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SPECIAL FEATURE: CASE REPORT

Accelerating Actions for Leveraging a Climate-Neutral, Sustainable Society

Industrial and infrastructural conditions for production and export of green hydrogen and synthetic fuels in the MENA region: insights from Jordan, Morocco, and Oman

Sibel Raquel Ersoy[1] · Julia Terrapon-Pfaff[1] · Thomas Pregger[2] · Josua Braun[2] · El Mostafa Jamea[3] · Ahmed Al-Salaymeh[4] · Patrick Braunschweig[5] · Zsuzsa Bereschi[5] · Oana Teodora Ciobotaru[5] · Peter Viebahn[1]

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Abstract
Green hydrogen and synthetic fuels are increasingly recognized as a key strategic element for the progress of the global energy transition. The Middle East and North Africa (MENA) region, with its large wind and solar potential, is well positioned to generate renewable energy at low cost for the production of green hydrogen and synthetic fuels, and is therefore considered as a potential future producer and exporter. Yet, while solar and wind energy potentials are essential, other factors are expected to play an equally important role for the development of green hydrogen and synthetic fuels (export) sectors. This includes, in particular, adequate industrial capacities and infrastructures. These preconditions vary from country to country, and while they have been often mentioned in the discussion on green hydrogen exports, they have only been examined to a limited extent. This paper employs a case study approach to assess the existing infrastructural and industrial conditions in Jordan, Morocco, and Oman for the development of a green hydrogen and downstream synthetic fuel (export) sector.

Keywords Renewable energy · Hydrogen economy · Power-to-X · Energy demand scenario · Cost-potential analysis · Export infrastructure · Middle East and North Africa

Introduction

Green hydrogen[1] generated from renewable electricity, and downstream products like synthetic fuels are pivotal components for the energy transition, as they enable emission reductions in hard to decarbonise sectors (IEA 2019; Odenweller et al. 2022; Roeb et al. 2020). The productions of green hydrogen and synthetic fuels require significant amounts of low-cost renewable energy. Countries in the Middle East and North Africa (MENA) region, which have extensive solar and wind energy resources, therefore, have particularly favorable conditions for producing large quantities of hydrogen and synthetic fuels from renewable energy sources at low cost. Yet, while the renewable energy potentials are an important prerequisite to develop green hydrogen and synthetic fuels export sectors, local conditions

[1] The term "green hydrogen" in general refers to hydrogen generated with renewable electricity. In this paper, only electricity generated from wind and PV is considered for the generation of hydrogen. Biomass and other renewable sources are not considered because of the limited potentials in all three analyzed countries.

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✉ Julia Terrapon-Pfaff
julia.terrapon-pfaff@wupperinst.org

1 Wuppertal Institute for Climate, Environment and Energy, Döppersberg 19, 42103 Wuppertal, Germany

2 Institute of Networked Energy Systems, German Aerospace Center (DLR), Curiestr. 4, 70563 Stuttgart, Germany

3 Mena Renewables and Sustainability (MENARES), Casa Bourse, B.P 7505, 20003 Casablanca, Morocco

4 Mechanical Engineering Department, University of Jordan, Amman 11942, Jordan

5 Horváth AG, Horváth & Partner GmbH, Rotebühlstraße 100, 70178 Stuttgart, Germany

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like existing industrial structures and infrastructures likewise play a crucial role (Terrapon-Pfaff et al. 2022; Dii and Roland Berger 2021; Roeb et al. 2020; Wijk et al. 2019). To export green hydrogen or synthetic fuels requires, for example, transmission or transport infrastructures within the country, as renewable potentials are often located inland (Lechtenböhmer et al. 2019). Likewise, port infrastructures are required to export the final product. Furthermore, storage infrastructures will be needed to build a reliable hydrogen economy (BloombergNEF 2020). Next to infrastructure requirements, the existing industrial structures are also relevant to consider, on the one hand, in terms of capacity to provide the required materials and know-how, on the other hand, as potential local demand drivers.

A number of studies and gray literature on the development of green hydrogen and synthetic fuels in the MENA region have been published recently. Van Wijk et al. (2019), for example, analyzed the overall role that North Africa could play in providing green hydrogen to Europe, whereas Dii and Roland Berger (2021) studied the potential for green hydrogen in the Gulf countries. Schindler (2019) studied the production costs of power-to-X (PtX[2]) products comparing Germany and North Africa; and Fasihi et al. (2017) calculated the costs for synthetically produced power-to-gas (PtG) and power-to-liquid (PtL) products from the MENA region. Next to these more general potential assessments and comparative cost calculations, more detailed national assessments of the local conditions like the industrial preconditions and available infrastructures are still missing. By analyzing the country-specific infrastructural and industrial framework conditions for the development of an export-oriented sector for green hydrogen and synthetic fuels in Jordan, Morocco, and Oman, this paper contributes to close this research gap. The case study analysis was part of the MENA-Fuels research project.[3]

Materials and methods

Research approach

A case study approach is applied, that combines qualitative and quantitative methods to give a systematic overview of the local conditions for each country. The selection of the case study countries was based on the analyses and results carried out in the framework of the MENA-Fuels project, the recommendations of the two project advisory boards as well as the feasibility under the financial and time frame of the project. Based on criteria such as diversity in terms of region, initial conditions and previous role as an energy exporter or importer, as well as practical feasibility, Jordan, Morocco, and Oman were selected as countries for the case studies. The three countries are located in different parts of the MENA region with different distances from potential European export markets. Furthermore, they are in different positions in terms of the main energy sources they use and their role as energy importing or exporting countries. Jordan and Morocco are, for example, net energy importers, meeting over 90% of their energy needs through imports, while Oman is a net energy exporter (World Bank 2023a).

The case study analysis comprises (a) desk research of scientific and gray literature, to provide an overview of the current situation considering particularly the given infrastructural and industrial conditions; (b) empirical analysis in form of expert interviews, focus groups, and workshops conducted with policy, energy, industry, and academic stakeholder groups and experts to enhance the knowledge of the local conditions, (c) results from bottom–up energy demand scenario modeling for the three countries that was conducted as part of the MENA-Fuels research project, and (d) country-specific results from modeling of cost-potential (CP) curves for renewable electricity and synthetic fuels, produced with the Fischer–Tropsch (FT)[4] process also done in the MENA-Fuels project.

[2] The term Power-to-X (PtX) covers the conversion of renewable electricity into hydrogen and the possible further processing into gases (e.g., methane), liquid energy carriers or fuels (e.g., kerosene and gasoil), or chemical feedstocks (e.g., ammonia and methanol).

[3] As part of the "Energy transition in the transport sector" funding initiative of the Federal Ministry of Economics and Climate Protection, the project MENA-Fuels investigated the potential to generate sustainable synthetic fuels in the MENA region for the decarbonisation of traffic in Germany.

[4] The Fischer–Tropsch (FT) process was chosen over other synthesis processes such as methanation as the main use of synfuels in the future will be for liquid fuels like gasoline or kerosene, so that the existing infrastructure and engines can continue to be used. Accordingly, specifically for Germany and the EU, scenarios foresee large shares of liquid fuels (Viebahn et al. 2022; ENTSOG 2022), while methane will have only a small share in the transport sector. For the production of liquid fuels, FT synthesis is the most developed technology so far. The alternative would be the methanol pathway with subsequent synthesis of liquid fuels. While the Methanol-to-DME and the Methanol-to-Gasoline processes might be commercially available from 2030, in particular the Methanol-to-Kerosene process is currently on a low TRL level (5–6) and might not reach commercial availability before 2040 (Viebahn et al. 2022). Since, in particular, aviation will need liquid fuels, we focused on FT-fuels in our analysis. Specifically for Germany and the EU, resulting fuel mixes are shown by the meta-scenario analyses carried out in MENA-Fuels (Viebahn et al. 2022, p. 24). It is also evident in other scenarios such as those of ENTSO-E and ENTSOG (2022, p. 21ff).

Data collection and analysis

For each country under consideration, extensive secondary research was conducted to collect data and information on the current industrial framework and relevant infrastructure, such as ports, pipelines, or electricity grid connections. Information that was not publicly available, especially on planned developments, was obtained from relevant agencies. In addition to the analysis of existing data, empirical research was carried out in the form of expert interviews and a stakeholder workshop in each country to obtain further information on both green hydrogen visions and strategies by integrating local perspectives. In Morocco, additionally, two focus group workshops were conducted. The experts included project developers, company deputies, administrative and governmental representatives, energy utility experts, as well as members of academia. The interviews were conducted in 2021. Furthermore, the case study analysis integrated results from three scenarios for the domestic demand of electricity, green hydrogen, and synthetic fuels in Jordan, Morocco, and Oman. The reference scenario (REF) assumes the continuation of current policies, considering only policies that have been enacted by 2017. These assumptions are derived from the regional Current Policies scenarios of the IEA World Energy Outlook 2017 (IEA 2017) for Africa and the Middle East; specific national developments cannot be taken into account. Without demand for green hydrogen or synthetic fuels and an energy system that is still dominated by fossil fuels, the REF serves as a comparison for the other two scenarios. The advanced scenario (ADV) corresponds to an energy system that becomes significantly more efficient by 2050, especially through electrification, and at the same time is based on 100% renewable energies. The alternative scenario (ALT) represents a moderate transformation path in terms of efficiency improvement, electrification, direct use of renewable energies, and resulting fuel demand. The ALT scenario was combined in the variant ALT2 with the assumption that the remaining fossil fuels are completely replaced by green synthetic fuels by 2050 to achieve the 100% renewables' target. This scenario variant thus provides a maximum estimate of the potential domestic demand in the countries. The scenarios are derived from sectoral storylines with a bottom–up accounting framework from regional trajectories, national energy balances, and other statistics.[5]

Next to the potential domestic demand, results from the modeling of techno-economic potential and their costs were added to the case study analysis that provide insights on the quantity and costs of future export potentials of renewable electricity, green hydrogen, and synthetic fuels produced with the FT process. These CP curves were modeled for electricity and synthetic fuel from photovoltaics (PV), concentrated solar power (CSP), and wind energy technologies for the year 2030 and 2050. To illustrate the impact of country-specific risks on costs, four different cases (ref, bau, pos, and neg) are considered in the form of different weighted average cost of capital (WACC).[6] In addition, infrastructural restrictions on fuel production and potential long-term domestic demand were taken into account when determining export potential and costs. The CP curves show the annual export potentials and associated production costs, with the data sorted in ascending order of production costs and the potentials cumulated. For the estimation of the techno-economic potentials, unsuitable areas for installing wind or solar power plants are excluded. For this, geological and meteorological criteria are considered [e.g., land-cover types, slope, average wind speed, and direct normal irradiation (DNI)]. Furthermore, it is an economic potential, where PtX components are designed in a cost-optimized way. The related curtailment leads to an overall lower potential.[7]

Results

Characterization of green hydrogen policies and strategies

An important precondition for the development of a green hydrogen and synthetic fuel (export) sector is a strong political commitment for the development of the renewable energy sector and a sustainable energy transition as a whole. In *Jordan's* energy strategy, the emphasis is placed on diversifying the country's energy mix. The target is to increase the share of renewable energy in the total electricity generation capacity to 31% (Fig. 1) and in the total final energy demand to 14% by 2030 (MEMR 2018). In its updated version of the Nationally Determined Contribution (NDC), Jordan sets an even higher target and aims for a 35% share of renewable energy in electricity generation by 2030 (MoE Jordan 2021). Work is underway to create a national green hydrogen roadmap that is expected to emphasis on export of green hydrogen and synthetic fuels. *Morocco's* energy strategy aims at increasing the share of renewable energy in installed electricity generation capacity to more than 52%

[5] A detailed methodology description can be found in (Pregger 2022). The Supplementary Material contains a brief explanation of the procedure for scenario building and tables with the main assumptions and scenario results.

[6] Please refer to Terrapon-Pfaff et al. (2022) for a detailed description of the methodology to determine country-specific WACCs. The applied WACCs can be found in the supplementary Material.

[7] Please refer to Braun et al. (2022) for a detailed methodology and model description. The Supplementary Material contains a brief description of the method and main assumptions used.

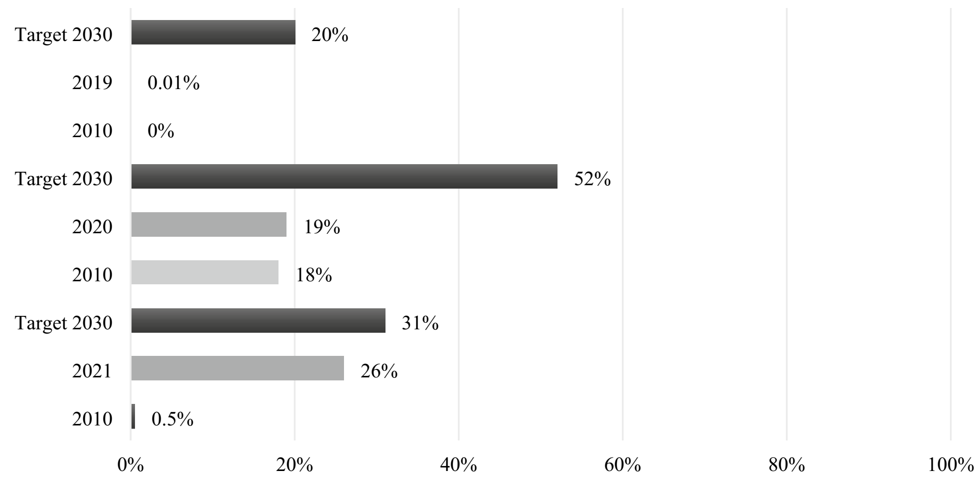

Fig. 1 Renewable energy share in electricity generation and targets in Jordan, Morocco, and Oman. Source: Enerdata (2021), IEA (2021), K&L Gates (2021), MEM (2020), MEMR (2020)

by 2030. This target has also been highlighted in the country's NDC (GoM 2021). In regard to green hydrogen, the National Green Hydrogen Commission (NHC), which was established in November 2019, prepared a roadmap for green hydrogen production for Morocco, which was then published by the Ministry of Energy Transformation and Sustainable Development in 2021 (MEM 2021a). The roadmap defines green hydrogen as a key vector of the energy transition and for sustainable growth. According to this roadmap, Morocco plans to export approximately 7 TWh of green hydrogen by 2030, 32 TWh by 2040 and 81 TWh by 2050 (MEM 2021a). Export targets have been set as well for synthetic fuels, 3 TWh by 2030, 13 TWh by 2040, and 33 TWh by 2050, while for the domestic use, the synthetic fuel demand for the fertilizer industry is estimated at 3 TWh in 2030, 13 TWh in 2040, and 19 TWh in 2050 (ibid.). The plans require an additional installed renewable capacity reaching up to 55 GW in 2050. The initial export derivate is expected to be green ammonia, while from 2030 Morocco plans to export green hydrogen as liquid fuel or as gas. From 2035, green hydrogen is planned as storage medium in the electricity sector, and from 2037, it will be used in the transport sector, whereas from 2047, the energy carrier is planned to be used in the residential sector (MEM 2021a). In *Oman*, the strategic goals are outlined in the "Vision 2040", which aims at approximately 5000 MW renewable energy capacity to be installed by 2040 (GoO 2021). Green hydrogen is also part of the political debate since 2018 and a national hydrogen strategy is currently being developed. Presumably, Oman will set its hydrogen target at 10,000 MW of electrolysis capacity by 2030 and 30,000 MW by 2040 for both exports as well as local demand through the creation of new businesses, but as well the potential conversion from gray to green hydrogen within industrial processes (Prabhu 2021a). Accordingly, 30–40% of the generation capacity will be allocated to local use and the remaining capacity will be dedicated to export purposes (Horváth 2021). In terms of cooperation, the national hydrogen alliance "Hy-Fly" was established by Oman's Ministry of Energy and Minerals, comprising 13 governmental and private entities (Energy and Utilities 2021). None of the three countries has implemented carbon pricing measures, yet only Morocco is considering the introduction of a carbon tax (World Bank 2023b). The same applies to carbon capture and storage (CCS). So far, none of the studied countries have discussed or implemented policies or regulatory frameworks related to CCS. Figure 1 provides an overview of the renewable energy share and the targets in the studied countries.

Thus, all three countries pursue ambitious goals regarding the expansion of renewable energies. In terms of implementation, Jordan and Morocco lead the way in renewable energy development in the MENA region. And while all three countries have expressed clear interests in developing sectors for green hydrogen and synthetic fuels, so far only Morocco has published a detailed strategy. Morocco and supposedly Jordan only include green hydrogen, while Oman's strategy is also expected to include blue hydrogen to continue making use of the domestic natural gas resources.

Institutional landscape and relevant stakeholders

The support and active engagement of relevant stakeholder groups is important for the expansion of renewable energy and also for the development of a green hydrogen sector. Various stakeholders, including political actors, national utilities from the energy and water sectors, technology manufacturers, potential buyers and users of green hydrogen and synthetic fuels, the R&D sector, as well as investors and financiers, are involved in the development of a green hydrogen export sector. In the three analyzed countries, the energy ministries and the national power and transmission utilities are key players. In *Jordan*, the state-owned electricity utility National Electric Power Corporation (NEPCO) plays an essential role as Jordan's single-buyer, transmission system operator, and dispatcher. NEPCO is also responsible for the development and expansion of the electricity transmission grid. The power generation itself is largely privatized. In *Morocco*, the state-owned electricity utility ONEE monitors the grid stability and the entire power generation chain, and in *Oman*, the Oman Electricity Transmission Company (OETC) is responsible for the power sector, while independent power and water producers play a key role as well.

At the political level, the energy ministries are involved in the development of energy and hydrogen strategies. Additionally, in *Morocco*, the Ministry of Water and the National Hydrogen Commission (NHC) is relevant, while in *Oman*, the so-called "Hy-Fly" alliance helps to shape the national hydrogen strategy. Prominent examples as "one-stop-shops" are the Regulatory Commission for Energy and Minerals (EMRC) in *Jordan* and the Moroccan Agency for Sustainable Energy (MASEN).

Besides state actors, oil and gas companies are expected to play a role for the development of an export sector for green hydrogen and synthetic fuels. In *Oman*, the Energy Development Oman (EDO) holding of Oman Petroleum Group (PDO) is responsible to develop renewable energy and in the future hydrogen business segments. International technology companies, such as Siemens, Linde, Thyssen Krupp, and Enertech, are active in promoting their generation technologies for hydrogen and synthetic downstream production in all studied countries.

In addition to exports, potential domestic users of the green hydrogen are also relevant players. Particularly, fertilizer producers, such as the Jordan Phosphate and Mining Company, the Arab Potash Company (APC), but as well the Moroccan state-owned phosphate company OCP Group (formerly Office Chérifien des Phosphates) or the Sohar International Urea & Chemical Industries LLC in Oman represent some of the major industrial players. Overall, a broad number of stakeholders from different sectors, which have different interests and influence need to be brought together to advance the development of a green hydrogen (export) sector in the long term.

Key production factors for green hydrogen and synthetic fuels

For the production of green hydrogen and synthetic fuels, the availability of electricity from renewable energy sources, water resources, and carbon sources are essential.

Renewable energies

Jordan, Morocco, and Oman have abundant technical potential for solar and wind energy generation. The average daily solar DNI ranges between 5 and 6 kWh/m^2, which is ideal for the deployment of solar PV and CSP technologies (IRENA 2022). Moreover, there is high potential for wind energy in all three countries. Wind speeds of up to 10 m/s can be recorded along the Moroccan coast (Choukri et al. 2017; Leidreiter und Boselli 2015). The north-west and south of Jordan are likewise suitable regions for wind power generation, with average wind speeds of around 9 m/s (Abu-Rumman et al. 2020). And also in the southern coastal regions of Oman, wind speeds of 10 m/s can be measured (World Bank Group et al. 2022). These conditions potentially allow not only to use wind or solar energy separately but also to use hybrid PV-wind power plants to increase the full load hours of electricity generation, which would be favorable for the production of green hydrogen and synthetic fuels.

Although fossil fuels still dominate the electricity sectors (with a share of 65% coal, 11% natural gas, and 2% oil in electricity generation in Morocco; 80% natural gas in Jordan, and 96% natural gas and 4% oil in Oman), the ambitions to increase the renewable energy share are politically supported in all three countries. In *Morocco*, the frontrunner, about 37% of the installed capacity is currently already renewable power production (MEM 2021b). The share of renewables in the electricity generation was 19% in 2019 (IEA 2021a). In *Jordan,* the capacity of renewable energy plants that is connected to the grid amounts to 1579 MW installed capacity (NEPCO 2020). Counting as well the decentralized installations, the total electricity generation out of renewables reached over 20% in 2021 (Jamea 2021). Compared, *Oman's* installed renewable energy capacity remains still low with around 200 MW (Table 1). However, Oman is planning a number of large-scale renewable projects in the coming decade. While in Morocco and Jordan, the primary driver is to reduce energy import dependency, in Oman, the focus is on diversifying the economy.

Water

Water is an essential component for the production of hydrogen. About 9–10 L of water are needed to produce 1 kg of hydrogen (Zelt et al. 2022). However, water consumption could be significantly higher in practice due to process inefficiencies, ranging between 18 and 24 L per kg hydrogen (IRENA 2020). Therefore, large-scale hydrogen production plants can consume significant amounts of fresh water at the local level.

Jordan, Morocco, and Oman are already today suffering from dwindling freshwater resources, dropping precipitation rates, and droughts due to climate change patterns (Charabi 2013; Tarawneh und Kadıoğlu 2003). The demand for water exceeds the supply in many areas resulting in overuse of groundwater resources. The main current uses of water in *Jordan* are agriculture, which accounts for

Table 1 Estimated technical potential of renewable energy and current electricity production in the studied countries

	Jordan	Morocco	Oman	Sources
Current electricity generation in 2020 [GWh/yr]				
PV	1646	417	211	IRENA (2023)
CSP	0	1130	0	
Wind (onshore)	1379	4607	0	
Total renewables*	3047	7062	211	
Techno-economic potential in 2030 [GWh/yr]				
PV	3,900,000	23,900,000	13,500,000	Braun et al. (2022) (Scenario 2030-ref)
CSP	1,400,000	9,000,000	6,200,000	
Wind (onshore)	400,000	3,600,000	1,100,000	

*Includes solar, wind, and other renewable energy technologies

51% of total water use, while the domestic sector accounts for 45% and the industry for 4% of the water use (MWI 2015). In *Oman,* the agriculture sector is also the largest consumer of water, accounting for almost 83% of total consumption, followed by households (10%) and industry (7%) (MRMWR 2022). Similarly, in *Morocco*, about 88% of water is allocated to the agricultural sector, 10% to households, and 2% to industry (Worldometers 2022).

All countries aim at increasing the reuse of water and expanding their water desalination capacities. Several smaller seawater desalination plants have recently started operating in *Jordan*, and a large-scale water plant with 130 million m^3 capacity annually is planned in Aqaba, which is supposed to provide water via a pipeline to Amman (Aqaba-Amman Water Desalination and Canal Project, *AAWDCP*). In *Morocco*, a number of fossil fuel-fired desalination plants exist. New seawater desalination projects are planned in *Morocco* to reach a capacity of 510 million m^3 annually by 2027 (Jamea 2021). In *Oman*, nine desalination plants are in operation that provide more than 100,000 m^3 of water per day, and in the next 6 years, the desalination capacity of independent water projects is planned to increase by additional 107,300 m^3 per day (Horváth 2021). However, so far, it is not clear how much of the planned capacities are to be operated with renewable energy.

To ensure the sustainability and avoid competition with other sectors, such as agriculture and drinking water supply, desalinated water will have to be used for the production of green hydrogen. For these purposes, additional desalination capacities have to be established that should be powered by renewables. To avoid conflicts and create local benefits, these additional desalination plants should be designed to meet multiple water needs and not just supply water for hydrogen production (IRENA 2020).

Carbon

For the production of several types of synthetic fuels from green hydrogen, for example, methane, methanol, or synthetic paraffin, carbon dioxide (CO_2) is required (Zelt et al. 2022). CO_2 can be extracted from point sources, such as existing carbon emitting industries, sucked from the atmosphere with Direct Air Capture technologies (DAC), or captured from biomass combustion.

Point sources in *Jordan* include, for example, the chemical and mining industries, which is mainly located in the south of Jordan, where also large renewable energy potentials are given (Jamea et al. 2021). *Morocco's* potential CO_2 sources exist mainly in phosphate processing, heavy industry, and coal-fired power plants (Jamea 2021). With regard to point sources, the Omani petroleum company PDO considers carbon capture and use (CCU) as an option for the tertiary oil (Enhanced Oil Recovery) and gas production (Enhanced Gas Recovery) and potentially for the production of synthetic fuels (Horváth 2021). However, to reach net zero emissions, the CO_2 used to produce synthetic fuels would increasingly have to be directly captured from the air or biomass sources. The indirect extraction of CO_2 via biomass is not a significant option for any of the three countries as the sustainable biomass potential is low. DAC can be differentiated in low-temperature (LT) and high-temperature (HT) DAC. When comparing both, LT DAC is currently the most advanced one, furthermore, LT technology can be composed of small decentralized units and generates water by extracting it from the atmosphere together with CO_2 (Okzan et al. 2022; IEA 2022), and therefore, only LT DAC technology was considered for the countries analyzed here.

Advanced project plans for DAC of CO_2 from the atmosphere so far solely exist in *Oman*. According to an Omani start-up, the world's first solar-powered DAC plant is to be built in Oman. The captured CO_2 will, however, not be used to produce synthetic fuels, but to store the CO_2 in basalt formations underground. It will therefore be necessary to build sufficient DAC capacity in the countries, once the LT technology will be upscaled and more cost-effective. Due to its modularity, the plants can be located in close proximity to synfuel production facilities to provide both water (for hydrogen production) and CO_2 (for fuel production).

Renewable energy demand and export potential in Jordan, Morocco, and Oman

In addition to the availability of the necessary production factors for the generation of green hydrogen and synthetic fuels, both the potential domestic energy demand and the production costs of renewable electricity, green hydrogen, and synthetic fuels play a decisive role for the development of export sectors.

Development of future electricity demand

Besides new economic opportunities arising from the export of green hydrogen and synthetic fuels, the domestic use to defossilise the economy and reduce import is also expected to become a relevant demand driver in the future. In Fig. 2, three scenarios for the potential own electricity demand developments in Jordan, Morocco, and Oman are presented. Demand is expected to increase significantly in all scenarios and countries. Main drivers are population growth and economic development, increases in living standards, and consumption, but also, depending on the scenario, additional electricity demand from electrification and electricity-based fuels.

The REF scenario assumes no demand for green hydrogen or synthetic fuels to develop and the energy system to continue to be dominated by fossil fuels. CO_2 emissions increase by a factor of about 1.5–2 from 2015 to 2050. The rising demand in the already existing consumption segments is primarily responsible for the increase in electricity demand. In the ADV scenario, about half of the overall demand in all countries results from the generation of hydrogen and synthetic fuels for own consumption. In Morocco, electricity demand in the ADV scenario will almost quadruple compared to REF, and in Oman, it will more than double. In Jordan, however, electricity demand increases less, by about 57%, in an energy system based on 100% renewable energies by 2050. Here, the demand for electrification in end-use sectors is expected to be lower, as Jordan has fewer energy-intensive industries compared to Morocco, but also to Oman, and thus, less electricity is expected to be needed to decarbonise the industrial sector. The strong increase of synthetic fuel generation in Morocco compared to the other two countries is mainly due to the rising demand in transport, driven by a significant increase in motorization in the large population. Furthermore, the storyline of the ALT2 scenario, which combines moderate efficiency improvement, electrification, and direct use of renewables with the complete substitution of fossil fuels with green hydrogen and synthetic fuels, leads to by far the highest electricity demand (see also scenario tables in the Supplementary Material).

Altogether, if the countries themselves pursue ambitious decarbonisation strategies and, at the same time, green hydrogen or synthetic fuels are to be exported in significant quantities, renewable energies must be expanded more rapidly on a large scale, as the current expansion rates will not be sufficient. In the scenarios, the required installed power plant capacity in the case of 100% renewable self-supply in ADV is estimated at about 42 GW for Jordan, 105 GW for Oman, and over 180 GW for Morocco, not including exports. In the ALT2 scenario, the assumed moderate developments combined with the replacement of all fossil fuels even lead to more than a doubling of installed capacity in Jordan and Oman and to a factor of 1.8 higher capacity in Morocco, which would require enormous expansion rates.

Cost-potential analysis of export potential

An important factor for the development of an export sector for green hydrogen and synthetic fuels are the costs at which these can be produced and made available for export. The modeled cost-potential (CP) curves presented below quantify the annual export potentials and the associated production costs for the synthetic fuel for the year 2030 (Fig. 3). The potentials used for own consumption estimated above based on the ALT2 scenario have already been deducted from the export potentials shown. Compared to the expected green hydrogen and synthetic fuel import demand of industrialized countries and regions like Germany or Europe, the potential is large. The demand for Germany, for example, ranges between 40 and 60 TWh in 2030 and 170 and 587 TWh in 2050 depending on the scenario (Samadi and Lechtenböhmer 2022; Krüger and Doré 2022). In terms of cost, it becomes clear that the cost differences in the ref case with assumed uniform WACCs of 6% are significantly lower than when country-specific risks are included in the form of varying WACCs. In the bau case, the cheapest potential in Oman costs 240 €/MWh, in Morocco 253 €/MWh, and in Jordan 364 €/MWh. In comparison, past production cost for crude oil lay between 10 $/bbl and 70 $/bbl, which corresponds to approx. 5–37 €/MWh under consideration of the historic exchange rate, inflation as well as the lower heating value of crude oil (IEA 2013). For the development after 2030, further cost reductions are expected for renewable energy technologies, which will lead to lower levelized cost of electricity (LCOE). The LCOE from PV, CSP, and wind are an important cost factor for the production of green hydrogen and synthetic fuels. Accordingly, the cost potentials for synthetic fuels also show smaller cost differences with uniformed WACCs and larger differences when country-specific risk costs are taken into account. This underlines the importance of further improving the framework conditions for renewables and green hydrogen in the countries to reduce the risks and therewith the capital costs and in the end the export costs (Figs. 4 and 5).

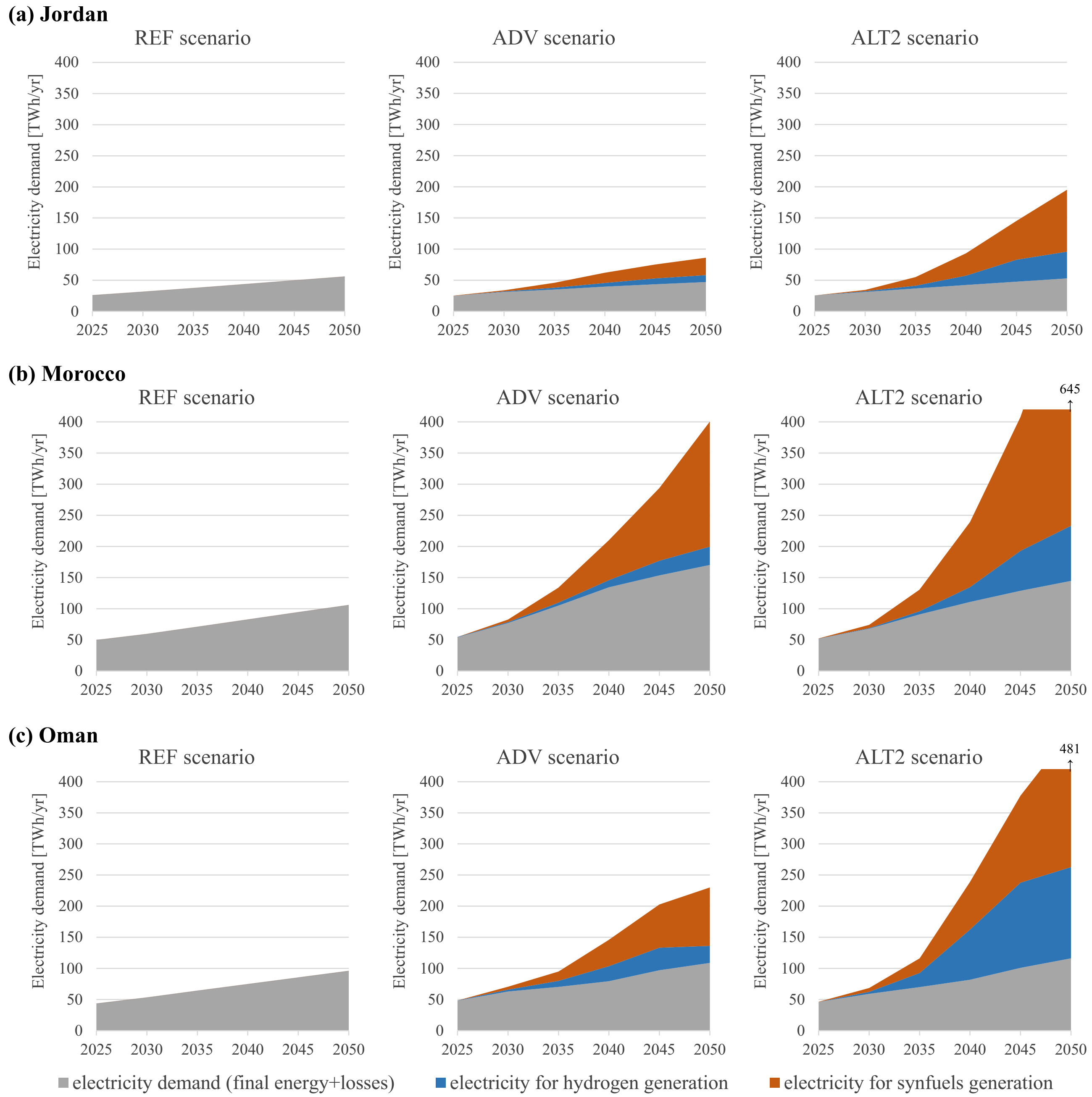

Fig. 2 Electricity demand scenarios for **a** Jordan, **b** Morocco, and **c** Oman (TWh/yr). Source: Based on data from Pregger (2022)

Infrastructure analysis

The following section presents the results of the infrastructure analysis. The current state and planned expansion of the electricity, oil, and gas as well as the transport and storage infrastructure are outlined.

Power grid and transmission lines

The expansion of power transmission lines has progressed in all three countries in the recent years, especially the 400 kV grids have been expanded. This helps to make electricity grids more efficient and flexible, which is an important prerequisite for the integration of large amounts of renewable electricity. The Jordanian transmission grid consists of 400 kV and 230 kV lines. The Moroccan transmission grid has 400 kV and 225 kV lines, and in Oman 400 kV, 220 kV

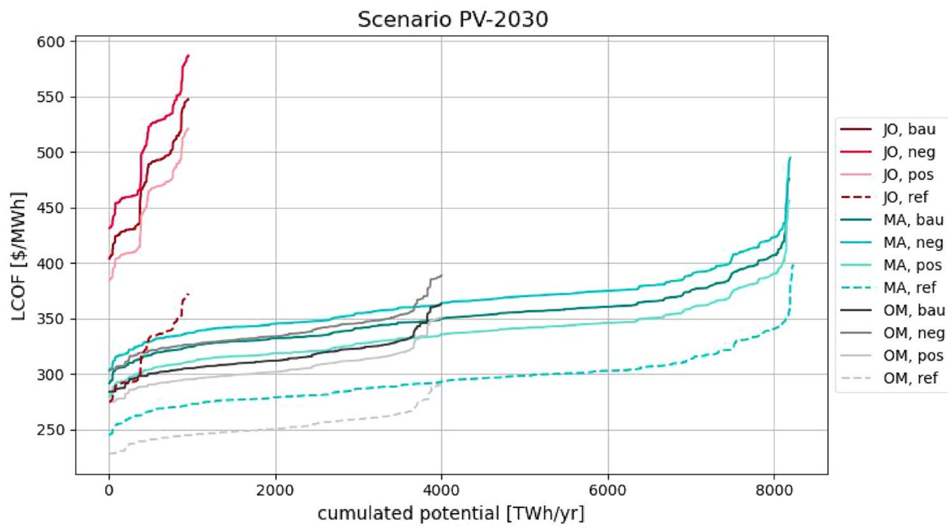

Fig. 3 CP curves for FT fuel from PV power in 2030 by country and WACC case. Source: Braun et al. (2022)

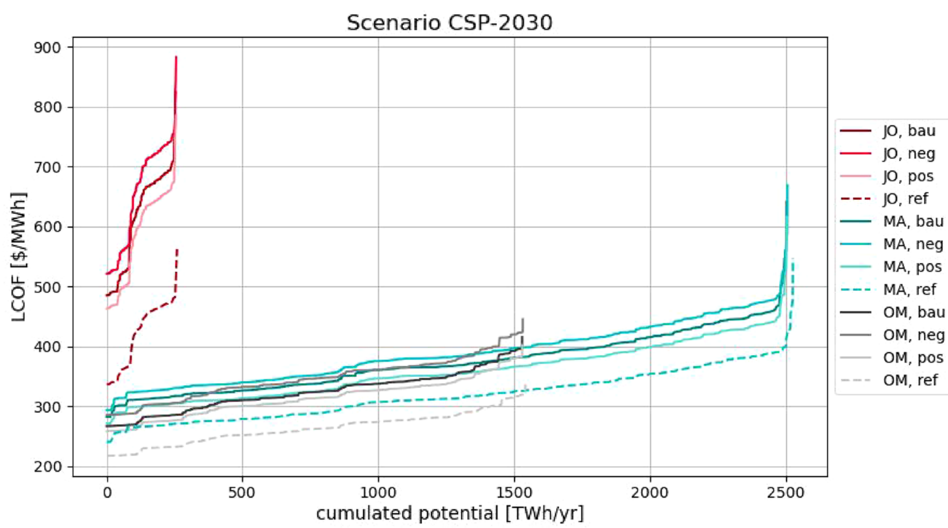

Fig. 4 CP curves for FT fuel from CSP power in 2030 by country and WACC case. Source: Braun et al. (2022)

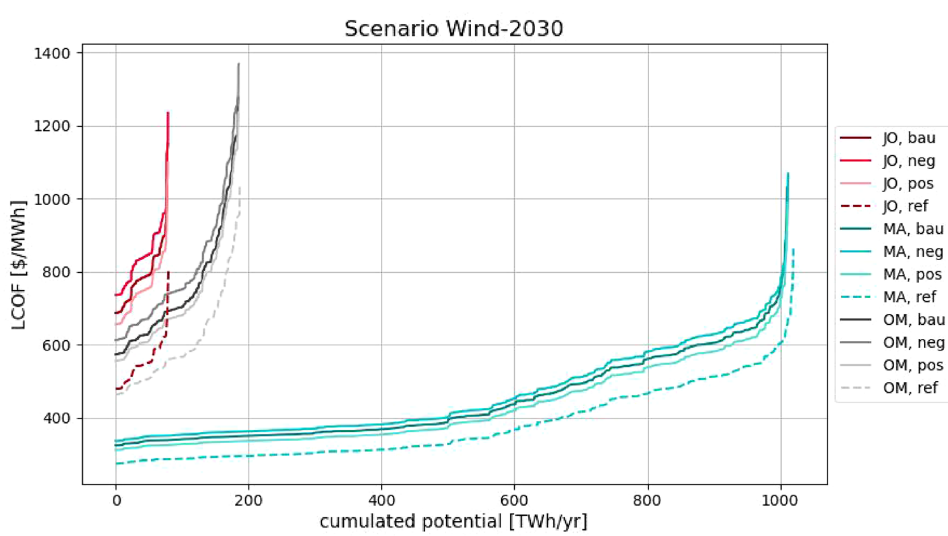

Fig. 5 CP curves for FT fuel from wind power in 2030 by country and WACC case. Source: Braun et al. (2022)

and 132 kV lines are in operation (Abu-Rumman et al. 2020; Enerdata 2021; NEPCO 2020; Sahbani et al. 2016). All three countries have power grid connections to neighboring countries which will be important to balance the fluctuating energy production from renewables and to potentially export electricity. In *Jordan*, further interconnections are planned to Iraq and Saudi Arabia. In *Morocco*, further connections are planned to Spain and Mauretania and even to the UK via a subsea cable. Overall, the large-scale generation of green hydrogen and synthetic fuels will, however, require a much larger and faster expansion of power transmission capacities in all three countries.

Oil and gas infrastructure with potential for conversion

Existing oil and gas infrastructure can potentially be used for the transport of green hydrogen and synthetic fuels under certain conditions and requiring non-negligible technical adaptations and investments. *Jordan*, for example, has a number of gas pipelines, i.e., the Risha Gas Pipeline that is connected to a gas field at the Iraqi border, the Arab Gas Pipeline that transports Egyptian gas through Aqaba toward Syria and Lebanon, and the Noble Energy Gas Pipeline that delivers up to 8.49 million m^3 natural gas per day from Israel (Ghazal 2018). *Morocco* currently operates four gas pipelines: the Euro-Maghreb Pipeline that originates from the Hassi R'Mel gas field in Algeria and continues toward Spain (but the operation has been suspended since 2022 due to political tension); the Mohammedia Gas Pipeline that transports liquefied natural gas (LNG) for industrial purposes; the OCP gas pipeline in Essaouira; and the Gharb ONHYM Pipeline which transports the natural gas produced in the Gharb region to industrial sites. Further gas pipelines are in discussion, especially to expand the network connections between the industrial regions around Casablanca, Safi, El Jadida, but as well Tanger, Kenitra, Mohammedia, and Berrechid (MEME 2020). With regard to oil, a pipeline connects the port of Mohammedia with the oil refinery in Sidi Kacem. As major gas producer and exporter, *Oman* has an onshore gas network of about 2500 km length with further expansions of 500–600 km planned. In addition, *Oman* foresees the realization of a subsea gas pipeline that runs from Iran through Oman to the United Arab Emirates (UAE). The country also has an LNG plant for export purposes, with a capacity of 10.4 million tons per year (Enerdata 2021). With regard to oil, *Oman* has no international pipeline connection, all exports occur by ship.

Loading and storage infrastructure with potential for conversion

Loading and storage infrastructures are crucial for the export of green hydrogen and synthetic fuels. *Jordan* has a very narrow coastal strip in the south, where the port of Aqaba is located. Divided into several terminals for oil and liquefied petroleum gas (LPG), LNG, and phosphate, the port represents an important industrial hub. A floating storage unit (FSU) and the Sheikh Sabah Al Ahmed LNG terminal with a capacity of 170,000 m^3 are located here (ADC 2022). In terms of storage options, Jordan currently stores natural gas in salt caverns near Amman and Aqaba. These storage capacities could potentially also be used to store green hydrogen, but the technical feasibility of this option would need to be examined.

Morocco with an over 3000 km-long coastline has a number of ports that act as transhipment points for raw materials and trade. Fuel storage capacities are concentrated at the Port of Mohammedia, Port of Jorf Lasfar, and Port of Tangier Med with a total capacity of 1,165,970 m^3 (Jamea 2021). In terms of ammonia, the OCP Group operates ammonia storage tanks at the port of Jorf Lasfar, and according to a representative of the Ministry of Equipment, the planned port in Safi will also include ammonia storage tanks. Additionally, the development and construction of a floating LNG storage and regasification facility is being discussed (MEME 2021). Like Jordan, Morocco has salt caverns in Safi-Essaouira, Mohammedia-Benslimane, and the Tangier region that have potential for green hydrogen storage.

Oman's has five sea ports: Port of Sohar, Port of Duqm, Port of Salalah, Port Sultan Qaboos, and Port of Khasab. The Port of Duqm, which is still being finalized, includes a 2000 km^2 Special Economic Zone (SEZ), where first developments of large-scale production plants for green hydrogen and ammonia are planned (DEME 2022). According to experts, the conversion of existing storage facilities, refinery, and logistics infrastructure to synthetic fuels could be possible, but should be investigated.

In summary, oil, gas, LNG, or ammonia loading and storage infrastructures exist in the three countries, which could theoretically be converted. However, the technical feasibility must be examined for each individual case. For the large-scale export, the existing loading infrastructures will probably have to be expanded and adapted in all countries.

Industrial sector analysis

In addition to the necessary infrastructure, industrial structures are equally important for the development of an export sector for green hydrogen and synthetic fuels. In the three analyzed countries, the industrial sector plays an important role in the overall economy. While the industry in *Oman* contributes more than 50% to the gross domestic product (GDP), its share in *Jordan* and *Morocco* is around a quarter (GTAI 2022).

Chemical industry

The chemical industry plays an important role in both the use and production of hydrogen and synthetic fuels. In *Jordan,* the overall demand for hydrogen is limited and comes mainly from the refinery and steel sectors as well as the research and development sector. Hydrogen today is mainly imported. In *Morocco*, according to the Ministry of Industry and Trade, there are six companies that produce and market industrial gases. The two leading companies are Maghreb Oxygène and Air Liquide Maroc. However, according to the managing director of Maghreb Oxygène (Maghreb Oxygène 2017), the local market for hydrogen in *Morocco* is also limited. Current applications are in oil refineries, metallurgy, food processing, and the steel industry. In *Oman*, hydrogen is mainly used in the chemical industry. A total of about 1.09 million tons of gray hydrogen are produced annually in Oman, which is used as a feedstock for the production of methanol (50%) and ammonia (45%) as well as in oil refineries (5%) (Ferrostaal 2021). *Oman* is also one of the world's largest exporters of methanol.

Next to hydrogen itself, another important raw material in the chemical industry that is produced with hydrogen is ammonia. Ammonia is mainly used for the production of phosphate fertilizers. Today, *Jordan* and *Morocco* import fossil-based ammonia. In *Morocco,* demand for ammonia increased from 0.8 million tons in 2013 to 1.8 million tons in 2018. OCP has stated that in the future, it seeks to use green ammonia produced in Morocco, starting with the launch of a pilot project that is expanded to an annual production of 0.6 million tons of green ammonia (OCP 2019). *Jordan* stated that it will consider green ammonia once it becomes economically attractive (Jamea et al. 2021). In *Oman*, on the other hand, ammonia is already being produced today but with natural gas.

Refineries

Refineries can become important players in the production and storage of synthetic fuels. Moreover, the refining process today requires hydrogen from fossil fuels, which could be replaced by green hydrogen in the future. *Jordan* has one oil refinery which is located close to Amman in Zarqa with a capacity of 60,000 barrels per day that is planned to be increased to 120,000 barrels (Hydrocarbons Technology 2022). *Morocco* has two oil refineries in operation and one in the planning stage. The Samir refinery at Mohammedia with a production capacity of 6.25 million tons per year is covering 64% of Morocco's refined products' market. The second Moroccan refinery is located close to Rabat, with a processing capacity of around 30,000 barrels per day and a storage capacity of 190,000 m^3 of petroleum products (Jamea 2021). Another oil refinery is expected to be built in Nador West Med, in northern Morocco with a capacity of around 200,000 barrels per day (Kasraoui 2019). *Oman* has two refineries with a combined capacity of 304,000 barrels per day at Sohar and Mina Al Fahal. The Sohar refinery site was expanded in 2019 to a capacity of 198,000 barrels per day, with much of this production output set to fuel the petrochemical production (BP 2021). Plans for the Duqm refinery project with a capacity of 230,000 barrels per day are currently being negotiated (ibid.).

Cement industry

The cement production is a potential carbon point source for the production of synthetic fuels. For each produced ton of cement, 0.5–0.95 tons of CO_2 are released (IEA 2021b; Plaza et al. 2020). In *Jordan*, the annual cement production capacity increased from 4.4 million tons in 2014 to 5.1 million tons in 2018 (Statista 2021), while *Morocco* produced 13.8 million tons of cement in 2017 (Terrapon-Pfaff and Amroune 2018). *Oman*'s five cement plants have an annual total capacity of 11.5 million tons of cement (Espey 2022). Due to rapid urbanization and ongoing infrastructure development in all three countries, the sector is expected to grow in the coming decades.

Renewable energy industry

The expansion of renewable energy capacities is one of the main prerequisites for the development of an export sector for green hydrogen and synthetic fuels. Accordingly, the capacities of the renewable energy industry in the countries play an important role. *Jordan* has local capacities for solar panel manufacturing of 500 MW annually and supplies modules for local projects, but also exports to other countries. Further, the construction of a new production facility for solar modules is planned in Maan. As Jordan's silicon reserves have a high degree of purity and are easily minable (MEMR n.d.) the potential for polysilicon production in Jordan could provide a competitive advantage for the further expansion of solar cell production in the country. In *Morocco*, the renewable energy industry is also well developed. Significant capacities have, for example, been developed in the wind industry, enabling the local industry to supply all required project components except turbines and generators. The integration rate of the industry could be increased to around 70% in 2021, as a significant number of rotor blades, towers, and electrical and electronic components are now manufactured locally (Jamea 2021). For the solar energy sector, the local industry is able to produce about 40% of the components needed in CSP projects (ibid.). *Oman*, on the other hand, has so far only few service providers in the renewable energy field for solar PV projects and maintenance. For the planned scale-up of renewables in the country, these capacities will have to be expanded very rapidly.

Synthesis of the results

The case study analysis indicates that *Jordan*, *Morocco*, and *Oman* all show considerable potential for the production and export of green hydrogen and synthetic fuels. However, the pace and concrete steps taken by the countries toward the development of a green economy vary. *Jordan* is still at the beginning of discussion and, accordingly, no concrete targets have been set yet. So far, there have been only few activities both from the political side and the private sector. *Morocco*, on the other hand, has already published a hydrogen strategy with concrete export targets. In *Oman*, the hydrogen strategy with concrete quantitative targets is about to be published. In addition, there are already a number of announced large-scale projects in *Oman* and the first demonstration plants are already being planned in *Morocco*. In terms of infrastructure, the countries studied also differ. While Oman, as an energy exporter, already has extensive charging and storage infrastructure that could be converted under certain conditions, Jordan and Morocco, as fossil fuel importers, have comparatively fewer infrastructures and technical experience in their handling. In terms of industrial structure, Jordan and Morocco already have extensive expertise in the renewable sector. Oman, on the other hand, has so far limited capacity and expertise in this area. On the other hand, the chemical industry in Oman is already an important export-oriented sector that could in theory be converted toward green fuels. Table 2 provides an overview of the different stages of development, estimated based on the conducted case study analysis.

Discussion and conclusion

The analysis has shown that while all countries under consideration have some factors in their favor, it is clear that it is still a long way toward the development of large-scale exports of green hydrogen and synthetic fuels. This will require not only political willingness and support, but in terms of industry and infrastructure development, the fast and massive expansion of renewable capacities on a gigawatt scale, which far exceeds the previous growth rates of renewables in all three countries. This holds especially true for Oman where currently only very limited renewable capacities have been installed. It will be interesting to see whether the countries that are already advanced in renewable energy development, such as Morocco and Jordan, can take advantage of this, or whether Oman, which is already an energy exporter, has the better starting conditions for developing a green hydrogen sector. Next to the expansion of renewables, also the parallel development of transport and storage systems that connect renewable energy sources with domestic and foreign demand centers will be essential. The efficient design of the infrastructure will largely depend on the choice of production sites, in coastal industrial centers where direct export is possible, but electricity transport from the interior is required or close to renewable energy capacities, which are mostly located inland. The current discussions and planning of projects in the countries seem to favor production sites located near ports. However, land availability near ports could become a barrier especially in Jordan, due to the limited coastal area. Also in Oman, decision-makers discuss the inland production in the vicinity of renewable energy production sites, due to limited land availability near ports. This assumption is in line with the findings of Weichenhain (2021) who addressed the hydrogen production locations and estimates that the most cost-competitive renewable electricity and green hydrogen production hubs typically are located distant from demand centers for the case of Morocco among others. However, to identify the most efficient and cost-effective solutions, individual cases need to be examined that also consider aspects such as transport and storage infrastructure.

Another critical infrastructure aspect will be the provision of water for the production of green hydrogen. A sustainable production in countries with water scarcity requires seawater desalination. This is in line with the findings of Ansari (2022) and WEC and Frontier Economics (2018), among others. Thus, to establish a green hydrogen production, desalination capacities and water transport pipelines must also be expanded. One approach under discussion is to build large centralized, multi-purpose plants instead of a number of smaller plants that provide only water for hydrogen production. Moreover, almost all desalination plants today operate on fossil fuels. However, green hydrogen production will require desalination based on renewable energy. And even then, desalination can become a bottleneck and lead to conflicts if water is used for export purposes, while the local population suffers from water shortages.

Given the regional dynamics in green hydrogen development, partnerships or division of labor could unlock synergies in the development of green hydrogen value chains. For Jordan in particular, this could be an option, for example, with the close by NEOM project in Saudi Arabia. Such cooperation could build on Saudi Arabia's experience in the oil and gas industry and water desalination, as well as Jordan's expertise in the renewable energy sector.

While the analysis provides an initial overview of country-specific circumstances, additional technical analysis and research, as well as increased cooperation between

Table 2 Assessment overview of the studied countries

	Jordan			Morocco			Oman		
Key production factors									
Renewable potential		●			●			●	
Water desalination capacities		○			◍			◍	
Carbon sources		○			◍			●	
State of development renewable energy (RE), hydrogen (H_2) and synthetic fuel (SYN)	**RE**	**H_2**	**SYN**	**RE**	**H_2**	**SYN**	**RE**	**H_2**	**SYN**
Potential assessment	■	□	□	■	■	■	■	▒	▒
Policy and strategies	■	□	□	■	■	■	▒	▒	▒
Institutional landscape	■	▒	□	■	▒	▒	▒	▒	▒
Domestic demand in relation to potential	○	○	○	○	○	○	○	○	○
Export cost-potential analysis	◍	◍	◍	●	●	●	●	●	●
Presence of relevant infrastructures									
Power grid and transmission line		◍			◍			◍	
Oil and gas infrastructure with potential for conversion		◍			◍			●	
Loading and storage infrastructure with potential for conversion		◍			◍			●	
Presence of relevant industry structures									
Industrial zones and parks		◍			●			●	
Chemical industry		◍			●			●	
Refineries		○			◍			●	
Cement industry		○			◍			◍	
Renewable energy industry		◍			●			○	

■ existing ▒ development in progress □ missing ○ low ◍ medium ● high

importing and exporting countries, but also between potential exporting countries, is essential for the development of green hydrogen export sectors. This includes a detailed technical analysis of existing infrastructure conversion options and extends to the need for a holistic sustainability assessment to ensure that exporting countries benefit economically from the development while not causing social and environmental disadvantages. Furthermore, financing options and market incentives for the production of green hydrogen and synthetic fuels also need to be explored to drive the development of the sector. Only with more in-depth knowledge, the development of a green hydrogen and synthetic fuels (export) sector can be shaped in the best possible way.

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