Renewable Hydrogen from Oman

A producer economy in transition

International Energy Agency

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Abstract

The production of hydrocarbons has a dominant role in Oman's economy with oil and gas representing around 60% of total export income in recent years. In 2022, Oman announced a target to become net zero by 2050 and an aim to significantly ramp up the domestic production of hydrogen from renewable electricity.

The country is well placed to produce large quantities of renewable hydrogen and hydrogen-based fuels like ammonia thanks to its high-quality renewable resources. Oman has also vast amounts of land for large-scale project development, and existing fossil fuel infrastructure that can be used or repurposed for low-emission fuels. Oman can become a competitive producer and exporter of renewable hydrogen and ammonia already by the end of this decade, while simultaneously increasing the share of renewables in its power mix.

This new IEA report – the first of its kind analysing the potential of renewable hydrogen in a producer economy – indicates that renewable hydrogen is set to bring multiple benefits in terms of investment, natural gas savings and avoided CO_2 emissions as Oman transitions towards a net zero economy.

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Executive summary

Oman is a producer economy with net zero ambitions. Hydrocarbon production has a dominant role in Oman's economy with oil and gas representing around 60% of the country's total export income in recent years. Currently, Oman's energy needs are almost entirely met by domestic fossil fuel resources, with natural gas accounting for over 95% of electricity generation. In 2022, Oman announced a target to become net zero by 2050. It also aims to significantly ramp up domestic production of hydrogen from renewable electricity. This commitment is in addition to earlier targets to increase the use of renewables in the power mix.

Long-term targets for renewable hydrogen exceed the size of current LNG exports. The country has set targets to produce at least 1 Mt of renewable hydrogen by 2030, up to 3.75 Mt by 2040 and up to 8.5 Mt by 2050. Achieving this would make renewable hydrogen a significant new source of export revenue. Meeting Oman's 2040 hydrogen target would represent 80% of today's LNG exports in energy-equivalent terms, while achieving the 2050 target would almost double them.

The country is well placed to produce large quantities of renewable hydrogen and hydrogen-based fuels. Oman benefits from high-quality renewable resources (both solar PV and onshore wind) and a convenient location, well-placed to access the main import markets like Europe and Japan. The country also has vast amounts of land for large-scale project development, and existing fossil fuel infrastructure that can be directly used or repurposed for low-emission fuels. The country has extensive expertise in handling and exporting both LNG and ammonia that are directly applicable to renewable hydrogen and hydrogen-based fuels.

Oman has the potential to become one of the most competitive producers of renewable hydrogen. Under the current global pipeline of hydrogen projects, the total installed capacity of electrolysers is expected to increase by a factor of almost 300 by 2030, leading to capital cost reductions of 70%. With this trend, the cost of producing renewable hydrogen in Oman could be as low as USD 1.6/kg H_2 by the end of the decade, positioning Oman as one of the most competitive producers of renewable hydrogen globally.

Oman is on track to become the sixth largest exporter of hydrogen globally by 2030. According to the IEA's global assessment of announced hydrogen projects as of end 2022, Oman could become the largest exporter of hydrogen in the Middle East this decade. Oman is actively working to realise its renewable hydrogen targets. In 2022, the government established an independent entity, Hydrogen Oman (HYDROM), to lead and manage the implementation of its

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hydrogen strategy. So far, 1 500 km^2 of land has been put aside for development with a potential to produce around 1 Mt/yr of renewable hydrogen. By April 2023, HYDROM had released the result of the first auction for land allocation to renewable hydrogen projects, with six projects being awarded. The total amount of land identified by Oman as suitable for renewable hydrogen production in the long term is 50 000 km^2, an area the size of Slovakia. This amount of land would be enough to potentially produce 25 Mt of hydrogen, three times Oman's 2050 targets.

Renewable hydrogen exports are likely to be transported initially in the form of ammonia. Based on globally announced export-oriented projects, ammonia seems to be the carrier of choice for marine transport of hydrogen until at least 2030 due to the lack of suitable infrastructure for handling and transporting liquid hydrogen in large quantities. Given the anticipated reductions in the cost of hydrogen and the relatively low cost of transporting ammonia by sea, the supply cost of renewable ammonia from Oman could be as low as USD 450/tonne (over a distance of 10 000 km) by the end of this decade. This would make renewable ammonia cost comparable with the higher end of ammonia market prices over the period of 2010-2020, and well below the record levels of more than USD 1000/tonne experienced globally in 2022 due to price hikes of natural gas.

Ammonia infrastructure needs to significantly expand to facilitate anticipated export volumes. Oman already exports around 0.2 Mt/yr of ammonia, but this must expand if its hydrogen targets are to be realised in the form of ammonia. Depending on the share of domestic H_2 use, by 2030 Oman could need up to 20-30 times more ammonia export capacity than today. This would require significant growth in new export infrastructure, in particular storage tanks and dedicated deepwater jetties. As the completion of ammonia infrastructure usually takes more than three years, the planning and construction of export facilities would need to begin in the next few years for them to be operational by 2030.

Developing a domestic market for renewable hydrogen can strengthen Oman's position while international demand develops. Currently, only 17% of planned global export projects for 2030 have potential off-takers. The infrastructure for transporting fast growing trade volumes needs time to scale. Domestic demand for renewable hydrogen can start with the refining sector, which uses around 0.35 Mt of fossil hydrogen today and which could be replaced by renewable hydrogen at a production cost of USD 1.6/kg by 2030. Unlike exports, domestic use of renewable hydrogen will also reduce Oman's emissions. Displacing fossil hydrogen in refining would cut emissions by more than 3 $MtCO_2$/yr, or 4% of current domestic emissions.

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Renewables can also benefit the power system, as solar PV and onshore wind can produce cost-effective electricity today. Meeting Oman's hydrogen targets requires massive build-out of renewable captive power. Around 50 TWh of electricity would be already needed to meet the 2030 target, more than the current size of the electricity system. This will have positive implications for cost-effectively achieving Oman's renewables targets, respectively 20% by 2030 (10 TWh), rising to up to 39% by 2040, which take into account technical and contractual flexibility constraints in the power system. Based on the recently awarded bid prices in the region, utility solar PV and wind are likely already competitive with natural gas in Oman. Simultaneous large-scale deployment of captive renewables for hydrogen production can further improve the competitiveness of renewables in the power mix. A secure system integration of the 20% renewables target can be achieved via more flexible operation of gas-fired power plants, renewables forecasting and grid expansion.

Scale-up of renewable hydrogen production requires significant investments. Cumulative investment needs by 2030 would be around USD 33 billion, respectively USD 20 billion for captive renewable power dedicated to H_2 production and USD 13 billion for electrolysis and ammonia conversion, with an additional USD 4 billion required for achieving the 20% renewables share target in the power mix.

Renewables and domestic use of hydrogen reduce the need for natural gas. By 2030, total annual gas savings could be 3 bcm, of which half could be saved annually by replacing 20% of natural gas in power generation with renewables and further half by replacing fossil hydrogen in refining. These savings would be equivalent to roughly 20% of 2021 LNG exports. Oman may consider expanding its LNG infrastructure to increase export volumes, depending on LNG demand and supply trends in the coming years.

Renewable hydrogen can bring multiple benefits to Oman's net zero transition. Already in this decade, a large-scale roll-out of renewable hydrogen and renewables in the power mix would require an investment of USD 37 billion, reduce domestic need for natural gas by 3 bcm/yr and avoid Oman's total CO_2 emissions by 7 $MtCO_2$, equivalent to 7% of baseline emissions by 2030. By then, ammonia export and domestic replacement of fossil hydrogen could generate an economic value of more than USD 2 billion a year, which could rise to double-digit USD billion levels in the long term. Regardless of the eventual allocation of renewable resources between electricity production and hydrogen for domestic use or exports, renewable hydrogen is set to bring multiple benefits as Oman transitions towards a net zero economy.

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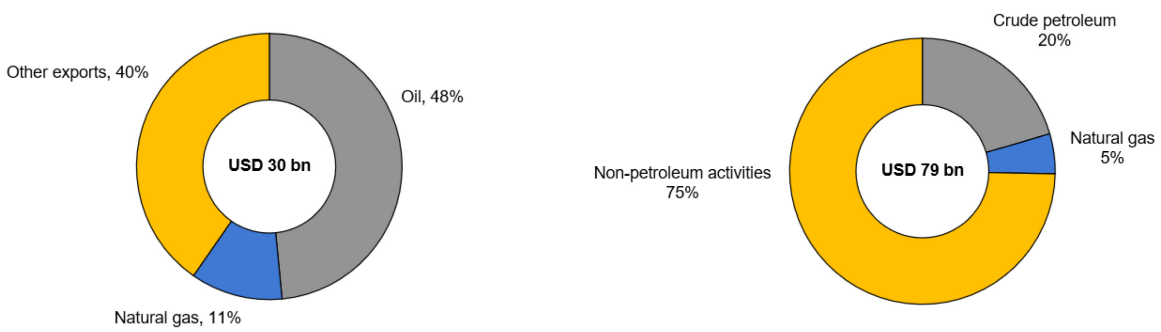
Chapter 1. Oman: A producer economy on the brink of transition

Oman is located on the south-eastern coast of the Arabian Peninsula. It borders Saudi Arabia and the United Arab Emirates on the north and Yemen on the west and faces the Arabian Sea and Gulf of Oman on the south-east. Located at the crossroads of Africa, Europe and India, Oman is well positioned for global trading. The capital and most populated city of Oman is Muscat, and the country covers a territory of 309 500 square kilometres (km^2) with a total population of 4.5 million people in 2021.

The economy of Oman relies on its national oil and gas industries. After oil was first discovered in the country in 1964, commercial production and export started quickly, subsequently contributing to the country's social and economic development. With a production of 971 million barrels (mb) of oil and 43.6 billion cubic metres (bcm) of natural gas in 2021, Oman was the fourth-largest producer of oil and natural gas among the Gulf Cooperation Council (GCC) member states.[1]

Oman is a producer economy[2] and has the largest production of oil and natural gas in the Middle East outside the Organization of the Petroleum Exporting Countries (OPEC). The production of hydrocarbons dominates Oman's economy: revenues from exporting oil and gas are a key source of income for the government. In 2020, they represented 60% of total export income and 25% of the country's GDP (Figure 1.1).

Figure 1.1 Oman's total export revenues, 2020 (left) and GDP by economic activity, 2020 (right)



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Source: Oman's National Centre for Statistics & Information

[1] The six GCC member states are: Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates.
[2] The IEA defines "producer economies" as large oil and gas exporters who are pillars of global supply and rely on hydrocarbon revenues to finance a significant proportion of their national budgets.

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Oman's vision for the clean energy transition

In 2022, ahead of COP27, Oman announced a commitment to reach net zero emissions by 2050, becoming the third Middle East oil and gas producer to make a net zero pledge, after the United Arab Emirates and Saudi Arabia in 2021.The commitment is supported by Oman's National Strategy for an Orderly Transition to Net Zero, a document detailing how Oman plans to reach net zero emissions by 2050 in the energy sector. The document identifies industry, oil and gas, and transport as the main emissions sources in the country. The total investment needed to support the clean energy transition is estimated at USD 190 billion, which would cover primarily power and hydrogen infrastructure needs (i.e., upgrading and extension of electricity grid, hydrogen pipelines and storage, electric vehicle charging infrastructure and deployment of long-duration energy storage). In addition to emissions reduction, the strategy also recognises positive impacts on the Omani economy (i.e., higher GDP, freeing-up natural gas), society (i.e., new jobs) and improved energy security. To lead the clean energy transition, an independent body – the Oman Sustainability Centre – has been set up to lead and supervise the implementation of Oman's plans and programmes for emissions reduction.

Beyond decarbonisation targets, the clean energy transition is further motivated by the following additional drivers:

Limited gas reserves. Although natural gas has long been a key driver of Oman's economic growth, resources are now slightly dwindling. Oman has managed to stabilise gas reserves through the recent gas field discoveries such as Khazzan, Ghazeer and Mabrouk, but with 0.7 trillion cubic metres (tcm), Oman has the smallest gas reserves in the Middle East after Syria (0.3 tcm) and Bahrain (0.2 tcm). Whilst in the short- and medium term, gas reserves are expected to be enough to fulfil current levels of consumption, in the long-term growing population and industrial aspirations could put a strain on domestic gas resources.

Uncertainty of fossil fuel export revenues. The global oil market today is facing both short and long-term uncertainties driven by current energy crisis, the tightening of climate commitments and rising appetite for clean fuels and products. As countries strive to meet their climate goals, they need to reduce their demand for oil and gas in favour of clean fuel options. For producer economies like Oman, the uncertainty around future fossil fuel demand puts oil and gas export revenues at stake.

Rising emissions. Between 2000 and 2022, total greenhouse gas emissions in Oman rose from 22 million tonnes (Mt) CO_2/year to 81 Mt CO_2, due to an increase in domestic fossil-based energy demand. National electricity and energy demand are also projected to increase until 2028 as a result of population growth, rising demand for air conditioning, infrastructure investments and growth in energy-

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intensive industries. If no action is taken now, emissions are projected to surpass 100 Mt CO_2/year before 2030, jeopardising the country's ambitious net zero emissions goal by 2050.

Box 1.1 Facts on Oman's energy sector

Oman's energy supply is entirely generated by nationally produced fossil fuel resources: in 2020, natural gas accounted for 64% of total energy supply and crude oil for 36%. Petroleum Development Oman (PDO) is the main exploration and production company in Oman, partly owned by the government, and it accounts for more than 70% of the country's crude oil production and more than half of its natural gas production and supply. Natural gas accounts for 96% of Oman's power generation. The main electricity consumer is the residential sector, requiring 47% of the total electricity generation, followed by commercial and public services (36%) and industry (15%).

Oman's power system relies on two main publicly owned electricity networks: the Main Interconnected System (MIS) and the Dhofar Power System (DPS). The MIS is located in the north and delivers around 87% of Oman's electricity. The DPS mainly serves the city of Salalah and the surrounding areas, contributing to 10% of the Oman total electricity supply. The rest of the country is powered by the Rural Areas Electricity Company (Tanweer) through diesel-based generation plants. Both the MIS and DPS systems are connected to the PDO power system. In 2020, the majority state-owned Oman Electricity Transmission Company (OETC) awarded contracts for the Rabt project, which aims to connect the national grid with other electricity transmission networks in the country. The first phase of the project is set to be completed by 2023, and it will connect MIS with the isolated networks of PDO and Tanweer. Phase two will complete the integration by 2026. All power generation in MIS is currently privately owned, while both MIS and DPS are owned and operated by OETC. However, efforts have begun for the privatisation of the electricity transmission and distribution networks, and once completed, Oman will be the first country in the Middle East to do so.

Oman's electricity market was liberalised after the introduction of the Sector Law in 2004. The Authority for Public Services Regulation (ASPR) is responsible for regulating the electricity sector, as well as the water, gas and wastewater sectors. The ASPR is financially and administratively independent from the government to ensure fair and transparent management. The electricity market is based on a capacity market model, where Oman Power and Water Procurement Company (OPWP) has the role of the electricity off-taker for the whole country, and thus it distributes capacity charges to the different independent water and power producers for their plants' contracted power capacity. Additional variable charges are also applied depending on the available power plant capacity. Since January 2022, the first electricity spot market in the Middle East-North Africa region has

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been launched and operated in Oman by OPWP, working alongside long-term power purchase agreements. The spot market is expected to further liberate the electricity market by allowing bilateral sale outside the control of the single purchaser. This means that OPWP is expected to slowly become market operator much more than single purchaser and it is expected to lower the cost of electricity procurement.

Since 2012, Oman's power grid is interconnected with the power systems of the GCC Interconnection Authority via Abu Dhabi. The 220-kilovolt interconnection gives Oman access to the power systems of the other five GCC member states. In 2022, OPWP started exploring a new electrical interconnection of 700 MW of approximately 700 kilometres with Saudi Arabia. It is envisaged that the interconnection would offer power transmission flexibility between the two countries, and it would open opportunities for electricity trades, firm capacity purchases and co-ordinated reserve planning.

Developing the renewables potential

A large-scale development of renewable energy and hydrogen would offer a way to diversify Oman's economy and its energy mix. Oman has excellent renewable resources. The intensity of solar radiation is among the highest in the world, which, together with vast amounts of available land, offers an excellent opportunity for large-scale solar exploitation. Oman also has significant wind energy potentials in the south and south-eastern coasts and coastal highlands facing the Arabian Sea and in the mountains in the north of Salalah. In these locations, average wind speeds exceed 8 metres per second, which is similar to European sites where commercial wind power already successfully operates today.

Table 1.1 Summary of existing and planned renewable energy projects in Oman

Name of project	System	Technology	Capacity	Status
Miraah Solar Thermal Project	-	Solar thermal for EOR	330 MW_t	Online in 2018
Dhofar I Wind Project	DPS	Wind	50 MW	Online in 2019
Amin Solar	MIS	Solar	125 MW	Online in 2020
Ibri II Solar	MIS	Solar	500 MW	Inaugurated in January 2022
Liwa Solar project	MIS	Solar	100 MW	Estimated operation in 2023
Manah I Solar	MIS	Solar	500 MW	Estimated operation in Q1 2025
Manah II Solar	MIS	Solar	500 MW	Estimated operation in Q2 2025

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Name of project	System	Technology	Capacity	Status
MIS Solar IPP 2025	MIS	Solar	500 MW	Estimated operation in Q1 2026
Jalaan Bani Bu Ali	MIS	Wind	100 MW	Estimated operation in Q1 2026
Duqm I Wind IPP	Ad Duqm Power System (Rural Areas Electricity Company)	Wind	200 MW	Estimated operation in Q1 2026
Dhofar II Wind Project	DPS	Wind	100 MW	Estimated operation in 2026
Ras Madrakah Wind IPP	Ad Duqm Power System (Rural Areas Electricity Company)	Wind	200 MW	Estimated operation in 2027
MIS Solar IPP 2027	Al Wusta Governorate	Solar	500 MW	Estimated operation in 2027

Note: EOR = enhanced oil recovery; MW_t = megawatt thermal; MW = megawatt; MIS = Main Interconnected System; DPS = Dhofar Power System.

Oman is already taking first steps towards developing its renewable energy potential, and its plans are outlined in the Oman Vision 2040, which aims to significantly ramp up renewables in the country's electricity generation mix from 1% today to 20% by 2030, and to 35-39% by 2040. Development of renewable energy projects is currently ongoing to meet the announced targets. There is already a pipeline of renewable projects under development set to boost renewable electricity generation to meet the decarbonisation targets (Table 1.1). In 2022, a total of 675 MW of renewables came online – 50 MW of wind and 625 MW of solar PV. Once completed, the current project pipeline would generate around 8 terawatt-hours (TWh) of renewable electricity by 2027. This is well on track with the 20% renewable electricity share in 2030 (10 TWh). This represents only 0.1% of Oman's total estimated potential for renewable electricity generation, which is around 7 000 TWh per year. In 2021, electricity generation in Oman was about 42 TWh, representing only 0.5% of the country's total renewables potential. Part of this renewable energy potential could be exported in the form of hydrogen,[3] creating a new low-emission revenue source.

Emerging international hydrogen trade

An increasing number of countries are showing strong interest in scaling up the use of low-emission hydrogen (and its derivatives) to decarbonise domestic industry and transport sectors as well as providing low-emission dispatchable power. However, some countries have limited resources to produce low-cost low-

[3] See Explanatory notes annex for renewable hydrogen definition in this report.

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emission hydrogen (and derivatives) and may need to rely on imports to satisfy their needs. Significant hydrogen exports are currently being planned in many regions with low-cost renewable resources to meet the expected demand and to create new revenue streams for the abundant (but otherwise unused) renewable resources. Based on the current global project pipeline, 12 Mt of low-emission hydrogen could be exported annually worldwide by 2030, of which 2.4 Mt is planned to come online by 2026.

The emerging international hydrogen trade offers producer economies the possibility to simultaneously address climate challenges rising from fossil fuel use and provide a vision of new revenue streams based on renewables. Producer economies are well-placed for becoming key players in the production and export of low-emission fuels by leveraging two aspects. First, existing fossil fuel assets and infrastructure could be repurposed to produce and distribute low-emission fuels. Second, producer economies can benefit from existing expertise and know-how in handling, processing, and exporting hydrogen-derived fuels and apply it for the low-emission alternatives.

Initially, export earnings from hydrogen will only partially match those from oil and gas exports, but they will become increasingly important when demand for fossil fuels is reduced as countries strive to meet their climate goals. Export-oriented large-scale renewable hydrogen projects could also trigger spill-over impacts and domestic opportunities through the creation of new and competitive clean energy industries. In particular, renewable hydrogen can replace existing uses of fossil-based hydrogen, but also certain industrial uses of natural gas. By leveraging its large potential for renewables, and the prospects of emerging trade in low-emission hydrogen, Oman is well positioned to be among the first movers and to benefit from the emerging new trade.

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Chapter 2. Opening the door to hydrogen exports

Current targets and project pipeline

Oman is currently building competencies for hydrogen export, enabled by its existing infrastructure and extensive experience in exporting LNG. The Ministry of Energy and Minerals established a National Hydrogen Alliance ''Hy-Fly'' in 2021. The alliance gathers 15 public and private organisations including government bodies, oil and gas operators, academia, research institutes, and ports that will work together to support and facilitate the production, transport, and utilisation of renewable hydrogen for domestic use and export. As a follow-up, in October 2022, the government of Oman unveiled its green hydrogen strategy, which includes a target of 1 Mt to 1.25 Mt of green hydrogen production by 2030, rising to 3.25 Mt to 3.75 Mt per year by 2040 and further to 7.5 Mt to 8.5 Mt per year by 2050. The government has estimated that a cumulative investment of USD 140 billion until 2050 would be needed to achieve these targets (this comes in addition to the USD 190 billion of cumulative investments needed for the National Strategy for an Orderly Transition to Net Zero).

Three regions along the coastline have been identified as locations for renewable hydrogen production: Duqm, Dhofar and Al-Jazir, and a total of 50 000 square kilometres of land – an area the size of Slovakia – have already been identified for hydrogen project development. This land area is estimated to have the potential to produce 25 Mt of hydrogen per year (from 500 GW of renewables). The produced hydrogen is set to cover domestic demand, as well as exports, mainly to European and Asian countries. To lead the strategy, the government has established Hydrogen Oman (HYDROM), a fully owned autonomous subsidiary of Energy Development Oman. The mandate of HYDROM includes the structuring of the large-scale green hydrogen projects and managing the auction process for allocating government-owned lands for green hydrogen projects, assisting in the development of common infrastructure and connected ecosystem industries and hubs, and overseeing the execution of hydrogen projects. In mid-March 2023, the first public bids were held for the awarding of the first land blocks to meet the 2030 target. By April 2023, HYDROM had released the result of the first auction for land allocation to renewable hydrogen projects, with six project worth USD 20 billion being awarded. The earmarked area stretches over 1 500 km^2 and will supply a total of 15 GW electrolyser capacity. The agreements are for a period of 47 years, which includes 7 years for development and construction and 40 years of operation.

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Table 2.1 Planned hydrogen and ammonia projects in Oman, 2022-2030.

Name of project	Status	Date online	Electrolysis capacity (MW)	Production capacity (kt H_2) per year	Export-oriented
Hyport@Dqum, Phase I	Feasibility study	2026	500	87	Yes
Green Hydrogen Oman (GEO) project	Feasibility study	2028	4 700	809	Yes
Salalah H_2	Feasibility study	2024	400	69	Yes
Sohar port, Phase I	Concept	2024	35	6	No
Green Hydrogen and Chemicals SPC	Feasibility study	2026	300	52	Yes
Sur Hydrogen Cluster	Pre-feasibility study	2030	1 300	225	No
H_2Oman (Dhofar)	Concept	2030	1 040	180	Yes
Sur Hydrogen Cluster	Pre-feasibility study	2030	1 300	225	No
BP Alternative Energy Investments Limited-Duqm	Feasibility study	2030	-	150	No
BP Alternative Energy Investments Limited-Dhofar	Feasibility study	2030	-	150	No

Notes: Only projects with a disclosed start year for operation are included. Only part of the production of ''export-oriented'' projects is planned for export.
Source: IEA hydrogen projects database.

Based on IEA analysis of the current pipeline, Oman could become the sixth-largest exporter of hydrogen globally by 2030, and the largest exporter in the region. Oman would represent 61% of total hydrogen exports from the Middle East (equal to 1.1 Mt H_2/year), followed by the United Arab Emirates (20%) and Saudi Arabia (16%) (Figure 2.1). Even if projects have not yet stated a clear preference, ammonia would represent the most common form for the export of hydrogen by sea in 2030.

Many of the export projects are planned in shared industrial hubs, namely ports, such as Duqm, Salalah and Sohar. Concentrating developments to industrial hubs offers opportunities for shared infrastructure and energy integration. Furthermore, establishing large, dedicated land areas for such industrial zones away from densely populated areas or sensitive ecosystems could also reduce infrastructure permitting and siting challenges.

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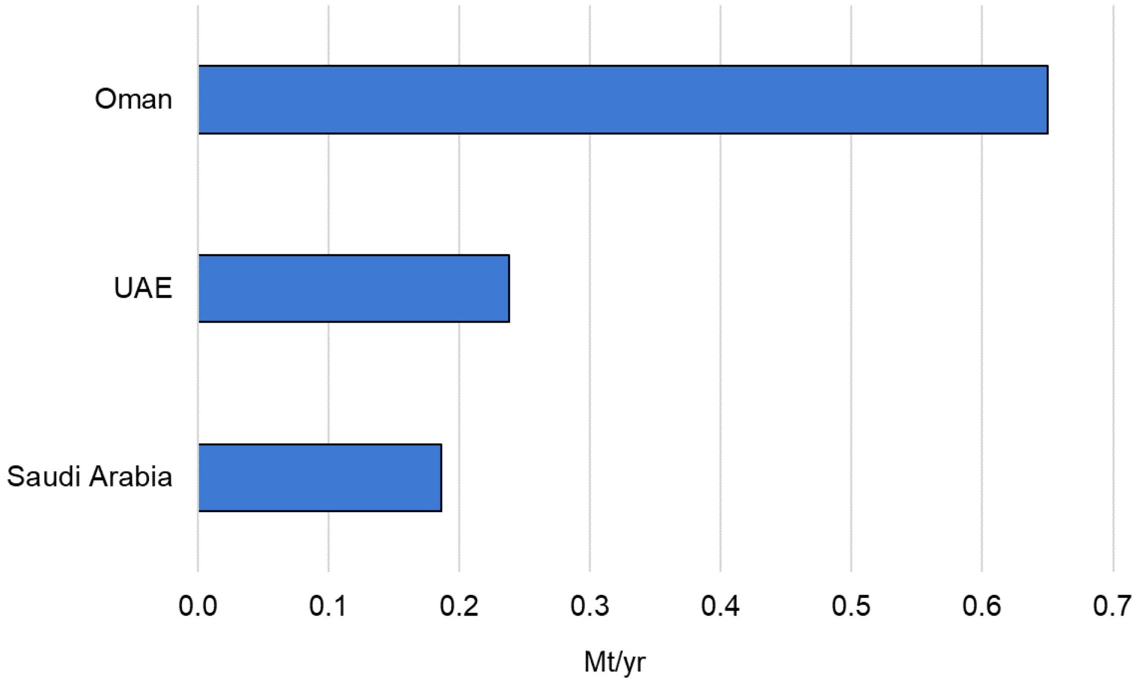
Figure 2.1 Export volumes for hydrogen in the Middle East based on planned projects, 2030



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Note: UAE = United Arab Emirates.
Source: Based on IEA (2022), Global Hydrogen Review.

To put Oman's current hydrogen ambition in proportion, it is useful to contrast it against the current level of LNG trade. With almost 14 bcm (560 petajoules [PJ]), Oman was the third-largest LNG exporter in the Middle East-North Africa region (behind Qatar and Algeria) in 2021. Based on the IEA's analysis of the current project pipeline, the 78 PJ (0.65 Mt) export of hydrogen in 2030 would represent only one-seventh of today's LNG exports. However, meeting its 2040 renewable hydrogen production targets would already represent 80% of current LNG export volumes in energy-equivalent terms. Meeting the 2050 target of 1020 PJ (8.5 Mt) would significantly exceed current LNG volumes (Figure 2.2).

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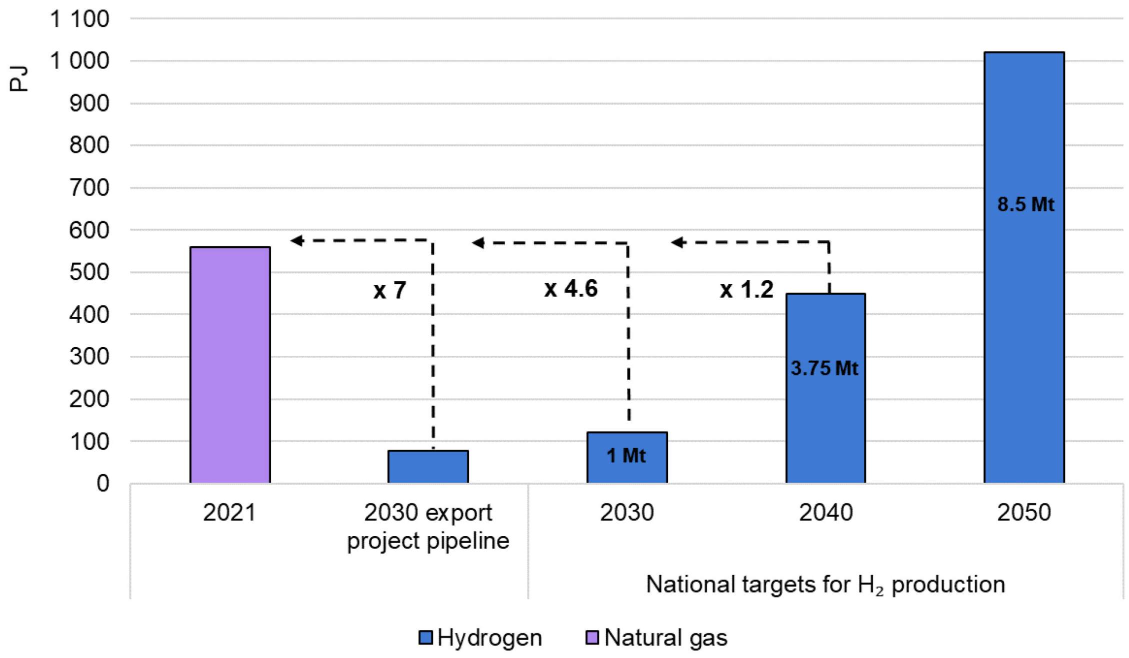
Figure 2.2 Size of Oman's LNG exports in 2021 vs. renewable hydrogen export project pipeline and renewable hydrogen targets (2030, 2040, 2050)



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Note: Natural gas export estimates are based on IEA analysis.

Even if today's size of the hydrogen market is well below that of oil and gas, there is a great uncertainty around the evolution of global demand for fossil fuels. At the same time, the IEA's Net Zero Emissions Scenario by 2050 expects the demand for low-emission hydrogen to increase strongly, reaching 452 Mt by 2050. If Oman can meet its 2050 hydrogen production target, it would be able to capture 1.8% of the global hydrogen market, a higher share than Oman's current contribution to supplying global oil and natural gas use (0.8% and 0.3% respectively) (Table 2.2).

Table 2.2 Comparison of Oman's share of the world's oil and natural gas demand in 2021 vs. share of the world's low-emission hydrogen demand in the IEA's Net Zero by 2050 Scenario

	2021		2050
	Oil (mb/d)	Natural Gas (bcm)	Low-emission H_2 (Mt)
World demand	94.5	4 213	452
Oman supply	0.79	14	8

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	2021		2050
Oman's share of the world demand	0.8%	0.3%	1.8%

Source: IEA's World Energy Outlook 2022; world demand of low-emission H_2 in 2050 from the NZE by 2050 scenario; Oman supply of low-emission H_2 in 2050 according to the country's supply target; Oman NG and oil exports: IEA & Oman National Centre for Statistics and Information

Box 2.1 Water requirements for hydrogen production through electrolysis

Water is the main feedstock for renewable hydrogen production through electrolysis, and typically around 10 litres of purified water is needed to produce 1 kg of hydrogen. When compared with other hydrogen production processes, electrolysis has the smallest water footprint. The IEA's Global Hydrogen Review 2021 estimates that producing hydrogen from natural gas with carbon capture, utilisation and storage (CCUS) uses between 13 kg and 18 kg of water per kilogramme of H_2, while coal gasification uses between 40 kg and 86 kg of water per kilogramme of H_2, depending on water consumption related to coal mining.

Electrolysers require high levels of water purity, and freshwater access can be an issue in water-stressed areas. However, seawater desalination could become an alternative in coastal areas. Using reverse osmosis for desalination requires 3 kWh to 4 kWh of electricity per cubic metre of water. This has only a minor impact on the total costs of water electrolysis, increasing total hydrogen production costs by less than USD 0.1/kg H_2.

In the context of Oman's renewable hydrogen production targets, meeting the 2030 target of 1 Mt of H_2 production would require 10 Mt of purified water, the 2040 goal of 3.25 Mt H_2 to 3.75 Mt H_2 would require 33 Mt to 38 Mt of purified water, and the 2050 target of 7.5 Mt H_2 to 8.5 Mt H_2 would require 75 Mt to 85 Mt of purified water.

Cost of renewable hydrogen

The cost of electrolysers and the cost of electricity are the two main components in the production cost of electrolytic hydrogen. Today, an electrolyser (including the equipment, gas treatment, plant balancing, and engineering, procurement, and construction cost) costs in the range of USD 1 400 per kilowatt (kW) to USD 1 770/kW. The costs are expected to be significantly reduced by 2030 as many more electrolysers are rolled out. These cost reductions can be attributed to scale benefits in manufacturing, innovation, technological learning, and more efficient and competitive markets.

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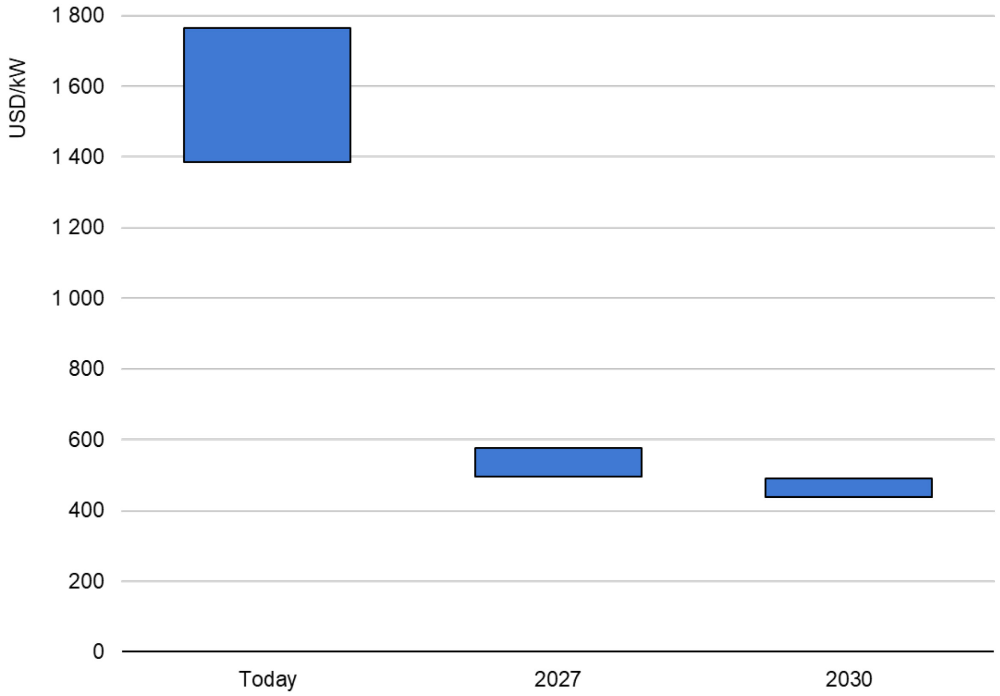
This relationship between deployment and falling equipment cost has been observed over the past decade for other modular energy technologies such as solar PV. Between 2010 and 2021, PV module costs fell by almost 90% from USD 2.5/W to less than USD 0.5/W. This was a result of an around 60-fold increase in cumulative installed utility-scale capacity from less than 8 GW to 500 GW over the same time period.

Future electrolyser costs can be estimated using a learning curve approach, which describes costs as a function of cumulative capacity deployment. Under the current global pipeline, the installed capacity of electrolysers[4] would increase from 0.5 GW in 2021 to 35 GW in 2025 and 134 GW in 2030.[5] As a consequence of this expansion, the capital cost of electrolysers would be reduced by 64-67% by 2027, and 68-72% by 2030 (USD 440/kW to USD 500/kW) (Figure 2.3).

Figure 2.3 Evolution of electrolyser capital costs based on global project pipeline, 2027 and 2030



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Source: IEA (2022), Global Hydrogen Review.

A concentrated effort to scale up the domestic renewable hydrogen value chain will also lead to reductions in soft costs. As deployment increases to meet local

[4] This only considers hydrogen from water electrolysis and excludes alkaline electrolysers, for which hydrogen is a by-product.
[5] This could increase to 240 GW if projects at very early stages of development are included, e.g., only a co-operation agreement among stakeholders has been announced.

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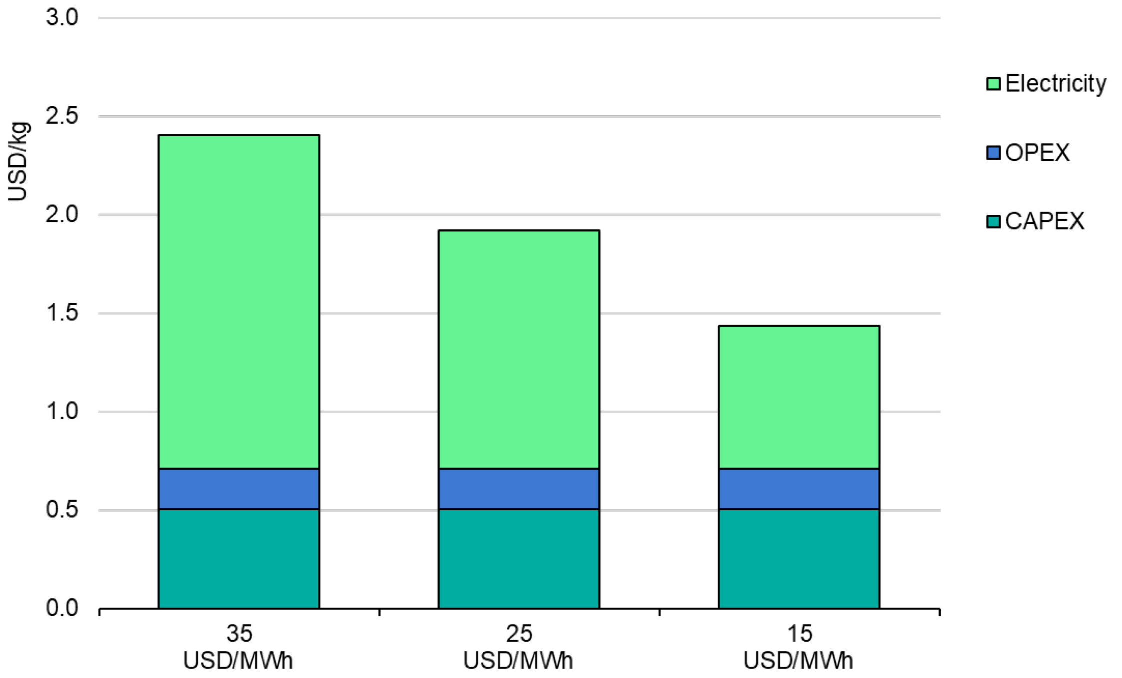
demand, the experience gained from construction and permitting will be applied to future projects, resulting in faster delivery and lower overall costs. Increasing and aggregating demand in industrial clusters can also spread infrastructure costs over more users and lower production costs. Furthermore, as investors see more projects commissioned, it will increase confidence and lead to lower perceived risk and financing rates, a key factor influencing the economic attractiveness of a project.

Having access to a low-cost low-emission electricity source is a significant advantage for economically competitive production of hydrogen because electricity makes a large contribution to the total costs as exemplified by the parametric analysis in Figure 2.4. For example, reducing the cost of electricity from USD 35/MWh to USD 25/MWh reduces the levelised cost of hydrogen by 30% from an estimated USD 2.4/kg down to USD 1.9/kg by 2030.

Figure 2.4 Production cost variations for renewable hydrogen as a function of electricity cost, 2030



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Note: Following assumptions were used for 2030: Technical lifetime 25 years; electrolyser efficiency: 69%; CAPEX USD 320/kW_e, annual OPEX 3% of CAPEX, Solar PV capacity factor 29%.

Combining the high-quality renewable resources of Oman with global cost reductions in electrolysers, PV and wind; the cost of renewable hydrogen is expected to decline significantly by 2030. Assuming that hydrogen deployment stays on track with global climate ambition, the levelised cost of renewable

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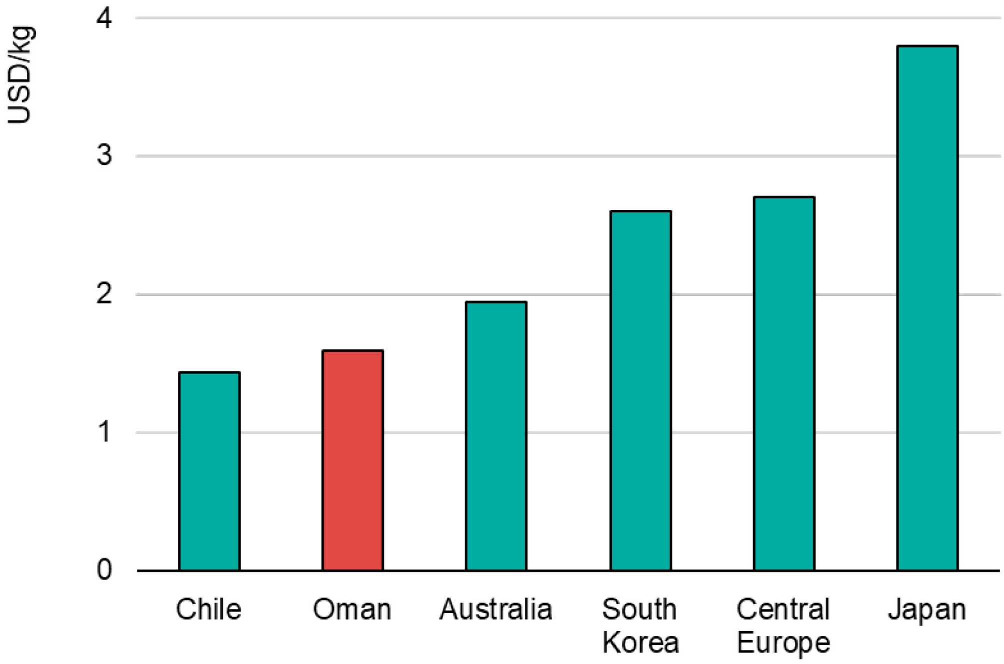
hydrogen from solar PV and wind by 2030 could be as low as USD 1.6/kg H_2 in Oman, USD 1.4/kg H_2 in Chile, USD 1.7/kg H_2 in the United States, and USD 1.9/kg H_2 in Australia. Countries and regions like Central Europe, Japan and South Korea would have comparatively higher levelised costs ranging between USD 2.6/kg H_2 and USD 3.8/kg H_2 (Figure 2.5).These higher production costs, combined with more limited production potentials due to higher population densities, will likely result in these countries or regions being global importers of low-emission hydrogen and derived fuels.

Figure 2.5 Renewable hydrogen production costs in selected potential export countries and import markets in 2030



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Notes: Technical lifetime 25 years; electrolyser efficiency: 69%; electrolyser CAPEX USD 320/kWe; annual OPEX 3% of CAPEX, WACC 3.5%-5% depending on the country.

Ammonia as a hydrogen carrier

Extensive transport and storage infrastructure is a prerequisite for establishing global value chains for low-emission fuels and connecting low-cost production regions with potential users. In this respect, production costs of renewable hydrogen are only one component of the total supply costs, which should also consider conversion and transport costs.

Transmission of hydrogen via pipelines is a mature technology and represents a relatively small proportion of the overall supply cost. However, no commercial ships are today available to transport large quantities of hydrogen by sea. Such ships would be broadly similar to LNG ships and would require hydrogen to be

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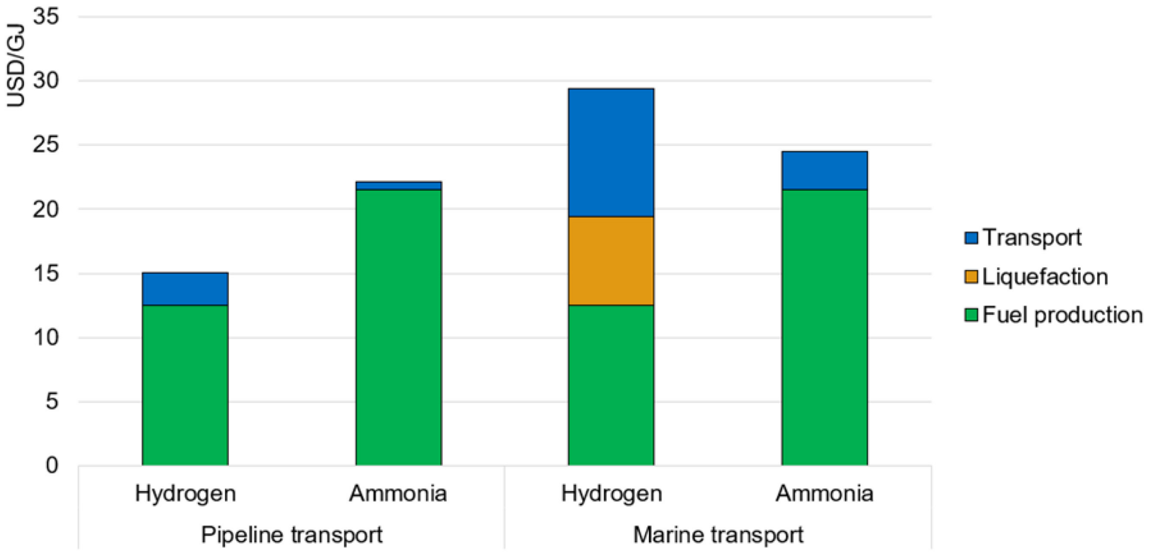
liquefied prior to transport. An excellent insulation of the ship's storage tanks is also required to minimise the unavoidable boil-off. The world's first prototype liquefied hydrogen carrier, the Suiso Frontier, has a capacity of 1 250 m^3 and delivered its first cargo of liquefied hydrogen in early 2022.

In contrast to hydrogen, marine transport of ammonia is already well developed today, relying on chemical and semi refrigerated liquefied petroleum gas (LPG) tankers. Despite the costs associated with hydrogen conversion to ammonia, the overall supply cost by sea is lower than for liquid hydrogen, making ammonia the likely carrier of choice for long-distance hydrogen transport in this decade (Figure 2.6).

Figure 2.6 Supply cost comparison of hydrogen and ammonia based on pipeline or marine transport



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Note: Pipeline transport 1 000 km, marine transport 10 000 km. Source: IEA (2021), The Role of Low-Carbon Fuels in the Clean Energy Transitions of the Power Sector.

Out of Oman's five industrial ports (Duqm, Muscat, Salalah, Sohar and Sur) the ports of Salalah, Sohar and Sur have existing ammonia infrastructure and host ammonia terminals. Given that hydrogen exports will likely go mainly to Europe and some countries in the Asia Pacific region, transport will therefore rely on shipping. Due to the current maturity of technologies and supply chain status, exports are expected to be in the form of ammonia. Oman already exports around 0.2 Mt/yr of ammonia, but this must expand if its hydrogen targets are to be realised in the form of ammonia. Depending on the share of domestic H_2 use, by 2030 Oman could need up to 20-30 times more ammonia export capacity than today. This would require significant growth in new export infrastructure, in particular ammonia storage tanks and dedicated deepwater jetties. Low-emission

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methanol could be another possible hydrogen carrier, but it requires a sustainable source of CO_2 in addition to the hydrogen (see Box: The potential for direct air capture deployment in Oman in Chapter 3).

Table 2.3 Current and planned handling in Oman's main ports

Port	Current handling	Current capacity (Mt)	Planned handling	Planned renewable H_2 and NH_3 capacity (Mt)
Duqm	Existing refinery	0.28 Mt	Developing hydrogen and ammonia facilities	1.2 Mt of ammonia and 0.87 Mt of hydrogen
Sohar	Existing ammonia, urea and methanol facilities	0.19 Mt	-	-
	Existing refinery	0.16 Mt		
Salalah	Existing methanol and ammonia facilities	0.25 Mt	Developing renewable ammonia facility	1 Mt of ammonia
Sur	Existing ammonia and urea facilities	0.2 Mt	-	-
Muscat	Existing refinery	0.02 Mt	-	-

Note: H_2 = hydrogen, NH_3 = ammonia.

European and Asian countries have already begun developing plans for importing hydrogen and ammonia. As part of the plan to reduce reliance on Russian fossil fuels, the European Union's REPowerEU plan has set a target to produce 10 Mt of renewable hydrogen domestically and a target to import 10 Mt by 2030. The import target is 6 Mt of renewable hydrogen and 4 Mt of hydrogen in the form of ammonia (which would be equivalent to 24 Mt NH_3) or other derivatives. Japan's Roadmap for Fuel Ammonia sets a plan to import 3 Mt of clean ammonia by 2030, with demand rising to 30 Mt by 2050, and even if its targeted proportion of low-emission hydrogen imports is unspecified, Japan plans to consume 3 Mt H_2/yr by 2030 (including imports), of which 0.42 Mt H_2/yr is to be low-emission hydrogen. Korea's hydrogen plan targets nearly 2 Mt/yr of low-emission hydrogen imports by 2030.

The 2030 estimate for the levelised cost of renewable ammonia in Oman is USD 400/tonne. After accounting for shipping of 10 000 km to 20 000 km, the total supply cost of ammonia (i.e., production, conversion and transport) is increased to USD 440/t NH_3 to USD 520/t NH_3 for Australia, Chile and Oman (Figure 2.7). This would make Oman a competitive supplier of renewable ammonia, with supply costs comparable with the higher end of ammonia market prices over the period of 2010-2020, and well below the record levels of more than USD 1000/tonne experienced globally in 2022 due to price hikes of natural gas.

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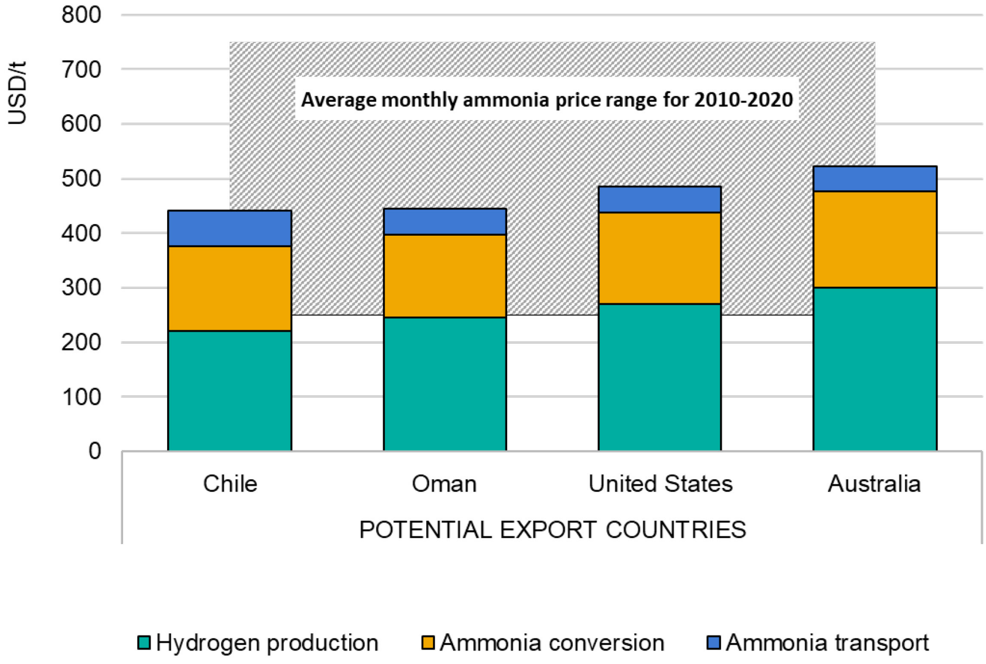
Figure 2.7 Renewable ammonia supply costs in potential export countries in 2030



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Notes: Cost estimates based on IEA analysis. Assumptions: technical lifetime 25 years; Haber-Bosch synthesis CAPEX USD 40/GJ per year; annual OPEX 3% of CAPEX; Haber-Bosch synthesis efficiency 86% (LHV). Transport costs assumed for 10 000 km (representing the distance of shipping from Oman to Europe, from United States to Japan and from Australia to Korea) and for 20 000 km (representing the distance of shipping from Chile to Japan). Between 2010 and 2020, the average monthly ammonia prices in international markets were in the range of USD 250/t to USD 750/t.

Box 2.2 Shipping infrastructure needs for transporting low-emission ammonia.

International trade of ammonia and the infrastructure required for its storage and transport are well-established and technologically mature. Countries with abundant natural gas resources export ammonia globally, mainly for use as a fertiliser feedstock. Ammonia is traded as anhydrous ammonia, which is a gas at ambient conditions and is transported in fully refrigerated (-33°C) liquefied tankers. Global ammonia trade amounts to around 20 Mt, equal to just over 10% of global ammonia supply of 182 Mt in 2019. Global trade is small relative to production, as other ammonia derivatives – particularly urea – offer a more convenient way to transport nitrogen for fertiliser as a solid bulk cargo.

Oman currently produces 2.2 Mt of ammonia, mainly for export. About one-tenth of ammonia was directly exported in 2020, while the largest share (1.9 Mt of ammonia) was further processed to produce and export urea. Oman has set a goal of producing 1 Mt to 1.25 Mt of hydrogen from renewable electricity by 2030, both for domestic demand and for export. Renewable hydrogen exports will likely be

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directed mainly to Europe and some countries in the Asia Pacific region, so transport will therefore rely on shipping. Due to the current maturity of technologies and supply chain status, exports are expected to be in the form of ammonia.

As Oman currently exports almost 90% of its ammonia production as urea, until 2022 there was only one terminal for handling ammonia, in the port of Sur. However, a new export terminal located in the Salalah Free Zone in Dhofar Governorate became operational in September 2022. If all the renewable hydrogen in Oman's 2030 target were to be exported as ammonia, it would be equivalent to up to 6 Mt, more than 30 times the country's current ammonia exports, requiring significant growth in new port infrastructure to handle it, in particular storage tanks and dedicated deepwater jetties. In addition, when planning the location of export terminals, it should be considered that ammonia handling requires strict technical safeguards and distance provisions for safety, so adequate space should be considered for any new terminals and their eventual expansion beyond 2030.

Based on the announcements made so far on the location of renewable hydrogen projects for export, Oman would need ammonia export terminals at the Port of Duqm and in Salalah by 2030. Up to 0.7 Mt per year of ammonia could be exported from Salalah, so the recently commissioned ammonia export facility may be able to accommodate this demand and be expanded if necessary. About 2.8 Mt per year of renewable ammonia could be exported from the port of Duqm, which would require an installed storage capacity of at least 160 kt,[6] with the construction of several large storage tanks (the world's largest ammonia storage tanks have a capacity of 50 kt) and dedicated jetties.

In total, exporting 6 Mt to 7 Mt of renewable ammonia would require at least 400 kt of ammonia storage separated to different ports. New hydrogen projects should consider the proximity to a deepwater port that could host an ammonia export terminal, or the construction of hydrogen or ammonia pipelines to a deepwater port that could host this terminal. Moreover, as the completion of ammonia storage tanks takes usually more than three years, the planning and construction of the export facilities would need to begin in the next few years if 2030 targets are to be met.

Based on its target, Oman's expected ammonia exports by 2030 would be equivalent to around 30% of today's global ammonia trade and would require 12 to 14 very large ammonia tankers dedicated year-round to transporting ammonia from Oman. There are few countries that can manufacture these tankers, and shipyards may struggle to keep pace with these needs, given competing demand for other types of liquefied gas tankers and for vessels in general. While shipbuilding may take a few years, the order should be placed well in advance to reserve capacity at the yard.

[6] Assuming that the ammonia storage tanks are loaded and unloaded between 15 and 20 times per year.

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Chapter 3. Domestic opportunities for renewable hydrogen

A growing number of export-oriented projects are being developed, in response to the growing appetite and long-term ambitions of many governments for importing renewable-based hydrogen. While prospects for international trade are a driver for renewable hydrogen growth, there is uncertainty over how demand will evolve by 2030. Currently, only 17% of planned export projects for 2030 have potential off-takers, and infrastructure for transporting high trade volumes needs time to scale. Similarly, governments have yet to implement specific hydrogen trade policies and regulations, and the international community still has not developed a standard certification system for emissions intensity of hydrogen production and transport.

In the meantime, creating domestic demand for renewable hydrogen can help mitigate uncertainty and making renewable hydrogen increasingly competitive in Oman as international markets develop. In the case of Oman, the most cost-competitive domestic opportunity for renewable hydrogen is replacing existing hydrogen use in refining. In 2021, industry was responsible for 32% of Oman's total emissions and was the largest emitter of energy-related CO_2 emissions in the country. Industrial emissions are projected to grow by 27% to 36 Mt by 2050 under a business-as-usual scenario driven largely by petroleum refining, petrochemicals, cement, aluminium, iron and steel. Oman's national carbon neutrality strategy identifies replacement of natural gas with green hydrogen as the second-largest emissions reduction opportunity for the industry sector (6.8 Mt CO_2 by 2050), behind electrification of industrial processes.

Existing uses

Oman is already using vast quantities of natural gas-derived hydrogen as a feedstock. Total hydrogen production was 1.1 Mt in 2021 of which 0.46 Mt is used in the industrial sectors, namely in oil refining (0.35 Mt) for hydrotreatment and hydrocracking and in steelmaking (0.1 Mt) for direct reduction of iron. Jindal Shadeed is the biggest steelmaker in Oman and has plans to switch to using renewable hydrogen. The group is planning to invest USD 3 billion for the construction of a green steel manufacturing facility at the Special Economic Zone at Duqm (Sezad), expected to produce annually 5 Mt of low-emission steel. Other notable manufacturers in the country are Sohar Steel,[7] Muscat Steel and Vale.

[7] Sohar Steel comprises three manufacturing units located in the fastest-growing city of Sohar in Oman: Sharq Sohar Steel Rolling Mills LLC and Middle East Conversion Industries that are located at Sohar Industrial Estate and Steel Melt Shop located at the Sohar Port Area.

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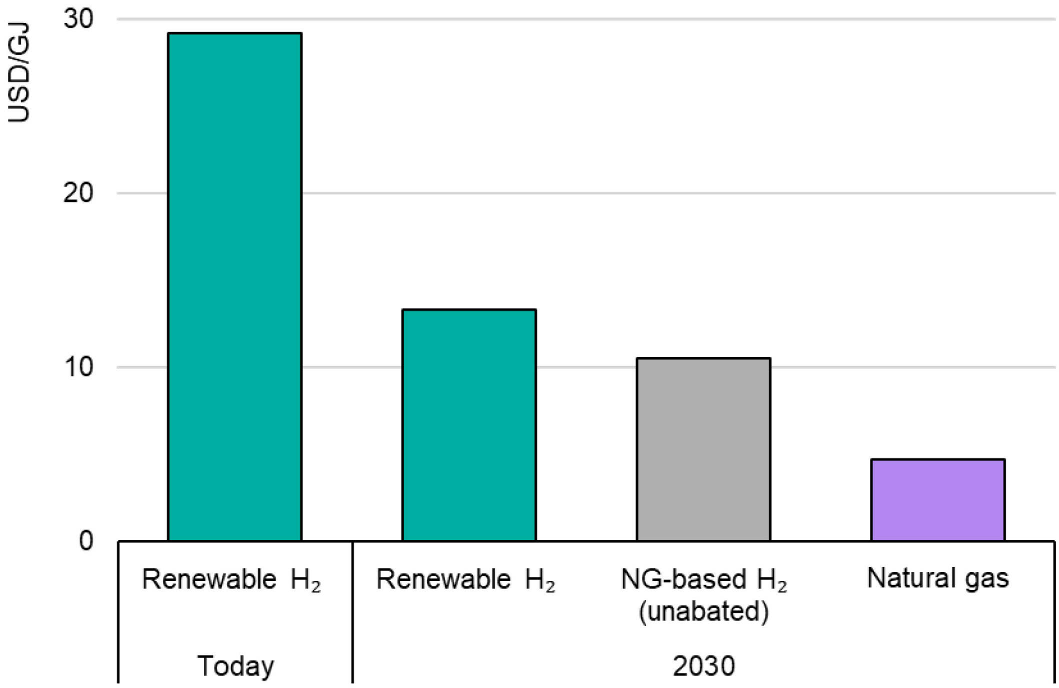
The remaining 0.64 Mt of hydrogen is used as a feedstock by the chemicals sector and exported in the form of urea, ammonia and methanol. The main companies are: Sohar International Urea & Chemical Industries, which exports urea to Australia, India, Latin America, South Africa, Thailand and the United States; Oman India Fertiliser company (OMIFCO), which has a urea offtake agreement with India; and OQ Methanol and Oman Methanol, which export mainly to Asia and Europe. In addition, the chemical industry produces hydrogen as a by-product of operations, which is normally used in refining or in the downstream chemical industry.

New uses

In addition to its role as feedstock, renewable hydrogen can also find use as a low-emission fuel for industrial processes that require high-temperature heat. Assuming a price of USD 4.7/GJ for natural gas in 2030, the cost of producing unabated hydrogen would be around USD 1.3/kg (USD 11/GJ) still somewhat lower than the cost of renewable hydrogen in Oman by 2030. However, for renewable hydrogen to be cost-comparable with natural gas as a fuel, it would require natural gas prices above USD 15/GJ or a high carbon price of USD 155 per tonne of CO_2 (Figure 3.1).

Figure 3.1 Cost comparison of natural gas and renewable hydrogen in the industry sector in Oman by 2030



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Note: The following assumptions were used: natural gas price, USD 4.7/GJ; efficiency SMR, 74% (LHV); electrolyser efficiency, 69% (LHV).

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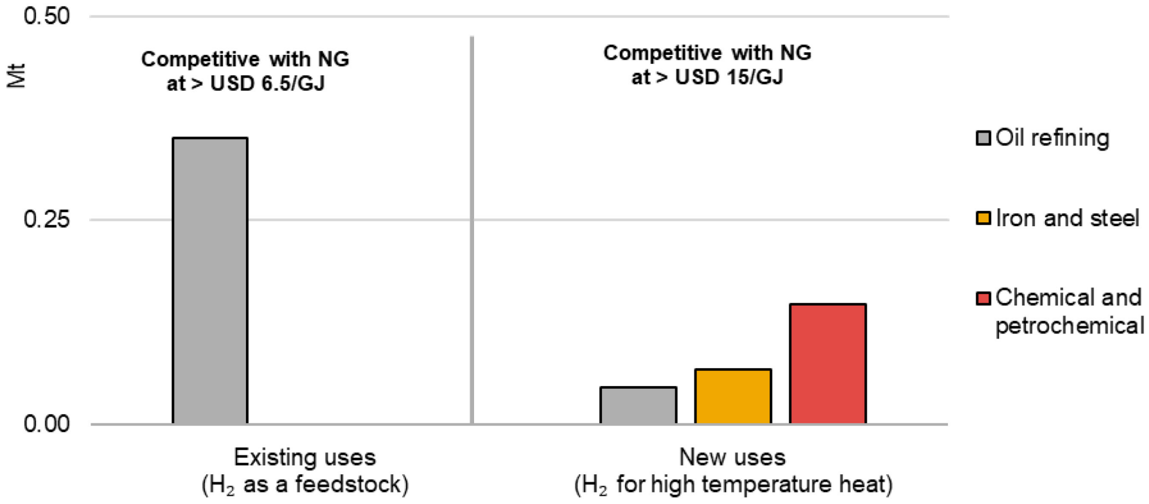
Today, the Oman industrial sector relies entirely on natural gas to supply its heat needs. In total, almost 5 billion cubic metres (or almost 60 TWh) of natural gas was used in 2021 to provide heat for industry.[8] High-temperature heat (above 400°C) is responsible for 81% (49 TWh) of the total heat needs, while steam and low-temperature heat cover the remaining 19% (11 TWh). High-temperature heat is mainly needed in the cement, chemical and petrochemical, petroleum refinery, and iron and steel industries. The use of electricity is also widespread throughout industry, and it has a significant role in the steel industry to drive electric arc furnaces and in aluminium smelting to drive electrochemical reactions.

Figure 3.2 Renewable hydrogen potential in the domestic industry for existing uses (feedstock) and new uses (high-temperature heat)



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Notes: Chemicals like methanol and urea is not considered in existing uses as they cannot be decarbonised with renewable hydrogen alone but require also a sustainable carbon source. ''New uses'' includes replacement of natural gas for providing heat for high temperatures (above 400°C) with 30% (energy share) blending of renewable hydrogen.

Around 0.6 Mt of renewable hydrogen could be used in the industry sector (Figure 3.2). The existing use of 0.35 Mt of fossil-based hydrogen in oil refining could be directly replaced by the same amount of renewable-based hydrogen at a cost of USD 1.6/kg by 2030, leading to emissions savings of 3.2 $MtCO_2$/yr. With a higher natural gas or carbon price, around 0.3 Mt of renewable hydrogen could also be used to substitute natural gas using a 30% hydrogen blend to supply high-temperature heat for industry, saving additional 1.7 $MtCO_2$/yr.

[8] The industry sector includes chemicals and petrochemicals, iron and steel, and oil refining. The cement and aluminium sectors are excluded from the analysis.

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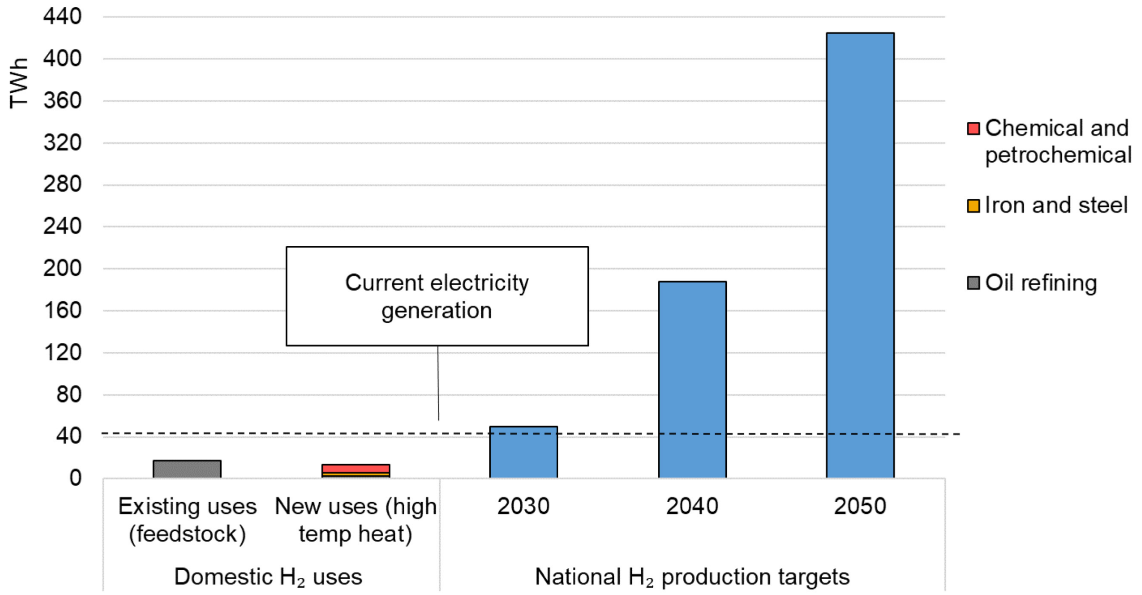
Figure 3.3 Renewable electricity needed to produce electrolytic hydrogen for the industrial sector and for meeting the national production targets



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Notes: Electrolyser efficiency 69% (LHV).

The production of large quantities of electrolytic hydrogen requires significant investments in electricity supply. Meeting Oman's 2030 hydrogen production target would require around 50 TWh of additional captive renewable electricity, which would be more than today's total generation capacity. Cumulative investment needs by 2030 would be around USD 33 billion, respectively USD 20 billion for captive renewable power dedicated to H_2 production and USD 13 billion for electrolysis and ammonia conversion.

However, to meet the long-term hydrogen production targets, the demand for new renewable electricity generation would significantly exceed the size of today's power market. Around 180 TWh of electricity would be needed to meet the 2040 hydrogen target and around 430 TWh to meet the 2050 target, ten times the size of the power market today (Figure 3.3).

Attracting energy-intensive industries

In addition to existing industrial needs, a large scale up of renewables supply can position Oman as an attractive location for new energy-intensive industries seeking to decarbonise at a low cost. Demand for low-emission goods is expected to increase as governments and companies aim to meet their climate goals. Some governments are already considering various policy tools to incentivise cleaner manufacturing such as carbon taxes or carbon border adjustment mechanisms. Such tools put an additional charge on goods whose manufacturing exceeds a

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certain emissions threshold, effectively creating demand for low-emission goods. Industries where high-emission energy makes up a large part of their consumption, such as polysilicon, cement and steel, will be particularly vulnerable to such measures and may seek to diversify their supply chains to remain competitive.

Energy-intensive industries tend to be located in areas where energy prices are low, as energy makes up a substantial part of their costs. In order for these industries to remain competitive while decarbonising, they will need access to both low-cost and low-emission energy, and may consider locating to areas where both are abundantly available.

Box 3.1 The potential for direct air capture deployment in Oman

The production of other low-emission fuels from hydrogen beyond ammonia such as methanol, synthetic natural gas and synthetic Fischer-Tropsch fuels is also possible. However, in addition to low-emission hydrogen, their production requires the availability of a sustainable carbon source, either from sustainably sourced biomass or from directly capturing CO_2 from the air using a technology called direct air capture (DAC).

The captured CO_2 can be used for a number of products including low-emission synthetic hydrocarbon fuels (in combination with hydrogen), or can be stored in geological formations for carbon removal. Globally DAC deployment is currently extremely limited, with only 18 plants operating worldwide (in Europe, the United States, Canada and Japan), capturing less than 10 kt of CO_2 per year. Only a few commercial agreements are in place to sell or store the captured CO_2. All the operating plants are small-scale, with the largest one capturing 4 000 t CO_2/year in Iceland. Most of the plants commissioned to date are being operated for testing and demonstration purposes, with only two plants storing the captured CO_2 permanently in geological formations. Three DAC projects are currently under construction, with the largest ones expected to come online in 2024 in Iceland (nominal capture capacity of 36 kt CO_2/year) and in 2025 in the United States (initial nominal capture capacity of 500 kt CO_2/year, with plans to scale up to as much as 1 000 kt CO_2/year).

Oman could be well suited for the deployment of DAC technologies. This is because of its abundant solar resources to power the DAC plants and availability of water resources and peridotite formations – both needed for CO_2 mineralisation with the goal of carbon removal. While the deployment of DAC for CO_2 utilisation is not currently pursued in the country, a couple of projects aim to test DAC operation for CO_2 storage. These projects could be a starting point in Oman for a more widespread deployment of this technology for a number of purposes including the

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production of low-emission synthetic hydrocarbon fuels (such projects are currently ongoing in Canada, Chile and the United States).

The British-Omani company 44.01 (which recently won a 2022 Earthshot Prize in the Fix Our Climate category) and the Swiss company Climeworks (a company delivering carbon removal via DAC technologies) are currently collaborating on a project exploring the deployment of direct air capture with storage (DACS) in peridotite formations in Oman. The DAC collector unit has nominal capture capacity of around 20 t CO_2/year. The 44.01 is also collaborating with Mission Zero Technologies (a United Kingdom-based DAC company) through the project Hajar (which was awarded a US 1 million XPRIZE Carbon Removal prize), while in the United Arab Emirates it has recently announced a collaboration with ADNOC (Abu Dhabi National Oil Company), FNRC (Fujairah Natural Resources Corporation) and Masdar (Abu Dhabi Future Energy Company) to store air-captured CO_2 in peridotite formations in the Fujairah region. When operational, this pilot would be the first DAC-based carbon removal project in the Middle East region relying on seawater for its operation.

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Chapter 4. Benefits from scaling up domestic renewable power

While opening the door to exporting low-emission fuels, and creating domestic opportunities for renewable hydrogen, there are several benefits that could follow the scaling up of domestic renewable power generation.

First, renewable electricity is already cost-comparable with existing sources of generation, and accelerating its deployment would have the benefit of immediately reducing fuel costs. Moreover, as a source of emission-free power, it is a low-cost abatement option that can be implemented today to help Oman move towards its net zero ambitions by 2050. Second, increasing the penetration of renewable electricity and hydrogen would reduce the consumption of natural gas. This would reduce the need to tap new supplies and save gas for exports. Finally, scaling up renewable electricity projects brings down costs as the local power industry gains experience. This would help ensure lower cost of electricity and consequently, lower cost of hydrogen.

Solar PV and onshore wind can produce cost-effective electricity today

An additional benefit from accelerating the deployment of utility-scale solar PV and onshore wind are lower generation costs in Oman. Over 95% of Oman's electricity generation is from natural gas, operating at an estimated levelised cost of electricity (LCOE) between USD 30/MWh and USD 40/MWh. Recently awarded bid prices for utility solar PV projects in the region are comparable or below these costs (Figure 4.1). Since 2019, all but one utility-scale solar PV project was awarded below USD 40/MWh in the Middle East and North Africa (with the only exception of Israel). Bid prices in other markets where solar irradiation is similar to Oman such as Qatar, the United Arab Emirates and Saudi Arabia have seen prices well below USD 20/MWh owing to high-capacity factors, beneficial financing and land costs, and large project size, which allows for economies of scale. Onshore wind benchmark prices, which can be used as proxy for Oman, also fall within the range for natural gas-fired plants. This suggests that the generation cost of utility-scale solar PV and wind in Oman is likely already competitive with natural gas and using it today would lower electricity costs for both electric utilities and consumers.

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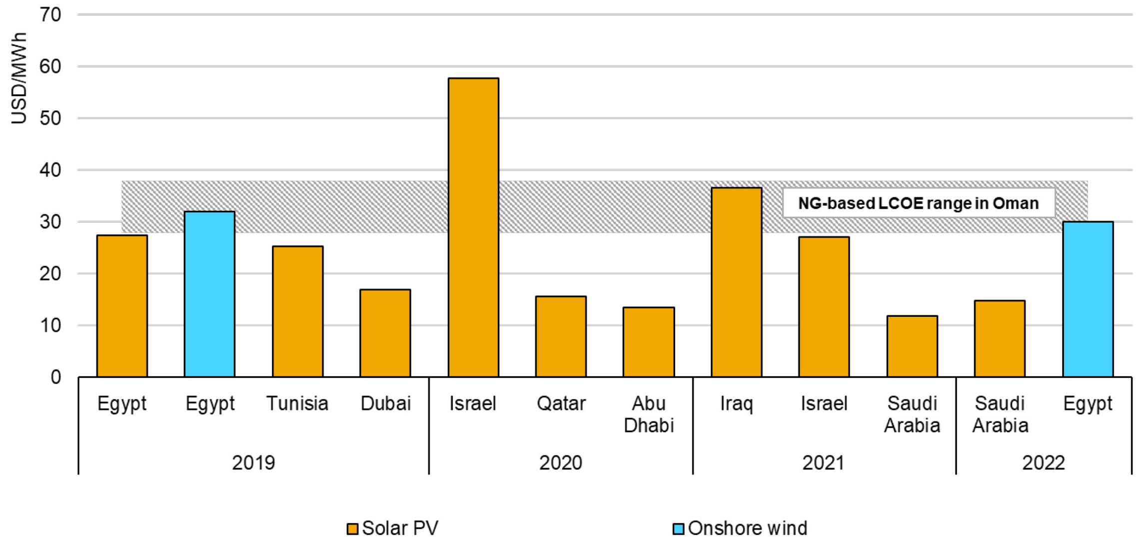
Figure 4.1 Awarded bid prices for solar PV and onshore wind in selected MENA countries versus estimated levelised cost of electricity generation of gas-fired plants in Oman



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Notes: Assumed natural gas price USD 3.7/GJ.

Economically attractive solar and wind prices can reduce fossil fuel subsidies and help the transition to more cost-effective electricity tariffs. For utilities, lower generating costs can reduce what is spent on subsidies to bridge the cost between the generation and end-user tariffs. This in turn lowers deficits, frees up capital for new power system investments and can help improve the overall financial health of the utility. Lower generating costs also reduce the gap that consumers will face as subsidies are phased out and end-user tariffs rise.

Increasing the pace of renewable electricity also helps achieve climate goals in a cost-effective way. Renewables can be considered an optimal starting point for emissions reduction pathways that favour deploying low-cost abatement first. Such is the case for Oman, where the net zero emissions strategy aims for an orderly transition that prioritises minimising energy system costs while optimising economic impact, among others. Therefore, increasing renewable project development can help save costs while simultaneously progressing towards net zero goals.

Renewable electricity and hydrogen can save natural gas for exports

Natural gas exports play a key role in Oman's economy, accounting for around USD 3 billion in 2021. However, most of the increase in Oman's natural gas

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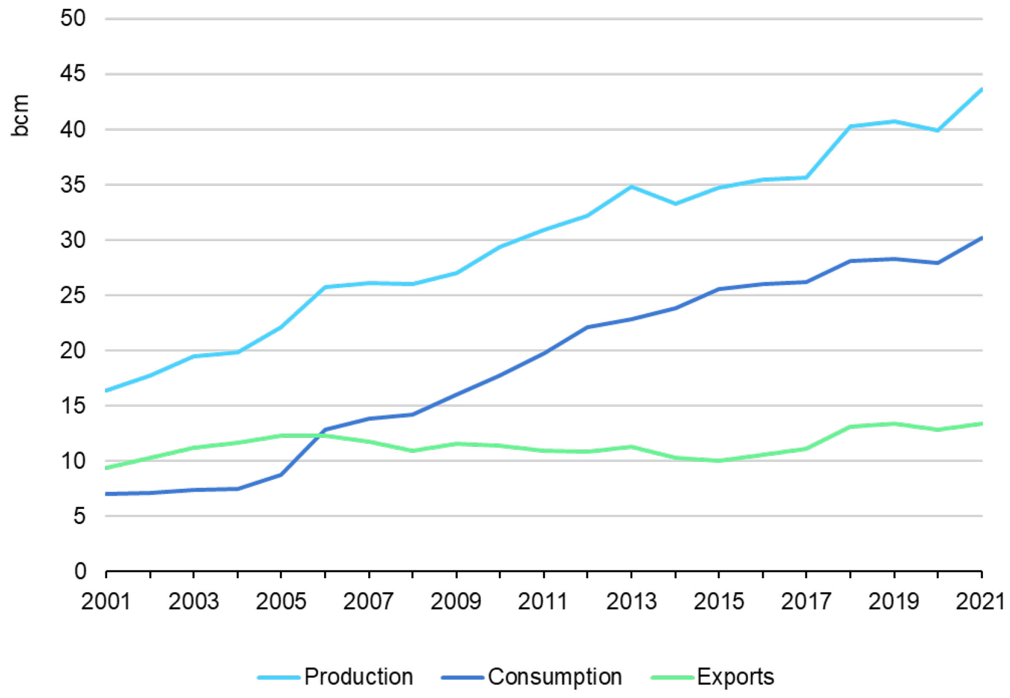
production has been diverted to meet rising domestic demand. In fact, domestic demand has outpaced exports since 2001: gas consumption increased four times since 2001, compared with 40% for exports (Figure 4.2).

Figure 4.2 Oman's natural gas production, consumption, and exports, 2001-2021



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Source: IEA (2022), World Energy Balances.

Switching to renewables for power and renewable hydrogen for industry reduces natural gas consumption and makes more available for export or later exploitation. As Oman's current export capacity is almost fully in use, gas savings would contribute to extending the lifetime of supply reserves. By 2030, total annual natural gas savings could be around 3 bcm, roughly 20% of 2022 exports (Figure 4.3). In particular, 1.4 bcm could be saved by replacing fossil hydrogen in refining, while an additional 1.5 bcm could be saved by replacing 20% of natural gas in the grid with renewable power (in line with the national 2030 target). In the long-term, replacing renewable hydrogen as a fuel for high-temperature needs could lead to an additional 0.8 bcm of annual natural gas savings.

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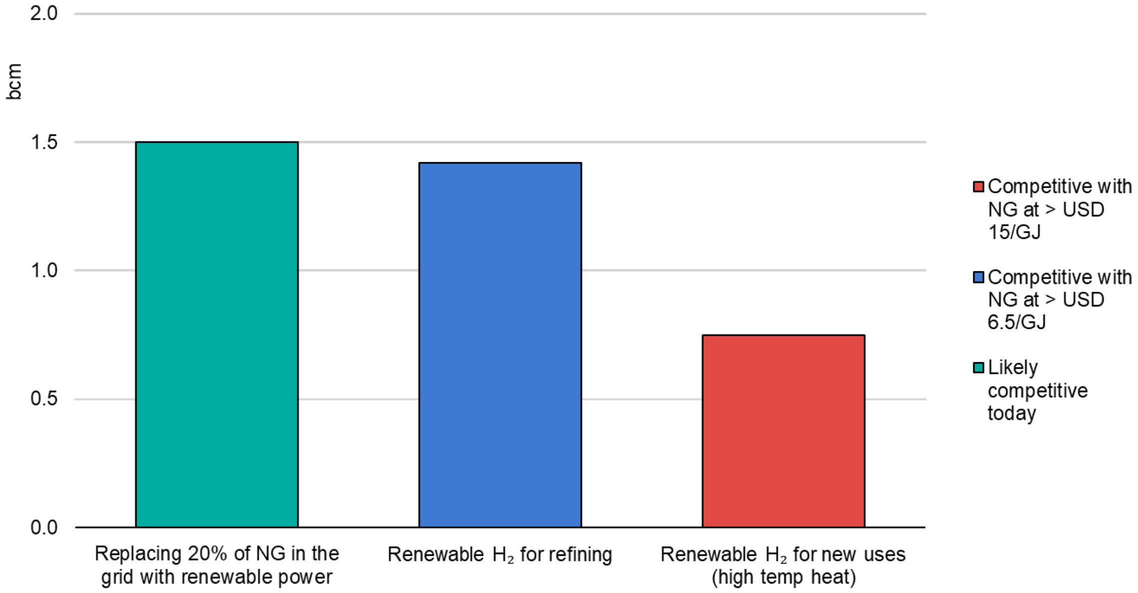
Figure 4.3 Potential annual natural gas savings from renewables in power generation and industrial use of renewable hydrogen



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Notes: ''New uses'' features 30% (energy) blending of hydrogen with natural gas for high-temperature heat (above 400°C).

Box 4.1 Renewables integration is an increasing priority for Oman

The global energy crisis has kicked renewables to even faster growth as countries seek to capitalise on their energy security benefits. Due to their variable nature, the rapid growth in wind and solar PV installations around the world raises questions about how to ensure their cost-effective and secure integration.

The IEA conceptualises renewables integration in a series of phases that systems experience as their share of variable renewable energy (VRE) increases. At low levels of VRE (Phase 1), these resources have little or no impact on power system operations. As the share grows, a number of integration measures are required, initially focused on leveraging existing flexibility in the system and later potentially requiring new sources of flexibility from demand response, dispatchable power plants, grids and energy storage.

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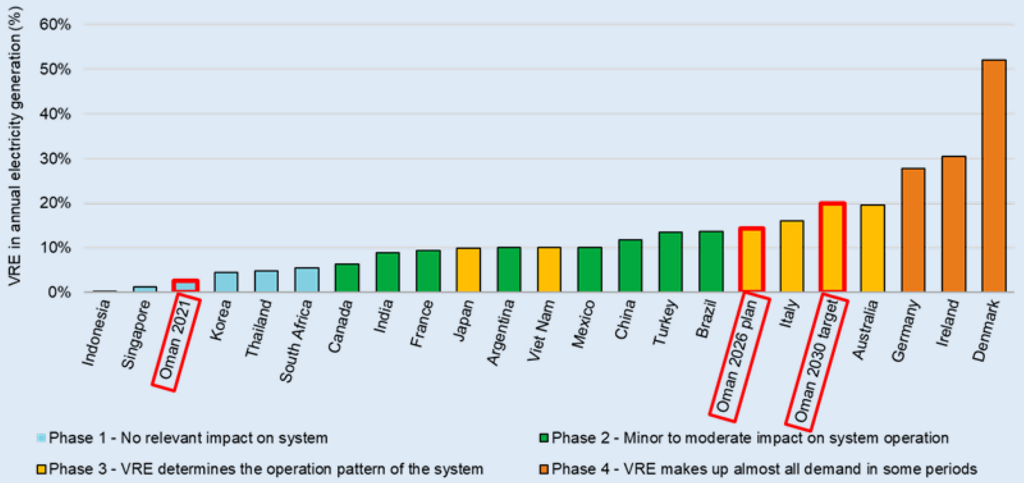
Renewables integration phases of selected countries in 2021 with Oman MIS in 2026 and 2030 based on current targets



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Note: Renewables integration phase assessments for Oman are based on the MIS.

Source: Annual variable renewables generation shares for whole countries are based on 2021 estimates from Renewables 2022, Electricity Market Report 2023 and Monthly Electricity Statistics.

The Oman power system consists of three main grid areas with limited interconnections between them. The MIS is the largest, serving around 89% of Oman's electricity demand in 2020, with 9% of demand in Dhofar and around 1% each in Duqm and Musandam. In 2021, the share of variable renewables in the MIS was only around 4%, and the system was in integration Phase 1, where VRE has a minimal impact at the system level.

The coming years will see a rapid increase in VRE as Oman pursues its 20% by 2030 target of renewables in consumption. Due to the large share of solar in the planned additions (2 GW solar versus 300 MW wind in 2026 in the MIS) this will result in a high peak in supply during daylight hours. Oman also has a particularly strong seasonal pattern in its electricity demand driven by cooling requirements in the summer (for analysis on seasonal variability of renewables see the IEA's report on Managing Seasonal and Interannual Variability of Renewables). Average monthly demand in winter typically falls to 35-40% of peak demand. Our analysis based on the demand forecast and project pipeline to 2026 indicates renewables could frequently reach 60-70% of MIS demand during winter days, placing the system in Phase 3.

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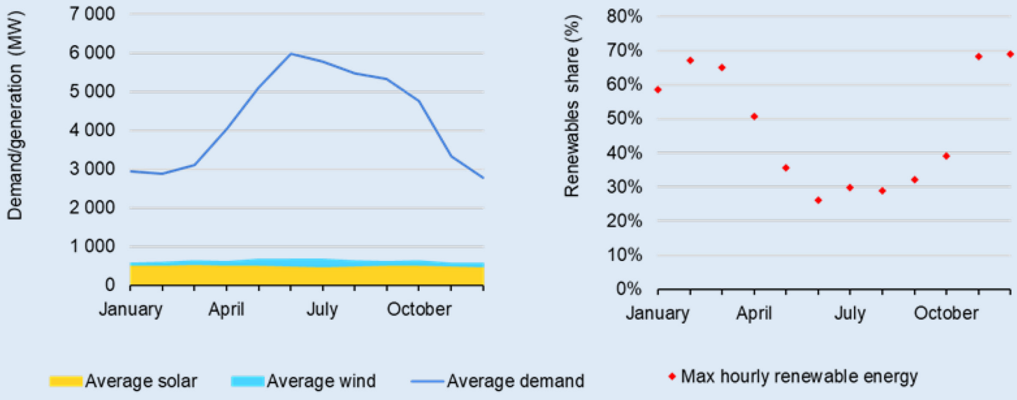
Average simulated monthly demand and renewables generation (left) and maximum hourly renewables shares by month (right) in Oman MIS, 2026



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Source: IEA analysis based on MIS hourly demand data, the OETC Five-Year Annual Transmission Capability Statement 2022-26, OPWP's 7-year Statement 2021-2027 and simulated hourly solar and wind generation

By 2030 with the achievement of the 20% target, available VRE generation could reach more than 90% of demand in some hours. A range of proven flexibility solutions are available to help integrate these shares. Oman has put forward a plan to integrate up to 35% renewables based on integration measures including more flexible operation of thermal generators, weather forecasting and interconnections with neighbouring countries. Additional measures targeted to Phases 3 and 4 such as demand response to shift load towards the daytime and fast frequency response services could also help the system to accommodate more renewables.

Exploitation of Oman's rich wind resources also has the potential to better distribute renewables supply across the day, although this benefit will need to be balanced against the cost to connect areas of strong wind resource to the grid. Integrating renewables beyond the 35% target may require investment in additional technologies such as energy storage.

Accelerating solar PV electricity now can lower soft costs later

Increasing installed capacity in a market can lower the "soft costs" associated with the local solar PV industry, mainly non equipment expenses arising from engineering and design, permitting, installation, and financing. In general, soft costs tend to be higher in new markets compared with more mature markets because the industry has not had the opportunity to build up efficiencies in the

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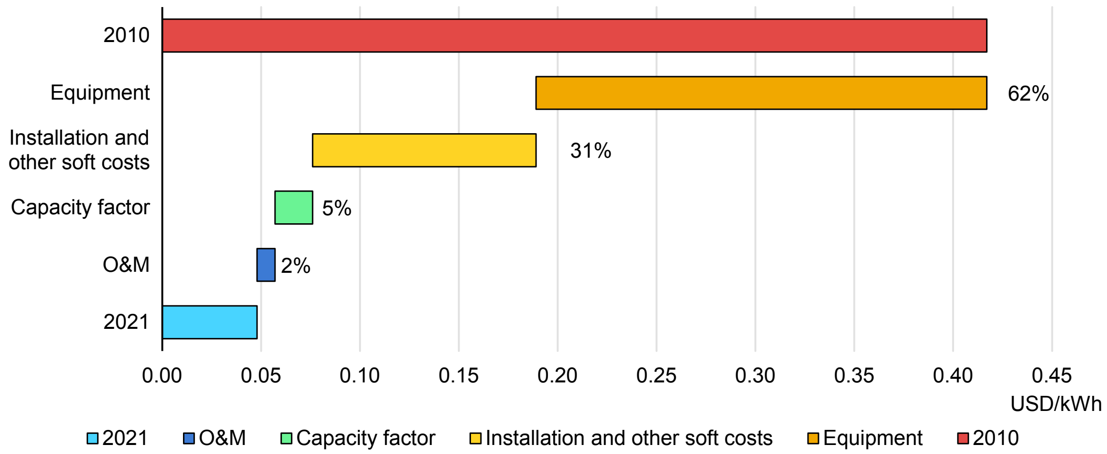
value chain. As more projects are installed, increased competition and the accumulation of learning results in reduced time and costs. As the market grows with successful project development, investor confidence increases, which can lead to lower financing rates. As a result, global utility-scale generation costs declined by 31% as installations grew from 8 GW to 500 GW, thanks to the cost reductions achieved in installation, financing, and other soft costs from learning.

Figure 4.4 Cost reductions for the levelised cost of generation of utility solar PV between 2010-2021



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Source: Data from IRENA Power Generation Costs 2021.

Soft costs depend on specific local conditions along the project development stages, for example, the cost and availability of skilled labour, permitting and grid connection fees, local contractors' rates, and familiarity of local banks with solar PV project risks. As result, the soft costs vary widely by country and can range from as low as USD 154/kW in Germany thanks to installer experience and streamlined permitting to as high as USD 950/kW in Japan due to high installation costs.

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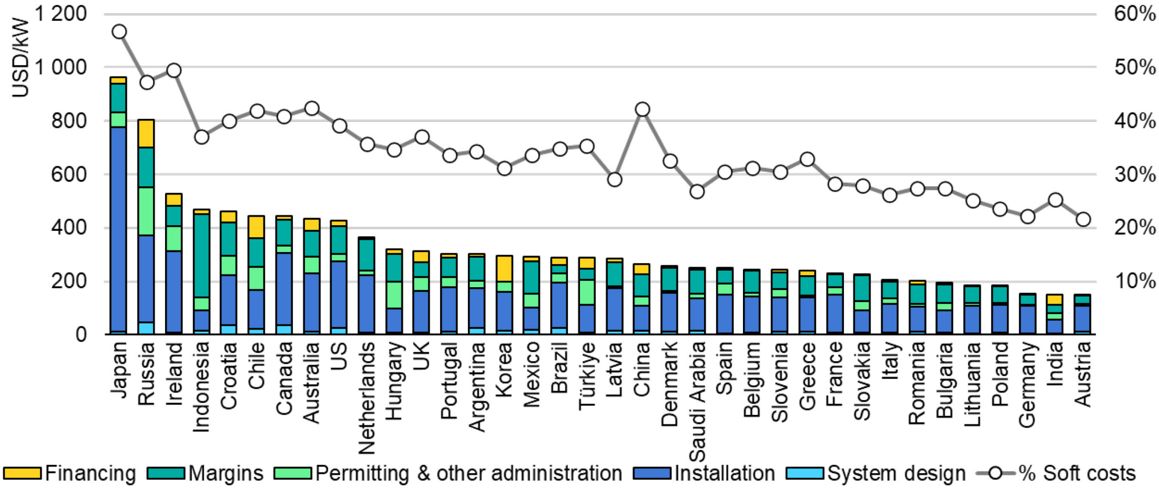
Figure 4.5 Utility-scale solar PV total installed costs vs. share of soft costs, 2021



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Source: Data from IRENA Power Generation Costs 2021.

The role of soft costs in Oman and the potential for their decline is not known yet given the size of the installed base. Oman's solar PV market is relatively new, comprising only of two projects less than 1 GW combined by the end of 2022. Nonetheless, increasing utility PV project development could have several benefits. Firstly, increased development would help shed light on some of these costs. In addition, an increase in successful projects commissioned will also likely lower the risk perception for investors as they become comfortable with the market. Installation and administrative procedures could also become more efficient thanks to a combination of industry learning and policy and regulatory actions. As a result, lower generating costs for both grid-connected plants and captive plants dedicated to hydrogen production could be possible.

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Chapter 5. Policy objectives and best practices

The following section has two purposes. The first is to highlight three objectives to consider for future policy making regarding Oman's policy priorities to reduce emissions while diversifying the economy. The second purpose is to illustrate global best policy practices commonly employed to achieve each objective. The applicability of these principles to Oman would need further assessment which is beyond the scope of this report.

Becoming a major renewable hydrogen producer and supplier would help Oman simultaneously meet two important goals: reducing emissions while diversifying the economy. Getting a head start on policy making and planning to achieve this ambition can help ensure market success. At the same time, developing a domestic market for renewables also has benefits which can strengthen the position of Oman while international demand develops. Scaling up domestic use can have several cost-effective advantages for exports of renewable hydrogen:

- Using renewable hydrogen in domestic industry creates local learning needed to drive down costs by 2030.
- Scaling up the penetration of renewable electricity can help lower soft costs and generate electricity at prices below competitors.
- Increased project activity in both markets establishes credibility among lenders, which helps lower financing for investors.

Developing a domestic market for renewable energy also diversifies revenue streams for export markets. Affordable, clean electricity can attract energy-intensive industries seeking to diversify supply chains and produce low-emission goods. Having domestic hydrogen demand can further benefit export-oriented projects. Accelerating domestic demand can also help achieve climate goals faster and save on fuel costs.

Therefore, in parallel to creating a low-emission exports market, the development of a domestic market for renewable energy should be a priority. However, successful scale-up requires markets for renewable hydrogen and the pace of renewable electricity deployment needs to be accelerated in concert. It is important that policy support for both electricity and hydrogen be accompanied by planning and investment in the appropriate infrastructure.

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In light of these considerations, the IEA has identified three policy objectives to be considered in parallel:

- Lay the groundwork for renewable hydrogen exports.
- Accelerate renewable electricity deployment.
- Stimulate domestic renewable hydrogen demand for industry.

The following section aims to give the characteristics of policy design and action to help scale both international and domestic demand for renewable hydrogen. In addition, general best practices for renewable electricity development are included. However, the effectiveness of policies depends on a detailed assessment of the market and policy framework, which are outside the scope of this report. The following considerations are considered common characteristics of successful policy approaches.

Lay the groundwork for low-emission fuel exports

The market for renewable hydrogen trade is nascent. Its development will depend on many aspects, including how technologies, costs and demand, and various non-technical economic and geopolitical factors evolve over the coming years. Yet, there are actions that governments can take today to reduce barriers and facilitate trade. The following are considered general characteristics of policy design and action that can help de-risk investment, develop a market, and lower costs.

- **Facilitate de-risking investment.** Large capital-intensive projects with high upfront costs benefit from government support that mitigates investment risks. Mitigation instruments can take many forms, such as financial support, loan guarantees and other tools that shift part of the project risks or costs to the government. In the absence of examples of low-emission projects to draw on, policies used for capital-intensive renewable electricity deployment can serve as an indication for best practices. In those cases, one mitigation tool that has been successful has been government-assisted site selection.

  Government involvement in selecting the site to be developed can help de-risk a project in several ways. In some cases, governments have covered early-stage project costs that help assess the performance and future cash flows from a site such as feasibility studies (i.e., with pumped storage in Australia) and exploratory drilling (i.e., with geothermal in Kenya). In other cases, governments have earmarked land to be developed that is accompanied by beneficial conditions such as free connection to nearby infrastructure (offshore wind in the North Sea), pre-approved permitting and lower land leasing rates.

  With regards to renewable hydrogen, one example is in Oman, where the government in 2022 earmarked land to be auctioned for the development of

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renewable hydrogen projects. The conditions offered with the sites include beneficial leasing rates and long tenures which are expected to reduce project risks and help attract financing.

- **Engage with the development of international standards, regulations and certifications.** Quantifying and measuring the carbon intensity of hydrogen production will be necessary to develop international trade (for more analysis on the topic see the IEA's report Towards hydrogen definitions based on their emissions intensity). While there is currently not an internationally agreed standard on the accounting methodology, substantial progress has been made by the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). In October 2022, the IPHE's Hydrogen Production Analysis Task Force (H2PA TF) released a proposal for a methodology to determine the GHG emissions from different hydrogen production pathways which will serve as the basis for common global standard currently under development developed by the ISO.

  Engaging and keeping abreast of the development of these standards is beneficial for design certifications that comply with the regulations of importing markets. Participating in international dialogues (such as those occurring under the umbrella of the IPHE, the Hydrogen Energy Ministerial, Clean Energy Ministerial Hydrogen Initiative or the Breakthrough Agenda) to help harmonise certification schemes also facilitates the development of trade. Having harmonised certifications help minimise the compliance costs for developers and increase market opportunities.

- **Collaborate with international stakeholders.** Participating in international collaborative action can accelerate the development of a global hydrogen market. Bilateral agreements between governments are one such action and can take many forms such as funded feasibility studies, memorandums of understanding, and co-operation agreements. These arrangements can help identify customers, facilitate project implementation between stakeholders, and kickstart pilot shipments. Eventually this can foster new trade partners and shipping routes. For example, in September 2020, Portugal and the Netherlands signed an MoU to develop a export-import value chain and are exploring the feasibility of transporting liquified hydrogen between the two markets.

  Multilateral collaboration is equally critical for developing global hydrogen trade. Participation in international platforms brings together various stakeholders in one forum where knowledge can be shared, and best practices can be identified. This can take the form of participating in dialogues through programmes and initiatives, workshops, studies, and technical assistance. The results of such engagement can inform high-level decision making, identify synergistic opportunities in policymaking, build partnerships, and help harmonise international standards and codes. For example, the Clean Energy Ministerial Hydrogen Initiative (CEM H2I) currently coordinates a working group on hydrogen trade, involving 13 governments, and 7 non-governmental partners.

- **Develop trade infrastructure**. Much of the trade infrastructure may be located at and co-ordinated by ports, including storage tanks, ammonia cracking facilities,

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and expanded and updated shipping fleets. New infrastructure development can have long lead times, high capital costs and, in some cases, require technological advances. Repurposing existing infrastructure can reduce costs and lead times. For example, Australia and Singapore announced a AUD 30 million partnership to accelerate deployment of low-emission fuels at maritime and existing port operations. One challenge for governments in this regard is to develop permitting and siting processes that ensure infrastructure projects do not harm local communities and ecosystems, while not inhibiting such projects from being built at the scale and speed necessary.

Accelerate renewable electricity deployment

With less than 1 GW of renewable electricity installed today, increasing the pace of deployment not only helps Oman to achieve its net zero commitments, but it can also trigger cost reductions for both electricity generation and hydrogen production. Global experience shows that there are numerous ways to achieve ambitious renewable targets. The success depends on the detail of the policy design, which is outside the scope of this report. However, there are several best policy practices that contain setting clear targets, providing long-term visibility over support schemes, removing barriers to market entrants and streamlining administrative procedures.

- **Set long-term targets for renewable electricity.** Renewable electricity targets are used at various stages of policy making to serve different functions. In the early stages, they are often used as part of announced strategies, which signal government ambition and set the direction for further strategy development. In the next stage, they can often be implemented as part of the legal system which helps harmonise future policy planning in a holistic way. Clear long-term targets are also critical for attracting investors and reducing the cost of financing. Binding targets indicate government commitment, which in turn motivates investors to develop longer-term business strategies and lowers the risk perception for lenders. For example, Germany’s announced renewable electricity targets for 2030 were adopted in its National Energy Law and used to create a multi-year schedule for competitive tendering for renewable electricity projects.
- **Provide long-term revenue certainty.** Governments have used various policy tools to achieve national renewable energy plans. One successful element has been to provide long-term visibility over revenues to de-risk investment. The prices offered can be either administratively set (feed-in tariffs) or competitively set (auctions), with the latter being used more recently. The two most important factors of a successful policy are visibility over the time horizon and volume of capacity eligible for the scheme. This is particularly important for governments that use competitive auctions to attract foreign investment: having a long-term, publicly published multi-year schedule gives investors’ confidence on government commitments, helps them plan business models and allows for value chains to be built up locally in the region. The timeliness of the tendering process also

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influences investor appetite and risk perception, which subsequently affects financing costs. For example, France, Germany and the Netherlands have published a calendar when auctions with specific volumes will be open. This has allowed developers to prepare project bids and plan for future investment opportunities.

- **Remove barriers to new market entrants.** In addition to targets and support policies, the regulatory environment is equally important to accelerate private investment in renewable electricity. A regulatory environment that allows for multiple options for plant ownership and contractual arrangements with buyers can increase the types of business models and financing structures for developers. There are multiple avenues for sales revenue such as through wholesale markets, solicited (open tender) or unsolicited (privately negotiated) bilateral contract with a utility, or private-to-private selling (i.e., corporate power purchase agreements). A regulatory environment that allows for various ways to buy and sell electricity gives private investors options to create business models that lead to bankable projects.
- **Streamline permitting and grid connection.** The pace of project development depends heavily on the permitting and grid connection processes. Delays can result from unclear, lengthy or new administrative processes for licensing and network connection. Streamlining the application and requirements for permitting and grid connection will decrease project lead times and lower costs for investors.

Stimulate industry demand for renewable hydrogen

Stimulating domestic industry demand for renewable hydrogen can start a learning cycle that leads to cost reductions. Current practices focus on creating supportive frameworks for the most mature market applications first. In this light, replacing existing hydrogen uses with renewable hydrogen offers the most cost-effective option by 2030 and could be prioritised.

Policy best practices highlight several basic principles to stimulate industry demand for renewable hydrogen starting with having a strategy and setting targets. However, targets alone are insufficient to trigger deployment and need to be backed by tools to catalyse demand such as mandates, quotas, and financial incentives. In addition, policy actions are also needed to create an enabling environment.

- **Consider developing strategies to decarbonise industry.** Strategies are useful tools to communicate government long-term goals and how they plan to achieve them. Strategies to create demand for renewable hydrogen can take many forms ranging from a specific sector to a comprehensive approach across the entire value chain. For example, in China, guidelines for the chemical and petrochemical industries were released to encourage the use of renewable hydrogen to replace

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fossil fuels. To be most effective, individual sector specific strategies though should be developed in line with national hydrogen and other energy or economic strategies. For example, in India, the strategy for renewable hydrogen demand is incorporated as part of a larger integrated strategy that proposes to incentivise supply, create an enabling regulatory environment, and develop export markets.

- **Set long-term targets for renewable hydrogen use in industry.** Targets are valuable tools to set the intention of the government and signal direction for investors. They are also used to establish future policy making in a consistent way. In recent years, many governments have announced low-emission hydrogen production targets; however, relatively few have announced targets for end-user sectors such as industry and transport. Setting renewable targets for industrial hydrogen use would help the industry prepare strategies to transition to low-emission hydrogen feedstocks and fuels. For example, the United Kingdom set a goal for industry to consume 20 TWh of low-carbon fuels (hydrogen, electricity, bioenergy) by 2030 in its industrial decarbonisation plans and the European Union has announced proposals to set a target that a percentage of hydrogen demand in industry should be from renewable sources by 2030.
- **Consider stimulating demand with mandates and quotas.** Mandates and obligations have been successful policy tools used to increase the demand for renewable energy in the heat and transport sectors. For example, in transport, biofuels blending mandates are used to require a certain percentage of fuel to be from renewable origins. Another example are building codes that require heat pumps or solar water heaters. While similar policy tools for hydrogen have yet to come into force, governments are beginning to consider them.
- **Support innovation and demonstration of technologies needed for handling, storage, and end-use.** Accelerating the demand of hydrogen will require cost reductions in transport, storage, and end-use technologies. Governments can advance innovation in these areas by supporting R&D in various ways. One common way is by directly funding basic science and research. Governments can also help accelerate commercialisation by funding technology demonstration projects. For example, the United Kingdom allocated GBP 55 million for the Industrial Fuel Switching competition to support feasibility studies and other project costs for pre-commercial technologies to enable industries to switch to low-carbon fuels including hydrogen. Exchanging experiences and collaborating on international research also facilitates innovation. For example, the Clean Hydrogen Mission aims to lower end-to-end hydrogen costs by stimulating research in storage and end-use sectors, deploying hydrogen valleys, and coordinating governments.
- **Implement policies aimed to lower cost barriers.** Increasing the competitiveness of renewable hydrogen is critical for demand creation. Policies that price in carbon externalities would raise the price of alternative fuels or feedstocks and could help make renewable hydrogen more economically attractive to industry even before 2030. For example, depending on the level, carbon taxes could make renewable hydrogen competitive with existing natural

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gas-based uses. Policies that lower the cost of hydrogen production such as grants, loans and tax incentives could also be considered. For example, the European Union has earmarked EUR 1 billion for projects aimed to decarbonise industry including renewable hydrogen, and the United States passed the Bipartisan Infrastructure Law that provides grants to create hydrogen hubs. While no examples are yet in force, new policy options that provide long-term revenue certainty for hydrogen use such as feed-in tariffs or contracts for difference could also be developed.

- **Evaluate infrastructure needs and plan accordingly**. Evaluate the expenses associated with transporting renewable hydrogen to consumers and identify cost-effective options. If pipelines are needed, evaluate when it is possible to repurposes existing natural gas pipelines and infrastructure. Chile's National Hydrogen Strategy highlights plans to review existing natural gas infrastructure and regulation to integrate low-carbon hydrogen. Storage will be needed to address supply and demand imbalances and the costs and technology options would need to be considered. Co-locating industries with similar energy needs together into "industrial clusters" can help reduce transport costs by using shared infrastructure. For example, the United States' Bipartisan Infrastructure Law earmarks USD 8 billion toward the development of "hydrogen hubs"; a close-proximity network of producers and consumers connected by shared infrastructure. Aggregating hydrogen industries also has the added benefit to create the skilled workforce needed to accelerate deployment.

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Chapter 6. Conclusions

Renewable hydrogen and renewable energy will play a key role in achieving Oman's ambitious climate goals and economic diversification objectives. Crude oil and natural gas exports are currently a key source of revenue for Oman, representing 60% of total export income. Ahead of the 27th Conference of the Parties (COP27) in 2022, Oman launched its Net Zero National Strategy. The country commits to reach net zero emissions by 2050 and to broaden energy transition objectives, including expanding renewable capacity to free up domestic natural gas consumption for exports.

Oman is endowed with high-quality renewable resources, a convenient location well-placed to access the main import markets, and vast amounts of land for large-scale project development. Oman also has a skilled workforce, existing infrastructure, and extensive experience in producing and exporting LNG and ammonia. Large-scale development of the renewables potential together with repurposing of existing fossil fuels infrastructure and expertise can help Oman to simultaneously achieve its climate, energy and economic objectives.

Oman is among the top candidates for producing and exporting renewable hydrogen. Owing to its high-quality renewable resources and ongoing global cost reductions in PV, wind and electrolysers, the cost of renewable hydrogen in Oman is expected to decline significantly this decade. By 2030, the cost of renewable hydrogen production in Oman could be as low as USD 1.6 per kilogramme of hydrogen. The current project pipeline slates Oman as the sixth-largest global exporter by 2030.

Ammonia export capacity needs to be expanded to enable growing trade. Based on globally announced export-oriented projects, ammonia will likely be the carrier of choice for marine transport of hydrogen in this decade. However, building the needed infrastructure involves significant investments combined with concerted and co-ordinated efforts across many stakeholders, including duly addressing health and safety risks.

Depending on the share of domestic H_2 use, by 2030 Oman could need up to 20-30 times more ammonia export capacity than today. This would require significant growth in new port infrastructure to handle it, in particular ammonia storage tanks and dedicated deepwater jetties.

Securing demand is fundamental for realising the project pipeline. International trade is a driver for renewable hydrogen growth but also a source of uncertainty. Many national governments are signalling long-term import targets, including 10 Mt by European Union by 2030. However, bringing projects

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to a financial close will require securing off-takers, and there is an uncertainty over how this will evolve by 2030.

In the meantime, creating domestic demand for renewable hydrogen can help mitigate international demand uncertainty by providing alternative off-takers for hydrogen and other low-emission manufactured goods. In Oman, around 0.6 Mt of renewable hydrogen could be used in the industry sector. By 2030, existing use of 0.35 Mt of fossil-based hydrogen as feedstock in oil refining could be directly replaced by the same amount of renewable-based hydrogen. With a higher natural gas or carbon price, around 0.3 Mt of renewable hydrogen could also be used to substitute natural gas using a 30% hydrogen blend to supply high-temperature heat for industry.

Cheap renewable electricity is a precondition for competitive hydrogen exports. Hydrogen production costs depend heavily on the costs of electricity generation. Ensuring that these are as low as possible will be a significant advantage for the competitiveness of hydrogen both domestically and abroad. Increasing project development and large-scale deployment of renewables can contribute to lowering the soft costs (i.e., non-equipment expenses associated with design, permitting, installation, and financing), having a major influence on the competitiveness of local electricity generation from renewables. Bid prices in the Middle East-North Africa region have been well below USD 20 per megawatt-hour, suggesting that renewable power generation is already cost-comparable with natural gas today. Accelerating the uptake of renewables in the power market can help lower the cost of hydrogen production, improving its competitiveness both domestically and for trade.

Scaling up domestic renewable supply can position Oman as an attractive location for new energy-intensive industries seeking to decarbonise supply chains. Energy-intensive industries (i.e., cement, steel and polysilicon) tend to be located in areas where energy prices are low, as it makes up a substantial part of their costs. Demand for low-emission goods is expected to increase as governments and companies aim to reach their net zero goals. In order for these industries to remain competitive while decarbonising, they will need access to both low-cost and low-emission energy, and may consider locating to areas where both are abundantly available. With its potential abundant low-cost renewable electricity and hydrogen and vast amounts of available land, Oman is among the best countries to attract industry relocations during the global energy transition.

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Annex

Explanatory notes

Terminology for hydrogen production

In this report, low-emission hydrogen includes hydrogen produced via electrolysis where the electricity is generated from a low-emission source (renewables or nuclear), biomass, or fossil fuels with CCUS. Renewable hydrogen refers only to hydrogen produced via electrolysis where the electricity is generated from renewables. The same principle applies to low-emission feedstocks and fuels made using low-emission hydrogen, such as ammonia.

The IEA does not use colours to refer to the various hydrogen production routes. However, when referring to specific policy announcements, programmes, regulations and projects where an authority uses colour to define a hydrogen production route, e.g., green hydrogen, we use that terminology to report developments in this review.

Abbreviations and acronyms

ASPR	Authority for Public Services Regulation
CAPEX	capital expenditure
CCUS	carbon capture utilisation and storage
CO_2	carbon dioxide
DAC	direct air capture
DACS	direct air capture with storage
DPS	Dhofar Power System
EOR	enhanced oil recovery
GCC	Gulf Cooperation Council
H_2	hydrogen
HYDROM	Hydrogen Oman
IEA	International Energy Agency
LCOE	levelised cost of electricity
LHV	lower heating value
LNG	liquefied natural gas
MIS	Main Interconnected System
NH_3	ammonia
OETC	Oman Electricity Transmission Company

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OMIFCO	Oman India Fertiliser company
OPEC	Organization of the Petroleum Exporting Countries
OPEX	operational expenditure
OPWP	Oman Power and Water Procurement Company
PDO	Petroleum Development Oman
PV	photovoltaic
Sezad	Special Economic Zone at Duqm
SMR	steam methane reforming
UAE	United Arab Emirates
USD	United States Dollars
VRE	variable renewable energy

Units of measurement

bcm	billion cubic metres
GJ	gigajoule
GW	gigawatt
kg	kilogramme
km^2	square kilometres
kt	kilotonne
kW	kilowatt
kW_e	kilowatt electrical capacity
kWh	kilowatt-hour
mb	million barrels
Mt	million tonnes
Mtoe	million tonnes of oil equivalent
MW	megawatt
MWh	megawatt-hour
MW_t	mgawatt thermal
PJ	petajoule
t	tonne
tcm	trillion cubic metres
TWh	terawatt-hour
W	watt

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