovenia	36	7	0
Spain	1317	1098	1
Sweden	141	138	31

Table 8.A.7. Fuel demand in the case study per fuel type and transport subsector (European Commission, 2021i).

Fuel type	Transport subsector	Period	D [M tonnes/year]
Liquid fuel	Rail & Road	2025	270
Liquid fuel	Rail & Road	2030	198
Liquid fuel	Rail & Road	2035	167
Liquid fuel	Rail & Road	2040	137
Liquid fuel	Rail & Road	2045	106
Liquid fuel	Rail & Road	2050	77
H ₂ fuel	Rail & Road	2025	0
H ₂ fuel	Rail & Road	2030	0
H ₂ fuel	Rail & Road	2035	2
H ₂ fuel	Rail & Road	2040	4
H ₂ fuel	Rail & Road	2045	5
H ₂ fuel	Rail & Road	2050	7
Gas fuel	Rail & Road	2025	4
Gas fuel	Rail & Road	2030	6
Gas fuel	Rail & Road	2035	6
Gas fuel	Rail & Road	2040	5
Gas fuel	Rail & Road	2045	5
Gas fuel	Rail & Road	2050	5
Liquid fuel	Aviation	2025	6
Liquid fuel	Aviation	2030	4
Liquid fuel	Aviation	2035	4
Liquid fuel	Aviation	2040	4
Liquid fuel	Aviation	2045	4
Liquid fuel	Aviation	2050	3
Liquid fuel	Maritime	2025	5
Liquid fuel	Maritime	2030	4
Liquid fuel	Maritime	2035	4
Liquid fuel	Maritime	2040	4
Liquid fuel	Maritime	2045	3
Liquid fuel	Maritime	2050	3

Table 8.A.8. Levelized cost of import in the case study (Liebich et al., 2021).

Fuel type	Period	Price of import fuels [€/tonnes]
Liquid fuel	2025	3168
Liquid fuel	2030	3054*
Liquid fuel	2035	2939*
Liquid fuel	2040	2825*
Liquid fuel	2045	2710*
Liquid fuel	2050	2595
Gas fuel	2025	1800
Gas fuel	2030	1730*
Gas fuel	2035	1660*
Gas fuel	2040	1590*
Gas fuel	2045	1520*
Gas fuel	2050	1450
H ₂ fuel	2025	4163
H ₂ fuel	2030	4000*
H ₂ fuel	2035	3837*
H ₂ fuel	2040	3675*
H ₂ fuel	2045	3512*
H ₂ fuel	2050	3349

* Estimated by interpolation.

8.A.2. Economic objective formulation

Here, we describe in detail the total net present costs. For clarity, they are explained by terms defined in Equation (8.A.1). To ensure consistency in comparison with costs over time, a discounting factor, $1/(1 + \tau)^{(t-1)}$, is applied to all costs over the planning horizon.

$$Z_1 = \sum_{t \in T} \frac{1}{(1 + \tau)^{(t-1)}} [I_t^{inv,e} + I_t^{op,e} + I_t^{inv,p} + I_t^{op,p} + I_t^{inv,t} + I_t^{op,t} + I_t^{var,t} + I_t^{var,res} + I_t^{var,f} + I_t^{imp}] \quad (8.A.1)$$

Equations (8.A.2) and (8.A.3) represent the investment and operating costs of facilities for generating electricity from all renewable electricity generation technologies $e \in E$ in period t .

$$I_t^{inv,res} = \sum_{i \in I} \sum_{e \in E} f_e (\sigma_{eit} - \sigma_{ei(t-1)}) \quad \forall t \in T \quad (8.A.2)$$

$$I_t^{op,res} = \sum_{i \in I} \sum_{e \in E} c_e \sigma_{eit} \quad \forall t \in T \quad (8.A.3)$$

Equations (8.A.4) and (8.A.5) represent the investment and operating costs of production facilities in period t .

$$I_t^{inv,prod} = \sum_{i \in I} \sum_{p \in P} f_p (\delta_{pit} - \delta_{pi(t-1)}) \quad \forall t \in T \quad (8.A.4)$$

$$I_t^{op,prod} = \sum_{i \in I} \sum_{p \in P} c_p \delta_{pit} \quad \forall t \in T \quad (8.A.5)$$

Equations (8.A.6)- (8.A.8) denote the investment, operating and variable costs for transmission facilities corresponding to the investment cost for the number of facilities installed in period t .

$$I_t^{inv,tran} = \sum_{i \in I} \sum_{i' \in I | i \neq i'} \sum_{q \in Q_{inv}} f_q l_{ii'} (\kappa_{qii't} - \kappa_{qii'(t-1)}) \quad \forall t \in T \quad (8.A.6)$$

$$I_t^{op,tran} = \sum_{i \in I} \sum_{i' \in I | i \neq i'} \sum_{q \in Q_{inv}} c_q l_{ii'} \kappa_{qii't} \quad \forall t \in T \quad (8.A.7)$$

$$I_t^{var,tran} = \sum_{i \in I} \sum_{i' \in I | i \neq i'} \sum_{m \in M} \sum_{q \in Q} u_q z_{qmii't} \quad \forall t \in T \quad (8.A.8)$$

Moreover, the utilization cost of resource origin is calculated in Equations (8.A.9).

$$I_t^{var,res} = \sum_{o \in O} \sum_{i \in I} v_{oit} \omega_{oit} \quad \forall t \in T \quad (8.A.9)$$

Equations (8.A.10) represent the costs of non-renewable fuel supply in period t .

$$I_t^{var,f} = \sum_{i \in I} \sum_{v \in V} \sum_{f \in F} v_{fit} \left(D_{fvit} - \sum_{r \in R | \eta_{fr}=1 \wedge \zeta_{rv}=1} d_{rvit} \right) \quad \forall t \in T \quad (8.A.10)$$

The import of renewable fuels from outside the system boundary is calculated by Equations (8.A.11).

$$I_t^{imp} = \sum_{r \in R} \sum_{i \in I} v_{rt}^{imp} z_{rit}^{imp} \quad \forall t \in T \quad (8.A.11)$$

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