

Techno-economic impacts of shipping liquid hydrogen, ammonia or methanol on exporting nations: The case of Morocco

Eddy Jalbout^{1,3,a*}, Hazem Abdel-Khalek^{1,2,4,b}

¹Fraunhofer Research Institution for Energy Infrastructures and Geothermal Systems IEG, Cottbus, Germany

²Albert-Ludwigs Universität Freiburg, Faculty of Environment and Natural Resources, Freiburg im Breisgau, Germany

³Brandenburg University of Technology, Chair of Integrated Energy Infrastructures, Cottbus, Germany

⁴Open Energy Transition, Königsallee 52, Bayreuth, 95448, Germany

^aeddy.jalbout@ieg.fraunhofer.de, ^bhazem.abdelkhalek@openenergytransition.org

Abstract—As greenhouse gas mitigation efforts under the Paris Agreement increase, current fossil-based commodities are expected to shift toward green energy sources. However, studies on green Power-to-X exports from renewable-rich countries often overlook the techno-economic impacts on domestic energy systems. This study examines the effects of exporting liquid hydrogen, ammonia, or methanol via ship on Morocco’s domestic energy system by 2050, comparing additional system costs, cost components, export marginal prices, and geospatial infrastructure. Ammonia is identified as the most cost-effective option, with lower hydrogen production, synthesis, and transport costs, minimal storage needs, and concentrated infrastructure. Hydrogen exports, while less cost-competitive due to high liquefaction and shipping costs, reduce domestic electricity prices for exports up to 200 TWh. Methanol is the least attractive, burdened by high direct air capture and hydrogen production costs. Overlapping investments in solar photovoltaic and electrolysis present a no-regret option for any PtX export pathway.

Index Terms—Ammonia, Hydrogen, Integrated energy systems modeling, Methanol, PtX export supply chain.

I. INTRODUCTION

The global effort to reduce greenhouse gas emissions (GHG) and combat climate change has led to significant international commitments, with 195 countries having submitted their Nationally Determined Contributions as of February 2025 [1]. Many of these nations are also developing comprehensive energy strategies, including hydrogen-specific plans, to shape their energy futures. The European Union’s (EU) energy import dependency is projected to remain significant by 2050 to meet its consumption needs, highlighting the importance of diversified energy sources and suppliers [2].

In response to this anticipated demand, numerous studies [3]–[8] have analyzed the potential import costs of hydrogen and Power-to-X (PtX) products from various countries, including those neighboring the EU. These studies often focus on the importer’s perspective of assessing the feasibility and economic implications of supplying the EU with alternative energy carriers, contributing to its energy security and sustainability goals. However, limited attention has been given to the impacts on exporting countries and their energy systems.

In [9], the impact on exporting countries is partially addressed. However, the PtX export optimization is conducted using a two-step model by first optimizing hydrogen production domestically, followed by conversion and shipping. This approach overlooks the integrated dynamics of the entire supply chain. Therefore, there is a clear need for a comprehensive sector-coupled model that fully captures the implications of PtX exports for exporting nations, covering the entire supply chain from production to delivery.

Morocco is deemed to be one of the key players in exporting energy to Europe due to its geospatial proximity and abundance of cost-efficient renewable energy sources (RES). The EU has already shown interest by signing the EU-Morocco Green Partnership in 2022 [10]. Additionally, the German-Morocco Hydrogen Agreement signed in 2020 aims at the development of PtX sector [11]. Similarly Portugal signed the Portugal-Morocco Declaration on Cooperation on Hydrogen in 2021 for green hydrogen and ammonia [12]. However, to reduce reliance on hydrogen exports to the EU, Morocco could adopt a strategic approach by exporting PtX products via ship rather than pipelines, as mentioned in their Hydrogen Strategy [13]. This shift could help mitigate energy infrastructure investment risks, enhance export flexibility, and deliver significant domestic benefits, such as fostering cross-sectoral infrastructure development and lowering overall system costs.

Our research aims to address the central research question of what are the techno-economic impacts of shipping PtX export products—liquid hydrogen, ammonia, and methanol—on Morocco’s domestic energy system by 2050. We use a sector-coupled model covering the export supply chains, to analyze key economic factors such as system investments, domestic electricity and marginal PtX export prices, alongside technical aspects like the geospatial expansion of energy infrastructure.

II. METHODOLOGY

In this section, the energy system model, its input data, as well as techno-economic assumptions are described. Moreover, the implementation of the three PtX export supply chains within the model are explained.

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A. Model description

In this study, we utilize the recently published sector-coupled PyPSA-Earth model [14], a cutting-edge global open-source energy system optimization tool that builds upon the electricity model PyPSA-Earth [15]. The sector-coupled model integrates additional key demand sectors and energy carriers with high spatial and temporal resolution, facilitating comprehensive energy transition studies on a global scale. The model is designed to minimize total system costs, including both investment and operational expenses, while ensuring compliance with various boundary conditions and constraints. For more detailed description, formulation and exemplary case studies, refer to [14].

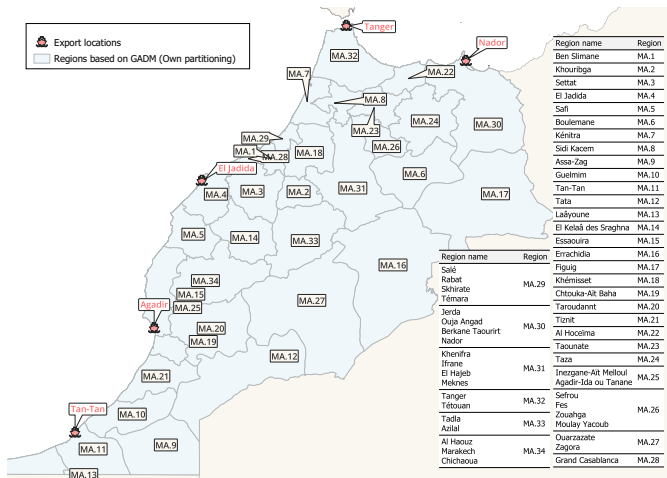


Fig. 1. Considered Morocco's administrative regions and potential export locations via ship

A key contribution of this study is the extension of the model to optimize the fully sector-coupled energy system, incorporating supply chains for exporting liquid hydrogen, ammonia, and methanol via ship to the import country—in this study Germany. Exports can take place through five potential ports along Morocco's coastline, as illustrated in Fig.1. The export supply chains are based on the methodology presented in [16] and have been integrated into our sector-coupled energy system for the year 2050. This model includes 34 nodes, depicted in Fig.1, and operates with a 3-hour temporal resolution throughout the year, capturing both spatial and temporal dynamics such as seasonal and diurnal variations, alongside infrastructural constraints. The export formulation is detailed in Appendix A.

The export supply chains use green hydrogen produced via electrolysis, adhering to the EU's Delegated Regulation 2023/1184 for post-2030 [17], which mandates additionality and hourly temporal matching between renewable electricity generation and the electricity consumed for hydrogen production. Each export supply chain is modeled as a separate scenario, with the optimization performed individually. Hydrogen is chosen as it is considered a fundamental energy carrier in

the future and is already a feedstock for key industrial products such as steel, cast iron, fertilizers, and higher-value chemicals (HVCs). Additionally, green ammonia and methanol, both derived from hydrogen as an intermediate product for further processing or end-use product, play a crucial role in the green value chain by reducing GHG emissions in hard-to-abate industries. While the share of energy in production costs decreases along the value chain, intermediate products offer advantages in long-distance transportability and lower storage costs, making them potentially more cost-effective for export [18]. The analysis in this study does not compare identical end-use products directly. Instead, it evaluates different PtX export volumes based on their energy content in megawatt-hours and associated costs per unit of energy. This approach ensures that all products deliver the same usable energy at the import destination, allowing for a fair comparison. The following outlines the key considerations for each scenario examined in this study.

1) *Liquid hydrogen*: In all scenarios, hydrogen is produced using alkaline electrolyzers (AE). AE offers several advantages, including technological maturity, lower costs compared to proton exchange membrane (PEM) electrolyzers, and the absence of rare-earth metals or platinum in their construction. These factors reduce supply chain risks, making AE a more scalable option for large-scale deployment in the future [16]. The produced hydrogen can either be stored underground for later liquefaction before shipping or directly liquefied for immediate export. Upon arrival in the importing country, the liquid hydrogen is re-gasified. Storage tanks at the import destination act as a buffer, with hydrogen demand assumed to remain constant.

2) *Ammonia*: Ammonia is synthesized through the hydrogenation of nitrogen via the Haber-Bosch process. The required nitrogen gas is sourced from the atmosphere through cryogenic air separation units (ASUs). Ammonia storage is considered in the importing country, while liquefaction and storage locations within the export country are flexible and subject to optimization.

3) *Methanol*: Methanol is produced through the hydrogenation of CO₂ using a direct catalytic methanolization reaction. In Morocco's domestic energy system, both carbon capture in industrial processes and power generation as well as direct air capture (DAC) are considered. However, for methanol synthesis, CO₂ cannot be sourced from fossil origins, especially at the large scale required. This restriction is due to two primary factors: Morocco lacks a gas network, and developing one is not a sustainable option; additionally, the country's low solid biomass potential limits the viability of biomass with carbon capture (CC). As a result, CO₂ for methanol synthesis is exclusively sourced from dedicated DAC to ensure sustainability. The heat required for the DAC process is supplied by medium-temperature industrial heat pumps. Methanol storage buffer is considered in the importing country, while DAC, methanolization and storage locations within the export country are flexible and subject to optimization.

B. Assumptions

In this study, we analyze an ambitious decarbonization pathway for Morocco's future energy system, targeting an 80% reduction in GHG emissions by 2050 compared to 2019. This pathway is based on a range of technical and economic assumptions, with one of the most influencing factors being the weighted average cost of capital (WACC). For Morocco, the WACC is assumed to be 8.6% in 2050, derived from historical values of the equity risk premium and country-specific risk premium. The country risk premium, derived from [19], is calculated based on Morocco's default spread, which is estimated using Moody's local currency sovereign rating. For a detailed calculation, refer to [20].

C. Data input

1) *Renewable energy sources*: RES potentials, CAPEX and generation timeseries are generated using the renewable potential calculator 2.0 of the Enertile model [21]. This tool evaluates the potential of utility-scale PV, CSP, onshore wind, and offshore wind based on ERA5 weather data (2010) [22] with high geographical resolution (6.5×6.5 km² tiles). Feasible areas are determined using GlobCover 2009 [23], while IUCN-protected zones (Ia, Ib, II) are excluded. Further details can be found in [21] and [24].

2) *Water costs*: are a key model input due to potential future scarcity and competing demands. Groundwater stress for the study regions is assessed using World Resource Institute data [25]. Freshwater use for PtX production is restricted in regions where Baseline Water Stress (BWS) exceeds 40%, promoting sustainable water management. In these areas, desalination via reverse osmosis (RO) is used as an alternative. Desalination and transport costs are sourced from [26] and incorporated into the model.

3) *Underground hydrogen storage (UHS)*: is generally more cost-effective than aboveground options like tanks or pipeline systems, but its feasibility depends on a country's geological conditions. Currently, no UHS or CO₂ storage sites are planned in Morocco, although the government is developing a storage strategy following its National Hydrogen Strategy [13]. While some locations have been proposed by stakeholders, Morocco's UHS potential remains largely unexplored. To address this, desk research identified suitable storage structures, such as aquifers and salt caverns, resulting in an estimated storage potential of 23.64 TWh [27].

The above-mentioned input data are custom datasets specifically used for this study, partially replacing the built-in data typically fetched and curated within the PyPSA-Earth workflow. The remaining input data, including existing infrastructure assets, are obtained directly from the model workflow. The electricity network is sourced from OpenStreetMap [28] and curated as detailed in [15]. Existing power plants are retrieved using the Powerplantmatching tool [29], which compiles, merges, and filters data from various open datasets. Additionally, geospatial assets such as industries (steel, cement, refineries, and paper), ports, and airports, essential for demand

distribution across administrative regions, are integrated within the workflow, as presented in [14].

III. RESULTS

The following results highlight key aspects that can help answer our research question of what are the techno-economic impacts of shipping three different PtX products on Morocco's domestic energy system: investment and export costs as well as geospatial infrastructure implications. The results below are obtained by subtracting export scenarios from a reference scenario with no exports, ensuring that domestic energy demand is met first. This method isolates the expansions and costs directly linked to PtX exports.

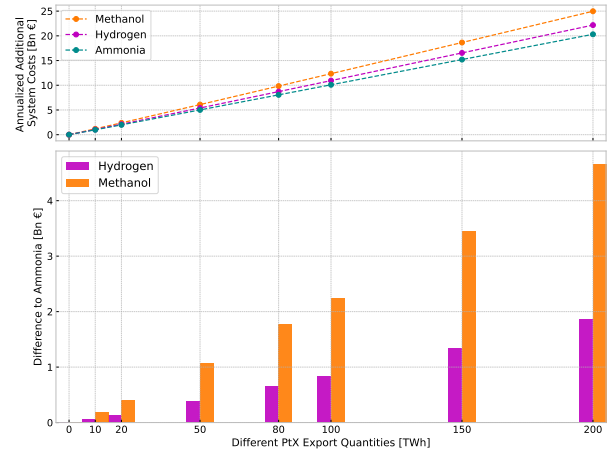


Fig. 2. Annualized additional total system costs and and the cost differences relative to ammonia in [Bn €]

A. Additional Total System Costs

We analyze the additional system costs required to export each PtX product, representing expenses beyond those needed to meet domestic energy demand. Fig. 2 shows the results: the top panel illustrates annualized additional system costs, while the bottom panel compares costs relative to ammonia across different export levels.

System costs increase linearly with higher PtX export volumes, with methanol being the most expensive, followed by hydrogen, and ammonia as the least costly option. The linear trend suggests no critical infrastructural limitations were reached, avoiding sudden cost spikes. As export volumes rise, cost disparities widen. At 200 TWh, methanol incurs over 4.5 billion euros in additional costs, while hydrogen remains under 2 billion euros compared to ammonia.

B. Cost components and PtX marginal export prices

To understand the drivers behind additional total system costs, we analyze the capital and variable cost components specific to PtX exports, normalized per unit of exported quantity for comparability. Fig. 3 presents these cost components alongside marginal PtX export prices and gaseous hydrogen marginal prices for all three export scenarios. It is important to note that the cost components provide only an indication

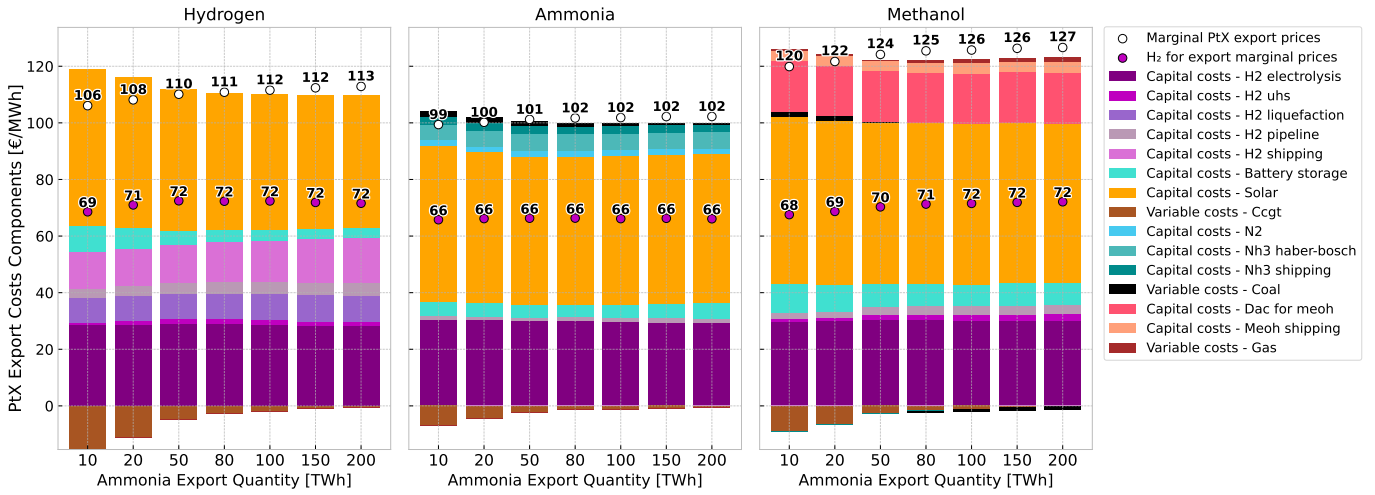


Fig. 3. Normalized PtX export cost components per exported unit, including marginal PtX and hydrogen export prices [€/MWh]

of the factors influencing marginal price formation and do not account for other aspects, such as infrastructural bottlenecks.

The results indicate that methanol and hydrogen exhibit similar hydrogen marginal prices, with slight variations in cost composition that affect these prices. In the hydrogen scenario, pipeline costs account for 4.8% of the total costs, exceeding the 3% share observed in the methanol scenario. Conversely, battery storage and solar PV costs are more significant for methanol, at 8.5% and 57.4%, compared to 5.4% and 52% in the hydrogen scenario, respectively. Ammonia shows the lowest hydrogen marginal prices, remaining stable with increasing export volumes, with minimal hydrogen pipeline costs compared to the other scenarios.

Beyond hydrogen marginal prices, PtX conversion, storage, and shipping further shape overall export prices. Methanol incurs the highest export costs, with 18% attributed to the DAC process for CO₂ feedstock. For liquid hydrogen, liquefaction and shipping contribute 9% and 13% of export costs, respectively. Ammonia remains the most cost-effective option, with synthesis and shipping costs at 5.7% and 2.7%, resulting in export prices between 99 and 102 €/MWh for 10 TWh and 200 TWh, respectively.

We also observe cost savings in the form of negative variable costs for combined cycle gas turbines (CCGT), primarily driven by the energy spillover effect of increased share of renewables in the electricity mix. Among the scenarios, the hydrogen export scenario exhibits the largest cost savings, particularly for smaller export volumes, which is reflected in the decline of market electricity prices shown in Fig. 4.

Although methanol demonstrates greater cost savings than ammonia, its overall performance in domestic electricity prices remains weaker due to the increased variable costs of gas. Gas is used for electricity generation in times of solar deficit to balance methanolization minimum run capacity of 94% at all times. Hence, as shown in Fig. 4, market electricity prices for methanol quickly lose the advantage of additional RES, leading to rising electricity prices beyond the no-export case

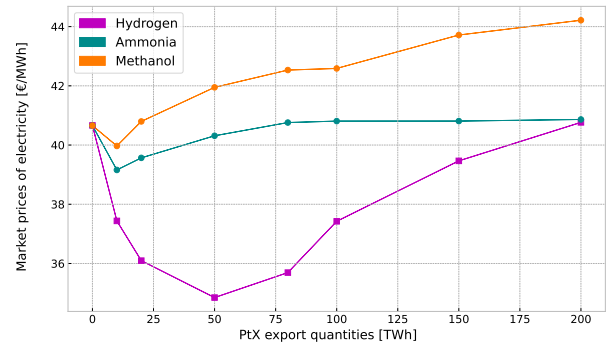


Fig. 4. Domestic market prices of electricity in [€/MWh]

at an export volume of 20 TWh. While the hydrogen scenario initially shows the largest electricity price reductions for small export volumes, prices reach those of the ammonia scenario at 200 TWh. In contrast, the ammonia scenario benefits from the spillover effect up to 50 TWh, after which the system stabilizes, maintaining electricity prices close to the no-export case across all export volumes.

C. Geospatial infrastructure distribution

The geospatial distribution of the above discussed investments and infrastructure expansions plays a crucial role in differentiating between the export scenarios. Understanding these geospatial dynamics is essential for optimizing resource allocation and ensuring the effective deployment of energy infrastructure. For that, key infrastructure expansions are illustrated in Fig. 5, with three maps representing each PtX export scenario for an export volume of 100 TWh.

A key observation is the consistent overlap of most RES expansions and electrolysis across all scenarios in the Tata and Essaouira regions, presenting no-regret investment opportunities regardless of the PtX export product. Additionally, ammonia and methanol synthesis primarily take place in the

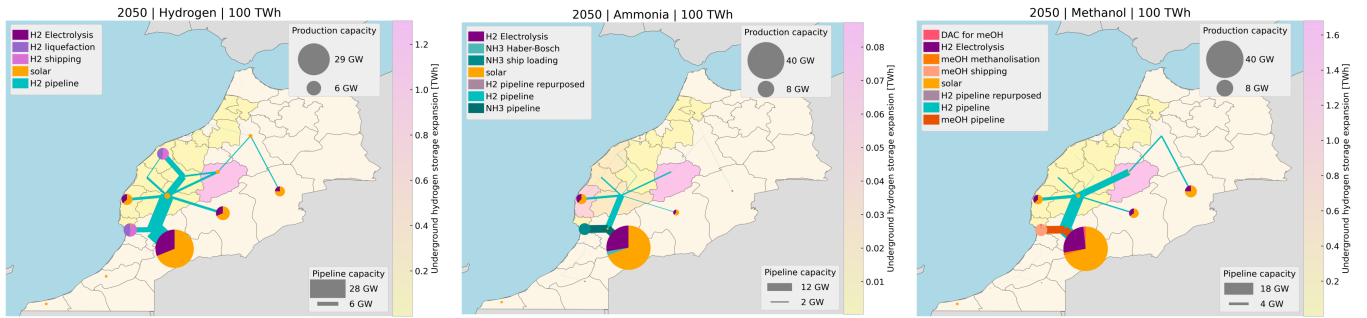


Fig. 5. Geospatial expansion of PtX infrastructure for a 100 TWh export quantity, covering the three export scenarios: liquid hydrogen, ammonia and methanol

Tata region, where most RES expansions occur, with the final products transported via pipeline to Agadir port for export. Whereas in the hydrogen scenario, exports are more distributed, occurring from both Agadir and El-Jadida ports. In the ammonia export scenario, RES and electrolysis capacity expansions are highly concentrated in Tata. In contrast, hydrogen and methanol scenarios feature more distributed expansions, shifting slightly from Tata to regions such as Errachidia, Ouarzazate, and Zagora. In the hydrogen export scenario, gaseous hydrogen is transported via pipelines either to potential UHS sites for later extraction when liquefaction and shipping are required or directly to liquefaction facilities. As for ammonia and methanol scenarios, any hydrogen not immediately required for synthesis is first stored underground and later transported back to the largest production site for synthesis before being further transported for export. The spatial mismatch between optimal RES locations and potential UHS sites drives the need for larger hydrogen pipeline expansion, increasing infrastructure costs.

Nevertheless, the ammonia scenario relies minimally on UHS compared to the hydrogen and methanol scenarios, as shown in Fig. 5. This explains the higher hydrogen pipeline costs previously observed in the other two scenarios. Moreover, the ammonia scenario offers several advantages, including the co-location of RES, electrolysis, and synthesis in a single region, minimal hydrogen storage requirements, low-cost ammonia pipeline transportation, and a centralized export hub at a single port. These factors collectively make the ammonia scenario the most cost-effective PtX export option.

IV. CONCLUSION AND LIMITATIONS

In the results section, we highlighted major techno-economic impacts for three different PtX export options—liquid hydrogen, ammonia, and methanol—for Morocco. Our findings show that in the case of Morocco, overlapping investments in solar PV and electrolysis in Tata and Essaouira regions represent a no-regret option, regardless of the chosen PtX export pathway.

Additionally, ammonia emerges as the most cost-effective option in terms of additional total system costs, marginal export prices and stability in domestic electricity prices, due to its lower hydrogen production, synthesis and transport

costs, minimal underground hydrogen storage requirements, and concentrated infrastructure. In contrast, hydrogen exports require extensive liquefaction, shipping, transportation and storage costs with distributed hydrogen production investments, making them less competitive to ammonia exports. Nevertheless, hydrogen export significantly reduces domestic electricity prices for export volumes of up to 200 TWh inducing benefits in other electricity consuming sectors. Methanol, despite its advantages in transportability, incurs additional costs from DAC for CO₂ sourcing and higher hydrogen storage and production costs, making it the least attractive export option compared to the other two options. These limitations could be mitigated by improving methanolization flexibility in the future—reducing the considered 94% minimum part-load—which would lower hydrogen generation, storage and pipeline costs. Additionally, anticipated reductions in the cost of DAC technologies may further enhance the competitiveness of methanol as an export vector.

These findings offer valuable insights for policymakers and stakeholders to assess the domestic techno-economic impacts of PtX exports, helping to balance economic benefits with infrastructure requirements when selecting the optimal export product. However, this study is limited to the domestic impacts of three PtX export pathways. Future market dynamics, including demand volumes and price fluctuations for hydrogen, methanol, and ammonia, will also play a critical role in determining the preferred export strategy.

Future research should explore several key aspects to refine the techno-economic assessment of PtX exports. This study considers export quantities of up to 200 TWh, but at larger scales, the system may face technical and infrastructural limitations that could influence the preferred export scenario. Additionally, UHS is still at an early research stage, and the estimated storage potential remains highly uncertain. Another avenue for further investigation is hybrid export strategies, where different PtX products are combined in varying shares, potentially revealing synergies or cost efficiencies. Moreover, in countries with an existing gas network or abundant biomass resources, alternative technologies incorporating CC could reduce methanol production costs by leveraging different cost structures.

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APPENDIX

Appendix A

The formulation of PtX exports in this study builds upon the export modeling approach introduced in the PyPSA-Earth model publication [14]. The extended formulation is presented below, representing the export quantity balance at export nodes and the demand balance at import nodes for each time step. Additionally, to account for the time delay between export and import, the relationship between exported and imported quantities is also specified.

The export quantity balance at export nodes at time t is presented in Equation 1 :

$$Q_{p,t}^{exp} = \sum_{n \in N_{exp}} \left(\sum_{k \in K} \dot{C}_{n,p,k,t} + \sum_{k \in K} \dot{E}_{n,p,k,t} + \sum_{l \in L_n} \dot{F}_{l,p,t} \right) \quad (1)$$

Where

- $Q_{p,t}^{exp}$: **Exported quantity** for PtX product p at time t .
- N_{exp} : Set of **export nodes**.
- K : Set of **technologies**.
- L_n : Set of **pipeline** in and out from export node n .
- $\dot{C}_{n,p,k,t}$: **Dispatch of conversion technologies** at export node n for product p using technology k at time t .
- $\dot{E}_{n,p,k,t}$: **Dispatch of storage** using technology k for product p at export node n at time t .
- $\dot{F}_{l,p,t}$: **Pipeline flow** in or out for product p through link l from export node n at time t .

Similarly, the demand quantity balance at import nodes and time t is represented in Equation 2.

$$D_{p,t} = \eta_r \cdot \left[\sum_{n \in N_{exp}} \sum_{m \in N_{imp}} Q_{p,n,m,t}^{imp} + \sum_{m \in N_{imp}} \sum_{k \in K} \left(\dot{E}_{m,p,k,t} \right) \right] \quad (2)$$

Where

- $D_{p,t}$: **Demand** for PtX product p at time t .

- N_{imp} : Set of **import nodes**.
- η_r : **Reconversion efficiency**. Fraction of the imported product reconverted to a usable form at the import node, applicable only to hydrogen, as ammonia and methanol can be directly used (e.g., as fertilizer or fuel).
- $Q_{p,n,m,t}^{imp}$: **Imported quantity** of product p at time t from export node n to import node m .
- $\dot{E}_{m,p,k,t}$: **Dispatch of storage** using technology k for product p at import node m at time t .

The total imported quantity per shipping route $Q_{p,n,m}^{imp}$ between export node n and import node m is defined in Equation 3. This quantity results from multiple shipments, with a time delay relative to the exported quantities, as detailed in Equation 4.

$$Q_{p,n,m}^{imp} = \sum_T Q_{p,n,m,t}^{imp} \quad (3)$$

Where

- T : Set of **time steps** in the simulation.
- $Q_{p,n,m}^{imp}$: **Total imported quantity per shipping route** between export node n and import node m .

Due to time delay between export and import, the shipping time series of $Q_{p,t}^{exp}$ shown in Equation 1 comes with a time offset that accounts for travel time TT, unloading time UT and pause time PT, as described in Equation 4.

$$Q_{p,t}^{exp} = \sum_{n \in N_{exp}} \sum_{m \in N_{imp}} \left(\frac{U(t)_{n,m}}{\sum_T U(t)_{n,m}} \cdot \frac{Q_{p,n,m}^{imp}}{\eta_{p,n,m}^{ship}} \right), \quad \forall t \in T$$

where

$$U(t) = \begin{cases} 1 & \text{if } t \in \text{FT} \\ 0 & \text{if } t \in \text{TT} + \text{UT} + \text{PT} \end{cases} \quad (4)$$

and

$$\eta_{p,n,m}^{ship} = \min\{ship_{BO}, ship_{ED}\}$$

and

$$ship_{BO} = \left(1 - \frac{BO_p}{100} \right)^{TT}$$

$$ship_{ED} = 1 - \frac{2 \cdot distance_{n,m} \cdot ED_p}{capacity_p}$$

Where

- $Q_{p,t}^{exp}$: **Exported quantity** for PtX product p at time t .
- FT: **Fill time**: timesteps where the ship loads the PtX product.
- TT: **Travel time**: timesteps where the ship travels from export node n to import node m .
- UT: **Unloading time**: timesteps where the ship unloads the PtX product.
- PT: **Pause time**: timesteps where the ship is paused or in buffering time.
- $Q_{p,n,m}^{imp}$: **Total imported quantity per shipping route** between export node n and import node m .

- $\eta_{p,n,m}^{ship}$: **Shipping efficiency** for shipping route between export node n and import node m .
- $ship_{BO}$: **Efficiency of shipping due to Boil-off** for product p and TT for shipping route between export node n and import node m .
- $ship_{ED}$: **Efficiency of shipping due to Energy Demand** for product p with a ship capacity $capacity_p$ in in [MWh] and distance traveled $distance_{n,m}$ in [Km] by shipping route between export node n and import node m .
- BO_p : **Boil-off** of product p in [%/h].
- ED_p : **Energy Demand** of shipping product p in [MWh/Km].

Appendix B

The administrative regions considered as nodes in the model are based on GADM Level 1 and 2 classifications, grouped to simplify calculations.

TABLE I
MOROCCO'S CONSIDERED REGIONS AND THEIR CORRESPONDING CODES IN THE STUDY.

Region	Region name
MA.1	Ben Slimane
MA.2	Khouribga
MA.3	Settat
MA.4	El Jadida
MA.5	Safi
MA.6	Boulemane
MA.7	Kénitra
MA.8	Sidi Kacem
MA.9	Assa-Zag
MA.10	Guelmim
MA.11	Tan-Tan
MA.12	Tata
MA.13	Laâyoune
MA.14	El Kelaâ des Sraghna
MA.15	Essaouira
MA.16	Errachidia
MA.17	Figuig
MA.18	Khémisset
MA.19	Chtouka-Aït Baha
MA.20	Taroudannt
MA.21	Tiznit
MA.22	Al Hoceïma
MA.23	Taounate
MA.24	Taza
MA.25	Inezgane-Aït Melloul, Agadir-Ida ou Tanane
MA.26	Sefrou, Fes, Zouahga, Moulay Yacoub
MA.27	Ouarzazate, Zagora
MA.28	Grand Casablanca
MA.29	Salé, Rabat, Skhirate, Témara
MA.30	Jerda, Ouja Angad, Berkane Taourirt, Nador
MA.31	Khenifra, Ifrane, El Hajeb, Meknes
MA.32	Tanger, Tétouan
MA.33	Tadla, Azilal
MA.34	Al Haouz, Marakech, Chichaoua

Appendix c

Relevant techno-economic assumptions used for the study that affect the cost components development seen in Fig. 3 are listed below. The remaining parameters assumptions are based on the data taken from github.com/pypsa/technologydata version 0.11.0 for the year 2050. For shipping distance calculations, the workflow employs the Searoute-py Python package, which computes the shortest maritime route between two geographic locations [30].

TABLE II
TECHNOLOGY PARAMETERS

Technology	Parameter	Value	Unit
CCGT	FOM	3.25	%/year
	VOM	4.2329	EUR/MWh
	c_b	2.2	50°C/100°C
	c_v	0.15	50°C/100°C
	efficiency	0.6	per unit
	investment	846.5773	EUR/kW
	lifetime	25	years
OCGT	FOM	1.8023	%/year
	VOM	4.762	EUR/MWh
	efficiency	0.43	per unit
	investment	435.818	EUR/kW
	lifetime	25	years
Electrolysis	FOM	4	%/year
	efficiency	0.6994	per unit
	efficiency-heat	0.1294	per unit
	investment	410	EUR/kW_e
	minimum part-load	20	%
	lifetime	25	years
H2 (g) pipeline	FOM	1.5	%/year
	electricity-input	0.017	MW _e /1000km/MW _{H2}
	investment	303.6845	EUR/MW/km
	lifetime	50	years
H2 (l) transport ship	FOM	4	%/year
	capacity	11000	t _{H2}
	investment	393737000	EUR
	lifetime	20	years
	(un-) loading losses	2	%/transfer
	(un-) loading time	48	h
	average speed	30	km/h
	boil-off	0.01	%/h
	energy demand	0.41	MWh/km

Technology	Parameter	Value	Unit
H2 evaporation	FOM	2.5	%/year
	investment	57.8463	EUR/kW _{H2}
	lifetime	20	years
H2 liquefaction	FOM	2.5	%/year
	electricity-input	0.203	MWh _{el} /MWh _{H2}
	hydrogen-input	1.017	MWh _{H2} /MWh _{H2}
	investment	533.9655	EUR/kW _{H2}
	lifetime	20	years
Air separation unit	FOM	3	%/year
	electricity-input	0.25	MWh _{el} /t _{N2}
	investment	514601.13	EUR/t _{N2} /h
	lifetime	30	years
Haber-Bosch	FOM	3	%/year
	VOM	0.0225	EUR/MWh _{NH3}
	electricity-input	0.2473	MWh _{el} /MWh _{NH3}
	hydrogen-input	1.1484	MWh _{H2} /MWh _{NH3}
	nitrogen-input	0.160	t _{N2} /MWh _{NH3}
	investment	915.4941	EUR/kW _{NH3}
	minimum part-load	30	%
	lifetime	30	years
MeOH transport ship	FOM	5	%/year
	capacity	75000	t _{MeOH}
	investment	35000000	EUR
	lifetime	15	years
	(un-) loading losses	0	%/transfer
	(un-) loading time	48	h
	average speed	27.8	km/h
	boil-off	0	%/h
	energy demand	0.24	MWh/km
NH3 (l) transport ship	FOM	4	%/year
	capacity	53000	t _{NH3}
	investment	81164200	EUR
	lifetime	20	years
	(un-) loading losses	0	%/transfer
	(un-) loading time	48	h
	average speed	37	km/h
	boil-off	0	%/h
	energy demand	0.48	MWh/km
NH3 (l) storage tank incl. liquefaction	FOM	2	%/year
	investment	166.8201	EUR/MWh _{NH3}
	lifetime	20	years

Technology	Parameter	Value	Unit
NH3 (l) pipeline MeOH pipeline	FOM	1	%/year
	investment	212.67	EUR/MW/km
	lifetime	50	years
	efficiency	0.983	% per 1000Km
Battery Inverter	FOM	0.9	%/year
	efficiency	0.96	per unit
	investment	63.4933	EUR/kW
	lifetime	10	years
Battery Storage	investment	79.3666	EUR/kWh
	lifetime	30	years
Methanolisation	FOM	3	%/year
	capture rate	0.9	per unit
	carbondioxide-input	0.248	t _{CO2} /MWh _{MeOH}
	electricity-input	0.271	MWh _e /MWh _{MeOH}
	heat-output	0.1	MWh _{th} /MWh _{MeOH}
	hydrogen-input	1.138	MWh _{H2} /MWh _{MeOH}
	investment	519738.882	EUR/MW _{MeOH}
	minimum part-load	94	%
	lifetime	20	years
Solar	FOM	6.59	EUR/KW _{el} /year
	investment	329	EUR/kW _e
	lifetime	20	years
Coal	CO2 intensity	0.34	t _{CO2} /MWh _{th}
	FOM	1.31	%/year
	VOM	3.26	EUR/MWh _e
	efficiency	0.33	p.u.
	fuel	9.55	EUR/MWh _{th}
	investment	3827.16	EUR/kW _e
	lifetime	40	years
Hydrogen storage underground	FOM	0	%/year
	VOM	0	EUR/MWh
	investment	1.27	EUR/kWh
	lifetime	100	years
Direct Air Capture	FOM	4.95	%/year
	compression-electricity-input	0.15	MWh/t _{CO2}
	compression-heat-output	0.2	MWh/t _{CO2}
	electricity-input	0.4	MWh _{el} /t _{CO2}
	heat-input	1.6	MWh _{th} /t _{CO2}
	heat-output	0.75	MWh/t _{CO2}
	investment	4000000	EUR/(t _{CO2} /h)
	lifetime	20	years