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Opportunities of hydrogen and ammonia trade between Europe and MENA

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ABSTRACT

This paper examines the potential role of hydrogen and ammonia in the European energy transition to reach net-zero greenhouse gas targets. We analyse trade of green hydrogen and ammonia between Europe and the Middle East and North Africa (MENA), since the latter possesses a high potential for solar power, making it a possible low-cost supplier of these two clean energy carriers. The economic attractiveness of such trade depends on the additional infrastructure and transportation costs required for the roll-out of these clean energy carriers. Using a global integrated assessment model, TIAM-ECN, we evaluate the trade-off between costs and benefits of establishing import-export links between Europe and MENA for hydrogen and ammonia. Our study assumes the availability of hydrogen pipelines from North Africa to Europe, and of liquefied hydrogen and ammonia shipping from the Middle East to Europe. We find that MENA could realize cost savings of over 6% by 2050 through hydrogen and ammonia trade. Furthermore, despite the availability of gaseous green hydrogen from North Africa (via pipelines), for Europe the import of liquefied green hydrogen and ammonia from MENA (through shipping) can also be economically viable. Although this trade could generate cost savings of 40 billion dollars per year by 2050, we conclude that for Europe import diversity, rather than cost savings, could become the main factor driving hydrogen and ammonia imports.

1. Introduction

In the aftermath of Russia's invasion of Ukraine, and the ensuing decrease in imports of Russian natural gas to Europe, the EU has devised a comprehensive long-term strategy to promote energy diversification and accelerate the development of renewable energy within its borders [1]. This strategy requires careful consideration of potential future dependencies on energy sources, including traditional fossil fuels that are being phased out and emerging renewable energy technologies. As Europe strives to transform and diversify its energy system, renewable energy imports are expected to play a vital role in achieving the goals of the European energy transition [2,3].

Among the main energy carriers that can be produced under net-zero emissions, and supplied either locally or via imports, are hydrogen (H_2) and ammonia (NH_3). Hydrogen can be deployed as a fuel for a large array of applications in all economic sectors, i.e. transport, buildings, industry and agriculture, while its projected cost decrease over time further bolsters its potential for widespread utilization [4]. Indeed, many recent studies support the notion of hydrogen as a primary fuel for the future, thanks to advancements in electrolysis technology, the potential for global hydrogen trade, and the diversity of chemical compounds (including ammonia) that can carry hydrogen atoms [5,6].

Green hydrogen is considered a key element in Europe's efforts to reach its climate neutral target by 2050 [7]. Green hydrogen, produced by electrolysis with renewable electricity, involves splitting water into hydrogen and oxygen and is referred to as 'renewable fuels of non-biological origin'. This versatile and carbon-free source of energy can be used to decarbonize various sectors such as industry, transport, and heating, where other alternatives might be unfeasible or more expensive. Investing in green hydrogen infrastructure and technology can help Europe accelerate its transition to a more sustainable and low-carbon economy, ultimately contributing to the continent's efforts to combat climate change and achieve its climate neutral target by 2050 [8]. However, meeting the desired volume of renewable hydrogen domestically would seem ambitious considering the availability of wind and solar energy, and electrolizer costs, potential, and installation rate. Therefore, the EU is also considering the option of importing hydrogen from elsewhere. To achieve its goals, the EU aims to import 10 million tons of H_2, in addition to producing 10 million tons within the EU itself [7].

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One potential source of low-cost renewable hydrogen and ammonia is the North Africa and Middle East region (MENA), given its abundant solar energy potential and proximity to the EU ([7,9–11]; ENTSOG, 2023). The feasibility of green hydrogen and ammonia trade between MENA and Europe has become a focal point of the current strategic and political energy discourse in the EU, as attested by the increasing number of dedicated studies on this topic (see e.g. Ref. [12–18]). However, production of green hydrogen in MENA can be hampered by a lack of water resources [19,20].

Concurrently, from the perspective of the MENA countries, several potential advantages can be envisioned of developing an extensive green hydrogen and ammonia infrastructure [21]. For North Africa, this could represent part of the extensive energy system transformation that is expected to take place in the coming decades throughout the African continent [22]. Such a transformation entails raising the levels of energy access for a substantial share of the population, in line with the Sustainable Development Goals [23], possibly leapfrogging a phase of fossil-fuel dependance to directly realize a modern low-carbon society [24]. Moreover, the economic gains for North Africa can reduce inter-regional migration due to economic incentives [25]. In this context, possible future gains from hydrogen exports to Europe may further contribute to increasing prosperity in the North Africa region.

Similarly, the Middle East can in multiple ways take advantage of its abundant solar and wind resources, which can be harnessed to generate clean and sustainable electricity. This clean electricity can then (partly) be used to produce hydrogen and other synthetic fuels such as ammonia [26] to be employed in the short term as a clean fuel for navigation, and in the future as generic and versatile hydrogen carriers. The region has significant experience and infrastructure in the gas industry, making it well-suited for hydrogen and synthetic fuel production. Countries like Saudi Arabia, Qatar, and the United Arab Emirates have already expressed interest in developing hydrogen export capabilities [27]. By shifting towards renewable energy sources, the Middle East can reduce its dependence on fossil fuels and mitigate the environmental impact of its energy sector. This transition can also create new economic opportunities for the region [28]. The development of renewable energy projects can drive job creation and stimulate local economies [29]. In addition, investing in renewable energy technologies can position the Middle East as a leader in the global energy transition, attracting foreign investment and promoting sustainable development. Furthermore, the Middle East can leverage its energy transition efforts to address other pressing issues in the region. For example, renewable energy can be utilized to power desalination plants, addressing water scarcity and ensuring access to clean drinking water [30,31]. These integrated approaches can contribute to overall sustainable development and enhance the region's resilience to climate change, economic growth, and energy security [32,33].

In the present paper, we contribute to the expanding literature exploring the implications of hydrogen and ammonia trade between Europe and MENA. We do so by further building on our framework for analyzing a hydrogen-based partnership between Europe and North Africa [34,35]. This framework entails the use of an Integrated Assessment Model (IAM) to study, from the perspective of system-cost optimization, the trade-offs of Europe and North Africa collaborating vs 'going solo' in their respective energy transition pathways. Our previous results indicate that Europe may still need to bear a net price to leverage the advantages of establishing large-scale trade routes for electricity and hydrogen with NA, despite the reduction in the domestic investments required for meeting the objectives of the EU's Green Deal that such a collaboration would entail. This conclusion is, however, dependent on the extent to which renewable hydrogen can be domestically produced in Europe, and may be reversed if the potential for local hydrogen production in the EU turns out to be limited, for example as a result of land availability restrictions. In this study we add to this framework along two main axes: (i) we extend our analysis to also cover the possibility of trading liquid hydrogen (as opposed to only pipeline-transported gaseous hydrogen in our previous work), as well as ammonia, and (ii) we consider a wider region – i.e. MENA – as a possible partner for exchanging these energy carriers with Europe.

Liquified hydrogen and ammonia present several potential advantages in comparison with gaseous hydrogen. First, these carriers can be transported through shipping, which opens the possibility to trade over long distances, thereby connecting regions with abundant renewable energy sources to faraway regions with high demand for hydrogen and ammonia. This can help promote the uptake of renewable energy by allowing surplus energy to be transported and utilized elsewhere. Second, shipping is a cost-effective mode of transportation compared to other alternatives, such as pipeline infrastructure, especially for transporting large volumes of liquified hydrogen and ammonia [36]. The existing infrastructure for shipping can be adapted to accommodate these renewable substances, thereby reducing the need for additional investment in new transportation infrastructure [37].

In light of its abundant solar and wind energy resources, the MENA region is in an optimal position to harness renewable electricity, hydrogen and ammonia through advanced technical methods. However, the feasibility of large-scale trade of these carriers between MENA and Europe remains uncertain from an economic standpoint, as accurately estimating the associated costs and benefits is a complex task. The implications of such a collaboration in terms of technological diffusion and sector-specific impacts, remain largely unexplored by the energy community. Furthermore, the broader implications pertaining to geopolitical, institutional, social, and strategic considerations within this partnership also require thorough examination. With the present paper we aim at tackling some of these knowledge gaps through IAM analysis, by inspecting the sector-specific cost-optimal energy mix in Europe and MENA with and without hydrogen and ammonia trade, under ambitious low-carbon energy scenarios.

Section 2 of this paper describes our research approach in terms of (i) the IAM that we use to investigate the subject of renewable energy trade between Europe and MENA, and (ii) the scenarios that we developed to undertake this analysis. In section 3 we report our results regarding the cost implications of our scenarios for Europe, Middle East, and North Africa until 2050, as well as the electricity, hydrogen, and ammonia demand and supply impacts of these variations. In section 5 we discuss our findings and their limitations, draw some overall conclusions and policy messages, and formulate recommendations for future work.

2. Energy system modeling

An IAM is utilized to assess the costs and technological options associated with various levels of production of electricity, hydrogen, and ammonia in the MENA region, and their transport to Europe through pipelines or shipping. IAMs are instrumental in identifying the most cost-effective energy systems across different global regions. These models facilitate the determination of the cost-optimal balance between domestic production of (potentially expensive or limited) renewable energy sources like electricity, hydrogen, and ammonia, and the importation of cheaper energy commodities from other regions considered in the model. The importance of IAMs is underscored in research by the IPCC [6,38], highlighting their significance in understanding the measures necessary to meet the Paris Agreement's goals [39]. Furthermore, IAMs are crucial in supporting policy development, especially noted by the EC [40], demonstrating their value in exploring strategies to achieve a sustainable energy future.

2.1. TIAM-ECN

We conducted the present study utilizing TIAM-ECN, rooted in the TIMES framework and part of the broader IAMs global network. TIAM-ECN is designed to simulate the global energy economy's evolution over a century, leveraging a linear optimization model, TIAM, as its foundation. The model's geography is divided into 36 distinct regions, creating a segmented global view. The essential mechanics and equations that govern the model's objective function are detailed in the works of Loulou [41] and Loulou and Labriet [42]. At its core, TIAM-ECN's objective function aims to minimize the total discounted aggregated costs of the energy system across these regions throughout the model's extensive time horizon. Through this, the model intricately simulates how global energy economy dynamics unfold, offering insights into cost-minimal energy transition pathways that not only adhere to the Paris Agreement's objectives but also consider the constraints posed by resource potentials and rates of technology diffusion. This objective function incorporates various cost components, such as investment costs, fuel costs, and fixed plus variable operation and maintenance (O&M) costs [24]. Additionally, the TIAM-ECN database encompasses a wide range of technologies across numerous sectors such as industrial, transportation, power generation, commercial, and residential areas. Moreover, TIAM-ECN is equipped to endogenously calculate the prices of energy commodities, referring to the dual variable values of the energy demand and supply constraints. We cannot elaborate further on the remaining key aspects of TIAM-ECN in this context; for a comprehensive description, we direct you to earlier studies (e.g. Ref. [24,43–46]).

In this study, TIAM-ECN depicts North Africa as a collective region of the five Maghreb nations and the Middle East as a unified area comprising all countries in the Middle East. Europe is represented as including both Western and Eastern Europe, with a selection of countries whose energy portfolios mirror those of the EU-28 member states. Regarding the production of renewable electricity and hydrogen, the Middle East and North Africa (MENA) region is expected to predominantly utilize solar PV and solar thermal energy. Wind power is also modeled, notably with Morocco possessing significant wind energy capacity. Conversely, biomass is not seen as a feasible option in the MENA region due to its inability to outcompete the affordability of solar energy and due to the scarcity of water and nutrients for biomass production. The analysis includes an assumption about average availability factors (AF) for PV-electrolysis, estimated at 0.30 for Europe and 0.52 for the MENA region on a typical summer day [34]. This difference significantly influences the levelized cost of electricity and, consequently, the production costs of green hydrogen.

Electrolyzers powered by renewable energy sources produce green hydrogen, which must then be liquefied at liquefaction facilities before it can be shipped between regions. Using the Haber-Bosch process, ammonia is synthesized from green hydrogen and renewable electricity. Ammonia can be utilized directly as maritime fuel or transformed back into green hydrogen via the ammonia cracking process. The model facilitates trade across Europe and other regions beyond the Middle East and North Africa (MENA), covering fossil fuels, biomass, and electricity. However, the trade pathways for hydrogen and ammonia are limited to a hydrogen pipeline between the European Union (EU) and North Africa (NA), and shipping routes for liquefied hydrogen and ammonia between the EU and the Middle East (ME).

2.2. Scenarios

For the present analysis we use two of the scenarios that we developed in our previous work on an electricity and hydrogen partnership between Europe and North Africa [34] – named Autarkic and Efficient – for reasons of consistency and because the purpose of the current study is to compare our earlier findings with the additional region, Middle East, and extra energy carriers, liquified green hydrogen and ammonia (see Fig. 1). As before, in both scenarios we assume climate mitigation efforts in line with the goals of the Paris Agreement [39] and adopt net-zero GHG emissions in Europe by 2050, since this is the EU's formal policy target under its Green Deal and Fit-for-55 package [40,47]. For the world as a whole we adopt an exogenous constraint that implies GHG emissions to remain on a trajectory compatible with a global 2 °C target; this is implemented as a global carbon budget over the period 2011 to 2100 of 1150 $GtCO_2$. Table 1 summarizes the main features of our scenarios for energy trade between Europe (EU), Middle East (ME), and North Africa (NA), aggregated over the five Maghreb countries (see Table A1 in the appendix of van der Zwaan et al. [34] for numbers for each of these countries as well as their justification).

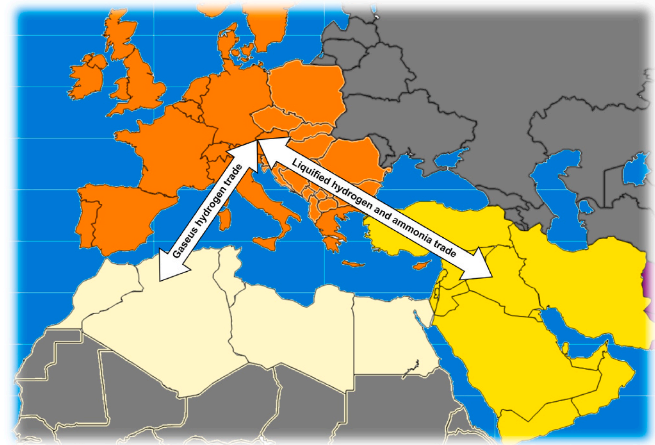

Fig. 1. An indicative geographical representation of EU (orange), ME (yellow), and NA (cream) regions in TIAM-ECN and corresponding hydrogen and ammonia trade possibilities between regions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

In the Autarkic scenario we assume low imports of electricity and no imports for hydrogen and ammonia. For electricity we impose an upper limit of 6 GW until 2050 for trade between Europe and North Africa and 23 GW for trade between Europe and Middle East, which corresponds to the capacity of interconnections currently in operation and/or planned between the continents (see Ref. [48]). For hydrogen and ammonia we adopt no trade at all, hence a continuation of the current situation. In the Efficient scenario we allow for high imports of the three mentioned energy carriers. For electricity we apply no trade limit between EU and NA, so that TIAM-ECN calculates an optimum for electricity production levels and the localization thereof. This optimum is determined independent of constraints that may exist in reality but that the model is unable to represent (think of e.g. resource, geopolitical, legislative and regulatory limitations or shortcomings). Between EU and ME, we keep the current electricity trade capacity as the relevance of this region in the present study is the hydrogen and ammonia shipping. For gaseous hydrogen trade we adopt an upper limit that increases from 250 PJ/yr in 2030–3750 PJ/yr in 2050, corresponding to 2 and 32 MtH_2/yr respectively. For liquified hydrogen and ammonia trade, we assume no upper

Table 1
Summary of scenarios for energy trade between MENA and Europe.

Scenario/Region	Autarkic		Efficient	
	Middle East	North Africa	Middle East	North Africa
Electricity import (2030–2050)	High (23 GW)	Low (6 GW)	High (23 GW)	High (No limit)
H_2 import (2030–2050)	None	None	High (No limit)	High (max 250–3750 PJ/yr)
H_2 production (2030–2050)[a]	Minimum 150 (PJ/yr) in Europe			
NH_3 import (2030–2050)	None	None	High (No limit)	None
Global 2 °C policy[a]	Yes			

N.B. Numbers for North Africa are aggregated across the 5 Maghreb countries.
H_2 import from North Africa is only allowed through pipelines.
H_2 and NH_3 import from Middle East is only allowed through shipping.
[a] Shared across all scenarios.

limit. As previously discussed in our previous study [34], the numbers presented here are based on scenario assumptions. By implementing TIAM-ECN, we generate scenarios that provide projections of the energy system's future, while adhering to the principle of cost-minimization based on the objective function. These scenarios represent optimization outcomes derived from various assumptions that could potentially be realized in practice. It is essential to reiterate, as we have emphasized in numerous previous publications, that scenarios produced with TIAM-ECN, or any other energy system or integrated assessment model, should not be interpreted as predictions.

3. Results

Fig. 2 illustrates our projections for hydrogen supply in both the autarkic and efficient scenarios until the middle of the century. The graph displays the evolution of hydrogen production for Europe, the Middle East, and North Africa, across four distinct time periods (2020, 2030, 2040, and 2050). The data is broken down by the type of underlying process, including coal gasification with CCS, natural gas reforming, electrolysis, and imports through pipeline and shipping. In Europe, we observe a consistent growth in hydrogen supply in both scenarios. However, the levels of hydrogen supply are higher in the efficient scenario. Electrolysis becomes the dominant hydrogen production pathway, but there is still some share of natural gas reforming in the autarkic scenario by 2030. In the efficient scenario, the majority of hydrogen is supplied through pipelines from North Africa, while it is cost-effective to import liquefied hydrogen from the Middle East starting in 2030. For the Middle East, regardless of the scenario, there is considerable growth in H_2 supply, reaching more than 2000 and 3500 PJ in 2040 and 2050 respectively. The high levels of H_2 supply are driven by the region's need to reduce emissions and contribute to global climate control objectives. Therefore, investing in clean fuel production, such as hydrogen, can be seen as a no-regret policy for this region. In North Africa, the H_2 supply is heavily dependent on the scenario. In the autarkic scenario, H_2 supply grows slowly, reaching 500 PJ in 2050. However, in the efficient scenario, H_2 supply can exceed 2000 PJ in 2050.

Fig. 3 presents our projections for hydrogen demand in both scenarios until mid-century. For Europe, hydrogen is used primarily in industry and buildings (mainly in 2050) in both scenarios. H_2 consumption in these sectors is achieved in TIAM-ECN via mixing up to 15% of gaseous hydrogen in natural gas pipelines. When allowing for hydrogen trade, Europe uses the extra available hydrogen to produce biofuels. In the Middle East, H_2 demand is more diversified. From 2040 onwards, this region starts to produce ammonia as a proxy for clean shipping fuel. In 2040, some H_2 is used for power generation, to provide electricity during peak-demand periods while solar radiation – upon which this region is highly dependent – might be low. Compared to 2040, H_2 demand increases in 2050 to produce methanol, which can be used to produce other fuels such as synthetic diesel and kerosene. Across both scenarios, H_2 demand mix remains fairly similar, with notable differences being an increased demand for liquefied hydrogen and ammonia for export, and a decreased demand for methanol in the efficient scenario. Utilizing the available electricity for the production and exportation of liquified H_2 and NH_3 proves to be more cost-effective compared to its use in producing methanol for synthetic diesel and kerosene. This results in a decrease in the overall demand for H_2 by 2050, due primarily to the higher efficiency of the Haber-Bosch ammonia production process (in terms of hydrogen utilization), when compared to the process for synthesizing methanol. In North Africa, domestic demand kicks off with the industrial sector in 2030 and experiences a modest rise with increasing ammonia demand in 2040 and methanol demand in 2050. The ammonia and methanol produced are utilized to decarbonize the navigation and aviation sectors. Ammonia serves as a direct fuel, while methanol is converted into synthetic jet kerosene. In the efficient scenario, H_2 demand quickly gets dominated by H_2 exports through pipelines. In 2050, similar to ME, we see a decline in the domestic H_2 demand due to efficiency gains thanks to trade.

Fig. 4 represents the ammonia supply (left) and demand (right) in the three regions until mid-century. TIAM-ECN includes two options for decarbonizing the navigation sector: biofuels and ammonia. In Europe, navigation demand is mostly met with biofuels (given their relatively high availability), until ammonia imports become cost-competitive in 2050. In the other two region, due to low availability of domestic biofuels, it is more cost-effective to produce ammonia for decarbonizing the navigation sector, irrespective of trade opportunities. Therefore, investments in a low-carbon fuel production options for the navigation sector (such as ammonia) can be considered a no-regret decision for these regions.

Fig. 5 shows the electricity supply projections with TIAM-ECN: in all three regions, power supply increases substantially due to higher electrification rate. In Europe, although the penetration of variable renewable sources (VRES) increases over time, nuclear and hydro power remain in the mix. Compared to the autarkic scenario, the overall electricity supply of the EU in the efficient scenario is 14% lower in 2050, which can be described by a lower need for producing domestic green hydrogen and ammonia. In the Middle East, although natural gas remains in the mix (with CCS) until 2040, solar power becomes the dominant source of electricity in 2050. The lack of meaningful differences between the two scenarios can be explained by the high dependency of ME on a low-carbon energy sources (i.e., green electricity) to meet global emissions reduction targets. In North Africa, the power supply in 2050 increases substantially in the efficient scenario, as it is used in electrolizers to produce (mostly exported) hydrogen.

Electricity demand projections in TIAM-ECN are depicted in Fig. 6. In Europe, we see the higher electricity need, particularly in buildings and transport sectors. The electricity in the transport sector is mainly used for passenger cars (see Figure A2 in Appendix). Moreover, starting from 2030, electricity demand for synthetic fuel production (mainly hydrogen and biofuels) starts growing. The higher electricity demand in

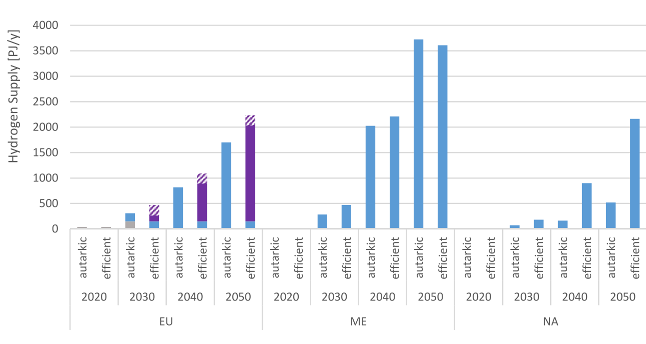

Fig. 2. The hydrogen supply projections with TIAM-ECN in three regions: Europe (EU), Middle East (ME), and North Africa (NA).

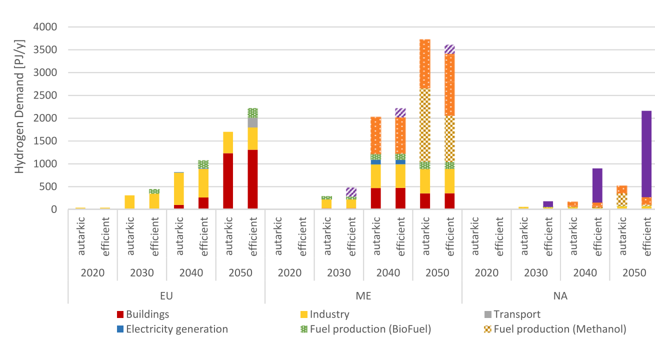

Fig. 3. Projections with TIAM-ECN for the hydrogen demand.

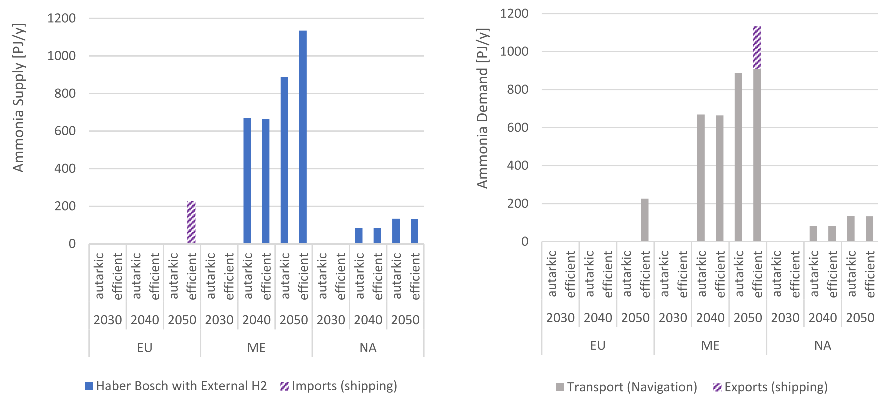

Fig. 4. Projections with TIAM-ECN for ammonia: supply (left) and demand (right).

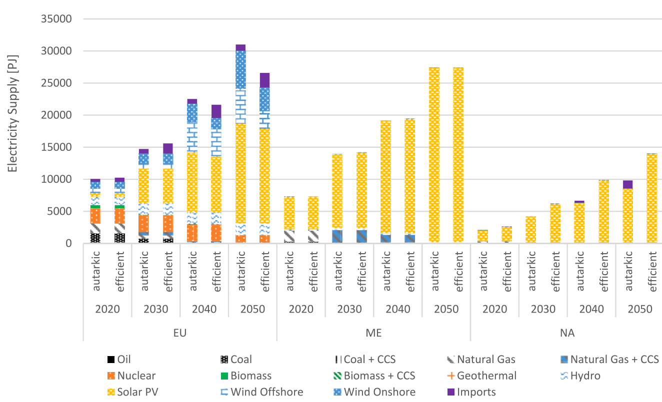

Fig. 5. Electricity supply projections with TIAM-ECN.

the autarkic scenario, comes from the need for hydrogen production and electricity exports. Allowing for hydrogen and ammonia trade with MENA does not considerably affect the electricity demand mix in all periods. Between the two scenarios, the electricity demand mix of Middle East is least affected among the three regions. For North Africa, however, the electricity demand increases considerably in the efficient scenario for electricity exports (primarily to Europe) and green hydrogen production (mainly for export to Europe).

Fig. 7 illustrates hydrogen price in 2050 across the three regions in both scenarios, in M$/PJ (left axis) and $/kg (right axis). This is calculated endogenously in TIAM-ECN as a shadow-price, and as such it does not necessarily reflect real-world hydrogen prices. Its variations across regions, time periods and scenarios provide, nevertheless, some relevant insights. In Europe, we see that allowing trade can reduce H_2 prices by roughly 1.8 $/Kg (52%) to below 2 $/Kg level. However, hydrogen exporting regions, Middle East and North Africa, can experience H_2 price increases by roughly 60% and 16%, respectively.

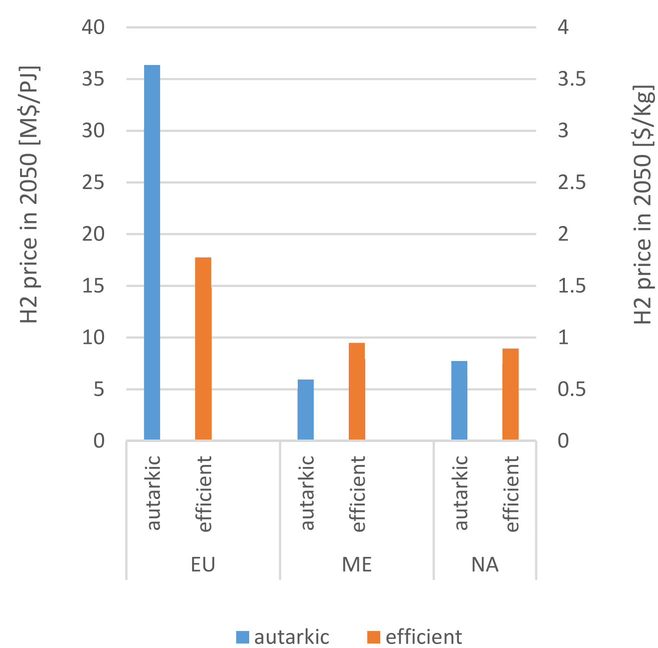

Fig. 7. Hydrogen price projection in 2050 with TIAM-ECN.

On a global multi-regional level, additional energy system costs are

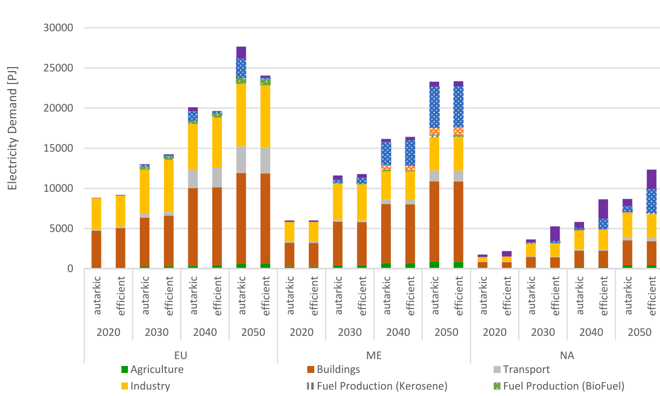

Fig. 6. Electricity demand projections with TIAM-ECN.

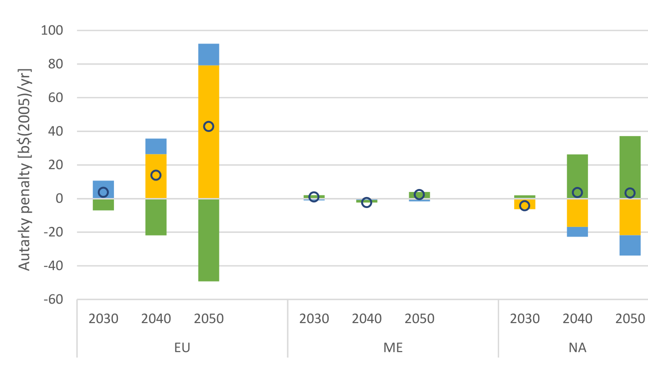

Fig. 8. Projections with TIAM-ECN for the autarky penalty.

incurred when switching from the efficient to the autarkic scenario. Following the terminology introduced by Dalla Longa et al. [35], in Fig. 8, we refer to these extra system costs as the Autarky Penalty (AP). Usually, a positive AP at the global or multi-regional level translates into positive AP values at the level of individual regions, but we showed in previous studies [34,35] that this may not always necessarily be the case. Fig. 8 shows that in long-term, the AP is positive for the three regions, meaning that allowing for trade pays off for all the regions in 2050. In the autarkic scenario, Europe needs to incur vast investment and operational costs, while saving costs on imports, resulting in a net AP increase up to 40 G$/yr in 2050. The opposite trend occurs in MENA regions: high export gains (i.e., the positive Trade bar) offset investments and operational costs (e.g., higher solar PV and electrolyzer installations) in the long-term. Overall, the sum of the AP of the three regions can increase from 0.2 G$/yr in 2030 to 15 G$/yr and 48 G$/yr in 2040 and 2050, respectively, i.e. the efficiency gains of allowing H_2 and NH_3 trade are mostly realized in the long-term.

In order to assess the relevance of the AP for each region, we propose an additional metric, the Relative Autarky Penalty (RAP), defined as the absolute value of the autarky penalty divided by the energy system costs in the autarkic scenario.

$$\textit{Relative Autarky Penalty}_{r,p} = \left| \frac{\textit{Autarky Penalty}_{r,p}}{\textit{Autarkic System Costs}_{r,p}} \right|$$

Where r and p refer to each region and period, respectively.

Fig. 9 presents the cumulative projections of the RAP with TIAM-ECN. It is shown that although the AP in Europe is highest among the three regions, the RAP remains less than 1% by 2040 and only reaches 2% of the total system costs in 2050. This cost reduction is not considerable considering all the uncertainties, notably technological cost projections and resource availability. Some key processes in this study are not deployed in large-scale yet, including electrolizers, transportation vessels for liquified hydrogen and ammonia, and synthetic fuel production and demand processes. Consequently, the modeling assumptions regarding their costs are primarily speculative and may vary significantly upon actual deployment. For the MENA region, however, the RAP increases substantially to more than 6% by 2050. For Middle East, we can observe a considerable RAP starting from 2040, while in North Africa, it already starts above 4% from 2030. These findings are complementary to Fig. 8, as allow us to capture the high relevance of low absolute AP for MENA regions with respect to their total system costs.

4. Discussion and policy implications

Producing renewable electricity and green hydrogen in the MENA region for transport to the EU could be strategically and environmentally beneficial. The MENA region's high solar potential makes it ideal for solar farms and cost-effective green hydrogen production. Its closeness to Europe and advancements in hydrogen technology could enable an efficient and stable green hydrogen supply to EU. However, to validate such a proposition, it is critical to employ integrated assessment and/or energy system modeling for a comprehensive evaluation. In this paper, we explore the implications of establishing a green energy partnership between Europe and the MENA region on their overall energy system. We specifically address the question: How would a green energy partnership between Europe and MENA affect the energy systems of both regions?

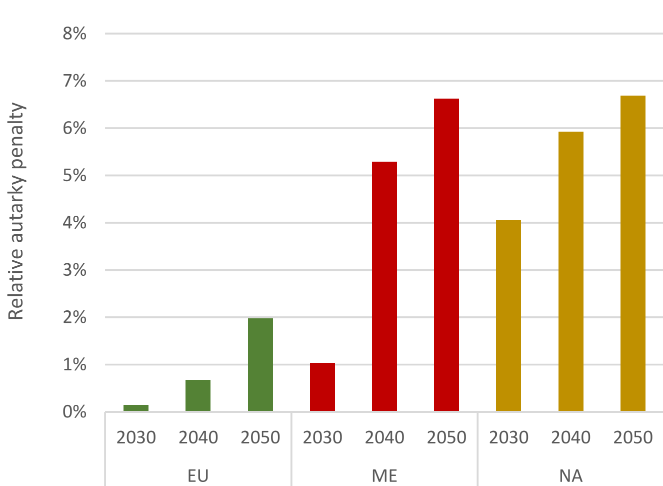

Fig. 9. Cumulative projections with TIAM-ECN for relative autarky penalty.

In our previous research [34,35], we assessed the cost efficiency of establishing a partnership across the Mediterranean for exchanging renewable electricity and hydrogen between Europe and North Africa. Yet, our prior analysis did not consider the possibility of trading clean energy carriers with farther regions. The present study expands on our earlier work by incorporating the trade of liquefied green hydrogen (H_2) and ammonia (NH_3) with the Middle East, and presents a novel concept – the Relative Autarky Penalty (RAP) – which expresses the proportion of the additional costs incurred from limiting energy trade with other countries or regions against the overall costs of the energy system. Essentially, this concept quantifies the relative economic repercussions of choosing to isolate an energy system from external trade, highlighting the cost of 'going solo' in terms of energy production.

The findings of the present study on the economic feasibility of hydrogen trade are consistent with existing literature. Extensive scenario analyses on the long-term decarbonization of the EU suggest significant hydrogen imports from North Africa, in the whole range of assumed costs. Similar to our study, Cristina Pinto et al. [49] showed that the imported hydrogen is primarily used for decarbonizing the transport sector (via synthetic fuels) and the heat sector of Europe. Additionally, research by Franzmann et al. (2024) identifies substantial hydrogen potential in solar-rich countries within the MENA region. Using the integrated assessment model TIAM, Lippkau et al. [50] also highlight the Middle East as a key region for exporting hydrogen and synthetic fuels. These findings align with our results regarding ammonia exports from the Middle East, serving as a proxy for synthetic fuels.

In the present study, we demonstrate that if liquified hydrogen and ammonia trade options are available, for example through shipping from the Middle East, Europe's autarky penalty is positive and may increase to 40 billion $/yr by 2050. Moreover, we find that allowing this trade decreases the EU's investment in domestic renewable energy capacity necessary for the realization of its Green Deal and Fit-for-55 Program by 14%. This reduction is mainly attributed to a decreased demand for both onshore and offshore wind energy. Additionally, we show that the MENA region can significantly benefit from such trade, achieving a savings of over 6% in its own energy system costs by the year 2050. At the same time, our analysis underlines that the economics of such trade are complex, as also broadly recognized in the literature (see e.g. Ref. [12,16]). In order to complement our study, it is thus necessary to also consider other aspects of a possible hydrogen economy as well as other production options, transportation modes, or trade routes, such as a global green hydrogen credit trading framework [51] or other hydrogen-based synthetic fuels (see e.g. Ref. [50,52]).

Our findings indicate a significantly higher autarky penalty for the EU in comparison to the MENA region by the year 2050. This suggests that forming a partnership between the EU and MENA in the production and trade of green hydrogen and ammonia would greatly benefit the EU. However, while the EU stands to gain significantly from trading hydrogen and ammonia with MENA, the magnitude of these benefits (that is, avoided costs) does not represent a large fraction of the overall energy system costs, especially when taking into account the cost uncertainties, particularly related to the cost of electrolizers, transportation vessels for liquified hydrogen and ammonia, and synthetic fuel production and demand processes. Conversely, while the benefits from such a trade are smaller in absolute terms for MENA, they account for a significant proportion of the total energy system costs in these regions. As a result, the motivation for engaging in H_2 and NH_3 trade in Europe should perhaps primarily be based on enhancing diversity and ensuring security, rather than expecting major cost savings, while in the MENA region, the drive should stem from the potential for long-term economic benefits on a regional scale. This finding is supported by Nuñez-Jimenez et al. [53] who showed that long-distance hydrogen imports can boost energy security of EU through diversifying suppliers.

In 2022, the EC unveiled the REPowerEU Plan, its response to the challenges and disruptions in the global energy market triggered by Russia's invasion of Ukraine [1]. A key component of this plan includes goals to achieve 10 million tons of domestic renewable hydrogen production and an equal amount of imports by the year 2030. This initiative is aimed at substituting natural gas, coal, and oil in industries and transportation sectors that are difficult to decarbonize. Our research supports these objectives, revealing that the EU can secure cost-saving opportunities by enhancing energy partnerships with countries in the MENA region to boost the import of renewable hydrogen and ammonia. These two energy carriers may serve as proxy for low-carbon synthetic fuels more generally.

In our study, we considered utilizing ammonia as an alternative zero-carbon fuel for navigation purposes. Ammonia represents a proxy for other low-carbon navigation fuels, specifically for the three regions that are the focus of this paper. While we consider this simplification a reasonable starting point for analyses such as ours, we recognize that the explicit inclusion of other possibilities, such as synthetic diesel and compressed natural gas (CNG), would be desirable in follow-up work. Considering the importance of decarbonizing the navigation sector in the context of global climate change mitigation efforts, it would be essential in forthcoming modelling assessments to incorporate these alternatives.

Given Europe's proximity to the Middle East and North Africa, it seems sensible to prioritize the assessment of possible trade partnership with countries in this region – as we do in the present article. However, given the potentially global scope of future hydrogen (and, more generally, synthetic fuels) markets, it is becoming increasingly relevant to also address the possible role of other regions, such as South America. This is not only based on Europe's interest in exploring the potential of importing biofuels from this region, but also on the fact that South America, particularly countries like Argentina, Brazil and Chile, has vast solar and wind energy resources that make it a potential major exporter of renewable hydrogen.

Finally, another possible extension of our scenario analysis would entail a more detailed assessment of the demand for green hydrogen and derived fuels from the perspective of end-use sectors. Specifically, a thorough assessment of emerging energy conversion routes for the production of clean synthetic fuels, as well as decarbonization options for industrial processes, would offer invaluable insights with regard to the need for hydrogen penetration in the European economy, and provide guidance for establishing robust policy frameworks to support industrial transformation and identify the most desirable mix of imported versus locally-produced hydrogen.

CRediT authorship contribution statement

Amir Fattahi: Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francesco Dalla Longa:** Writing – review & editing, Visualization, Project administration, Methodology, Formal analysis, Conceptualization. **Bob van der Zwaan:** Writing – review & editing, Project administration, Investigation, Funding acquisition, Formal analysis, 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 A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2024.08.021.

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