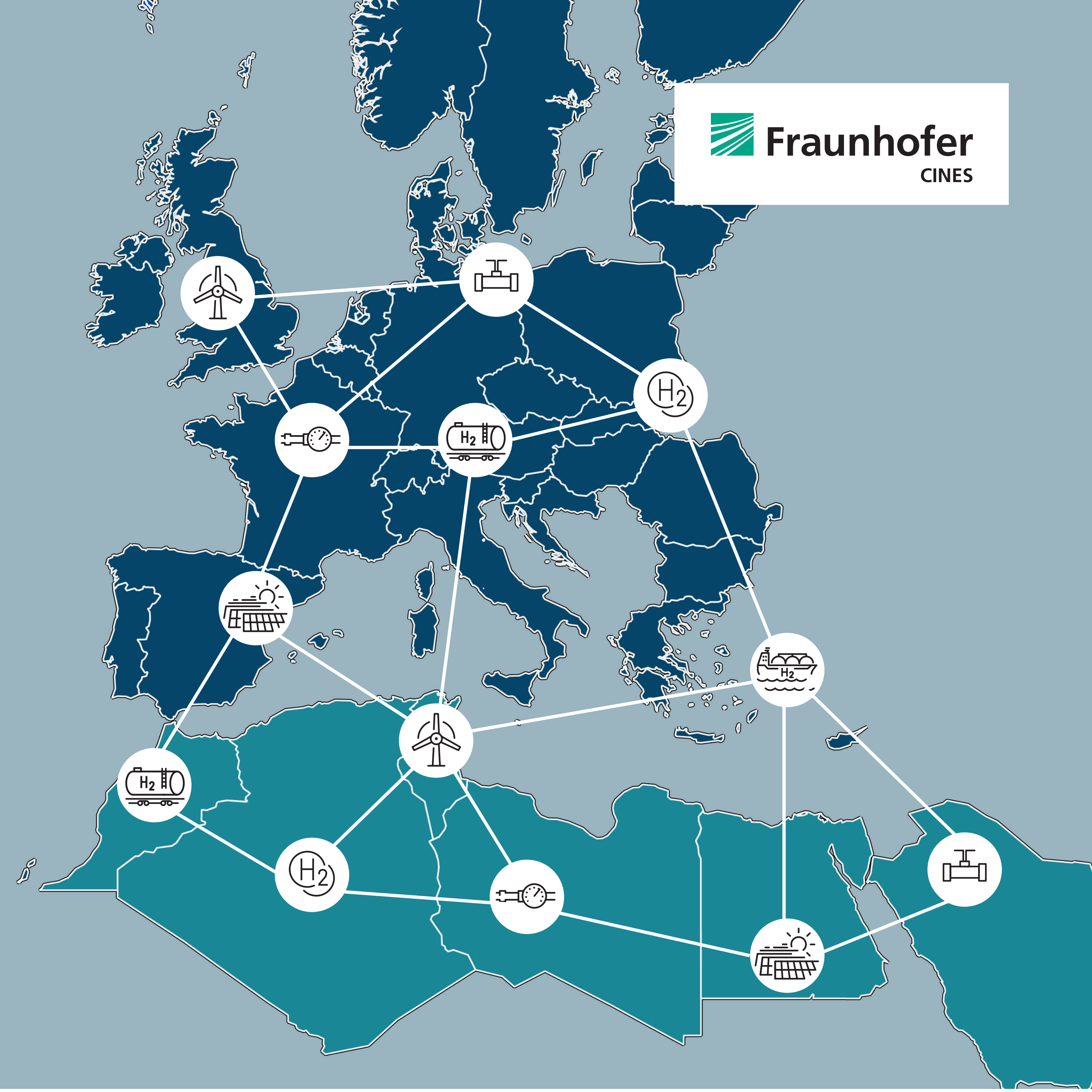


# Clean Hydrogen Deployment in the Europe-MENA Region from 2030 to 2050

**A Technical and Socio-Economic Assessment**

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# Abstract

This paper assesses the technical feasibility and socio-economic aspects of the European Union's (EU) REPowerEU target of producing, importing, and transporting 20 million tonnes (Mt) of clean hydrogen by 2030. Due to their geographical proximity, low-cost hydrogen production potential and existing gas infrastructure, six MENA ('Middle East and North Africa') countries are considered key players for realizing the REPowerEU import target: Morocco, Algeria, Tunisia, Libya, Egypt, and Saudi Arabia. The central questions addressed by this paper are:

- What hydrogen production and import volumes are technically feasible in the Europe-MENA region?
- Can imports from the MENA countries be integrated into the existing European natural gas grid?
- How much technical storage capacity is available for hydrogen in the Europe-MENA region?
- What socio-economic issues must be considered in a strategic analysis of clean hydrogen deployment in the Europe-MENA region?

# Table of Contents

**Main findings** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . **4**

**Aim** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . **6**

**1. Introduction** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . **7**

**2. Methodology** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . **9**

2.1. Technical-economic assessment: Fraunhofer SCOPE SD and IMAGINE . . . . . . . 9

2.2. Technical and socio-economic assessment:
Fraunhofer Global Power-to-X (PtX) Atlas . . . . . . . . . . . . . . . . . . . . . . . . . . 11

**3. Clean hydrogen in Europe** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . **15**

3.1. Hydrogen production and consumption: Technical-economic assessment. . . . 16

3.2. Infrastructure and storage: Technical and strategic aspects . . . . . . . . . . . . . 19

**4. Clean hydrogen in the MENA region** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . **26**

4.1. Technical-economic assessment. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 27

4.2. Theoretical storage potential in salt caverns . . . . . . . . . . . . . . . . . . . . . . . . 33

4.3. Socio-economic assessment. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 39

**5. Conclusion** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . **42**

**6. References** . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . **44**

# Main findings

- The analysis presented here is a starting point for further research on the technical and socio-economic aspects of the nascent Europe-MENA hydrogen economy and for testing the feasibility of strategies like REPowerEU.
- Hydrogen deployment's technical and socio-economic dimensions including strict sustainability criteria and domestic and primary energy demand must be considered before the export potential from MENA countries to Europe can be determined.
- For almost half of its hydrogen demand and up to 2050, Europe will depend on hydrogen imports from the MENA countries selected here based on low production costs, geographical proximity, and existing infrastructure. The bulk of imports from these countries to Europe must occur via pipeline. Simultaneously, from 2030 onwards, there is also a substantial role for ammonia imports via ship. This paper indicates a significant techno-economic potential for hydrogen exports from Morocco and Tunisia in 2030, followed by Libya, Algeria, Egypt, and Saudi Arabia from 2045 onwards. Figure 1 summarizes these findings.

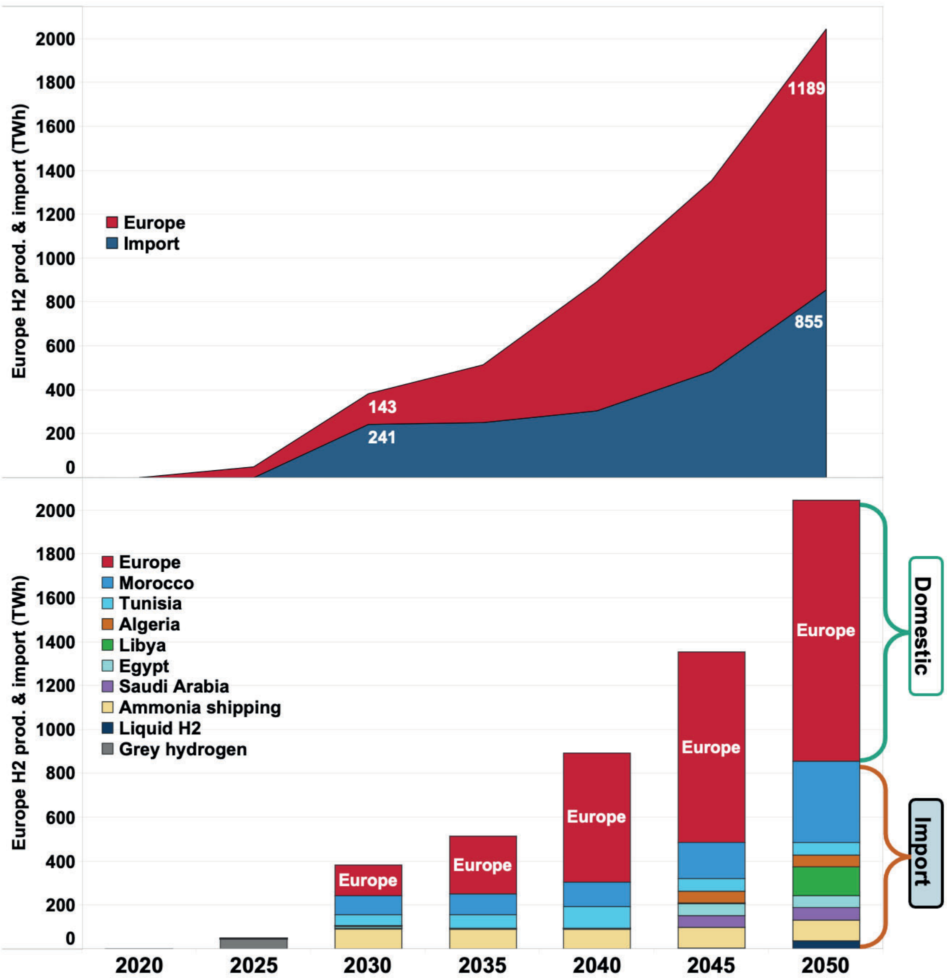


*Figure 1: European hydrogen production and import from MENA countries (2020-2050). Source: Authors based on the SCOPE SD and IMAGINE model linkage (2023).*

- Our technical, cost-optimization analysis shows that Europe's hydrogen production capacity could reach 143 TWh (or 4.3 Mt) by 2030 and might reach the REPowerEU 10 Mt (or 330 TWh) $H_2$ per year production target sometime between 2035 and 2040. Our analysis is based on several scenario analyses, including one from the European Association for the Cooperation of Transmission System Operators (ENTSOG and ENTSO-E), and assumptions regarding the expansion potential of renewable energy sources in Europe by 2030 and the implementation of the EU's climate targets.
- Regarding sectoral hydrogen demand in Europe, our model-based analysis shows that 11.4 Mt constitutes a very ambitious and maximum hydrogen demand that can be met by 2030.
- Up to 2030, Europe's current salt cavern storage facilities are sufficient for repurposing, but these will no longer be adequate after 2030. The analysis shows the need for additional repurposed and new hydrogen storage capacities of 216 TWh by 2050.
- An early and purely theoretical analysis of the technical potential for hydrogen storage in salt caverns in the selected MENA countries shows good potential in Morocco and Algeria and good to medium potential in Saudi Arabia. For the countries with limited storage potential in salt caverns, other alternatives need to be investigated, like repurposing depleted oil and gas fields.
- Up to 2030, there is substantial potential offered by repurposing the existing gas infrastructure in Europe for hydrogen transport. From 2050 onwards, the analysis shows the need for new pipeline capacity between MENA countries and Europe. Any pipeline planning needs to take into account various aspects, including socio-economic and geopolitical considerations.

> **"Strict sustainability criteria and domestic and primary energy demand must be considered before the hydrogen export potential from MENA countries to Europe can be determined"**

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# Aim

This paper assesses the technical feasibility and socio-economic aspects of the European Union's (EU) REPowerEU target of producing, importing, and transporting 20 million tonnes (Mt) of clean hydrogen by 2030[1]. Clean hydrogen refers to renewable and natural gas-based variants with extremely low methane emissions and high carbon capture rates (IRENA 2022). Very high capture rates imply a $CO_2$ capture rate of 95% by 2030 and 99% either well before or around 2050 (House of Commons 2022). Due to their geographical proximity, low-cost hydrogen production potential and existing gas infrastructure, six MENA ('Middle East and North Africa') countries are considered key players for realizing the REPowerEU import target: Morocco, Algeria, Tunisia, Libya, Egypt, and Saudi Arabia. For the technical assessment of clean hydrogen production, demand, transport and storage, the paper links the Fraunhofer energy system model SCOPE SD with the new gas market model IMAGINE. The energy system model SCOPE SD covers the power, heat, and transport sectors to model cost-optimization and long-term decarbonization scenarios. IMAGINE minimizes all the investment and operation costs for hydrogen and methane infrastructures and markets in daily resolution and for several planning periods.

Linking the SCOPE SD and IMAGINE models enables a cost-optimal analysis of clean hydrogen production, demand, transport, and storage developments for a given hydrogen demand in the EU. For socio-economic considerations related to clean hydrogen deployment across the Europe-MENA region, this paper uses research approaches applied by the Fraunhofer Cluster of Excellence Integrated Energy Systems (CINES) in projects such as the Global Hydrogen Potential Atlas (HYPAT) and Global PtX Atlas[2]. Based on secondary data analysis, Geostock provides insights into the technical storage capacity of salt caverns in the six key MENA countries. This research on the nascent hydrogen economy across the Europe-MENA region provides a strong basis from which to consider the feasibility of more strategic ambitions.

**1** The authors thank Martin Lambert (Oxford Institute for Energy Studies), Suhail Z. Shatila (APICORP), Magnolia Tovar (Clean Air Task Force), Benedikt Häckner, Christopher Hebling, Anne Held, Benjamin Pfluger, Mario Ragwitz, Bastian Weissenburger, and Marijke Welisch (Fraunhofer CINES) for their valuable contributions.

**2** For more information on HYPAT, see: https://hypat.de/hypat-en/. For more information on the Fraunhofer Global PtX-Atlas and the methodology used, see: https://maps.iee.fraunhofer.de/Global PtX-Atlas/ and https://devkopsys.de/methoden/.

# 1. Introduction

REPowerEU, the European Union's (EU) current energy security strategy developed in response to Russia's war against Ukraine, includes the ambition to reach 20 Mt of renewable hydrogen production, import and transport, i.e., 10 Mt of production and 10 Mt of imports (or 660 TWh $H_2$ /yr.) by 2030 (European Commission 2022a). Based on the expectation that supply capacity for transporting hydrogen into Europe is established, REPowerEU assumes 6 Mt will be imported via pipeline as hydrogen and 4 Mt as ammonia or other hydrogen derivatives, probably imported by ship (European Commission 2022b; Lambert 2022).

By leveraging its strong potential, the Middle East and North Africa ('MENA') region is well-positioned to supply around 10% to 20% of the global hydrogen market by 2050, or between approximately 42 Mt and 84 Mt (Al-Ashmawy and Shatila 2022; IEA 2022a)[3]. Regarding large-scale energy transport, molecules can be transported more quickly and cost-efficiently than electrons. This is one of the reasons a new Europe-MENA energy cooperation could emerge based on hydrogen, as this could be transported via existing pipelines with some infrastructural adjustment, i.e., coating (Hafner 2022). Due to their geographical proximity, low-cost production potential, and existing gas infrastructure, this paper considers six MENA countries to be the key players in realizing the EU's target of importing 6 Mt of hydrogen by pipeline and 4 Mt of ammonia.

These countries are:

- **Morocco**
- **Tunisia**
- **Algeria**
- **Libya**
- **Egypt**
- **Saudi Arabia**

Unlike REPowerEU, with its exclusive focus on renewable hydrogen, this paper focuses on clean hydrogen production and demand in the 'Europe-MENA' region, i.e., the EU member states, Great Britain, Norway, Switzerland, and the six MENA countries. The focus on clean hydrogen acknowledges the importance of renewable and fossil gas-based hydrogen for countries in Europe and the MENA region. It is argued that

3 The World Bank (2021) uses the term Middle East and North Africa (MENA) to cover an extensive region of twenty-one countries. This paper focuses on six of these.

the land use and infrastructure issues related to rapidly scaling up the necessary additional and dedicated renewable energy for green hydrogen production across the Europe-MENA region are highly challenging. These include access to cheap capital, additional renewable electricity consumption, and high population density. Furthermore, current renewables capacity is mainly destined for decarbonizing national electricity systems. These combined issues mean that the rapid deployment of renewable hydrogen from the MENA region to Europe is extremely challenging and should therefore be supplemented by fossil fuel-based hydrogen options. However, these options should include requirements for associated CCS, including a strict certification system for low-carbon gases based on a life-cycle assessment of GHG emissions (Azadegan et al. 2022). Using the REPowerEU target of 20 Mt of hydrogen production and import as a starting point for this analysis, i.e., 10 Mt of production within the EU and 10 Mt of imports (or 660 TWh $H_2$ /yr.), and focusing on the period between 2030 and 2050, the central questions addressed by this paper are:

- What hydrogen production and import volumes are technically feasible in the Europe-MENA region?
- Can imports from the MENA countries be integrated into the existing European natural gas grid?
- How much technical storage capacity is available for hydrogen in the Europe-MENA region?
- What socio-economic issues must be considered in a strategic analysis of clean hydrogen deployment in the Europe-MENA region?

This paper aims to contribute to the literature by addressing the technical and socio-economic dimensions of clean hydrogen deployment in the Europe-MENA region. These dimensions include indicators such as the cost of production, transport, capital, primary energy demand, water availability, land use and protected areas, distance to existing infrastructure and political stability. This paper argues that technical and socio-economic dimensions should underpin strategic analyses and decision-making on clean hydrogen deployment across the Europe-MENA region.

# 2. Methodology

## 2.1. Technical-economic assessment: Fraunhofer SCOPE SD and IMAGINE

This paper analyses the nascent hydrogen market and infrastructure development across the Europe-MENA region by soft-linking two economic models developed by Fraunhofer. The term "soft-linked" refers to the fact that the modelling is carried out sequentially, that two separate objective functions are pursued and that the results are not merged in one cost-optimization tool. The main methodological approach links the existing pan-European cross-sectoral capacity expansion planning framework SCOPE Scenario Development (SD) with the market-based expansion planning framework IMAGINE (Infrastructure and Market transformations for Gas In Europe). There is a detailed description of this approach in the literature (Frischmuth, Schmitz, Härtel 2022). The two models are soft linked by passing data from model to the other on fuel demand for each European country and domestic hydrogen production via electrolysis.

SCOPE SD is a bottom-up and techno-economic partial equilibrium model and able to develop coherent long-term, low-carbon (or net-zero) energy system scenarios in Europe for a given target scenario year. As a large-scale linear programming (LP) approach, SCOPE SD minimizes the generation, storage, and cross-sectoral consumer technology investments and system operating costs. Figure 2 illustrates SCOPE SD's structure, components, and typical input and output data. The upper part shows the input and output data, including interactions with technology options (lower part) in the corresponding markets and policy instruments (middle part). The different colors of the dots for the technology options and frames for the markets indicate the multiple participation of technology options in the corresponding markets or policy instruments (Schmitz, Naversen, Härtel 2023).

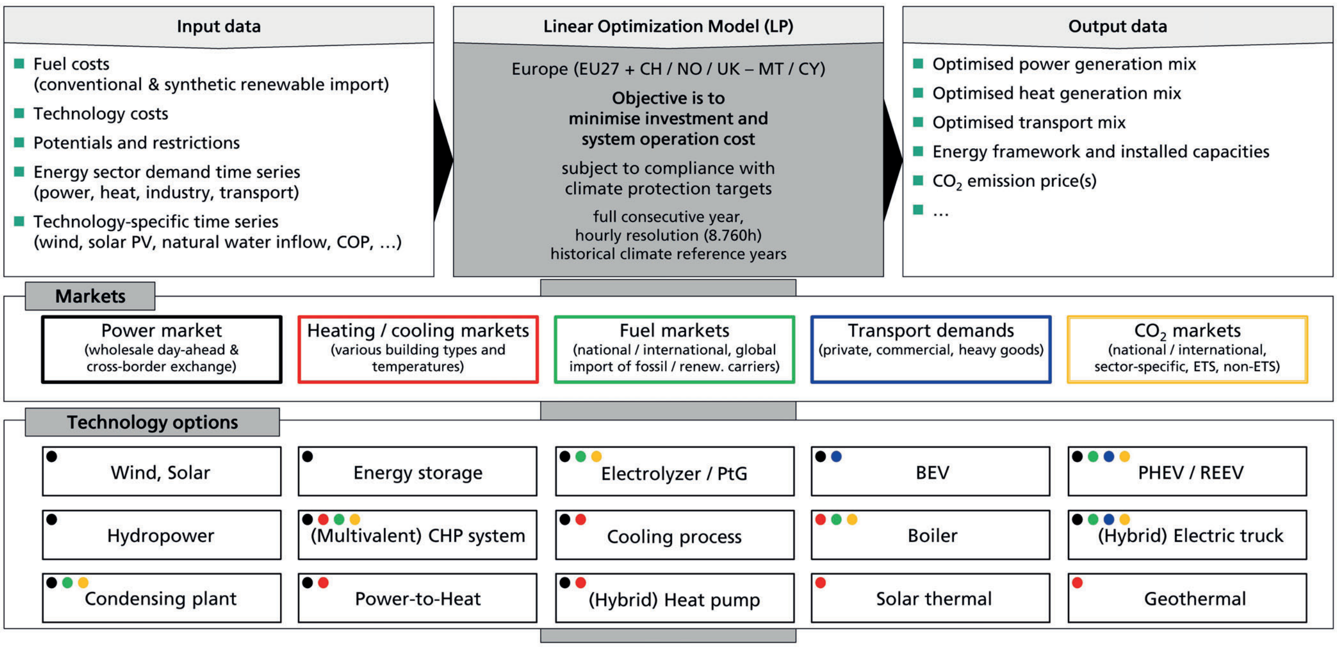


*Figure 2: Schematic overview of the pan-European cross-sectoral capacity expansion planning framework SCOPE SD. Source: Schmitz, Naversen, Härtel (2023).*

SCOPE SD covers the traditional power system and all relevant technology combinations in the industry, building, and transport sectors. Each European country, i.e., the EU member states (excluding Malta and Cyprus), Norway, Great Britain, and Switzerland, is represented by one node. All units, i.e., generation, storage, cross-sectoral demand technology options and their most important parameters (e.g., costs, potentials, and operating characteristics) and relevant interactions are modelled at one-hour intervals.

By explicitly modelling national and pan-European fuel markets, it is possible to distinguish between the use of fossil fuels, on the one hand, and synthetic renewable fuels, on the other hand, which are either produced domestically or imported from the MENA region. To ensure net-zero greenhouse gas (GHG) emissions in future scenarios, national and international GHG emission budgets are implemented as the driving force behind investments in clean technologies (Schmitz, Naversen, Härtel 2023). Detailed information on input data, assumptions, and use cases for SCOPE SD can be found in recent publications (Böttger and Härtel 2022; Härtel and Ghosh 2022; Härtel and Korpås 2021; Frischmuth and Härtel 2022; Schmitz, Naversen, Härtel 2023).

Linking the SCOPE SD and IMAGINE models involves the following steps (Figure 3).

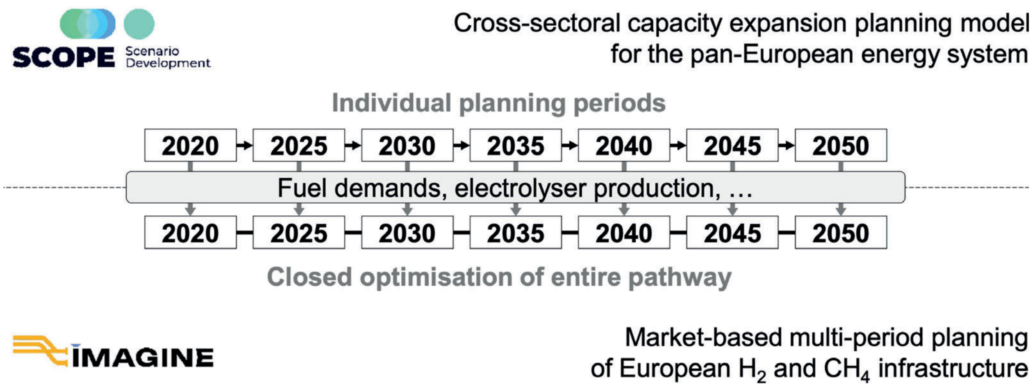


*Figure 3: SCOPE SD and IMAGINE model linkage. Source: Frischmuth, Schmitz, Härtel (2022).*

In the initial step (upper part of Figure 3), SCOPE SD generates medium- and long-term scenarios for the future net-zero European energy system. These scenarios are based on the historical meteorological year 2012, which reflects hourly renewables feed-in. This year was selected because it features a two-week period of cold, dark doldrums, or "kalte Dunkelflaute" in German, and is therefore well-suited to represent extreme weather conditions and their implication for design choices by the modelling framework (ENTSOG and ENTSO-E 2022). The scenarios can include up to seven expansion periods from 2020 to 2050 in five-year steps. In the second step (lower part of Figure 3), the SCOPE SD results are used as input for IMAGINE. This input includes sectoral hydrogen and methane demands, hourly demand profiles, and hydrogen production schedules from domestic electrolysers. While SCOPE SD calculates individual scenario years, IMAGINE represents a closed path optimization.

Figure 4 gives a schematic overview of the market-based expansion planning framework IMAGINE. It shows the structure and principal components of IMAGINE, including the multi-fold participation and interactions of technology options in the corresponding markets or according to specific policy instruments.

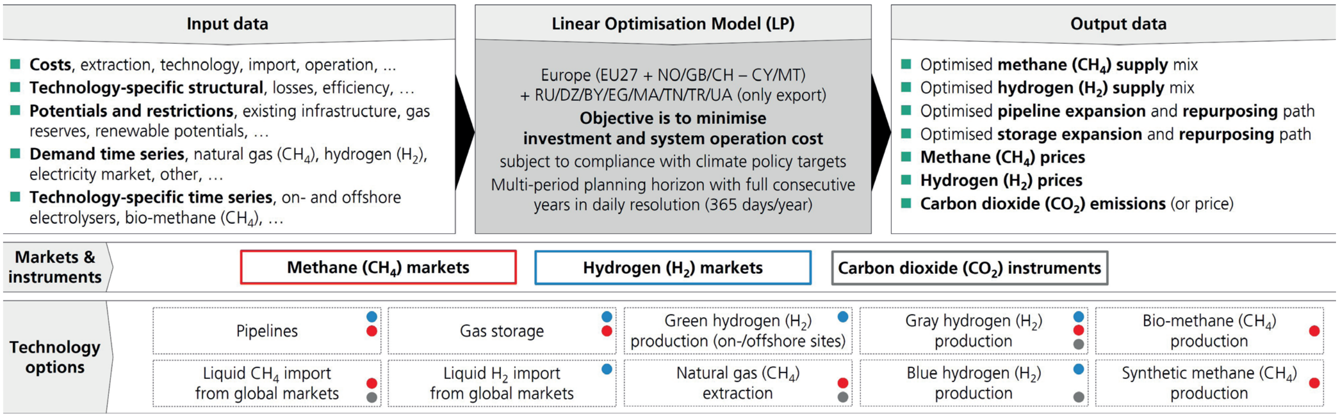


*Figure 4: Schematic overview of the market-based expansion planning framework IMAGINE.*
*Source: Frischmuth, Schmitz, Härtel (2022).*

IMAGINE is a linear programming (LP) optimization model in the Python-based Pyomo package (Hart et al. 2011; Bynum et al. 2021). It is a bottom-up, techno-economic partial equilibrium model that makes deterministic, multi-period capacity expansion and system operation decisions for a scenario pathway. As in SCOPE SD, each country, i.e., the EU member states (excluding Malta and Cyprus), Norway, Great Britain, and Switzerland, is represented by one node. Additionally, so-called 'export-only' countries are also represented by a respective and singular node. The term 'export-only' refers to the fact that these countries are represented exclusively with their export potential, i.e., without domestic demand. The system operation descriptions correspond to economic dispatch formulations. The model captures different national and global hydrogen and methane production options and national day-ahead markets integrated through a cross-border exchange. By modelling national and pan-European markets, it is possible to differentiate fossil use from synthetic renewable energy carriers produced domestically or imported. Frischmuth, Schmitz, and Härtel (2022) describe the model in detail with all the mathematical formulas and restrictions.

This paper links the SCOPE SD and IMAGINE models for clean hydrogen deployment across the Europe-MENA region for two reasons: First, this can couple the electricity and hydrogen markets on a European (and global) scale. Second, it enables path-dependent investment decisions or the avoidance of "stranded assets", and optimal system operation decisions regarding European electricity, hydrogen, and methane markets (Frischmuth, Schmitz, Härtel 2022).

SCOPE SD considers only a simplified representation of gas and fuel infrastructure developments (no gas storage or gas pipelines). IMAGINE focuses explicitly on production, transport, and storage developments. It uses time-series data and structural inputs to minimize all costs incurred for the investment and operation of pipeline and storage facilities and the import and domestic production of renewable and clean fuels. Also, the model coupling approach is used because coordinating power and gas markets in net-neutral systems requires optimal temporal granularity and must consider the interaction of $H_2$ and $CH_4$ infrastructure, and multiple sourcing strategies. Hydrogen use in the transportation, electricity, and heating sectors is represented in the model as an endogenous investment decision, while hydrogen use in industry (e.g., steel, cement, chemicals) and heavy-duty transport is specified exogenously.

Regarding the limitations of this approach, IMAGINE provides a high-level indication of the future development of an integrated power and gas infrastructure. Simultaneously, the modelling and linking with SCOPE SD ignores some physical effects and market design issues. The fact that IMAGINE is formulated as an LP optimization model means that no decisions are made regarding individual investments in pipelines or storage. As every pipeline project is highly specific, simplifying pipeline cost parameters is necessary. Furthermore, a transport modelling approach simplifies the physical connections in gas networks.

## 2.2. Technical and socio-economic assessment: Fraunhofer Global Power-to-X (PtX) Atlas

Fraunhofer's Global PtX Atlas is a Web Geographical Information System (GIS) application that identifies potential production sites of electricity-based fuels worldwide up to 2050, including hydrogen (gaseous and liquid) and its derivatives (ammonia, methanol) (Fraunhofer IEE 2022). The Atlas's technical and economic assessment is based on high temporal (one hour) and spatial (one km) resolution data. While the primary goal of the PtX Atlas is to analyze which regions could produce significant amounts of PtX fuels and at what cost, it also considers the available land and prevailing weather conditions. Other factors, such as local water availability, protected areas, and distance to infrastructure, are defined as exclusion criteria[4]. Table 1 summarizes the criteria that underpin the land potential for PtX generation. The techno-economic potential for each country is identified under strict sustainability criteria based on the area results and the modelled cost-optimal PtX system design.

4 Regarding weather conditions, the analysis for 2050 is based on historical weather data from 2008-2012. Further research should focus on the effects of climate change on local prevailing weather conditions and the subsequent PtX potentials.

**Table 1: Catalogue of criteria for identifying suitable PtX production locations. Source: Pfennig et al. (2022).**

| Criteria | Exclusion criterion | Argument |
|---|---|---|
| General | Land use | Forests, built-up areas, cropland, water bodies, snow, and ice areas |
| | Slope | > 5 ° (1 km resolution) |
| | Settlement areas | All settlement areas with a buffer of 1 km |
| | Population density | > 50 inhabitants/km$^2$ |
| | Protected areas | Nature and landscape conservation and potentially critical habitats with a buffer (1 km) |
| Economic | LCOE wind | > 40 Euro/MWh |
| | LCOE photovoltaics | > 30 Euro/MWh |
| PtX specific | Distance to ports | > 500 km |
| | Distance to pipelines | > 50 km |
| | Distance to cities | > 200 km |
| | Distance to the national coastline | > 50 km |
| | Marine protected areas | Coastline along marine protected areas with a buffer of 4 km |
| | Distance to an inland water source | > 50 km |
| | Water stress | > low |

Regarding CAPEX and OPEX, the estimation of PtX fuel production costs is based on an investment and dispatch optimization included in Fraunhofer's SCOPE SD optimization model. The techno-economic assumptions for the scenario years 2030 and 2050 are summarized in Table 2.

The Global PtX Atlas can also be used for socio-economic analysis. It yields the socio-economic potential of a PtX exporting country as an average value based on the six thematic areas of economics, politics, society, technology, natural conditions, and proximity to Germany. The analysis uses the individual values of forty indicators and seventy associated indices in the six thematic areas. All indices are based on studies, calculations and statistics from public national and international organizations or private consulting groups. Intervals are formed from the individual values of the indices, each of which is assigned a value between 1 and 5 (1 = highly negative, 5 = highly positive). The average value of the indices shows the value of each indicator, and the average value of all indicators gives the "final value" for a topic area. Finally, the average value from all topic areas provides information about the socio-economic conditions for building a 'PtX economy'.

**Table 2: CAPEX, OPEX, and efficiency percentage of selected technologies. Source: Global PtX-Atlas.**

| Technology | CAPEX | | | OPEX (% of CAPEX) | Efficiency (%) | |
|---|---|---|---|---|---|---|
| Scenario year | 2030 | 2050 | Unit | 2030 / 2050 | 2030 | 2050 |
| Wind power plant | 1,052,000 | 886,000 | $EUR/MW_{el}$ | 4.0% | - | - |
| Photovoltaic plant | 425,000 | 321,000 | $EUR/MW_{el}$ | 2.5% | - | - |
| Battery storage | 479,500 | 479,500 | $EUR/MWh_{el}$ | 1.0% | 93.8% | 93.8% |
| PEM electrolyser | 590,000 | 470,000 | $EUR/MW_{el}$ | 5.0% | 68.0% | 71.0% |
| Compression | 3,900 | 3,900 | $EUR/kW_{el}$ | 4.0% | 95.2% | 95.2% |

It is essential to point out that the Global PtX Atlas has limitations. For example, strict exclusion criteria for nearby infrastructure availability like water sources, ports, pipelines, and cities are defined to identify the best-located regions (Pfennig et al. 2022). As a result, in some regions, the potential areas are enormously restricted, e.g., to isolated regions in a country's interior. For the Global PtX Atlas 2.0, it is currently being considered whether to adjust these strict exclusion criteria. Other issues that need further research include the following:

- A detailed downstream analysis requires site-specific criteria related to local conditions to consider all the factors influencing the suitability of a PtX site.
- The effects of climate change on local weather conditions and area identification parameters (e.g., water stress level).
- Water stress needs to be considered whether this plays a role as variable in hydrogen production as water usage here can be set up circular and adds very little cost. Point of water source might be a more accurate criterion.
- Measuring country-specific differences regarding future production costs of PtX fuels.
- Considering the load behavior of individual and all plant components to account for periods of repair and maintenance work as higher outage times would increase PtX generation costs.
- Considering other transport options beyond transportation by ship from the largest port of each country, for example, gaseous transport by pipeline from nearby regions.
- Examining the development of the global trade volume and market prices of the respective PtX markets based on multi-criteria approaches, transformation scenarios and detailed modelling of production and transport potentials and demand volumes.

# 3. Clean hydrogen in Europe

In March 2022, the EU's new energy strategy REPowerEU introduced the EU goal of 10 Mt of renewable hydrogen production (or 330 TWh $H_2$ /yr.) by 2030 (European Commission 2022a).

This is an audacious target, considering that Europe's hydrogen capacity at the end of 2020 was approximately 11.5 Mt per year, of which almost a hundred per cent (99.3% to be exact) constituted conventional capacity (Hydrogen Europe 2022)[5].

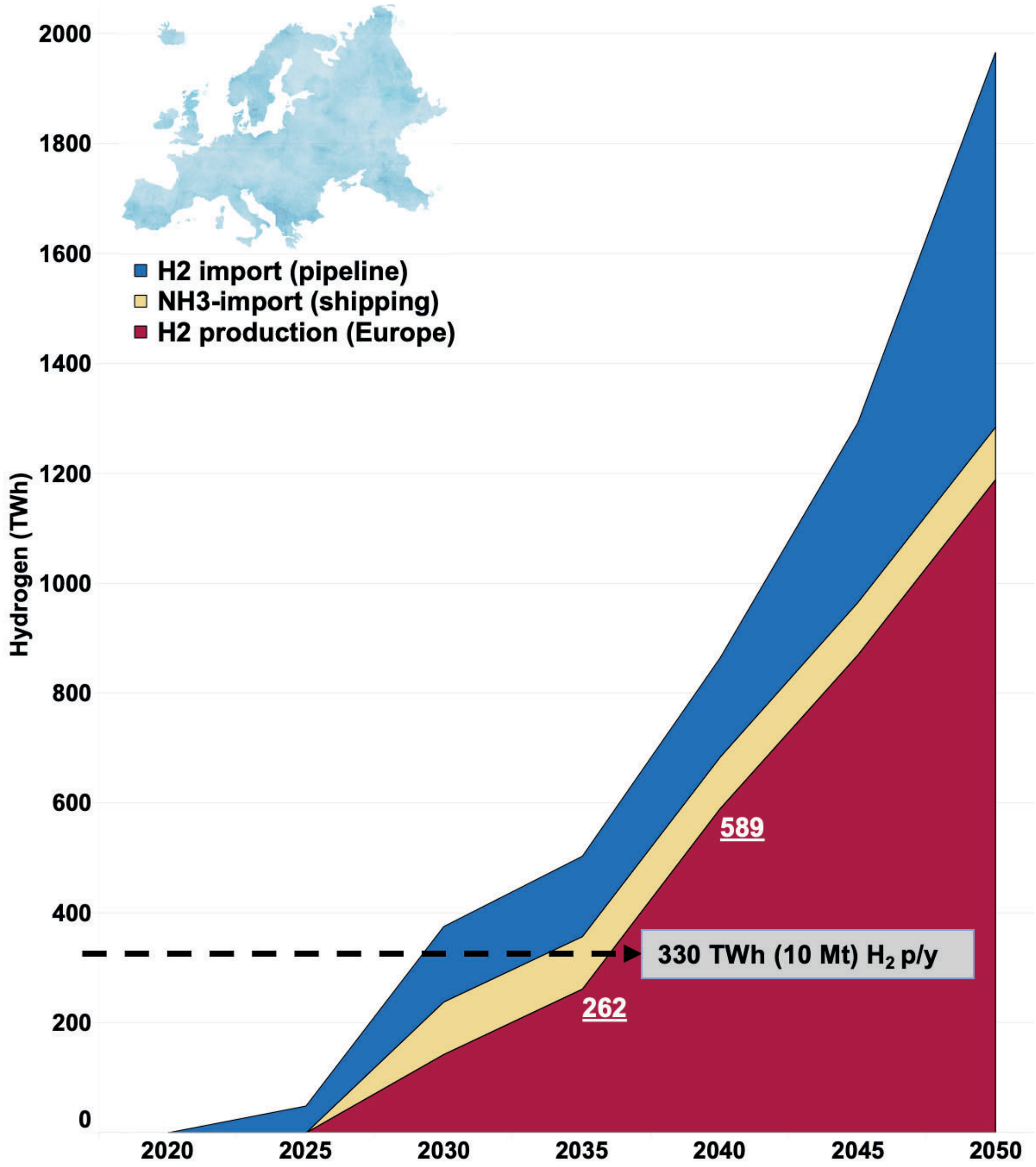


*Figure 5: Hydrogen import (and ammonia), production and consumption in Europe (2020-2050). Source: Authors based on the SCOPE SD and IMAGINE model linkage (2023).*

5 Conventional production consists of captive and merchant reforming, which also includes partial oxidation and gasification, and by-product hydrogen capacities from ethylene, styrene, and the electrolysis of brine. The average production capacity utilization across Europe in 2020 was 76%.

## 3.1. Hydrogen production and consumption: Technical-economic assessment

The estimate resulting from linking SCOPE SD and IMAGINE is that Europe, i.e., the EU member states excluding Malta and Cyprus but including Great Britain, Norway, and Switzerland, will reach a total renewable hydrogen production capacity of 4.3 Mt (143 TWh) by 2030 and 36 Mt (1189 TWh) by 2050.

From this macroeconomic perspective of cost optimization, Europe will reach the REPowerEU target of 10 Mt (330 TWh) domestic hydrogen production sometime between 2035 and 2040 (Figure 5 and Table 3).

The analysis in Figure 5 and Table 3 is based on several scenarios, including one from the European Association for the Cooperation of Transmission System Operators (ENTSOG and ENTSO-E), and assumptions regarding the expansion potential of renewable energy sources in Europe by 2030 and the implementation of the EU's climate targets (ENTSOG & ENTSO-E 2022).

Regarding hydrogen consumption per sector, we show that Europe will require approximately 2000 TWh (or 60 Mt) of clean hydrogen by 2050. This ambitious scenario, which is used for optimization purposes in SCOPE SD and IMAGINE, is composed of several data sources (ENTSOG & ENTSO-E 2022; Netzentwicklungsplan 2022; AGORA Energiewende and AFRY Management Consulting 2021)[6].

Our analysis based on the model linkage of SCOPE SD and IMAGINE in Figure 6 shows that 376 TWh (11.4 Mt) constitutes a very ambitious and maximum $H_2$ demand realization that can be met in Europe by 2030.

**Table 3: Hydrogen import (and ammonia), production and consumption in Europe between 2020 and 2050 (TWh). Source: Authors based on the model linkage of SCOPE SD and IMAGINE (2023).**

| TWh | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|
| $H_2$ import (pipeline) | 0 | 49 | 138 | 147 | 179 | 327 | 682 |
| $H_2$ consumption | 0 | 49 | 280 | 410 | 768 | 1197 | 1871 |
| $H_2$ production in Europe | 0 | 0 | 143 | 262 | 589 | 870 | 1189 |
| Ammonia import ($H_2$ eq.) | 0 | 0 | 95 | 95 | 95 | 95 | 95 |
| Total production and import | 0 | 49 | 376 | 504 | 863 | 1292 | 1966 |

When breaking down the overall European consumption per sector over the same period, the analysis shows a dominant role for hydrogen as a feedstock in industry, increasing roles in transport and power and heating plants from 2040 onwards, and a decrease in refining purposes (Figure 6).

6 From Agora Energiewende and AFRY Management Consulting (2021), data from "Industrial hydrogen demand from 2020 to 2050 within the specific demand sectors in TWh per year" are used here.

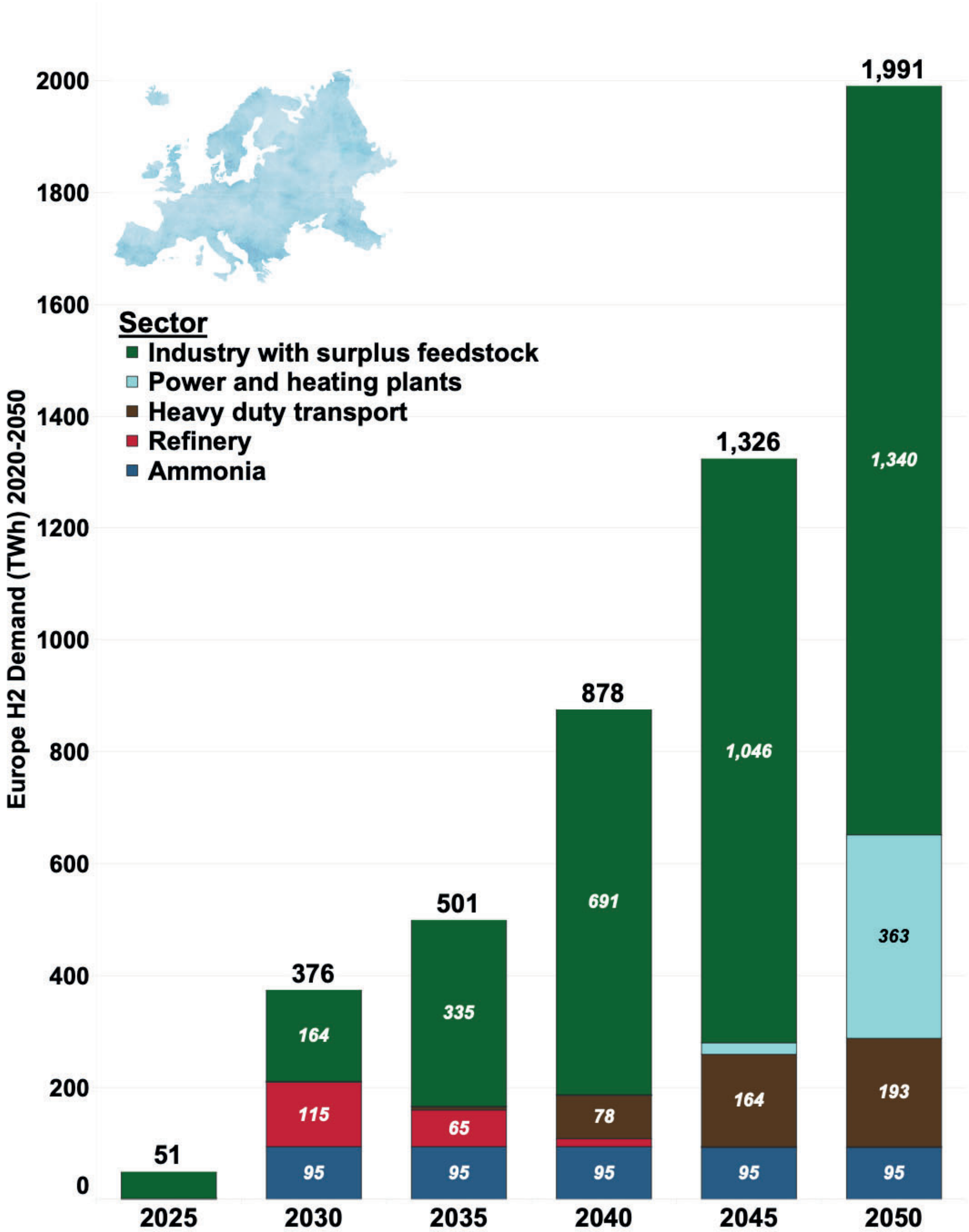


*Figure 6: European sectoral hydrogen demand (TWh) between 2020 and 2050.*
*Source: Authors based on the SCOPE SD and IMAGINE model linkage (2023).*

Hydrogen consumption in the industry refers to furnaces and feedstocks, and these are primarily the chemical and steel industry, but also the paper, food, non-metal, and non-metallic mineral industries. Ammonia consumption will switch completely to green imports from 2030 onwards and stays constant over time. It is not defined here where these green imports will exactly come from, but an option could be via shipping from Oman.

Moving from the overall demand and supply at the European towards the country level, Figures 7a and 7b visualize the differences between production and demand per European country in 2030 and 2050, respectively.

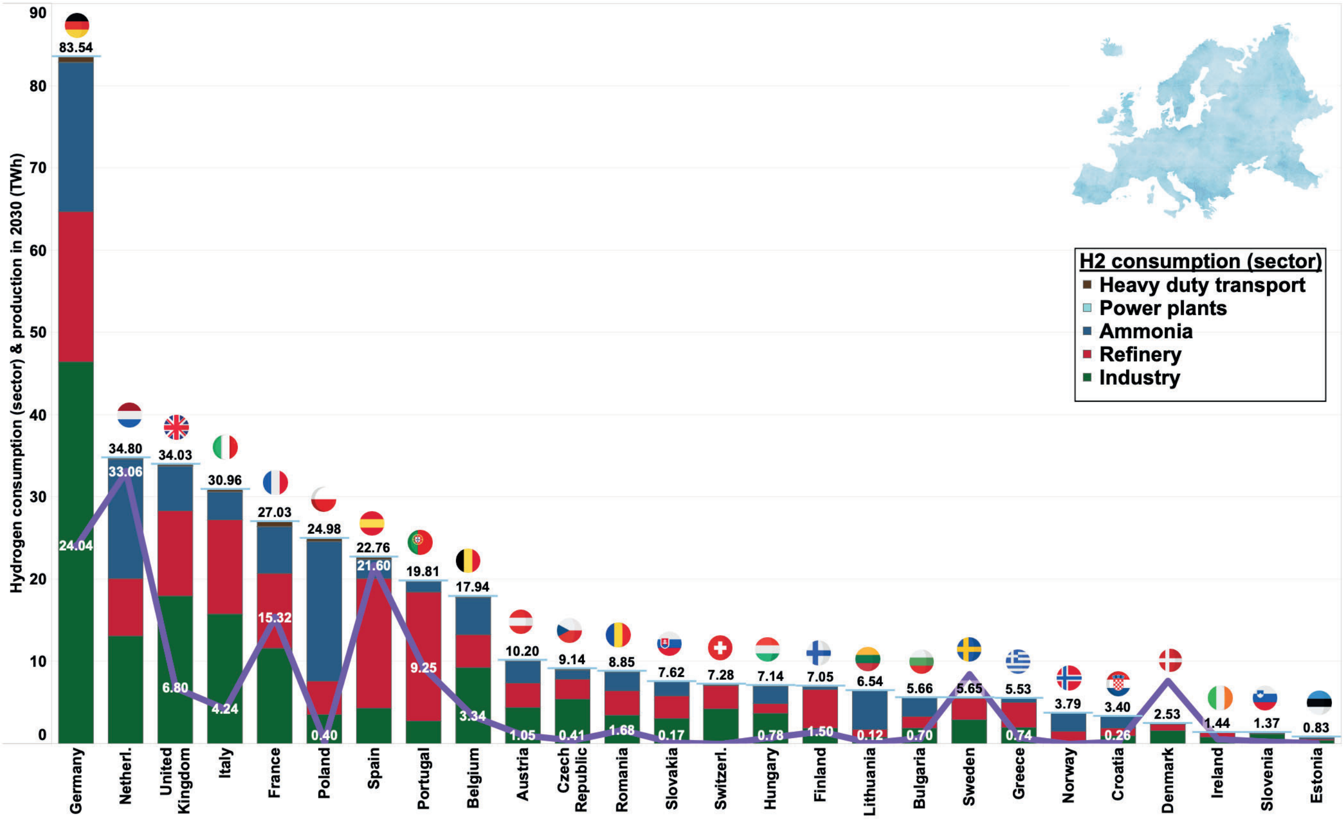


*Figure 7a: Hydrogen sectoral consumption (stacked bars) and production (line) in Europe in 2030 (TWh) and excluding Latvia, Luxembourg, and Cyprus.*

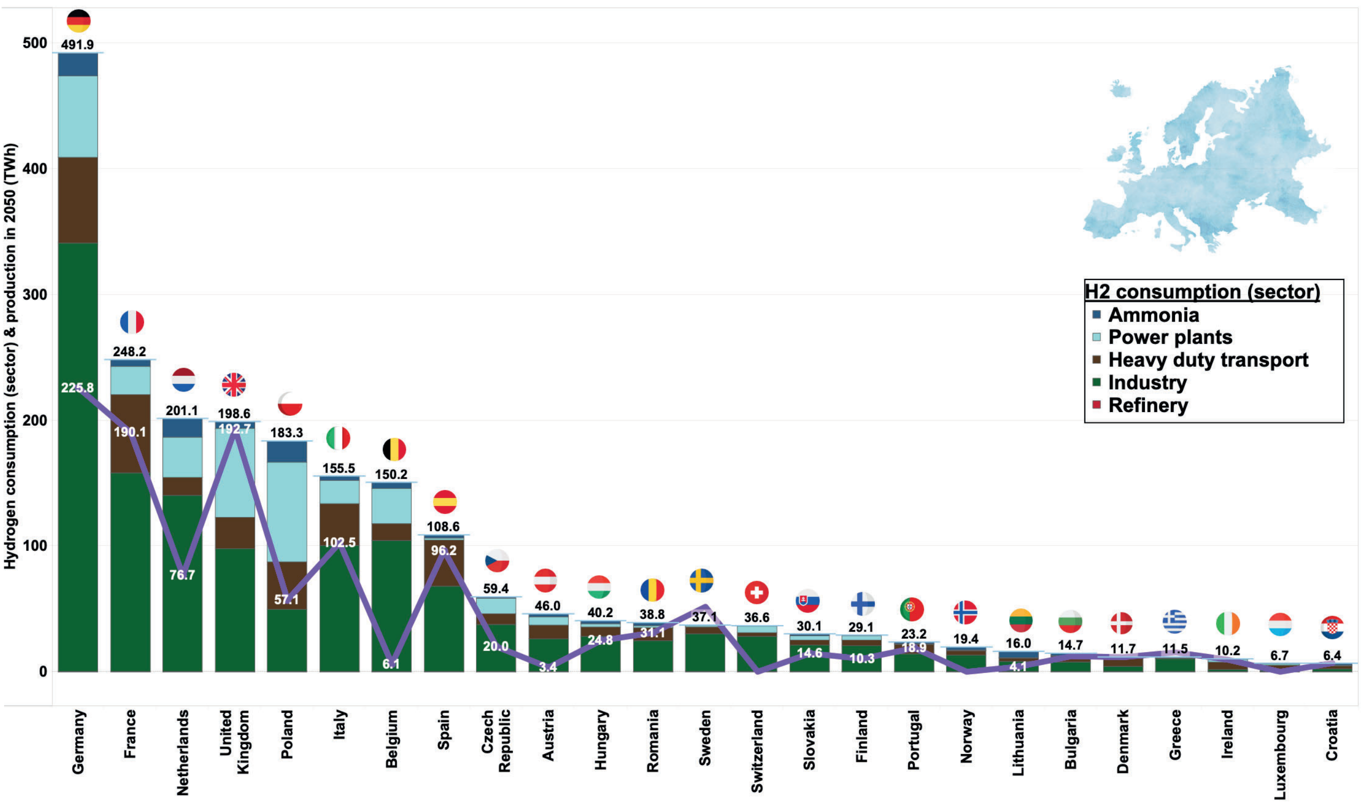


*Figure 7b: Hydrogen sectoral consumption (stacked bar) and production (line) in Europe* in 2050 (TWh) and excluding Slovenia, Estonia, Latvia, and Cyprus. Source: Authors based on the SCOPE SD and IMAGINE model linkage (2023).*

What stands out from these figures is that Germany will be Europe's hydrogen import 'juggernaut', as it faces a gap between production and sectoral consumption of approximately 1.8 Mt (60 TWh) in 2030 and almost 8 Mt (266 TWh) in 2050. Other countries that are poised to become significant importers by 2050 are Belgium (4.3 Mt/144 TWh), Poland (3.8 Mt/126 TWh), the Netherlands (3.7 Mt/124 TWh), and Italy (1.6 Mt/53 TWh). Figures 7a and 7b also point towards a shift in consumption from 2030 to 2050, as hydrogen for refining purposes has disappeared almost completely and hydrogen usage in power plants and heavy-duty transport has started playing a significant role. Overall, the modelling results underline the general assumption that north-western Europe, led by Germany, will be a significant hydrogen importer.

## 3.2. Infrastructure and storage: technical and strategic aspects

Storage infrastructure will be necessary to secure the supply of hydrogen imported from the MENA region and to help maintain the efficiency and affordability of the nascent regional markets. The best options for large-scale hydrogen storage are (new) salt caverns followed by depleted natural gas reservoirs (Table 4).

**Table 4: Hydrogen storage technologies and associated considerations. Source: Kuhn and Yovchev (2022).**

| Energy storage type | $H_2$ storage option | Stor. cap. (TWh) | Response / turn-around time | Durat. | TRL | Deploy timef. | Dem. side appl. | Hazard toxicity |
|---|---|---|---|---|---|---|---|---|
| Geolog. | New salt cavern | 1.5 | Fast response (1 hour) | Multiple annual cycles | High | High | Various users across power, industry, and heat | Low |
| | Repurposed hydrocarbon reservoir | 9 | Slow response (12-24 hours) | Single seasonal cycles | Low | High | Large-scale seasonal heat demand | Medium |
| Import | $H_2$ pipeline | | Fast response | n/a | High | Medium | Multiple users across power, industry, and heat | Medium |
| | Ammonia | | Slow response (days dependent on shipping) | n/a | Medium | High | Limited due to response time, target large predictable swings in demand such as heat | High |

Salt caverns have outstanding properties such as high integrity (tightness of gas), inertness (limited reactions), increased flexibility (multiple annual cycles), and moderate investments and operating costs (Kuhn and Yovchev, 2022). A recent study estimates that the technical potential for hydrogen storage in Europe is 2,596 Mt (84.8 PWh) of hydrogen in caverns in bedded salt and salt domes located outside of rural, urban and protected areas and away from major infrastructure (Caglayan et al. 2020). It is important to point out that the term "technical potential" means the maximum storage potential that could be utilized without considering ecological, economic, or social aspects (Figure 8).

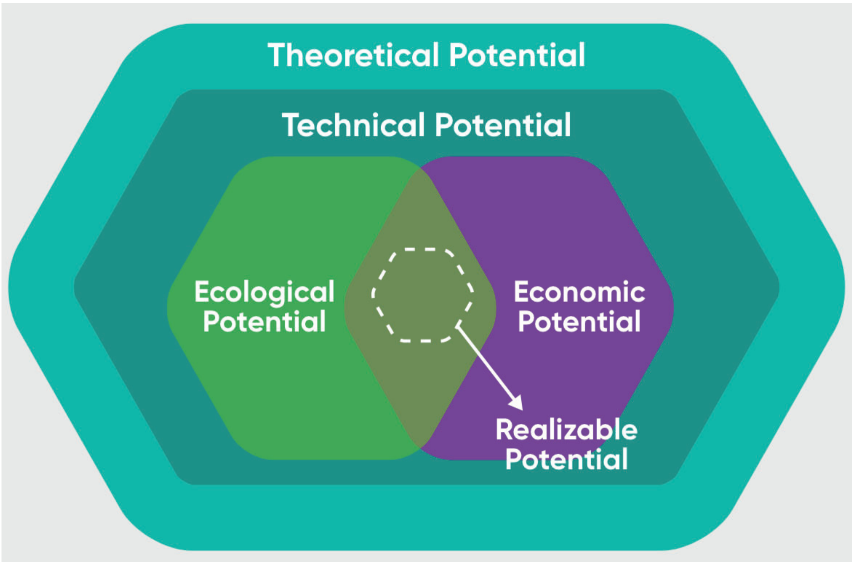


*Figure 8: Different types of hydrogen storage potential.*
*Source: Kuhn and Yovchev (2022).*

Considering these additional aspects reduces the realizable potential for hydrogen storage. Another fact is that the technical potential is unequally distributed across Europe. As much as 42% of Europe's total theoretical hydrogen storage capacity is in Germany's onshore and North Sea areas, equivalent to 1,079 Mt (35.61 PWh) of hydrogen. The Netherlands is next with 315 Mt (10.4 PWh), followed by Great Britain with 272 Mt (9 PWh) and runners-up Denmark, Norway, and Poland.

Storing hydrogen in depleted natural gas reservoirs is potentially possible by repurposing existing facilities. The advantages of this type of reservoir lie in their availability, large capacity, proven tightness for hydrocarbons and operational experience. However, the disadvantages are their low technological readiness level (TRL), the risk of geo-chemical or microbiological reactions, the need for higher amounts of cushion gas, the tightness of the reservoir for hydrogen that needs to be examined, and the gas treatment that can increase the costs of storage. The literature indicates that 80 operational depleted natural gas reservoirs are currently being used across Europe to store natural gas (Kuhn and Yovchev, 2022). Hydrogen storage in depleted natural gas reservoirs has not yet been demonstrated commercially. The total technical working gas capacity is 842.28 TWh of natural gas, which would be 202.14 TWh when converted to hydrogen (Kuhn and Yovchev 2022).

Following a decrease in natural gas storage capacity, the analysis shows an economically optimized assessment of the long-term expansion of hydrogen storage in salt caverns up to 2050, which would amount to around 216 TWh of technical potential by 2050. Most of this would consist of new capacity (Figure 9).

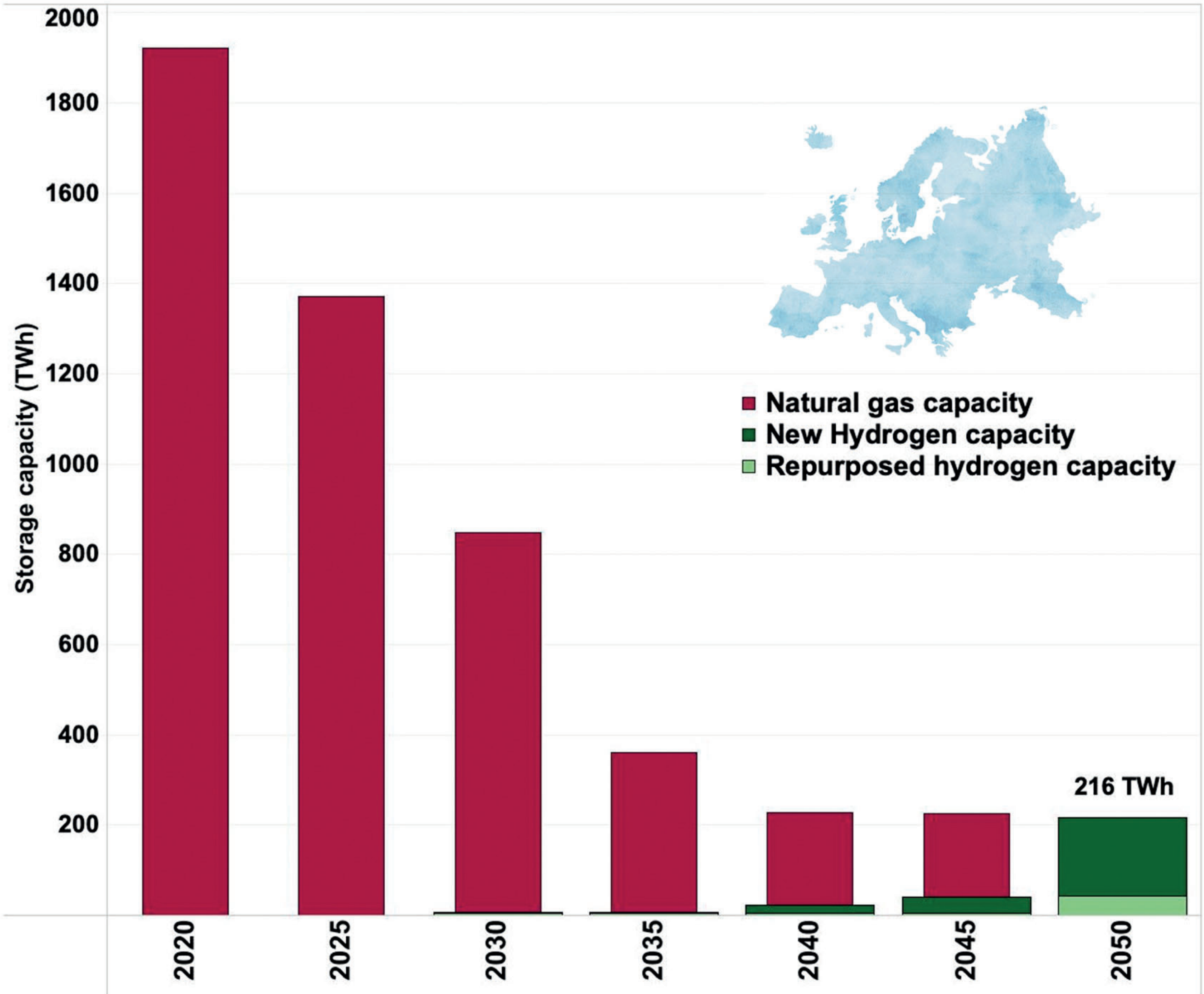


*Figure 9: Decrease in natural gas storage and expansion of hydrogen storage in salt caverns in Europe between 2020 and 2050 (TWh). Source: Authors based on the SCOPE SD and IMAGINE model linkage (2023).*

In this analysis, the need for hydrogen storage before 2045 is low, because it is assumed that hydrogen is mainly needed in the industry sector, which shows limited seasonal variation in demand patterns. From 2045 onwards, however, hydrogen demand takes off in end-use sectors like transport, heating, and electricity, which are much more prone to seasonal variation. This analysis does not incorporate dispatch or load flow restrictions within markets, which could lead to increased storage needs. It is also endogenous to the SCOPE SD and IMAGINE model that it does not consider options that align with reaching the REPowerEU target. These options include an EU Strategic Hydrogen Reserve with 90 days of net hydrogen imports and storage options beyond salt caverns like empty gas fields or ammonia tanks (Van Wijk, Westphal, Braun 2022). These strategic considerations would drastically scale up the EU's hydrogen storage requirements and capabilities as early as 2030 and would be hugely challenging considering the short timeframe and still evolving regulatory framework.

Developing 216 TWh of hydrogen storage capacity across Europe should be regarded as a massive endeavor relative to today's existing repurposing potential of a maximum of 49 TWh. Figure 10 illustrates the figures at country level across Europe. Regarding hydrogen capacity (new and repurposed), this undertaking needs to be carried out in five European countries: Germany, France, Great Britain, Poland, and the Netherlands.

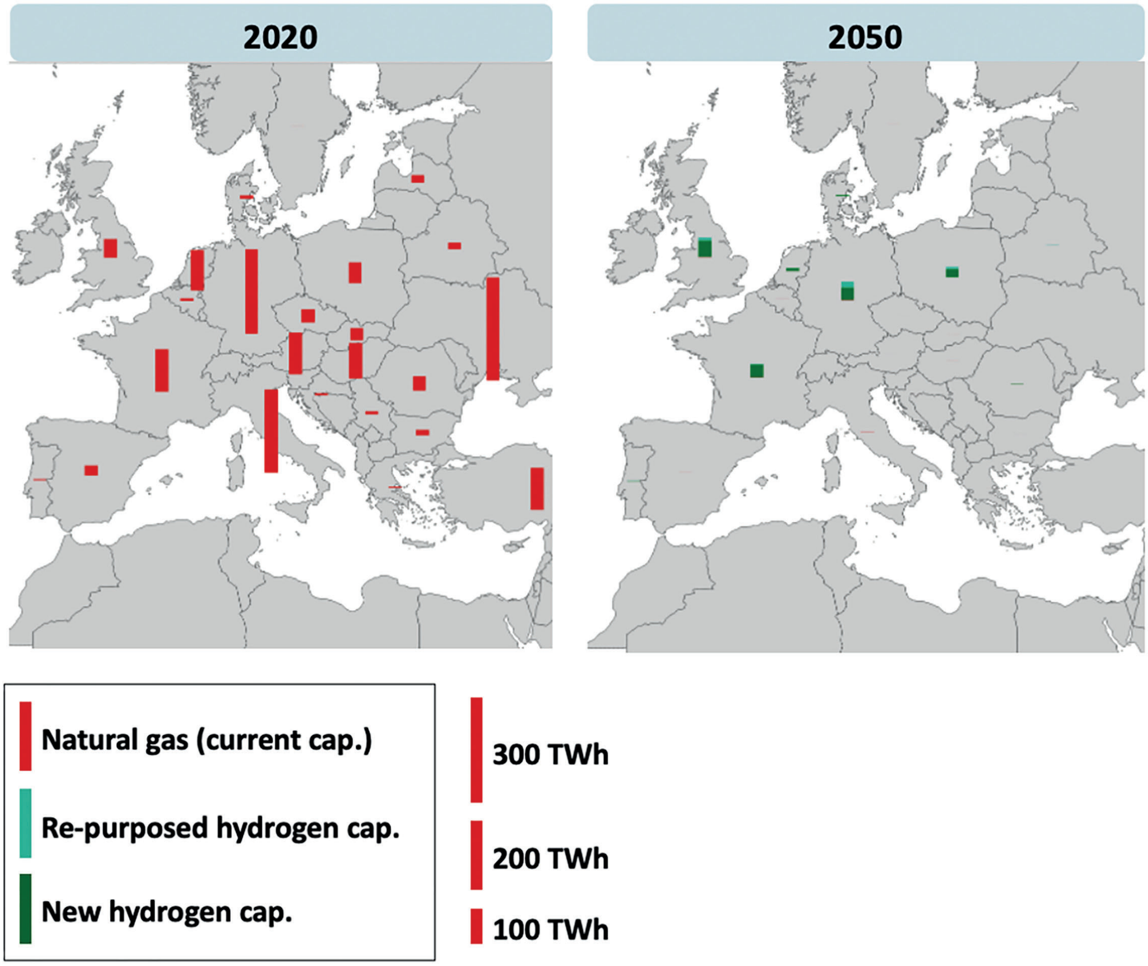


*Figure 10: Natural gas, repurposed and new hydrogen storage capacity across Europe (TWh) between 2020 and 2050. Source: Authors based on the SCOPE SD and IMAGINE model linkage (2023).*

The technical estimations regarding imports from the MENA region and domestic production also significantly affect Europe's infrastructure requirements. Figure 11 shows the decline of the natural gas pipeline infrastructure and favors the expansion of hydrogen pipelines, including the considerable and required repurposing potential and the new construction needed by 2050.

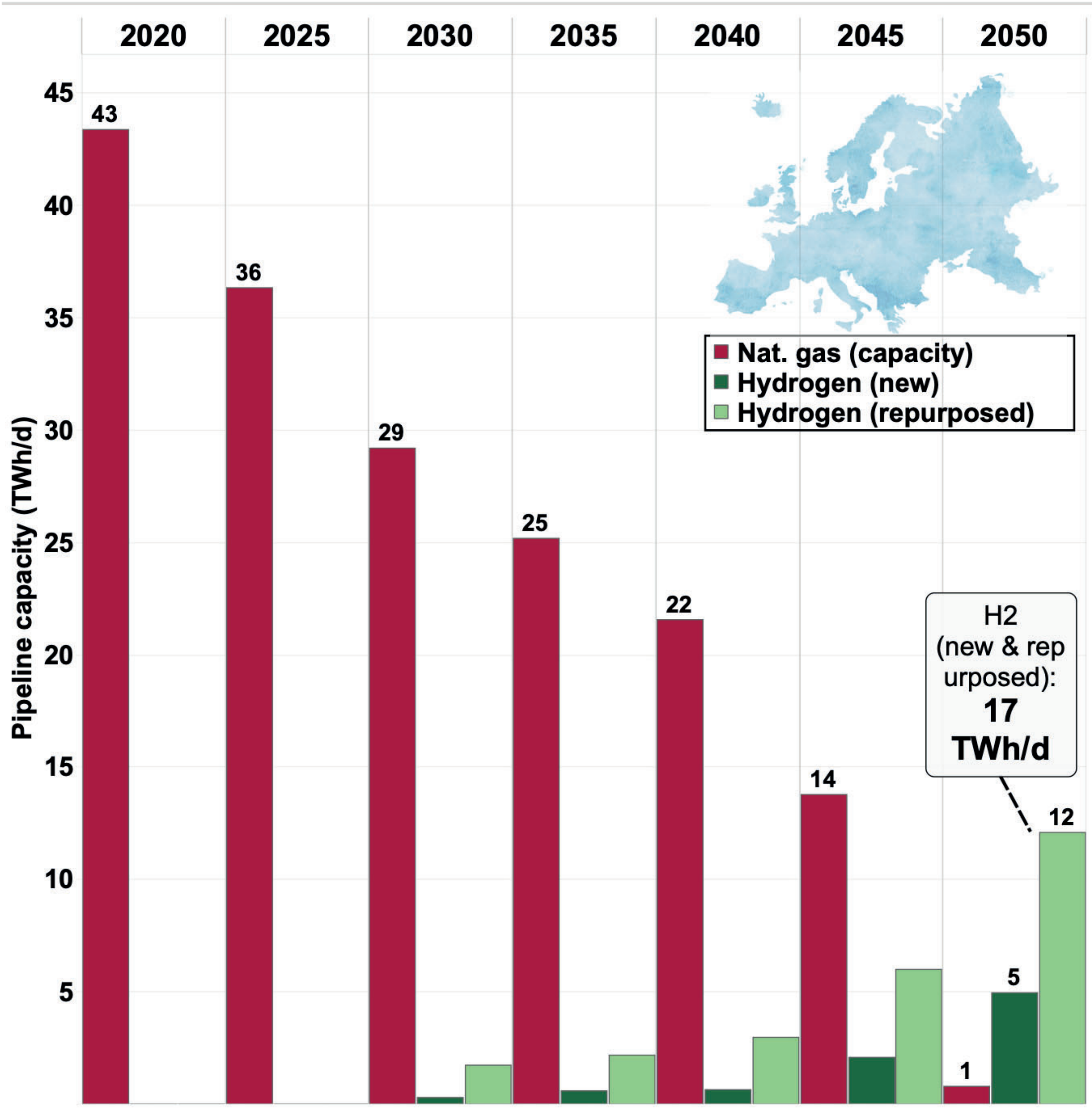


*Figure 11: European pipeline transmission capacity for natural gas and hydrogen (2020-2050).*
*Source: Authors based on the SCOPE SD and IMAGINE model linkage (2023).*

It is possible to integrate larger quantities of hydrogen by repurposing existing natural gas-based infrastructure in Europe. Here, MENA imports by pipeline can contribute to European energy security in the medium term. Figure 11 also shows that substantial new hydrogen pipeline capacity is required from 2050 onwards.

From 2050 onwards, Figure 12 shows the need for new pipeline capacity from MENA rope, especially between Morocco and Spain, between Algeria and Italy and from Egypt/Saudi Arabia to (possibly) Turkey.

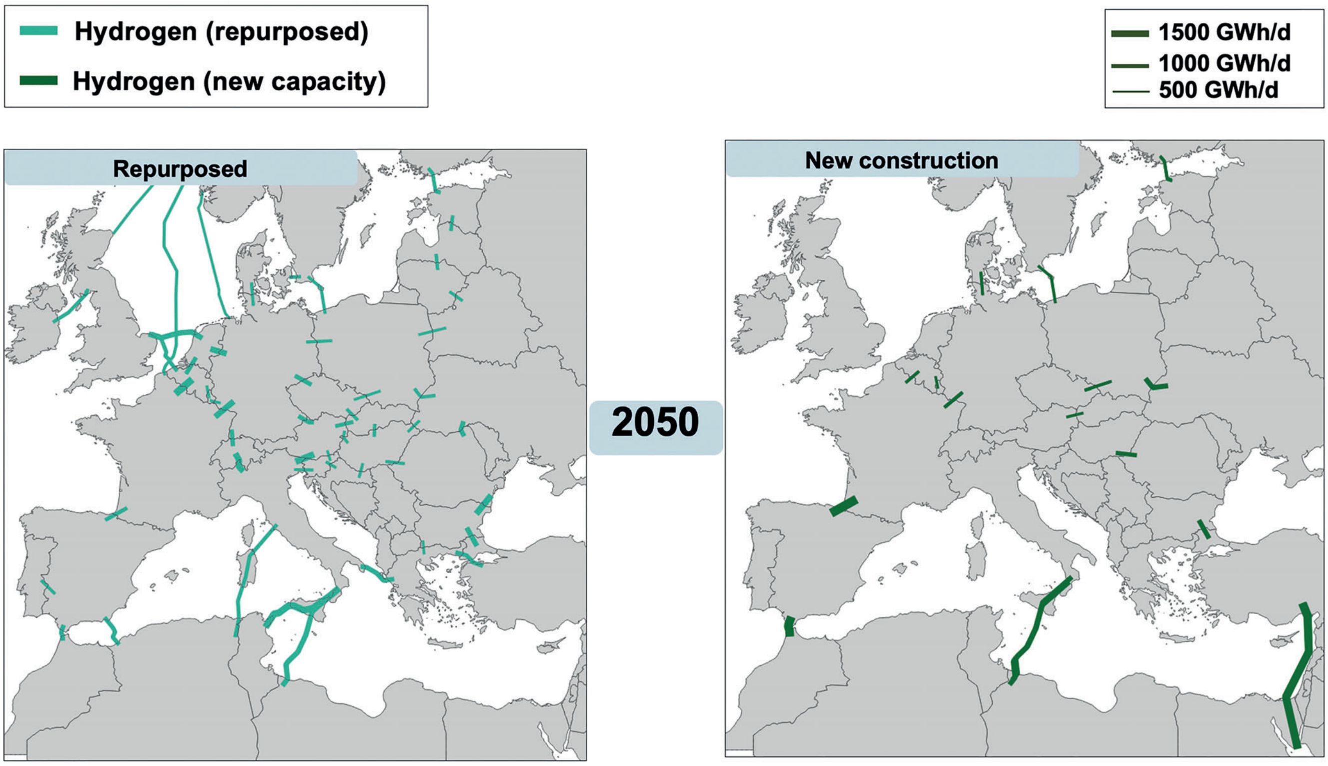


*Figure 12: Hydrogen (new and repurposed) pipeline transport capacity (2020-2050).*
*Source: Authors based on the SCOPE SD and IMAGINE model linkage (2023).*

Note that this macroeconomic and technical analysis is focused on cost optimization. The war in Ukraine and REPowerEU has highlighted the increasing importance of the strategic dimension of Europe's hydrogen economy ambitions. Box 1 provides an example and suggests redesigning the proposed and politically controversial 'EastMed' natural gas pipeline for clean hydrogen as soon as 2030.

## Box 1: The EastMed hydrogen pipeline


*Figure 13: The EastMed pipeline as a repurposed clean hydrogen pipeline linked with Egypt and Saudi Arabia. Source: Braun, Van Wijk, Westphal (2023).*

In the Eastern part of the Mediterranean Sea, natural gas has been found under the seabed in areas belonging to Egypt, Israel, Turkey, and Cyprus, and concessions for exploration have been granted. The EastMed pipeline was meant to transport gas from offshore deposits near Israel and Egypt across 1,250 kilometers via Cyprus and Greece to European markets using the Poseidon interconnector pipeline in Italy. The problem with the original natural gas-based project is that the US government pulled its support in early 2022, citing environmental reasons for its decision to no longer support energy projects that are not green, the lack of the project's economic and commercial viability, but also the fact that the project was creating tensions in the region by excluding Turkey (Stamouli 2022). In compliance with the aims and ambitions of REPowerEU, there are plans to designate and develop this 'EastMed' pipeline as a clean hydrogen pipeline (Van Wijk, Westphal, Braun 2022). The 'Mediterranean' natural gas could be converted into hydrogen and solid carbon, e.g., via methane pyrolysis, and fed into the EastMed pipeline. The EastMed hydrogen pipeline could be linked with production sites in NEOM in northwest Saudi Arabia and Sharm El-Sheik, and others in Egypt. This pipeline linkage would allow these MENA countries to transport clean hydrogen to the European hydrogen backbone. Making the 'EastMed' hydrogen-ready would serve the decarbonization ambitions of the involved countries and diversify Europe's transport and supply options. Simultaneously, the EastMed clean hydrogen pipeline would require the resolution of a range of high-level political issues, including long-running tensions between Turkey and neighboring countries, plus the fact that the EastMed pipeline network would also include Israel, with whom Saudi Arabia currently has no diplomatic ties.

# 4. Clean hydrogen in the MENA region

Countries in the MENA region, particularly those on the Gulf Cooperation Council (GCC), have all the prerequisites for producing cost-effective clean hydrogen: fossil-fuel capacities, an abundance of cheap natural gas resources for 'blue' hydrogen and excellent conditions for the low-cost renewables needed for renewable ('green') hydrogen. Coupled to their proximity to growth markets across Europe and Asia, MENA countries are therefore well positioned to develop into top global suppliers of hydrogen and its derivatives in the emerging global market.

For the MENA region, suitable near-term applications include the petrochemicals and refining industries (which currently depend on grey hydrogen and could shift to cleaner hydrogen vectors), steel and aluminum smelters, ammonia, and methanol. In the medium to long term, the prospective applications include large-scale seasonal energy storage, long-haul transportation, and maritime shipping.

In the medium term, natural gas-based (or 'blue') hydrogen is a more attractive option for the MENA region. Blue hydrogen can be produced relatively cheaply, and only slightly disrupts the existing business models of International Oil Companies (IOCs) and National Oil Companies (NOCs). This is a key metric in the energy transition since hydrocarbon producers will play a major role in decarbonizing the upstream oil and gas sector to help reach net-zero targets by mid-century.

Solar PV leads project investments at both the planned and committed stages of development, with a 50% share by project value, as shown in Figure 14, followed by clean hydrogen (21%), nuclear (14%), and wind (10%).

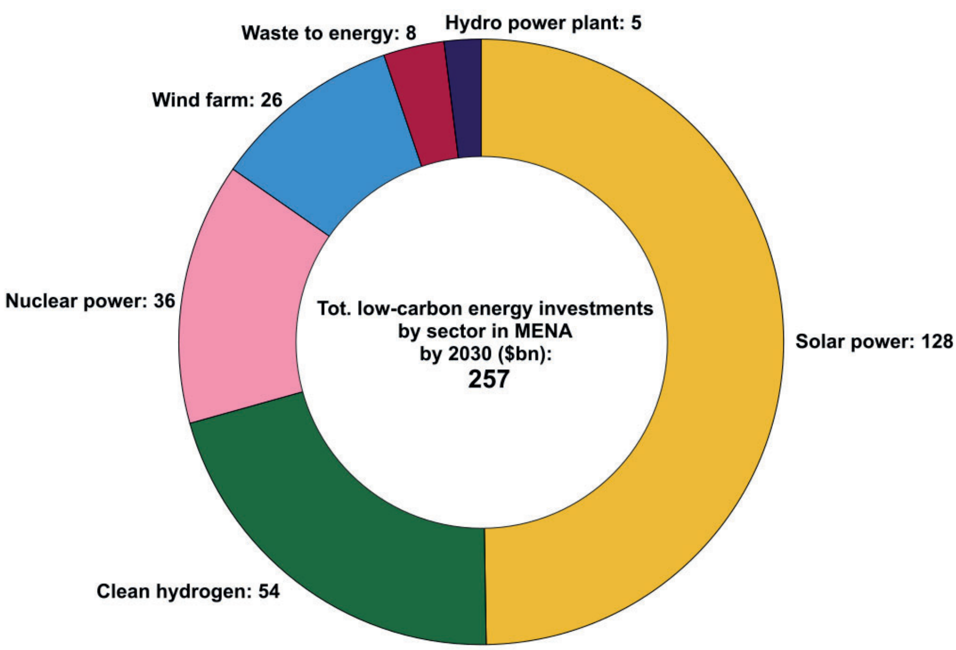


*Figure 14: Low- and zero-carbon energy investments by sector in the MENA region by 2030. Source: Al-Ashmawy and Shatila (2022).*

Of the more than sixty projects announced in the Middle East (mainly in Egypt, Oman, the United Arab Emirates and Saudi Arabia), 80% focus on producing renewable hydrogen (Roland Berger Middle East 2023). Simultaneously, the literature recognizes five significant challenges that are currently hindering the development of a hydrogen ecosystem in MENA countries and across the region (ibid.). These are:

- Lack of national strategies, regulations, and institutional design.
- Inadequate infrastructure (including solar PV plants, electrolysers, pipelines, and storage units).
- Low local demand for clean hydrogen (lack of regulations and incentives).
- Lack of certification and standards.
- Insufficient human capital development, educational programmes, sector-specific training, and capacity for local technology development.

These and other challenges make it hard to accurately estimate the local clean hydrogen production and demand in MENA countries. Despite these uncertainties, the SCOPE SD and IMAGINE energy system models, as well as the evaluation criteria used in the Global PtX-Atlas and HYPAT projects, can assess the technical potential and socio-economic aspects of the hydrogen value chain in the selected MENA countries.

## 4.1. Technical-economic assessment

Renewable hydrogen projects are capital-intensive, with relatively high upfront investment costs and then lower operating and fuel expenditures over their lifetime. Rapidly increasing investment in clean hydrogen is strongly dependent on improving access to low-cost financing, particularly in emerging and developing economies (IEA 2021). Calculating the cost of capital for an investment is commonly expressed as the weighted average cost of capital (WACC). For utility-scale solar PV projects, for example, the WACC can amount to 20% - 50% of the levelized cost of electricity, so lower financing costs are critical for the affordability of renewable-based hydrogen (IEA 2021).

In addition, there are uncertainties about the development of capital costs over time and until 2050. Since the political and regulatory framework in the respective MENA country is decisive for investments, the World Bank's Regulatory Indicators for Sustainable Energy (RISE) are used here as an indicator of capital costs. This assumes that countries with good investment conditions will have low capital costs.

The RISE score is used to evaluate the political and regulatory conditions in countries in the three categories of "energy access," "energy efficiency," and "renewable energy" (Banerjee et al. 2016). The assessment of the "Renewable Energies" category is based on various indicators and sub-indicators, which are used, for example, to map national targets for renewable energies, legal framework conditions or the characteristics of financial and regulatory incentives.

This paper makes two different assumptions for 2030 and 2050: For 2030, the cost of capital is estimated based on the "Renewable Energy" category from the RISE Score. This score is used to scale up the WACC from 4% to 14%. For 2050, on the other hand, no country-variable assumptions are made, and a WACC range between 4% and 14% is assumed for all countries. Table 5 summarizes these variables for the selected MENA countries.

**Table 5: RISE Score, capital costs, and mean capital costs for selected MENA countries (2030 and 2050). Source: Authors based on Global PtX-Atlas.**

| Country | RISE Score[2] | Capital costs (2030) | Mean capital costs (2050) | Bandwidth of capital costs (2050) |
|---|---|---|---|---|
| Morocco | 71 | 6.9% | 8% | 4% - 14% |
| Algeria | 45 | 9.8% | | |
| Tunisia | 79 | 6.0% | | |
| Libya[8] | - | 12.1% | | |
| Egypt | 77 | 6.2% | | |
| Saudi Arabia | 39 | 10.4% | | |

The production cost analysis for the MENA countries is based on the variables in Table 2 (CAPEX, OPEX, and efficiency percentage of selected technologies) and considers up to thirty simulated sites for each country (Pfennig et al. 2022). Based on these assumptions, Table 6 derives the following hydrogen production costs, which are visualized in Figure 15.

**Table 6: Production costs (EUR/MWh) in the MENA countries in 2030 and 2050. Source: Authors based on Global PtX-Atlas.**

| Country | Production costs (2030) | Production costs (2050) | | |
|---|---|---|---|---|
| | | Mean | Lower limit | Higher limit |
| Morocco | 76.2 | 63.3 | 49.5 | 79.0 |
| Algeria | 104.5 | 72.4 | 56.6 | 90.3 |
| Tunisia | 84.6 | 73.2 | 57.2 | 91.3 |
| Libya | 110.6 | 69.4 | 54.3 | 86.6 |
| Egypt | 79.3 | 67.8 | 53.0 | 84.6 |
| Saudi Arabia | 106.4 | 70.9 | 55.4 | 88.5 |

7 https://rise.esmap.org/.

8 Libya is not included in the RISE Score, so it was categorized manually using the socio-economic indicator from the Global PtX Atlas.

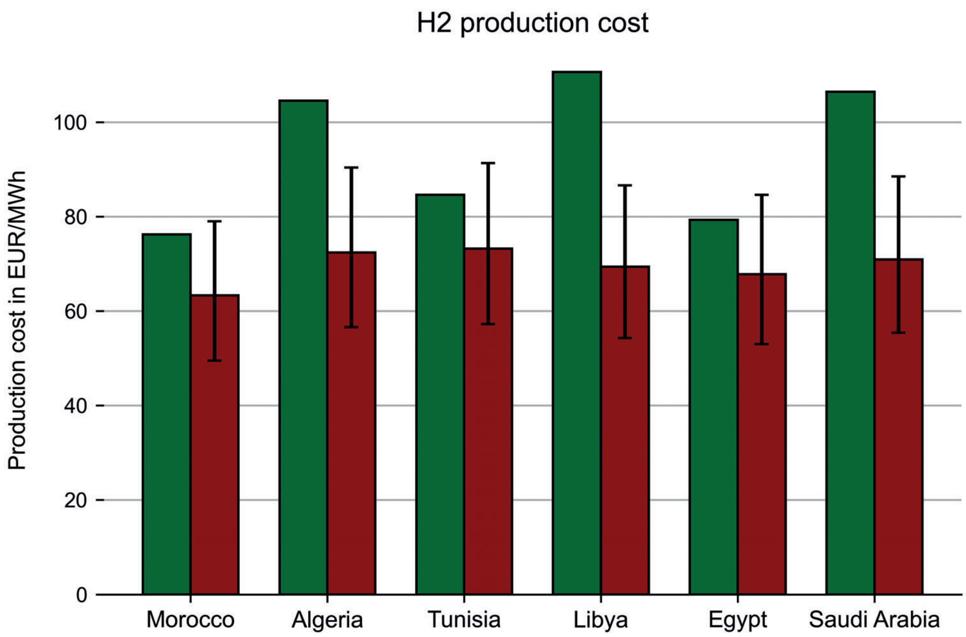


*Figure 15: Production costs (2030) in green and mean production costs (2050) in red, including lower and higher limits, for six MENA countries. Source: Authors based on Global PtX-Atlas.*

Based on the techno-economic potential for hydrogen and the primary (domestic) energy demand, the export potential of the selected MENA countries that could be connected to Europe via pipeline is shown in Table 7 and Figure 16. Considering diversification in line with the REPowerEU strategy of possible supplier countries, a minimum export volume to Europe of 55 TWh per selected MENA country is assumed here (or 330 TWh $H_2$ /yr. divided by the six countries).

**Table 7: Primary energy demand and hydrogen potential (incl. export for the selected MENA countries). Source: Authors based on Global PtX-Atlas.**

| | Primary energy demand TWh/ a yr. | Hydrogen production potential TWh/ a yr. | Hydrogen export potential TWh/ a yr. |
|---|---|---|---|
| Egypt | 728 | 4908 | 4180 |
| Libya | 127 | 3776 | 3649 |
| Saudi Arabia | 1813 | 2685 | 872 |
| Morocco | 198 | 574 | 376 |
| Tunisia | 96 | 361 | 265 |
| Algeria | 493 | 650 | 157 |

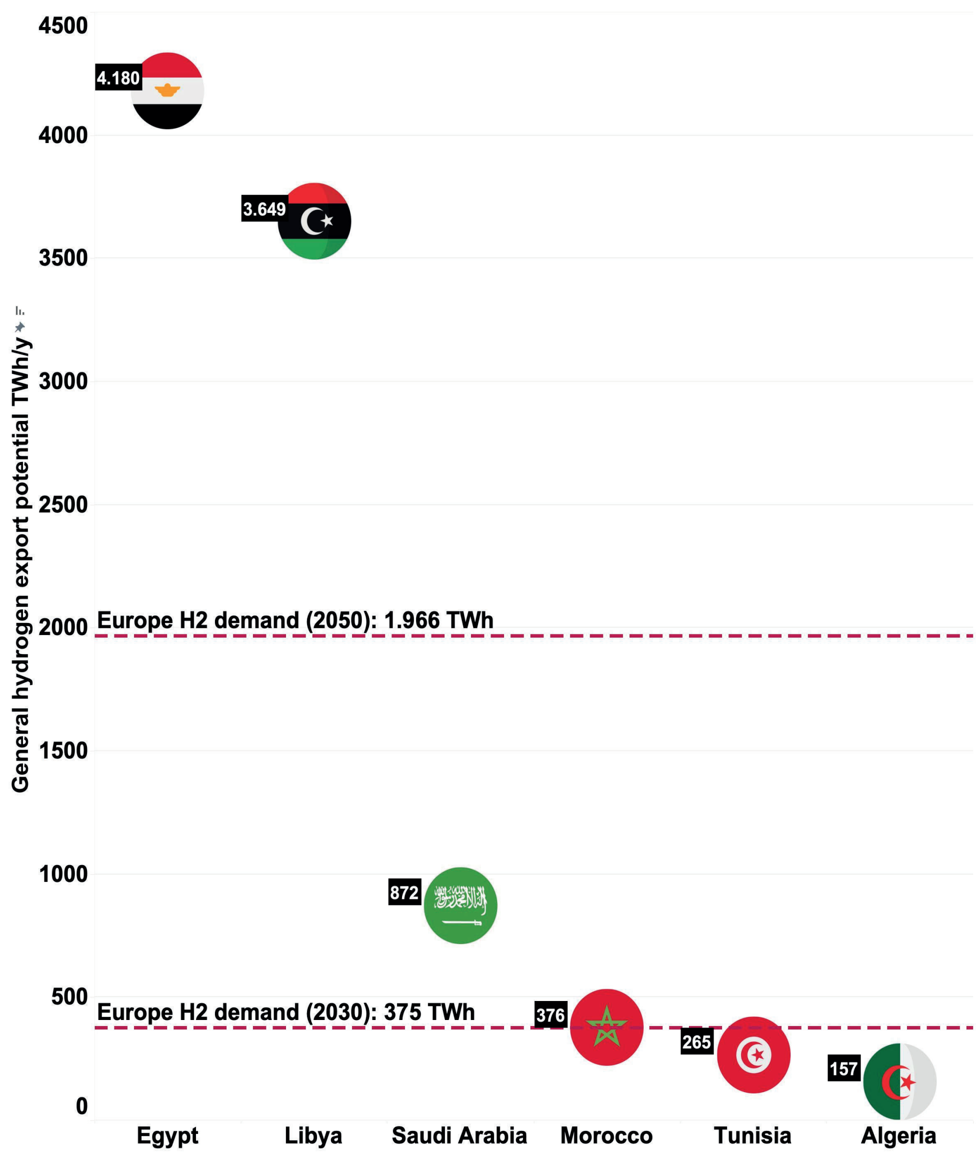


*Figure 16: Techno-economic hydrogen export potential via pipeline (TWh) of selected MENA countries (x-axis) and Europe's hydrogen demand for 2030 and 2050 (y-axis).*
*Source: Authors based on Global PtX-Atlas.*

It is essential to consider primary energy demand, as in many cases the renewable power capacity planned for green hydrogen production is in direct competition with the capacity required to decarbonize local electricity generation. This is especially relevant in the MENA region, where oil and gas currently account for almost 95% of electricity generation (IEA 2022b). Renewables account for around 10% of electricity generation in Egypt, but for less than 3% (ibid.) in nine of the region's ten producer economies. The dominance of fossil fuels makes the emissions intensity of power generation in the MENA region almost 25% higher than the global average (ibid.).

Complementing the potential export analysis, Figure 17a shows the optimal area identified for PtX-production in the six selected countries and the MENA region.

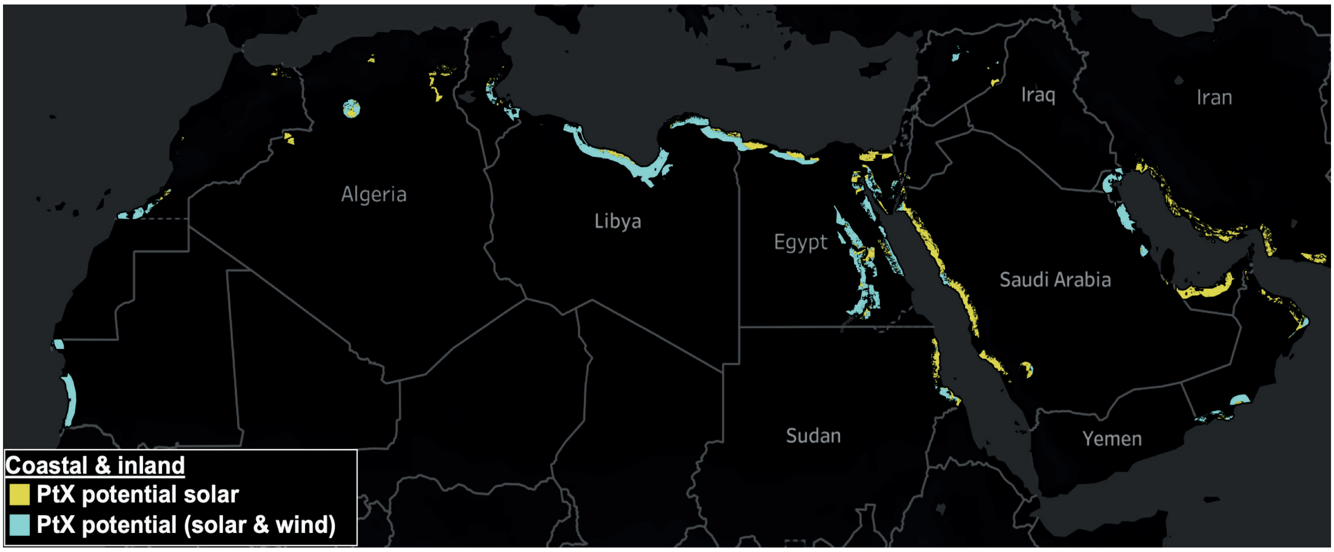


*Figure 17a: Area identified for optimal PtX-production (solar and wind coastal and inland) across the MENA region. Source: Authors based on Global PtX-Atlas.*

The area identified here is based on the exclusion criteria mentioned in Table 1, including nature conservation, infrastructure, water availability, unsuitable areas, PV LCOE, and wind LCOE.

Figure 17a highlights the following:

- The exceptionally large solar and wind potential along the coast of Libya and Egypt, in particular.
- Exceptionally large inland solar and wind capacity in Egypt.
- Limited solar and wind capacity in Algeria, apart from a specific region in the northwest of the country.
- Exceptional solar capacity along the western coast of Saudi Arabia and solar and wind capacity in the country’s Eastern Province.

Figure 17b zooms in on the area identified for optimal PtX production in Saudi Arabia. The analysis confirms the optimal location of the NEOM Green Hydrogen Company plant (on the left-hand side of the figure), which would use 4 GW of wind, solar and battery storage to produce 1.2 Mt of green ammonia per year from 2.2 GW of electrolysers. The areas in the Kingdom's oil-producing Eastern Province identified as optimal in the PtX-Atlas are also noticeable. These areas present a massive opportunity for clean hydrogen production but also for Saudi Aramco to decarbonize some of its operations and electricity usage.

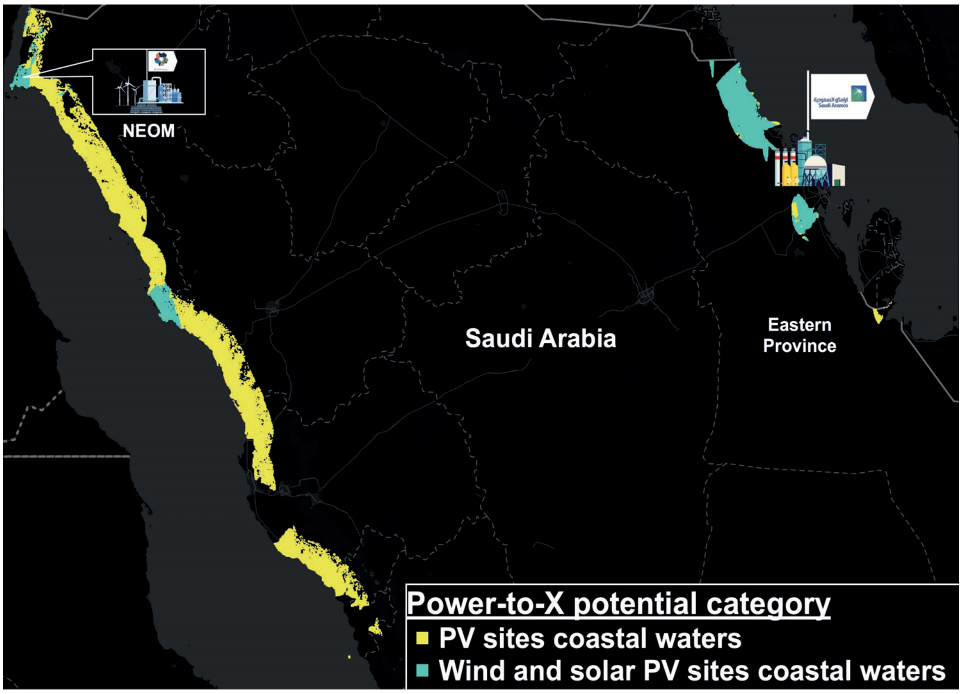


*Figure 17b: Techno-economic PtX-potential of solar and wind along the coastal waters of Saudi Arabia. Source: Authors based on Global PtX-Atlas.*

## 4.2. Theoretical storage potential in salt caverns

As explained in section 3.2, salt caverns represent one of the best options to store large quantities of gaseous hydrogen. Unlike Europe, the MENA region has only a few facilities to store hydrocarbon products. Therefore, the potential of repurposing existing assets for hydrogen storage is very low here. As so few storage sites have been developed in the past, it is also not easy to assess the potential for new storage and this remains a theoretical evaluation, mainly based on a literature review of the geology of the salt deposits.

Factors like depth, diapir geometry, salt heterogeneities, accessibility, availability of water and brine disposal options could limit storage development in salt caverns in the MENA region. These factors are not considered in this evaluation.

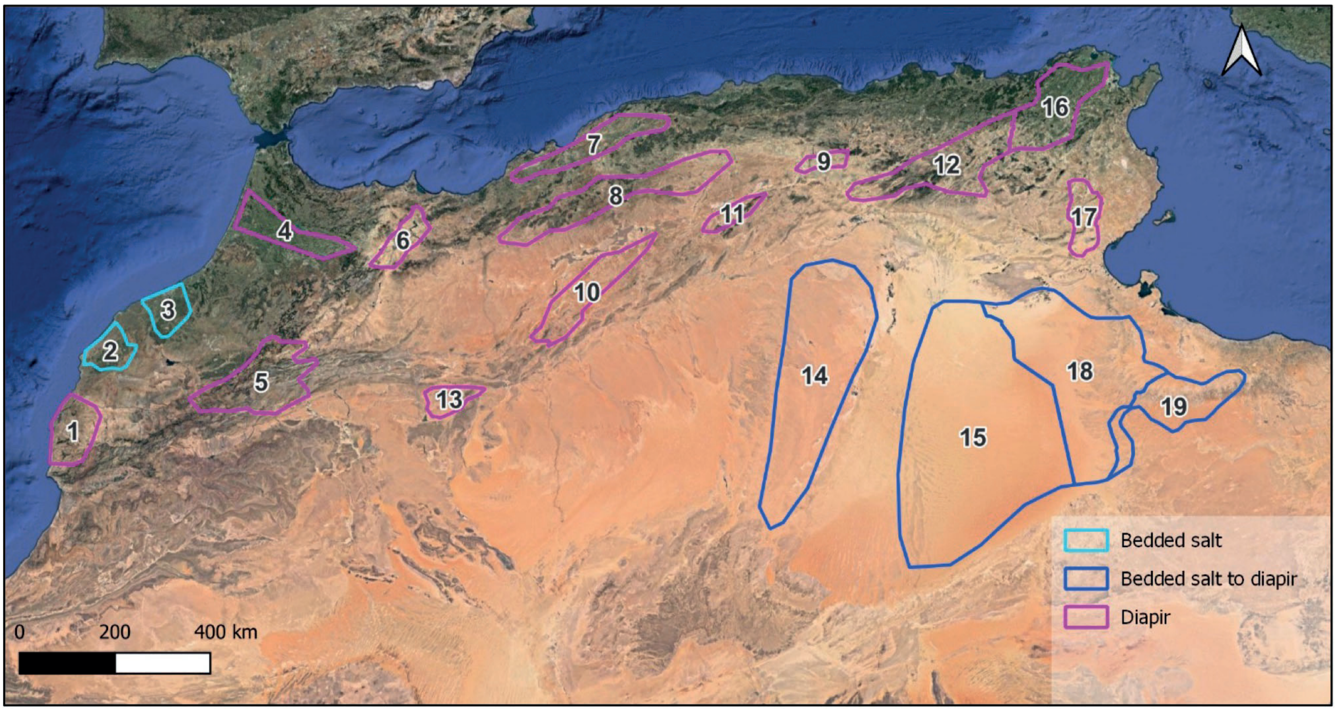


*Figure 18: Schematic map of salt provinces in Morocco, Tunisia, Algeria, and Libya.*
*Map data: Google-Landsat / Copernicus (2015). Sources: Table 8.*

**Table 8: Sources for Figure 18.**

| Map reference | Country | Zone | Surface (km2) | Salt geometry | Source |
|---|---|---|---|---|---|
| 1 | Morocco | Essaouira Basin | 11300 | Diapir | Michard 1976 |
| 2 | Morocco | Doukkala Basin | 6400 | Bedded salt | Michard 1976 |
| 3 | Morocco | Sidi Larbi, Berrechid, El Gara Basins | 6700 | Bedded salt | Michard 1976 |
| 4 | Morocco | Prérif | 11800 | Diapir | Michard 1976 |
| 5 | Morocco | Haut Atlas Marocain | 23400 | Diapir | Vergès et al. 2017 |
| 6 | Morocco | Guercif Basin | 6500 | Diapir | Michard 1976, Hassa et al. 1999 - modified |
| 7 | Algeria | Chellif Basin | 13500 | Diapir | Merabet 1971 |
| 8 | Algeria | Telagh-Prerif trough | 26600 | Diapir | Vergès et al. 2017 |
| 9 | Algeria | Hodna Basin | 2800 | Diapir | Vergès et al. 2017 |
| 10 | Algeria | Saharian Atlas | 16100 | Diapir | Vergès et al. 2017 |
| 11 | Algeria | Atlas-Rocher de sel | 4000 | Diapir | Vergès et al. 2017 |
| 12 | Algeria | Atlas-Milla-El Outaya | 25700 | Diapir | Vergès et al. 2017 |
| 13 | Algeria | Becher Basin | 5000 | Diapir | Merabet 1971 - modified |
| 14 | Algeria | Oued Mya Basin | 73900 | Bedded salt to diapir | Soto 2017 - modified |
| 15 | Algeria | Berkine Basin | 141000 | Bedded salt to diapir | Soto 2017 - modified |
| 16 | Tunisia | Tunisian Atlas | 20300 | Diapir | Vergès et al. 2017 |
| 17 | Tunisia | Kairouan Basin | 8200 | Diapir | Troudi et al. 2017 |
| 18 | Tunisia | Berkine Basin | 70500 | Bedded salt to diapir | Bishop 1975 |
| 19 | Libya | Ghadamis-Sabratah Basins | 21200 | Bedded salt to diapir | Bishop 1975 |

### Morocco

Morocco has several salt deposits are present in Morocco, and some salt caverns have already been developed around Mohammedia to store LPG. This proves the feasibility of creating a salt cavern in Morocco and, in theory, this could comprise several TWh of storage.

### Algeria

Algeria has several salt deposits, some covering a vast area of more than 100 000 km2, but only a small proportion would be suitable for creating a salt cavern due to the quality of the salt or the excessive depth of the salt layer. Salt diapirs are found in the north of the country, with some close to the Mediterranean coast. More than 40 diapirs are known, suggesting considerable storage potential. Further investigation is needed to confirm the storage potential in the Sahara Desert (14 and 15), as the quality of the salt and the thickness of the layer might not be suitable for creating salt caverns.

### Tunisia

Tunisia has three salt domains, two diapir structures in the north and one bedded salt formation in the south of the Sahara Desert. The Tunisian Atlas (16) is tectonised, which can limit the options to create storage. Kairaoaun Basin might contain a few interesting diapirs, but the depth of the salt could be a challenge in some. The bedded salt basin to the south is an extension of the Algerian one mentioned above and subject to the same issues.

### Libya

Libya has two neighboring salt basins on its western border, i.e., the Ghadamis and Sabratah basins. Salt quality could be an issue for storage, and further investigations must be conducted to confirm the storage potential.

### Egypt

Salt is mainly present to the south of the Gulf of Suez. Onshore and offshore diapiric piercement structures are suspected in Southwest Gebel El Zeit (Atta, et al. 2002). Preliminary screening has revealed potentially good geological conditions (depth, thickness, and presence of halite), and the salt unit is deemed potentially favorable for salt storage cavern development. The area of the onshore salt deposit is limited, but a large storage capacity could still be developed at first glance. This storage potential is in an area with high renewable production capacities. Additional possibilities could also be investigated offshore, along the Red Sea coast.

**Saudi Arabia**

Salt formations in Saudi Arabia are located along the Red Sea coast and the Arabian Gulf coast, i.e., as part of the Hormuz basin. On the Red Sea, the formation mainly consists of bedded salt (halite) in faulted blocks and several salt domes in different locations. The information available on the salt thickness and insolubility suggests that the creation of underground storage would be possible but very localized and possibly deep (mainly around Midian).

On the Arabian Gulf coast, the Arabian platform is a sedimentary basin with a thick continuous sequence of sediments from the Late Proterozoic (Silurian/Devonian) to Holocene (Recent) on the north-eastern margin of the Arabian sector of Gondwana. During the Hormuz period (Cambrian age), a thick evaporite up to 2500m was deposited, predominantly composed of halite interbedded by carbonate layers. After the consolidation of the Arabian shield, a late Proterozoic extensional phase, Najd rifting, created several sub-basins currently located in the Persian Gulf sector. The sedimentary sequences in these sub-basins reach a thickness of more than 8-10km, and as a result, the Hormuz salt deposits are stratigraphically deemed too deep to make salt caverns. Structurally, Hormuz salt is known in more than 200 salt domes distributed throughout the south-eastern part of the Cretaceous-Tertiary Zagros fold-thrust belt and forms the diapiric cores of several Arabian Gulf islands and topographic features along the coast of Arabia and the United Arab Emirates. These diapiric core structures result from salt piercement intrusion during the Miocene tectonic activity of the Arabian Gulf. These salt diapiric structures are assumed to be the only structures with the potential for salt cavern storage.

Figure 19 and Table 9 summarize the potential storage locations in Egypt and Saudi Arabia.


*Figure 19: Potential storage locations in Egypt and Saudi Arabia. Source: Lefond (1969).*

**Table 9: Map references for Figure 19.**

| Map ref. | Country | Zone | Salt geometry | Source |
|---|---|---|---|---|
| 1 | Saudi Arabia | Jizan | Diapir | S.J. Lefond 1969 |
| 2 | Saudi Arabia | Yanbu Al Bahr | Diapir | S.J. Lefond 1969 |
| 3 | Saudi Arabia | Al Khobar | Diapir | S.J. Lefond 1969 |
| 4 | Saudi Arabia | Jebel Berri | Diapir | S.J. Lefond 1969 |
| 5 | Saudi Arabia | Jebel Dharan | Diapir | S.J. Lefond 1969 |
| 6 | Saudi Arabia | Midian | Bedded salt to Diapir | S.J. Lefond 1969 |
| 7 | Egypt | El Zeit | Diapir | |

There is, to date, no public work estimating the technical possibility of storing hydrogen in salt caverns in the MENA countries. The following paragraphs propose an estimation like the approach taken by Weber (2018) and Caglayan et al. (2020), whereby only the most favorable salt deposits are considered.

No detailed GIS-based analysis was carried out in this initial approach to assess the eligibility of the areas for developing caverns, e.g., distance to cities and other land uses, nor was the availability of water and the ability to reject brine considered in detail.

The general assumption is that 10% of the favorable bedded salt basins and diapirs can be converted into salt caverns. The cavern parameters were taken from the Hystories Conceptual Design of Salt Caverns, MID case. These correspond to a cavern located at a depth of 1000m, with a free geometrical volume of 380 000 $m^3$. One cavern can store 31 MM $Sm^3$ of hydrogen, or 0.09 TWh. All the design parameters can be found in Hystories report D7.1-1 (Jannel and Torquet 2022). Figure 20 and Table 10 summarize the findings of this section.

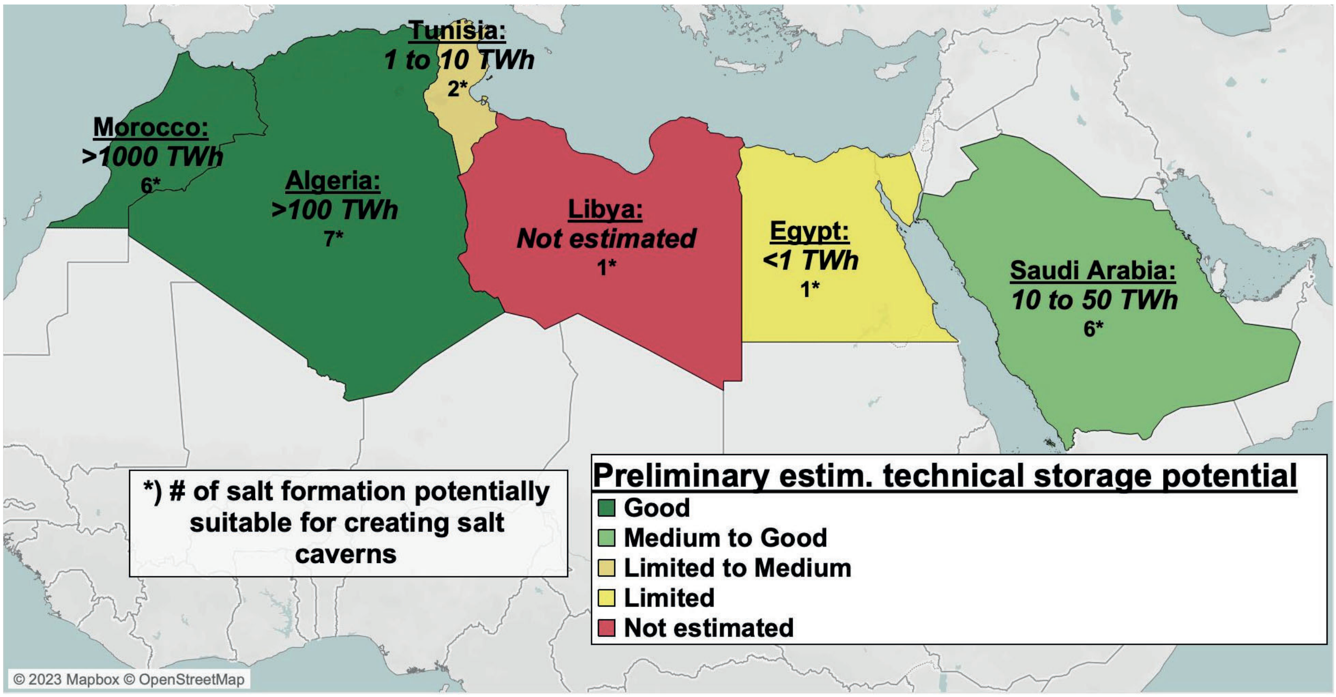


*Figure 20: Storage potential and numbers of salt formations potentially suitable for creating salt caverns. Sources: Caglayan et al. (2020); Horvath et al. (2018); Jannel and Torquet (2022); Weber (2018).*

**Table 10: Overview of salt formations potentially suitable for the creation of salt caverns.**

| Country | Number of salt formations potentially suitable for the creation of salt caverns | Overall theoretical storage potential | Preliminary estimation of the technical storage capacity | Comments |
|---|---|---|---|---|
| Morocco | 6 | Good | >1000 TWh | |
| Algeria | 7 | Good | >1000 TWh | Analysis mainly based on the diapir areas, bedded salt not considered |
| Libya | 1 | Limited | Not estimated | Additional investigation required |
| Egypt | 1 | Limited | <1 TWh | Very localized potential |
| Tunisia | 2 | Limited to Medium | 1 to 10 TWh | Estimation to be confirmed by further investigations |
| Saudi Arabia | 6 | Medium to Good | 10 to 50 TWh | |

Other alternatives could be considered for countries with limited storage potential in salt caverns or with potential not in an area of interest. Storage in Lined Rock Caverns could also be an interesting option, including some closer to locations of renewable energy production. Many MENA countries are oil and gas producers, and repurposing depleted oil and gas fields is another (major) possibility.

### 4.3. Socio-economic assessment

The analysis presented in Section 4.1 on aspects of hydrogen production, such as capital costs in the selected MENA countries, depends on socio-economic factors like political stability. Political stability alone comprises a range of indicators such as government effectiveness, the rule of law and control of corruption, and Box 2 describes the factors comprising political stability.

**Box 2: Political stability**

Political and institutional aspects are the main factors driving the development and expansion of hydrogen production. In this context, it is essential to understand political stability as a multidimensional construct that considers the current political regime in terms of its legitimacy, behavior, compliance with human rights and international law, but also the nature and effectiveness of state institutions. Five composite indicators are used by the World Bank (2022) to account for such a systemic approach:

**Political Stability:** Measures perceptions of the likelihood of political instability and politically motivated violence, including terrorism.

**Government Effectiveness:** Reflects perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressure, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies.

**Voice and Accountability:** Reflects perceptions of the extent to which a country's citizens can participate in selecting their government, as well as freedom of expression, association, and free media.

**Regulatory Quality:** Reflects perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development.

**Rule of Law:** Reflects perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular, the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence.

**Control of Corruption:** Reflects perceptions of the extent to which public power is exercised for private gain, including petty and grand forms of corruption and "capture" of the state by elites and personal interests.

Figure 21 summarizes these indicators under the header of political stability and rates political stability from a weak performance of -2.5 (a country with the lowest value) to a strong performance of 2.5 (a country with the highest value).

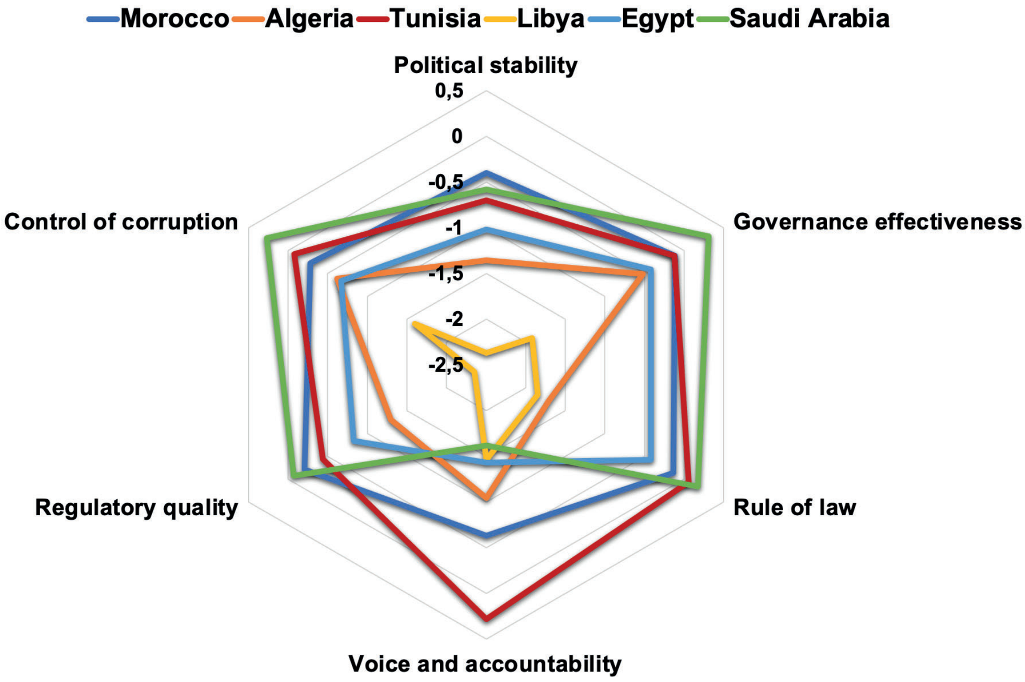


*Figure 21: Political stability, or a set of relative indicators (weak performance: -2.5 = country with the lowest value); strong performance: 2.5 = country with the highest value).*
*Source: Fraunhofer HYPAT based on World Bank (2022).*

Figure 21 shows that Libya has the overall weakest score and that countries such as Saudi Arabia and Tunisia score better in areas like control of corruption, the rule of law, and accountability. Nevertheless, political stability is just one of many factors considered here when discussing the socio-economic potential of the selected MENA countries.

Figure 22 shows the results of the high-level country analysis, which was based on the individual values of forty indicators and seventy associated indices used in the six thematic areas as explained in Section 2.2. While techno-economic research indicates that MENA countries like Egypt and Libya could supply large quantities of hydrogen to Europe, their socio-economic potential is much lower, especially when compared to that of most European countries.

One consequence of a lower socio-economic score is that, for example, investment risks in the MENA region are higher. This increases the cost of financing and reduces the likelihood of realizing large-scale hydrogen projects (Pfennig et al. 2022).

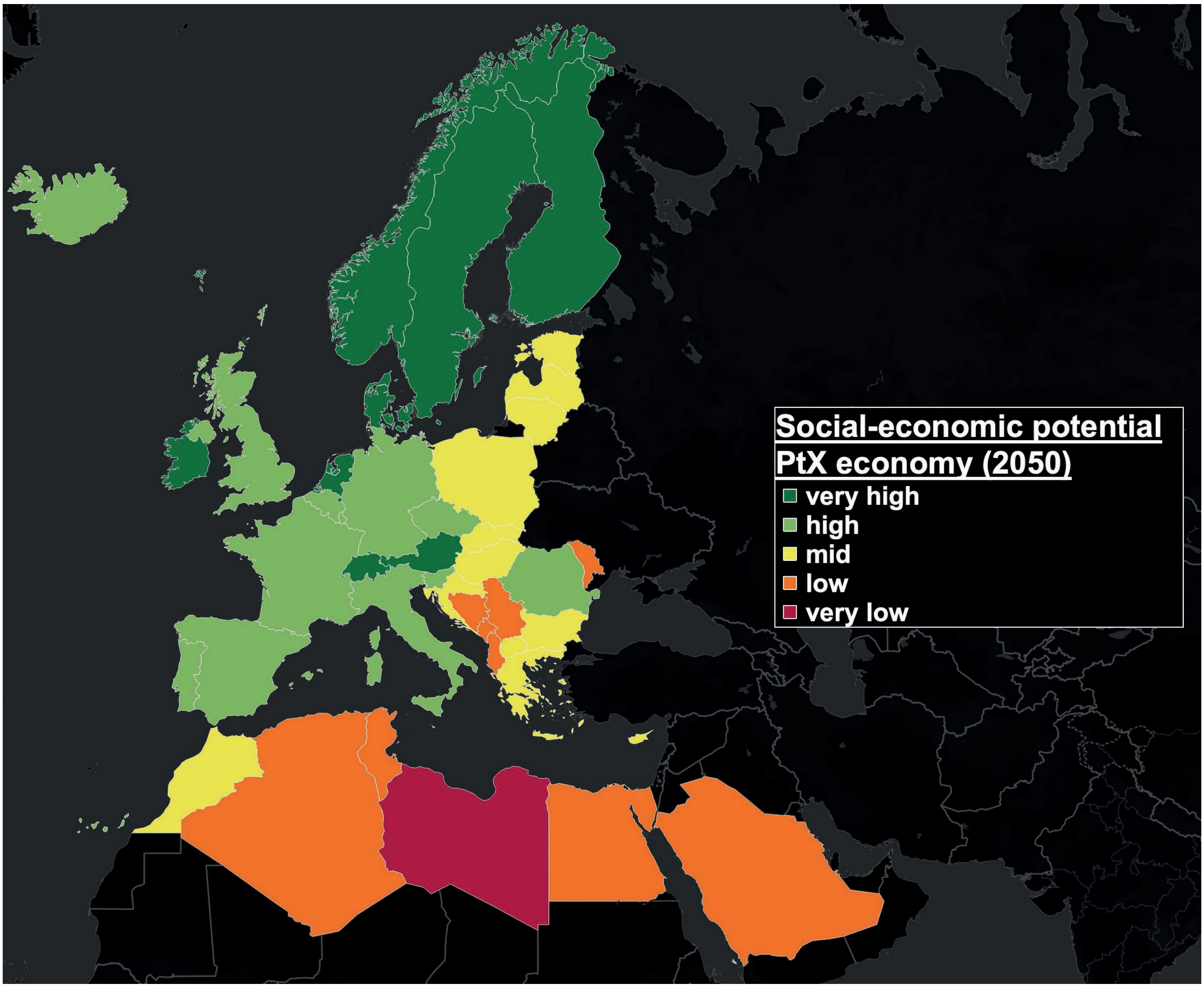


*Figure 22: Socio-economic potential for PtX in the Europe-MENA region. Source: Authors based on Global PtX Atlas.*

# 5. Conclusion

This paper provides a technical and socio-economic assessment of the EU's strategic REPowerEU target of 20 Mt hydrogen production and import target by 2030. Due to their geographical proximity, low-cost production potential, and existing gas infrastructure, six MENA ('Middle East and North Africa') countries are regarded as crucial players for realizing the REPowerEU 10 Mt import target (i.e., 6 Mt of hydrogen by pipeline and 4 Mt of ammonia): Morocco, Algeria, Tunisia, Libya, Egypt, and Saudi Arabia.

The technical assessment conducted in this paper by linking the Fraunhofer energy system model SCOPE SD with the new gas market model IMAGINE does not see a domestic (European) hydrogen production capacity of 10 Mt p/yr. materialize until sometime between 2035 and 2040. Regarding sectoral demand, the analysis shows that 376 TWh (11.4 Mt) constitutes a very ambitious, maximum hydrogen demand that can be covered by domestic European production by 2030.

In terms of infrastructure, this paper argues that integrating larger quantities of hydrogen by repurposing existing natural gas-based infrastructure in Europe is possible and could be a building block in the continent's transition towards a climate-neutral energy system. Imports by pipeline from the selected MENA countries could contribute to diversifying Europe's transport and supply options in the medium term. These pipeline imports are essential in the case of high hydrogen demand in the long term, i.e., up to 2050 and beyond. From 2050 onwards, the paper shows the need for new pipeline capacity from several MENA countries to Europe, especially Morocco, Algeria, Egypt, and Saudi Arabia. Sufficient hydrogen storage capacity in salt caverns in Europe is also available in the short to medium-term. From 2045 onwards, however, there will be an increasing need for new hydrogen storage capacity. Although a massive endeavor, the 216 TWh of new and repurposed hydrogen storage potential in salt caverns by 2050 does not consider other storage options and strategic possibilities like the reserve required to achieve the REPowerEU target by 2030.

The paper also points out that the technical analysis conducted here focuses on cost optimization, and that the war in Ukraine, and the EU's response in the form of REPowerEU, have made it very clear that strategic considerations are becoming increasingly important for Europe's ambitions regarding hydrogen. The paper touches upon possibly repurposing the proposed EastMed pipeline for clean hydrogen as an example of geopolitical concerns in a 'post-Ukraine war' Europe.

The selected MENA countries have a huge technical potential to export clean hydrogen. Under the right conditions, including production capacities, policies, infrastructure, financing, certification and human capital development, this potential could meet Europe's demand for hydrogen. However, there are major hurdles to be overcome when turning this technical potential into a realizable one. The initial remarks on the theoretical storage potential of hydrogen in salt caverns require more extensive and in-depth analysis, including of depleted oil and gas fields.

Capital costs depend on various socio-economic indicators like the rule of law, level of corruption, and regulatory quality. The analysis based on the Global PtX-Atlas, which considers forty indicators and seventy associated indices across six thematic areas, shows that the socio-economic potential in the selected MENA countries is in sharp contrast to that of most countries in Europe. The low overall socio-economic score of MENA countries influences essential variables like the cost of capital and investment risk. At the same time, this paper also indicates some of the current limitations of the Global PtX Atlas and that some of its features need to be refined and adjusted. In any case, the analysis presented here provides a starting point for further research on the technical and socio-economic aspects of the nascent Europe-MENA hydrogen economy. Any strategic focus on scaling up hydrogen production in MENA countries for export purposes must consider these aspects, including strict sustainability criteria.

# 6. References

Agora Energiewende, and AFRY Management Consulting. 2021. 'No-Regret Hydrogen: Charting Early Steps for $H_2$ Infrastructure in Europe'. Berlin: Agora Energiewende. https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_02_EU_H2Grid/A-EW_203_No-regret-hydrogen_WEB.pdf.

Al-Ashmawy, Ramy, and Suhail Shatila. 2022. 'MENA's Sustainability Journey in Light of COP27'. Dammam: Arab Petroleum Investments Corporation (APICORP). https://www.apicorp.org/publication/menas-sustainability-journey-in-light-of-cop27/.

Askri, H., A. Belmecheri, B. Benrabah, A. Boudjema, K. Boumendjel, M. Daoudi, M. Drid, T. Ghalem, A. M. Docca, H. Ghandriche, A. Ghomari, N. Guellati, M. Khennous, R. Lounici, H. Naili, D. Takherist, M. Terkmani. 2007. 'Géologie de l'Algérie'. Contribution de SONATRACH Division Exploration, Centre de Recherche et Développement et Division Petroleum Engineering et Développement, WEC-2007, 93 p. https://www.calameo.com/books/00069611938d69b2bedde.

Atta, M., O. Gilbert, H. David. 2002. 'The Ranim dipir – Active salt diapirism and the relationship of salt structures to sub-salt exploration targets. Southern Gulf of Suez, Egypt'. https://www.searchanddiscovery.com/documents/abstracts/cairo2002/images/atta01.htm.

Azadegan, Olivia, Steve Brick, Stacey Davis, and Magnolia Tovar. 2022. 'Poised to Lead: How the Middle East and North Africa Can Accelerate the Global Energy Transition'. Clean Air Task Force. https://www.catf.us/resource/poised-to-lead-how-the-middle-east-and-north-africa-can-accelerate-the-global-energy-transition/.

Bishop, William F. 1975. Geology of Tunisia and Adjacent Parts of Algeria and Libya. AAPG Bull, 59, 3, pp413-450. https://archives.datapages.com/data/bulletns/1974-76/data/pg/0059/0003/0400/0413.htm.

Böttger, Diana, and Philipp Härtel. 2022. 'On Wholesale Electricity Prices and Market Values in a Carbon-Neutral Energy System'. Energy Economics 106 (February): 105709. https://doi.org/10.1016/j.eneco.2021.105709.

Bracene, R., and D. Frizon de Lamotte. 2002. 'Origin of intraplate deformation in the system of the western and Central Algeria: From Rifting to Cénozoic-Quaternary Inversion'. Tectonophysics, 357. pp 207- 226. https://ui.adsabs.harvard.edu/link_gateway/2002Tectp.357..207B/doi:10.1016/S0040-1951(02)00369-4.

Braun, Jan Frederik, Ad Van Wijk, Kirsten Westphal. "European Hydrogen Pathways: Towards a Balanced Partnership with Saudi Arabia and the Gulf." In The Clean Hydrogen Economy and Saudi Arabia: Domestic Developments and International Opportunities, edited by Rami Shabaneh, Jitendra Roychoudhury, Jan Frederik Braun, and Saumitra Saxena. Environment & Economics. Oxfordshire: Routledge, 2023 (forthcoming).

Busson, G. 1970. Le Mésozoique Saharien: Essai de synthèse des données des sondages algéro-tunisiens. 2 volumes, Centre National de la Recherche Scientifique, 810 p.

Bynum, Michael L., Gabriel A. Hackebeil, William E. Hart, Carl D. Laird, Bethany L. Nicholson, John D. Siirola, Jean-Paul Watson, David L. Woodruff. 2021. Pyomo — Optimisation Modeling in Python. Vol. 67. Springer Optimization and Its Applications. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-68928-5.

Caglayan, Dilara Gulcin, Nikolaus Weber, Heidi U. Heinrichs, Jochen Linßen, Martin Robinius, Peter A. Kukla, Detlef Stolten. 'Technical Potential of Salt Caverns for Hydrogen Storage in Europe'. International Journal of Hydrogen Energy 45, no. 11 (28 February 2020): 6793–6805.https://doi.org/10.1016/j.ijhydene.2019.12.161.

Dachkevitch, V., N. Beroutcrachvili, B. Tchoupilko, A. Inamov. 1984. 'Sur la prospection détaillée du gisement de sel d'Aïn Nouissy'.

ENTSOG, and ENTSO-E. 2022. 'TYNDP 2022 Scenario Report'. Brussels: ENTSOG & ENTSO-E. https://2022.entsos-tyndp-scenarios.eu/wp-content/uploads/2022/04/TYNDP2022_Joint_Scenario_Full-Report-April-2022.pdf.

European Commission. 2022a. 'REPowerEU Plan'. COM(2022) 230 final. Brussels: European Commission. https://ec.europa.eu/info/publications/key-documents-repowereu_en.

European Commission. 2022b. 'Commission Staff Working Document: Implementing the REPowerEU Action Plan: Investment Needs, Hydrogen Accelerator and Achieving the Bio-Methane Targets'. COM(2022) 230 final. Brussels: European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=SWD%3A2022%3A230%3AFIN&qid=1653033922121.

Folle, Stefan. 2006. Middle East Salt Deposits - Distribution and Potential Use. SMRI, Conference, 30 April- 3 May, Brussels, Belgium, 15p.

Fraunhofer Institute for Energy Economics and Energy System Technology. 'Global PtX Atlas'. Fraunhofer IEE | PtX Atlas, 2022. https://maps.iee.fraunhofer.de/ptx-atlas/.

Frischmuth, Felix, and Philipp Härtel. 2022. 'Hydrogen Sourcing Strategies and Cross-Sectoral Flexibility Trade-Offs in Net-Neutral Energy Scenarios for Europe'. Energy 238 (January): 121598. https://doi.org/10.1016/j.energy.2021.121598.

Frischmuth, Felix, Richard Schmitz, Philipp Härtel. 2022. 'IMAGINE – Market-Based Multi-Period Planning of European Hydrogen and Natural Gas Infrastructure'. In 2022 18th International Conference on the European Energy Market (EEM), 1–11. https://doi.org/10.1109/EEM54602.2022.9921154.

Hafid, Mohamad, Mahmoud Zizi, Albert W. Bally, Abdellah Ait Salem. 2006. 'Styles structuraux de la terminaison occidentale onshore et offshore du Haut Atlas, Maroc'. Comptes Rendus Geoscience. https://doi.org/10.1016/j.crte.2005.10.007.

Hafner, Manfred. 2022. "EU Energy Policy and the MENA Region in the Wake of Russia's Invasion of Ukraine." In Energy Politics in the MENA Region: From Hydrocarbons to Renewables, edited by Valeria Talbot, 13–35. Milan: Ledizioni LediPublishing. https://www.ispionline.it/it/pubblicazione/energy-politics-mena-region-hydrocarbons-renewables-36797.

Hart, William E., Jean-Paul Watson, David L. Woodruff. 2011. 'Pyomo: Modeling and Solving Mathematical Programs in Python'. Mathematical Programming Computation 3 (3): 219–60. https://doi.org/10.1007/s12532-011-0026-8.

Hassan, T., Tahiri, A., Ait Brahim, L., Chotin, P. 1999. 'Evolution tectono-sédimentaire du Nord-Est du Maroc au cours du Trias supérieur: Apport des données microtectoniques'. Géologie Méditerranéenne. Tome 26, 3-4, pp. 231-243. https://www.persee.fr/doc/geolm_0397-2844_1999_num_26_3_1659.

Härtel, Philipp, and Debraj Ghosh. 2022. 'Modelling Heat Pump Systems in Low-Carbon Energy Systems with Significant Cross-Sectoral Integration'. IEEE Transactions on Power Systems 37 (4): 3259–73. https://doi.org/10.1109/TPWRS.2020.3023474.

Härtel, Philipp, and Magnus Korpås. 2021. 'Demystifying Market Clearing and Price Setting Effects in Low-Carbon Energy Systems'. Energy Economics 93 (January): 105051. https://doi.org/10.1016/j.eneco.2020.105051.

Horvath, P.L., Mirau, S., Schneider, G.S., Weiler, C., Bödeker, J., Ratigan, J., 2018. Update of SMRI's. Compilation of Worldwide Salt Deposits and Salt Cavern Fields – SMRI Research Report U2015-2.

House of Commons / Science and Technology Committee. 2022. 'The Role of Hydrogen in Achieving Net Zero'. HC 99. London: House of Commons. https://committees.parliament.uk/publications/33292/documents/180198/default/.

IEA. 2021. "The cost of capital in clean energy transitions." Paris: IEA. https://www.iea.org/articles/the-cost-of-capital-in-clean-energy-transitions.

IEA. 2022a. "Global hydrogen demand by sector in the Sustainable Development Scenario, 2019-2070." Paris: IEA. https://www.iea.org/data-and-statistics/charts/global-hydrogen-demand-by-sector-in-the-sustainable-development-scenario-2019-2070.

IEA. 2022b. "How Producers in the Middle East and North Africa Can Free up More Natral Gas for Exports."Commentary. Paris: IEA. https://www.iea.org/commentaries/how-producers-in-the-middle-east-and-north-africa-can-free-up-more-natural-gas-for-exports.

IRENA. 2022. "Geopolitics of the Energy Transformation: The Hydrogen Factor." Abu Dhabi: International Renewable Energy Agency (IRENA). https://www.irena.org/publications/2022/Jan/Geopolitics-of-the-Energy-Transformation-Hydrogen.

Jannel, H., Torquet, M., 2022. Conceptual Design of salt cavern and porous media underground storage site, Hystories Deliverable D7.1-1, 2022.

Kuhn, Maximillian, and Ivan-Petar Yovchev. 2022. 'Hydrogen Transport and Storage Infrastructure'. In Clean Hydrogen Monitor 2022. Brussels: Hydrogen Europe. https://hydrogeneurope.eu/reports/.

Lambert, Martin. 2022. 'REPowerEU: Can Renewable Gas Help Reduce Russian Gas Imports by 2030?' Oxford: Oxford Institute of Energy Studies. https://www.oxfordenergy.org/publications/repowereu-can-renewable-gas-help-reduce-russian-gas-imports-by-2030/.

Landon, Susan M., and Anny B. Coury. 1994. 'Interior Rift Basins'. AAPG Memoir, 59.

Lefond, S. 1969. Handbook of world salt resources. New York: Springer US.

Mérabet, O., and A. Popov. 1971. 'Les bassins salifères d'Algérie'. Serv. Géol. Algérie, 41, pp. 59-70.

Michard, A., O. Saddiqi, A. Chalouan, E.C. Rjmati, A. Mouttaqi. 2011. 'Nouveaux guides géologiques et miniers du Maroc'. Notes et Mémoires du Service Géologique du Maroc, éd. Serv. Géol Maroc, Vol. 1 à 9, 556. https://www.researchgate.net/publication/258521744_Nouveaux_guides_geologiques_et_miniers_du_MarocNew_Geological_and_Mining_Guidebooks_of_Morocco_volume_1_Presentation_des_circuits_-_Introduction_a_la_geologie_du_Maroc.

Michard, A., 1976. 'Eléments de Géologie Marocaine'. Notes et Mémoires du Service Géologique du Maroc, Serv. Géol Maroc, 252, 408 p. https://www.researchgate.net/publication/258521777_Elements_de_Geologie_Marocaine.

Netzentwicklungsplan. 2022. 'Genehmigung Des Szenariorahmens 2023-2037/2045'. https://www.netzentwicklungsplan.de/sites/default/files/paragraphs-files/Szenariorahmen_2037_Genehmigung.pdf.

Pfennig, Maximilian, Diana Böttger, Benedikt Häckner, David Geiger, Christoph Zink, André Bisevic, Lukas Jansen. 2022. 'Global GIS-Based Potential Analysis and Cost Assessment of Power-to-X Fuels in 2050'. arXiv. https://doi.org/10.48550/arXiv.2208.14887.

Roland Berger Middle East. "Unlocking Hydrogen Growth in the Middle East." Dubai: Roland Berger Middle East, January 2023. https://www.rolandberger.com/en/Insights/Publications/Unlocking-Hydrogen-Growth-in-the-Middle-East.html.

Schmitz, Richard, Christian Naversen, Philipp Härtel. 2023. 'Influence of hydrogen import prices on hydropower systems in climate neutral Europe'. Energy Systems (forthcoming).

Soto, Juan, Joan F. Flinch, Gabor Tari. 2017. 'Permo-Triassic Salt Provinces of Europe, North Africa, ATTA and the Atlantic Margins'. https://www.sciencedirect.com/book/9780128094174/permo-triassic-salt-provinces-of-europe-north-africa-and-the-atlantic-margins.

Stamouli, Nektaria. 2022. 'EastMed: A Pipeline Project That Ran Afoul of Geopolitics and Green Policies'. POLITICO. 18 January 2022. https://www.politico.eu/article/eastmed-a-pipeline-project-that-ran-afoul-of-geopolitics-and-green-policies/.

Troudi, H., G. Tari, W. Alouani, G. Cantarella. 2017. 'Styles of Salt Tectonics in Central Tunisia: An Overview'. Ed. Elsevier, Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins, pp. 543-561. https://doi.org/10.1016/B978-0-12-809417-4.00026-4.

Tubbs Jr., Robert E., Hussein G. Aly Fouda, Abdulkader M. Afifi, Nickolas S. Raterman, Geraint W. Hughes, Yousuf K. Fadolalkarem. 2014. 'Midyan Peninsula, northern Red Sea, Saudi Arabia: Seismic imaging and regional interpretation'. GeoArabia, 19, 3, pp 165-184.

Turner, P., and K. Pelz. 2017. 'Development of an Upper Triassic-Lower Jurassic Evaporite Basin on the Saharan Platform, North Africa'. Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins, pp. 581-599. https://doi.org/10.1016/B978-0-12-809417-4.00028-8.

Weber, M., 2018. Assessment of the Technical and Economic Potential of Salt Deposits for Hydrogen Storage. Master Thesis, RWTH Aachen University. 28/09/2018.

World Bank. 2021. Population, total – Middle East & North Africa, World. https://data.worldbank.org/indicator/SP.POP.TOTL?locations=ZQ-1W.

World Bank. 2022. Worldwide Governance Indicators. https://inof.worldbank/governance/wgi.

Wyn, Geraint, and Robert S. Johnson. 2005. 'Lithostratigraphy of the Red Sea Region'. GeoArabia, 10, 3, pp 49-126. https://doi.org/10.2113/geoarabia100349.

Van Wijk, Ad, Kirsten Westphal, Jan Frederik Braun. 2022. 'How to Deliver on the EU Hydrogen Accelerator'. Discussion Paper. Brussels: Hydrogen Europe, 2 May 2022. https://hydrogeneurope.eu/in-a-nutshell/reports/.

Vergés, J., M. Moragas, J.D. Martín-Martín, E. Saura, E. Casciello, Ph. Razin, C. Grelaud, M. Malaval, R. Joussiame, G. Messager, I. Sharp, D.W. Hunt. 2017. 'Salt Tectonics in the Atlas Mountains of Morocco'. Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins, pp. 563-579. https://doi.org/10.1016/B978-0-12-809417-4.00027-6.

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