UNITED ARAB EMIRATES
MINISTRY OF ENERGY & INFRASTRUCTURE

WORLD ECONOMIC FORUM

Clean Skies for Tomorrow

In collaboration with
ICF International

Power-to-Liquids Roadmap: Fuelling the Aviation Energy Transition in the United Arab Emirates

WHITE PAPER

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Foreword

H. E. Suhail bin Mohamed Al Mazrouei
Minister of Energy and Infrastructure
United Arab Emirates

The opportunities for the power-to-liquids (PtL) roadmap produced by the World Economic Forum build on the United Arab Emirates' leading role in tackling climate change, both in the region and globally. It paves the way for decarbonization at scale in one of the hard-to-abate sectors at the heart of the modern way of life we have come to enjoy, aviation.

The United Arab Emirates is an advocate of climate action and sustainability, and we are proud to be a sustainable aviation fuel (SAF) ambassador under the Clean Skies for Tomorrow initiative. We believe that the growth and sustenance of the aviation sector are integral to the United Arab Emirates socioeconomic prosperity. Still, we are also mindful of the importance of the transition to cleaner sources of energy to promote decarbonization and sustainable development. We know that liquid hydrocarbons will be a key energy source in aviation for many years. Lower carbon aviation fuels will need to be deployed as soon as possible to expedite decarbonization, furthermore SAF strategies and policies will need to be developed to help us invest in energy-efficient and cost-effective technologies.

This report serves as a fundamental step to guide the global decarbonization agenda by promoting PtL technologies in the United Arab Emirates with special attention to feedstock availability, scalability and affordability, and technology operations. Chaired by Yousif Al Ali and led by the World Economic Forum, and with the collaboration of the United Arab Emirates aviation sector, this report is an exemplar product of a public-private partnership between the General Civil Aviation Authority (GCAA), the Ministry of Energy and Infrastructure, academic institutions, fuel suppliers, carriers and airports. The aviation sector is one of the United Arab Emirates' success stories and has a central place within the national and the regional economies, helping diversification, tourism and supporting job creation. Growing and protecting the aviation sector will only be possible to the extent that it is decarbonized.

Executive summary

Power-to-liquids sustainable aviation fuel production is the most important technology for the United Arab Emirates to decarbonize aviation.

The power-to-liquids (PtL) approach will allow the Emirates to use its considerable advantages – including intense sunshine and sustained winds – to decarbonize while avoiding some of the challenges of traditional sustainable aviation fuels (SAFs) pathways. PtL involves the conversion of electricity into hydrogen, which is then combined with captured carbon to synthesize renewable hydrocarbons. Both dedicated and surplus electricity can be used for production, allowing PtL to create value from surplus power when the Emirates' supply exceeds the demand. The sustainable crude produced by PtL can be refined in conventional facilities using the existing national infrastructure. The resulting SAF can be used to power existing and future aircraft sustainably.

Aviation is uniquely important to the United Arab Emirates, with more aviation activity compared to the size of the economy than any other large country. The aviation industry supports over 13% of the national GDP, and more than one in every ten people in the Emirates depends on aviation for a job. Emissions from aviation, however, are projected to double by 2050 – even allowing for increased fuel efficiency – so the energy used to power the aircraft must be decarbonized.

The lack of biological resources makes it hard to scale traditional methods of SAF production. It is unlikely that hydrogen aircraft will be available in time to decarbonize the Emirates' predominately long-haul network. PtL mitigates many of these challenges and supports existing national initiatives. These initiatives and advantages compound to create an opportunity for the Emirates to lead the production of low-cost, low-carbon jet fuel from electricity while supporting the national energy and industrial sectors.

This report puts forth a PtL roadmap showing the financial, economic and environmental benefits of PtL in decarbonizing the United Arab Emirates aviation industry. Seven initiatives along two themes have been identified that could be used to unlock this opportunity:

Establishing foundations:

– **A target for the PtL industry** would provide a clear direction for market participants. Replacing as much as 73% of conventional jet fuel with PtL would align the United Arab Emirates' aviation industry with the 2050 net-zero ambition.

– **Align the target with international efforts**. Global ambitions will create a global market for the fuels the United Arab Emirates could produce and will accelerate the development of the underlying technologies.

– **Consolidate links** between the development of a PtL industry and existing national roadmaps.

Implementing policy instruments to scale the PtL industry:

– **Government-led funding for a demonstration facility** should bring together partners across the industry, ensuring that energy, refinery, aviation, construction and supply chain contributors gain experience in the technology.

– **Ongoing research and development support** should build on the ambitions of the industrial and climate roadmaps to reduce the technology and local risks of deploying the PtL technologies

– **Loan guarantees and capital grants** to reduce the volume or risk of capital invested are crucial during the initial industry development.

– **Revenue support** will be critical. Potential mechanisms could reward the physical fuel produced, the carbon emissions avoided, or provide revenue stability.

This report shows that it would be ambitious but feasible for the United Arab Emirates to produce as much as 11 million tonnes of PtL SAF by 2050 – equivalent to approximately 70% of national jet fuel consumption. While there would be a cost premium as the industry develops, by 2050, the combined price of PtL physical fuel and the carbon avoided is expected to be less than the historical price of fossil jet fuel. Flight ticket prices are not expected to rise between today and 2050 as aircraft efficiencies reduce the volume of fuel required and production costs decrease, supporting the affordability of decarbonization. Deploying the industry at scale could create and sustain over one million jobs across the United Arab Emirates by 2050, driving meaningful GDP growth. This work shows that PtL technology is an affordable, practical approach to achieving sustainable economic growth.

Introduction

The United Arab Emirates has announced a strategic initiative to achieve net-zero emissions by 2050,[1] supported by Etihad, Emirates and other major airlines' pledges to achieve the 2050 net-zero carbon target established by the International Air Transport Association (IATA). The Emirates presents unique opportunities and challenges to achieve these ambitions. As a major international hub, aviation is crucial to the Emirates' economy. Yet, the long-haul route structure challenges the adoption of electric and hydrogen aircraft, and there is limited availability of biological feedstock for the conventional waste-to-fuel pathways.

The United Arab Emirates can draw on considerable advantages. The intense sunshine, sustained winds and emerging nuclear expertise support cheap renewable energy generation, while the domestic energy industry provides world-leading knowledge and infrastructure. Much of this is highly transferrable to emerging technologies such as hydrogen production, carbon transport, and synthetic fuel production and logistics. Power-to-liquids (PtL) production can reuse existing refinery infrastructure, reducing the risk of stranded assets, and would be able to support the decarbonization of both aviation and other industrial hard-to-abate sectors in the Emirates, such as steel and cement, through the use of point source carbon capture.

This creates a unique opportunity for the Emirates to employ the PtL approach, both as an end-to-end technology and as a part of the value chain. The PtL approach uses renewable energy to synthesize hydrocarbons from clean hydrogen and captured carbon. This produces opportunities for cheap energy, existing knowledge and refinery infrastructure, and mitigates the challenges of limited biomass availability.

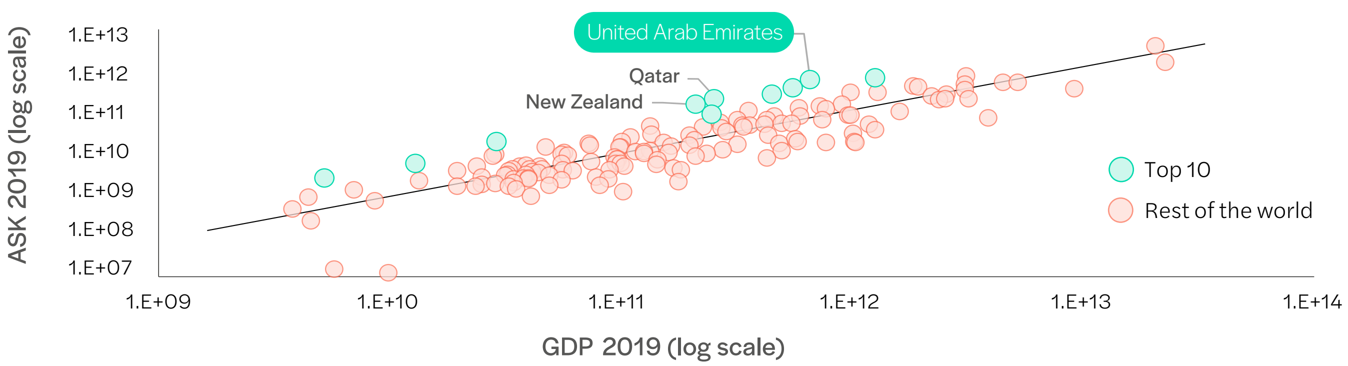
> **More than at any other point in recent history, fundamental changes to the economic model of resource-rich countries look unavoidable. The future will look very different from the past… first movers – countries that take a proactive approach to this – could do especially well.**
>
> Fatih Birol, Executive Director, International Energy Agency

> In 2018, the aviation sector directly employed 180,000 people and supported 777,000 jobs through the supply chain and from employee and tourist spending.

Developing a domestic PtL industry is strategically critical to the United Arab Emirates. It could further diversify the 30% of GDP directly reliant on oil and gas output,[2] and sustain the Emirates' aviation industry in a carbon-constrained economy. This is particularly important to enable the projected growth in the aviation GDP footprint from $47 billion in 2017 to $128 billion over the next 20 years, increasing the domestic jobs supported by aviation to 1.4 million.[3] These would be supported by the energy, economic and employment benefits created through the expansion of the renewable energy economy, creating essential opportunities for the demographic wave of Emirati nationals under 25 years old – representing over a third of the population who will soon be looking for employment.[4]

The United Arab Emirates has used travel, transport and tourism as key levers to promote economic diversification, and by 2018 more than an eighth (13.3%) of total GDP was directly or indirectly supported by aviation.[5] In 2018, the aviation sector directly employed 180,000 people and supported 777,000 jobs through the supply chain and from employee and tourist spending. This means that more than one in ten employed people in the United Arab Emirates depends on aviation for work. This is one of the highest rates for any country in the world and has been supported by the strong growth of the aviation sector. Between 2012 and 2019, United Arab Emirates airlines' total available seat kilometres (ASKs) grew by 73%, considerably more than the global average growth of 52%. Consequently, the United Arab Emirates has the highest ratio of aviation activity to economic footprint of any country with a population over 1 million (this can be seen as the distance above the trend line in Figure 1). Ensuring the continued value and expected growth of the aviation sector in a carbon-constrained world will be critical to the economy and employment in the United Arab Emirates.

FIGURE 1 **The United Arab Emirates has the highest ratio of aviation activity to economic footprint of any country**



Note: Scale is logarithmic, meaning that each increment represents a 10-fold increase. Scientific notation has been used, where for example 1.E+09 can also be written as 1×10^9, or 1,000,000,000. This allows countries with vastly different GDP and ASK to be more easily compared.

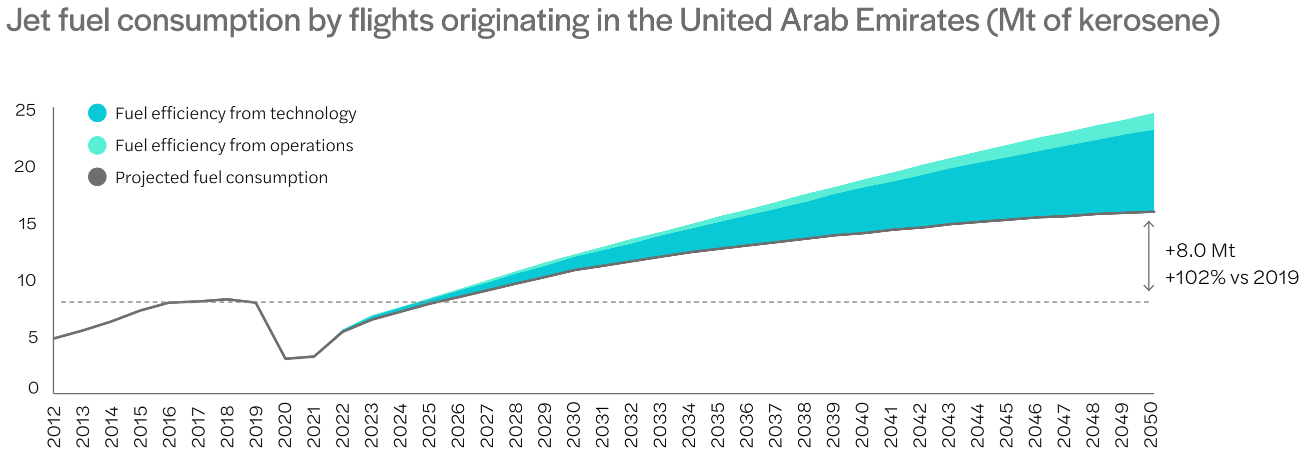
Source: World Bank GDP Data: https://data.worldbank.org/country and ICF feedstock database

New aircraft and better operations will continue to improve the fuel efficiency of aviation activity. Still, if no further action than this is taken, it is estimated that the volume of jet fuel consumed by the United Arab Emirates will double to nearly 16 million tonnes annually by 2050.[6]

This forecast was developed by combining the long-term growth forecast in the Boeing Commercial Market Outlook[7] with an analysis of pandemic recovery. The potential to reduce emissions through technology and operations was taken from the International Civil Aviation Organization's (ICAO) long-term aspirational goal analysis,[8] with adjustments to account for regional differences and reconcile with historical emissions. The full calculations are included in the technical appendix.

This forecast gave an increase in available tonne kilometres (ATK) from 40 billion in 2018 to 117 billion in 2050 (+192%), slightly offset by a reduction of adjusted fuel consumption from 0.027kg/ASK in 2018 to 0.019kg/ASK in 2050 (-27%), and cumulative operational efficiencies of -6%. The net impact is an increase in fuel consumption from 7.9 million tonnes (Mt) in 2019 to 15.9 Mt in 2050, a near-exact doubling. Between 2012 and 2018, jet fuel consumption in the United Arab Emirates increased by nearly half[9] (+47%), showing that while this analysis projects

FIGURE 2 | **Jet fuel consumption in the United Arab Emirates is projected to double by 2050**



Source: "Commercial Market Outlook 2021–2040", Boeing, 2021; ICAO, *Report on the Feasibility of a Long-Term Aspirational Goal (LTAG)*, 2022; UN Data, "Kerosene-type Jet Fuel" [Graph], http://data.un.org/Data.aspx?d=EDATA&f=cmID%3AJF; ICF analysis

a significant increase in fuel consumption, it is meaningfully below the historical growth.

In 2019, the aviation jet fuel consumption was equivalent to 0.7 exajoules (EJ) of energy, equal to 7.7% of primary energy consumed in the United Arab Emirates.[10] Just 0.04 EJ of energy is generated by renewables on an input-equivalent basis, meaning the 2019 jet fuel energy consumption is equivalent to nine times the 2019 primary energy from renewable sources, and the projected 2050 jet fuel energy consumption of 0.70 EJ would be equal to 18 times the 2019 renewable energy input. This illustrates the considerable increase in installed renewable capacity required to decarbonize the Emirates' electrical grid and aviation industry.

The well-to-wake emissions from the nation's jet fuel consumption in 2019 are equivalent to 30.8 megatonnes of CO_2 equivalent ($MtCO_2e$), using the ICAO fossil fuel baseline of 89 grams of CO_2 equivalent per megajoule (gCO_2e/MJ). This is equivalent to 11% of the nation's emissions from oil, gas and coal consumption (270 $MtCO_2e$ in the same year). The projected baseline aviation fuel emissions could contribute as much as half[11] of national emissions by 2040 – and considerably more if the aviation industry grows faster or fails to achieve the assumed improvements in technology and operations.

1 Introducing power-to-liquids technology

A lack of biological materials means that the United Arab Emirates will need to use alternative methods of producing SAFs.

The importance of SAF in decarbonizing the global aviation industry is widely recognized. Globally, most SAF is currently produced using biological materials, such as waste fats and oils, crops and waste wood. The Middle East region has a notable scarcity of these materials, limiting the volume of SAF that can be produced through this approach. The continued growth of air traffic[12] in the United Arab Emirates will further accentuate the challenge to produce enough SAF and will require additional approaches. One of these is likely to be the production of liquid hydrocarbon fuels from renewable electricity, known as power-to-liquids, or PtL.

1.1 Where does PtL fit in the development of a SAF industry?

The SAF industry is in its infancy, with less than 0.01% of global aviation fuel produced from sustainable feedstocks. With strong demand from airlines, rapidly strengthening policies and developing technologies, aviation fuel's carbon intensity is expected to decrease rapidly. The production capacity for SAF is expected to rapidly grow, with multiple large SAF refineries due to come online over the next few years. Many of these use a technology called the hydroprocessed esters and fatty acids (HEFA) pathway, which can process waste fats, oils and greases (FOG) into jet fuel. The technology to achieve this is relatively mature and can be used to scale the industry and achieve initial aspirations quickly. This can be supported through the adoption of fossil-derived lower carbon aviation fuels (LCAF),[13] which can reduce the carbon footprint of fossil fuels through more efficient processes, the use of clean energy and potential combination with carbon capture technologies. There is limited availability of these FOG feedstocks and LCAF can only offer a limited reduction in carbon intensity, so scaling the SAF capacity to decarbonize a meaningful percentage of aviation fuel will need to use different feedstocks.

The second generation of feedstocks will focus on biomass, including wastes from agriculture (such as the stems and leaves from crops), woody waste, municipal solid waste and dedicated crops that do not compete with food or feed. These feedstocks can be converted to SAF using technologies that are currently being commercialized, such as the alcohol-to-jet (AtJ) process, the Fischer-Tropsch (FT) process and others, such as pyrolysis. Both the AtJ and FT pathways have been certified as safe by the ASTM International. The key aim is to develop and deploy facilities to produce commercial-scale fuels using these pathways. As of 2022, notable facilities under development include the Fulcrum Sierra Facility, which will use the Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) pathway to produce SAF from municipal solid waste (MSW) (in commissioning at the time of writing), the Velocys Bayou facility, which will use the Fischer-Tropsch synthetic paraffinic kerosene with alkylation of light aromatics (FT-SPK/A) pathway to produce SAF from woody biomass, and the LanzaJet Georgia and Gevo NZ-1 facilities, which will both convert alcohol to SAF using the AtJ pathway. Demonstrating the commercial use of these technologies will allow many more refineries to be built, continuing the decarbonization journey for aviation.

While there is significant availability of these waste biomass feedstocks, many other industries will also need to use these resources to decarbonize. This should be supported; there is no value in decarbonizing aviation while other sectors continue to emit carbon, so this is a challenge where all must succeed. It will be essential to use feedstocks selectively, particularly given the limited volume that can be sourced sustainably. A critical factor should be the availability of alternatives, with industries using affordable, practical alternatives where they can. Given the challenges in designing, deploying

There is no value in decarbonizing aviation while other sectors continue to emit carbon, so this is a challenge where all must succeed.

and commercializing alternatives such as electric aircraft, aviation should be prioritized for access to the waste biomass feedstocks. Analysis by the International Energy Agency (IEA)[14] assessed the global availability and demand of biomass feedstocks and allocated between 10-15 exajoules to aviation. Depending on the industry growth and technology assumptions, this is likely to be sufficient to produce enough SAF to decarbonize between 40%-55% of aviation fuel by 2050.[15]

The aviation industry will need to use alternative approaches to decarbonize the remaining emissions, and the power-to-liquid approach will be crucial. PtL is a broad term used to refer to the production of liquid fuels using renewable energy. There are several ways this can be done. It generally includes using renewable electricity to produce hydrogen and capturing carbon from a source that is already part of the carbon cycle. The hydrogen and carbon are processed into syngas and then used to produce liquid fuels. The resulting products must then be converted, upgraded, and separated into jet fuel (SAF), with a portion of naphtha and diesel also produced. The SAF can be blended with conventional jet fuel and be used in aircraft without modification.

There are several strong tailwinds for PtL development. The cost of renewable energy has decreased at an astonishing rate over the last decade, with International Renewable Energy Agency (IRENA) estimating that solar photovoltaic (PV) and onshore wind have reduced in levelized cost of electricity (LCOE) by 85% and 56%, respectively.[16] Both are now less expensive than fossil fuels. Investments over $500 billion into developing a clean hydrogen industry were announced in 2021, and the United Arab Emirates has pioneered developments, with an ambitious Hydrogen Leadership Roadmap[17] to capture 25% of the global clean hydrogen market by 2030. The same technologies currently being developed and deployed to convert biomass into SAF can be used to convert PtL feedstocks into SAF, de-risking and reducing the cost of the conversion process.

The United Arab Emirates has a unique opportunity to pioneer the PtL industry. The nation has access to the world's lowest-cost renewable electricity, and can draw on growing expertise in carbon capture, liquid hydrocarbons, and hydrogen. This is compounded by the importance of the aviation industry and the low availability of biological feedstocks that will constrain the volume of SAF that can be produced through other approaches. The rapid development of a PtL industry in the Emirates will create further economic opportunities, diversification and employment, support decarbonization, and create opportunities to export the technologies, expertise and sustainable fuels.

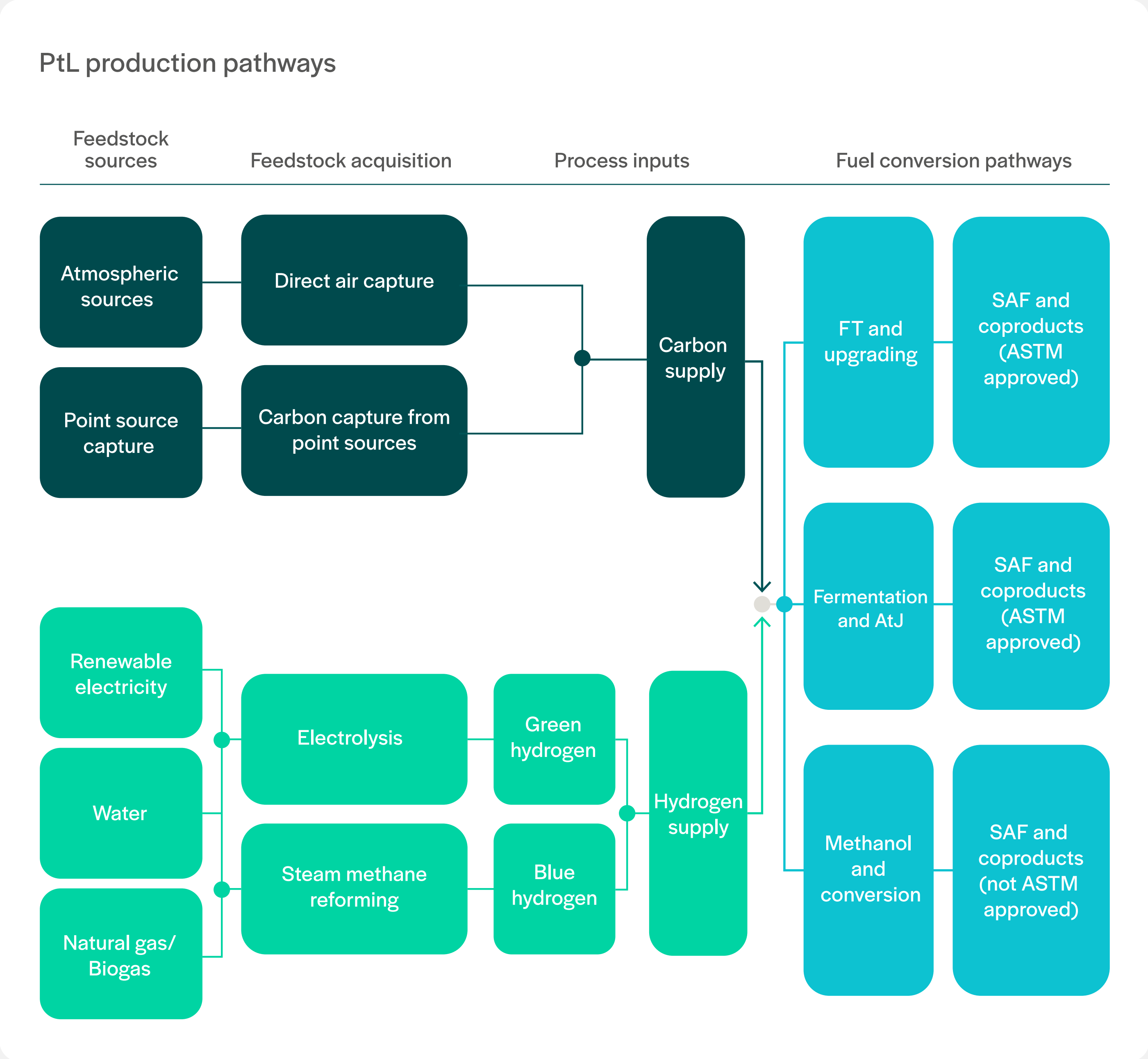
1.2 What is the PtL process?

There are many approaches to using renewable energy to produce sustainable jet fuel, with each approach comprising of three main elements:

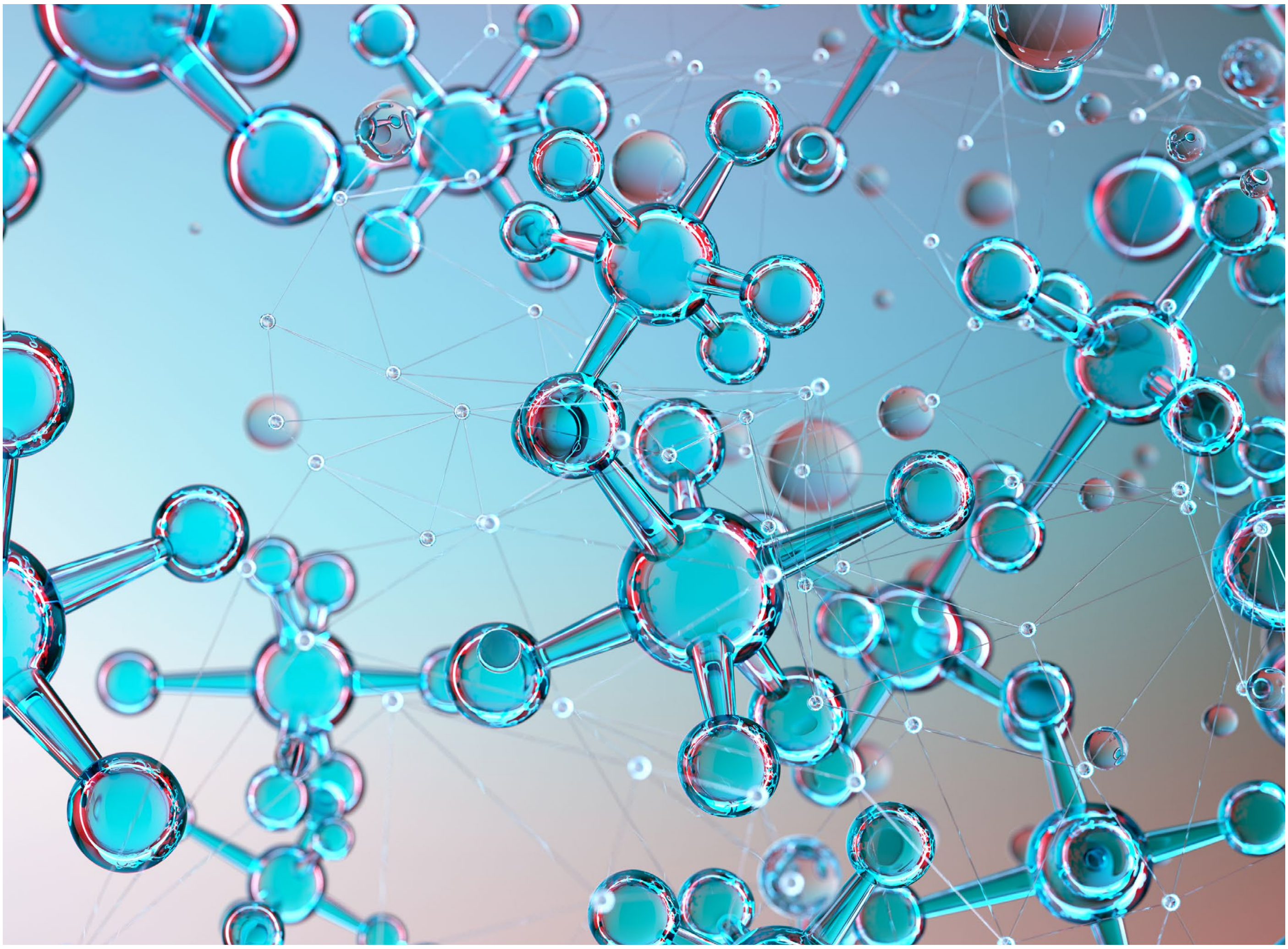
1. **A source of clean hydrogen**: This is a crucial source of energy for SAF and, by weight, will make up around 15% of the jet fuel produced. Most PtL approaches propose to use hydrogen that is produced using renewable electricity to electrolyse water (H_2O), which splits into hydrogen and oxygen. The hydrogen can be collected and used. When made using renewable electricity, it is called "green hydrogen".

As the industry develops, there may also be a transition role for hydrogen produced through steam methane reforming (SMR) of natural gas or biogas. As there is limited biogas availability in the United Arab Emirates, this approach is likely to focus on using fossil natural gas. This process generates approximately 9kg of CO_2 for every kilogram of hydrogen produced, so the carbon must be captured and sequestered to ensure it does not enter the atmosphere. Using fossil natural gas is referred to as steam methane reforming and carbon capture and storage (SMR+CCS). This is "blue hydrogen".

FIGURE 3 **PtL production pathways**



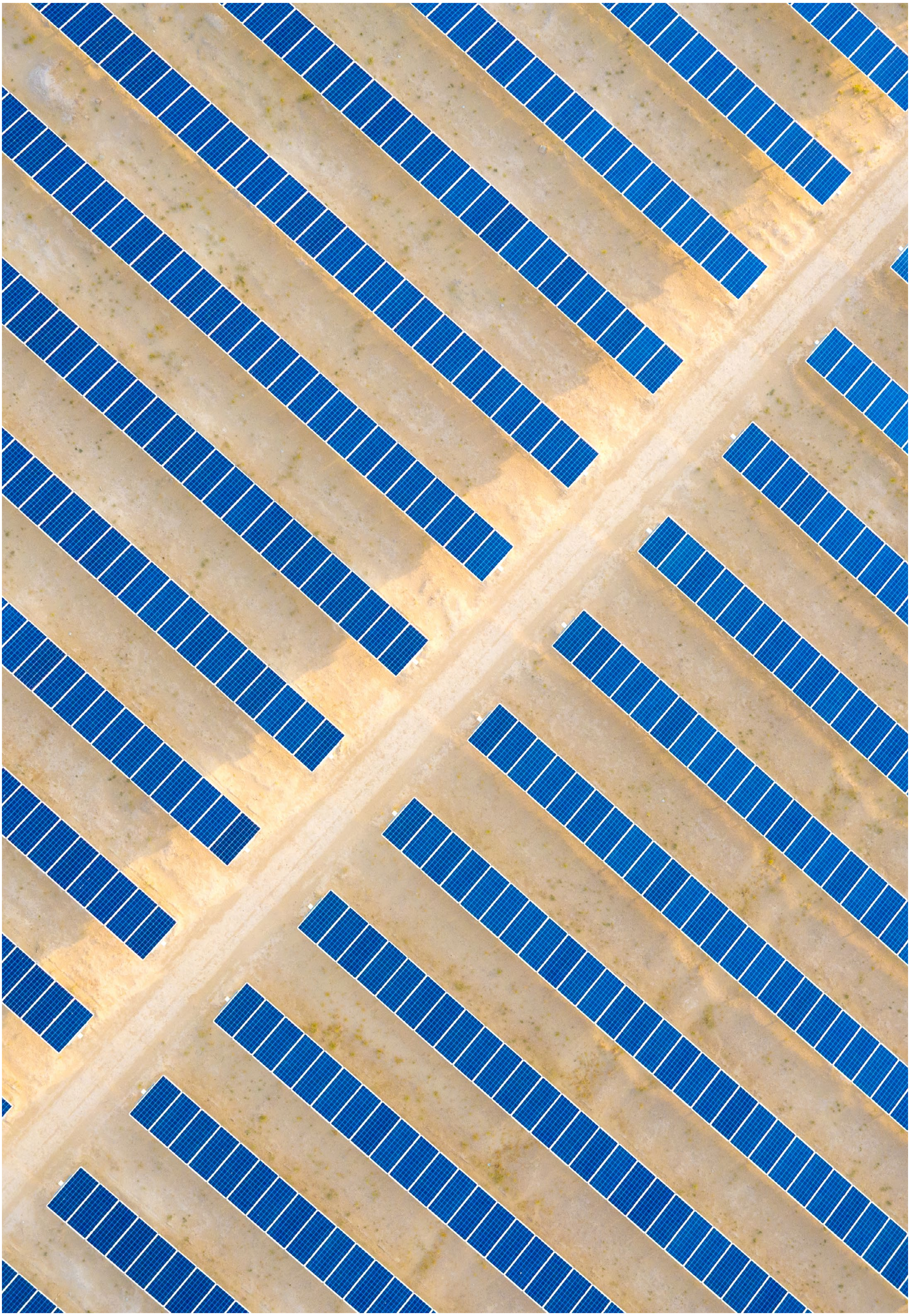
Source: https://www.icf.com/insights/transportation/deploying-sustainable-aviation-fuel-to-meet-climate-ambition



❝ **To be renewable, the carbon used to produce the fuel must already be part of the carbon cycle, ensuring no net addition to the carbon in the atmosphere.**

2. **A source of carbon:** Carbon forms the backbone of hydrocarbons and is about 85% of jet fuel by weight.[18] When jet fuel is combusted, the carbon returns to the atmosphere as CO_2. To be renewable, the carbon used to produce the fuel must already be part of the carbon cycle, ensuring no net addition to the carbon in the atmosphere. There are two main approaches to sourcing this carbon. The ambition is for most carbon to be sourced directly from the atmosphere through a process known as direct air capture (DAC). While the concentration of CO_2 in the atmosphere is increasing, in absolute terms, it is quite diluted and makes up just over 412 parts per million. It is therefore relatively difficult to extract, and while the technologies are quickly improving, it is still expensive. Therefore, some initial PtL approaches use point source capture (PSC), which captures carbon from concentrated sources, such as industrial waste gases or the combustion of biological material. The waste carbon can have a concentration of over 90%, significantly reducing the capture cost. The use of industrial waste gases still results in the addition of fossil carbon to the atmosphere but benefits by reusing the carbon before emitting it. This is, therefore, a useful transition approach to develop technologies but is not appropriate for a net-zero carbon society, so it must be phased out over time. Biogenic materials are not suitable for the United Arab Emirates given the scarcity of available materials, and the lack of water and fertile land constrains the ability to create more.

3. **An approach to synthesize fuel:** The carbon and hydrogen must be combined into high-density liquid hydrocarbons to be drop-in for existing aircraft. Several techniques can be used, with leading approaches including the FT pathway, the AtJ pathway and methanol synthesis. The FT and AtJ pathways are already certified through ASTM International, while the methanol process is under review. The FT approach uses a catalytic process to form FT liquids, which can then be upgraded to fuels. The AtJ process uses biological processes to ferment hydrogen and oxygen into alcohol, which can then be processed into fuels. The methanol process creates methanol as an intermediary, which can then be further processed into jet fuel. These processes are versatile, with the intermediaries useful as fuels (e.g. ethanol can be blended with gasoline for use in cars, and methanol could be used to power shipping), and the final products will always produce a portion of other fuels such as naphtha and diesel as well as jet fuel – and the distribution can be tweaked to reflect market conditions.



1.3 The global outlook for power-to-liquids production

Developing each part of the PtL value chain is essential to deploying the end-to-end technology. This provides two crucial benefits: firstly, it allows great flexibility in developing an industry in the United Arab Emirates, with each part of the value chain creating benefits individually. Secondly, the reduction in the cost of the PtL technology will be compounded by the rapid cost reduction in each part of the value chain.

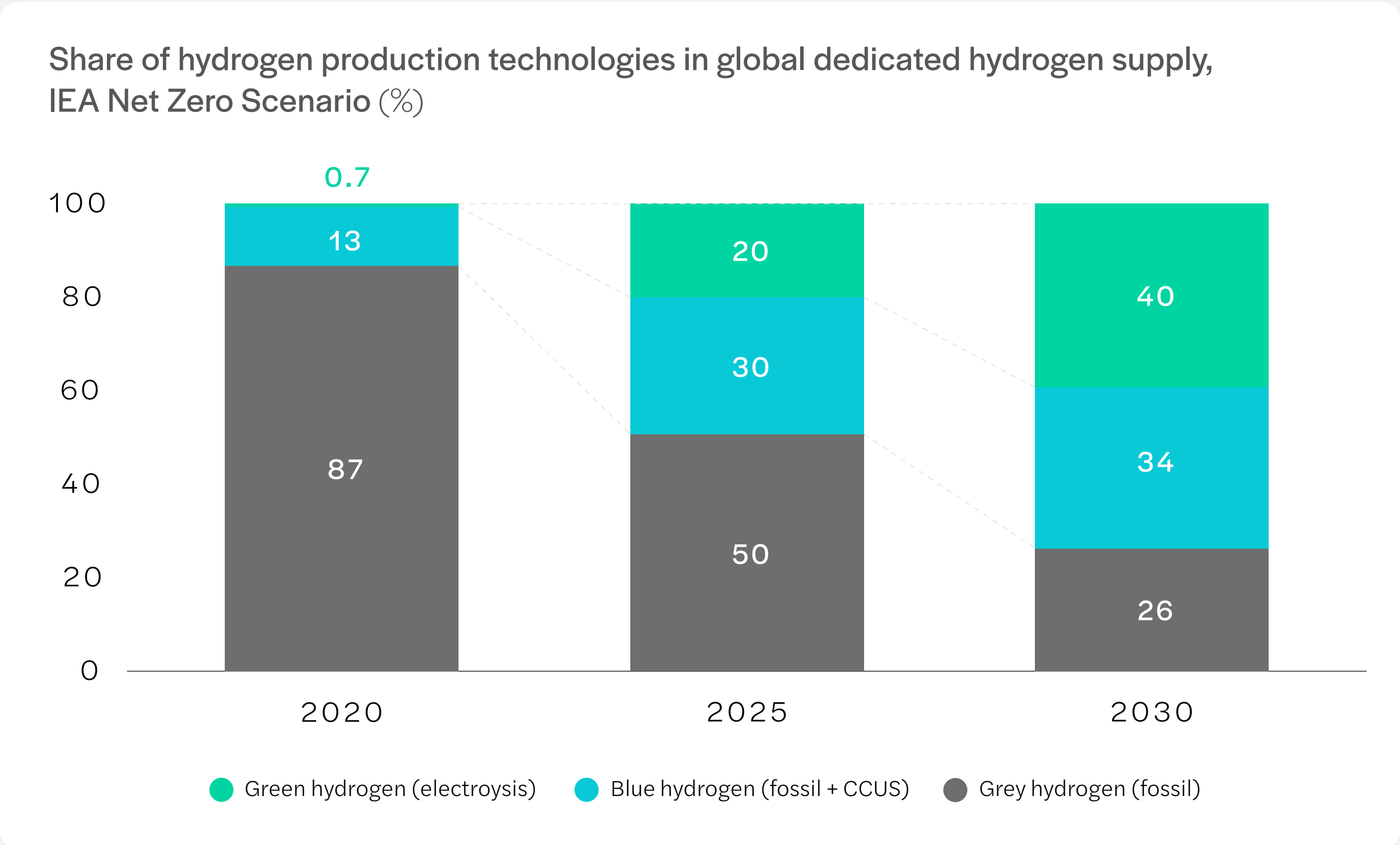
This section describes developments for renewable energy, hydrogen production and carbon capture and then covers progress in deploying integrated PtL facilities.

Renewable energy

Renewable energy is typically the single largest cost for PtL production. The energy is primarily used for green hydrogen production through electrolysis, with further use for desalination before electrolysis and for carbon capture.

The United Arab Emirates has led the rise in renewable energy capacity in the Middle East over the last 15 years through research and development (R&D), policies, investment and deployment. The United Arab Emirates has over half (58%) of the market share of the operational and in-the-pipeline solar projects in the Middle East and North Africa (MENA). Supported by the abundant and intense solar radiation, the Emirates has one of the lowest auction prices for a single project in the world at $0.135 per kilowatt hour (kWh).[19] Some of the world's largest solar plants are located in the Emirates, including Shams 1 (0.1 gigawatt (GW)), Mohammed bin Rashid Al Maktoum (5 GW by 2030), Noor Abu Dhabi (1.2 GW) and al Dhafra (2.0 GW), supported by the zero-carbon energy generated by the Baraka nuclear power. A combination of policy mechanisms to further increase capacity are also being implemented, including as incentives and mandatory solar rooftop installations.

FIGURE 4 **Low-carbon hydrogen is expected to dominate 2030 hydrogen market**



Source: https://www.iea.org/data-and-statistics/charts/global-hydrogen-demand-by-production-technology-in-the-net-zero-scenario-2020-2030

Significant research, investment and ambition have been invested in green hydrogen production, but today this method represents less than 1% of the global dedicated hydrogen production.

Hydrogen

Most renewable electricity in power-to-liquids production is used for hydrogen production via the electrolysis of water. There are various ways to produce hydrogen, and depending on the route used, they are referred to as grey, blue, or green hydrogen.[20]

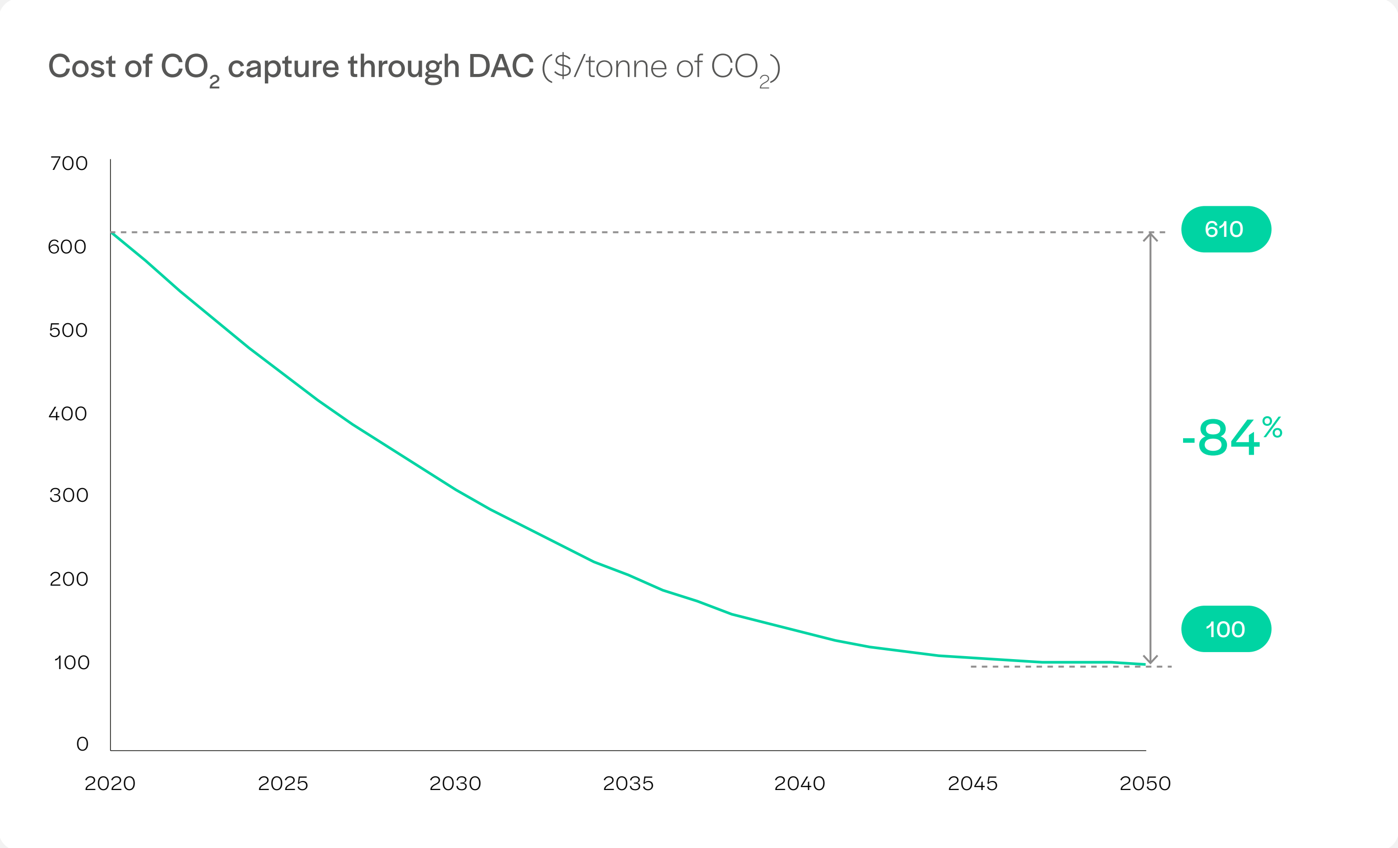
Grey hydrogen refers to the production of hydrogen from fossil-based resources and is the most common route today. Most (70%) of grey hydrogen is produced using natural gas through the SMR process, with most of the balance using coal gasification. These are highly carbon-intensive methods.

Up to 90% of the CO_2 emissions released from these processes can be captured and used/stored. Integrating conventional hydrogen production methods with carbon capture technologies is referred to as blue hydrogen production. Less than 13% of the global hydrogen supply currently captures the carbon emitted. It is mainly used for ammonia production, in which the captured carbon is used for urea fertilizer production.[21] Less than 1% of hydrogen production today sequesters the carbon.[22]

Significant research, investment and ambition have been invested in green hydrogen production, but today this method represents less than 1% of the global dedicated hydrogen production. This is largely due to the high cost compared to other production approaches and the incentives for the industry to reduce carbon emissions. As nations continue to develop regulatory mechanisms to achieve climate goals, the share of green hydrogen production is expected to increase. The IEA Net Zero Scenario estimates a need for up to 40%[23] of hydrogen production to be green by 2030.

Several technologies can be used for electrolysis. Currently, alkaline electrolysers dominate the green hydrogen production market due to their use in the chlor-alkali industry.[24] However, proton exchange membrane (PEM) electrolysers are increasingly used, with 89 megawatts (MW) of installed capacity and significant manufacturing capacity coming online. For example, ITM Power have recently started production[25] at the Bessemer Park Gigafactory in the UK, producing up to 1,000 MW of electrolyser capacity every year. PEM electrolysers can provide higher pressure hydrogen with a smaller footprint than alkaline electrolysers and are expected to have lower maintenance requirements and quicker reaction times to fluctuations typical of renewable power generation. Solid oxide electrolyser cell (SOEC) systems are not yet commercially available but may further reduce costs over the coming decades. These may be particularly applicable for PtL production, as SOEC systems operate at high temperatures and could efficiently use waste heat from FT reactors or nuclear facilities.

FIGURE 5 **The cost of carbon capture from DAC is expected to decrease by over 80% by 2050**



Source: Fasihi, Mahdi, Olga Efimova, Christian Breyer, "Techno-economic assessment of CO_2 direct air capture plants", Journal of Cleaner Production, vol. 224, 2019, pp. 957-980; IEA, Net Zero by 2050: A Roadmap for the Global Energy Sector, 2021; Expert interviews

Direct air capture/carbon capture utilization (DAC/CCU)

Carbon is the backbone of hydrocarbon-based fuels and is typically sourced from CO_2 molecules captured from the atmosphere or point sources. Point sources refer to capturing CO_2 emissions released from industrial, power or biogenic operations. Around 40 $MtCO_2$/year globally is currently captured from point sources and is either stored or utilized for other purposes (such as enhanced oil recovery). DAC technology allows CO_2 to be captured directly from the atmosphere. Yet, the concentration of CO_2 in the air is less than 0.04%, which significantly increases the complexity and costs. The current global operational DAC capacity is around 0.01 $MtCO_2$/year. Still, companies like Carbon Engineering and Climeworks are pioneering the large-scale use of this technology, and PtL would be both enabler and benefiter in this scenario.

Carbon capture is an enabler for the United Arab Emirates' carbon-neutral future. Almost all of the United Arab Emirates' oil and natural gas resources (95% and 92%, respectively) are located in Abu Dhabi, making Abu Dhabi National Oil Company (ADNOC) the biggest energy company in the region and 12th in the world. Currently, there are two large-scale CCUS plants in the Middle East region, and ADNOC has been operating one of them in the United Arab Emirates since 2016, which has a capacity of 0.8 $MtCO_2$/year. That corresponds to 2% of global capacity and is the first application in the world to capture iron and steel production CO_2 emissions, which are then used for enhanced oil recovery (EOR).[26] ADNOC announced its targets for capturing 5 $MtCO_2$/year by 2030 from its natural gas processing plants.[27] Increased capture capacity from point sources can create opportunities for further use of CO_2 beyond EOR, where PtL can play a key role.

Starting the PtL production with point source carbon capture could be considered a lower-cost transition solution while scaling up the DAC capacity. The cost of carbon capture with DAC systems is around $600 per tonne of carbon captured today, but it is expected to halve by 2030 (see Figure 5). The global transition from point source carbon capture to direct air capture to supply CO_2 as feedstock is expected to speed up after 2030, and the share of DAC in the CO_2 feedstock market is expected to match that of point source capture by 2037. Beyond that point, DAC is expected to dominate the CO_2 feedstock market by providing up to 80% of the CO_2 required for synthetic fuel production by 2050.[28]

The global outlook for integrated PtL facilities

Currently, no large-scale integrated facilities produce SAF through the PtL pathway, but several facilities are under development. A pilot-scale PtL demonstration was conducted in 2014 in Germany. Since then, there have been ongoing efforts to scale up the production while decreasing the costs. In August 2019, the German government funded the Power-to-X (P2X) project within the Kopernikus initiative and delivered the world's first integrated PtL production[29] with a capacity of 10 litres per day. While this is a small volume of fuel, it represented a milestone through the successful integration of DAC, electrolysis, FT synthesis and jet fuel upgrading. The P2X project plans to scale up capacity to 2,000 litres per day, having boosted collaboration across industries with the involvement of 18 research institutions, 27 industrial companies and three civic organizations.[30]

There are large-scale commercial plants under development for the PtL pathway, and they mostly constitute collaborations across technology providers and other stakeholders. Norsk e-fuel, established in June 2020, aims to be Europe's first large-scale commercial plant to produce SAF from renewable electricity, water and a combination of atmospheric CO_2 and point sources. The plant will be located in Herøya, Norway, and is expected to start production with 12.5 million litres per year of renewable fuel capacity in 2024, scaling up to 25 million litres per year by 2026. Each of the four shareholders will bring their expertise in specific areas: Sunfire will deliver electrolysis technology, Climeworks will provide DAC, Paul Wurth (SMS Group) will be the engineering, procurement and construction (EPC) provider and Valinor (parent company of Norsk Vind) will provide investment and wind energy.

Net-zero, for us, is about new industries, new skills and new jobs. For us, the business of tackling climate change is simply good business.

Sultan Ahmed Al Jaber, United Arab Emirates Special Envoy for Climate Change

The Green Fuels for Denmark consortium was established in Denmark in May 2020 to produce large amounts of renewable fuels through the PtL pathway. Six leading Danish companies, Copenhagen Airports, DSV Panalpina, A.P. Moller-Mærsk, DFDS, Scandinavian Airlines (SAS) and Ørsted joined forces to position Denmark as a leader in renewable fuel production by 2030. The project will use water and offshore wind to produce green hydrogen through electrolysis while sourcing CO_2 from a bioenergy plant. It is planned to have three stages and is expected to deliver green hydrogen and e-methanol alongside SAF. In total, more than 250,000 tonnes per year of renewable fuels are expected to be produced starting from 2030. The facility will also contribute to Denmark's ambitious climate goal to achieve 70% emission reductions by 2030, compared to 1990 levels. It is expected to reduce 0.85 $MtCO_2$/year,[31] corresponding to more than 5% of Denmark's annual emissions.

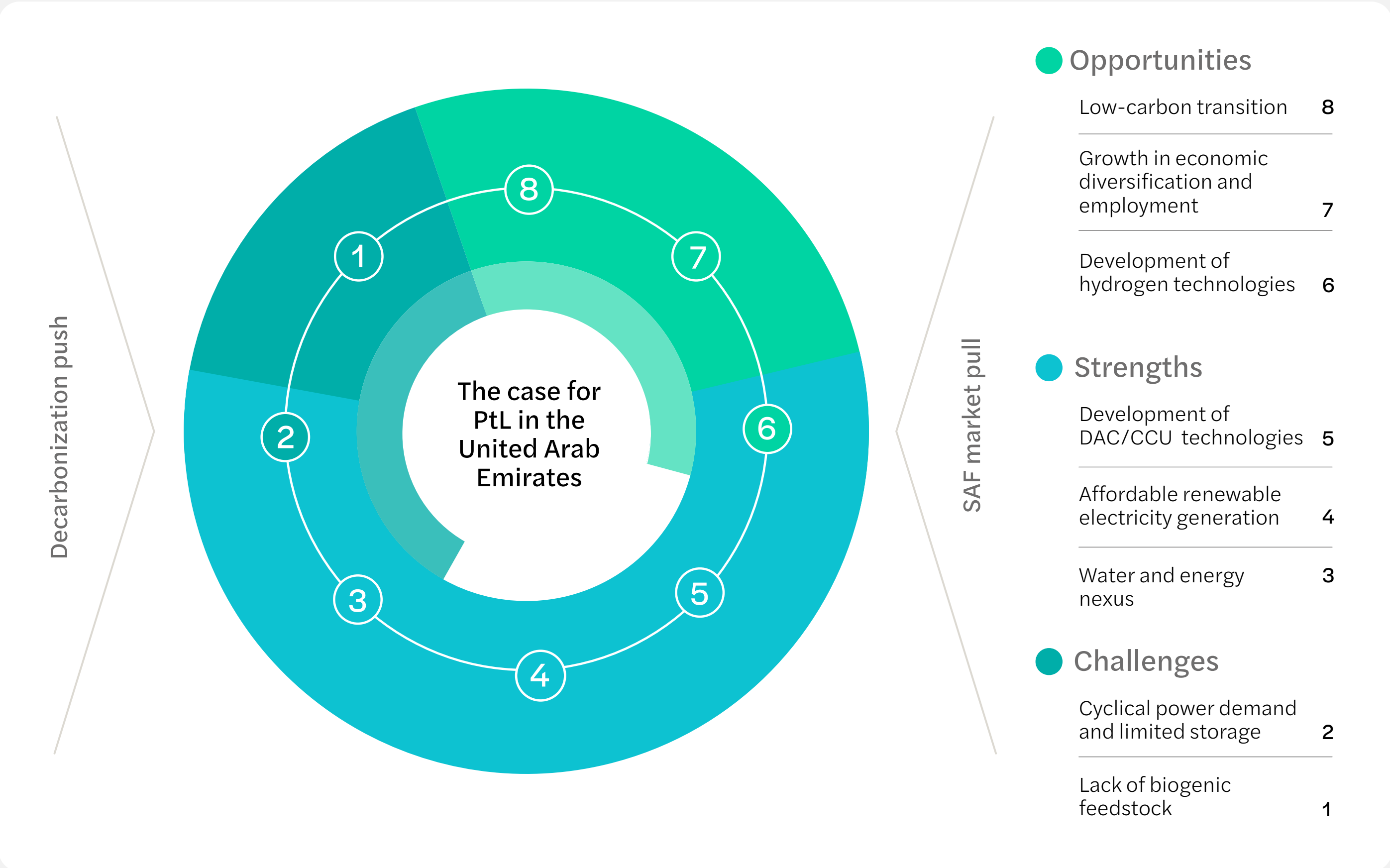
The United Arab Emirates has also been pioneering the PtL pathway. Since January 2021, government-owned renewable energy company Masdar has been leading an initiative on a PtL demonstration facility with Abu Dhabi Department of Energy, Etihad Airways, Lufthansa Group, Khalifa University of Science and Technology, Siemens Energy and Marubeni Corporation. As a part of this initiative, Masdar, TotalEnergies and Siemens Energy signed a collaboration agreement in January 2022 to develop a demonstrator plant to produce green hydrogen and SAF. The facility's front-end reengineering design (FEED) is expected to start by the end of 2022.

Other initiatives like Zenid,[32] Atmosfair,[33] Nordic electrofuels and Haru Oni[34] are also developing synthetic renewable fuel facilities. These facilities will use the PtL pathway to produce various fuel products, including SAF. Their carbon source is expected to be supplied from either atmospheric or point sources, and all are planning to use wind energy to produce green hydrogen through water electrolysis.

2 The PtL opportunity in the United Arab Emirates

PtL offers a unique opportunity for the Emirates to leverage domestic resources, infrastructure and expertise to grow and decarbonize the economy.

FIGURE 6 **The case for PtL in the United Arab Emirates present numerous opportunities**



Source: Expert interviews and ICF analysis

The United Arab Emirates is uniquely well-positioned for PtL, using national advantages to promote global trends. Both push and pull forces will drive PtL production in the Emirates, mitigating some regional challenges while creating export opportunities due to expected supply and demand imbalances in the global SAF market. From a national perspective, the PtL case for the United Arab Emirates can build upon the country's opportunities and strengths as well as the challenges it faces. The constrained availability of biogenic feedstock will make PtL a vital pillar of the Emirates' SAF strategy. The region has substantial potential for affordable renewable electricity generation. Yet, cyclical power demand and limited storage capacity require innovative solutions to maximize the benefits of this opportunity, in which PtL can play a crucial role. It can also bridge the gap for transitioning into a lower carbon aviation industry while enabling growth and diversification in the economy.

2.1 Mitigating local challenges

Limited biological feedstock available for SAF production

The United Arab Emirates has a hot and dry climate, resulting in limited availability of biogenic resources for SAF production. The following log-log chart, based on the global biogenic SAF feedstock availability database, presents the United Arab Emirates' global position, showing the nation's significant shortfall of biological feedstock compared to the size of the economy.

The United Arab Emirates has some opportunities to produce SAF from biogenic resources through halophytes, MSW and agricultural waste. The Sustainable Bioenergy Research Consortium (SBRC) lead Seawater Energy and Agriculture System (SEAS) project aims to convert halophytes into SAF through the HEFA pathway, which has the potential to provide 75 million litres to 200 million litres of SAF by 2033. MSW and agricultural waste feedstocks can use gasification and FT conversion to produce 110 million litres to 760 million litres of SAF by 2033. In total, biogenic SAF has the potential to meet 1.42% to 7.61% of the United Arab Emirates' jet fuel demand by 2033.[35] This constraint will require PtL to scale SAF capacity to decarbonize a meaningful percentage of the aviation industry.

Cyclical power demand and limited storage

Due to the intermittent nature of renewable power, grid stability and dispatchable power are challenges in the decarbonization effort for the Emirates' energy system. Outside of contributing to daily energy requirements, any excess renewable power can be used for cooling during the summer months. In the United Arab Emirates region, the daily demand in 2030 is estimated to be a minimum of 14 GW during a night in the winter and a maximum of 30+ GW during the summer due to cooling requirements.[36] Currently, fossil fuel-fired power plants are used for baseload power and can ramp up to meet peak energy demands when solar and wind resources are low. As fossil fuel prices remain volatile, such as liquified natural gas (LNG) from imports and fast-approaching decarbonization targets, other energy generation and storage modes can complement solar and wind power, such as nuclear energy and PtL.

Any surplus of renewable power can be stored using battery storage, although utility-scale battery storage capacities currently only range from two to ten hours. In Abu Dhabi, 108 MW or 648-megawatt hour (MWh)[37] of battery storage capacity are planned to come online, with each battery system having six hours of storage capacity. In addition to the battery storage deployment in Abu Dhabi, there are battery testing efforts for a 7.2 MWh battery system with Dubai Electricity and Water Authority. Due to the limited duration of support from the battery storage capacities, the excess renewable energy can also be used to support innovative technologies that support decarbonization efforts, such as DAC and electrolyser systems.

As part of PtL initiatives and ambitions to produce large amounts of hydrogen, PEM electrolysers can ramp up in less than 20 minutes. This capability allows for hydrogen production during surplus renewable power during the daylight or summer months. The hydrogen can be stored or used for

“ Due to the limited duration of support from the battery storage capacities, the excess renewable energy can also be used to support innovative technologies that support decarbonization efforts.

Seawater desalination plays a key role in the Emirates' water landscape, as it provides almost all industry and residential water supply in the country.

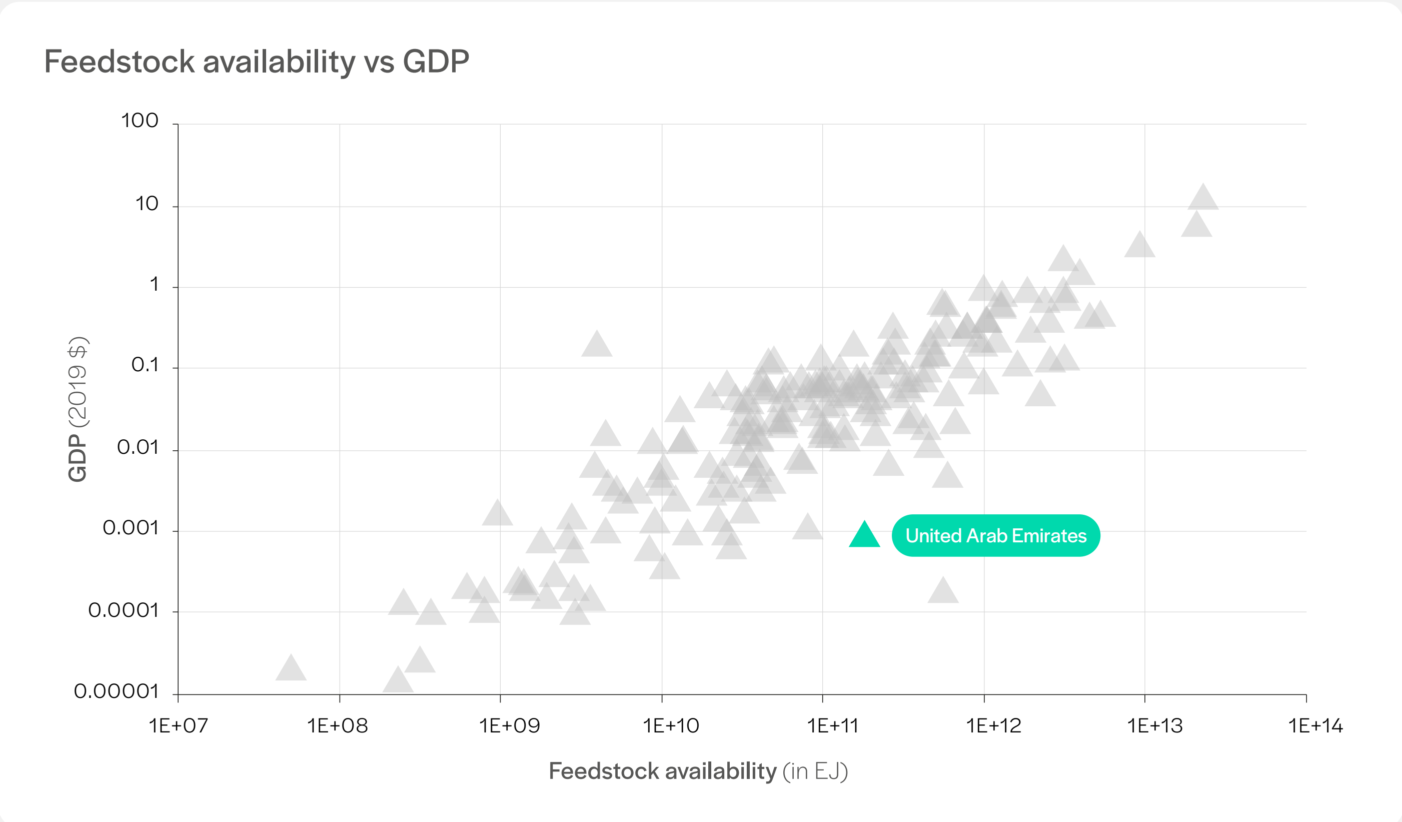
the PtL process. As the United Arab Emirates develops its hydrogen strategy, the region has the opportunity to use caverns to store large amounts of hydrogen and develop pipeline networks or other means of hydrogen storage and transport. Hydrogen can be used for several industries, especially for power through existing gas assets, such as combustion turbines. Depending on the frame of the combustion turbine, some frames can blend high percentages of hydrogen with natural gas. Other frames may require retrofitting the turbine and balancing plant sections at a nominal cost compared to replacing the turbine completely. Allowing hydrogen to be used in gas turbines during peak energy demand can resolve the renewable energy dispatchability challenges during winter or the day with low solar irradiance or wind.

The water and energy nexus

The Middle East and North Africa region is the most water-stressed region on Earth. It is expected to face the highest economic loss (6-14% of GDP) due to climate-related water shortages by 2050.[38] The United Arab Emirates also faces high water stress and ranks 10th in global water stress.[39] The United Arab Emirates government is taking action to ensure continuous access to water through its Water Security Strategy 2036, launched in September 2017.[40] Seawater desalination plays a key role in the Emirates' water landscape, as it provides almost all industry and residential water supply in the country. The water demand is expected to double by 2030, reaching up to 9 to 10 billion cubic metres (BCM) per year.[41] Decoupling water demand with other economic activities, such as power generation and decarbonization-focused initiatives, including PtL production, is a crucial consideration for the United Arab Emirates.

The water cost of PtL depends on the technologies chosen for the production and the means of production in an integrated or distributed facility. For example, DAC systems can consume or produce water as a by-product. Depending on the meteorological conditions of the deployment site and the process configuration, high-temperature aqueous solution DAC systems would consume up to 50 tonnes of water per tonne of CO_2 captured. Carbon Engineering, a company using this design, reported 4.7 tonnes of water per tonne of CO_2 captured. Low-temperature (LT) DAC systems would generate 0.8 to 2 tonnes of water per tonne of CO_2 captured. In doing so, LT DAC systems remove water demand as a barrier to CO_2 production and provide water input for the subsequent electrolysis system. In the case of the United Arab Emirates, where there is water stress, an integrated PtL production plant with an LT DAC system would decrease the cost of carbon capture up to $9 per tonne of CO_2, due to eliminated desalination and transport costs, compared to a high-temperature (HT) DAC system.[42]

FIGURE 7 **The biological feedstock availability in the United Arab Emirates is constrained**



Source: World Bank GDP Data: https://data.worldbank.org/country and ICF feedstock database

Water is more important than oil for the United Arab Emirates.

His Highness Sheikh Mohamed bin Zayed Al Nahyan,
President of the United Arab Emirates

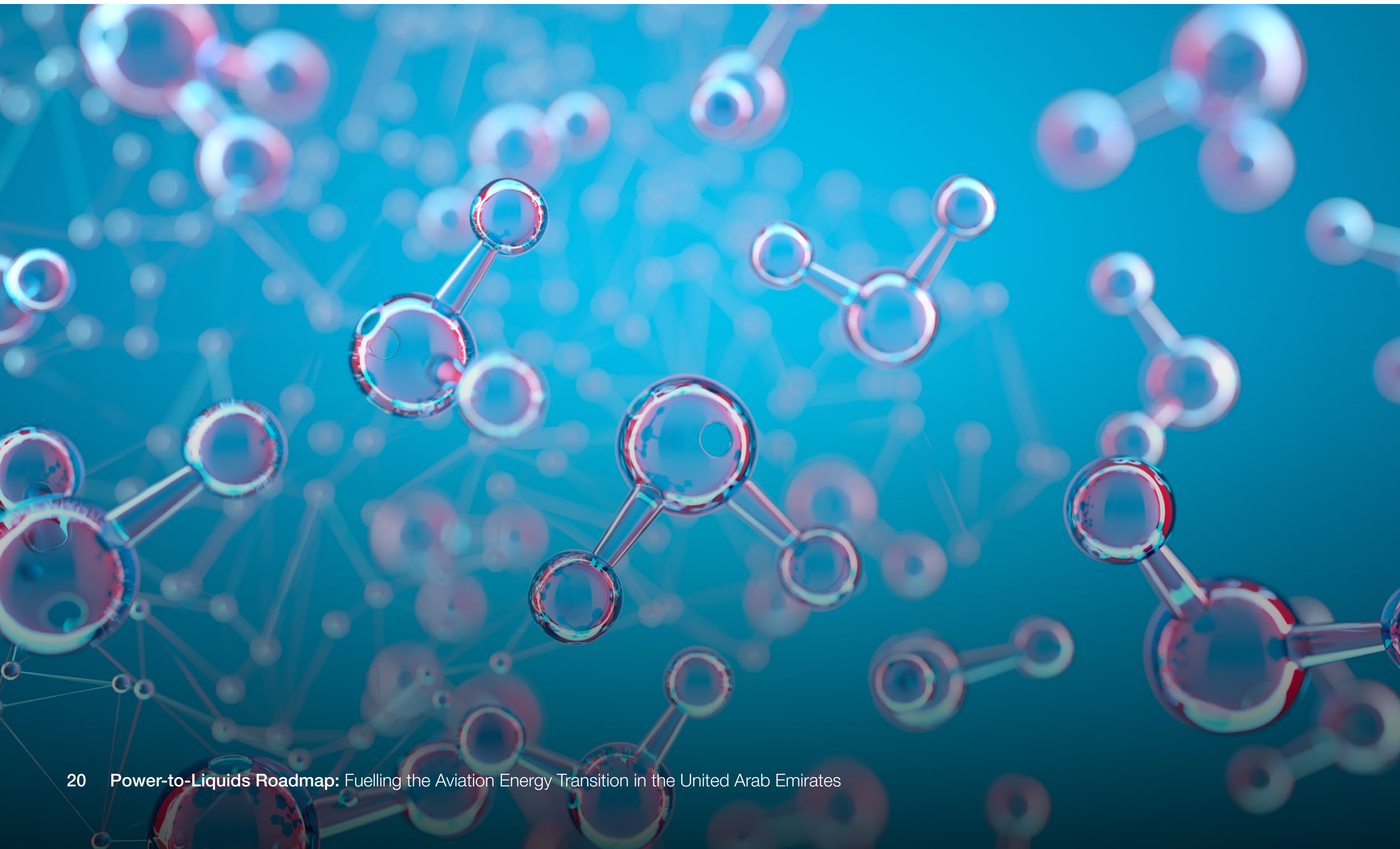
Another consideration in PtL water balance is hydrogen production. The amount of water required to produce hydrogen is a function of the production technology and energy source. Green hydrogen production through electrolysis and renewable energy is the least water-intensive way of producing hydrogen, consuming around 9 kg of water to produce 1 kg of hydrogen[43] through SOEC electrolysers. That value would increase to 18 kg of water per kg of hydrogen (kgH_2O/kgH_2) if PEM electrolysers were used.[44] The water inlet for the electrolysers should be deionized water, and so using seawater would require twice the amount due to desalination process water efficiency. Water demand for the blue hydrogen would significantly vary on the selected application, but SMR with CCS would require similar amounts of water for electrolysis.

An emerging solution could involve the direct electrolysis of seawater by offshore renewable energy generation. The Emirates has a large coastline, and marine renewable energy generation is rapidly improving, including fixed and floating wind, tidal and wave generators. Initial studies are underway to trial integration of offshore wind power with hydrogen production, which could be a solution uniquely valuable to the nation.

FT synthesis is a complex and heavily exothermic reaction that primarily converts CO_2 and H_2 into a mixture of saturated hydrocarbons ($-CH_2-$) and water.[45] This means a substantial amount of water and energy is expected to be released as a part of the process. In an integrated PtL production facility, by-product water can be recycled back to electrolysers for green hydrogen production, which can meet 67% of the electrolysis water demand, based on the process design configurations.[46] It is important to note that all water requirements, including electrolyser and DAC feed (if applicable), must be desalinated/treated water. Combined with the water produced by the LT DAC system, water demand for PEM electrolysers could decrease from 18 to 4 kgH_2O/kgH_2, hence reducing the energy and water requirements for desalination operations up to 78%. The heat released from the FT reactor can also be recycled to the DAC unit, which could decrease its energy consumption up to 70%, based on the DAC system selected.[47]

Decoupling its decarbonization efforts and water consumption is crucial for the United Arab Emirates. Various technologies are available to produce PtL, and considering the Emirates' water-related challenges, suitable ones can be chosen to minimize the need for water consumption. The early stages of PtL deployment would likely require the transport of hydrogen and CO_2 to the PtL production site, as blue hydrogen and point source capture can be used as transition feedstocks. As the integrated facilities are commissioned, energy and water requirements could be reduced through process integration opportunities.

Various technologies are available to produce PtL, and considering the Emirates' water-related challenges, suitable ones can be chosen to minimize the need for water consumption.



2.2 Leveraging domestic strengths

Affordable renewable electricity generation

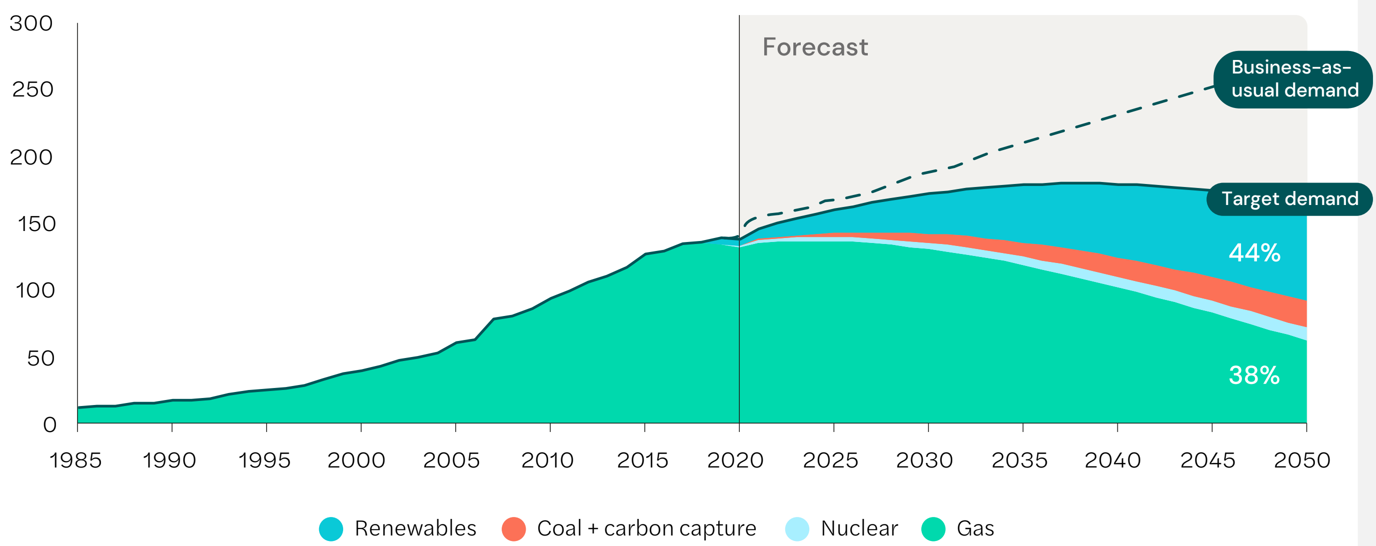
As the United Arab Emirates economy has grown, so has its energy demand. Industrial diversification has successfully shifted an impressive portion of the economy away from fossil fuel exports. A key driver of this is access to affordable energy, met through gas turbine generation. The growth in energy demand has gradually diverted gas from lucrative export to domestic consumption for electrical generation, and by 2008 the Emirates became a net importer of natural gas. Rising prices, energy security and climate pressures support a transition to a more diversified generation portfolio.

The shift to affordable, cleaner energy has been developed in the United Arab Emirates' National Energy Strategy 2050,[48] announced in 2017. This features two key 2050 objectives: a demand-side reduction in energy demand by 40% compared to business-as-usual and a supply-side shift to 50% clean energy. This would result in a gradual phase-down of gas, of which renewables would mostly replace, and a small share of nuclear and coal would be replaced with CCS. When finalized, Al Dhafra Solar PV is expected to provide enough power to energize 160,000 homes through its 2 GW capacity. By 2028, approximately half (13.66 terawatt hours)[49] the renewable target would be met through grid-scale solar PV, with the remainder by concentrated solar power (CSP), rooftop solar PV and small volumes of biomass and wind. The commissioning in March 2022 of the second of four 1.4 MW reactors at the Barakah Facility[50] shows substantial progress for the nuclear generation targets, while recent announcements suggest the use of coal may be less than anticipated.[51]

Since this plan was published in 2017, the renewable industry has reached a tipping point. Renewables have rapidly scaled, with the installed solar PV capacity increasing by 84% and the onshore wind capacity by 43%. Crucially, this has driven the technologies to mature, and solar PV and onshore wind have decreased in cost from parity with fossil fuels to cheaper in almost every case.

FIGURE 8 **The United Arab Emirates energy strategy includes a scaling of renewables, nuclear and clean coal, combined with demand reduction to phase down gas consumption**

Historical and forecast electricity consumption by generation type (terawatt-hour (TWh))



Source: ICF analysis of the United Arab Emirates National Energy Strategy 2017

> Over almost the entire year, solar PV installed in the United Arab Emirates is estimated to be in the top 10% of efficiency across all countries, with only a small reduction in July.

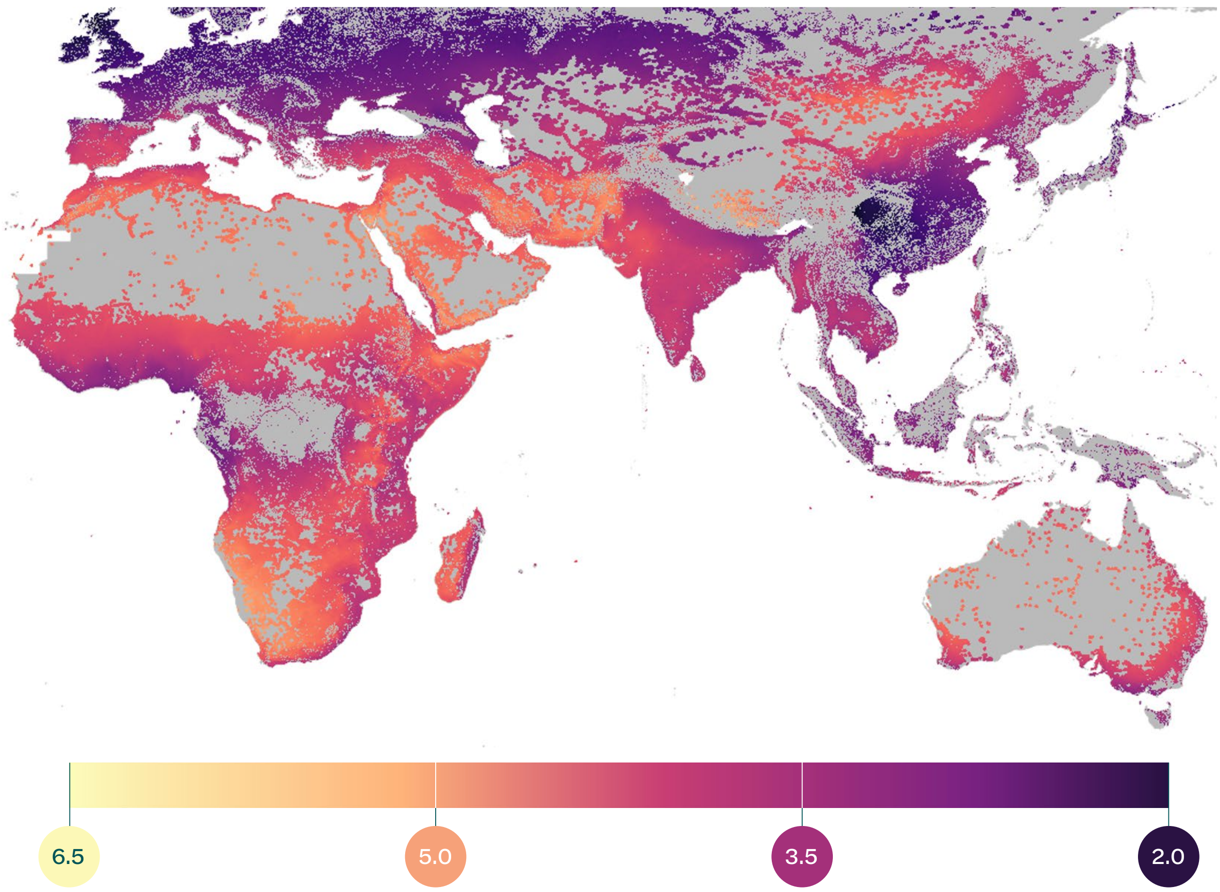
The exceptional efficiency of solar PV in the United Arab Emirates could allow this technology to be deployed more rapidly than the stated ambition and at a significantly greater scale. Analysis by the World Bank shows[52] that the achievable efficiency of solar PV generation in the United Arab Emirates is some of the highest in the world. This is driven by the high level of solar energy reaching the surface, and the cooling effect of the sea and winds, which further increase the energy conversion efficiency. The same analysis estimates that up to 60% of the Emirates landmass does not have physical or technical constraints, such as mountains, forests, lakes and buildings, or is too remote to be practical. Building solar PV on only this pragmatic land and considering all expected generation, conversion and transmission inefficiencies, the PV could still deliver over 10 EJ of energy every year – more than 30 times the total energy consumed by the Emirates aviation industry in 2019.

The solar PV generation opportunity in the United Arab Emirates is also remarkably consistent throughout the year. The proximity to the equator results in long daylight hours and little reduction during winter. Figure 10 shows the expected efficiency for solar PV generation throughout the year, overlaid with the global range (10^{th}-90^{th} percentile shaded in grey) and global average. Over almost the entire year, solar PV installed in the United Arab Emirates is estimated to be in the top 10% of efficiency across all countries, with only a small reduction in July due to the high surface temperatures. This consistency is an essential driver for lower-cost hydrogen production. It makes it easier for electrolyser production linked to the solar farm to achieve a higher capacity factor, allowing the electrolyser cost to be spread over a greater volume of hydrogen production and reducing the unit cost.

This consistency is notably not the case in the countries that have installed the most solar PV to date – China, the US, Germany and Japan endure longer and darker winters. Together these four countries have established over 63% of global PV capacity, suggesting a global mismatch between the currently installed capacity and the ideal location.

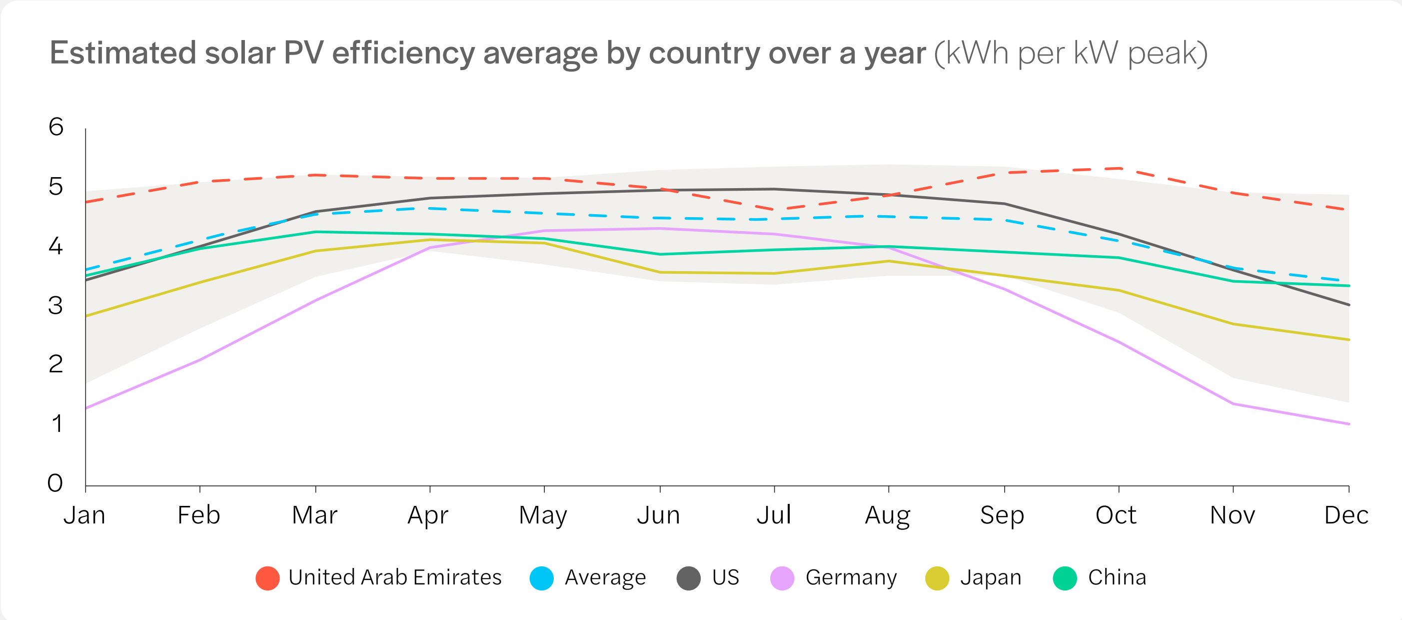
FIGURE 9 **The United Arab Emirates can achieve some of the highest solar PV efficiencies globally**

PV power output (kWh (kilowatt-hour) per kW peak)



Source: https://datacatalog.worldbank.org/search/dataset/0038379, illustrated by ICF

FIGURE 10 | **The United Arab Emirates can achieve some of the highest solar PV efficiencies globally more consistent solar PV output than many other countries**



Source: ICF analysis of data from the report *Global Photovoltaic Power Potential by Country* by the World Bank and Solargis

The next decade will be the era of widespread solar PV deployment, at a level far greater than many expect. The deployment of fossil fuel electricity generation has traditionally been at a slow, linear pace. Between 1996 and 2020, gas generation increased by 4.7% compound annual growth rate (CAGR), coal by 2.4% and oil reduced by -2.0%. By contrast, solar capacity was deployed at a CAGR of 41.5% over the same period, an order of magnitude greater than any fossil fuel. More than twice as much solar capacity has been deployed in the past five years than in the preceding 20 years (490 GW vs 217 GW), with the capacity deployed in 2020 over 30% greater than in 2019. The pipeline of announced projects suggests that the rate of increase will not diminish.

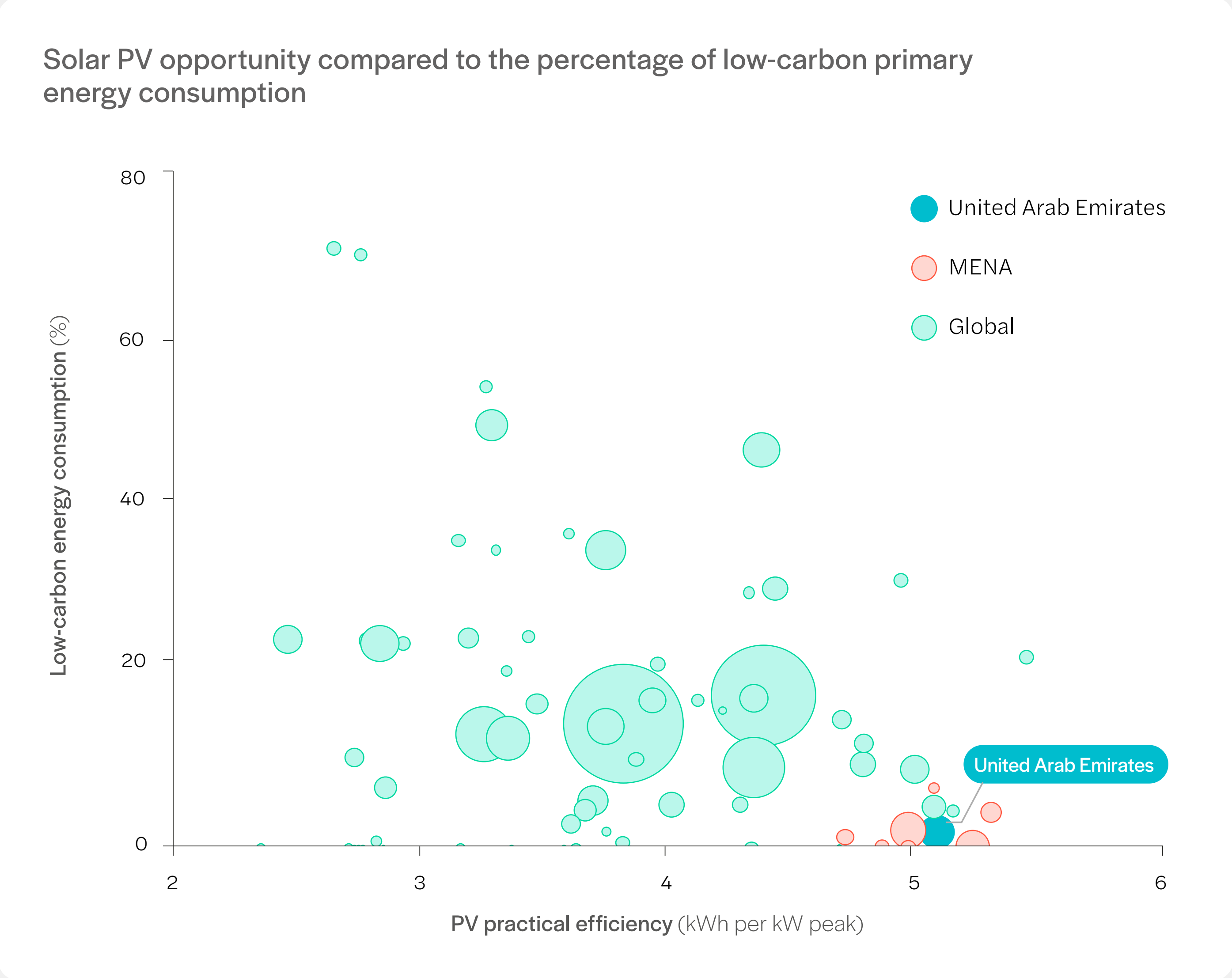
The economic rationale for this rapid and growing rate of deployment is clear: solar PV has a clear lead as the lowest cost of electricity generation, followed closely by onshore wind and trailed by fossil fuels. Every solar panel installed will likely reduce energy bills for households and industry while simultaneously reducing carbon emissions. This has never been more evident than in 2022, with record energy prices putting extreme pressure on energy consumers. While the United Arab Emirates has benefitted from the high selling price of its fossil fuel exports, it is notably a net importer of natural gas. Reduced consumption due to greater renewable deployment would have reduced the government's natural gas trade deficit and associated costs.

The United Arab Emirates and other MENA countries have not taken advantage of this remarkable natural resource. When the practical efficiency of solar PV in each country is compared to the percentage of renewable energy consumption, it is clear that many other countries have exploited their renewable energy generation opportunities far more than the United Arab Emirates – despite the significantly higher cost.

There is a clear economic and environmental incentive for the United Arab Emirates to accelerate the deployment of solar PV at a far greater rate than proposed, benefitting individual consumers, creating a cost advantage for the domestic industry and supporting the development of a world-leading PtL industry.

The affordability of energy creates the possibility of an affordable PtL industry. Using the IEA's Net Zero Scenario, the LCOE is expected at $17/MWh by 2030 and $12/MWh by 2050, nearly 50% lower than the global weighted average. The United Arab Emirates has recently broken records for LCOE with auction prices of $13.50 per MWh.[53] Continued macro and local developments should allow the Emirates to retain this cost leadership. For example, the Masdar Institute's Research Centre for Renewable Energy Mapping and Assessment's initiative to reduce the cleaning needed to remove dust from solar PV and CSP generation. This includes improved cleaning processes, dust-resistance surfaces and better timing using real-time monitoring.

FIGURE 11 | **Solar PV is a key emerging technology to decarbonize the Gulf economies**



Source: ICF analysis of data from the report *Global Photovoltaic Power Potential by Country* by the World Bank and Solargis, and the BP World Energy Outlook: 2022

"The United Arab Emirates has a large cement industry with 15 integrated plants and 31 million tonnes per year production capacity, much of which is in the Northern Emirate of Ra's al-Khaymah.

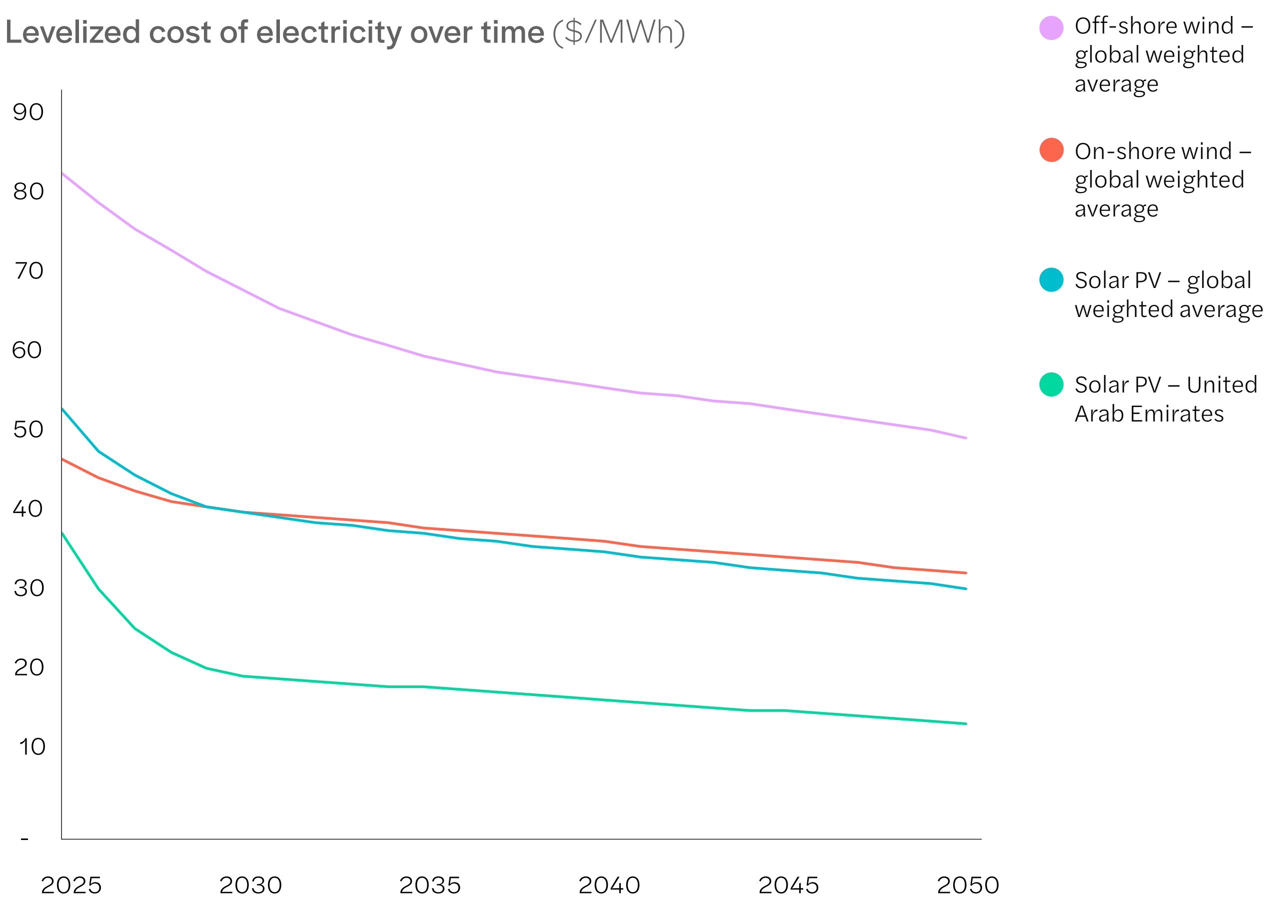
While this section has focused on grid-scale solar PV, deployment will be complemented with the deployment of CSP and wind. The opportunity for wind generation is less than solar PV, but is perhaps greater than featured in the 2017, United Arab Emirates Energy Strategy 2050. While this estimated a negligible contribution from wind, the 2015 International Renewable Energy Agency remap report[54] on the United Arab Emirates suggested that over 400 MW of wind could be installed. This may be materializing with plans[55] for an onshore wind farm on the Sir Bani Yas Island, which sits offshore on the west coast. CSP can also be coupled with thermal storage, allowing electricity generation to continue at night. Combined with wind power, this smooths the generation profile and will be critical to grid resilience. Increased deployment of affordable, clean power builds the foundation for the Emirates to develop and deploy a leading PtL industry.

Development of DAC/CCU technologies

The United Arab Emirates is one of the key players in developing carbon capture, usage and storage (CCUS) technology, with ADNOC already operating the world's first CCUS technology-integrated iron and steel production facility (Al Reyadah). This facility captures 0.8 $MtCO_2$/year and uses the carbon in EOR. ADNOC implemented this business model to maximize the benefits of capturing carbon dioxide and selecting a concentrated CO_2 source with good proximity to oil fields.[56] A similar approach can underpin the PtL industry's development, creating further opportunities to use the captured carbon dioxide. As a part of its decarbonization targets, ADNOC plans to increase its CO_2 capture capacity up to 5 $MtCO_2$/year by 2030 through CCUS integrated Shah and Habshan-Bab gas plants.[57]

Building upon the Emirates' ambitious industrial strategy (Operation 300bn) to develop the sector by increasing its contribution to GDP from AED 133 billion to AED 300 billion by 2031,[58] industrial emissions could be used for bridging the PtL production without substantial carbon capture related additional cost requirements. The United Arab Emirates has a large cement industry with 15 integrated plants and 31 million tonnes per year production capacity, much of which is in the Northern Emirate of Ra's al-Khaymah. Approximately 0.95 tonnes of CO_2 are produced for every tonne of cement, although process efficiencies may be able to reduce this. With a capture rate of 80%, up to 16 $MtCO_2$ would be available for use.[59] The Emirates' 5 million tonnes per year iron and steel production capacity, projected to grow to 6.7 million tonnes by 2030, could provide an additional 3.6 $MtCO_2$, with approximately 1.04 tonnes of CO_2 per tonne of production. However, 0.8 $MtCO_2$ is already captured and used for other applications, reducing the CO_2 available for SAF production. Consequently, most CO_2 available for SAF production will likely come from the cement industry. ICAO estimate that 142 kilowatt hours (kWh) of electricity and 1233 kWh of natural gas (or heat integration) are required for CO_2 capture and compression from cement facilities. It is estimated that this would give a cost per tonne of CO_2 captured in the Emirates of $60-120 per tonne of CO_2,[60] which will be reduced to $20-40 per tonne of CO_2 by 2050.

FIGURE 12 | **The cost of renewable electricity in the United Arab Emirates will remain lower than the global average**

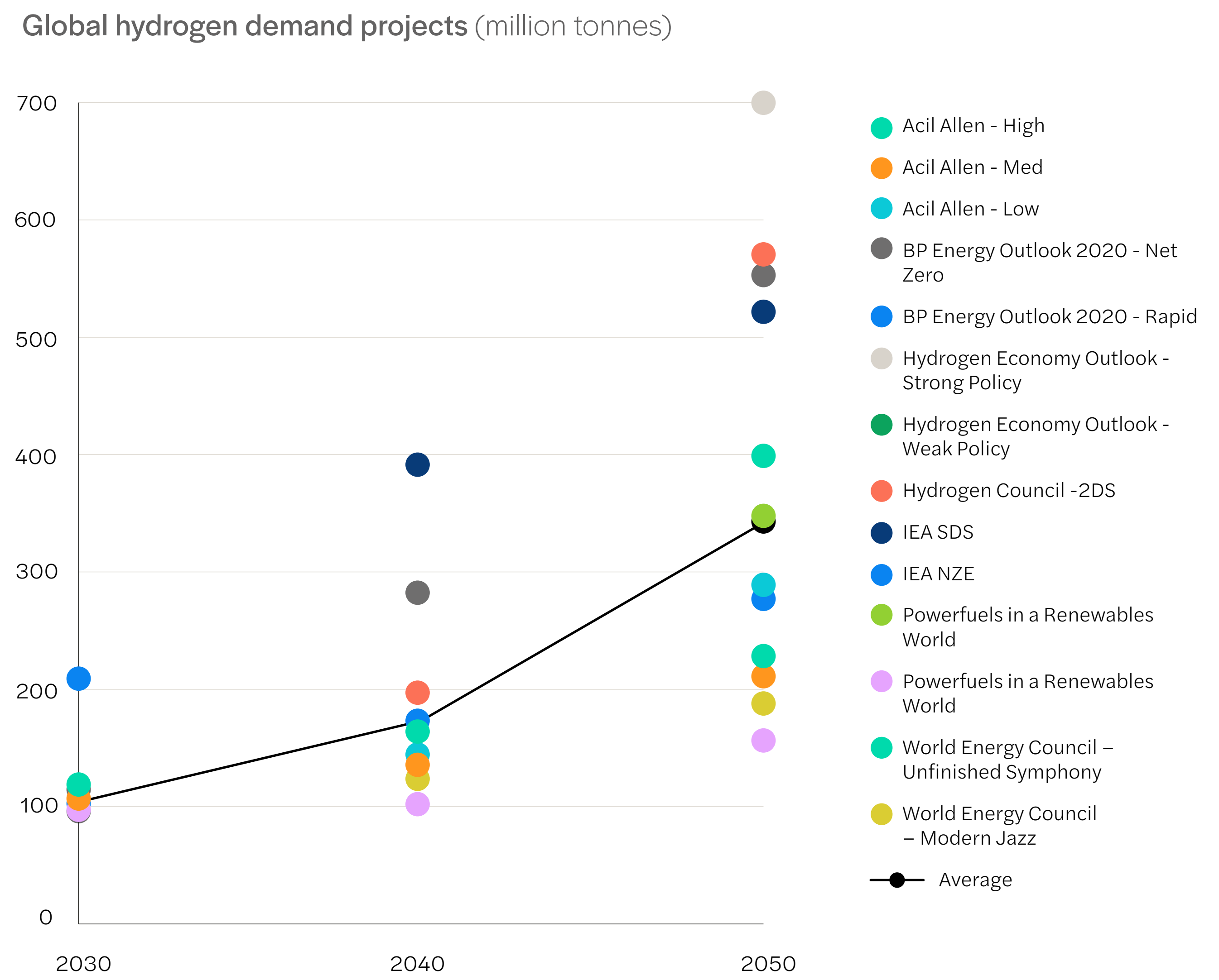


Source: https://www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019; https://atb.nrel.gov/; https://iea.blob.core.windows.net/assets/e57fd1ee-aac7-494d-a351-f2a4024909b4/GlobalHydrogenReview2021.pdf

LT DAC systems are likely to be more suitable for the United Arab Emirates as they are net water producers, while high-temperature systems consume water. LT DAC systems also have a lower energy requirement, which could be further reduced by coupling the systems with the excess heat released from FT reactors. Depending on the electrolyser technology used and the process configuration selected, it could be possible to energize the DAC system using only recycled heat within an integrated PtL plant. The carbon intensity of the sources used for energizing the DAC system can make a substantial difference in the carbon intensity of the SAF produced. If additional energy is required on top of the heat integration with the FT reactor, fossil sources to energize the DAC system should be avoided, and renewable energy or green hydrogen should be used. Currently, the largest operating LT DAC system has been built and operated by Climeworks and has a capacity of 4 kilotonnes per year (kt/year). The current electricity and heating requirements for the Climeworks' LT solid sorbent DAC system are reported as 200 kWh per tonne of CO_2 to 300 kWh per tonne of CO_2 and 1500 kWh per tonne of CO_2 to 2,000 kWh per tonne of CO_2, respectively. This is expected to reduce over the years and can be supplied through waste process energy.

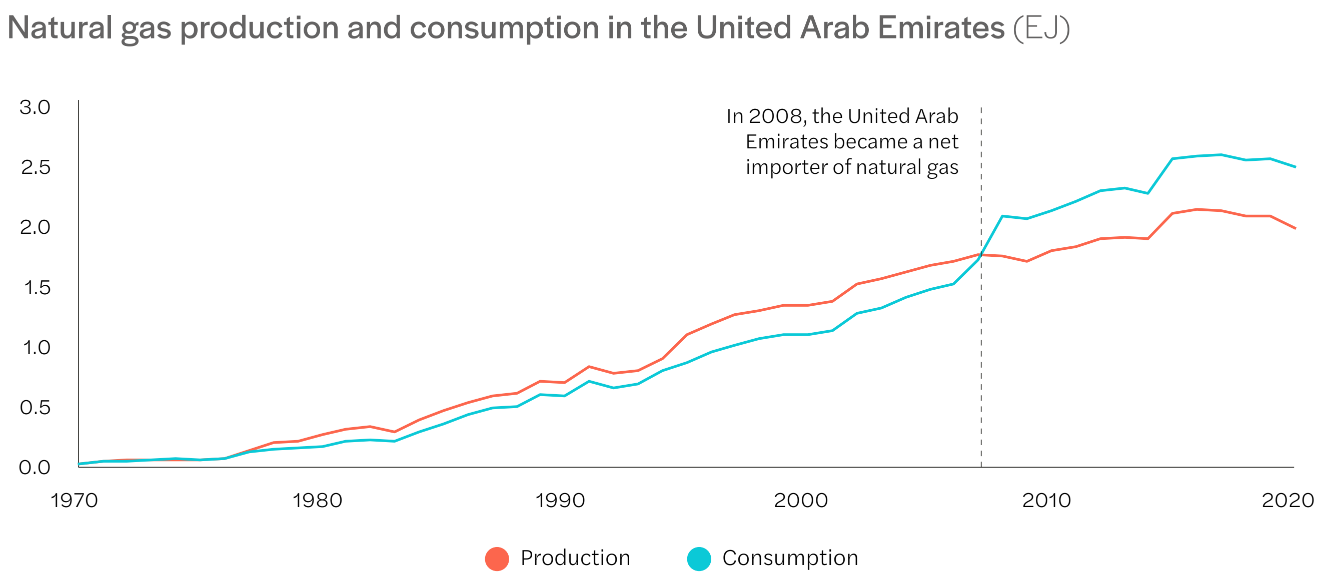
Point source capture systems would not require a substantial additional area for sitting as they are expected to be integrated into existing factories. DAC systems will require free area for sitting, although this is relatively limited. The area required is driven by the spacing between DAC units and the chemical storage and regeneration unit warehouses. Area demand for the LT and HT DAC systems are reported as 0.4 km^2 per $MtCO_2$, and 1.5 km^2 per $MtCO_2$, respectively, with reductions as technology improves.[61] Current LT DAC facilities require larger areas (up to 1.4 km^2 per $MtCO_2$), as these are standalone carbon capture and storage facilities with built-in control technology. The area needed for the PtL integrated DAC plants is expected to be substantially lower.[62]

FIGURE 13 | **The United Arab Emirates aims to capture up to 25% of the global hydrogen market by 2030**



Source: World Energy Council, Hydrogen Demand and Cost Dynamics, 2021, https://www.worldenergy.org/assets/downloads/Working_Paper_-_Hydrogen_Demand_And_Cost_Dynamics_-_September_2021.pdf?v=1646391021.

FIGURE 14 | **The United Arab Emirates became a net importer of natural gas in 2008**



Source: BP World Energy Outlook: 2022

With over $500 billion of investment announced globally in the clean hydrogen market by 2021, the cost of electrolysers is expected to decrease rapidly.

Development of hydrogen technologies

The United Arab Emirates' announced target to capture 25% of the global low-carbon hydrogen market by 2030 would equate to 19-53 Mt of hydrogen production, based on recognized demand projections.[63,64] The Emirates has made good progress towards this target. ADNOC has already produced initial volumes of blue ammonia, and announcements for a $1 billion investment in a 200,000 tonnes per year green hydrogen plant in the KIZAD industrial area,[65] and plans for a collaboration with BP for further hydrogen projects.[66,67]

Clean hydrogen can be produced from renewable electricity or natural gas with carbon capture. Using natural gas is a relatively mature technology, and while the conversion process is affordable, the cost of hydrogen is heavily dependent on the cost of the natural gas used. The record natural gas prices in 2022 significantly diminish the affordability of this production approach. In addition, it is difficult to capture all the CO_2 produced fully, and fugitive methane emissions during the transport of the natural gas mean that this pathway is not zero-carbon. By comparison, production via electrolysis from renewable electricity is zero-carbon.[68] Today, this approach is more expensive, but with over $500 billion of investment announced globally in the clean hydrogen market by 2021, the cost of electrolysers is expected to decrease rapidly. The United Arab Emirates is in a particularly advantageous position to take advantage of the cost reduction due to the possibility of low-cost renewable energy, as outlined in the previous section.

Due to the greater technical maturity of blue hydrogen, this approach is expected to drive the initial volumes.[69] However, consumption of natural gas in the United Arab Emirates has outstripped production (by 2008, the country became a net importer of natural gas). This will incentivize a rapid transition to green hydrogen, which can be produced domestically.

PEM technology will likely make up most of the electrolyser capacity, and almost all announced hydrogen projects propose using this technology. The cost will rapidly decrease, and the efficiency of the PEM electrolysers is expected to increase from 65% to 75% by 2050, which would reduce its energy requirements. Assuming an LCOE suitable for the United Arab Emirates, adjusted to include some energy storage via CSP and thermal (or grid-scale batteries as they become cost-competitive) that will increase the use of the electrolysers, the average cost of green hydrogen in the Emirates is expected to be just over $2,000 per tonne by 2030. This is well below the global range for the levelized cost of green hydrogen.

Several developing technologies may further accelerate the reduction in hydrogen production costs. Better energy storage may increase the electrolyser utilisation, reducing the cost allocated per unit of hydrogen. Technologies for high-temperature electrolysis, such as SOEC, are developing and may allow a higher energy conversion efficiency. This would be particularly advantageous if the electrolysers use waste heat that nuclear facilities and FT reactors produce.

The United Arab Emirates' hydrogen strategy is built on domestic consumption and developing export opportunities. Many countries, particularly within the European Union and South Korea, are looking to scale hydrogen consumption but recognize that the domestic production opportunities may not be as suitable as in other countries – such as the United Arab Emirates. An excellent example is the EU's hydrogen strategy,[70] which explicitly looks for 40 GW of domestic production and a further 40 GW of foreign production to be imported. The United Arab Emirates is well-positioned to take advantage of this opportunity.

Pure hydrogen is difficult to transport. It has exceptionally low volumetric density, meaning that much larger containers are needed to transport the same volume of energy compared to natural gas or oil. A 1-litre bottle of diesel will contain about 39 megajoules (MJ), while a 1-litre bottle of hydrogen would contain just 4.5 MJ (pressurized to 700 bar) or 8.5 MJ (if liquified). Some energy is lost during the pressurization or liquefaction process, and the liquid hydrogen must be stored at -253°C. Further, hydrogen can react with the material of the container in a process called embrittlement, damaging it over time. Combined, these mean that it would be preferable for the United Arab Emirates to export hydrogen in a form other than its pure form.

PtL kerosene is the ideal approach for the United Arab Emirates to take advantage of any export opportunities. So far, the Emirates has focused on the export of ammonia (a compound of three hydrogen atoms and a nitrogen atom), which has a slightly higher volumetric density than hydrogen (1 litre contains 12.7 MJ) and can be stored at a comparatively mild temperature of -33.3 °C. However, ammonia is a relatively low-value chemical mostly used for fertilizer. PtL kerosene is significantly higher in value, and the EU ReFuel policy[71] proposal may create a specific sub-mandate for its use, creating a clear market opportunity. It is also easier to transport; with a volumetric density similar to diesel, it can be transported at room temperature and use the existing stock of shipping tankers and pipelines.

2.3 The opportunities presented by the development of PtL

PtL can diversify sources for jet fuel in a low-carbon manner while creating new job opportunities due to investment requirements across its value chain.

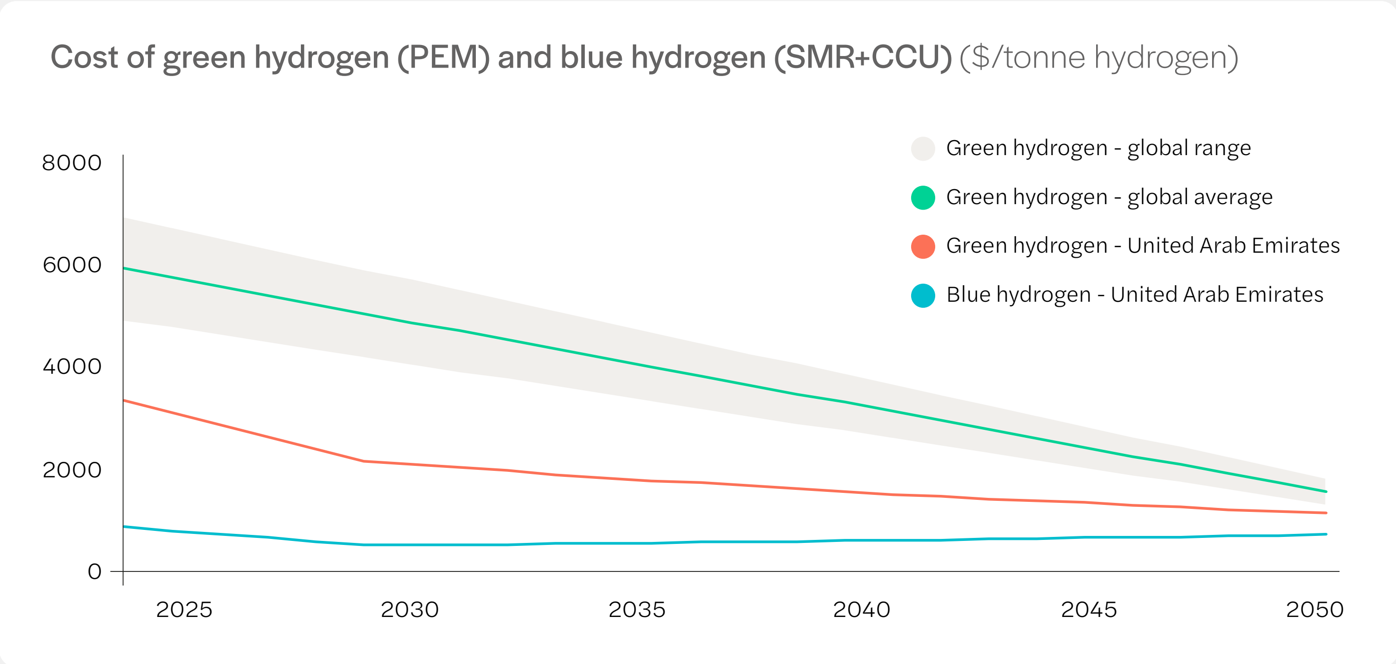
Growth in economic diversification and employment

Diversification of economic activities is key to sustainable economic growth, and through energy diversification, the United Arab Emirates can unlock the potential of its non-oil-dependent sectors.[72] Before the 1950s, the Emirates' economy was mainly based on date palm cultivation, fishing, pearling and seafaring.[73] After the discovery of oil, the United Arab Emirates developed and modernized rapidly, becoming one of the wealthiest countries in the world with over $42,000 pre-COVID GDP per capita.[74] The country's economy is dependent on oil and gas, with the industry representing a third of GDP. Over the past decade, the United Arab Emirates has been going through an economic diversification program to increase the share of other energy sources and industries within the economy. That vision aims to ensure the prosperity of current and future generations of the Emirates through several key initiatives, including a non-oil-based GDP growth and increased research and development expenditure.[75] As a result of ongoing diversification efforts, the share of oil and gas exports in total halved to 16% in 2019. Based on the IEA's assessment,[76] the United Arab Emirates has achieved the highest economic diversification compared to other oil producers in the region; yet still has room to improve its energy diversification performance,[77] and PtL can support the delivery of that target.

The aviation industry is expected to grow rapidly over the next three decades in the Emirates, increasing the demand for jet fuel. This is a significant growth opportunity but given the rapid pace of increase in aviation activity compared to most other regions in the world, fossil sources dependent on jet fuel consumption could put pressure on the United Arab Emirates' decarbonization targets. PtL can diversify sources for jet fuel in a low-carbon manner while creating new job opportunities due to investment requirements across its value chain.

The EU's ReFuel SAF mandate proposal is expected to create considerable demand for the PtL in the EU starting from 2030, and the United Arab Emirates can become a key supplier by acting as a PtL supply hub. In line with the EU strategy, Germany also announced its plans to produce 0.2 Mt of PtL by 2030,[78] but the announced PtL capacities in the EU remain below the level of ambition, with over 14.4 Mt of PtL SAF required to supply the 28% neat PtL discussed in the ReFuel proposal. PtL is also easier to transport than hydrogen, making it ideal as a vector to export hydrogen production. Export opportunities presented by PtL and its job creation potential would support the United Arab Emirates' diverse and low-carbon economic growth.

FIGURE 15 **The cost of hydrogen in the United Arab Emirates is estimated to decrease by over 60% by 2050**



Source: ICF analysis

> A 50% SAF blend has been shown to reduce the emissions of carbon monoxide (CO), sulphur oxides (SOx), and particulate matter (PM) by up to 11%, 37% and 65%, respectively.

The market for by-products from PtL production will create further opportunities for diversification. As a result of the production process, diesel/gasoline and naphtha are produced alongside jet fuel. Share of the outputs varies with changing process configurations, but jet fuel output ranges between 55% to 80%. For an average of 60% jet fuel output, 20% diesel and 20% naphtha outputs are expected. Low-carbon diesel can be used in trucks and ships, reducing emissions while adding value to PtL production. Fuel suppliers can use it to transfer PtL, further increasing the life cycle assessment-based (LCA) emissions reductions of PtL. Low-carbon naphtha is also a valuable by-product for reducing the petrochemicals industry's oil consumption. The Emirates' well-established petrochemicals industry could use this low-carbon naphtha in their existing processes. The PtL route considered in this study aims to maximize jet fuel output. With technological advancements, the share of diesel and naphtha as by-products is expected to decrease to 10% each, meaning there would not be enough products for export opportunities. Their potential to decrease oil consumption while reducing transport and petrochemicals production emissions contribute to the Emirates' low-carbon non-oil-dependent growth trajectory.

Low-carbon transition

The United Arab Emirates has 10% of the world's oil supply and the world's fifth largest natural gas reserves.[79] With current consumption levels, these reserves are expected to last for at least 100 more years,[80] but the nation is proactively seeking to decouple its economic activities from fossil-based resources. Available local knowledge and infrastructure could be transformed into emission reductions through PtL deployment, which can contribute to the Emirates' ambitious low-carbon transition targets by reducing aviation industry emissions and attracting investments for developing low-carbon hydrogen and CO_2 industries. PtL's potential for high emission reduction and unlimited feedstock availability make it a very attractive tool for decarbonization. Yet, selecting suitable low-carbon feedstocks is crucial in ensuring significant emission reductions.

Using fossil-based resources to produce hydrogen and CO_2 could increase the carbon intensity of the fuel. According to EU regulations, synthetic fuels should achieve at least 70% LCA-based emission reduction compared to conventional fuel and should be produced from low-carbon hydrogen.[81] Low-carbon hydrogen refers to hydrogen derived from non-renewable sources, achieving at least 70% emission reduction. This means that, in addition to green hydrogen, blue hydrogen produced through SMR with a 90% capture rate could also be used for PtL production as a transition solution while increasing the deployment rate of green hydrogen. Similar to the hydrogen transition scenario from fossil to fully green resources, a transition from point source carbon capture to DAC can be an ideal route for carbon supply in PtL production.

SAF can help reduce emissions of other non-CO_2 pollutants, particularly as airport activity increases.[82] A 50% SAF blend has been shown to reduce the emissions of carbon monoxide (CO), sulphur oxides (SO_x), and particulate matter (PM) by up to 11%, 37% and 65%, respectively, compared to conventional jet fuel operations. It is expected that SAF produced through the PtL pathway could achieve these same benefits.

3 Evaluating a PtL roadmap for the United Arab Emirates

Nine scenarios for PtL deployment have been produced and assessed for feasibility, and economic and environmental considerations.

To understand the potential routes the United Arab Emirates could follow on PtL deployment, three scenarios have been developed for PtL demand and three for low-carbon technology deployment, to produce nine different assessments of PtL deployment. The demand scenarios explore the role of PtL in the United Arab Emirates' decarbonization journey, while the technology deployment scenarios assess how these demand scenarios can be achieved through different technology combinations. Each scenario has been evaluated for feasibility, and the economic and environmental benefits assessed for select case studies.

PtL jet fuel demand scenarios

The need to fully decarbonize aviation is clear, but the pathways will depend on technological, economic and social considerations. This assessment considers three different levels of ambition for the deployment of PtL SAF, each representing a different split between PtL SAF and other mechanisms to achieve net-zero aviation. For example, the low PtL scenario represents a minimal use of this technology in the United Arab Emirates, with flights to and from the country reaching net zero through engineered carbon removals, demand reduction to reduce the fuel consumption, and investments and use of SAF production in other countries endowed with greater availability of biological feedstocks. By comparison, the high scenario represents a focused deployment of PtL capacity, with investment flowing to the Emirates and no demand reduction to achieve net-zero.

These scenarios have been aligned to the IEA Net Zero by 2050 (NZE Scenario) projections for low-carbon fuel requirements, considering the United Arab Emirates' jet fuel demand projection and lack of biogenic SAF availability.

1. **High PtL jet fuel demand ("H"):** This represents a focused effort to develop and deploy PtL SAF capacity in the United Arab Emirates. It is sized using the IEA's projection that 78% of jet fuel should be sustainable by 2050. It assumes that 5% of this volume can be met through other (biogenic) SAF pathways, requiring 73% of jet fuel, equal to 11.2 Mt, to be produced through PtL technologies. The deployment trajectory assumes 4.4% of fuel is PtL SAF in 2030.

2. **Medium PtL jet fuel demand ("M"):** This represents a scenario with PtL in line with the global ambition for PtL fuels in the IEA NZE scenario, which is also similar to the proposed EU ReFuel 2050 targets for PtL. This scenario, therefore, represents the Emirates adopting no leadership position in the industry. Many other countries have significantly greater access to biological feedstocks that can be used to complement PtL SAF production. This scenario represents the United Arab Emirates airlines and stakeholders investing and supporting SAF production in these other nations to compensate for the deficit. While the deployment cost may be lower, many jobs and economic value would be created in countries outside the United Arab Emirates. Other mechanisms, such as out-of-sector-engineered carbon removals and demand reduction may be necessary to achieve net-zero. In this scenario, the PtL blend ratio starts at 2% by 2030 and reaches 33% by 2050.

3. **Low PtL jet fuel demand ("L"):** This is a low ambition scenario, evaluating the outlook with a minimal deployment of PtL production capacity. The PtL blend ratio starts at 0.5% by 2030 and reaches only 15% by 2050. This represents a significant adoption of other mechanisms to achieve net-zero aviation, including importing SAF produced in other countries and engineered removals. To sufficiently reduce emissions, there is a high probability that this scenario would require a reduction in aviation activity and the corresponding reduction in employment, tourism and cargo revenues.

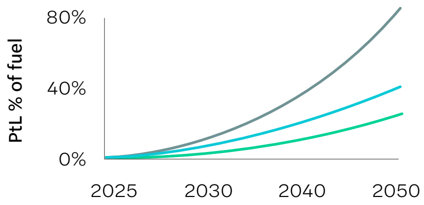
Objective

Evaluate the feasibility, economic and environmental factors for different PtL deployment pathways in the Emirates.

Method

Scenario based analysis of different levels of ambition and technology.

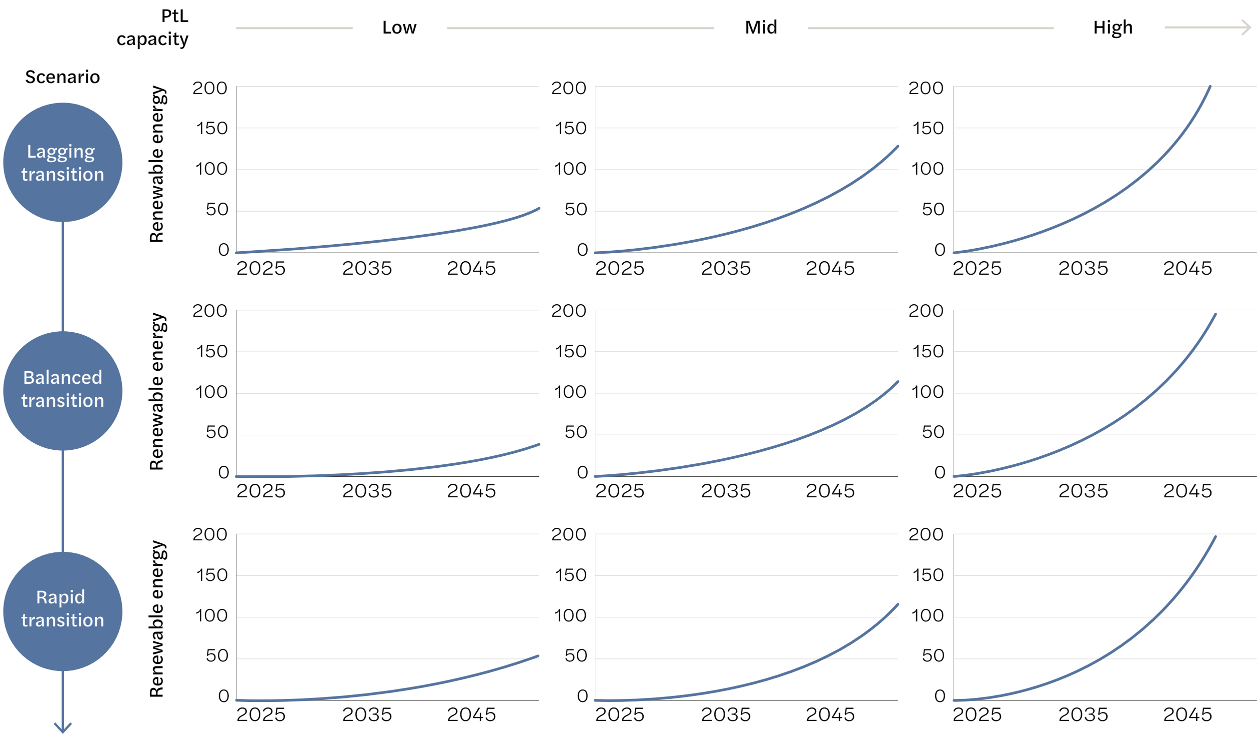
1 Ambition



2 Technology

3 Evaluation results

– Energy required
– Jobs created
– Investment required
– Carbon abated

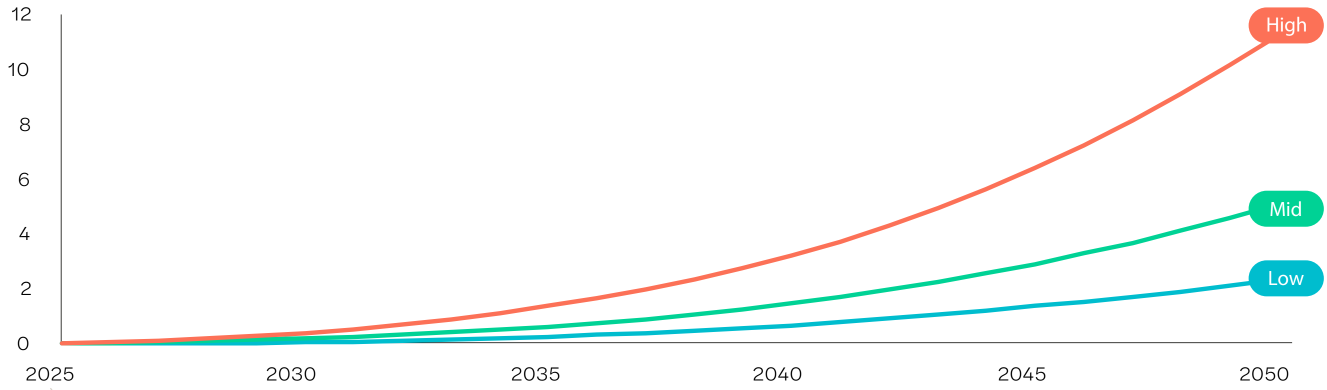


4 Detailed evaluation of case study scenarios

Source: ICF analysis

FIGURE 17 | **The scenarios range from 2-11 Mt of SAF by 2050, equivalent to 15-73% of jet use**

PtL jet fuel production (Mt/year)



	2025	2030	2035	2040	2045	2050
High	0.00	0.39	1.35	3.19	6.41	11.24
Mid	0.00	0.18	0.61	1.44	2.90	5.08
Low	0.00	0.04	0.24	0.66	1.35	2.31

Source: ICF analysis

These sections have all been designed with a focus on the domestic consumption of PtL SAF. They have been sized by applying the percentages calculated by the IEA to the jet fuel demand for flights refuelling in the United Arab Emirates. The opportunities to export PtL SAF are in addition to this level of demand and could be represented with qualitative alterations to the scenario definitions. For example, the high scenario could include some level of exported PtL SAF, with the deficit in United Arab Emirates SAF compensated through any other mechanisms discussed.

All SAF volumes are stated as neat SAF. SAF is currently limited to a 50% blend with conventional fuels, depending on the production pathway. It will therefore be essential to enable higher blend limits to achieve the higher volumes. There are multiple ongoing initiatives to achieve this, with Boeing, Airbus and other manufacturers working towards aircraft that can operate on 100% SAF.[83] A number of producers are also working to adjust SAF composition to enable higher blends in existing aircraft without retrofits.

Low-carbon technology deployment scenarios

This report has designed three scenarios focusing on different low-carbon technology deployment rates, particularly considering the technologies used to produce hydrogen and capture carbon. Hydrogen supply starts with blue hydrogen and transitions to hydrogen from electrolysis. Similarly, the CO_2 supply starts with point source carbon capture and transitions into DAC systems. The PtL produced in all scenarios meets at least a 70% emission reduction compared to fossil-based jet fuel by 2030.

4. **Lagging transition ("LT"):** This scenario focuses on starting PtL production with point source carbon capture and blue hydrogen, with a gradually increasing share of DAC and green hydrogen, as well as limited nuclear energy allocation for the PtL production (sized to equal one reactor at the Barakah plant: 1.4 GW), which is likely to be helpful in complementing the intermittent generation sources. The use of blue hydrogen will be phased out by 2050, while the share of DAC will reach 40% by the same year.

5. **Balanced transition ("BT"):** This scenario considers a more rapid deployment of green hydrogen and DAC, with a small allocation of nuclear energy. All the hydrogen will be supplied from wind, solar and nuclear energy by 2035, while the share of DAC will reach 60% by 2050.

6. **Rapid transition ("RT"):** This scenario focuses on the aggressive deployment of DAC and green hydrogen technologies. Blue hydrogen is used for the initial facilities only and would be phased out by 2030, while DAC would be proactively deployed, providing 50% of the carbon supply by 2030. This scenario also considers a greater use of nuclear energy for PtL production than other scenarios, reaching 1.4 GW by 2040 and 2.8 GW by 2050.

Many constituent technologies can be used across the PtL value chain. This assessment has made the following assumptions to provide an illustrative set of results, recognizing that deployment is likely to be far more diverse:

Blue hydrogen is produced through the steam methane reforming of natural gas with an integrated carbon capture storage system, with a 90% capture rate.

PEM electrolysers are primarily used for electrolysis, with the efficiency increasing to 74% by 2050. This may be achieved through refinements to the PEM design and a share of SOAC electrolysers as the technology matures.

Carbon capture facilities use post-combustion point source CO_2 capture (90% capture rate) and LT DAC system.

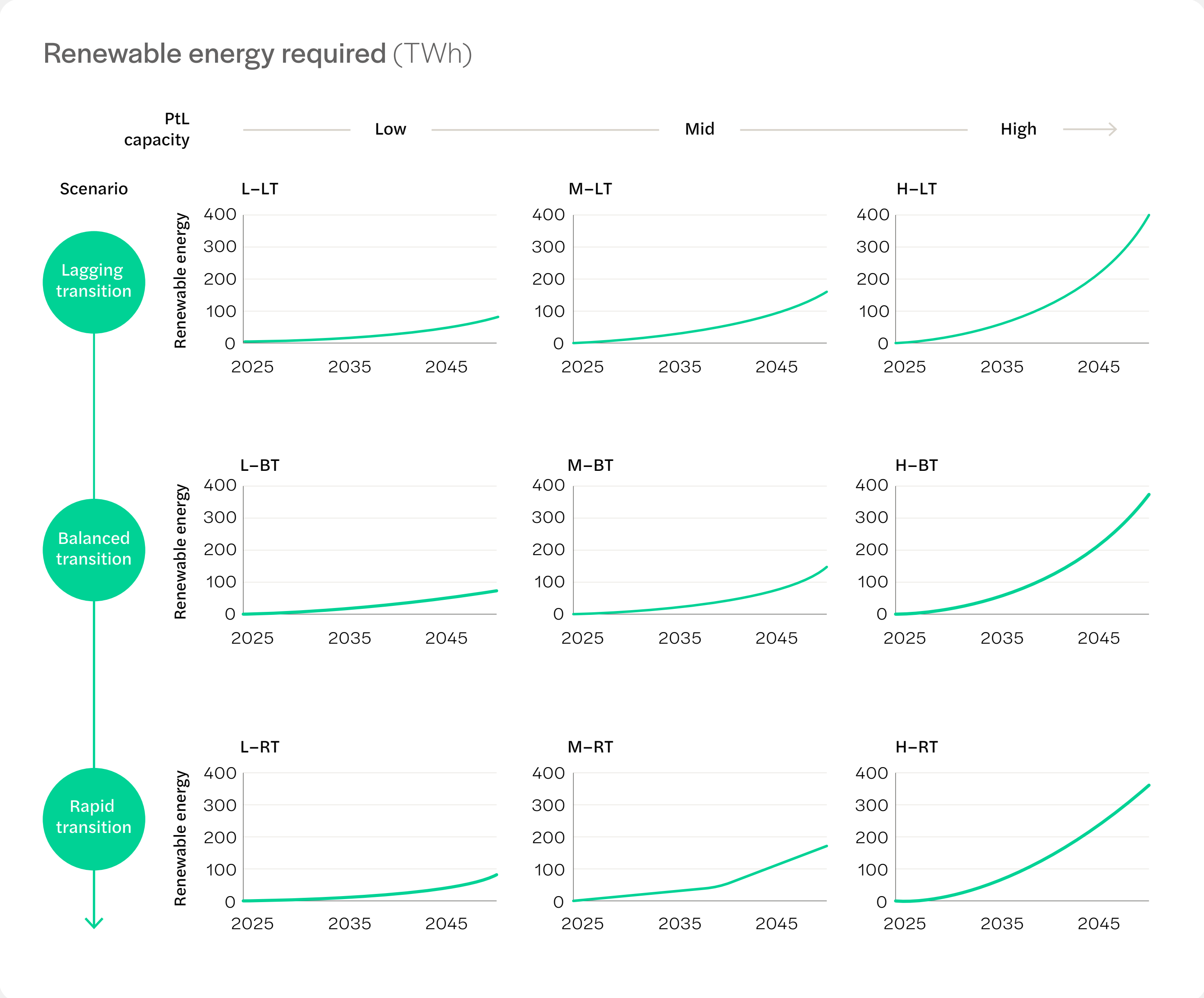
Integrated scenarios

The demand and technology deployment scenarios are integrated to provide a comprehensive understanding of the United Arab Emirates' alternative routes to PtL deployment. For each scenario, various considerations are analysed, such as renewable energy requirements, carbon emission reductions, costs and water requirements, etc.

Among many other opportunities and strengths assessed in earlier sections, as well as the challenges in the United Arab Emirates, arguably the most important reason for the country to produce PtL is its cheap renewable energy potential. As its name also implies, PtL would mean converting power (generated through the sun) into liquid hydrocarbons. Assessing the renewable energy requirements for each deployment and production ambition scenario, therefore, was a fundamental step in presenting the roadmap for the United Arab Emirates.

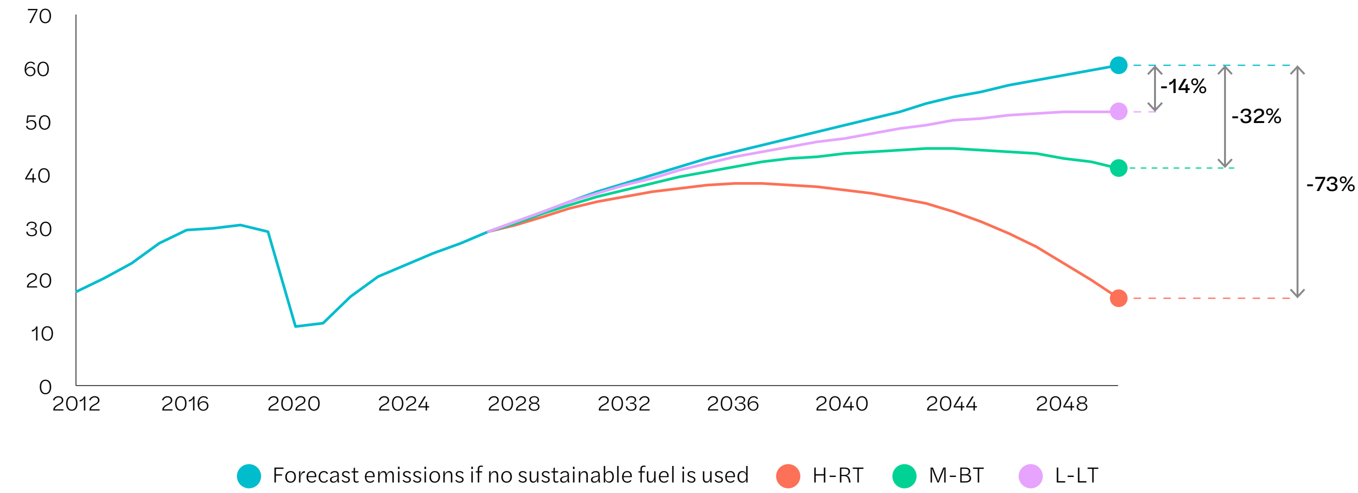
These scenarios have been assessed, with each evaluated for feasibility, cost and carbon abated. The key driver of practicality is the volume of renewable energy required, which has been illustrated for each scenario in the grid below.

FIGURE 18 **Access to large quantities of renewable energy is key for pragmatic PtL deployment**



Source: ICF analysis

FIGURE 19 | **Deployment of PtL will drive to a 14-73% reduction in 2050 aviation emissions**



Source: ICF analysis

To evaluate these in more detail, three scenarios were selected to represent alternative routes for PtL deployment in the United Arab Emirates from different perspectives with a broad coverage:

1. **Low demand - lagging transition (L-LT):** This route explores the case that the PtL demand in the United Arab Emirates remains very low and deployment of low-carbon technologies is slower than expected. Combined with the lack of biogenic availability, this route will require other measures to decarbonize the country's aviation industry further.

2. **Medium demand - balanced transition (M-BT):** This route aims to match the global ambitions for PtL production and low-carbon technology deployment. It reflects the dynamics of the global developments and presents a more conservative transition.

3. **High demand - rapid transition (H-RT):** This route builds upon ambitious low-carbon transition targets, with the United Arab Emirates becoming a global leader in the PtL market. Rapid technology deployment delivers a higher amount of PtL sooner than other routes, resulting in a substantial decrease in cumulative emissions.

These scenarios can rapidly drive down aviation emissions in the United Arab Emirates, with the H-RT scenario reducing 2050 emissions by 73%. Combined with the potential for some biogenic SAF and additional decarbonization measures, this is expected to be sufficient to achieve net-zero aviation. The M-BT case would need to be complemented with extensive imports of SAF from other nations. The L-LT scenario would likely require some reduction in aviation activity to achieve net-zero.

The increased uptake of PtL SAF would deliver substantial cumulative emissions avoided over the decades between the present and 2050. The high case would avoid cumulative emissions of 338 million tonnes by 2050, equal to nearly 140% of the annual emissions from the consumption of fossil fuels across the entire United Arab Emirates economy.[84] Each facility would also continue to operate for 20-30 years, allowing a continued reduction in emissions after the 2050 milestone.

The deployment of PtL SAF represents a rapid energy transition, effectively substituting energy from fossil kerosene with energy from electrical renewables. The deployment must therefore be considered through a holistic evaluation of the fossil and renewable energy required for the grid, the deployment of renewables specifically for PtL and the decline in energy required for fossil kerosene. This dynamic has been illustrated for the selected scenarios in Figure 20.

This shows the context and magnitude of the required transition. The total energy demand for the H-RT scenario is noticeably greater than the L-LT scenario due to the energy lost when converting renewable energy into a liquid hydrocarbon. The analysis excludes the co-products from PtL SAF production, including renewable diesel and renewable naphtha. These support the transition of the road and chemicals industries, respectively, with a similar substitution to that shown in these graphs.

“ Rapid technology deployment delivers a higher amount of PtL sooner than other routes, resulting in a substantial decrease in cumulative emissions.

FIGURE 20 Deploying PtL at scale represents a rapid transition from fossil energy to renewables

Historical and forecast energy required for the grid, PtL and jet fossil fuels (TWh)

Source: ICF analysis

3.1 Are these scenarios feasible?

Decarbonizing aviation represents a paradigm shift in the energy source used to power aircraft. Every approach faces challenges that need to be solved, but the emerging solar PV, wind, hydrogen, CCS, SAF and other industries have already yielded meaningful successes. There are still constraints, and this section evaluates the feasibility of the three selected PtL deployment scenarios along three dimensions: economic, deployment of renewables and water scarcity while answering the following questions:

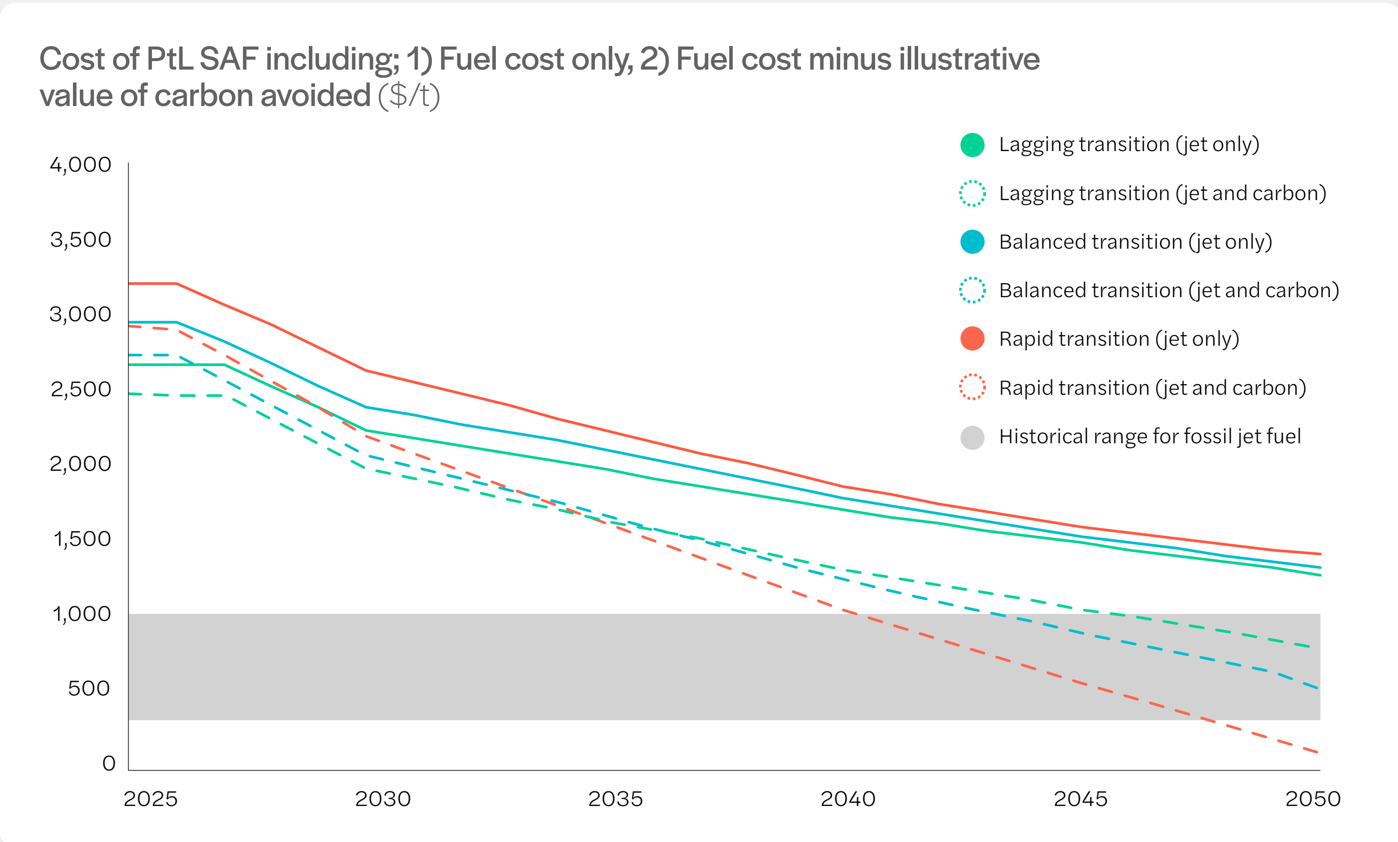
1. Are these scenarios economically beneficial?
2. What level of ambition is practical?
3. What is the impact on water scarcity in the United Arab Emirates?

1. Are these scenarios economically beneficial?

Sustainable fuels are complex to produce and require emerging technologies, resulting in costs higher than conventional fuels. These costs will reduce as technologies develop and economies of scale are achieved, but it is crucial to consider the cost of deployment against the benefits created.

A simplistic way to evaluate this is to consider the cost of production against the cost of conventional fossil fuels. As with all sustainable fuel production, PtL SAF is more expensive than conventional fuels, particularly in the early years when building pilot plants that produce small volumes. It is estimated that for the first Emirates demonstration facilities in 2025, the cost would be $2,700-3,200 per tonne of PtL SAF, depending on the technologies used (green hydrogen and DAC cost more than blue hydrogen and PSC but achieve a higher reduction in carbon). As the underlying technologies become rapidly more affordable, the cost would reduce and, by 2050, PtL SAF could be produced in the United Arab Emirates for $1,300-1,425 per tonne.

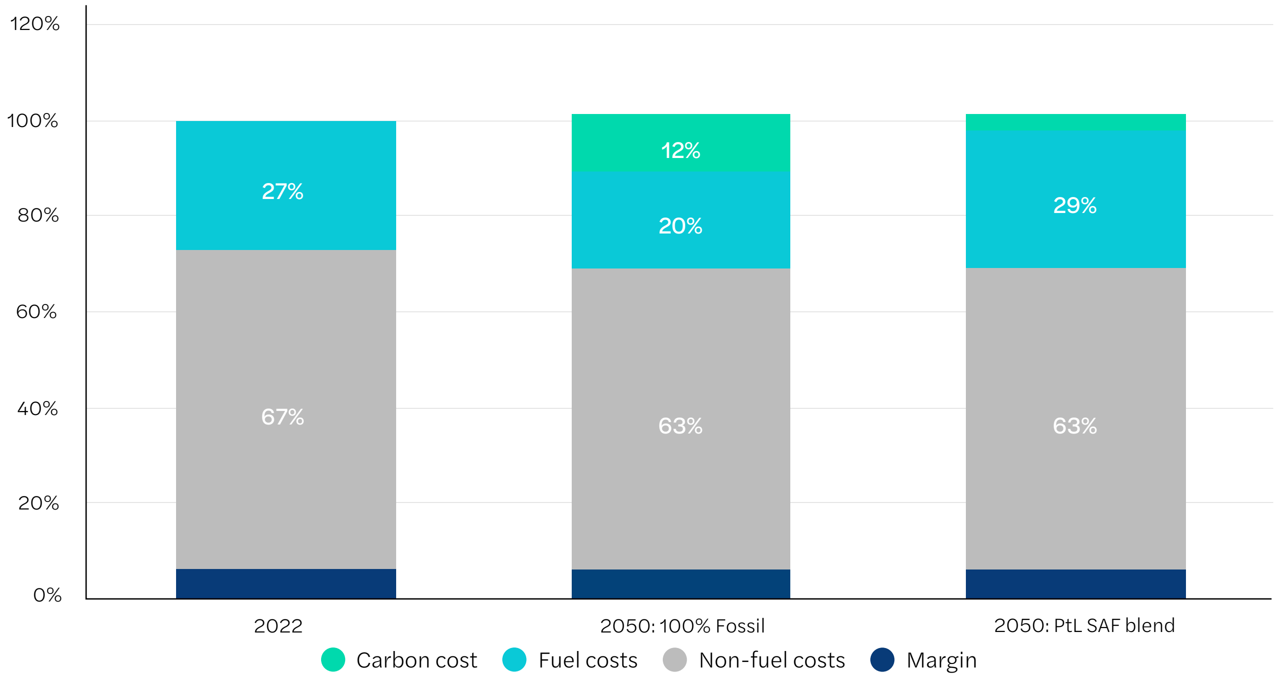
FIGURE 21 **The cost of PtL SAF will rapidly decrease, and should be supported by a recognition of the value of the carbon avoided**



Source: ICF analysis

FIGURE 22 | **Continued efficiencies will mitigate the cost of sustainable fuel use**

Impact on ticket costs, comparing 2050 costs with 100% fossil fuels and a PtL blend against 2022 costs



Source: ICF analysis

Even by 2050, this cost will be greater than the historical cost of fossil fuels. Conventional jet fuel has been volatile over the past decade, with the cost per tonne between $500-920 for half the time and between $340-1,035 for 90% of the time. While the outlook for fossil fuel price is highly uncertain, with demand and supply dynamics shifting as the global society looks to decarbonize, the cost for PtL will likely remain above this historical range for fossil fuels.

The critical rationale for producing SAF is recognizing the value of the carbon avoided and the associated employment and economic value. Every tonne of fossil jet fuel emits 3.9 tCO_2 on a well-to-wake basis, and the IEA estimates that an appropriate cost per tonne of CO_2 to achieve net-zero is $140/$tCO_2$ in 2030, increasing to $250/$tCO_2$ by 2050.[85] This represents an additional cost of $548-979 per tonne of fossil jet fuel consumed in 2030 and 2050, respectively. Including this cost and the expected reduction achieved by PtL SAF closes the gap between fossil jet fuel and PtL SAF. By 2050, the combined value of the physical fuel and carbon reduction drives PtL SAF to be cheaper than fossil jet fuel in most cases.

Deploying PtL SAF at scale would have a limited impact on ticket prices. Both Emirates and Etihad record fuel costs close to 30% of operating costs, which will further reduce with technology improvements. Fuel consumption per flight will decrease by nearly 27% by 2050[86] and non-operating costs by 5%. If the price of carbon is recognized at the level proposed by the IEA NZE scenario ($250/$tCO_2e$ in 2050), then the additional cost of carbon almost exactly offsets efficiency improvements, and a ticket would remain a similar price in 2050 compared to 2022. The adoption of SAF would reduce the ticket cost due to the significant decrease in carbon cost compared to the slight increase in fuel cost.

A one-way flight with Emirates or Etihad from the United Arab Emirates to Heathrow costs around 2,000 dirham, assuming economy class and advance booking.[87] Fuel and non-fuel efficiencies are forecast to reduce this cost to around 1,770 dirham by 2050. If no SAF is used, a flight in 2050 would emit around 260kg of CO_2 per passenger, equivalent to 240 dirham and resulting in fairly static ticket costs. Assuming the high case with 73% neat SAF, the fuel costs would increase but would be offset by reduced carbon costs, resulting in net ticket costs of 2,020 dirham – a very small increase compared to today.

FIGURE 23 | **Including an appropriate cost of carbon drives PtL SAF cost below fossil jet fuel**

$ per tonne CO_2e	2025	2030	2035	2040	2045	2050
0	3,210	2,640	2,250	1,880	1,610	1,420
50	3,080	2,490	2,070	1,680	1,380	1,160
100	2,950	2,330	1,890	1,480	1,160	900
150	2,820	2,180	1,710	1,280	930	640
200	2,690	2,020	1,530	1,080	700	380
250	2,560	1,870	1,350	880	470	120
300	2,430	1,710	1,170	680	240	−140
350	2,300	1,560	990	480	10	−400
400	2,170	1,400	810	270	−210	−660

Source: ICF analysis

The value of decarbonizing aviation is likely to be significantly greater than the IEA estimates, given the high economic value of aviation, difficulties in abating the sector, additional non-CO_2 environmental benefits and the economic growth stimulated by the development of the industry. Air Transport Action Group (ATAG) estimates that in 2019, aviation enabled $3.5 trillion in global GDP and emitted 915 million tonnes of CO_2 in the same year, suggesting an economic benefit of $3,800 per tonne of carbon.

Analysis in Figure 23 shows the impact that different levels of carbon value would have on the affordability of PtL SAF production, assuming the H-RT scenario. The cells shaded in green represent scenarios where the net cost of PtL is lower than the typical cost of fossil fuels, and yellow, when cheaper than the higher range of historical fossil fuel prices.

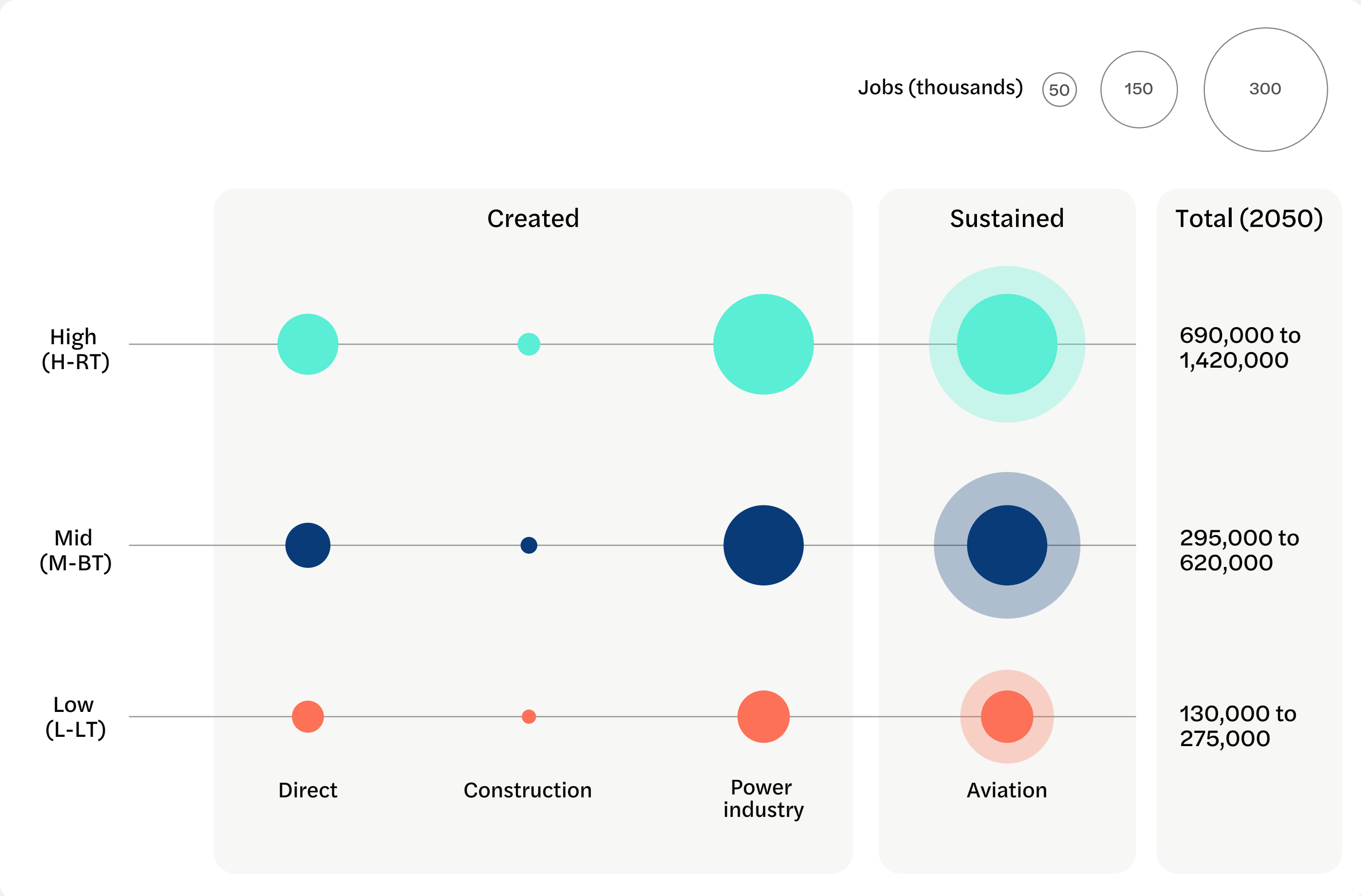
This analysis shows that the value of PtL is meaningfully greater than the cost of deployment, particularly in later years as the cost diminishes. Critically, the cost reduction is driven by the assumed deployment, so additional support is necessary to ensure the industry develops in the immediate years.

The development of a PtL SAF industry in the United Arab Emirates would create and sustain considerable employment, creating essential opportunities for the demographic wave of Emiratis under 25 years old, who represent over a third of the population and are increasingly looking for work.[88] The industry would create well-paid jobs to directly manage and operate the facilities, with further employment in design and construction. Expanding the renewable energy industry would create further employment opportunities, and together, these would result in an estimated 60,000 to 320,000 new jobs every year.

Decarbonization would also allow the aviation industry to continue operating in a carbon-constrained society. The rapid deployment of PtL SAF in the United Arab Emirates (H-RT) would reduce aviation emissions by 73% in 2050. Given the expected growth in the nation's aviation industry,[89] this would be equivalent to 300,000 direct jobs and a further 1,050,000 jobs across the aviation value chain. In total, this suggests that the development of a SAF PtL industry could create and sustain as many as 1,420,000 jobs, equivalent to almost a tenth of the current population of the United Arab Emirates. Detail to support these calculations has been given in the appendix.

“ Expanding the renewable energy industry would create further employment opportunities, and together, these would result in an estimated 60,000 to 320,000 new jobs every year.

FIGURE 24 | The development of a PtL industry will create and sustain up to 1,420,000 jobs per year



Source: See appendix C for assessment methodology; https://www.fs-unep-centre.org/global-trends-in-renewable-energy-investment-2020/; https://www.irena.org/-/media/files/IRENA/Agency/Publication/2020/Sep/IRENA_RE_Jobs_2020.pdf

2. What level of ambition is practical

There are many limitations to the practical deployment rate, including logistics, access to capital, market dynamics and the gradual de-risking of technologies. A key question for PtL is the level and rate of deployment for the required renewable electricity. It is critical that the energy used is additional to the grid renewables and does not result in continuing fossil fuel generation, ensuring people and companies can access enough power. The EU has proposed strict rules to demonstrate the additionality of energy used for hydrogen, and this approach is logically extended to PtL that would consume hydrogen.

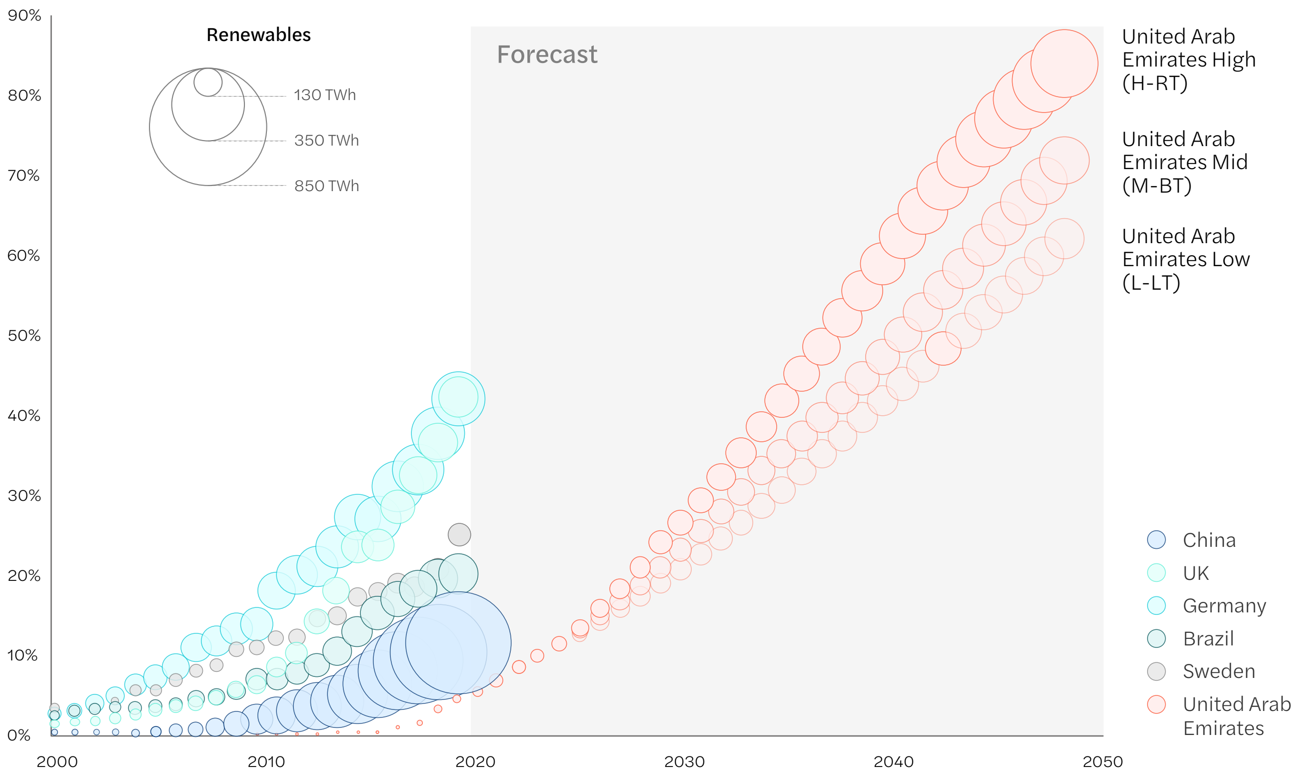
The required deployment of renewables to decarbonize the grid and PtL in the United Arab Emirates appears achievable compared to the historical deployment rate in other countries. Each country can access different resources, and the PtL capacity in the United Arab Emirates is likely to be met predominately through solar PV, CSP and wind. Over the past two decades, several countries have already matched the rate of capacity deployment (as a percentage of grid size) using these approaches, as shown in the following diagram. This excludes nuclear and hydro due to the long deployment timescales, but including these approaches, several countries have succeeded in decarbonizing over 70% of their grid already.

Since 2010, the global LCOE of solar PV has dropped by 85%, CSP by 68% and onshore wind by 56%. In 2010, only wind was close to parity with fossil fuel electricity (solar was nearly three times more expensive); by 2020, solar PV and wind are cheaper than fossil fuels, while CSP is at parity. It is now undeniably economically rational to deploy these renewables, and rapid capacity growth is expected. The historical trend will significantly underestimate the future trend, particularly in the United Arab Emirates, where solar PV generation is likely to be some of the cheapest on earth.

The projected deployment of solar, wind and other renewables to achieve the capacity required to decarbonize the United Arab Emirates grid and fuel a PtL industry is both practical and achievable. This does not mean it will be easy, and effort will be required for the nation to seize the opportunity.

FIGURE 25 The rate of renewable capacity deployment has been achieved in other countries

Select renewables as a percentage of grid electricity generation, bubble size shows renewables in TWh

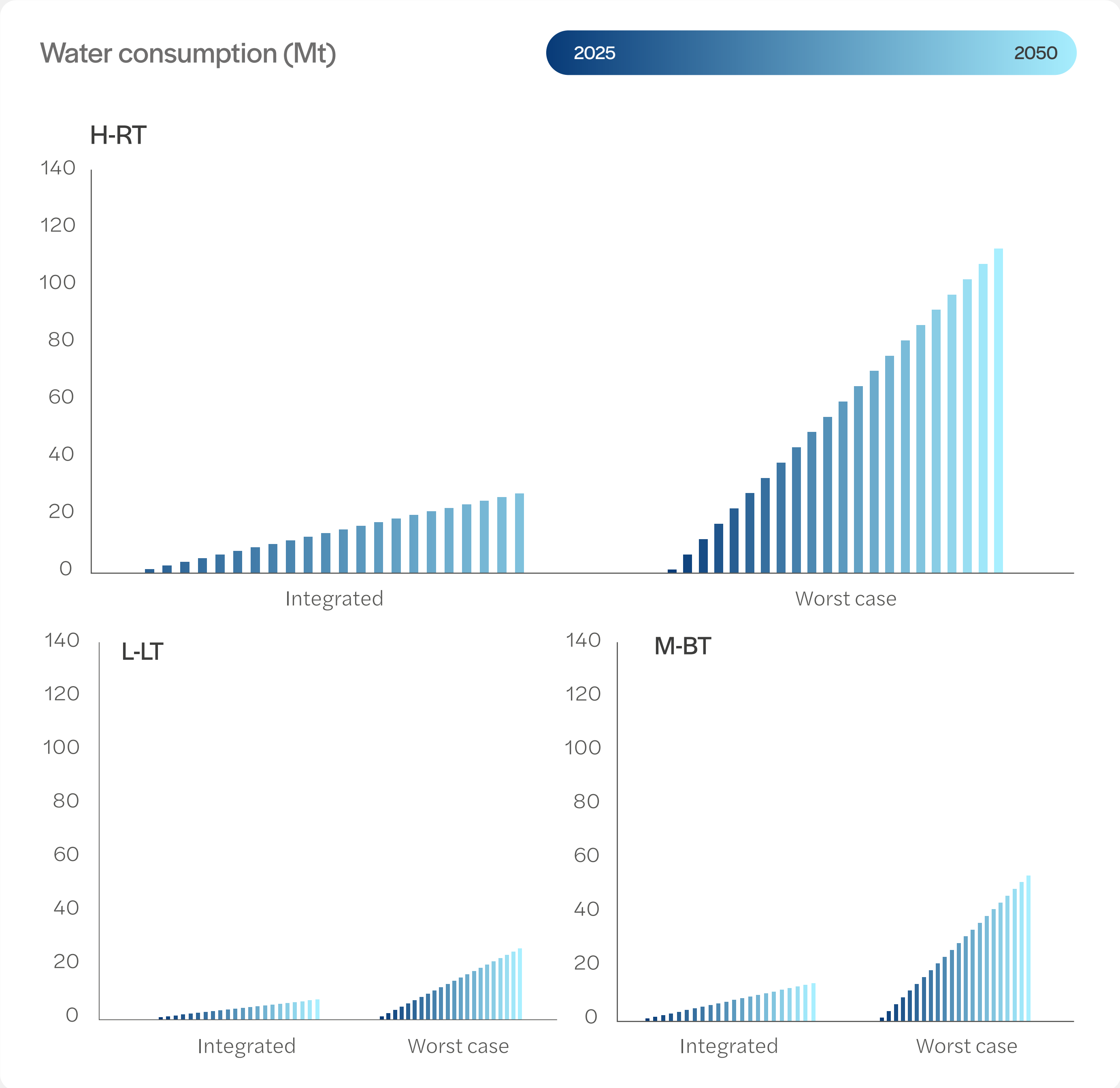


Source: BP World Energy Outlook: 2022, ICF analysis

3. What is the impact on water scarcity in the United Arab Emirates?

Water is scarce in the United Arab Emirates, and production of PtL mustn't harm the availability and access to water. It is assumed that all water used for PtL production will be sourced through desalination. The H-RT scenario would require up to 241 Mt of seawater and 260 MWh energy input for the desalination operation by 2050. This is less than 35% of the Taweelah reverse osmosis (RO) desalination plant's capacity on an annual basis. The water required for the most ambitious PtL production scenario would be less than 1% of the national water demand by 2050.[90] In an integrated PtL facility, large amounts of water produced in the reverse water-gas shift (RWGS), FT and LT DAC processes could be recycled back to electrolysers, reducing the water requirements up to 67%. PtL production is the least water-intensive method compared to other SAF production pathways. Figure 26 shows that the assessed scenarios would not put further pressure on the United Arab Emirates' increasing water stress.

FIGURE 26 **The worst-case PtL jet fuel production water consumption would still be less than 1% of the United Arab Emirates' water demand by 2050**



Source: https://hydrogencouncil.com/wp-content/uploads/2021/01/Hydrogen-Council-Report_Decarbonization-Pathways_Part-1-Lifecycle-Assessment.pdf; https://www.sciencedirect.com/science/article/pii/S1876610216310761; https://www.sciencedirect.com/science/article/pii/S1364032121011539?via%3Dihub; https://www.mdpi.com/2073-4441/11/12/2652

Conclusions and recommendations

The United Arab Emirates is in an excellent strategic position to build a globally leading PtL industry. Solar PV facilities have demonstrated access to some of the lowest renewable electricity costs globally. The United Arab Emirates is rapidly gaining experience across hydrogen production, carbon capture and fuel synthesis. Existing infrastructure and deep expertise in liquid hydrocarbons can be reused. The analysis in this report demonstrates that it will be financially beneficial, environmentally necessary and practical to deploy PtL capacity to decarbonize the United Arab Emirates aviation industry. The following policy roadmap provides an initial suggestion of how this could be achieved.

FIGURE 27 **Proposed PtL roadmap for the United Arab Emirates**

	Immediate (2025)	Short term (2030)	Medium term (2040)
Production	Demonstration facility	0.2-0.4 Mt	1.5-3.0 Mt
Facilities		1-2	4-10
Power requirement	<0.01 TWh	7-15 TWh	45-105 TWh
DAC capacity	<0.01 Mt	0.2-1 Mt	1-14 Mt
Green H_2 capacity	<0.01 Mt	0.1-0.2 Mt	0.7-1.6 Mt
Total CapEx	<$5 million	$5-10 billion	$25-65 billion

Investment requirement

- Small scale integrated facility
- Accessing capital markets to deploy large scale integrated PtL facilities

Estabilishing foundations

1. Establish a clear target
2. Developing mechanisms to ensure market demand for low-carbon fuels
3. Rapid deployment of renewable energy, hydrogen production and carbon capture

Policy instruments to scale industry

4. Government led funding
5. R&D incentives
6. Loan guarantees and capital grants
7. Revenue support, e.g. contract for difference (CfD)/carbon value

Estimations are based on M-BT and H-RT scenarios

Source: ICF analysis

Investment requirement

The critical role of policy is to support the development of the industry to a stage where the PtL industry can provide a net benefit to the United Arab Emirates' economy and environment. The technologies required are still developing, and there is currently no transparent market for low-carbon fuel in the United Arab Emirates. The government is best placed to kick-start the development through a demonstration PtL facility, proving the integration of the required technologies and partnering with local aviation, energy and environmental stakeholders to build familiarity and expertise with the approach. It would be practical to aim to commission a small demonstration PtL facility over the next 2-4 years to provide this valuable experience.

It will be essential to bring in additional capital to scale the industry. Capital requirements to design, build and commission the electricity, carbon capture, electrolyser and fuel production plants are estimated to be up to $65 billion over the next three decades. Not all of this capital requirement is incremental – significant additional refining infrastructure is necessary to meet the forecast doubling in aviation fuel consumption, meaning that much of this investment is required to sustain the growth of the United Arab Emirates' aviation industry. The sustainable attributes of PtL will allow the industry to access a greater pool of capital than fossil fuels, with the global capital markets rapidly shifting to sustainable industries. The Financial Times reported a 50% growth in sustainable funds in 2020, hitting a record $1.7 trillion,[91] largely in equities. The sustainable debt market has similarly grown, with the Climate Bonds Initiative recording over $1.83 trillion of green bonds issued by June 2022. The attributes of a PtL industry are a strong natural fit for green equity and debt. Seven initiatives along two themes have been suggested to unlock this opportunity: establishing the industry foundations and implementing policies to support the scaling.

Establishing foundations

- **Establishing a target for the United Arab Emirates PtL industry** provides a clear direction for market participants and is a crucial first step. The analysis in this report illustrates that a high level of ambition is feasible, replacing as much as 73% of conventional jet fuel with PtL to align the United Arab Emirates' aviation industry with the 2050 net-zero ambition.

- **Align the target with international efforts to create supply and demand for low-carbon aviation fuels.** This includes establishing a long-term aspirational goal through ICAO and the target set by the International Air Transport Association (IATA) member airlines to achieve net-zero carbon emissions by 2050. These global ambitions will create a global market for the fuels the United Arab Emirates could produce and will accelerate the development of the underlying technologies.

- **Consolidate the links between the development of a PtL industry and existing national roadmaps.** The decarbonization of the aviation industry strongly supports the United Arab Emirates Net Zero by 2050 strategic initiative. The deployment of renewable electricity is aligned with the United Arab Emirates Energy Strategy 2050, and the success of the United Arab Emirates Hydrogen Leadership Roadmap is critical to the PtL industry. The development and decarbonization of the nation's industrial sector described in Operation 300bn can supply PSC carbon for PtL production and focuses on increased research and development that could include PtL technologies. Explicitly including the supply and demand factors for PtL in future iterations of these roadmaps would consolidate the foundations to develop a world-leading PtL industry in the United Arab Emirates.

Implementing policy instruments to scale the PtL industry

The foundation initiatives will establish a clear market growth opportunity, and significant capital must be attracted to deliver on the target. The financial profile for PtL production is characterized by substantial initial investments, followed by comparatively low operating costs, driven by the zero-cost inputs to wind, solar and most other renewable power generation. Capital will be particularly sensitive to any risks that could reduce the ability of investments to pay back the initial investment, which often requires more than 15 years of operation. Reducing technology risk and ensuring revenue stability is therefore critical to attracting capital. Initiatives (4) and (5) address technology risk, and (6) and (7) are focused on revenue risk.

1. **Government-led funding for a demonstration facility.** Successfully demonstrating an integrated facility in the United Arab Emirates is a critical initial step. This facility should bring together partners across the industry, ensuring that energy, refinery, aviation, construction and supply chain contributors gain experience in the technology. It should reflect local conditions and existing infrastructure, such as existing refinery capacity to finish the syncrude into jet fuel.

2. **Ongoing research and development support.** The demonstration facility should be the manifestation of broader R&D initiatives to de-risk and improve the efficiency of the underlying technologies. This should build on the pioneering work conducted by Masdar and ambitions of the industrial and climate roadmaps to reduce the technology and local risks of deploying the PtL technologies in the United Arab Emirates. This aligns well with the nation's industrial strategy described in Operation 300Bn, which includes increased funding for R&D to 2% of the national GDP.

The development of a PtL industry creates opportunities for focused R&D to address challenges apparent in the United Arab Emirates, such as developments to better clean dust from PV panels while using minimal water and improving the ability of existing refineries to refine PtL crude into usable fuels.

3. **Loan guarantees and capital grants.** Reducing the volume or risk of capital invested is crucial during the initial industry development. Loan guarantees limit the losses to debt investors if the facility fails to perform as expected, making it easier for investors to support projects. These also reduce the required return of debt, improving the project economics. Capital grants provide direct support for projects and can be particularly effective during the initial development of projects when the uncertainty may be too great for many investors. Both loan guarantees and capital grants have been effectively used to support the SAF industry, with loan guarantees examples from the United States Department of Agriculture Section 9003 and Department of Energy Title 17, and capital grant examples including the US's Bioenergy Technologies Office's Technology Investment Agreements and the UK's Green Fuels, Green Skies competition.

4. **Revenue support.** As outlined in this report, PtL fuels can compete with conventional fuels if the value of the avoided carbon emissions is rewarded. Mechanisms to provide stable revenue at an appropriate level will be critical to ensuring projects can pay back the initial investments. There are several approaches, which vary in the scale, scope and source of funding. Potential mechanisms could reward the physical fuel produced, the carbon emissions avoided, or provide revenue stability. Examples include the EU's Renewable Energy Directive (RED II) and the US Renewable Fuel Standard (RFS), which allow SAF to be used to meet renewable fuel targets, and access capital from fossil fuel suppliers. The EU Emissions Trading System (ETS) and Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) enable airlines to reduce carbon obligations in line with SAF use, supporting their ability to pay a premium for SAF. Other mechanisms could be applied, such as the contract for difference mechanism that has been used to scale the UK's offshore wind capacity rapidly. Each of these has advantages and challenges beyond the scope of this analysis. A useful guideline is that, for PtL, the greater the stability of the incentive, the easier it will be to attract capital to scale the industry.

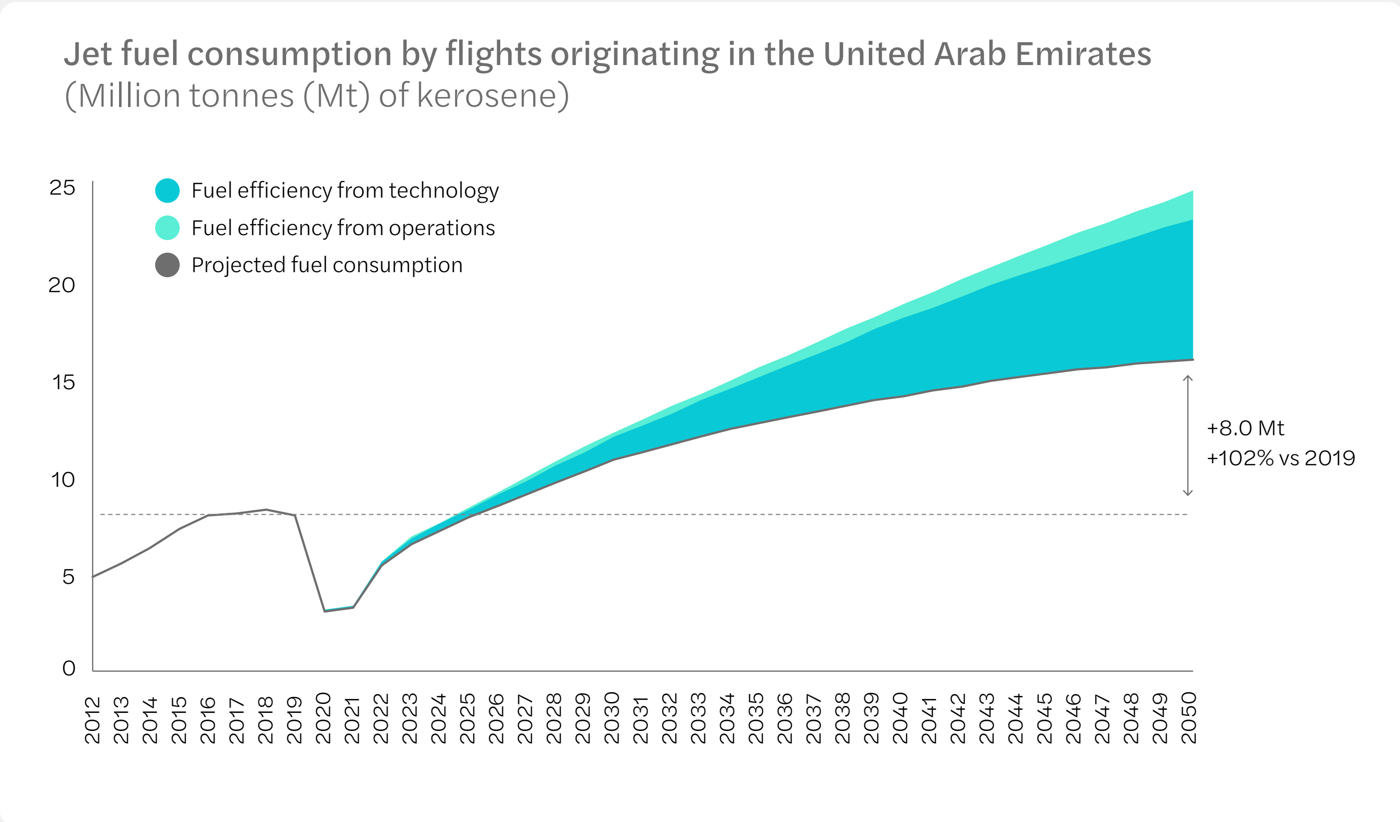
Technical appendix

Appendix A: Forecasting the aviation activity and emissions growth in the United Arab Emirates.

The consumption and emissions from jet fuel in the United Arab Emirates establish a baseline comparison for sustainable fuel production. The analysis estimates that the volume of jet fuel consumed by flights refuelled in the United Arab Emirates will double by 2050, from 7.9 million tonnes in 2019 to 15.9 million tonnes in 2050.

The historical activity was extracted from International Air Transport Association passenger intelligence services (IATA PaxIS) through 2021 and then projected to 2050 using the Boeing Commercial Market Outlook (CMO) growth expectations.[92] The imminent years (through 2023) were adjusted using an ICF International forecast to capture the pandemic recovery, before reverting to the (pre-pandemic) Boeing CMO forecast. While the CMO forecasts annual growth in the Middle East and North Africa (MENA) of 4.55% from 2018, the pandemic reduces this to a lower average annual growth of 3.41% over 2018-2050. The activity was assessed in capacity (available tonne kilometres (ATK)), aggregating cargo and passengers using the standard IATA assumption[93] that passenger weight is equivalent to 150kg, composed of 100kg for each passenger and baggage, and 50kg for the seat, fittings and consumables.

FIGURE A1 **Jet fuel consumption in the United Arab Emirates is projected to double by 2050**



Source: World Bank GDP Data: https://data.worldbank.org/country and ICF feedstock database

The fuel burn per ATK was projected using the considerable analysis conducted by the International Civil Aviation Organization (ICAO) to evaluate a long-term aspirational goal, detailed in the technology subgroup report (Appendix M3).[94] This provides fuel burn in kilograms of fuel consumed per ATK for four aircraft categories. Yet, given the lack of turboprop and regional jet activity in the United Arab Emirates, only narrow-body (NB) and wide-body (WB) data were relevant. Over 2012-2019 the ATK split for flights originating in the United Arab Emirates remained steady at 12% NB and 88% WB, and the fuel burn per ATK projection was weighted using the same split through 2050. The central scenario ("medium progress") was used, which provides a conservative baseline compared to the higher level of ambition underlying this power-to-liquids (PtL) analysis. The central scenario also includes a penetration of advanced concept aircraft (ACA) with a 10% reduction in energy consumption per ATK. The analysis used the central assumption that these aircraft would compose 5% of the United Arab Emirates' fleet by 2040 and 50% by 2050. This resulted in an average annual reduction in fuel burn per ATK of 1.17% between 2019-2050, slightly above the global average, as the ICAO projections assume a greater reduction in fuel consumption per ATK for WB compared to other aircraft categories. This may be a conservative assumption for the United Arab Emirates-based airlines, with the premium business model of Emirates and Etihad combining with the higher growth assumption for the country in the CMO (4.55% vs global 4%) to result in a greater number of new deliveries to the country. This would keep the average aircraft age lower than the global fleet and ensure technology efficiencies are rapidly incorporated into the domestic fleet.

Combining the activity recorded by IATA with the ICAO fuel burn per ATK allowed the estimated historical consumption to be compared to recorded consumption. Over the past five years (2015-2019), the actual consumption was 6.3% higher than the estimated consumption. This is likely because the ICAO analysis uses a modern A350-900 as the reference WB aircraft, providing fuel consumption per ATK based on the aircraft design range. Both factors will lead to a lower fuel consumption than reality. To accommodate this, the historical and projected values were adjusted by +6.3%, ensuring the historical calculated values were reconciled to the recorded values.

This results in an increase in ATK from 40 billion in 2018 to 117 in 2050 (+192%), which is slightly offset through a reduction of adjusted fuel consumption from 0.027kg per available seat kilometres (ASK) in 2018 to 0.019kg per ASK in 2050 (-27%), and cumulative operational efficiencies of -6%. The total impact is an increase in fuel consumption from 7.9 million tonnes (Mt) in 2019 to 15.9 Mt in 2050, almost double. This can be compared to historical UN data, which records an increase of half (+47%) in just six years between 2012 and 2018, showing that while this analysis projects a significant increase in fuel consumption, it is meaningfully below the historical growth.

In 2019, aviation jet fuel consumption was equivalent to 7.7% of primary energy consumed in the United Arab Emirates. Jet fuel consumption in 2019 was estimated at 7.9 Mt, and assuming 44 megajoules per kg (MJ/kg), the energy consumed is 0.35 exajoules (EJ), increasing to 0.70 EJ in 2050. The BP Statistical Review of World Energy 2021[95] gives the total 2019 primary energy consumption in the United Arab Emirates at 4.55 EJ, including 2.6 EJ from natural gas (primarily for electrical generation), 1.9 EJ from oil (primarily for transport) and just 0.04 EJ of renewables on an input-equivalent basis.

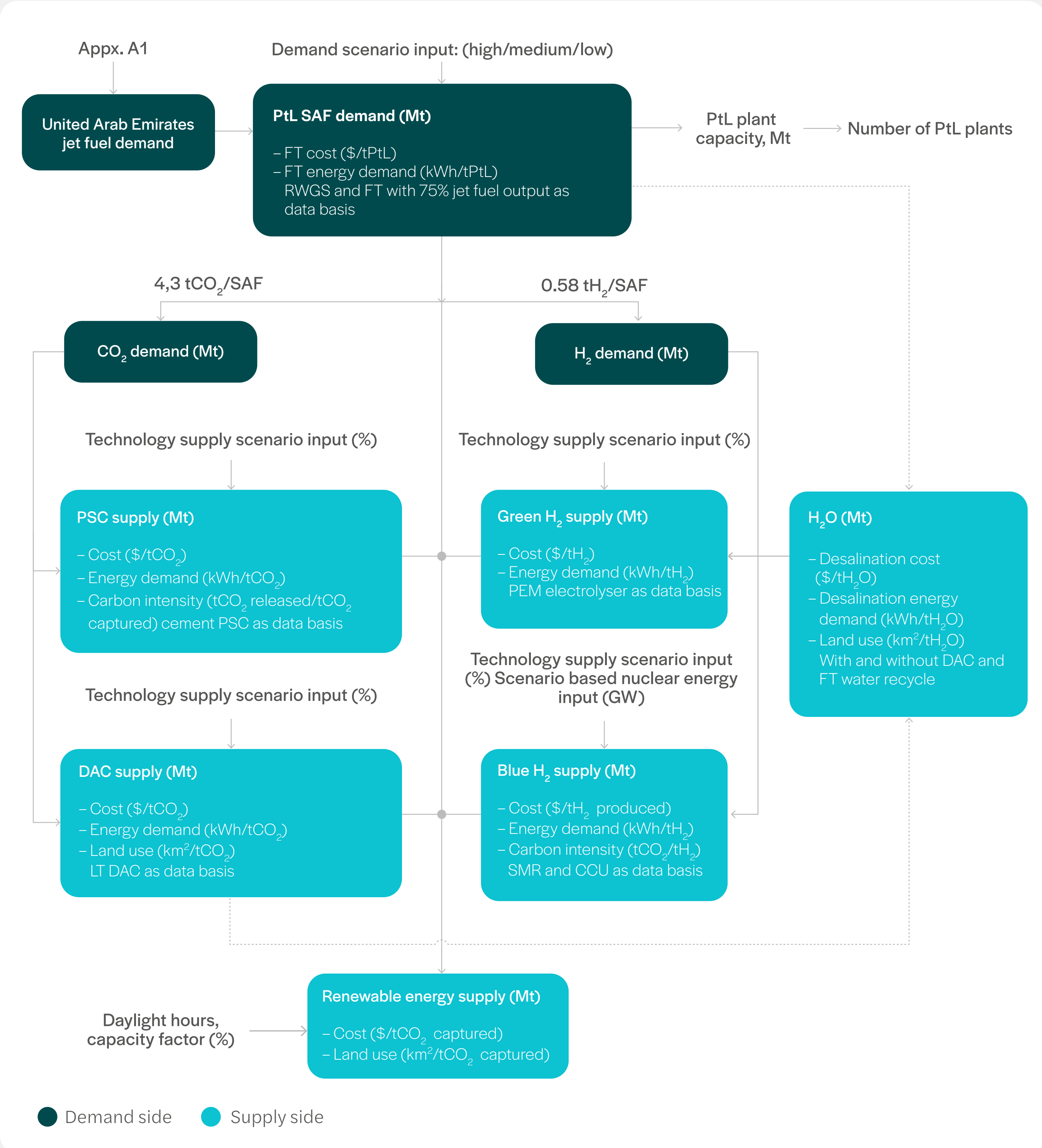
The 2019 jet fuel energy consumption is equivalent to nine times the 2019 primary energy from renewable sources. The projected 2050 jet fuel energy consumption of 0.70 EJ would equal 18 times the 2019 renewable energy input. The intermittency of renewables and the energy losses when converting electrical energy to liquid hydrocarbons illustrate the considerable increase in installed renewable capacity required to decarbonize the United Arab Emirates electrical grid and aviation industry.

The well-to-wake emissions from the United Arab Emirates' jet fuel consumption in 2019 are equivalent to 30.8 megatonnes of CO_2 equivalent ($MtCO_2e$), using the ICAO fossil fuel baseline of 89 grams of CO_2 equivalent per megajoule of energy (gCO_2e/MJ). This is equivalent to 11% of the nation's emissions from oil, gas and coal consumption of 270 $MtCO_2e$ in the same year. If the other United Arab Emirates sectors follow a linear trajectory to the net-zero by 2050 target, the projected baseline aviation fuel emissions will contribute a third of total emissions shortly after 2035, and half of national emissions by 2040 – and considerably more if the aviation industry grows faster or fails to achieve the assumed improvements in technology and operations.

Appendix B: PtL jet fuel supply/demand model

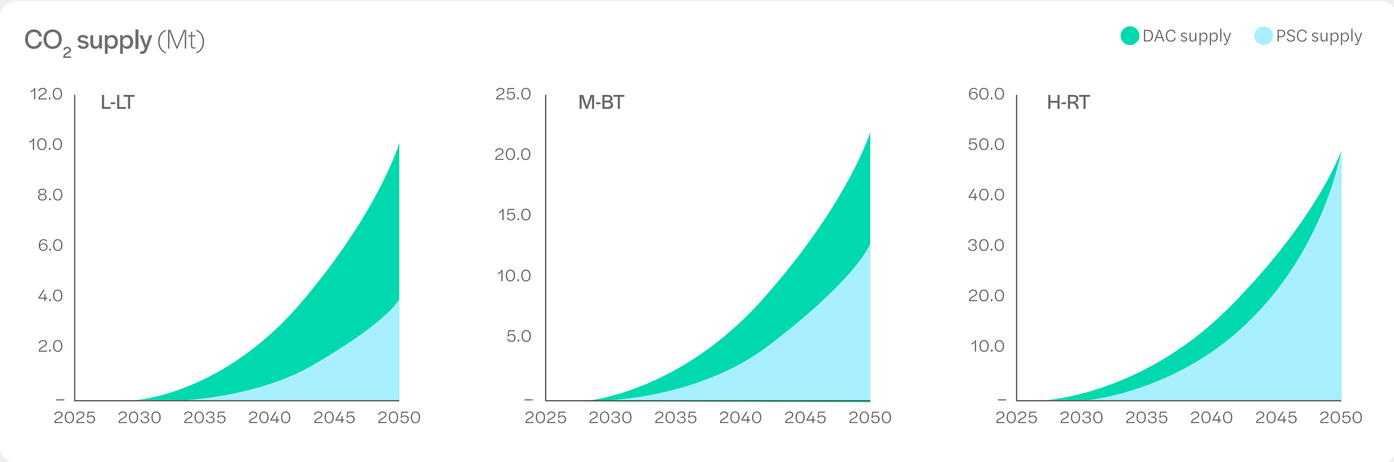
The supply side requirements were assessed with a top-down modelling approach. Three factors were analysed: CO_2, hydrogen and total renewable energy requirements. These supply side requirements were calculated based on the low-carbon technology deployment scenarios. Peer-reviewed articles, industry reports and expert interviews were used for mass and energy balance data sources.

FIGURE B1 **PtL Supply Demand Model**



Source: ICF analysis

FIGURE B2 | **Use of DAC increases over time based on technology scenario**



Source: ICF analysis

Carbon supply

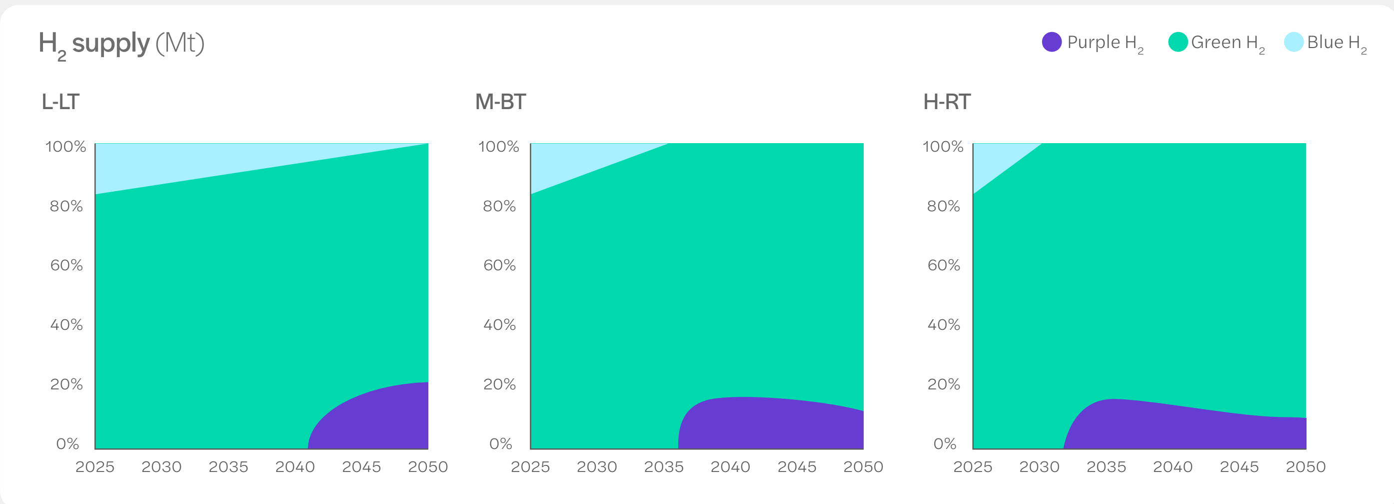
It is estimated that 4.3 tonnes of CO_2 is required to produce 1 tonne of PtL jet fuel. Based on the scenario inputs, this is supplied through a mixture of direct air capture (DAC) and point source capture (PSC) approaches. For each route, electricity intensity, heat intensity and cost of carbon capture were used to assess energy requirements and PtL costs. DAC is considered to be powered by renewable energy; therefore energy-related carbon intensities are considered to be zero. CO_2 emissions released from PSC are calculated based on the carbon released despite the carbon capture process.

Hydrogen supply

Considering the PtL jet fuel demand, and that 0.58 tH_2 are needed per tonne of PtL jet fuel production, the required amount of hydrogen supply was quantified. The same assessment was undertaken for carbon supply, which is delivered through a combination of blue and green hydrogen. A small portion of nuclear-powered hydrogen production (purple hydrogen) was also considered in these scenarios, mainly supporting the deployment of other renewable energy forms.

Polymer electrolyte membrane (PEM) electrolysers were considered as a part of the model with 65% efficiency. Considering that 1kg of hydrogen contains 33.33 kilowatt hour (kWh) of usable energy, 51 megawatt hour (MWh) energy requirement per tonne of hydrogen is taken into consideration. PEM efficiency is assumed to increase up to 74% by 2050, decreasing energy consumption down to 45 MWh per tonne of hydrogen.

FIGURE B3 | **Use of green hydrogen increases over time based on the technology scenario**

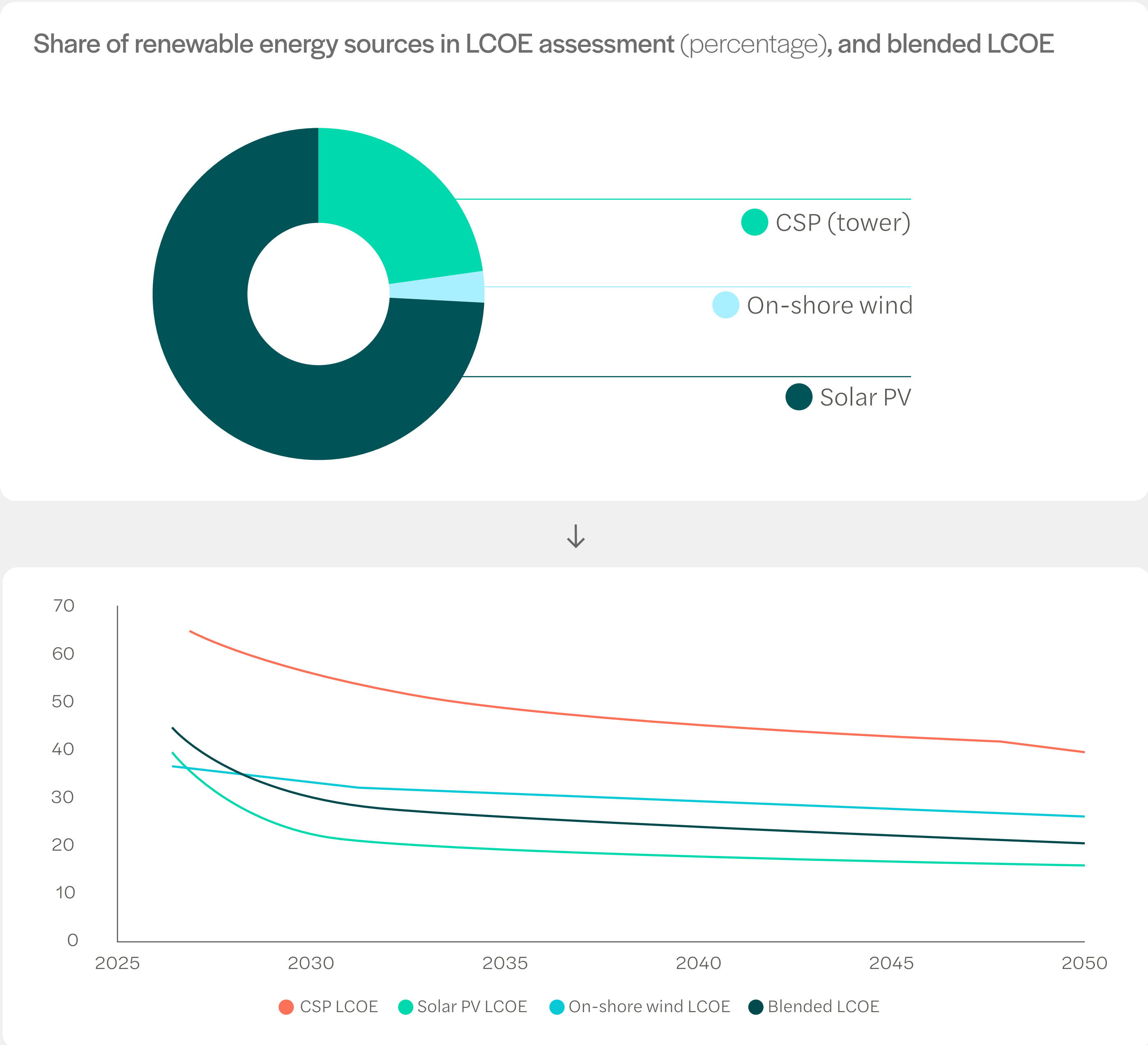


Source: ICF analysis

Renewable energy supply

Total renewable energy required was assessed based on the five energy vectors considered: DAC, PSC, green hydrogen, blue hydrogen, and Fischer-Tropsch (FT) synthesis. Due to the use of transition technologies like PSC and blue hydrogen, as well as nuclear energy, the total renewable energy required for PtL production was reduced compared to using green hydrogen and DAC. The majority of the renewable energy is expected to come from solar energy – solar photovoltaic (PV) and concentrated solar power (CSP)). Wind is also expected to play a small role, to ensure continuous energy supply. The United Arab Emirates has already deployed the world's largest CSP plant with parabolic trough collectors, which can provide up to ten hours of energy storage.[96] To ensure continuous PtL production and the worst-case daylight scenario, as low as 12 hours per day, solar tower CSPs with more than ten hours of storage capacity are taken into consideration. Since 2011, the levelized cost of electricity (LCOE) for CSP solar tower systems decreased by 48%, and current costs are considered as $0.1/kWh for large-scale facilities with over ten hours of storage capacity. Onshore wind LCOE has also decreased substantially within the last decade and taken as $0.04/kWh as the basis for 2020. As can be seen in the figure below, blended LCOE for 2030 is estimated at $26/MWh, which decreased to $17/MWh by 2050. Share of nuclear energy was considered separately from the renewable energy scenarios, as it is only used for purple hydrogen production.

FIGURE B4 **Use of green hydrogen increases over time based on the technology scenario**



Source: IRENA study (IRENA, "Renewable Technology Innovation Indicators: Mapping progress in costs, patents and standards", *International Renewable Energy Agency*, 2022, ISBN: 978-92-9260-424-0); 2020 NREL Annual Technology Baseline (https://atb.nrel.gov/)

Appendix C: Jobs created and supported

Developing a PtL SAF industry in the United Arab Emirates would create and sustain considerable employment. This report has included jobs across four categories: direct, construction, power industry and aviation.

Direct jobs include roles in the production of the fuels, such as engineers and operators running the PtL facilities and refineries. These roles are estimated using current employment estimates for biofuel facilities, which is just over 4,000 full-time equivalent (FTE) per million tonnes of SAF production, or approx. 130 for a 100 million gallons per year (mmgpy) facility.

Construction employment includes jobs created to build facilities. These have also been estimated from current facilities, giving 16,500 FTE per million tonnes of SAF production. As these jobs are only created during construction, they have been divided over an example 20-year facility operating lifetime, to give 825 per million tonnes of SAF production or 27 tonnes per year over the lifetime of a 100 mmgpy facility.

Many jobs are created upstream in the power industry. These jobs were based on the required investment multiplied by the jobs created per unit investment. The investment in solar between 2010-2019 was calculated[97] and divided by the number of people employed in the sector in 2020[98] – which suggested that over 2.7 jobs are created for every $1 million invested in solar capacity. Due to the expected prevalence of solar PV, this figure was used to estimate the total upstream jobs created.

Aviation jobs represent those sustained by ensuring the industry retains a license to operate in a low-carbon economy. They are based on the IATA estimation that 180,000 people were directly employed by aviation in the United Arab Emirates in 2018. As described in earlier sections, aviation activity is expected to increase by a factor of three by 2050. Staffing efficiencies of 20% have been assumed, resulting in an expectation that 430,000 jobs will be created directly by the aviation industry in 2050. The jobs shown represent the portion of these jobs sustained by the development of the PtL industry; for example, in the high scenario where PtL decarbonizes 73% of the industry, the jobs sustained are equal to 73% x 430,000 = 313,000. This provides the lower figure given. The upper figure is calculated using the IATA estimation of the direct and indirect jobs created by aviation in the United Arab Emirates. The same increase in activity and staffing efficiencies are assumed and multiplied by the percentage of the industry decarbonized.

Contributors

World Economic Forum

Laia Barbarà
Community Lead, Clean Skies for Tomorrow

Lauren Uppink Calderwood
Head of Aviation, Travel and Tourism Industries

ICF International

Alastair Blanshard
Senior Manager, Sustainable Aviation

Yasar M. Yetiskin
Senior Consultant, Sustainable Aviation

United Arab Emirates SAF Committee

Boeing
bp
Dubai Airports
Emirates Group
Etihad Airways
UAE General Civil Aviation Authority
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Endnotes

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World Economic Forum
91–93 route de la Capite
CH-1223 Cologny/Geneva
Switzerland

Tel.: +41 (0) 22 869 1212
Fax: +41 (0) 22 786 2744
contact@weforum.org
www.weforum.org