

Multi-objective supply chain optimization of renewable energy carrier imports for Europe

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HIGHLIGHTS

- We present an optimization approach examining renewable energy import partners.
- The approach considers economic, environmental, and supply security objectives.
- It identifies optimal exporting regions, their supply shares, and infrastructure.
- It considers multiple renewable energy carriers trade over the long-term horizon.
- We demonstrate the approach for the case of renewable energy imports to 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.

1. Introduction

Achieving climate neutrality aligned with the Paris Agreement requires global coordination and ambitious measures that accelerate the transition to clean energy [1,2]. 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 [1]. In particular, RECs (such as hydrogen, ammonia, and methane) are increasingly recognized as a promising pathway toward climate neutrality [3–6] 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 [7,8].

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 [9,10]. Some regions with abundant solar irradiation and wind potential have a distinct advantage for producing RECs, making them potential exporters [11]. As shown in Fig. 1, regions such as South America, the Middle East, and Africa may become major exporters because of their resource potential [12]. Conversely, regions with limited renewable resource availability and REC production potential below domestic demand, such

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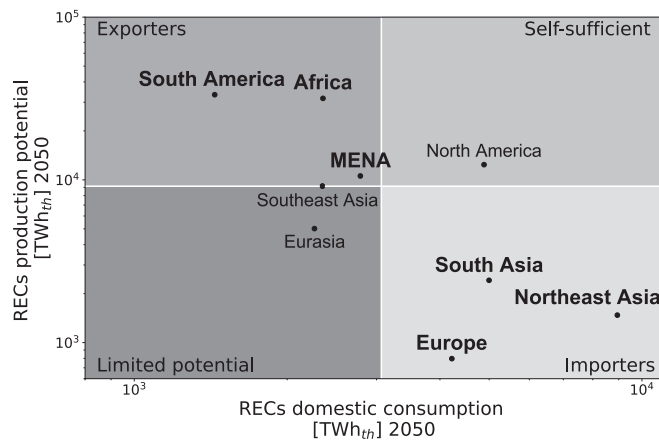


Fig. 1. Comparison of selected regions based on REC consumption and production potential. Own illustration adapted from Galimova et al. [12].

as Europe, will likely import RECs. These emerging international trading relationships necessitate establishing robust supply chains among regions [3]. Moreover, ensuring the long-term sustainability and reliability of REC supply necessitates a multifaceted perspective encompassing economic, environmental, and supply-security aspects [13,14].

From an economic perspective, one of the key factors influencing the widespread adoption of RECs is their affordability [15]. Affordability is typically assessed by lowering the overall system cost of the energy transition [16,17], including the cost of production [18], transportation [19–21], and conversion infrastructure [22]. These costs vary depending on factors such as renewable resource quality, geographic location, and the logistical complexity of transporting RECs to import regions [12]. Although the supply of RECs requires significant upfront capital expenditure [3,23], it is projected to become increasingly cost-competitive compared to fossil-based energy sources [7,24] as a result of technology improvements [25,26], economies of scale [27,28], and supportive policies [29,30].

From an environmental perspective, RECs offer significant advantages in reducing greenhouse gas (GHG) emissions compared to their fossil-based counterparts [12,31]. 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 [32,33]. 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 [34–36].

Beyond economic and environmental considerations, supply security also stands out as a critical factor for future REC development [28,37–39], particularly in light of recent geopolitical issues [40]. Supply concentration (i.e., limited diversification) [13] plays a crucial role in shaping supply security [41–43]. Reducing supply concentration can mitigate adverse effects stemming from disruptions [44] (e.g., extreme weather events, geopolitical conflicts, pandemics, and terrorism) by enabling access to alternative sources of supply [45,46]. Consequently, creating partnerships with low-cost, reliable suppliers [5,28,47] represents an effective strategy for boosting supply security [13].

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 [14], since mitigating GHG emissions [48,49] and avoiding supply disruptions (e.g., the 1970s oil crisis or Germany's reliance on Russian gas) are crucial [3,50–52]. 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.

2. Literature review

Numerous studies have explored how RECs can address global energy needs and support sustainability [3]. Building on the perspectives introduced in Section 1, we review existing methods for evaluating REC trade, categorizing the literature into assessment-based analyses (Sections 2.1–2.3) and prescriptive supply chain design approaches (Section 2.4). Sections 2.1–2.3 cover studies that evaluate REC trade from techno-economic, environmental, and supply-security perspectives, providing insights into each individual aspect. In contrast, Section 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 2.5 synthesizes these gaps and derives the modeling requirements for our study.

2.1. Techno-economic assessment

Techno-economic analyses examine the technical feasibility and economic viability of REC trade [53,54]. Many studies compare renewable resources, production processes, and transport technologies, covering route-level transport costing [20,55], regional supply cost comparisons [33,56,57], and global trade potential assessments [58–60]. For instance, Fasihi et al. [61] evaluated the feasibility and cost-effectiveness of exporting renewable fuels from the Maghreb region to Europe. Villalba-Herreros et al. [62] used a techno-economic model to assess large-scale hydrogen distribution, accounting for production, conversion, transportation, and reconversion steps. Galimova et al. [63,64] compared the costs of importing RECs (e.g., ammonia or hydrogen) with those of local production in the importing region. Abdelshafy et al. [65] investigated strategic cost drivers shaping global hydrogen markets.

Several studies emphasize future scenarios and technology comparisons. Using Monte Carlo simulations, Wolf et al. [66] estimated future leveled hydrogen costs across regions, identifying cost-effective green hydrogen import partners for Germany by 2050. Sterner et al. [67] 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. [68] 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. [69] 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 2.2) and supply security (Section 2.3) dimensions alongside economic factors.

2.2. Environmental assessment

Environmental assessments quantify the impacts of REC trade, most prominently life-cycle GHG emissions across production and transport chains [53]. 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) [32]. Accordingly, many studies quantify the GHG emissions of REC production, transport, and use to estimate overall climate impact [53]. For instance, Liebich et al. [33] analyzed the environmental impacts of imported RECs to Germany, considering differences in regional renewable resources, production pathways, and transportation technologies. Kolb et al. [49] compared the GHG emissions of liquefied hydrogen imports from Chile, Canada, and Morocco to Germany. Kockel et al. [70] 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. [71] 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. [72] 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. [73] 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. [74] analyzed hydrogen import scenarios, considering both techno-economic costs and the associated GHG emissions. Scheffler et al. [48] 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. [75] 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.

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 [42,76,77] and is increasingly emphasized for REC trade [13], especially in light of recent geopolitical energy crises [40]. Supply security is often assessed using concentration indicators such as the Herfindahl–Hirschman Index (HHI) [42,78,79].

HHI-based measures have been applied in energy-security contexts [13] (e.g., liquefied natural gas trade [80]) and in commodity-trade risk contexts [81] (e.g., phosphorus [77] and cobalt [82]). High concentration (low diversification) in supply, indicated by a high HHI, correlates with greater vulnerability to disruptions [13,42,43]. For instance, Vivoda [46] studied market concentration in liquefied natural gas (LNG) imports for major importers such as China, India, Japan, South Korea, and Taiwan. Li et al. [83] assessed trade risks for countries importing copper materials by calculating HHIs of supplier shares. Liu et al. [41] combined network analysis with HHI to study global rare metal trade. Li et al. [77] 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 [76,84], consistent with broader multi-dimensional energy security and dependency index approaches [81,85]. Therefore, several studies apply politically weighted versions of HHI that integrate geopolitical instability [86,87]. For instance, Wei et al. [88] 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. [89] evaluated European energy import diversification by integrating political stability indices into HHI calculations. Kim et al. [90] 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.

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) [53]. However, most studies have focused on a single objective function, typically cost minimization, when designing REC trade supply chains [53]. For instance, Zhuang et al. [91] developed a cost minimization model to evaluate offshore wind-based hydrogen trade among 15 Asia-Pacific countries (a regional network). Egerer et al. [92] developed a comprehensive optimization framework for green ammonia supply chains, integrating hydrogen production, ammonia synthesis, storage, and transport. Wang et al. [93] constructed a MILP model to design a cost-effective global ammonia network for maritime fuel use. Linsel and Bertsch [94] introduced a global hydrogen transport model emphasizing the integration of international hydrogen trade. Wan et al. [95] 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 [96–98]. For instance, Alanazi et al. [97] modeled the long-term evolution of hydrogen trade by introducing country-specific supply and demand curves, maximizing overall social welfare. Karbassi et al. [98] 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 et al. [96] 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. [55] incorporated carbon costs as a policy measure, thus evaluating both economic and environmental factors. Jansen et al. [99] 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 [92,96]. For instance, Egerer et al. [92] studied ammonia trade between Australia and Germany in 2030, and Kim et al. [96] 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 [95,100]. Wan et al. [95] proposed an optimization model of REC trade dynamics from 2024 to 2050 on an annual basis. Amjath et al. [100] 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 [92], or compare alternative hydrogen carrier chains in separate scenarios (e.g., liquefied hydrogen, ammonia, LOHC) [91]. Some models include multiple energy carriers such as hydrogen, methane, and Fischer–Tropsch fuel [95,98], and different forms such as liquid and gaseous hydrogen [100,101], 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 [53]. 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 [92,102]. For instance, Zhuang et al. [91] analyzed offshore-wind-based hydrogen across the Regional Comprehensive Economic Partnership economies. Kim et al. [103] compared international green hydrogen and ammonia supply chains using a high-resolution, multi-timescale optimization framework. Wan et al. [95] considered China's subregional potential for hydrogen trade to investigate the intra-China REC trade patterns and required infrastructure. Gado et al. [104] 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 [93,97]. Runge et al. [105] compared the economics of traded renewable e-fuels produced in low-cost supply regions and delivered to end-use markets, and Makepeace et al. [55] 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 [97,101].

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 [96,101]. For example, Hampp et al. [101] compared multiple REC import chains to Germany based on delivered costs across carriers and exporting regions. Kim et al. [96] 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 [98,100]. For instance, Amjath et al. [100] 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. [98] 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 2.5.

2.5. Research gap

Table 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.

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.

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 [32,106], 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.

Table 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. [91]	min. Costs						Import-oriented
Egerer et al. [92]	min. Costs						Export-oriented
Karbassi et al. [98]	min. Costs			max. Equity	✓		Export-oriented
Hampp et al. [101]	min. Costs				✓		Import-oriented
Kim et al. [96]	min. Costs	min. Emission costs					Import-oriented
Makepeace et al. [55]	min. Costs	min. Emission costs				✓	Export-oriented
Linsel and Bertsch [94]	min. Costs					✓	Import- and export-oriented
Wan et al. [95]	min. Costs				✓	✓	Import-oriented
Amjath et al. [100]	min. Costs					✓	Export-oriented
Jansen et al. [99]	min. Costs	min. Emission costs					Import-oriented
Alanazi et al. [97]	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.

3.1. Supply chain for importing RECs

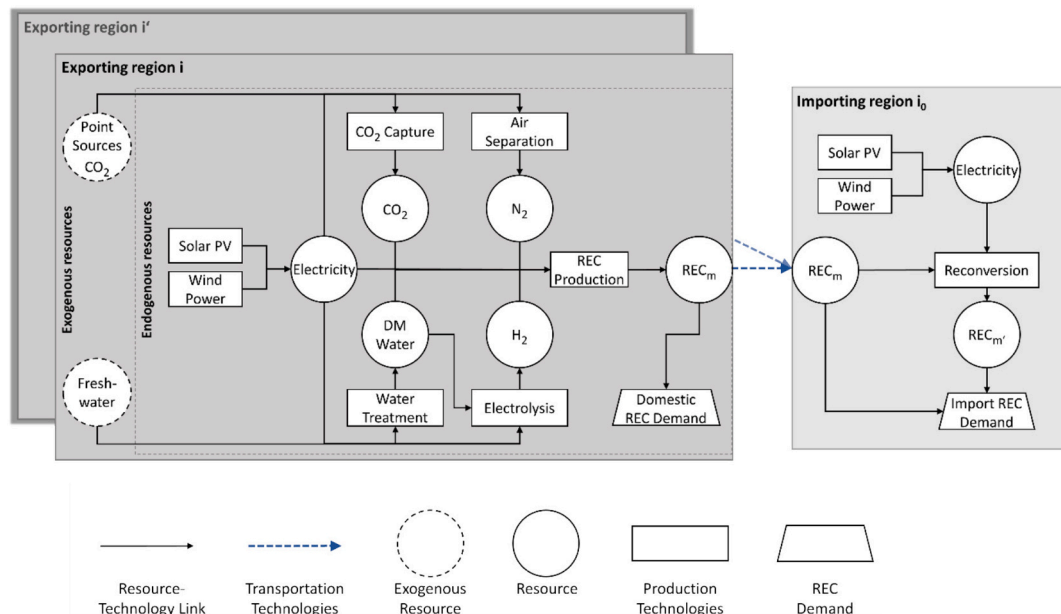
We consider a set of regions ($i \in I_0$), which includes an importing region (i_0) that seeks to meet part of its future energy needs through RECs supplied from various potential exporting regions ($i \in I$). Fig. 2 illustrates a broad supply chain design for all regions ($i \in I_0$), including potential 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 ($m \in M' \subset M$). 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 Fig. 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 Fig. 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 ($m \in M' \subset M$) 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 ($m \in M \setminus M'$) 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 (trape-

**Fig. 2.** Schematic structure of the international REC supply chain.

zoid “Domestic REC Demand” in Fig. 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 Fig. 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 S1).

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.

3.2.1. Total net present cost

As shown in Eq. (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.

Eqs. (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 .

Eqs. (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.

Eqs. (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} .

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

$$C_t^{inv,p} = \sum_{i \in I_0} \sum_{p \in P} f_p (\delta_{pit} - \delta_{pi(t-1)}) \quad \forall t \in T \quad (2)$$

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

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

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

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

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

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

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

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

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

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 [33]. 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 Eq. (12). Eq. (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. Eq. (14) accounts for GHG emissions from transportation technologies (e.g., ships), denoted by G_t^q , which are proportional to the transported REC quantities. Eq. (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).

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

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

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

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

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 [13,44]. The Herfindahl–Hirschman Index (HHI) is a common metric that assesses market or supply concentration (see Eq. (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.

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

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 [85]. Political stability and the absence of violence are closely linked to stable and reliable supply chains [89]. Thus, we adopt a political-risk-weighted HHI (Eq. (17)) by integrating political instability into the concentration index [76,88,89].

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 Eq. (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. [89], the political instability parameter (μ_{it}) is multiplied by a factor of two to maintain nominal comparability between the political-risk-weighted HHI in Eq. (17) and the standard HHI in Eq. (16).

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

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.

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 S.1–S.21).

4. Case study

We apply the model to a European import case study. Section 4.1 describes the dataset and case-study assumptions, and Section 4.2 reports the single-objective benchmarks, the Pareto frontier, and the resulting trade patterns. Section 4.3 examines robustness through sensitivity analyses.

4.1. Case-study data and assumptions

To transition toward defossilization, Europe is expected to face an import dependency of around 50% [107]. We apply the model to a European import case study for RECs over 2030–2055 with annual

resolution.

4.1.1. 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 [5,12,37,60] and consistency with European REC and hydrogen partnership strategies [8,51,108]. 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 C and the Supplementary Information (Section S2).

4.1.2. 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 S.2–S.13).

4.1.3. 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 [101]. In this study, technological progress is represented by exogenous changes in costs and performance [18,101,109]. Particularly, investment costs for renewable electricity technologies follow declining investment and specific annual operating cost trajectories (see Table S2). 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 S7.

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 [12,101], and lies near the middle of the 4–13% WACC range reported in the review by Genge et al. [16]. 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 S10).

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) [110,111] 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.

4.2.1. Solution procedure

The formulation is a mixed-integer quadratic program (MIQP), where quadratic terms arise from the political-risk-weighted HHI objective (Eq. (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 [110,111]. 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 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 , is included to avoid weakly efficient solutions. Each ε -subproblem solves

$$\min(Z_1 - \epsilon(s_2/R_2 + s_3/R_3))$$

subject to

$$Z_2 + s_2 = \varepsilon_2, Z_3 + s_3 = \varepsilon_3, s_2, s_3 \in \mathbb{R}^+ \quad (18)$$

where R_2 and R_3 denote the ranges of Z_2 and Z_3 obtained from the payoff table and $\epsilon = 10^{-3}$ 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 h.

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 S20).

4.2.2. 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 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.

Table 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

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 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 4.3.4 and 4.3.6.

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 [111]. Therefore, for this multi-objective problem, we generate the Pareto-efficient frontier to evaluate the trade-offs among the different objectives. Fig. 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. Fig. 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.

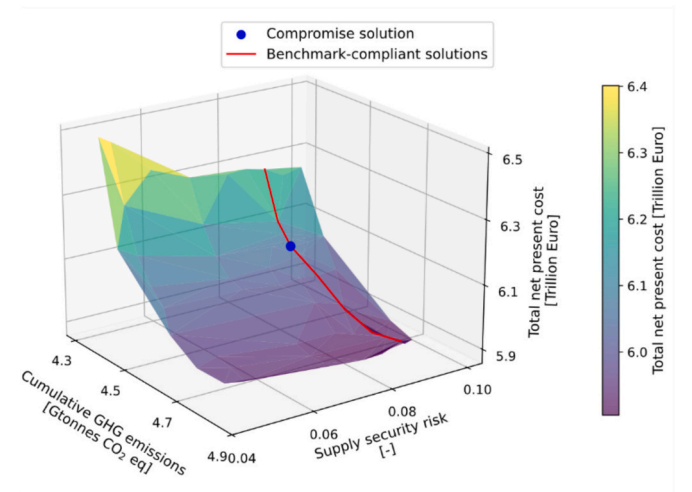


Fig. 3. Pareto frontier of objectives for importing RECs to Europe. The benchmark-compliant solutions (red line) illustrate the trade-offs between economic and environmental objectives when the supply-security risk is 0.09. The compromise solution (blue dot) lies about 5% above the minimal environmental objective. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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 [112] and political instability [113]. 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 Eq. (17). Fig. 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 Fig. 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.

To clarify the cost and environmental details of each solution, Fig. 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. Fig. 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 (Fig. 4). Thus, a balanced approach can achieve environmental and security objectives without sharply increasing costs.

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 Fig. 4: resource utilization (including renewable electricity), production, (re)conversion, and transportation (Supplementary Figs. S.2 and S.3; Table S14). 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 Fig. S.3), consistent with the shift in the PV–wind portfolio shown in Fig. 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 (Fig. 7), rather than being driven by transportation alone (Fig. 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 S15), 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 CO₂eq 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 Fig. 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

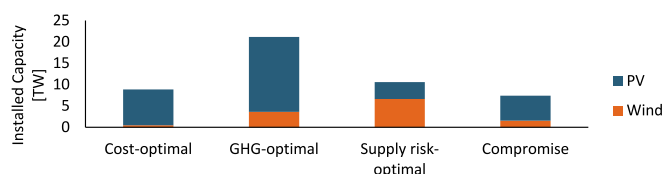


Fig. 5. Installed capacity of PV and wind in exporting regions over the planning horizon in the cost-optimal, GHG-optimal, supply risk-optimal, and compromise solutions.

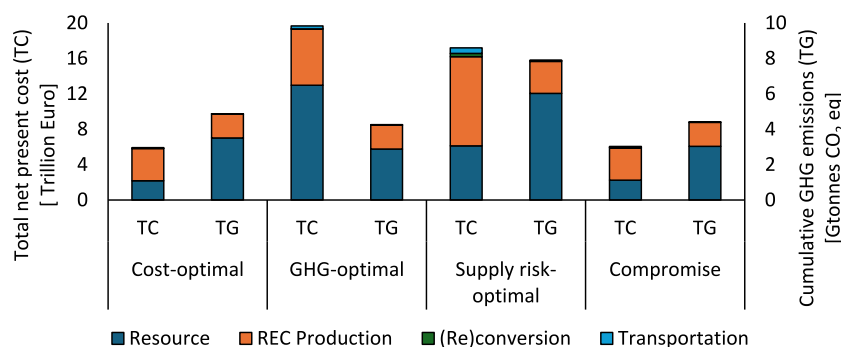


Fig. 4. Total net present cost (TC) and cumulative GHG emissions (TG) structure for REC supply chains in the cost-optimal, GHG-optimal, supply risk-optimal, and compromise solutions.

compromise solution, a balance among objective functions leads to about one-fifth wind capacity, despite its higher cost relative to PV.

Fig. 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 [19,101]. 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.

4.2.3. Contribution of exporting regions

Fig. 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 (Figs. S.4–S.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 Fig. 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.

To analyze how REC imports change over time, Fig. 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.

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.

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

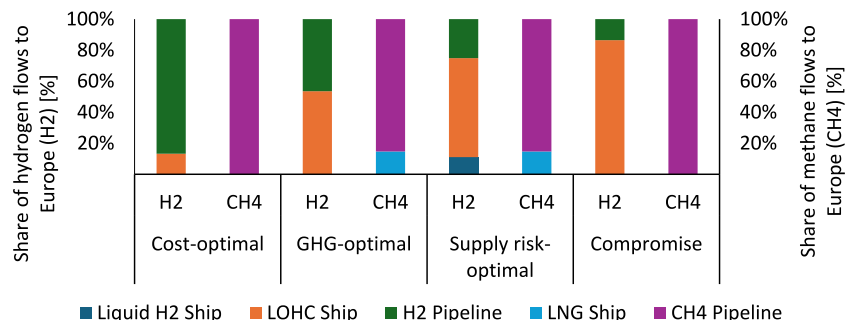


Fig. 6. Transportation structures for hydrogen (H_2) and methane (CH_4) import flows to Europe.

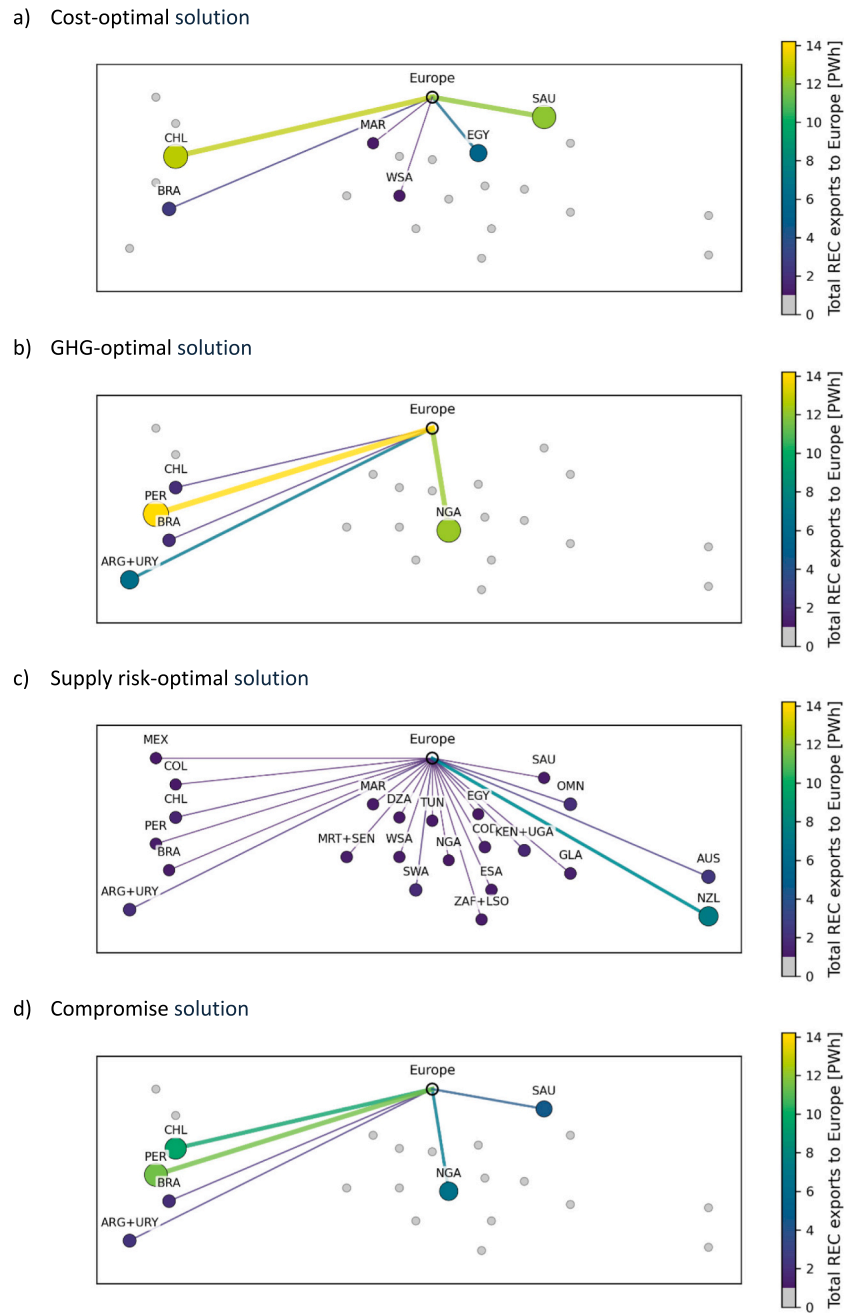


Fig. 7. Trade patterns of REC imports to Europe in the a) cost-optimal, b) GHG-optimal, c) supply risk-optimal, and d) compromise solutions. Each panel shows the main exporting regions and the dominant REC flows to Europe. For readability, WSA, ESA, SWA, and GLA denote the aggregated regions GHA + CIV + BEN + BFA + TGO, MWI + MOZ + ZMB + ZWE, NAM + AGO+BWA, and TZA + RWA + BDI, respectively.

to 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.

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 Figs. S.9 —S.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

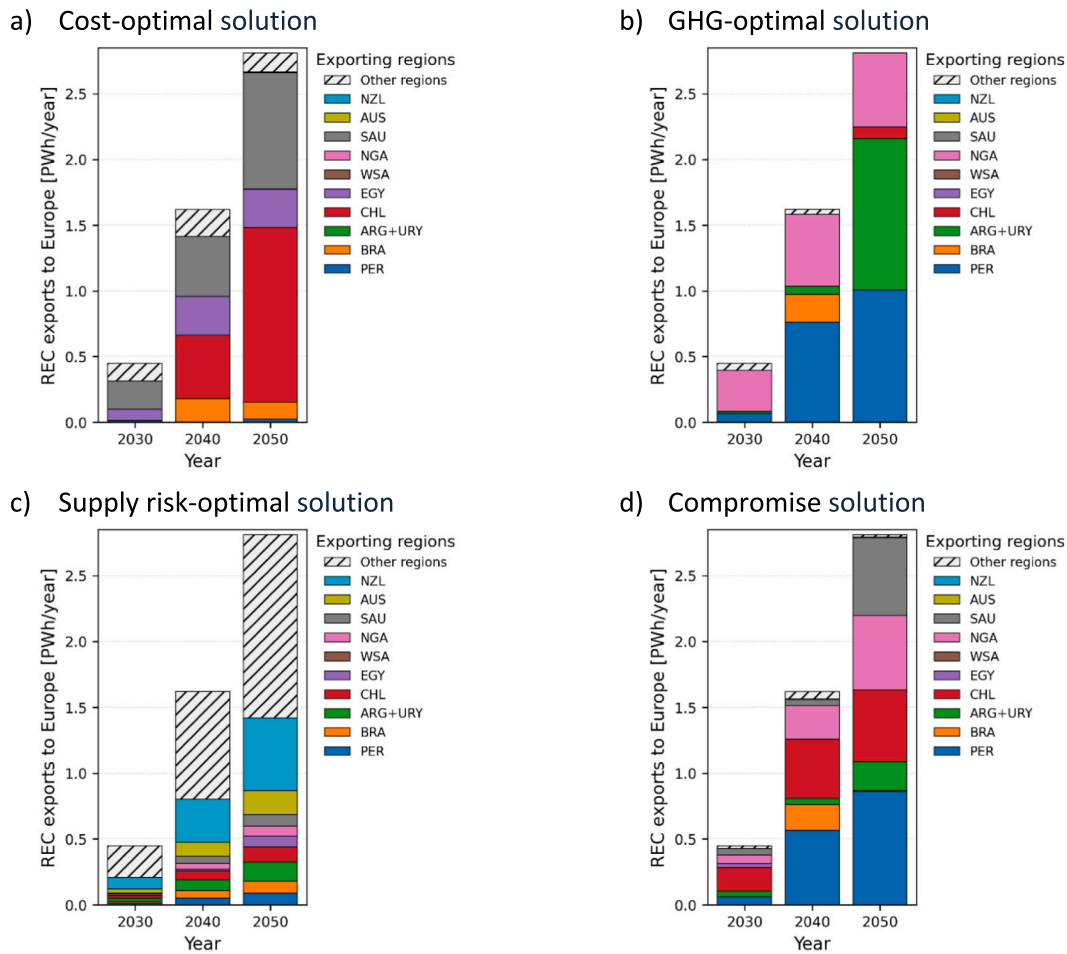


Fig. 8. Import flows of RECs to Europe over the planning horizon (2030, 2040, and 2050) in the a) cost-optimal, b) GHG-optimal, c) supply risk-optimal, and d) compromise solutions, by exporting region. For readability, WSA denotes the aggregated region GHA + CIV + BEN + BFA + TGO.

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.

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. Fig. 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

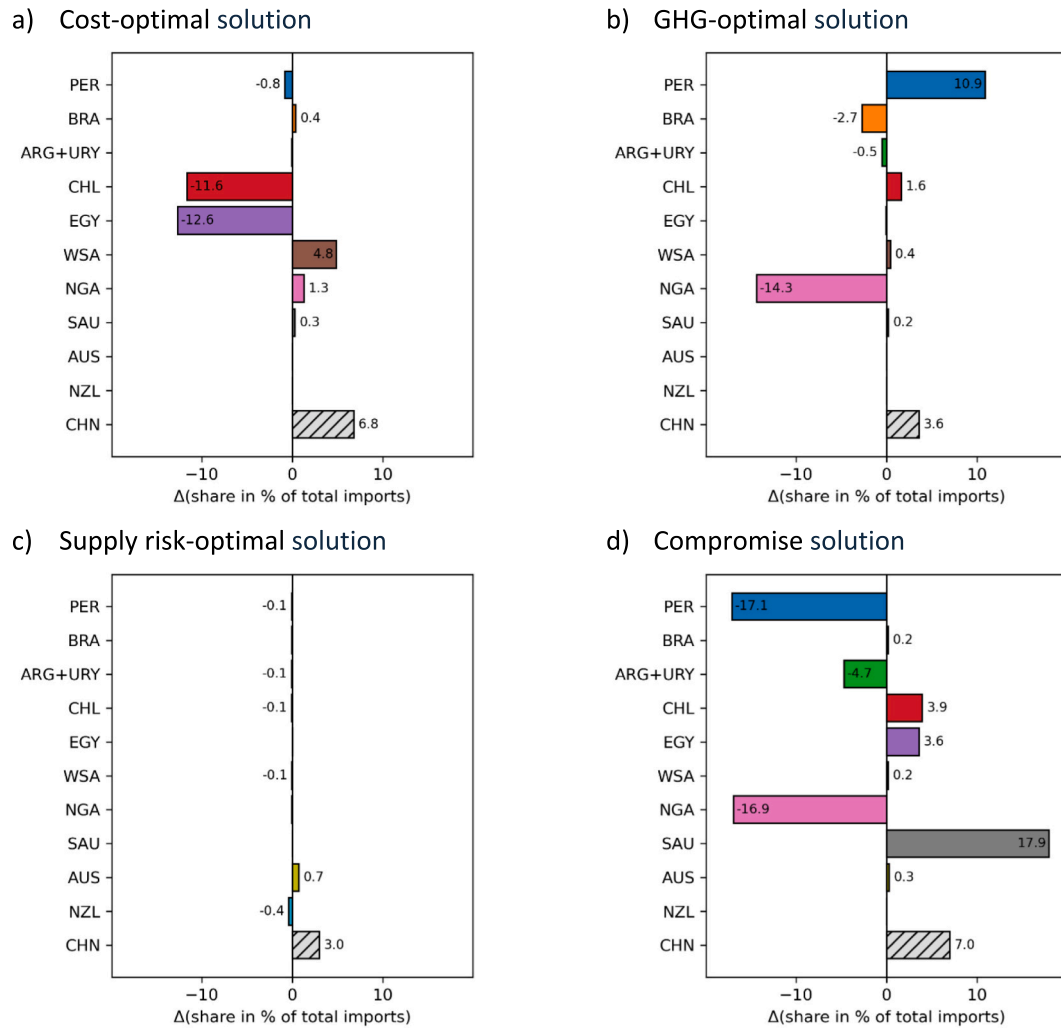


Fig. 9. Change in REC export shares to Europe when China (CHN) is included as a potential exporter in the a) cost-optimal, b) GHG-optimal, c) supply risk-optimal, and d) compromise solutions. Bars show Δ (share in % of Europe's total REC imports) for each exporting region, i.e., the difference between 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 GHG + CIV + BEN + BFA + TGO.

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.

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 S13), which represent different realistic shipping paths and distances [37,114]. 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 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,

Table 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

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.

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 S10). We focus on the supply risk-optimal and compromise solutions, where the political-risk term is most relevant. Fig. 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.

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 S10). Since long-run

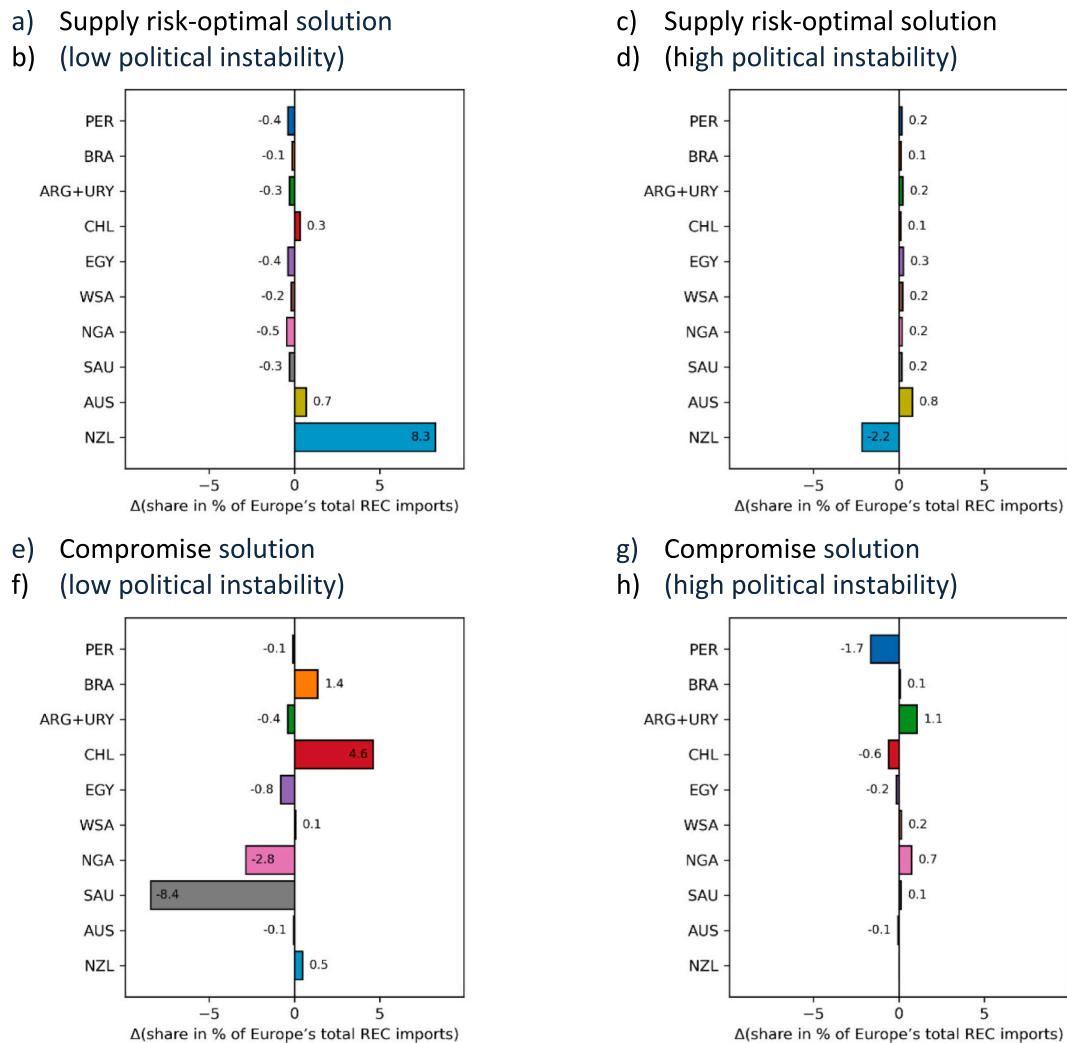


Fig. 10. Change in export shares under alternative political instability scenarios: supply risk-optimal solutions for a) low political instability and b) high political instability cases, and compromise solutions for c) low political instability and d) high political instability cases relative to the 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.

political stability is uncertain, we use bounded time-varying sensitivity trajectories rather than attempting political-risk forecasts [89].

Fig. 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.

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. Fig. 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.

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

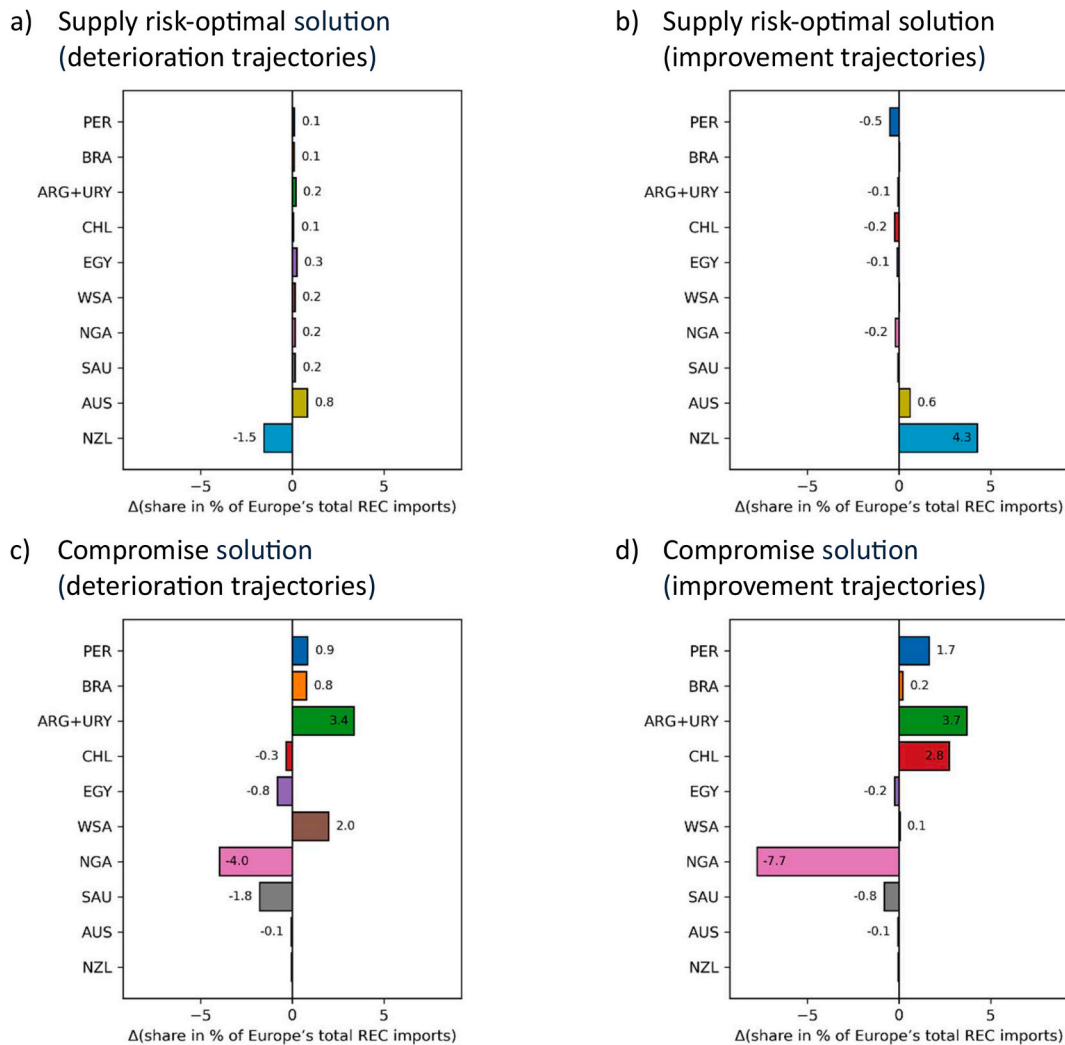


Fig. 11. Change in export shares under time-varying political instability trajectories: supply risk-optimal solutions for (a) deterioration and (b) improvement trajectories, and compromise solutions for (c) deterioration and (d) improvement trajectories relative to the base political-instability case.

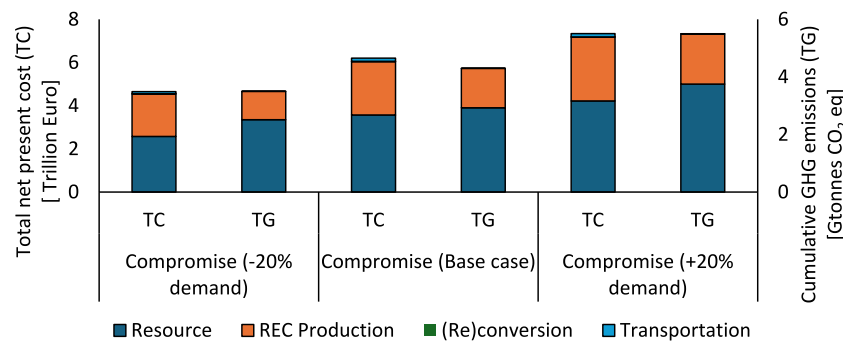


Fig. 12. Total net present cost (TC) and Cumulative GHG emissions (TG) structure for the REC supply chain in low (−20%) and high (+20%) demand scenarios.

covers resource utilization, transportation, production, and renewable electricity costs. Fig. 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% .

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 [5].

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 S7). 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.

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 [5]. 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 [4,38,61,115–117]. 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) [65,116–119], are in line with our results. Similarly, shipping-based imports from Chile, Peru, Brazil, and Argentina also align with earlier findings [4,12,37,58,120–122]. Recent strategies in Chile, Argentina, and Brazil further emphasize the development of REC trade partnerships [123–126].

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

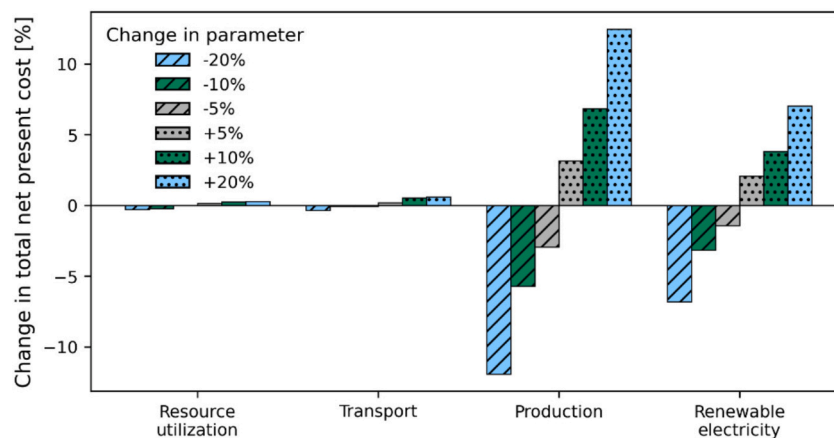


Fig. 13. Sensitivity of total net present costs for the REC supply chain to Europe. Percentage change in total net present costs when varying resource utilization, transportation, production, and renewable electricity costs by -5% , -10% , -20% and $+5\%$, $+10\%$, $+20\%$ relative to the base case.

REC trade partnerships beyond a small set of frequently considered countries, diversifying its future import dependencies [8,115,127]. Our analysis suggests that some regions less frequently mentioned in the literature, such as Peru and Nigeria, could be potential REC partners for Europe [116,122]. By informing policy and investment decisions, our study offers guidance for more comprehensive planning of sustainable REC development across Europe.

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.

Appendix A. Abbreviations

Table A1
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

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.

CRedit authorship contribution statement

Mohammad Zardoshti Zadeh Yazdi: Writing – original draft, Visualization, Software, Methodology, Data curation, Conceptualization. **Jörn-Christian Meyer:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Grit Walther:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix B. List of European countries included in the case study

Table B1

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

Appendix C. List of potential regions for exporting RECs in the case study.

Table C1

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 Figs. 8 and S.1-S.5, 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.

Appendix D. Supplementary Information

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apenergy.2026.127884>.

Data availability

Data will be made available on request.

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