Growth Lab

Catalyzing Green Growth in the UAE: Growth Opportunities in a Decarbonizing World

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About the Growth Lab

The Growth Lab's multidisciplinary team, led by Professor Ricardo Hausmann, pushes the frontiers of research on economic growth and development policy. The Growth Lab advances academic research on the nature of economic growth and conducts applied, place-based engagements that aim to understand context-specific growth processes, address key constraints, and identify promising opportunities. Key frameworks developed at the Growth Lab include Growth Diagnostics and Economic Complexity. Growth Diagnostics is a systematic methodology that aims to identify the most binding constraints to better growth outcomes, allowing policymakers to take the most impactful actions. Economic Complexity is a growing field of research that sees the economy as composed of distributed knowledge and productive capabilities that must be networked in order to be used in production and sees growth as the expansion of both the underlying knowledge and its uses. Through its research and teaching activities, the Growth Lab has become a global thought leader offering breakthrough ideas, methods, and tools that help policymakers, stakeholders, and scholars find ways to accelerate economic growth and expand opportunity across the world.

Acknowledgements

This report was produced in the context of the ongoing collaboration between Harvard's Growth Lab and the Ministry of Economy of the United Arab Emirates (UAE), which aims to produce novel research-based inputs to inform an ambitious, forward-looking economic policy agenda. The goal of this collaboration is to provide rigorous research that can support the Ministry of Economy and related policy-making entities in their mission of promoting high-quality, sustainable growth and fostering structural transformation in the UAE.

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1. Executive Summary

The world is rapidly shifting towards a lower-carbon economy, drawing a new map of comparative advantage in the process. As the global economy decarbonizes, it will bring about profound changes in the landscape of production, giving rise to new industries, markets, and pathways for economic development. This transformation will manifest through changes in global demand and prices for existing products but also through the emergence of novel technologies and industries, many of which will replace older, carbon-intensive practices and production methods. These trends will have a significant impact on the fundamental competitiveness of every economy. Therefore, it is crucial for national economic policies, including in the United Arab Emirates, to include a well-designed green growth strategy to harness the global drive towards a decarbonized world economy.

This report aims to identify green growth opportunities for the UAE through a structured approach and suggest concrete policy ideas to seize them. We analyze green growth opportunities along the following four pillars: (1) make the enablers of decarbonization; (2) make green versions of energy-intensive products; (3) capitalize on carbon capture utilization and storage (CCUS); and (4) export decarbonization-related know-how (Table 1).

Table 1: Summary of Green Growth Policy Ideas

Strategy	Policy Idea	Priority
1) Making things that enable others to decarbonize	Expand into critical minerals processing	Medium
2) Make Green Things	**Develop Green Industrial Parks to attract green production**	**High**
3) Monetize Carbon Sinks	Develop CCUS Hubs & CO2 Transport Infrastrucutre	Medium
4) Create and Export the Knowhow for Decarbonization	**Export Green Industrial Parks Internationally & Acquire Engineering, Procurement and Construction Management Company for this**	**High**
	Strengthen collaborations with most productive countries & entities in green patenting space	Medium
	Set up a green technologies working group of the Emirates Scientist Council	Medium
	Develop research hubs around electrochemistry and thermal energy management & storage	Medium

One of the most promising opportunities identified lies in the development of green industrial parks. The UAE should consider establishing such green industrial parks to attract energy-intensive industries aiming to switch to low-carbon production processes. These parks provide the necessary inputs to low-carbon industrial production in a concentrated geographical area. These include dedicated low-cost renewable energy, but also clean, high-temperature heat, low-carbon hydrogen as well as carbon capture technology and other services necessary to certify the green nature of the production. A net zero world will need to make things like steel, cement, chemicals, aluminum, and glass without emitting carbon. It will also need to develop fuels for ships, planes, and heavy-duty transport that have near-zero life cycle emissions, a large proportion of which are expected to come from renewable energy that is used to make hydrogen and liquid fuels.

Low solar energy costs make the UAE one of the best places to develop low-carbon energy-intensive industries. Additionally, the UAE has a low cost of capital which is an important comparative advantage since many of these industrial activities are highly capital-intensive. As the world transitions towards a decarbonized global economy, green industrial parks will drive high-value green economic activities to locate in the UAE, resulting in stronger exports, more value-added, and a future-proof economic model for the country.

As developing green industrial parks is complex, this is an opportunity to accumulate valuable know-how that in turn can be monetized. For instance, nobody yet knows how to build, manage, and operate a multi-gigawatt green hydrogen production facility. In the process of building green industrial parks in the UAE, the UAE will have to learn how to optimize a very complex renewable energy system, balance electricity, heat, and hydrogen across multiple energy users with different load profiles, and deploy multiple new technologies together that are still in pilot phase.

The UAE should consider monetizing its domestic experience by developing and exporting green industrial parks in other countries and developing a business model around these activities. Such a strategy could involve (1) owning the Engineering, Procurement, and Construction Management (EPCM) contractors and other related businesses that develop and operate parks; (2) where possible, having as much of the high-income knowledge workers who provide these services live and work in the UAE; and (3) helping UAE industrial companies that wish to expand abroad (such as Emirates Global Aluminium, or Emirates Steel Arkan) make profitable foreign investments in green industrial parks in other countries.

There may be another opportunity in critical minerals processing. A mining boom is required to provide the world with enough critical minerals to build a clean energy system. Currently, China is dominating the critical minerals processing market, but many countries are looking to diversify their critical minerals supply chain. Given its low cost of capital, strategic location, and good trading infrastructure the UAE is well-positioned to take advantage of this opportunity. The country already has nascent strengths in mineral refining to build off, in the aluminum and soon in the lithium value chains.

Other promising policy ideas are centered on accelerating the creation of green growth knowledge in the UAE and encouraging high-potential business applications. Given their potentially large implications for low-carbon industrial processes in the UAE we recommend that the government consider establishing applied research hubs in the areas of electrochemistry and thermal energy management & storage. Our research has already identified leading actors in this area that may be attractive partners for collaboration. Additionally, to ensure the close monitoring of the innovation and technology developed abroad, we recommend discussing the establishment of a green technologies working group within the Emirates Scientist

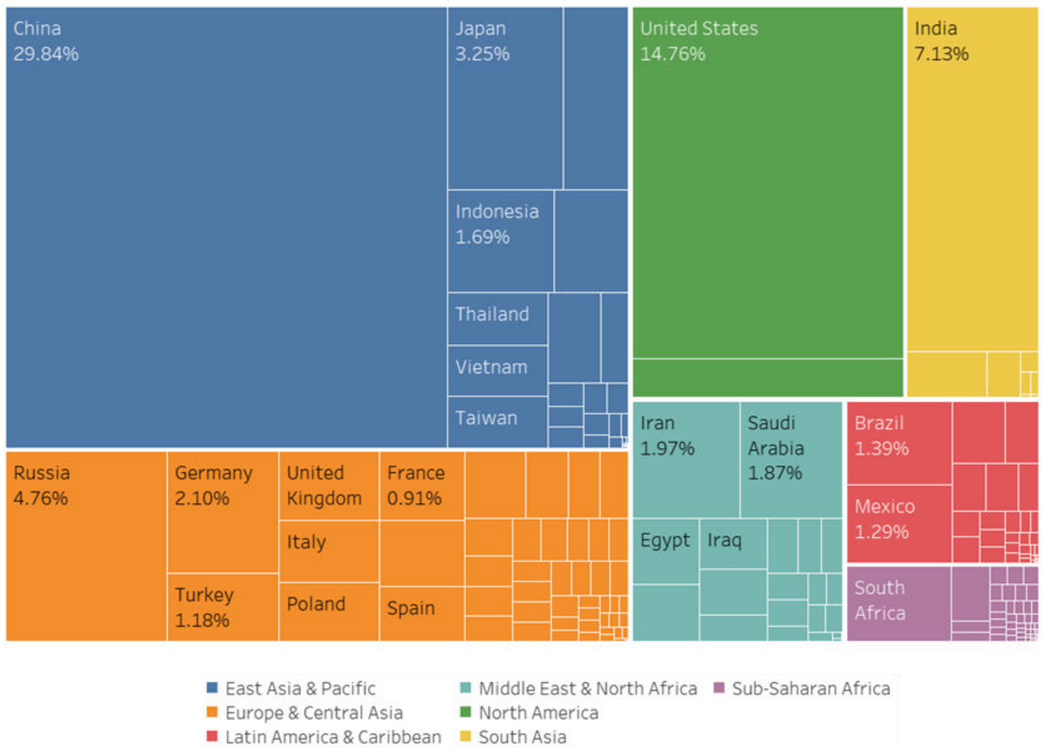
Council. This working group would continuously monitor advances in green technologies and their impact on the UAE, reporting findings to the higher levels of government to inform strategic decisions.

2. Green Growth in the UAE: A Framework

The transition towards a low-carbon economy is fully underway. Irrespective of when the world will reach Net Zero Emissions (NZE) the growth in demand for clean energy and technologies is continuously increasing. According to the International Energy Agency (IEA), achieving the NZE objectives by 2050 necessitates a 25% average annual growth rate in solar energy from 2022 to 2030 (IEA, 2022b). This growth rate is attainable given the 35% surge in solar PV capacity between 2021 and 2022 (IEA, 2023b). This increased capacity is also reflected in the compound annual growth rate of solar PV manufacturing which was 25% from 2010 to 2021 (IEA, 2023c). Other products that experienced a swift surge have been Electric Vehicles which went from 4% car market share in 2020 to 14% in 2022 as well as battery manufacturing which increased by 85% during 2021-2022 (IEA, 2023c).

The Paris Agreement goals require that the world shifts its productive structure towards cleaner activities. However, CO2 emissions are concentrated in a handful of countries (Figure 1). China (~30%), the United States (~15%), India (~7%), and Russia (~5%) represented 57% of global emissions in 2015-2021. While the UAE is one of the largest emitters on a per capita basis its absolute emissions represented only 0.63% of emissions during the same period. Therefore, if the UAE manages to completely decarbonize its economy in the short term, the reduction of global emissions would be limited. This does not mean that only high-emitting countries should work towards decarbonization; global collaboration is crucial to avoid falling into a tragedy of the commons. However, it implies that the UAE may be able to contribute to global decarbonization efforts in ways that are additional to its own CO_2 emissions reduction. As the world is facing the challenge of meeting the Paris Agreement goals it is demanding a range of products, services, and energy sources that fuel the global decarbonization. Since this demand must be met to achieve our global goals it opens opportunities for countries such as the UAE to play a role in the supply side of decarbonization. Through a green growth strategy, the UAE can identify how to contribute to this global challenge by developing industries that meet the global demand. In other words, ask not what you can do to decarbonize yourself but rather what you can do to help the world decarbonize.

Figure 1: CO2 Emissions by Country (2015 - 2021), % of Total



Source: Global Carbon Project 2020

Patterns of demand will shift quickly as the world decarbonizes. The demand for products and services that are needed for decarbonization, such as critical minerals, clean energy technologies, and carbon storage will increase drastically. The speed of the energy transition means that the window of opportunity to enter production lines for clean energy technologies is huge and that benefits will be greatest for early entrants. For example, building just the factories we need to make enough solar panels to meet expected demand will require $600-660 billion in investment over the next ten years, representing a tenfold scaling of manufacturing capacity. But from 2035, growth in manufacturing capacity in this supply chain is expected to slow substantially, and capacity may even shrink. Countries that want to enter solar industry supply chains have around ten years to do so, after which the structure of the industry may be largely set barring unforeseen technological, supply chain, and geopolitical disruptions. Countries may have longer to enter supply chains for less mature technologies, but the logic is similar.

Existing energy-intensive industries will move closer to good sources of renewable energy. The energy world of the 19th and 20th century has been flat since fossil fuels are extremely energy-dense by volume and easy to transport. This made it possible for places with poor fossil fuel endowments and energy resources, such as Germany and South Korea, to engage in energy-intensive industrial activities like steelmaking. Renewable forms of energy are much harder to transport than fossil fuels: electricity from solar and wind needs well-functioning grids to travel, and losses mount as distances increase.

Hydrogen made from renewable energy will be much less energy-dense by volume than coal or oil and more challenging to transport. In effect, the world will stop being energy-flat. Instead, regions with good renewable energy provision will have new comparative advantages in energy-intensive industries. These regions will need to develop these latent advantages to host the industries of the future. This shift is starting: whether Europe will have to lose its heavy industry has become a hot topic in European policymaking circles, and Germany has even proposed massive long-term subsidies for its heavy industries. These subsidies may be sensible in the short term but would be more or less impossible to maintain indefinitely.

The shifting tides of global production and supply chains in a decarbonized world present a wide array of growth opportunities. The Growth Lab has designed a framework[1] to help countries formulate strategies and policies that can stimulate green growth. The approach aims to assess the feasibility and practical value of four guiding strategies in local contexts: (1) make the enablers of decarbonization, (2) make green versions of grey products for the world, (3) capitalize on carbon capture utilization and storage (CCUS), and (4) export decarbonization know-how. The subsequent chapter will analyze the opportunities that the UAE has along those strategies. It is important to note that this work exclusively focuses on 'offensive' strategies, which revolve around crafting a growth strategy in alignment with new production networks in green growth industries, without addressing 'defensive' strategies that seek to safeguard and transition the UAE's productive capabilities in 'grey' or carbon-intensive industries amidst market changes and the impacts of climate change.

Strategy 1: Make things that enable others to decarbonize

The process of decarbonization will create a substantial demand for new energy resources, technologies, and related services. Nations capable of supplying these components will bolster their economic growth engines. It is useful to categorize these potential opportunities into two main groups: critical minerals, which rely on natural resources and their sourcing, and all other components essential for clean energy technologies, which are less dependent on natural endowments.

Expanding into critical minerals that are required for the world to decarbonize is a growth opportunity for the UAE. The country has already captured a significant share of the global aluminum market through the activities of Emirates Global Aluminum (EGA) without having the natural endowments of its critical mineral (bauxite). Additionally, the plan of the Australian firm Lepidico to process lithium mica mined in Namibia shows the attractiveness of the UAE as a location for these processing activities. Examining which minerals may be most conducive to being processed and exported from the UAE would be a first step to realizing this growth opportunity.

[1] https://growthlab.cid.harvard.edu/green-growth

Strategy 2: Make Green Things

As the global economy undergoes decarbonization, various industries will naturally expand and relocate to economies capable of powering production processes with clean energy. The United Arab Emirates boasts some of the world's most abundant solar resources, which positions it to gain a renewed comparative advantage in producing energy-intensive industrial goods without carbon emissions. The journey toward decarbonizing industries such as steel, chemicals, and ammonia entails electrifying production processes and harnessing renewable energy in many ways such as generating hydrogen through water electrolysis. Both renewable energy and hydrogen production are challenging to transport, making it more practical to utilize these resources in heavy industry where they are generated. While there may be pressure to relocate energy-intensive industries closer to renewable energy sources, such a transition is neither straightforward nor automatic.

The UAE could make a significant contribution to attracting these potentially relocating industries by creating green industrial parks that provide low-carbon energy sources and public inputs needed for the production of green goods. The main challenge in this context is to develop a sizeable and dedicated renewable energy capacity and address the problem of intermittency through developing more wind power and storage options that do not make green manufacturing activities cost-prohibitive. With its planned low-carbon hydrogen oases, the UAE and its Ministry of Energy & Infrastructure are already steering the discussion in the right direction but the planning should think beyond hydrogen-based applications to capture a wide array of potential industrial users. These parks should also leverage carbon capture utilization and storage applications that may provide a carbon feedstock for the production of synthetic fuels and chemicals.

Strategy 3: Monetize Carbon Sinks

The process of decarbonization will give rise to entirely new markets centered around carbon storage through carbon credits. Some natural landscapes possess significant, yet untapped, potential as carbon sinks. The primary challenge lies in establishing a reliable and enforceable carbon asset that can be traded internationally, thereby unlocking the value of these landscapes. At present, carbon credits exhibit substantial price variations based on their quality and the markets they can access. Securing access to high-priced carbon credits is crucial for capitalizing on the value of these natural landscapes. In addition, the potential for carbon storage in geological formations offers opportunities not only for carbon sequestration but also to support the relocation of energy-intensive industries, creating a dual benefit in terms of carbon storage and industrial production.

The UAE has significant factors that make CCUS applications attractive: Good geological storage opportunities, significant existing capabilities through ADNOC, and the potential to attract industrial users of CO2. Within this context, the UAE may consider developing carbon capture hubs at locations where point source emissions are concentrated. This should be conducted in concordance with the plans to develop green industrial parks given that CO2 offtakers may locate in these parks.

Strategy 4: Create and Export the Knowhow for Decarbonization

Countries that lead in developing green industries can also export the knowhow for decarbonization to accelerate projects in other places. This applies to countries leading the research and development of new technologies, to leaders in financing capital investments, creating carbon markets, or developing supply chains for energy technologies. Exporting that knowhow can drive growth at home and help the world decarbonize. This therefore represents a growth opportunity that thinks strategically about the knowhow that is created in the process of decarbonization.

As the UAE is engaging in large-scale renewable energy projects and potentially the construction of green industrial parks, it should capture the learning effects of these complex projects. This may be done through a strategic acquisition of an Engineering, Procurement, and Construction Management (EPCM) company. As the EPCM company captures the learning effects it will be well positioned to provide services to other countries for similar projects and the UAE will export the knowhow it generated in these processes. Moreover, coupling the design of these complex projects with an EPCM contractor, with financing through a related UAE-affiliated parent entity such as Masdar will decrease transaction costs and lead to more efficient processes.

3. Green Growth Opportunities for the UAE

Strategy 1: Make things that enable others to decarbonize

To meet global decarbonization goals, there will be a significant increase in the demand for products and services across various industries that enable the reduction of emissions. The International Energy Agency (IEA) has projected that to achieve zero emissions by 2050, the world needs to triple its investment in clean energy, reaching approximately $4 trillion annually by 2030 (IEA 2021a). Furthermore, to attain net-zero emissions by 2050, nearly half of the necessary emission reductions must come from technologies that are currently in the experimental or conceptual stage (Ibid.). This presents a considerable level of uncertainty regarding the input requirements for these technologies and their sources.

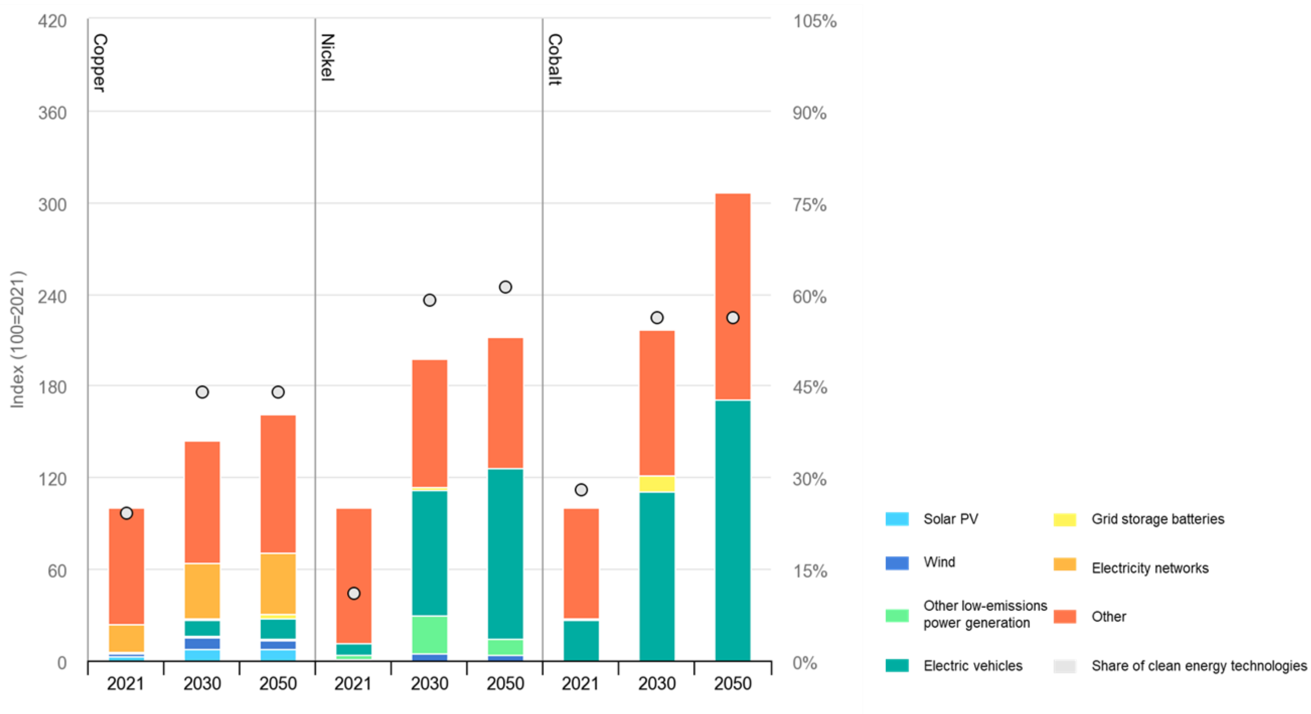
Countries and companies with the means are heavily engaged in research and development efforts to discover these technologies and secure a competitive advantage in emerging industries. However, it is important to note that different countries have varying levels of existing advantages and capabilities for innovation in this field, and most countries lack the financial resources to heavily subsidize such innovation. The increasing demand for products and services from technologies with varying level of maturity therefore offer a significant opportunity for countries to grow by participating in these supply chains. Within this context, we see two major growth opportunities for countries.

- **Take advantage of the mining boom through your natural resources.**
- **Participate in Green Supply Chains.**

Critical Mineral Processing

The clean energy transition will lead to a significant increase in demand for critical minerals as clean energy technologies require more minerals than their fossil fuel alternatives. For example, the amount of mineral inputs needed for an onshore wind farm is nine times larger than for a gas-fired power plant (IEA 2021b). The increased demand for minerals can already be seen today as the market for energy transition minerals doubled between 2017 and 2022 reaching 320 billion USD in 2022 (IEA 2023b) and the IEA estimates that to reach net-zero globally by 2050 the demand for minerals coming from the energy sector will increase by 600% (IEA 2021b). Not all minerals will necessarily see a surge in demand, but the impact is going to be focused on those that are critical inputs for clean energy technologies such as lithium, cobalt, copper, and neodymium. Figure 2 shows the surge in demand that is expected to take place in a net zero scenario over the next decades. The UAE does not have significant resources in any of the critical minerals listed by the IEA (IEA 2022). Hence, directly participating in the mining boom via mining minerals in the country is not a viable strategy for the UAE.

Figure 2: Total demand for selected minerals by end use in the Net Zero Scenario, 2021-2050



Source: IEA 2023b

The UAE can play a significant role in the minerals processing market even without having natural deposits of these critical minerals. It is the fourth largest exporter of aluminum without having natural deposits of bauxite ore which it imports from Guinea instead. As aluminum is an important input to many energy technologies the demand for it is expected to increase by 79% between 2020 and 2050 (International Aluminium Institute 2023). The ability to profit economically from the large demand for processed minerals without having natural deposits of the raw materials is something that China has been able to do very well. Currently, China holds around 35% of nickel refining, 50-70% of cobalt, and 90% of rare earth elements (IEA 2021b). This concentration on mineral processing activity in China has recently led to countries seeking to diversify their mineral supplies given geopolitical tensions[2].

Expanding beyond aluminum into the processing of other critical minerals will enable the UAE to benefit from efforts across the globe to diversify the critical minerals supply chain. This would be an opportunity for the UAE to capture the growth opportunities arising from the incoming mining boom even without having natural deposits in critical minerals. The UAE is well positioned to do so given its low electricity costs, conducive business environment, good geographical location, and established trading

[2] Examples of such efforts are the European Union's Critical Raw Materials Act, the United State's Inflation Reduction Act or Australia's Critical Minerals Strategy.

infrastructure. Additionally, the state-owned enterprise Emirates Global Aluminium (EGA)[3] has existing knowhow in this industry and would be well positioned to lead these efforts. The market dynamics will vary to some extent by the mineral. The UAE may, for example, be better positioned to focus on minerals whose processing require significant amounts of energy since cheap electricity is a source of comparative advantage for the country.

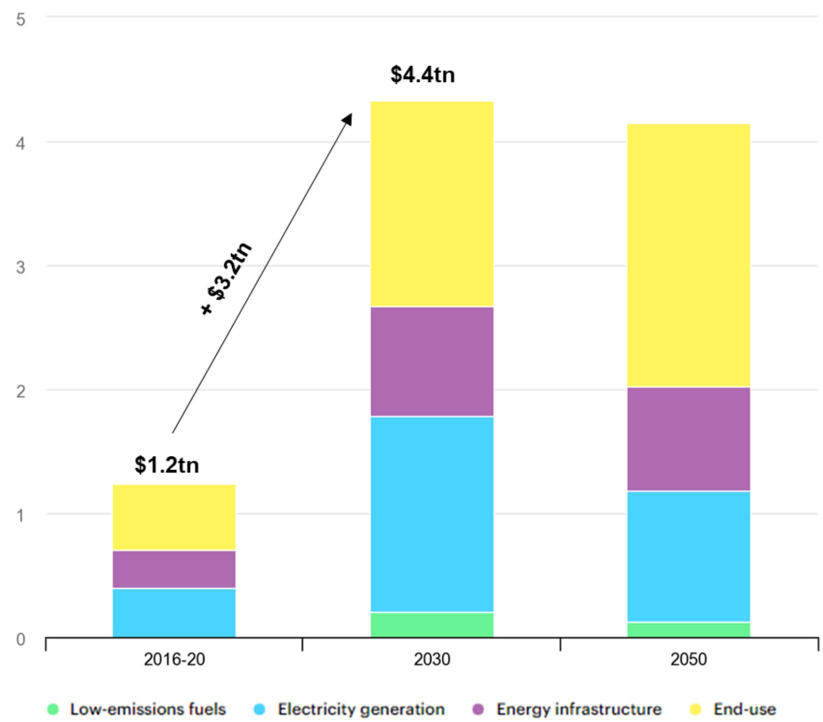
In terms of policy, the Ministry of Industry and Advanced Technology (MoIAT) together with EGA may lead or commission a focused study of the opportunities of specific critical minerals. This would help provide more detail regarding the investment opportunities and respective challenges. This study would have to address questions related to forecasted market dynamics of the respective minerals, it should identify potential customers, transport and processing costs, and barriers to entry for the UAE. The recent announcements of the Australian firm Lepidico to set up a lithium processing plant in Abu Dhabi showcase the potential that exists in this area.

Participating in Green Supply Chains

For the world to decarbonize an additional $3.2 trillion of investments by 2030 are needed across electricity generation, energy infrastructure, end use and low-emissions fuels (see Figure 3). This showcases how the demand for many products that enable decarbonization such as solar panels, electric vehicles, lithium-ion batteries, or transmission lines will increase. Many emerging products such as electrolyzers and grid-scale batteries are experiencing a similar dynamic. These are all products that have a longer production process and whose value chains are an area of opportunity for countries to participate in. In some cases, the low level of maturity provides ample opportunities to develop a comparative advantage and reap the economic benefits from rising demand for those products.

[3] EGA is owned equally by Mubadala Investment Company of Abu Dhabi and Investment Corporation of Dubai

Figure 3: Clean energy investment in the net zero pathway, 2016-2050



Source: IEA 2021a

The analysis of green supply chains mapped to the current capabilities of the UAE reveals a local concentration of chemicals and minerals. To analyze a number of these green supply chains we apply natural language processing techniques to industry-specific reports from the United States Department of Energy as well as the IEA[4]. In doing so we gain an understanding of the products that form part of the respective value chains and by using the product space methodology from Hausmann et al. (2014) we can evaluate how close they are to the current set of capabilities of the UAE. While these products also form part of other supply chains, we expect their involvement in green supply chains to increase demand for them in the future. Figure 4 shows all products that form part of the green supply chains. As the figure shows the range of products is wide and spreads across many different industries. When comparing global exports of green supply chain products with UAE exports of green supply chain products (Figure 5) it emerges that the UAE has a larger focus on Chemicals and Metals. The current set of capabilities in those green supply chain products can be informative to answer the question of which supply chain the UAE may be well suited to participate in.

[4] Most supply chain reports are from the Department of Energy of the United States (DoE); also utilized IEA reports on critical minerals and green hydrogen; excluded primary cells and primary batteries (HS code 8506), and semiconductor devices (HS code 8541), which are challenging to manufacture.

Figure 4: Green Supply Chain Products in the Product Space

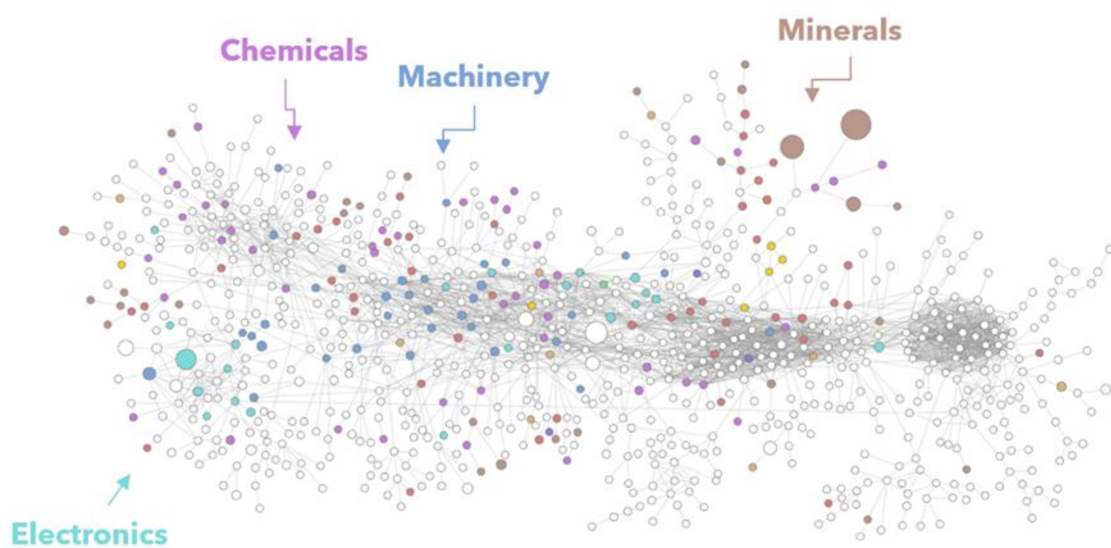
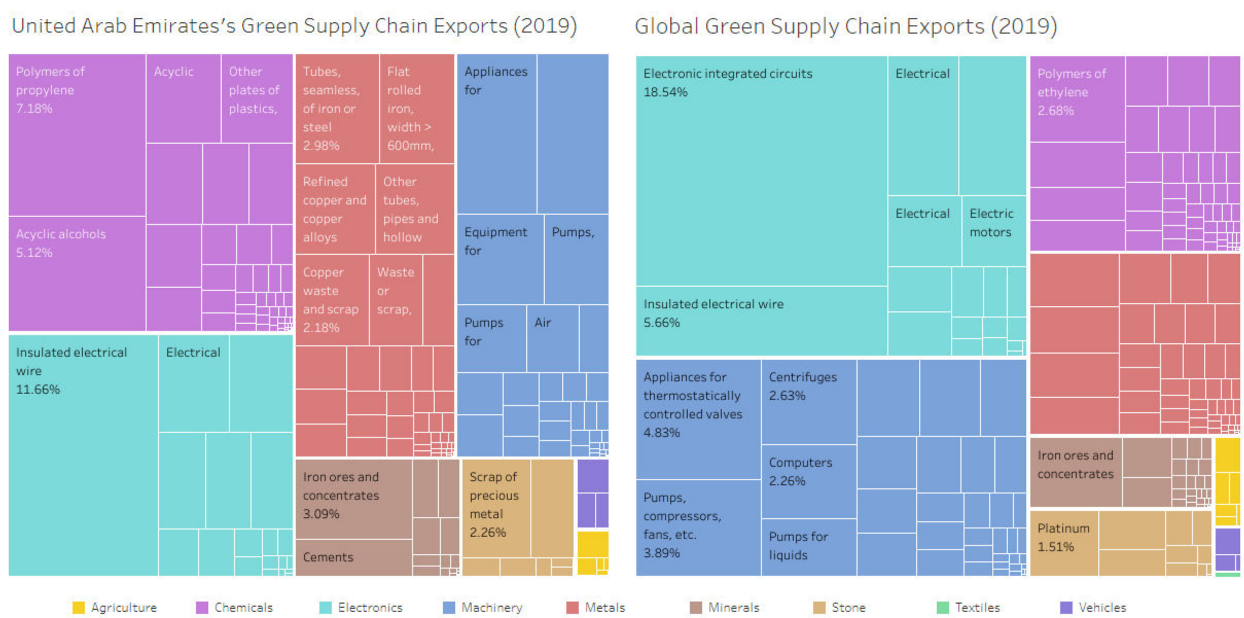


Figure 5: UAE & Global Green Supply Chain Exports



We can use different economic complexity measures to understand which of the green supply chains the UAE is better positioned to participate in.

Figure 6 does this by positioning the supply chains relative to the UAE's capabilities along a standardized measure of feasibility and attractiveness. The feasibility captures to what extent the UAE already has the capabilities in parts of the supply chain and how close they are to the existing capabilities. Attractiveness, on the other hand, is a composite measure of the extent to which developing a comparative advantage connects you to new attractive diversification opportunities and the growth rate over the past ten years. A detailed description is provided in the Appendix.

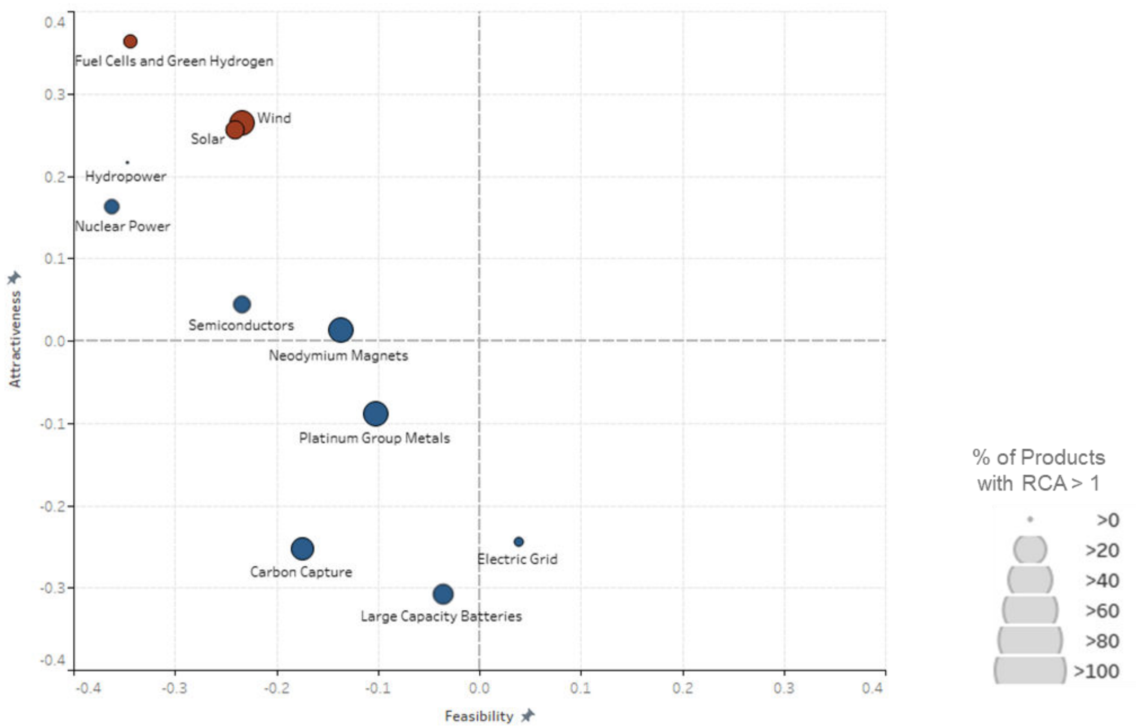
The fuel cell and green hydrogen supply chain, the solar supply chain, and the wind supply chain are the most appealing supply chains for the UAE just based on its current capabilities.

Figure 6 displays the tradeoff between targeting a supply chain that is closer to the current capabilities of the UAE, i.e. has higher feasibility, and one that may be more attractive as it opens up subsequent diversification opportunities. For example, the electric grid supply chain is closest to existing capabilities but is the third lowest in terms of creating opportunities for further diversification. On the other hand, the fuel cell and green hydrogen supply chain which is the most attractive one for the UAE in terms of offering subsequent diversification opportunities is also the one that is furthest away from its current set of capabilities. However, since both measures are standardized the distances on the axis can be compared so that in the tradeoff between attractiveness and feasibility the three supply chains that have the highest overall score are the fuel cell and green hydrogen supply chain, the solar supply chain, and the wind supply chain. These supply chains are significantly more attractive than all other supply chains but while they are low in feasibility the other supply chains are not that much more feasible. Tables 8-10 in the Appendix provide an indication which products within those supply chains may be strategic opportunities for the UAE to pursue. Given the novelty of this research this work will need further investigation and should be interpreted as indicative at this stage.

However, in an international comparison the UAE is far from being competitive in the supply chains identified – indicating the need for a concerted and sustained push. The previous analysis identified where the opportunities may arise given the UAE's current set of capabilities. However, as these tend to be global supply chains it is also important to situate this within the global context and analyze where the UAE ranks compared to other countries. In the case of the solar, wind as well as fuel cells and green hydrogen supply chain the UAE is at the lower end of the distribution in terms of feasibility. This signals that other countries may be better positioned to play a large role in this supply chain. While this should not be read as a sign that entering this supply chain is impossible for the UAE it does indicate that this is rather a "long jump" than a nearby opportunity. This implies that a concerted effort over a sustained period may be needed to enter these supply chains. While supply chains differ in their attractiveness given their complexity and future diversification outlooks,

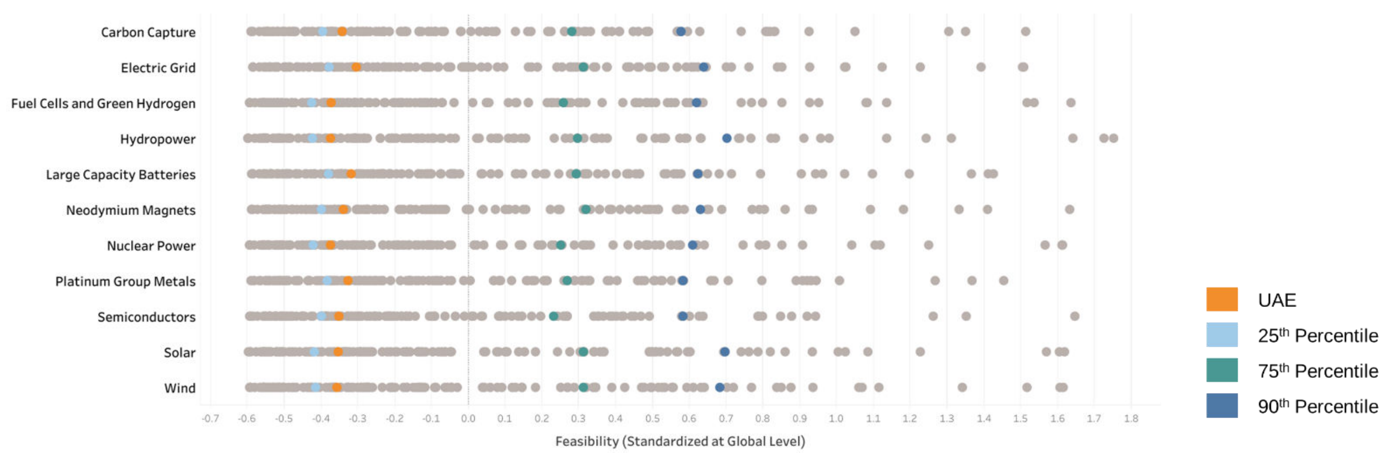
Figure 8 shows that the UAE currently has a comparative advantage in the lower complexity parts of nearly all supply chains. In turn, entering one of these supply chains will imply diversifying into more complex products. The Appendix provides tables by supply chains with the most attractive products for the UAE.

Figure 6: UAE Positioning in Green Supply Chains



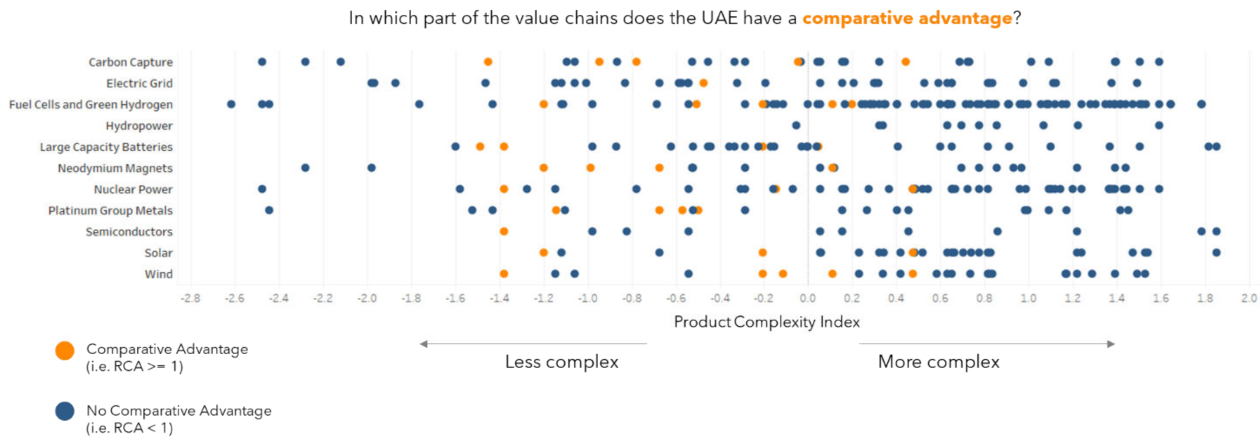
Source: Authors own elaboration based on DoE & IEA Reports as well as UNCTAD global trade data

Figure 7: Global Comparison of Capabilities in Green Supply Chains



Source: Authors own elaboration based on DoE & IEA Reports as well as UNCTAD global trade data

Figure 8: UAE's Positioning in Green Supply Chains in terms of Complexity



Source: Authors own elaboration based on DoE & IEA Reports as well as UNCTAD global trade data

Strategy 2: Make green versions of energy-intensive products for the world

Fossil fuels have allowed energy-poor countries to develop heavy industry, because of their low transportation costs. For most of human history, industry has located close to sources of energy: windmills and waterwheels accordingly ground grain and powered early manufacturing facilities. But fossil fuels are extremely energy-dense by volume and easy to transport, which made it possible for places with poor fossil fuel endowments and energy resources, such as Germany and South Korea, to engage in energy-intensive industrial activities like steelmaking.

Renewable energy is much more expensive to transport than fossil energy. Renewable electricity from sources such as solar and wind needs to be transported through power lines which are expensive to build, have limited capacity, and face large transmission losses. Converting renewable electricity into fuels such as green hydrogen involves large losses in energy, and these fuels are also very hard to transport. Solar PV became the cheapest source of electricity in 2020, providing a levelized cost of electricity of less than 34 dollars by barrel of oil equivalent (BOE) (International Energy Agency 2020). Still, in 2019, storing that energy in the form of green hydrogen increased the cost to over USD 476 per BOE on average (Bloomberg NEF, 2020). When converting the green hydrogen to green ammonia for more accessible transport, the costs increased to over USD 884 per BOE (Ibidem). Additionally, the transport of green hydrogen requires significantly higher degrees of infrastructure. Hydrogen would need 3-4 times more storage infrastructure to replace natural gas in today's global economy. This is anticipated to come at an expense of USD 637 billion by 2050 if it were to ensure a comparable degree of energy security (Ibidem).

Energy-intensive industries will therefore need to relocate near cheap sources of green energy as these industries decarbonize. Regions that develop competitive green sources of energy will be able to participate in this investment trend.

A New Comparative Advantage

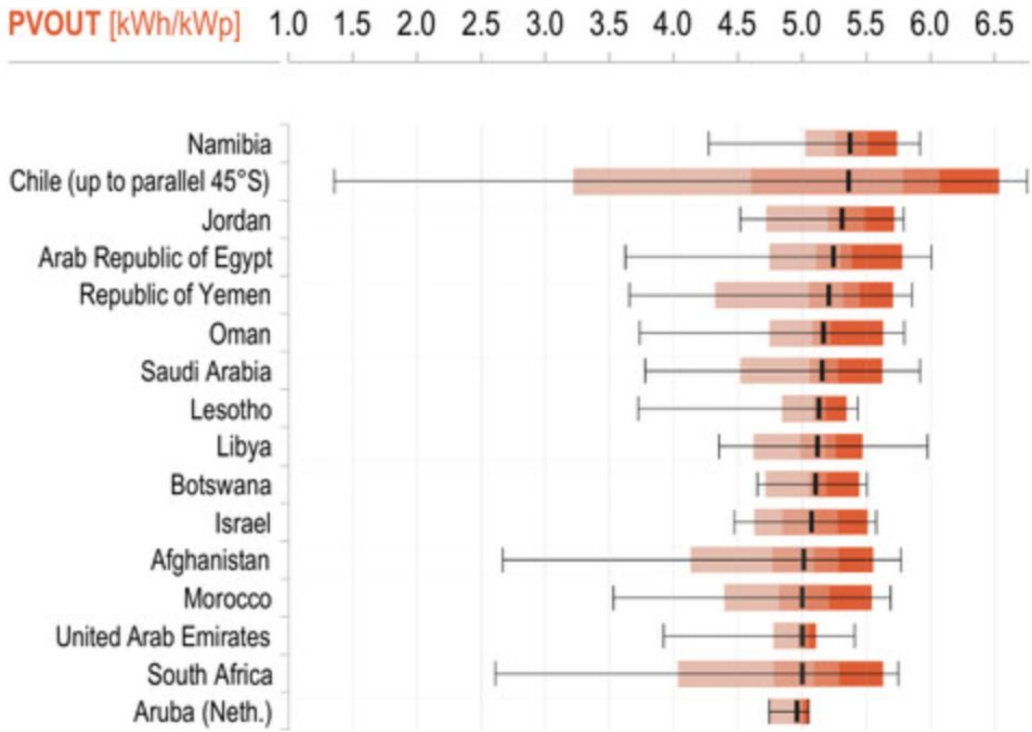
The UAE has remarkable potential for solar energy production, which should help it become competitive in attracting green heavy industries.

Figure 9 shows the seventeen countries with the highest maximum yields of photovoltaic power, excluding land with identifiable obstacles to utility-scale PV plants. The UAE ranks 14th in the world, with high maximum and median solar yields (comparable to Namibia, Saudi Arabia, or Egypt). This makes it an attractive location for the development of renewable energy projects. The scale of the UAE's generation potential is also very large: up to 60% of the Emirates' land mass is suitable for solar PV deployment, which could deliver over 10 exajoules of energy annually (WEF 2022). This is roughly equivalent to the energy output of 600 Al Dhafra solar fields.[5] The UAE solar potential is also very consistent, with only around 10 to 15 days of rain per year, and consistent output across

[5] Assuming Al Dhafra generates 4,700 GWh annually.

all seasons (WEF 2022). This is a huge asset in creating energy systems for net-zero industrial facilities, as it avoids the need for seasonal storage.

Figure 9: Solar Yields (Top 17 Countries)



Source: “Global Solar Atlas” n.d

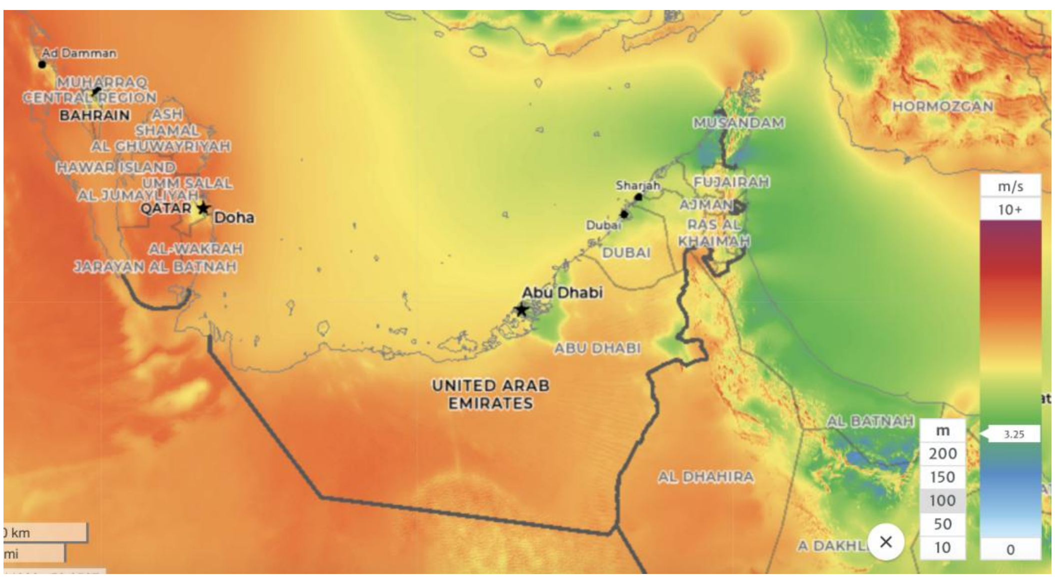
The UAE also had very low costs for financing and deploying solar projects, making it among the lowest-cost solar energy producers in the world. In 2023, the UAE awarded a contract to Masdar to build a 1.8GW solar park at its Mohammed bin Rashid Al Maktoum facility for USD 16.24 per MWh, which was among the lowest in the world (Hill 2023). Masdar, the UAE’s leading developer and operator of renewable energy projects, has been behind many of the UAE’s record developments.

The low financing cost can in part also be attributed to a very low cost of capital overall in the UAE which adds to its comparative advantage in a decarbonizing world. Given the stable economic and political environment in the UAE with no risk of the government defaulting, the country risk is very low as indicated by the 10-year yield on government bonds (see Figure 31 in Appendix). This positively impacts the cost of capital which otherwise can make investments in other countries with great renewable capacity at times cost prohibitive. Many of these large-scale utility projects as well as heavy industrial productions that may be attracted by the availability of renewable energy are highly capital intensive. The cost of capital, therefore, is a distinguishing factor that shapes the new comparative advantage together with the potential to provide stable low-carbon energy at affordable prices.

However, balancing the grid with renewable energy sources presents a problem for the UAE, and the UAE will have to likely rely on several different technologies to do so. Many industrial power users require 24/7 energy and are therefore incompatible with solar power's diurnal cycle. To localize clean industry in the UAE, the UAE needs to provide very competitively priced clean power across a whole daily cycle. Many places that seek to compete with the UAE in this respect have good sources of wind power at night, which can complement their daily solar cycle to provide 24/7 electricity. The UAE's wind power resources are middling, but the UAE can still be competitive in these industrial opportunities, owing to its low cost of finance, highly effective grid operators, and low cost of concentrating solar power. However, reducing the potential risks of intermittency will remain a key challenge.

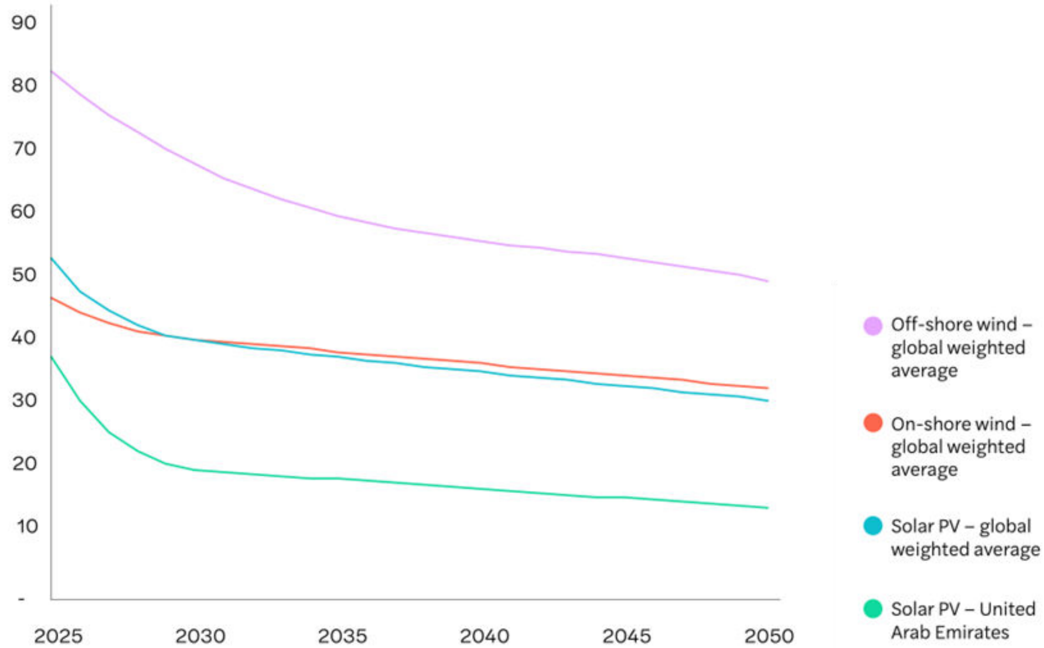
Wind offers potential in the UAE to help balance the grid and complement solar power's intermittency. Wind speeds in the UAE are middling, with the best winds in the south-west of the country and along the coast (Figure 10). While the UAE's wind resources will not make it competitive in international markets, wind can still be a useful resource in the UAE to balance the grid and complement solar power in renewable energy production. The UAE has started to develop its wind resources, with Masdar completing a 103.5 MW wind project in four locations across the UAE in 2023 (Benny 2023). These wind projects are feasible due to technological innovation which makes it possible to harness wind power even at lower speeds. Wind resources are particularly important where wind energy generates power during times when the sun is not shining, and the temporal distribution of winds in the UAE merits further study.

Figure 10: Wind Speeds in the UAE



Source: Global Wind Atlas 2022

Figure 11: Levelized cost of electricity over time ($/MWh)



Source: (World Economic Forum 2022)

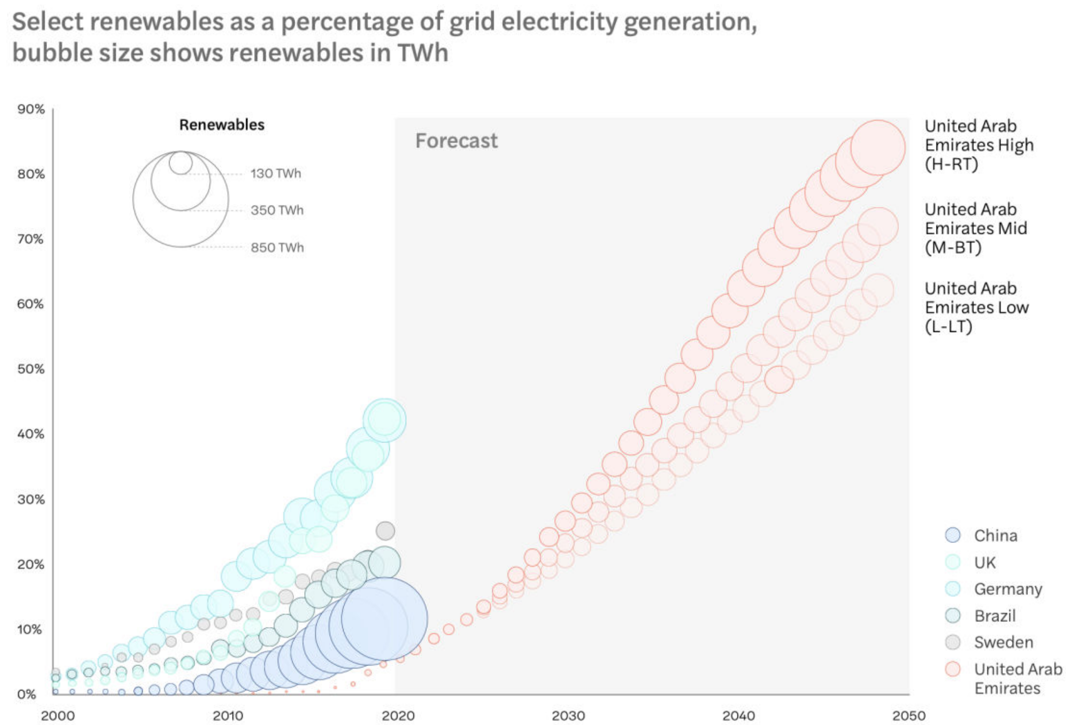
The UAE's ability to generate power cheaply using concentrating solar power is very important to balance the grid and provide low-cost heat for industrial power users. The UAE is among the world leaders in developing concentrating solar power, and this building is the world's largest CSP facility at Mohammad Bin Rashid Al Maktoum Solar Park. The UAE has reportedly been able to achieve a levelized cost of storage of 7.3 cents per kWh at this site ("Solar Energy | The Official Portal of the UAE Government," n.d.). This compares very favorably to energy storage with Lithium-ion batteries which have a levelized cost of storage of around $0.20 per kWh (Viswanathan 2022). An additional advantage of concentrating solar power when used as an energy resource for these 'strategy 2' opportunities is that much of the energy demand in heavy industry comes in the form of heat. Using heat from concentrating solar power in industry provides opportunities to deliver heat at low cost, even at night when the sun is not shining. There are, however, substantial logistical and plant design challenges involved in using heat from CSP plants directly in industry.

The UAE will nonetheless likely need a range of different energy storage technologies to generate clean power over a 24/7 period that is cheap enough to support low-carbon industrial production. Many of these technologies are currently at lab or pilot scale, requiring additional testing and deployment support. These technologies may include lithium iron phosphate batteries, flow batteries (particularly those employing very affordable chemistries, such as iron air batteries), thermal energy storage, and compressed air energy storage. Power from the UAE's nuclear facility, and existing utility-scale lithium battery storage technologies, is unlikely to be cheap enough on its own, at least under current system architectures.

Thermal energy storage systems (that are currently in pilot stage testing) will likely be a particularly important emerging technology for the UAE to develop 'strategy 2' industrial opportunities. These systems use electricity from solar PV or wind turbines to heat materials such as ceramic blocks, molten salts, or metals to very high temperatures, and then use these materials to provide heat in industrial facilities when renewable electricity is no longer available. These systems share substantial knowhow requirements in their design and operation with concentrating solar power facilities and are likely to be a good fit for the UAE's capabilities.

The UAE's grid is decarbonizing rapidly, but it remains too carbon-intensive to support the production of net zero industrial goods. This creates an incentive for the UAE to develop dedicated renewable generation capacity co-located with industrial production. The UAE's energy plan, announced in 2017, suggests that the UAE will aim to have 50% of its electricity powered by renewables by 2050 ("UAE Energy Strategy 2050 | The Official Portal of the UAE Government," n.d.). This rate of decarbonization puts the UAE behind other industrial competitors (Figure 12) and is likely insufficient to support industrial production of net zero energy-intensive goods. Fortunately, since 2017, solar power costs have come down such that solar power is now cheaper than fossil fuel generation in most circumstances. This makes it possible for the UAE to deploy renewable power generation more quickly than planned (World Economic Forum 2022). Decoupling energy-intensive industrial production from grid decarbonization will allow the UAE to move faster in developing heavy industries, keeping pace with international competitors.

Figure 12: UAE Grid Decarbonization Compared with Industrial Peers



Source: World Economic Forum 2022

Develop Green Industrial Parks in the UAE

The UAE should develop net zero industrial parks, co-located with renewable energy generation assets and other common infrastructure, that act as a platform for the production of multiple energy-intensive industrial goods. The UAE has some of the world's lowest costs of renewable energy but transforming the overall grid is a large challenge. Green industrial parks are an opportunity to leverage this potential and attract industrial users who need to switch to low-carbon production processes. As many of these industries will look to relocate their activities closer to the source of cheap renewable energy this is a policy that seizes the potential of the UAE in the wake of shifting global production patterns in a decarbonizing world. Importantly, it builds on the low cost of capital of the UAE, its attractive business environment, and well-developed trade infrastructure.

Heavy industries such as steel, aluminum, and hydrogen production are so sensitive to energy costs that development should minimize the cost of energy transportation infrastructure such as electric grids and pipelines. This necessitates co-locating heavy industries with solar PV fields and other renewable generation assets. Many heavy industries require a combination of capabilities to fully decarbonize, including low-cost renewable electricity, low-carbon heat, hydrogen, and carbon capture (DOE 2023a). It is very challenging for industrial companies that specialize in making a particular product to develop these capabilities on their own. Providing all these capabilities in a defined geography minimizes costs and allows companies to develop and deploy solutions that make use of a common infrastructure. Purchases of low-carbon industrial goods also require rigorous carbon accounting, which is easier to do where inputs are clear and traceable, instead of coming from many different places with poor carbon traceability

The path to decarbonizing many of these industries is specific to the industry and technology pathway that the industry uses, but the decarbonization of these industries requires many common inputs. These include:

- Low-cost renewable energy that is in most cases available 24/7.
- Clean, high-temperature heat for industrial processes that does not come from fossil fuels.
- Low-carbon hydrogen, that can be used as a feedstock for some industrial processes and a fuel for others.
- Carbon capture, to capture emissions from chemical processes (like reduction of limestone in cement), from burning fossil fuels that must be used, and to provide a carbon feedstock for production of synthetic fuels and chemicals.
- Access to natural gas coupled with carbon capture is useful (but not necessary) as a transition fuel in some industries before green hydrogen supplies are available at scale, such as in the production of steel from Direct Reduced Iron (DRI) furnaces, and to provide blue hydrogen.

Green industrial parks would be special economic zones that develop these capabilities in a defined region and make them available to heavy industrial users who want to operate in the parks. The UAE is very well-placed to develop these parks, as all required capabilities are within reach in defined geographies. The UAE also has specific initiatives that develop these capabilities or related industries, including plans to develop green hydrogen production, carbon capture, and sustainable aviation fuels. Green industrial parks involve looking past sector-specific verticals and strategies, and instead developing the capabilities needed for green heavy industry in one place, to both attract and empower private sector actors in the green transition. The opportunity is huge: up to 60% of the Emirates' land mass is suitable for solar PV deployment, which could deliver over 10 exajoules of energy annually (World Economic Forum 2022). This is roughly equivalent to the energy output of 600 Al Dhafra solar fields.

One of the biggest challenges involved in developing green industrial parks in the UAE lies in managing grid intermittency. The UAE solar output is also very consistent, with only around 10 to 15 days of rain per year, and consistent generation potential across all seasons (World Economic Forum 2022). This is a huge asset in creating energy systems for low-carbon industrial facilities, as it avoids the need for seasonal storage.

Nonetheless, many heavy industries require continuous 24/7 power supplies, in the form of electricity, heat, or hydrogen, and net zero parks will need substantial firm power throughout this daily cycle. One way to overcome this challenge is to build green parks in regions with complementary solar and wind resources—where the sun shines during the day and the wind blows at night. These regions exist in places like Namibia, Oman, Morrocco, and Australia, where industrial facilities are under active development. The UAE should develop its wind resources, which it has started to do, but wind resources in the UAE are middling.

The UAE's concentrating solar power (CSP) capabilities represent an asset in energy storage and grid management. The UAE is a world leader in developing concentrating solar power and is building the world's largest CSP facility at Mohammad Bin Rashid Al Maktoum Solar Park. The UAE has reportedly been able to achieve a levelized cost of storage of 7.3 cents per kWh at this site ("Solar Energy | The Official Portal of the UAE Government," n.d.). This compares very favorably to energy storage with Lithium-ion batteries which have a levelized cost of storage of around $0.20 per kWh (Vilayanur Viswanathan 2022). Storing and using energy as heat rather than electricity can also help solve this intermittency problem. Around half of industrial energy use is in the form of heat rather than electricity (DOE 2022). Storing energy as heat for use in industry (from CSP or thermal batteries) is markedly cheaper than storing energy in electrochemical batteries. The UAE can also pair exothermic industrial processes (such as Fischer-Tropsch processes) with endothermic processes (such as glassmaking or carbon capture) to minimize energy requirements. Otherwise, the UAE will need to deploy a portfolio of technologies to balance the grid, employing emerging low-cost storage technologies and battery chemistries, such as metal-air batteries and flow batteries, with natural gas peaker plants coupled with carbon capture as a backup generation source while emerging technologies to balance the grid at low cost remain pre-commercial.

The industrial actors producing in a green park will have to find ways to charge premia for their green products. While energy costs represent a substantial portion of the final cost for these industrial goods, they often represent a very small portion of the value of final consumer products: substituting grey steel for green steel might add 0.5% to the cost of a car in 2030. Charging premia will be easier when selling to customers with higher margin products, and that have direct relationships with consumers (charging green premia to luxury car manufacturers, for example, will be easier than charging green premia to construction companies). It will also be easier to recoup additional costs for green products where regulation or carbon border taxes oblige importers to buy green products or pay for embodied carbon. The EU has adopted carbon border taxes for aluminum, iron and steel, cement, fertilizer, electricity, and hydrogen. The US has announced an intention to adopt carbon border taxes for aluminum, iron, and steel, in part to encourage relocation of its supply chains outside China.

Regulations for accessing green premia and accounting for embodied carbon are complex and represent real costs of doing business for companies that try to make green products. Similarly, accounting for carbon and attracting companies that want to voluntarily pay green premia to appeal to certain consumer groups is challenging for individual industrialists who specialize in manufacturing products like cement or steel. Green parks should support companies in navigating these requirements, to reduce the costs of doing business to industrial players that locate within these parks. This could establish sufficient domestic demand to develop companies providing carbon accounting services which could then use their knowhow to export these services abroad.

Building and operating green industrial parks will require a supportive ecosystem of suppliers, technology providers, design and maintenance experts. Industry representatives expect a supply crunch for many parts of green industrial park ecosystems like hydrogen electrolyzers, and new technologies that are currently being piloted. Developing and managing an ecosystem of companies and suppliers that support a green industrial park will be essential for the UAE to successfully execute this strategy. The UAE can do this by (1) developing expertise in required technologies, systems, and supply chains required to operate a green industrial park; (2) conducting outreach, visiting these companies, and building relationships; and (3) sending a strong demand signal to appropriate companies that incentivizes them to operate in the UAE, and to prioritize the UAE above other locations they are considering for piloting, deployment, etc. The recommendation of a strategic acquisition of an EPCM company (outlined below) is an example of that. Engineering services will certainly be a key input to the green industrial park ecosystem. Other services may include carbon accounting as companies face the need to certify their low-carbon production process, specialized logistic services for the export processes and financial services with focus on green finance. The importance of the respective inputs and services will likey vary by industry and their identification will require more work.

Green industrial parks and certain industries which they serve (such as hydrogen) may involve large economies of scale in some cases with implications for land requirements. In other cases, new technologies, pilot processes, and specialized industrial applications may be smaller and more iterative. Parks may be able to start small and expand according to demand and market signals. In the long term, at least for certain industries, these parks may be very large (as envisioned by certain hydrogen oases in the UAE's current plans for a green hydrogen industry). The two most important areas which will require land is firstly the area for the green industrial park itself and secondly the land required for the renewable electricity generation. Most energy generation is likely to take place in Abu Dhabi, which has much of the available land, and the highest solar capacity and wind speeds. It would be favorable for industrial production to take place along the coast, to allow for low-cost shipping to export markets. Parks should otherwise be located to minimize the cost of developing infrastructure for common inputs such as carbon capture and ports and to incorporate existing heavy industrial sites in the UAE where possible. Globally, these parks are being scoped in large, costal deserts. Many of these sites exist: developing good supportive infrastructure, with proximity to workers, suppliers, logistics, and industrial capabilities, early on is key to positioning the UAE to best take advantage of these trends. In a next planning phase of respective parks these land requirements and the trade-offs between co-locating different areas relative to building more transmission infrastructure would have to be studied in more detail.

Potential Industries To Target

The success of green industrial parks depends on their ability to provide favorable conditions to anchor one or several energy-intensive industries. The industries in question are a small number of heavy industries that are responsible for an outsized share of global energy use and CO2 emissions in the industrial sector. They include cement, iron and steel, aluminum, ammonia and fertilizer production, glass production, and chemicals and refining. Hydrogen production and production of sustainable fuels for shipping, aviation, and heavy-duty transport are also expected to take large volumes of energy in a net zero world. The opportunity for the UAE lies in using its comparative advantages to localize the low-carbon production of these industries and export their products to the global market. We consider each of these industries in turn below.

Cement

Cement is responsible for 7-8% of the world's carbon emissions. It is a combination of calcium, silicon, and aluminum. The traditional process of making cement involves mixing limestone (calcium carbonate), clay, and other materials in a rotary kiln heated to 1400^{o}C. Around 51% of cement's carbon emissions come from process emissions involved in reducing limestone, and another 34% of emissions come from fossil fuels typically used to generate high kiln temperatures. Decarbonizing cement made through this process is likely to involve a combination of carbon capture for process emissions, electrification, provision of low-carbon heat sources, and green fuels like hydrogen (DOE 2023b). There are wide regional variations in costs for accomplishing this.

Cement is a modestly promising industry for the UAE to attempt to localize in green industrial parks. Cement is a heavy commodity product with a low weight-to-value ratio and is therefore expensive to transport. It is used ubiquitously and made with materials that are readily available in many regions. Although the global cement market is large, valued at 343.5 billion U.S. dollars in 2022, and growing fast, with a CAGR of 5.1% (SKYQUEST 2023), most cement is used close to where it is produced and relatively little is traded internationally. International trade in cement in 2021 amounted to $14.8 billion, of which the UAE exported $669 million. The UAE also exported $502 million of limestone for use in cement production (Harvard Growth Lab 2023). The UAE has fifteen integrated cement plants with 31 million tons per year production capacity, mostly located in Ra’s al-Khayamah. Cement producers typically have low pricing power: buyers of cement are construction companies with low margins, and the industry has many producers of a commodity product. This industry structure is, however, endogenous to current technology and production methods, and may change as countries adopt decarbonized production methods. Previous technology changes in the cement industry increased economies of scale, leading to larger plants, higher margins, and trading of cement over longer distances (Millet et al. 2023). Carbon pricing on cement in some regions, such as under Europe's CBAM, is likely to create premia for green cement, and geographical variation in renewable power resources and carbon capture facilities is likely to generate much larger dispersions in production costs for cement in different regions (Mckinsey 2023). As a result, one might expect green cement to be more broadly traded internationally in the export markets in the medium term.

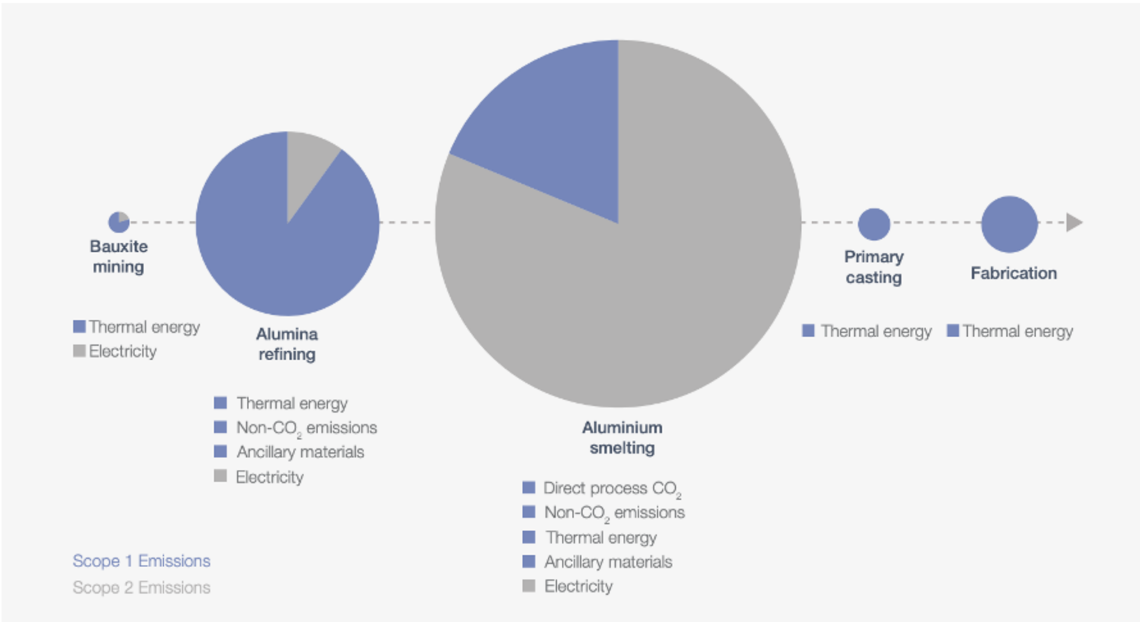
In the long term, new technologies for making cement that are currently in pilot stage are likely to substantially alter production methods, which the UAE would be prudent to monitor. One technology that seems promising is the electrolysis of low-carbon sources of calcium at low heat to make calcium silicate materials. This technology could be compatible with variable solar energy production and substantially decarbonized as the process of cement making by avoiding process-based CO2 emissions and employing much lower temperature heat sources. There are several other potential chemistries and technology pathways for making low-carbon cement.

Aluminum

Low-carbon aluminum is a significant growth opportunity for the UAE. The current global export market of aluminum is $70bn and demand for aluminum is expected to increase by up to 80% by 2050 (Mission Possible Partnership 2023) as it is an important input to many products and technologies that are required for a transformation to a net-zero economy (such as electric vehicles, grid infrastructure, etc.) and many other products. Producing aluminum is energy-intensive: it involves processing bauxite ore to extract aluminum oxide and then electrolyzing aluminum oxide at temperatures of around 950 ^{o}C. Aluminum production accounted for about 3% of the world's direct industrial CO2 emissions in 2022 (IEA 2023a). The UAE is the world's fourth largest exporter of unwrought aluminum capturing 8.3% of the global market ($5.78bn). The export of unwrought aluminum is an important exporting activity for the UAE and has been a driver of growth as exports grew by $4bn between 2010 and 2021 (Appendix - Figure 30). Besides the UAE the largest exporters of unwrought aluminum in 2021 were Canada (10.3%), Russia (11%), and China (31.6%) (Appendix Figure 29).

Decarbonizing aluminum primarily involves supplying low-carbon electricity to aluminum refiners and smelters, with some high-temperature, low-carbon heat in the refining process. It also involves adopting electrodes that do not emit carbon dioxide during electrolysis. The majority of emissions in the production come from electricity used in smelting alumina to aluminum. Decarbonizing the refining process involves substituting fossil fuels for heat provision with electric boilers, and using some other low-carbon heat source, such as green hydrogen. Around 10% of aluminum emissions come from the decomposition of carbon electrodes in the smelting process, which can be avoided by substituting with inert electrodes (Figure 13). Aluminum production can be compatible with intermittent renewable electricity: although aluminum smelters typically need to run 24/7, they can modulate their electric current requirements up or down to support grid balancing (World Economic Forum 2020).

Figure 13: Breakdown of Emissions in Aluminum Production



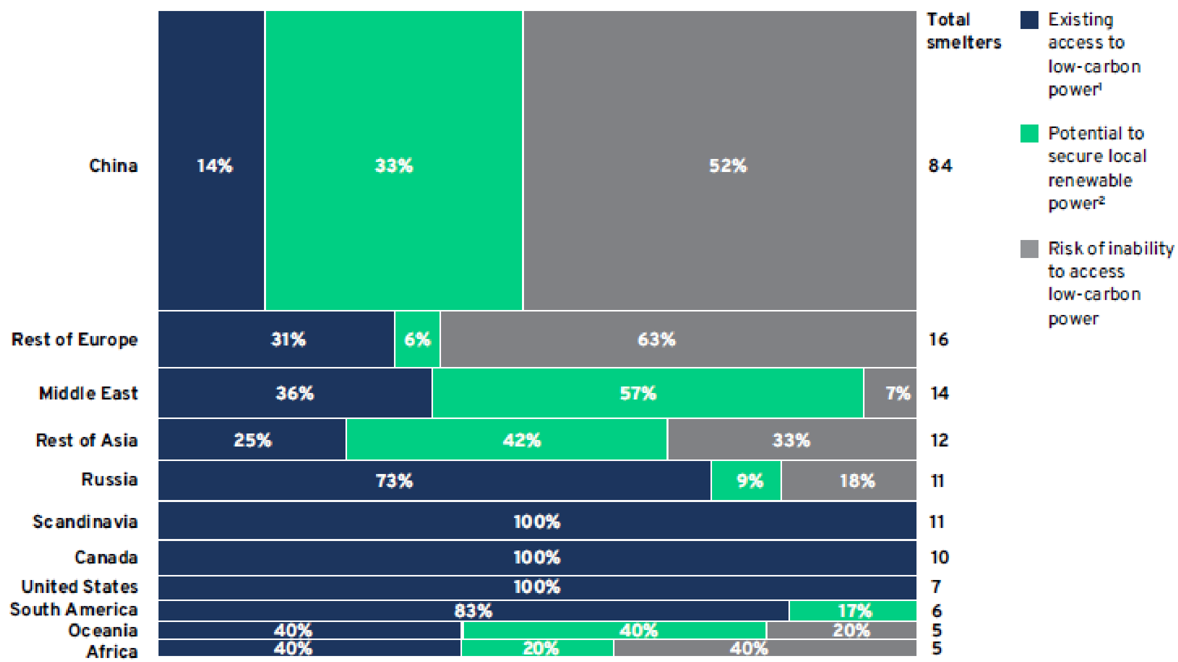
Source: World Economic Forum 2020

Expected costs for decarbonizing aluminum will vary widely between regions depending on electricity source and brownfield plant configuration. Places with low-cost clean energy will be able to smelt aluminum without incurring much additional cost. Aluminum producers with captive fossil fuel power plants will face the highest decarbonization costs, as they will need to install CCUS at their plants. Costs for doing so may amount to an additional $500 per ton of aluminum. Decarbonizing bauxite refining will add between 150 and $200 per ton to the cost of aluminum. Replacing carbon anodes with inert anodes in brownfield plants will likely increase the costs by up to $200 per ton of aluminum, whereas building Greenfield plants with inert anodes may reduce costs by a similar amount. The market price of aluminum is expected to be around $2500 per ton in 2025 (Mission Possible Partnership 2023).

Decarbonizing aluminum production is a commercial imperative for the UAE. Aluminum is an important sector for the UAE with exports of $7.19 billion, with electricity for production largely provided by natural gas. Around 40% of these exports are to the US and Europe (Harvard Growth Lab 2023), which have announced their intention to impose carbon-based trade barriers on carbon-intensive aluminum (White House 2021). Aluminum production in North America, Europe, and South America is largely based on hydropower, with comparatively low carbon intensities (Figure 14). This could put exports from Emirates Global Aluminum to the US and Europe at risk.

Decarbonizing aluminum also offers the UAE a significant opportunity. The UAE is expected to be one of the lowest-cost producers of green aluminum, owing to its cheap renewable power. By contrast, many of China's aluminum producers are stranded, because they have been built alongside captive coal-fired power plants, for which installing carbon capture is either impossible or prohibitively expensive (Figure 14).[6] This will significantly reshuffle global production patterns as China is currently the largest exporter of aluminum and may open up opportunities for the UAE. The structure of demand for aluminum also makes it possible to earn respectable green premia for low-carbon aluminum. Producers of high-value consumer products (such as cars and electronics) purchase substantial amounts of aluminum, are not hugely price sensitive, and can pass green premia onto their customers. Emirates Global Aluminium estimates that it currently earns a premium of 20% on its green aluminum which it sells to European car makers, making its investments in green aluminum profitable. Carbon border taxes such as the EU's CBAM are likely to provide additional support to prices for green aluminum.

Figure 14 Access to low-carbon power supply by smelter in 2020, % of regional smelters



¹ Includes captive hydropower, renewables, PPAs, and grids with carbon intensity currently less than 100 g CO_2/kWh.
² Defined by geolocational data for smelters with local capacity factors for solar PV or wind power greater than 20% or 30%, respectively.

Source: Mission Possible Partnership 2023

Emirates Global Aluminium (EGA) is already pioneering the production of green aluminum – a larger production rollout depends on the greening and capacity of the electric grid. Currently, EGA is producing 57,000 tonnes of green aluminum which makes up about 2% of their overall production. Its remaining production is based on captive

[6] Acknowledging this reality, Chinese aluminium producer the Hongqiao Group recently relocated an aluminium smelter to a new hydro-powered smelter in Yunnan (World Economic Forum 2023).

natural gas turbines at its production sites in Jebel Ali (Dubai) and Al Taweelah (Abu Dhabi) which have a total power generation capacity of 5.85 GW. The production of its green aluminum is based on solar power generated by the Emirates Water and Electricity Company (EWEC) in the solar power park Noor Abu Dhabi and Dubai Electricity and Water Authority (DEWA) from its Mohammed bin Rashid Al Maktoum Solar Park. EGA purchased clean energy certificates for 1.1 million MWh of electricity from EWEC for this production. Future plans may involve the Barakah nuclear power plant (The National News 2022). Ramping up green aluminum production depends on the availability of dedicated renewable energy for EGA.

Iron and Steel

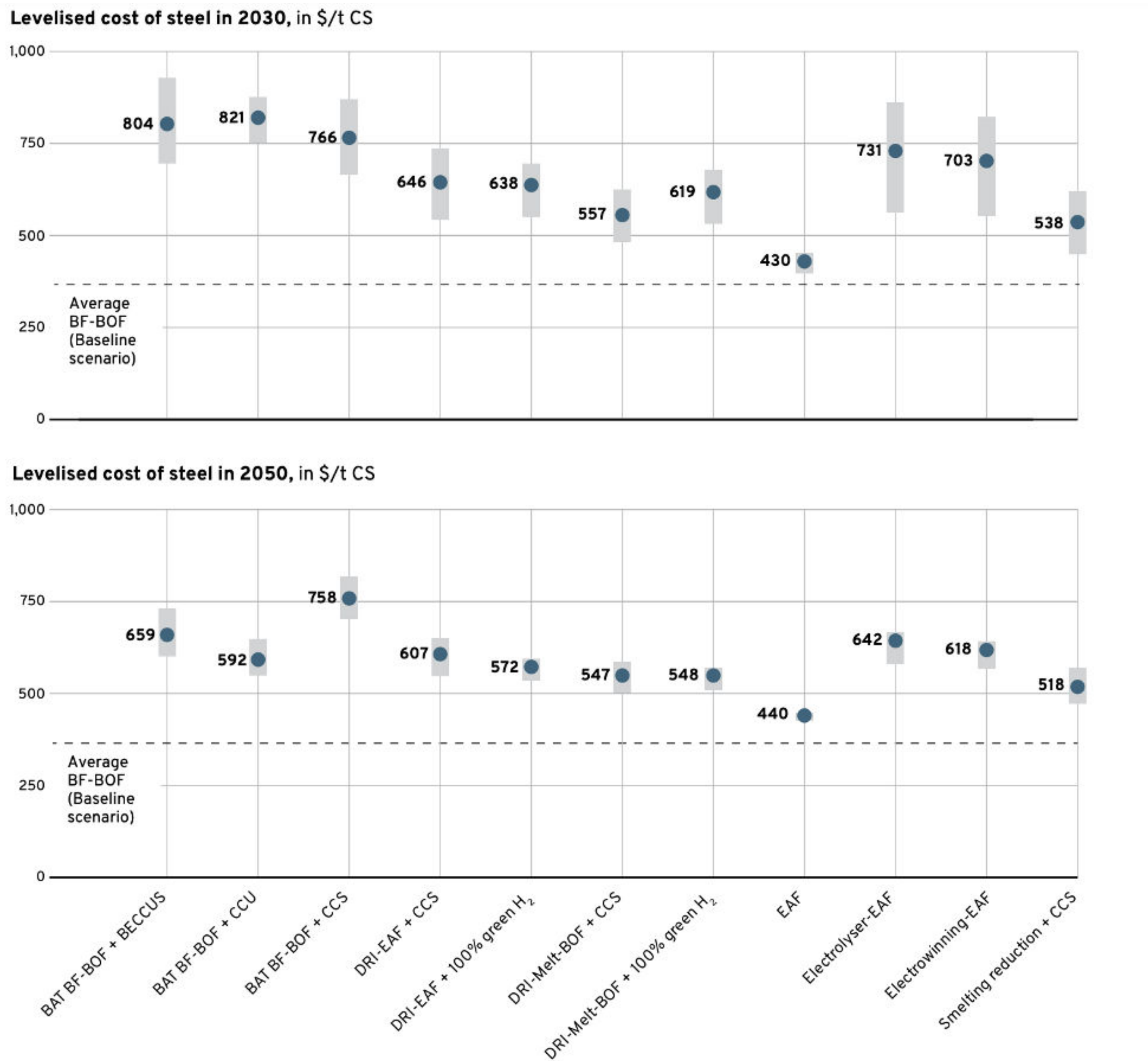
Decarbonizing steel production requires rapid build-out of new low-carbon steel-making facilities, which the UAE is well positioned to host. Steel production is responsible for 7% of global carbon emissions annually. It is extensively traded internationally, with around 25% of global steel production traded in export markets (Mission Possible Partnership 2022b). Traditional steelmaking involves reducing iron ore with coal in a blast furnace (the BF-BOF process). There are several pathways to decarbonizing steelmaking: the primary one involves switching to reducing iron ore using hydrogen and transforming iron into steel using an electric arc furnace (H2-DRI-EAF). Other pathways include fitting steel plants that use coal or natural gas with carbon capture, producing steel using bioenergy, and directly electrolyzing iron ore; these pathways are expected to be more expensive than the H2-DRI-EAF pathway, but there are substantial uncertainties around technology development and production costs will differ greatly in different locations for different pathways. Modeled net zero scenarios also include a larger role for scrap steel recycled using electric arc furnaces that are powered by renewable energy, but in 2050 the world will still need large volumes of primary steel production capacity to meet the growing steel demand. A net zero world will require a rapid build-out of new H2-DRI-EAF primary steel plants with 71 new plants needed to be built by 2030, and steel produced using this method is expected to supply between 35 to 45% of the world's demand for steel in 2050. Each new plant involves substantial investment, requiring around 5 gigawatts of renewable power generating capacity (Mission Possible Partnership 2022b).

Low-carbon steel production is a good commercial opportunity for the UAE. The international market for steel in 2021 was $545 billion, and around 25% of steel production is traded in export markets. The UAE exported $4.35 billion of steel in 2021, amounting to a 0.8% market share. China is by far the world's largest steel exporter, with around 12% market share, and annual exports of over $63 billion in 2021 (Harvard Growth Lab 2023). China's steel production is largely made with domestic coal resources; decarbonizing this production involves installing carbon capture at existing facilities which is likely to render production uncompetitive against new H2-DRI-EAF plants in favorable locations (Mission Possible Partnership 2022b).

The UAE is well placed to develop low-carbon steel production. The UAE produces 5 million tons of steel per year (which is expected to rise to 6.5 million tons by 2030) (WEF 2022). Its largest steel producer is Emirates Steel Arkan (with a capacity of 3.5 million tons). Emirates Steel Arkan is a capable exporter: 45% of its steel production is sold within the UAE, and 55% is traded in international markets (Rahman 2022). Its existing production capacity relies on natural gas-fueled direct reduced iron furnaces (Gnana 2021), which can be modified to use hydrogen as a reducing agent when hydrogen supplies become available in sufficient quantities. The UAE has the capability to produce steel, access to natural gas as a transition fuel, and the potential to be among the lowest-cost producers of renewable electricity and hydrogen. Emirates Steel has declared an intention to explore building a green steel hub in Abu Dhabi (IEEFA 2023) and is reportedly exploring a joint venture with JFE Steel involving producing direct–reduced iron (DRI) or hot briquette iron (HBI) in Abu Dhabi using local natural gas (Bloomberg NEF 2023).

Although green steel is likely to remain more expensive than carbon-intensive steel made using the BF-BOF process, the UAE will likely be able to earn a premium on its green steel production in international markets. The UAE is well positioned to deploy the two green steel production methods that are expected to be the cheapest: DRI furnaces using natural gas and carbon capture, and DRI furnaces using green hydrogen (Figure 15). As the cost of steel represents a small share of most consumer products and construction initiatives, it is likely to be possible to pass on these costs to end consumers (Figure 16). This is particularly true given that many countries seek to impose carbon border taxes on steel, such as Europe and the US (White House 2021). Other green steel manufacturers have been able to charge premium prices: H2 Green Steel charges a 25% premium, and SSAB's green steel will cost 300 euros ($325) per ton more than unabated steel.

Figure 15: Levelized Cost of Steel Made Using Different Production Methods



Source: Mission Possible Partnership 2022b

Figure 16: Cost of Steel as a Share of Final Products

Price difference of products containing steel produced by an average DRI-EAF fed with 100% green hydrogen (Carbon Cost scenario) compared to steel produced by an average BF-BOF (Baseline scenario)

Consumer Good	2020	2030	2040	2050
Passenger car	~$37,500	+0.5%	+0.4%	+0.3%
Building	~$0.8m	+2.1%	+1.9%	+1.4%
White good	~$400	+1.5%	+1.4%	+1.0%

Note: Percentage values show how much steel input prices would increase the final consumer price if the remaining bill of materials for the product remained the same as in 2020 with no inflation, assuming higher steel input costs do not induce any changes in product design.[xxi] The goods in question are assumed to require only crude steel. In reality, consumer products such as these would require finished or speciality steel products. However, the decarbonisation of steelmaking is expected to have a less significant impact on the cost of finishing processes and specialty steelmaking than on crude steel production. Consequently, the additional costs associated with steps beyond crude steel manufacturing have been excluded.

Source: MPP analysis; ETC and Material Economics, **https://www.energy-transitions.org/publications/steeling-demand/**; McKinsey & Company and ETC, **https://www.mckinsey.com/business-functions/sustainability/our-insights/net-zero-steel-in-building-and-construction-the-way-forward**

Source: Mission Possible Partnership 2022b

Changes in steel production methods will have large implications for steel manufacturing supply chains. DRI production methods require higher grades of steel ore than blast furnaces, and only 13% of ore shipped today is suitable for DRI production methods. Meeting demand for these production pathways will require additional processes to upgrade ore, or mining new higher-quality deposits of iron ore. Supply chains will also have to develop to accommodate the build-out of new plants using new technologies, and build-out of infrastructure for renewable electricity production, transmission, and hydrogen production. Steel producers using the H2-DRI-EAF method should take active steps to develop their supply chains and secure sources of appropriate iron ore.

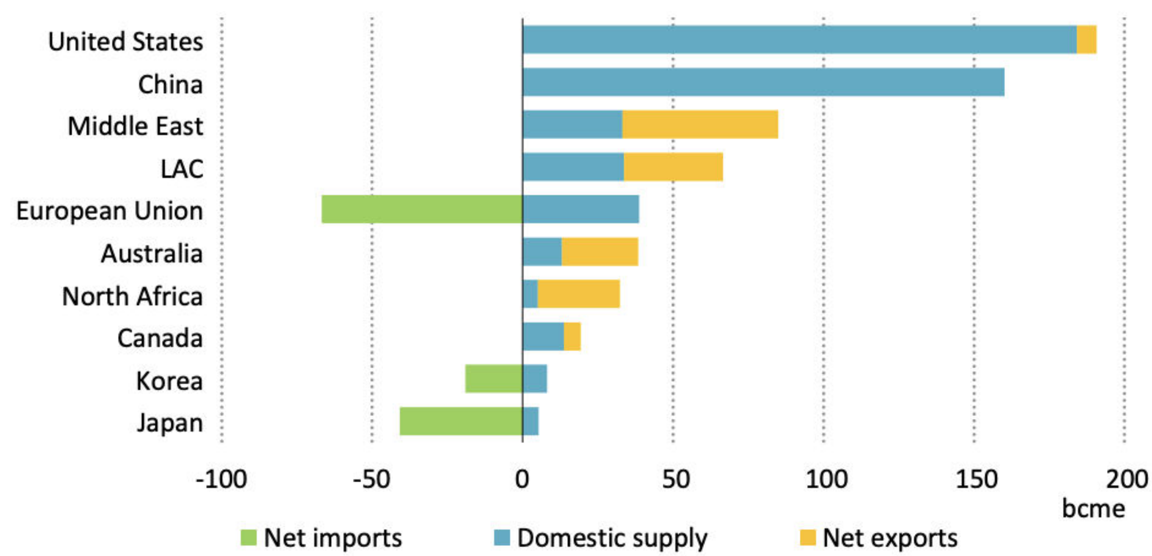
New technologies will likely emerge to enable the production of green steel in new ways, that the UAE should keep track of. A particularly promising one is the direct electrolysis of iron ore. This requires large volumes of firm power and has, as yet, been targeted close to hydropower resources. But should the UAE deliver competitive firm clean power available 24/7, this production method may become competitive in the UAE. An advantage of this production method is that it is expected to make use of lower-quality iron ore deposits than those required for DRI furnaces, alleviating this supply constraint.

Glass Production

Glass production requires many of the capabilities that the UAE would develop in green industrial parks. Glass production is responsible for roughly 0.3% of global carbon emissions (DOE 2023a). It is made by heating silica (from sand), soda ash, and limestone to a temperature of around 1700°C, removing bubbles and impurities, forming it into desired shapes, and undergoing finishing. 91% of carbon emissions from glass production come from the provision of electricity and high-temperature heat. Decarbonizing glass production involves providing cheap low-carbon electricity and using alternative fuels like hydrogen to provide high-temperature heat, coupled with some material substitution or carbon capture for process emissions. This would make glass production a good fit for green industrial parks in the UAE.

Green glass production represents a promising commercial opportunity that the UAE should monitor. The global market for glass in 2022 was $265 billion (GMI 2023), of which roughly 1/3, or $86.8 billion was traded internationally (Harvard Growth Lab 2023). China holds a 26% market share in glass exports, and the UAE holds a 0.7% market share, amounting to around $600 million annually. Glass production does not currently face carbon border taxes, but glass costs makeup a small fraction of total costs of many consumer products such as cars and electronics, which suggests it may be possible to pass on premiums for green glass to and consumers. As Europe's CBAM and other carbon border tax regimes develop, they may expand to incorporate additional products such as glass.

Figure 17: Projected low-emissions hydrogen demand and production by 2050



Note: bcme = billion cubic meters of natural gas equivalent (equivalent to 36 petajoules). Includes trade of hydrogen and hydrogen-based fuels. Final use may not be in the form of gaseous hydrogen. LAC = Latin America and the Caribbean

Source: International Energy Agency 2023

Hydrogen

Hydrogen is a crucial part of the global energy transition as it offers a pathway for the decarbonization of hard-to-abate sectors. Due to its versatility as an energy carrier hydrogen has received a lot of attention and its market is believed to have the potential to grow to US$1.4 trillion per year by 2050 (Deloitte 2023). It is already used at a global scale today with production reaching 95 Mt in 2022 and the vast majority of it being used in the refining, chemical, and steel industry[7] (IEA 2023c). The use cases of hydrogen in the future are believed to be much broader and range from sustainable transport fuels to grid storage applications. The main transformation and green growth opportunity lies in the transformation of the production process towards low-carbon hydrogen. Currently, global production of hydrogen is 99.3% based on fossil fuels[8]. The large potential that hydrogen has for the decarbonization of hard-to-abate sectors is through the production and use of low-carbon hydrogen. As of 2023, the industry has announced more than 1,000 large-scale projects with a cumulative capacity of 37.9 Mt which will lead to total investments of $320 billion through 2030 (Hydrogen Council 2023). However, there is still much uncertainty in the market since – half of the announced projects are undergoing feasibility studies and to be on a Net Zero trajectory the world would require close to double the amount of projects currently announced (IEA 2023c).

The two most feasible options for producing low-carbon hydrogen are blue hydrogen by using natural gas with carbon capture and green hydrogen, leveraging electrolysis powered by renewable energy. While blue hydrogen is currently more cost-effective the cost of electrolyzers and thus green hydrogen is expected to decrease significantly over time. This may lead to the UAE adopting blue hydrogen first but given that the UAE has become a net importer of gas since 2008 production will likely shift towards green hydrogen relatively swiftly once prices have come down (World Economic Forum 2022).

Given the UAE's large potential for renewable power, its low cost of capital, and existing industrial knowhow it is well positioned to become a significant producer of low-carbon hydrogen. The awareness of this opportunity amongst policymakers can be seen in the goals that the UAE National Hydrogen Strategy sets out. By 2031 the UAE aims to have a production capacity of 1.4 Mt per year. In the short term, the vision is to meet domestic industrial demand with the majority of the production capacity but the planning scenario already indicates that sectoral demand from the UAE may reach 2.1Mt with an additional 0.6Mt of export potential (Ministry of Energy & Infrastructure 2023). There are 14 current hydrogen projects in the country of which two are currently operational (Table 2).

The large focus and potential in the UAE as embodied by these planned projects is to produce green hydrogen based on Solar PV generation or blue hydrogen off of CCUS technologies. A prominent example of a planned blue hydrogen project is that of ADNOC developing a blue ammonia production facility that is based on blue hydrogen in

[7] Hydrogen use in refining reached more than 41 Mt in 2022, 53 Mt where used in heavy industry of which 60% was for ammonia production, 30% for methanol and 10% in the iron and steel subsector (Ibid.)
[8] The distribution of that is as follows: natural gas without CCUS - 62%, coal 21%, by-product of refineries – 16%

the TA'ZIZ industrial ecosystem in Ruwais, Abu Dhabi. The project is being developed in cooperation with the Japanese company Mitsui Co. Ltd and the Korean GS Energy Corporation and one discussed used case is the production of low-carbon fuels. In Dubai on the other hand, the Dubai Electricity and Water Authority has developed a green hydrogen project together with Siemens Energy which uses its solar power at the Mohammed bin Rashid Al Maktoum Solar Park. As this was a pilot project the capacity is relatively low at 1.25MW but it shows the ongoing planning and execution in the UAE. In general, Masdar is leading all hydrogen efforts in the country, and their hydrogen operations are jointly owned by ADNOC, TAQA, and Mubadala.

Table 2: Hydrogen Projects in the UAE (as of October 2023)

Project Name	Date online	Status	Technology	Type of Electricity	Product	Announced Size
Green hydrogen Project, Mohammad Bin Rashid Solar Park	2021	Operational	PEM	Solar PV	H2	1.25MW
Green Falcon, phase I	2024	FID	PEM	Others/Various	Synfuels	1000t H2/y
Al Reyadah CCUS	2016	Operational	NG w CCUS	N/A	H2	800000 t CO2/y
Khalifa Industrial Zone Abu Dhabi (KIZAD) - phase 1	2024	Feasibility study	Other Electrolysis	Solar PV	Ammonia	40kt NH3/y
Bee'ah waste-to-hydrogen		Concept	Biomass		H2	
TA'ZIZ blue ammonia	2025	Feasibility study	NG w CCUS	N/A	Ammonia	1000 kt NH3/y
Khalifa Industrial Zone Abu Dhabi (KIZAD) - phase 2	2026	Feasibility study	Other Electrolysis	Solar PV	Ammonia	200kt NH3/y
TAQA-Emirates Steel Green H2		Concept	Other Electrolysis	Solar PV	H2	
Engie - Masdar - Fertiglobe Abu Dhabi	2025	Concept	Other Electrolysis	Solar PV	Ammonia	200MW
TAQA & Abu Dhabi Ports		Concept	Other Electrolysis	Solar PV	H2	100kt H2/y
MoU BP - ADNOC		Concept	NG w CCUS	N/A	H2	
Maersk SCZONE		Feasibility study	Other Electrolysis	Unknown	H2	480kt H2/y
MoU ADNOC, ENEOS, Mitsui, phase 1		Concept	NG w CCUS	N/A	H2	50kt H2/y
MoU ADNOC, ENEOS, Mitsui, phase 1		Concept	NG w CCUS	N/A	H2	200kt H2/y

Source: (IEA 2023d)

There is industrial value in hydrogen. While the UAE is forecasted to see significant demand for hydrogen from its existing industry (see Figure 32 in Appendix) one of the largest opportunities is that it will provide a new comparative advantage and attract new industrial users to the UAE. Given the challenges and high costs associated with transporting hydrogen due to its low volumetric density, the local use and processing of it in various forms such as shipping or aviation fuels, green aluminum, or ammonia is likely to have higher economic benefits [9]. This would also support the further diversification of the country's economy. While this should be the main aim of the strategy, significant external demand exists such as from the EU which has already stated that half of its hydrogen demand will need to come from imports. As long as the added costs of exporting can be covered by the price the UAE could also become a significant exporter of low-carbon hydrogen.

Shipping Fuels

International shipping accounts for 2% of the world's global carbon emissions. While light vessels can use a variety of technologies to decarbonize, such as lithium batteries and hydrogen fuel cells, long-distance international shipping requires synthetic fuels with

[9] This does not mean that exporting opportunities should be disregarded but rather that the prioritization should be different. There are several projects & MoUs such as that between ADNOC, Fertiglobe and the port of Hamburg

high volumetric energy density (IEA 2023e). The most promising pathways for synthetic fuels for shipping are either biofuels or hydrogen derivatives such as ammonia or methanol. Biofuels are expected to provide only a small part of the required total shipping fuel volumes: there is limited available land for additional energy crop production without competing with agricultural or other land uses, and numerous sectors need to use biomass to decarbonize. Owing to supply constraints, increasing demands on biomass will likely drive up the price of biofuels. Available biomass is therefore likely to be used most extensively in sectors that lack other promising decarbonization pathways, such as those that require a zero-emission carbon source, or those that need drop-in replacements for existing fossil fuels (such as in aviation) (ETC 2023).

Ammonia and methanol fuel pathways appear to be the most promising for shipping, with ammonia preferable in the long term, and methanol as a bridge fuel. Ammonia and methanol are commodities that are substantially traded internationally today, with higher volumetric energy density than hydrogen. Both can be burned directly as fuel in appropriately configured ship engines. Ammonia, a compound of nitrogen and hydrogen, has the advantage that it does not require a renewable source of carbon, making it cheaper in the long run (Figure 18). Methanol, by contrast, requires a renewable source of carbon obtained from biomass or direct capture of carbon dioxide from the air (DAC): this makes it more difficult to estimate production costs of green methanol in the future, as it relies to some extent on direct air capture which is a nascent technology. Ship operators are accordingly starting to express a preference for ammonia-fueled vessels: in 2022 operators ordered 90 new ammonia-ready ships, 43 new methanol-fueled ships, and three hydrogen-ready ships (Clarksons Research 2023). Methanol does, however, have certain advantages, that make it a promising technology for decarbonizing shipping in the medium term: It is easier to convert existing ship engines to run on methanol, methanol is less toxic, will degrade naturally within seven days in a spill and doesn't create nitrous oxide pollutants (Maritime Executive 2023). Ships that run on ammonia are not currently in commercial operation (Mehta and Mehta 2023).

Figure 18: Costs of different green shipping fuels

Technology[1]	Long-term potential	TRL fuel prod.	TRL engine	TRL vessel	TCO 2030[2] $m/year	TCO 2050[2] $m/year
Green ammonia	Zero-emission fuel with existing infrastructure, possibility of hydrogen transport and increasing price competitiveness due to independence from carbon feedstock requirement	8	7	3	19	17
Green methanol	Considered the most advanced fuel with solutions already in use; long-term challenges for carbon feedstock procurement from non-fossil sources	8	8	8	23	20
Green hydrogen[3]	Technically challenging and **cost intensive storage** on ship due to fuel properties	9	7	2	24	22
Synthetic diesel	**Scalability challenges** due to carbon feedstock procurement from non-fossil sources; **higher electricity demand** results in greater production costs	7	9	9	24	20

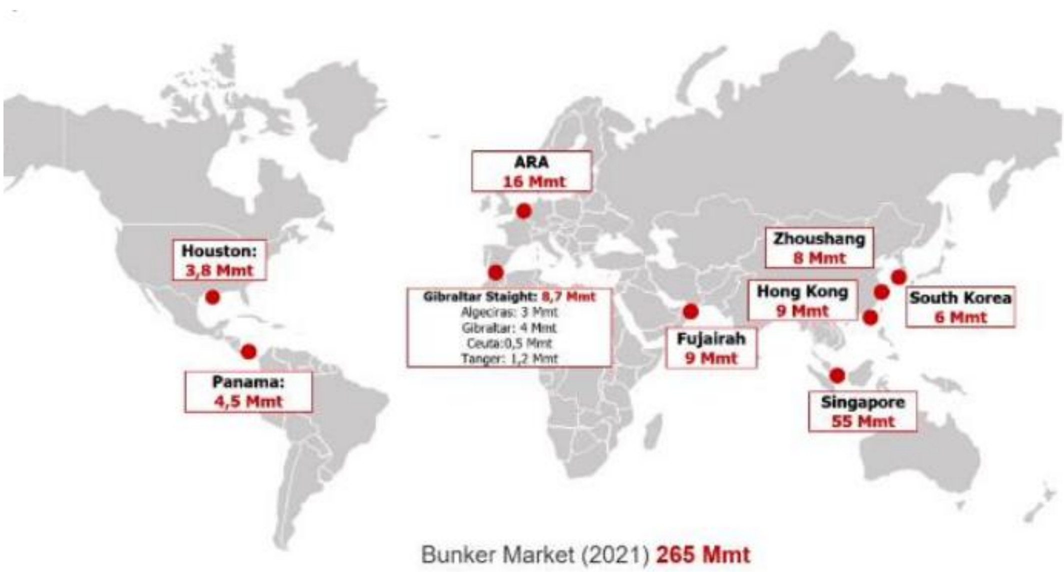
[1]Numbers based on direct air capture technology (DAC) for green methanol and synthetic diesel
[2]Based on a bulk iron carrier +200,000DWT with a speed 12 knots and 200 days at sea; green ammonia with 95% ammonia and 5% LSFO; green methanol with 97% methanol and 3% LSFO
[3]Assumes liquid hydrogen

Sources: Getting to Zero Coalition (2020), TRL: Lloyd's Register and UMAS (2020), TCO: Team analysis based on the Maersk Mc-Kinney Moller Center for Zero Carbon Shipping NavigaTE model

Decarbonizing shipping involves solving substantial coordination problems: ship operators must procure ships that burn certain fuel types, and ports need to stock the appropriate types of fuel. Developing supply, and demand, bunkering in ports in locations around the world, and international procedures for handling low-carbon fuel are essential steps that need to take place for shipping to decarbonize. The manner in which these steps happen will shape the ultimate structure of the international shipping industry. One could imagine, for example, that shipping technologies, fuel types, and bunkering develop in local or regional hubs among neighboring countries where coordination is easier. As these countries would then develop a critical mass of decarbonized vessels and support systems, other places might adopt their processes, technologies, and procedures. Japan, China, South Korea, and Singapore, are currently leading on the procurement of ammonia-fueled vessels, development of bunkering infrastructure, and creation of associated protocols (IEA 2023e). To cope with the uncertainty around fuel types and fuel availability in different locations, ship operators have begun to procure dual-fuel or tri-fuel ships, that burn traditional marine diesels as well as green ammonia and/or green methanol (IEA 2023e).

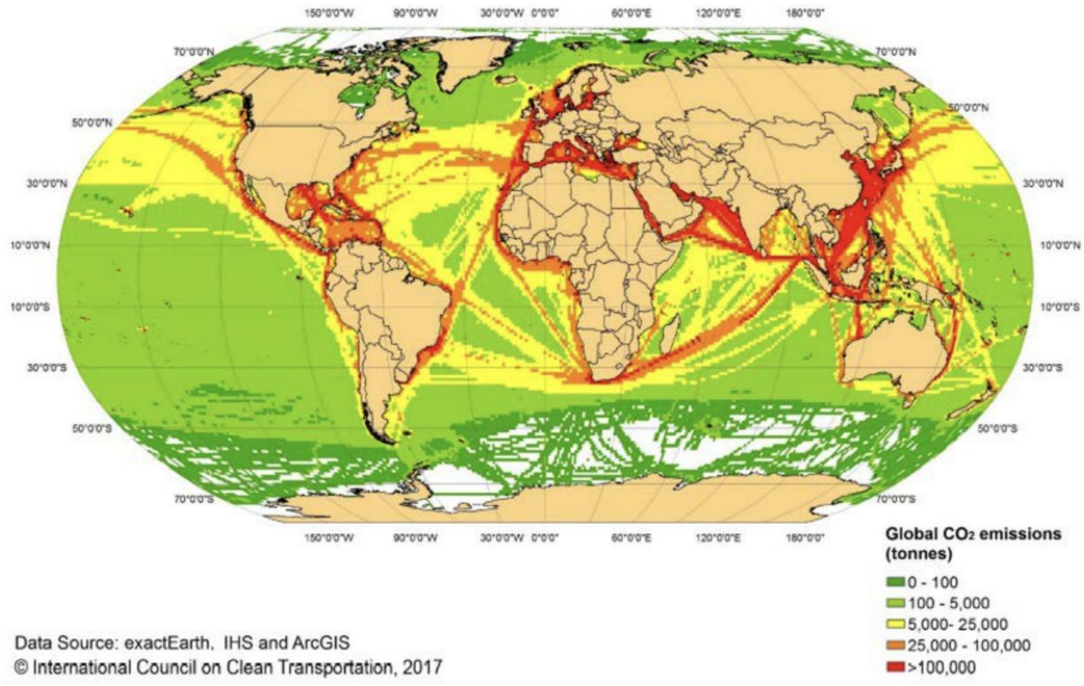
It is imperative for the UAE to protect its port in Fujairah as one of the world's top fuel bunkering hubs for international shipping. Close to half of shipping fuel bunkering takes place in 9 ports, one of which is in Fujairah (Figure 19). As the international shipping industry develops new fuel sources based primarily around green ammonia, fuel supply chains, and bunkering locations could reconfigure. Oman and Saudi Arabia are possibly even better located than the UAE to supply ship bunkering fuel on the Asia-Europe shipping route (Figure 19). Their clean hydrogen strategies call for substantial development of hydrogen hubs in the southwest of Oman, and on the west coast of Saudi Arabia, both of which are equally or slightly more favorable locations for the development of hydrogen hubs than the UAE. Organizations developing these hydrogen hubs have begun to explore ship bunkering using ammonia as a potential offtaker for their hydrogen production: for example, Intercontinental Energy is developing a hydrogen hub in southwest Oman and has sponsored research into developing a green shipping corridor between Asia and Europe (Getting to Zero Coalition 2021).

Figure 19: Main bunker hubs worldwide



Source: Repsol 2021

Figure 20: Shipping Routes and Distribution of Shipping CO2 Emissions



Source: Olmer et al., 2017

To project Fujairah's status as a leading hub for ship bunkering, and capitalize on opportunities in green shipping fuels, the UAE should develop a green shipping route between Asia and Europe, predominantly employing ammonia, with methanol as a bridge fuel. This involves coordinating between Asian and European shipping regulators to develop common standards on green ammonia and methanol management and carbon accounting, develop ample bunkering fuel sources along this route comma, and give companies shipping this route the confidence to invest in green ammonia-fueled ships. Plans should involve transitioning Fujairah's bunkering infrastructure to employ green ammonia and making Fujairah central to the shipping route. Replacing the energy stored in 9Mmt of diesel fuel (the amount of energy that Fujairah supplies in ship bunkering annually) with energy stored in ammonia would amount to 22Mmt of ammonia, representing a sizable commercial opportunity for the UAE, and a significant offtaker of the UAE's green hydrogen. Assuming a delivered cost of $500/ton for green ammonia in 2050, this represents an $11B annual opportunity. The UAE should work with international shipping organizations and operators to develop this route in conjunction with companies, regulators, and industry associations.

Developing a green shipping corridor may involve building alliances with other countries along this route that may stand to gain from ship refueling. A green shipping corridor may require additional stops for bunkering than a shipping corridor based on fossil fuels. This is because ammonia and methanol are less energy dense than diesel or other fossil fuels used in shipping: methanol's energy density is 19.7 MJ/kg, and ammonia's is 18.6 MJ/kg; diesel, by contrast, has an energy density of 45.6 MJ/kg. Ships burning methanol or ammonia, may therefore have to refuel roughly twice as often, or devote more cargo space to carrying fuel. Locations that could stand to gain fuel bunkering revenues from this corridor may therefore include India and Egypt, which are spaced equidistant from the UAE along this corridor and also have substantial clean energy resources to develop green hydrogen industries.

Green shipping fuels are expected to be more expensive, but ship operators are likely to be able to recoup these costs, owing to regulation, carbon taxes, and the fact that international shipping represents a small cost in most final consumer products. Europe, for example, will begin taxing the carbon content of international shipping through European waters in 2024 under its emissions trading scheme (Gray 2023).

Sustainable Aviation Fuels

The aviation sector accounts for 2.5% of global emissions (Ritchie 2020) but global efforts are underway to decrease this impact. The International Civil Aviation Organization (ICAO), for example, has adopted a net-zero goal by 2050. However, there are significant technological challenges with decarbonizing this sector given that aircrafts require energy-dense liquid fuels and their activity often takes place over long distance. The two main leavers in this context are fuel efficiency improvements of aircrafts and the role that Sustainable Aviation Fuels (SAF) will play. Sustainable Aviation Fuels are fuels that are made from non-petroleum feedstocks and that depending on their feedstock have the potential to reduce emissions by up to 94% compared to conventional jet fuel (US Department of Energy 2023). SAFs have the benefit that their chemical properties are very similar to conventional jet fuels so they are compatible with current airport infrastructure and aircraft engines.

Since the production methods and inputs to SAFs are very different from regular jet fuels there will be a shift of comparative advantages in the production of aviation fuels as the need to decarbonize increases. Currently, the two main variations of SAFs that seem promising are on the one hand SAFs based on sustainable biomass and on the other hand Power-to-Liquids (PtL). SAFs based on sustainable biomass currently have higher technological readiness and are more cost competitive the scalability of them is limited given the availability of sustainable biomass feedstock (Mission Possible Partnership 2022a).

Several projects in the UAE are developing biomass-based SAFs but they face significant feedstock limitations. The Sustainable Bioenergy Research Consortium (SBRC) in Abu Dhabi has been researching and developing alternative fuels derived from halophytic (saltwater tolerant) plants. The SBRC is a research consortium led by Khalifa University of Science and includes collaborations with UOP/Honeywell, Boeing, and Etihad who conducted a successful test flight from Abu Dhabi to Amsterdam in 2019. Besides that, the Abu Dhabi Waste Management Center (Tadweer) started a collaboration with Etihad Airways in 2021 to develop SAFs based on municipal waste. While both of these projects build on more mature technologies they face significant scalability constraints within the UAE. The production of SAFs based on halophytic plants is very land intensive which will limit its scale in the country[10]. Fuel production based on municipal solid waste (MSW) on the other hand faces the restriction coming from a comparatively low stock of MSW in the country given its population size[11]. While the limits are clear for a sizeable domestic production the UAE should think about strategic ways to commercialize this knowledge. This could be in the form of patenting the technologies or creating joint ventures in countries that may not face similar feedstock limitations.

The UAE is well suited to position itself as a producer of Power to Liquids (PtL) SAFs. PtLs are based on CO2, H2, and renewable energy to produce liquid hydrocarbons such as SAF. As discussed in earlier sections the UAE has a large comparative advantage in its renewable energy potential and is building out significant CCUS capabilities that are required for CO2 capture. Additionally, PtLs often require additional processing steps for which existing infrastructure can be used which also puts the UAE at an advantage due to its capabilities stemming from existing jet fuel production. Given the abundance of CO2 and renewable energy, PtLs do not face feedstock limitations. However, they still face a larger technological uncertainty and are at an earlier stage of development. There are ongoing efforts led by Masdar in the UAE to produce PtLs in line with its ambitions to be a competitive producer of hydrogen. These are taking place in collaboration with the Abu Dhabi Department of Energy, Etihad Airways, Lufthansa Group, Khalifa University, Siemens Energy, and Marubeni Corporation Recent announcements in collaboration with Airbus also include the intended aim to use direct air capture (DAC) for the CO2 part of the production process (Biomass Magazine 2023). However, given the high current cost of DAC ($600 per ton of carbon), the production of PtL in combination with CCUS based on point-source emissions will be more economical and thus the pathway forward in the UAE at least in the medium term.

The UAE has embraced the potential that it has in producing PtLs. The Power to Liquid Roadmap as well as the National Sustainable Aviation Fuel Roadmap of the UAE which are both led by the Ministry of Energy & Infrastructure set out ambitious goals in terms of PtL production in the country. Critical inputs to the development of PtLs in the UAE are the buildout of renewable energy capacity in conjunction with hydrogen production and CCUS capabilities coupled with the infrastructure to transport the CO2 to the production site of the PtLs. These are foundational elements that would be provided by green industrial parks which showcases their attractiveness for industrial uses such as this. While these are key enablers to the production of PtL SAFs the cost of capital for

[10] The SBRC pilot facility aims to scale up to 100,000 hectare and produce 80 – 152kton of SAF by 2033.

[11] The UAE's overall MSW produced is estimated to be 5.5 Mt and at least 40% of it is already being used by existing Waste-to-Energy projects. Assuming that the remaining 60% would fully be allocated to the production of SAFs (just for simulation purposes) the UAE could produce a maximum amount of 396 Million liters which is 0.09% of what the global demand for SAFs would have to be by 2050 to reach the announced Net Zero goals (IATA 2023).

these projects may be very high given the significant technological uncertainty connected with it. The UAE could, therefore, consider providing loan guarantees and capital grants for a demonstration project.

Strategy 3: Monetize carbon sinks and carbon storage

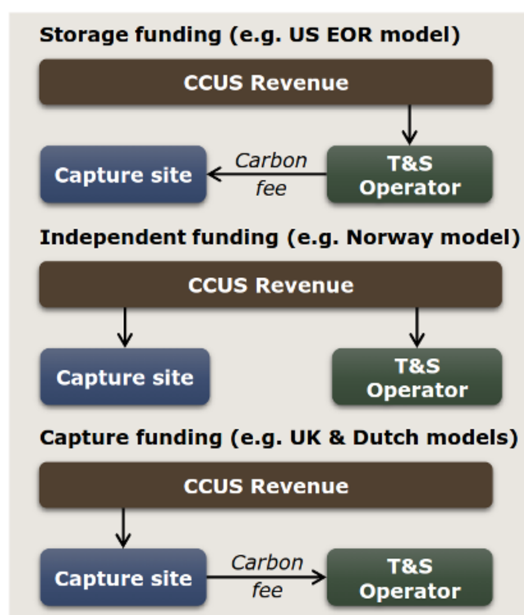
Carbon Capture, Utilization, and Storage (CCUS) in the UAE can both enable commercial opportunities and play a role in meeting net-zero decarbonization goals. Carbon Capture is a capability that enables the production of low-carbon and green materials, making CCUS infrastructure an important complement to green industrial parks. Developing a cohesive CCUS strategy is especially relevant for the UAE as it benefits from the presence of globally competitive renewable energy, access to large point-source emitters, a low cost of capital, and proximity to some of the most promising carbon storage sites on the planet. This gives the UAE a comparative advantage that it should press.

The state has an active role to play in the CCUS ecosystem. Stabilizing policy expectations over the investment horizons of actors involved in the CCUS ecosystem will be critical to spurring investment in the space. This policy must construct an incentive system for agents to capture carbon and avoid emissions, regulate the usage of geological storage sites, and create an enabling environment for innovations to displace outdated technologies while still providing enough protection for players to enter the market in the near term, overcoming technology uncertainty and market failures related to learning spillovers.

The UAE has already been a pioneer in the CCUS space, with the national oil companies motivated by the potential for Enhanced Oil Recovery (EOR). ADNOC built the first fully commercial CCUS facility for the iron and steel industry in the world at Al Reyadah in 2016. CO_2 is captured from a Direct Reduced Iron (DRI) plant, and transmitted through the highest-pressure CO_2 transfer pipeline in the world to Bab and Rumaitha, where it is utilized for EOR. The facility captures 800 thousand tons of carbon per year. ADNOC has begun development of the Habshan CCUS project to store a further 1.5 million tons of CO_2 per year into a network of wells for EOR, building on this experience (Global CCS Institute 2022).

The UAE's existing near-term CCUS strategy is on the right track, with a focus on the introduction of Carbon Contracts for Difference (CCfDs) to reduce cost uncertainty and unlock investment, and Transport and Storage regulations together with liability transfer policies to support CCUS infrastructure networks (United Arab Emirates Ministry of Climate Change & Environment 2023). ADNOC's carbon management strategy is aligned with this vision: "to create a unique platform that connects all sources of emissions and sequestration sites to accelerate the delivery of ADNOC and the UAE's decarbonization goals"

COMMERCIAL RELATIONSHIP MODELS



Source: AFRY & GaffneyCline

(ADNOC 2023). Given the presence of highly capable national oil and gas companies, it is logical to have a single entity build and manage both the Capture and the Transmission and Storage network infrastructure. This leverages the UAE's comparative advantage in this space and internalizes coordination and governance issues which would emerge in a multi-entity system, enabling rapid development and deployment cycles in the short run.

Double Down on CCUS Hubs and Shared Infrastructure

The UAE should signal that it will provide access to the CCUS infrastructure built by the national oil companies to private investors. In an energy-flat world, we expect energy-intensive industries to relocate to areas where renewable energy is relatively cheap. Similarly, the presence of Transportation and Storage (T&S) infrastructure and cheap storage for captured carbon can act as another magnet for industries that require carbon capture for comparative advantage. Opening access to CCUS infrastructure follows a principled economic approach, whereby the state prioritizes and subsidizes infrastructure that generates positive spillovers. In this instance, lowering the cost to integrate with an existing T&S network can give a competitive advantage both to low-carbon industries that build for customers behind Carbon Border Adjustment Mechanisms, and to Direct Air Capture plants that profit from carbon markets. It also diversifies the sources of captured carbon, reducing the exposure of T&S investments to commodity prices, and unlocks economies of scale for T&S operators who can then pass on the gains to carbon capturers.

CCUS Hub business models should ultimately facilitate an active market for captured carbon, storage, and usage. One end of the market consists of actors who capture carbon, either from point-source emissions or directly from the atmosphere. On the other end of the market are storage sites, which may be utilizing captured carbon for a variety of possible activities (ex: EOR), or are only storing the carbon permanently in the ground. Today, the value for captured carbon in the UAE has primarily been driven by EOR. Moving forward, government regulation will be key to driving value for captured carbon. This value will partially be passed through to industry via efforts like the Carbon Border Adjustment Mechanism (CBAM), and consumer demand for green products. In the absence of a carbon price in the UAE, industries may be incentivized to participate in CCUS ecosystems through direct government subsidies and tax credits for storing carbon, such as the 45Q tax credit in the US which provides $50/t for permanently storing CO2, and grant funding to cover significant portions of capital expenditure for capture and storage projects.

CCUS Hub business models should facilitate the transmission of price signals across the actors involved, which will act as a strong monitoring mechanism for the functioning of the system. Differences in utilization and storage patterns among off-takers make competition and transparency in offtake allocation an important principle as well. Transparency is also fundamental to the economics of the capture sites, which may participate in global carbon credit markets moving forward or need to comply with international carbon regulations. Finally, multi-tenant CCUS Hubs are complex and will involve increasing numbers of actors operating within them. The UAE will need to form regulatory authorities at the Hub level who are responsible for coordinating between T&S and Capture sites, both in the set-up of the Hub and as a running operation.

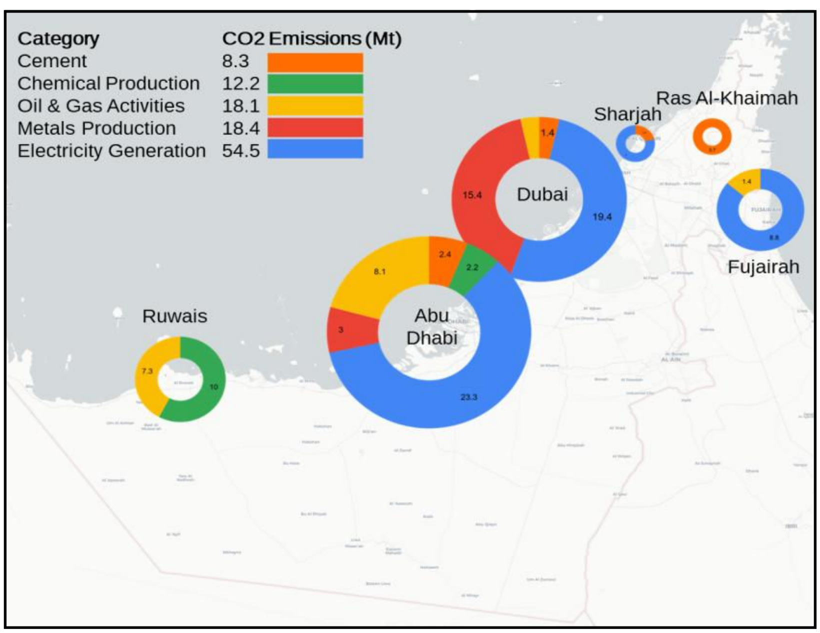
CCUS Hub locations should coincide with the location of green industrial parks. This implies that hub locations should take into account proximity to high-purity CO_2 emitters, the volume of CO_2 emissions, geological storage, and planned renewable energy sources. This ensures that hub locations are not only driven by the location of CO_2 emissions today but are relevant and accessible for the next generation of green and low-carbon industries relocating to the UAE. There may be significant opportunities to benefit from economies of scale by leveraging cross-border geological storage such as the Rub'al Khali basin.

Figure 21: Potential CCUS Hubs in UAE and the Gulf Region

Location	Very dilute (3 -8%)	Dillute (10 -25%)	High purity (40 - 100%)	Close geological sinks
Saudi Arabia - Jubail	38.7 Mt	7.4 Mt	80.7 Mt	Rub'al Khali
Saudi Arabia - Riyadh	19.7 Mt	-	1.1 Mt	Rub'al Khali
Saudi Arabia - Yanbu	27.6 Mt	-	14.0 Mt	Rub'al Khali/Red Sea
Kuwait	10.1 Mt	1.1 Mt	10.1 Mt	Rub'al Khali if connected to Jubail
Bahrain	11.7 Mt	0.6 Mt	5.4 Mt	Rub'al Khali if connected to Jubail
Qatar - North	35.4 Mt	-	33.1 Mt	Rub'al Khali if connected to Jubail
Qatar - South	9.5 Mt	2.3 Mt	15.0 Mt	Rub'al Khali if connected to Jubail
UAE - Abu Dhabi	13.8 Mt	3.0 Mt	25.7 Mt	Rub'al Khali/Oman Ophiolite
UAE - Dubai	25.1 Mt	-	1.3 Mt	Rub'al Khali/Oman Ophiolite
Oman	11.9 Mt	1.8 Mt	12.2 Mt	Rub'al Khali/Oman Ophiolite

Source: AFRY & GaffneyCline 2022

Figure 22: United Arab Emirates CO2 Emissions in 2019 - 112 Mt



Source: Author's elaboration based on AFRY & GaffneyCline 2022

Box 3.1: Research and Development in CCUS: Saudi Arabia

The CCUS ecosystem is on the frontier of technological development, and new innovations threaten to disrupt previous technology. New methods for capturing CCUS aim to decrease the cost and enable carbon to be captured from lower purity sources, including directly from the atmosphere itself. Some innovations operate on the utilization margin by extracting solid carbon from CO_2 for use in other production processes, while others look to enable CO_2 storage without the requirement of natural carbon sinks found in geology. The innovation space is large, and of high dimensionality. States that ignore movement at the frontier risk being saddled with an early technology which becomes outdated yet remains entrenched in the system.

To mitigate this risk, there should be rich interaction between actors in the CCUS space and R&D centers. Saudi Arabia provides an important example, as several significant collaborations between policy think tanks, research universities, oil and gas companies, and the government have emerged. Stakeholders include the King Abdulaziz City for Science and Technology (KACST), King Fahd University of Petroleum & Minerals (KFUPM), King Abdullah University of Science and Technology (KAUST), Saudi Aramco, and King Abdullah Petroleum Studies and Research Center (KAPSARC).

The Technology Innovation Center for CCS (KACST-TIC CCS) at KFUPM was awarded KACST baseline funding of US $2.7M per year from 2011-2015 for their research focusing on capture technologies, as well as monitoring and verification of CO2 storage (Liu et al. 2012).

More recently, a collaboration between King Abdullah University of Science and Technology (KAUST), NEOM's Energy & Water company ENOWA, and the Saudi Electricity Company has produced one of the largest demonstrations of cryogenic carbon capture technology (King Abdullah University of Science & Technology 2022). Cryogenic Carbon Capture is a method of carbon capture which has the potential to operate at half the cost and energy of current state of the art carbon capture processes (University of Brighton, n.d.).

The collaborations in Saudi Arabia exhibit a wide range of stakeholders, across universities, policy think-tanks, and government ministries. The environment created by the repeated interaction of these stakeholders around carbon capture enables high-bandwidth policy to emerge on the topic. While this is an important characteristic for all industrial policies, it is especially relevant here as the incentives to innovate in CCUS are created by government policies which aim to offset externalities imposed by CO_2 emissions. Therefore embedding research and development stakeholders into the ecosystem may hold outsized significance.

Strategy 4: Create and export the knowhow for decarbonization

In the process of reducing its emissions and helping the world decarbonize the UAE will build up significant know-how which it should think about strategically. Numerous organizations across the UAE will acquire specialized knowledge – examples may include how to deploy CCUS technologies, the processes of building wind turbines that provide energy even at low wind speeds, or how to build safe port refueling infrastructure that utilizes green navigation fuels such as ammonia or methanol. Leveraging the knowledge that is developed in those processes and exporting it is a significant growth opportunity. The two main avenues to do so are through capturing that knowledge in companies that then provide green services abroad or to patent/license the knowledge and monetizing the patent.

As the UAE considers developing green industrial parks it has a significant growth opportunity to profit from the learning process by developing and exporting these green industrial parks internationally as a business model. To do so successfully, the UAE may consider a strategic acquisition of an Engineering, Procurement, and Construction Management (EPCM) firm that can develop green industrial parks in the UAE, and in the process build the know-how needed to develop similar parks in different countries, and provide services to other customers. Other green services such as carbon accounting may see a similar logic where the UAE can profit off of its experience and then provide services to other countries that are seeking to decarbonize their economy.

The UAE should also consider its R&D activities strategically in this sector as the patenting activity presents a growth opportunity. Patenting is an additional avenue to export knowledge but also to advance technologies that may make localizing energy-intensive activities more attractive. Our analysis shows that the UAE has significant potential to improve its green patenting output and quality – strategic partnerships with actors in the global frontier may support this effort. Moreover, establishing applied research hubs in the areas of electrochemistry and thermal energy systems may be considered as they have broad applications that would make low-carbon production processes in green industrial parks more viable.

Green Services - Exporting Green Industrial Parks Internationally as a Business Model

Developing green industrial parks is extremely complex: nobody yet knows how to build, manage, and operate a multi-gigawatt green hydrogen production facility. In the process of building these parks in the UAE, the UAE will have to learn how to optimize a very complex renewable energy system, balance electricity, heat, and hydrogen across multiple energy users with different load profiles, and deploy multiple new technologies together that are still in pilot phase. The UAE should aim to capture value in developing and exporting green industrial parks in other countries, by developing a business model around these activities.

The UAE should have a strategy to capture the maximum value from the know-how that it will develop in building these parks. This strategy involves (1) owning the Engineering, Procurement, and Construction Management (EPCM) contractors and other related businesses that develop and operate parks; (2) where possible, having as many of the high-income knowledge workers who provide these services live and work in the UAE; and (3) helping UAE industrial companies that wish to expand abroad (such as Emirates Global Aluminium, or Emirates Steel Arkan) make profitable foreign investments in green industrial parks in other countries.

An important component of this strategy is for UAE investment funds such as Mubadala to acquire an EPCM contractor. This company can develop green industrial parks in the UAE, and in the process build the know-how needed to develop similar parks in different countries, and provide services to other customers. No company currently knows how to develop green industrial parks at scale on its own: acquiring a vehicle to develop these parks in the UAE would allow the UAE to capture the know-how that it generates and in the process build a profitable services business that would provide services to customers outside the UAE. The EPCM contractor would also be a vehicle to organize relationships with emerging industrial technology providers, supply chains, and solutions that will be used in green industrial parks. Developing a green industrial park will involve substantial low-value commodity EPCM work, such as deploying large solar fields, as well as very high-value customized design work, such as optimizing complex renewable energy systems integrated with industrial facilities. The acquired EPCM should specialize in high-value system optimization and overall facility design, while building relationships with commodity services providers that specialize in low-cost system elements, such as designing and deploying utility solar fields.

Green industrial parks involve large financial commitments with long time horizons stretching into decades. Financing green industrial parks represents a significant challenge, with large investment needs for developing the concept, acquiring land rights, designing contractual frameworks and infrastructure, before even starting construction on the parks. Financing the construction of the park itself and its related energy projects presents an even bigger challenge, requiring very substantial due diligence from external debt financers. Coupling design of the park through an EPCM contractor, with financing through a related UAE-affiliated parent entity such as Mubadala promises to generate efficiencies, reduce informational asymmetries, and lower transaction costs involved in seeking financing from other entities. Coupling finance with EPCM involves carefully managing risks, however, to ensure that financiers independently evaluate project quality.

A significant role is that of offtakers in this market as they are the buyers of the goods produced in the park. Given the nascency of some of these markets, businesses may require a long-term offtake agreement to mitigate potential risks and have secure revenue streams. Finding offtakers presents a sizeable challenge, which has delayed numerous park developments. Facilitating initial offtake agreements from parks developed internationally, either with industrial companies located in the UAE, or with a network of customers and relationships developed through green industrial park investments in the UAE, will also reduce transaction costs, help projects move to financial close, and speed development of international green industrial parks.

Operating green industrial parks requires specialized service providers to perform services such as carbon accounting. The UAE should develop, invest in, and partner with these service providers, and support their efforts to provide services in green industrial parks in other countries. As above, returns to the UAE would come from equity stakes UAE investors have in these service providers, and from having services provided by workers in the UAE (that then provide spillovers to other areas of the UAE economy).

Green Services – Finance, Advisory & Technical Services

The green transition brings about substantial changes in the opportunities and challenges faced by businesses and organizations. In this greening era, businesses and investors encounter many opportunities but also evolving imperatives that compel them to embrace environmentally responsible practices. Governments worldwide are enacting green legislation, compelling businesses to keep abreast of environmental laws and regulations. Investors are increasingly seeking companies with robust environmental, social, and governance (ESG) credentials, while society at large is demanding greater transparency. Therefore, businesses must effectively report on their sustainability efforts. The pursuit of green certifications as well as environmental audits enable companies to gauge their ecological footprint, identify areas for improvement, and demonstrate their commitment to sustainability. Additionally, the integration of risk assessments and green finance into financial planning becomes paramount, encompassing the identification of sustainable projects, comprehension of financial ramifications tied to environmental factors, and exploration of green financing options. Many businesses are now expected to participate in carbon offsetting initiatives aimed at balancing their emissions, a commitment that may need a better identification of investments in sustainable and green projects.

The UAE is well-positioned to capitalize on this opportunity due to several key factors. The government's commitment to ambitious environmental goals, including achieving net-zero emissions by 2050, fosters certainty in the development of green investments as well as green know-how. Moreover, Dubai's strategic location as a global business hub facilitates easy access for leading global companies, creating a conducive environment for knowledge exchange and expertise transfer. The active involvement of major global players in the UAE, including expanding financial institutions and top-tier consulting firms, as well as the ongoing investment in green research and development and innovation, strengthen the UAE's position in the green services world. Expanding in these areas and providing green services to countries that seek to decarbonize is both a growth and diversification opportunity as these often are complex services providing high-paying jobs.

Leveraging this opportunity requires fostering and nurturing green know-how within the UAE, aimed at assisting domestic and international enterprises in their

journey towards a greener economy. These green services can be broadly, though not exclusively, categorized into three core groups, as further elaborated in Box 4.1: green finance and investment, carbon reduction advisory, and environmental consultancy. Considering the three distinct strategies for catalyzing green growth in the UAE, the relevance of specific green service categories to each strategy, while not exhaustive, becomes evident. In the case of Strategy 1 and 3, which focuses on producing the inputs and products that the world needs to decarbonize, the primary need revolves around green finance and investment services as it is crucial to identify viable green investment opportunities and the optimal way to finance them. Strategy 2, which aims at manufacturing green alternatives of energy-intensive products for a worldwide market, underscores the need for carbon reduction advisory services as companies will need to assess the current carbon emissions of their products to formulate strategies for their reduction. Furthermore, there is an array of complementary green services, classified under environmental consultancy services, which are needed in all strategies. For instance, compliance, certification, and audit services hold pivotal roles in ensuring alignment with regulatory standards and environmental best practices.

The UAE has delineated its green finance strategy in the recent Sustainable Finance Framework 2021-2031, which aims to create a conducive environment for green private investment and sustainable finance products (UAE Ministry of Climate Change and Environment 2021). Given its infancy and while leading banks in the UAE have been actively embracing private green finance, there remains substantial potential for further growth. Among financial institutions, the First Abu Dhabi Bank, the UAE's largest bank, stands at the forefront of green finance. It secured a pioneering role in the MENA region as an arranger and book-runner by issuing the first green bond in 2017. With a green bond portfolio totaling USD 2.3 billion as of 2022, it has carried out 13 issuances spanning 16 projects. These projects are distributed across four different countries, with the UAE accounting for 54% of them, while the USA, France, and Uzbekistan represent 30%, 15%, and 1%, respectively. Furthermore, 73% of the projects pertain to green building initiatives, with 19% allocated to renewable energy projects (First Abu Dhabi Bank 2023). Abu Dhabi Commercial Bank, the third largest bank in the UAE, also started to engage in green bonds with issuances of USD 500 million and USD 650 million in September 2022 and 2023, respectively (Abu Dhabi Commercial Bank 2023: Dey 2023).

While the UAE is the leader in green finance in the MENA region, its green bond market represents a small fraction of the global green bond market. Mostly concentrated in China, the USA, and Germany, global green bond issuances reached USD 473.2 billion in 2022, accounting for 7.8% of the global bond market and totaling 741 issuers and 51 countries (Standard & Poor 2023; Climate Bonds Initiative 2023). This represents a large increase as the green bond market was USD 182.5 billion in 2018.

Box 4.1: Green Services

1. Green Finance and Investment Services

Companies require assistance in identifying viable green investment opportunities as well as in determining the financing aspects of these projects. Among these services, we can find:

- ***Investment Strategy Services*** to help businesses identify viable green investment opportunities as well as assess their financial viability and potential returns. This includes market research, impact assessments, cost-effective analyses, feasibility studies, risk evaluations, and financial modeling services. These analytical tools help companies make informed decisions about their investments, minimizing risks and maximizing returns.
- ***Financing Strategy Services*** to assist businesses in their decision about how to finance the green investment. Financial institutions offer a diverse array of green financial instruments tailored to various customers and investment needs, enabling businesses to access capital for their green and sustainable initiatives. These may include green loans, sustainability-linked loans, green bonds, green sukuks, social-impact bonds, green mortgages, green preferred stocks, carbon offsetting credits, among others. Moreover, financial institutions can offer other financial products designed to investors that want to support green initiatives, such as green mutual funds, green exchange-traded funds, and green crowdfunding platforms.
- ***Venture Capital Services*** to provide financial backing and mentorship to entrepreneurs and start-ups working on innovative solutions to environmental and green challenges.
- ***Climate Risk Assessment and Insurance Services*** to support companies in their climate risk assessment and choice of climate insurance solutions.

Box 4.1: Green Services (cont.)

2. Carbon Reduction Advisory Services

Businesses and organizations require guidance in transition to sustainable practices. Services play a vital role in helping organizations understand their environmental impact, reduce their carbon footprint, and align with sustainability goals and regulatory requirements. These services are increasingly important in a world where environmental responsibility and carbon reduction are becoming central considerations for businesses and institutions. Among them, we have:

- ***Carbon Accounting Services*** to help businesses measure and manage their greenhouse gas emissions – such as carbon dioxide, methane, and nitrous oxide -- and environmental impact. These emissions can come from various sources, including energy consumption, transportation, production processes, and waste.
- ***Carbon Footprint Reduction Planning Services*** to help businesses develop and implement sustainability strategies to reduce its carbon footprint, helping them set and achieve environmental and social responsibility goals through, among others, carbon reduction, waste and hazardous materials management practices, and resource efficiency strategies.
- ***Carbon Trading and Offsetting Services*** to advise on carbon trading and offsetting strategies in those cases where an organization cannot completely eliminate its emissions. By investing in carbon offset projects like reforestation, renewable energy, or carbon capture, they can balance its emissions.

3. Environmental Consultancy Services

In addition to the investment, financing and sustainable practices decisions, businesses need help in a wide array of complementary green services. Among them, we have:

- ***Compliance Services*** to assist organizations in complying with local, national, and international environmental regulations. They help secure the necessary permits for operations and ensure that activities meet legal standards.
- ***Certification Services*** to assist businesses in obtaining environmental certifications such as ISO 14001 on environmental management and LEED for green building practices.
- ***Audits Services*** to determine whether the business is complying with regulations and identifying areas for improvement.
- ***Data Management and Reporting Services*** to provide support in collecting, managing, verifying, and tracking emissions and environmental data from various sources within the organization -- including utility bills, fuel consumption records, production data, and more. - They also provide support in producing the emissions and sustainability reports that detail businesses' environmental

The development of green know-how in carbon reduction and environmental consultancy is a dynamic and growing field in the UAE. Dubai, as a global business hub, has attracted several leading global companies specializing in sustainability consulting and environmental services. These companies, including PricewaterhouseCoopers (PwC), Deloitte, KPMG, DNV GL, ERM, Jacobs, and AECOM, have established a significant presence in the region. Their expertise spans a wide range of sustainability-related areas, from carbon accounting and reporting to environmental impact assessments and regulatory compliance. In addition, several domestic financial institutions have recognized the significance of ESG factors in investment and finance and are actively engaging in promoting awareness and education about ESG practices among their stakeholders. They are encouraging the gradual integration of ESG considerations into investment decisions, ownership practices, and ESG reporting.

While adapting to the ever-evolving global and local regulatory landscape is crucial for the UAE, it is equally important that these green regulations foster the development of the expertise and skills required to meet the increasing demand for green services. Sustainability laws, regulations, and targets are in constant flux, impacting the growth and nature of services required in the green sector. The UAE must remain nimble in responding to these changes while ensuring that its policies support the cultivation of a skilled workforce capable of meeting the expanding needs of the green service industry. To accelerate the development of capabilities and knowhow in green services within the country is crucial, the UAE can consider the following suggestions:

- ***Localize available and needed know-how in the UAE.*** The government should initiate a comprehensive assessment of the green services required by various industries and sectors. To do so, it should regularly engage with industry stakeholders, experts, and associations to identify the specific skills and expertise that are in demand. This evaluation will allow the identification of existing expertise across different sectors in the country and pinpoint current and future gaps that need to be addressed. Having a clear understanding of the specific skills needed is crucial for effectively developing the needed workforce.
- ***Attract green know-how and talent through partnerships with consulting companies and green organizations.*** The government can facilitate the bridging of immediate knowledge gaps by fostering partnerships with consultancy firms and organizations specialized in green growth and climate change. Through these partnerships, the government can encourage these organizations to attract and concentrate green know-how and talent from abroad in their offices in the UAE. While immigration policies and job incentives are needed to attract foreign talent, the implementation of a *"local knowledge requirements"* policy, requiring green investments to hire green services providers available in the country, should facilitate the concentration of talent within the UAE. Through different knowledge-sharing initiatives, such as workshops, mentorship programs, seminars, and training courses, this green knowledge can be then transferred to the local workforce.

- ***Invest in education through the establishment of green services training institutes and collaboration with universities and research institutions.*** To nurture a skilled and knowledgeable local workforce capable of contributing to the UAE's leadership in green services, the government should consider the establishment of specialized green services training institutes or centers; partnerships with universities and research institutions to develop academic programs focused on green services, both at the undergraduate and postgraduate levels; and, the implementation of scholarships to students and professionals pursuing education, training or research in fields such as sustainability, environmental science, and green finance.
- ***Replicate as closely as possible developed countries' best practices and sustainability or green frameworks.*** In response to the continuously evolving global and domestic regulatory landscape related to sustainability and environmental practices, the UAE should proactively adapt its policies, regulations, and climate targets to align with emerging global standards. This adaptability ensures a stable and predictable environment for green service providers and investors in the country. Furthermore, the implementation of a robust and transparent system for monitoring and reporting on the progress of green initiatives and projects in the UAE can help build trust with investors and demonstrate the country's commitment to sustainability.

Knowledge creation and export through patenting activities

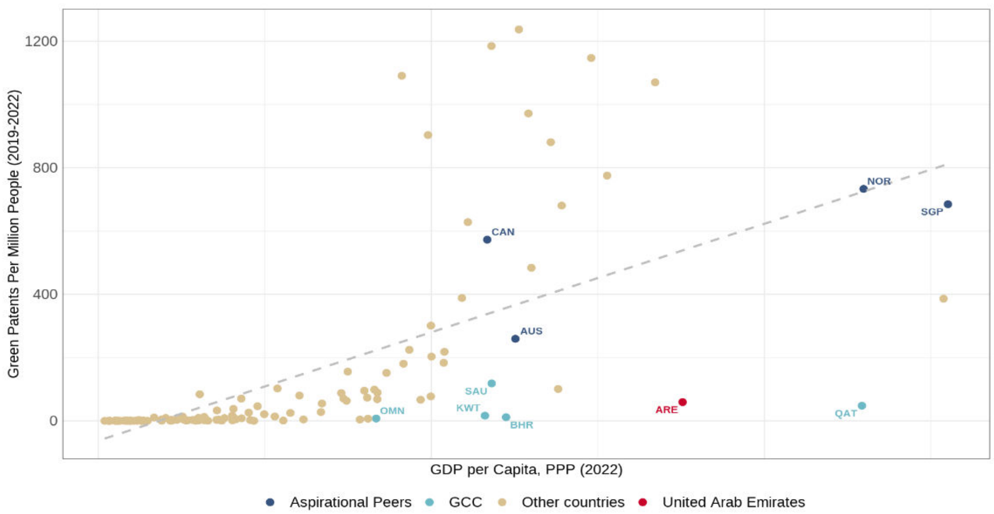
The creation and commercialization of knowledge may also take place through patents stemming from R&D activities. As much of the decarbonization processes are based on technological innovations this avenue presents a significant growth opportunity for the UAE, if leveraged strategically. An ongoing example is that of Emirates Global Aluminium which developed a smelting process that is more energy efficient. While EGA previously relied on trade secrecy to protect its innovations the move towards patents allowed it to commercialize this knowledge – Aluminium Bahrain selected EGA's aluminum smelting technology for their expansion project (Zawya 2016).

The UAE is lagging in terms of green patents per capita which may in part be attributed to its comparatively low research capability overall. As Figure 23 shows the UAE is significantly below expectations in terms of green patents per million people relative to its GDP per capita. While the relationship between these factors is certainly not causal, it is noteworthy that the UAE has fewer green patents per million people than Saudi Arabia and is significantly below its aspirational peers (Australia, Canada, Norway, and Singapore) in this respect. The gap with the aspirational peers may be partially attributed to the fact that the UAE in general has much fewer researchers per million people (

Source: Author's own elaboration based on WIPO & PATSTAT data

Figure 24). The overall lower research capability thus leads to fewer green patenting activity. Given its overall research capability, the UAE performs as expected in terms of green patenting activity[12]. In this metric Saudi Arabia once again performs better than the UAE as it records more green patenting activity with significantly fewer overall research capabilities[13] pointing towards a higher researcher productivity.

Figure 23: Green Patents relative to the GDP per capita

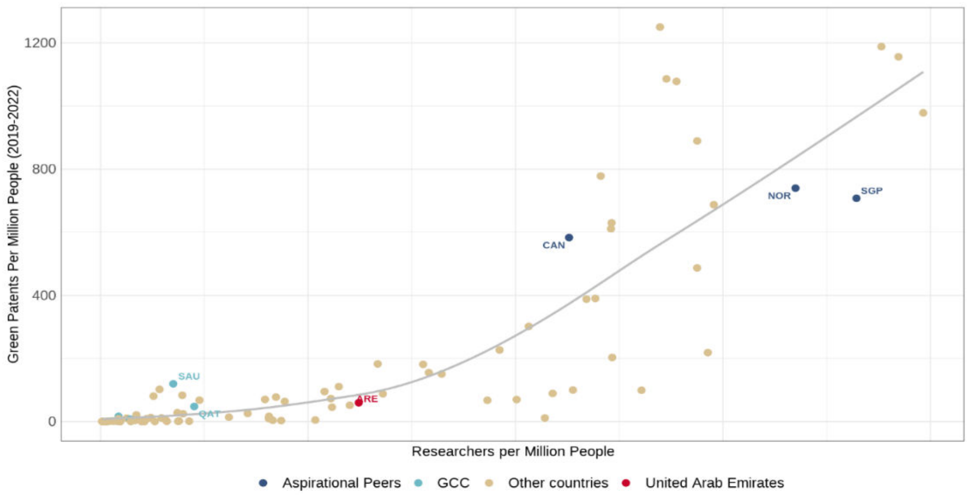


Source: Author's own elaboration based on WIPO & PATSTAT data

[12] It is important to note that the measure "Researchers per Million People" includes all researchers as there is no detailed data available about the number of researchers that work in research fields related to "green activities and patents".

[13] This could be due to a combination of two factors: R&D activity in Saudi Arabia may be more focused on areas related to green patents, additionally, the research productivity in Saudi Arabia in this field may be higher.

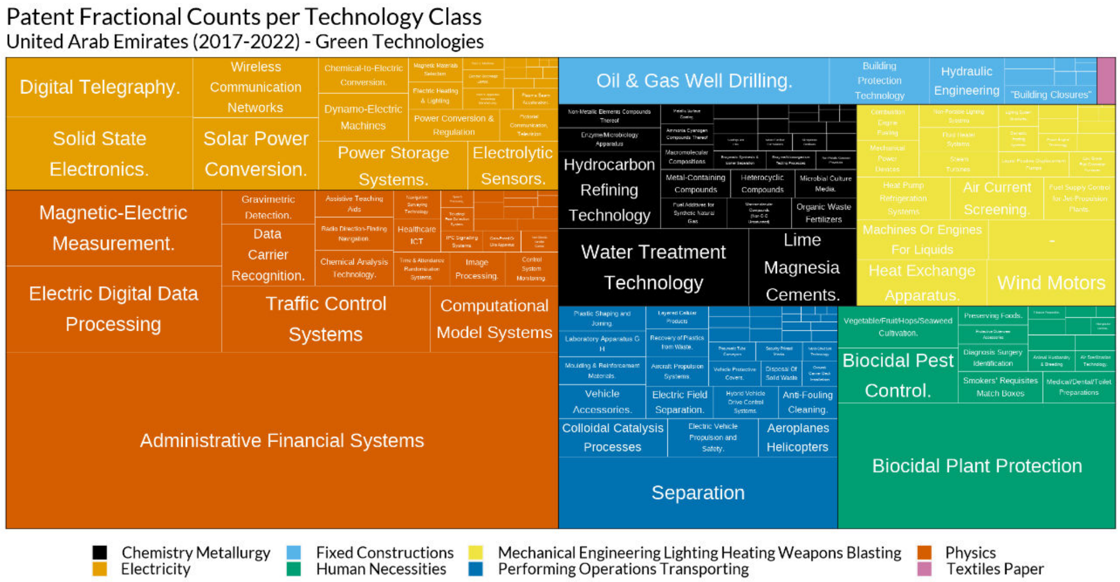
Figure 24: Green Patents Relative to the Overall Research Capability



Source: Author's own elaboration based on WIPO & PATSTAT data

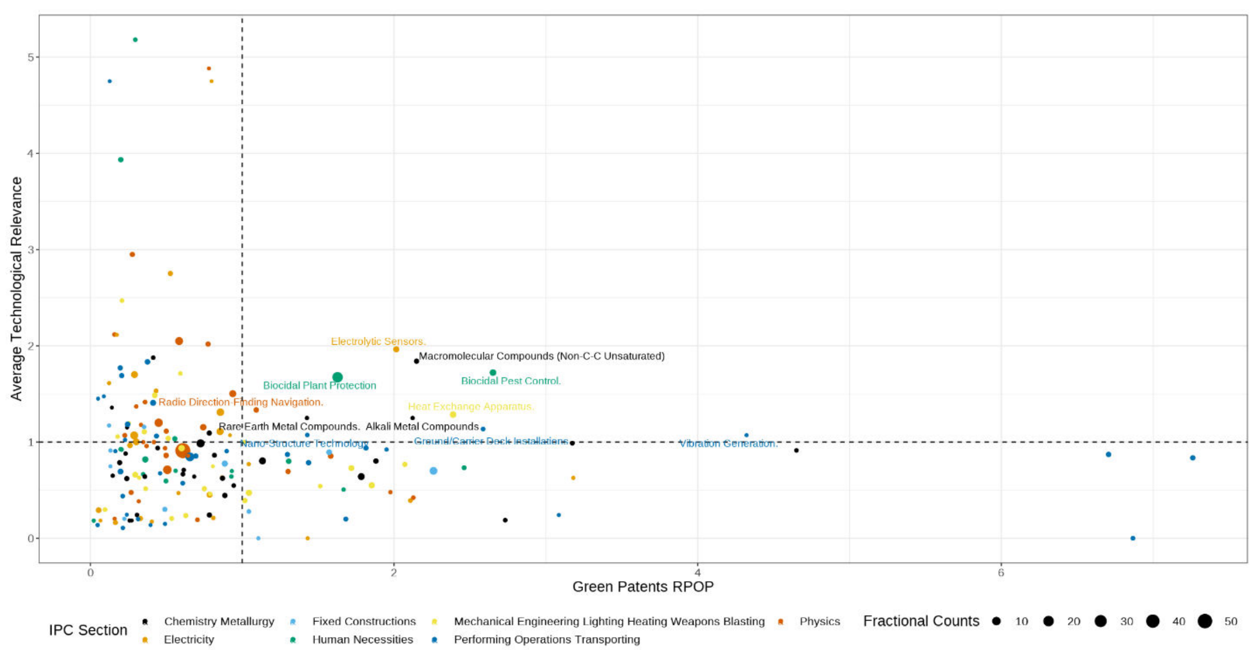
The UAE's green patenting activities show a high concentration in the broader field of physics and electricity. While this shows where the overall green patenting activity in the UAE takes place it is important to look at measures of relative quantity and quality to have a deeper understanding of these activities. Figure 26 shows average measures of quality and quantity by technology class. Observations in the bottom left quadrant indicate below-average quality and lower-than-expected quantity. The worrying sign is that the majority of patents in the UAE fall in this category. Conversely, observations in the top right quadrant indicate above-average quality and above-expected quantity. The few instances that fall in this category are the patents from technology classes such as Heat Exchange Apparatus, Electrolytic Sensors and Biocidal Pest Control and Plant Protection, and Macromolecular Compounds which all have higher concentration in the UAE than expected and have an above average quality. There are also numerous instances such as that of Solar Power Conversion where the quality of patents is relatively high, but the quantity is lacking, as of now - here targeted funding for research and development in the sector and expanding existing capabilities could prove beneficial. Lastly, the bottom right quadrant shows patent classes such as CCUS where the UAE has a lot of activity, but the quality is lagging. In the specific case of CCUS, this may be because the measure is averaging over the quality of all patents from the UAE within this technology class. An analysis of the top 1% of green patents in terms of quality reveals that there are some high-value CCUS patents in the UAE (see Appendix - Figure 33). However, the average quality within this technology class is decreased by lower-quality research within this field. This may merit a closer look into the entities that are producing high vs. low-quality patents in this context.

Figure 25: UAE Green Patents by Technology Class (2017 - 2022)



Source: Author's own elaboration based on WIPO & PATSTAT data

Figure 26: Quality and Quantity of Green Patents in the UAE by Technology Class (2017 - 2022)

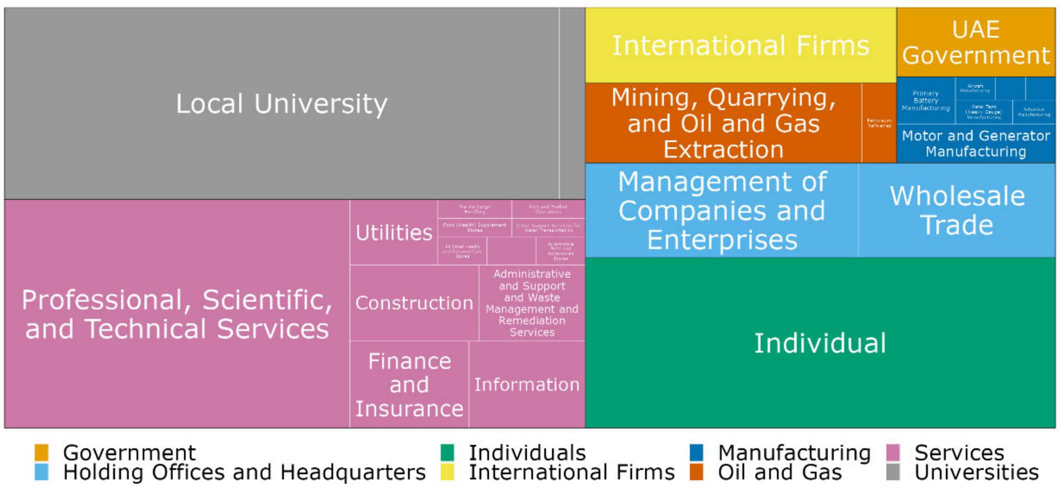


Source: Author's own elaboration based on WIPO & PATSTAT data

Most of the green patenting activity in the UAE is driven by the service sector, universities, and individuals (Figure 27). The largest actor in the past five years has been the sustainable agriculture firm UPL which has 52 green patents (see Table 11 in

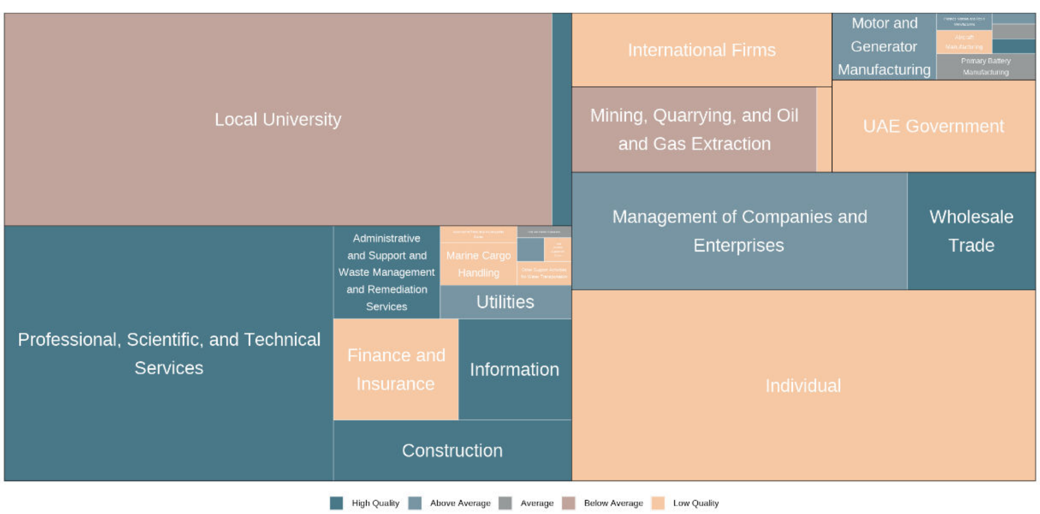
Appendix) which were granted – this has been the driver behind biocidal pest control and plant protection being a comparative advantage in the UAE as seen above. The activity coming from universities is driven by United Arab Emirates University (39 green patents) and Khalifa University of Science and Technology (28). ADNOC is also among the top assignees of green patents in the UAE in that period. Interestingly, the green patents originating in local universities appear to be of below-average quality, while those coming from the service sector are of high quality. This points towards the need for a more detailed analysis of the green patenting activities coming from local universities to understand why they are lacking in quality. The fact that the quality of green patents coming from international universities is high also points to the fact that the issue has to do with circumstances specifically impacting local universities.

Figure 27: UAE's Green Patents by Industry



Source: Author's own elaboration based on WIPO & PATSTAT data

Figure 28: UAE's Green Patents by Industry & Quality



Source: Author's own elaboration based on WIPO & PATSTAT data

As the quality of the UAE's patents is lagging behind its peers in several technology classes it should aim to foster stronger collaborative ties with actors at the global frontier. The analysis displayed in Figure 26 has shown that there are numerous patent activities where the UAE lacks quality while having a larger-than-expected output or lacking output while the quality is above average. A promising practice to address these areas that indicate potential but are underperforming is to establish collaboration with actors that are at the frontier in that field. Based on the patent data we can observe the current patterns of collaboration in the UAE as well as where productive research capabilities in the green patenting space are concentrated. From the list of countries with a high concentration in green patenting activity, the UAE has developed strong collaborative ties with the USA (Table 3). With many of the other top performers, the collaboration is not as significant. However, the potential impact of these collaborations will depend on several factors. A deep dive into specific technology classes and high-performers within the technology class may identify a more clearly defined set of opportunities. Additionally, dynamics may differ by the respective entity that would be engaged in the collaboration. Table 4 shows the top 15 assignees of green patents globally. The list is dominated by Chinese public entities where collaborations also be connected to political considerations. However, the good relationships between China and the UAE may be helpful in this context.

Table 3: Top Investors of Green Patents - World (2017 - 2022)

COUNTRY	GREEN PATENTS*	UAE - BILATERAL PATENTS	% OF UAE PATENTS†
United States	105,321 Patents	77 Patents	19.2%
South Korea	85,043 Patents	4 Patents	1.0%
Germany	45,786 Patents	10 Patents	2.5%
Japan	39,653 Patents	2 Patents	0.5%
China	33,851 Patents	4 Patents	1.0%
France	15,277 Patents	12 Patents	3.0%
Russia	11,343 Patents	6 Patents	1.5%
Canada	8,187 Patents	10 Patents	2.5%
United Kingdom	8,108 Patents	45 Patents	11.2%
India	7,673 Patents	64 Patents	15.9%
Netherlands	5,197 Patents	3 Patents	0.7%
Brazil	4,930 Patents	18 Patents	4.5%
Turkey	4,303 Patents	0 Patents	0.0%
Spain	4,070 Patents	5 Patents	1.2%
Poland	3,995 Patents	0 Patents	0.0%

*Fractional Counts assigned by the number of countries involved in the invention of a patent

†Percentage based in the number of patents in which UAE inventors collaborated with an inventor of this country between 2017 and 2022 (402 Patents)

Source: Author's own elaboration based on WIPO & PATSTAT data

Table 4: Top 15 Assignees of Green Patents – Globally (2017 – 2022)

APPLICANT/ASSIGNEE	GREEN PATENTS*
CHINESE ACADEMY OF SCIENCES	18,420 Patents
GUANGDONG POWER GRID CORPORATION	9,967 Patents
SGCC(STATE GRID CORPORATION OF CHINA)	9,049 Patents
TOYOTA MOTOR CORPORATION	7,792 Patents
SINOPEC (CHINA PETROCHEMICAL CORPORATION)	7,703 Patents
ZHEJIANG UNIVERSITY	6,821 Patents
ROBERT BOSCH	6,774 Patents
LG CHEM	6,671 Patents
GREE ELECTRIC APPLIANCES	6,263 Patents
TOYOTA MOTOR CORPORATION	5,885 Patents
TSINGHUA UNIVERSITY	5,779 Patents
SOUTH CHINA UNIVERSITY OF TECHNOLOGY	5,566 Patents
TIANJIN UNIVERSITY	5,304 Patents
SAMSUNG ELECTRONICS COMPANY	5,195 Patents
SOUTHEAST UNIVERSITY	5,072 Patents

*Number of patents in which the firm appears as the first applicant, regardless of collaborations and location of inventors.

Source: Author’s own elaboration based on WIPO & PATSTAT data

Applied Research Hubs in Electrochemistry and Thermal Energy Systems

The UAE should consider developing applied research hubs around key technologies that have the potential to significantly impact low-carbon production processes in the country, namely: electrochemistry and thermal energy systems. The previous analysis has shown that the UAE has a lot of growth potential across green technology classes. While a direct improvement in all of them is not immediately feasible the country should focus on areas of high strategic value.

Currently, innovation in this context is focused on particular constraints: 1) reducing heat requirements in industrial processes, allowing industry to use a greater proportion of its energy as (cheap) renewable electricity rather than (expensive) green fuels; 2) making industrial processes compatible with intermittent renewable energy production so plants can turn off at night (and thereby removing the need for costly energy storage and firm power); 3) developing low-cost energy storage to continue production during the night; and 4) recycling, managing and applying heat in industry without the use of fuels.

Two underlying technological domains that have broad applications in innovating around these constraints are electrochemistry and thermal energy storage. Electrochemical innovations are helping create new ways to electrify industrial processes, such as the electrolysis of iron ore and raw materials used to make cement. They are also driving innovations in energy storage such as in flow batteries. Thermal energy storage and management systems are engineering systems that store energy as very high-temperature heat for use in power generation and industry. They involve melting salts and metals such as tin, or heating solids such as ceramic blocks, storing this heat and then applying it as needed. Heat can be captured from sunlight (as in concentrating solar power) or by using excess electricity from solar power during the middle of the day. Thermal energy storage systems have the potential to be cheaper than electrochemical energy storage in industrial applications.

Establishing collaborations early on in these fields when building the capacity of the applied research hubs may support their development. Based on the patent data it is possible to identify leading actors in the R&D field of those technologies, as can be seen in Table 5 and Source: Author's own elaboration based on WIPO & PATSTAT data

Table 6. However, especially the electrochemistry field encompasses more than just fuel cells. This is, therefore, just an indicative suggestion that may enrich discussions around this policy idea.

Developing strong capabilities in these areas would be of high strategic value to the UAE as innovations from this realm may be beneficial for green industrial parks. The applied research hubs may begin to develop and commercialize new technologies that help industrial decarbonization. These research hubs would be supportive of and synergistic with green industrial parks in the UAE. Attracting and developing the technology needed in the green transition will help the UAE carve out a space in some of the highest-value sectors of the transition, helping to sustain the UAE's high incomes and quality of life in a low-carbon world.

Table 5: Top Inventors of Thermal Energy Storage Patents - Globally (2017 - 2022)

CHINESE ACADEMY OF SCIENCES	235 Patents
WUHU MIDEA KITCHEN AND BATH ELECTRICAL APPLIANCE MANUFACTURE LIMITED COMPANY	129 Patents
GREE ELECTRIC APPLIANCES	121 Patents
QINGDAO ECONOMIC TECHNOLOGY DEVELOPMENT ZONE HAIER WATER HEATER COMPANY	101 Patents
LG CHEM	100 Patents
XIAN JIAOTONG UNIVERSITY	85 Patents
SAMSUNG ELECTRONICS COMPANY	85 Patents
SINOPEC (CHINA PETROCHEMICAL CORPORATION)	77 Patents
SAMSUNG DISPLAY	73 Patents
SOUTH CHINA UNIVERSITY OF TECHNOLOGY	72 Patents
VATTI	64 Patents
SOUTHEAST UNIVERSITY	63 Patents
XIAN THERMAL POWER RESEARCH INSTITUTE COMPANY	60 Patents
SHANDONG UNIVERSITY	57 Patents
NORITZ CORPORATION	57 Patents

*Number of patents in which the firm appears as the first applicant, regardless of collaborations, quality and location of inventors.

Source: Author's own elaboration based on WIPO & PATSTAT data

Table 6: Top Inventors of Fuel Cells (Electrochemistry) Patents - Globally (2017 - 2022)

	LG CHEM	3,173 Patents
	TOYOTA MOTOR CORPORATION	2,309 Patents
	NINGDE CONTEMPORARY AMPEREX TECHNOLOGY	2,100 Patents
	CHINESE ACADEMY OF SCIENCES	2,017 Patents
	LG ENERGY SOLUTION	1,955 Patents
	HEFEI GUOXUAN HIGH-TECH POWER ENERGY COMPANY	1,937 Patents
	ROBERT BOSCH	1,459 Patents
	SVOLT ENERGY TECHNOLOGY COMPANY	1,452 Patents
	ZHUHAI COSMX BATTERY COMPANY	1,090 Patents
	BYD COMPANY	1,079 Patents
	PANASONIC INTELLECTUAL PROPERTY	1,054 Patents
	TOYOTA MOTOR CORPORATION	1,051 Patents
	EVE ENERGY COMPANY	1,049 Patents
	TOYOTA INDUSTRIES CORPORATION	961 Patents
	SAMSUNG SDI COMPANY	928 Patents

*Number of patents in which the firm appears as the first applicant, regardless of collaborations, quality and location of inventors.

Source: Author's own elaboration based on WIPO & PATSTAT data

4. Summary of Policy Ideas & Agents of Change

The UAE has significant opportunities to contribute to global decarbonization by helping the world reduce its emissions, while simultaneously benefiting through increased economic growth. The opportunities identified leverage the large renewable energy potential of the country, its low cost of capital, investment-friendly environment, and high-quality trade infrastructure. The strategies also build on the significant capabilities of entities such as ADNOC, Masdar, Mubadala, and EGA to name a few. These organizations and their know-how are assets that the country must use strategically, and it should enable them to grow further. It will be able to do so by leveraging them across different green growth opportunities.

Table 7: Summary of Green Growth Policy Ideas

Strategy	Policy Idea	Priority
1) Making things that enable others to decarbonize	Expand into critical minerals processing	Medium
2) Make Green Things	**Develop Green Industrial Parks to attract green production**	**High**
3) Monetize Carbon Sinks	Develop CCUS Hubs & CO2 Transport Infrastrucutre	Medium
4) Create and Export the Knowhow for Decarbonization	**Export Green Industrial Parks Internationally & Acquire Engineering, Procurement and Construction Management Company for this**	**High**
	Strengthen collaborations with most productive countries & entities in green patenting space	Medium
	Set up a green technologies working group of the Emirates Scientist Council	Medium
	Develop research hubs around electrochemistry and thermal energy management & storage	Medium

In the context of a decarbonizing global economy, the following policy suggestions appear to be promising growth opportunities for the UAE:

Develop Green Industrial Parks in the UAE

The UAE should consider developing green industrial parks that provide the necessary inputs to low-carbon industrial production in a concentrated geographical area. These include dedicated low-cost renewable energy, clean, high-temperature heat, low-carbon hydrogen as well as carbon capture technology and other inputs to low-carbon industrial production. The low renewable energy costs make the UAE one of the best places to develop low-carbon energy-intensive industries. A net zero world will need to make things like steel, cement, chemicals, aluminum, and glass without emitting carbon. It will also need to develop fuels for ships, planes, and heavy-duty transport that have near-zero life cycle emissions, a large proportion of which are expected to come from renewable energy that is used to make hydrogen and liquid fuels. Additionally, the UAE has a low cost of capital which is an important comparative advantage since many of these industrial activities are highly capital-intensive.

The development of green industrial parks is a large initiative that would involve various stakeholders such as the Ministry of Energy & Infrastructure (MoEI), the Ministry of Industry & Advanced Technology (MoIAT), the respective departments in individual

Emirates such as the Abu Dhabi Department of Energy and the utility companies such as EWEC, TAQA or DEWA. It will be useful to build and expand on the work done by the Abu Dhabi Department of Energy and MoEI on low-carbon hydrogen oases. While the planning for these parks is something that could take place in the short term (i.e. 2023/2024) the execution and construction of these parks will unfold over a longer period.

Develop and Export Green Industrial Parks Internationally as a Business Model

Developing green industrial parks is extremely complex: for instance, nobody yet knows how to build, manage, and operate a multi-gigawatt green hydrogen production facility. In the process of building these parks in the UAE, the UAE will have to learn how to optimize a very complex renewable energy system, balance electricity, heat, and hydrogen across multiple energy users with different load profiles, and deploy multiple new technologies together that are still in pilot phase.

The UAE should consider monetizing its domestic experience by developing and exporting green industrial parks in other countries and developing a business model around these activities. Such a strategy could involve (1) owning the Engineering, Procurement, and Construction Management (EPCM) contractors and other related businesses that develop and operate parks; (2) where possible, having as many of the high-income knowledge workers who provide these services live and work in the UAE; and (3) helping UAE industrial companies that wish to expand abroad (such as Emirates Global Aluminium, or Emirates Steel Arkan) make profitable foreign investments in green industrial parks in other countries.

This policy could largely be driven by Mubadala and/or ADQ as well as Masdar. The investment process and structuring of the acquisition would likely be led by Mubadala or ADQ. However, Masdar is likely to be key for the successful integration of the EPCM company in ongoing project development both domestically and abroad. Therefore, it may be considered to involve Masdar at most levels of the decision-making process. Together with other stakeholders, they should plan how the EPCM company may best be embedded in future planning and processes.

Expand into critical minerals processing

The UAE could attract critical minerals processing activities and benefit from the mining boom needed for global decarbonization. A mining boom is required to provide the world with enough critical minerals to build a clean energy system. Currently, China is dominating the critical minerals processing market, but many countries are looking to diversify their critical minerals supply chain. Given its low cost of capital, strategic location, and good trading infrastructure the UAE is well-positioned to take advantage of this opportunity. Additionally, EGA has already established itself in the aluminum market and gathered important industry-specific know-how.

In terms of policy, the Ministry of Industry and Advanced Technology (MoIAT) together with EGA may study which specific minerals would be best suited for processing in the country. This would help provide more detail regarding the investment opportunities and specific challenges. This study would have to address questions related to forecasted market dynamics of the respective minerals, it should identify potential customers, transport and processing costs, and barriers to entry for the UAE. The UAE may, for example, be well positioned to enter the market of critical minerals whose processing requires large amounts of energy, given the low cost of energy that the country can provide.

Create Applied Research Hubs Around Electrochemistry and Thermal Energy Systems in the UAE

The UAE should consider developing research hubs in electrochemistry and thermal energy systems given their potential impact on localizing energy-intensive industries in the UAE and enabling their low-carbon production processes. Innovations in these areas would be beneficial for green industrial parks in the UAE, and applied research hubs may begin to develop and commercialize new technologies that help industrial decarbonization. These research hubs would be supportive of and synergistic with green industrial parks in the UAE. Attracting and developing the technology needed in the green transition will help the UAE carve out a space in some of the highest-value sectors of the transition, helping to sustain the UAE's high incomes and quality of life in a low-carbon world.

These research hubs may be established by the science department of MoIAT in collaboration with Khalifa University as it took over Masdar Institute in 2017 and has adjacent research activities. However, for the success of these research hubs, a direct link with industrial actors would be beneficial. It may be supportive of the mission of the hubs to discuss with potential industrial partners whether they may co-sponsor the establishment of such a hub. This would mean that innovative approaches and pilots could immediately be tested within industrial processes.

Strengthen R&D Collaboration Ties & Green Technology Working Group

The UAE should aim to establish collaborations with actors that are at the global frontier of green R&D activities as shown by their patenting output. While the UAE has developed high-quality green patents in some areas there is significant room for growth as an analysis of the UAE's green patenting activity has shown. This may be addressed by establishing collaborations with entities that are at the frontier of research within a specific field of interest. For these collaborations to be successful a well-suited partner on the UAE side must exist that can retain the knowledge gained from the collaboration. Identifying key areas for improved research activities, as well as UAE entities and partners for collaborations are the main steps to follow. The Ministry of Industry & Advanced Technology with its mandate for science is well suited to do so and the patenting analysis from the Growth Lab enables this process.

Moreover, the UAE could benefit from establishing a green technology working group that monitors the impact of innovations in the field on economic opportunities for the country. As the technological advances in this field have profound implications for the economic future of the UAE their development and impact must be studied to inform policymaking. The UAE has numerous organizations with large topic-level expertise such as ADNOC in CCUS or Masdar concerning hydrogen and other renewable energy technologies. To ensure that this knowledge is not hidden in silos but that a centralized deposit of knowledge exists which informs policymakers, the establishment of a green technology working group within the Emirates Scientists Council may be considered. This working group would continuously monitor advances in green technologies and their impact on the UAE. Its role would be to provide advice to the cabinet and deliver insights into the effect that certain technological advances may have on the local economy and areas that may require policy intervention.

Bibliography

Abu Dhabi Commercial Bank. 2023. "2023 ADCB Green Bond Report." https://www.adcb.com/en/multimedia/pdfs/2023/august/2023-adcb-green-bond-report.pdf.

ADNOC. 2023. *ADNOC to Invest in One of the Largest Integrated Carbon Capture Projects in MENA*. September 6. https://www.adnoc.ae/en/News-and-Media/Press-Releases/2023/ADNOC-to-Invest-in-One-of-the-Largest-Integrated-Carbon-Capture-Projects-in-MENA.

AFRY & GaffneyCline. 2022. "CCUS Deployment Challenges and Opportunities for the GCC."

Benny, John. 2023. "UAE Launches First Wind Farms in Net-Zero Push." The National, October 5. https://www.thenationalnews.com/business/energy/2023/10/05/uae-launches-first-wind-farms-in-net-zero-push/.

Biomass Magazine. 2023. *Masdar, Airbus Sign Agreement To Support Development Of SAF*. https://biomassmagazine.com/articles/masdar-airbus-sign-agreement-to-support-development-of-saf-20043.

Bloomberg NEF. 2023. "Asian Steel Giants Spread Bets on Hydrogen, Carbon Capture." Report. *BloombergNEF*, June 20. https://about.bnef.com/blog/asian-steel-giants-spread-bets-on-hydrogen-carbon-capture/.

Clarksons Research. 2023. "Green Technology Tracker: January 2023." Clarksons Research, January 16. https://insights.clarksons.net/green-technology-tracker-january-2023/.

Climate Bonds Initiative. 2023. "Sustainable Debt. Global Starte of the Market. 2022." https://www.climatebonds.net/files/reports/cbi_sotm_2022_03e.pdf.

Deloitte. 2023. "Emerging Green Hydrogen Market Set to Help Reshape Global Energy Map by End of Decade, Creating US$1.4 Trillion Market by 2050." https://www.deloitte.com/global/en/about/press-room/new-deloitte-report-emerging-green-hydrogen-market.html.

Dey, Paromita. 2023. *ADCB Issues $650m Five-Year Green Bonds*. Bonds. September 6. https://citywire.com/middle-east/news/adcb-issues-650m-five-year-green-bonds/a2425118.

DOE. 2022. "Industrial Decarbonization Roadmap." https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf.

DOE. 2023a. "Pathways to Commercial Liftoff - Industrial Decarbonization." https://liftoff.energy.gov/wp-content/uploads/2023/10/LIFTOFF_DOE_Industrial-Decarbonization_v8.pdf.

DOE. 2023b. "Pathways to Commercial Liftoff: Low Carbon Cement." https://liftoff.energy.gov/wp-content/uploads/2023/09/20230921-Pathways-to-Commercial-Liftoff-Cement.pdf.

ETC. 2023. “Bioresources Within A Net-Zero Emissions Economy - ETC.” *Energy Transitions Commission*. https://www.energy-transitions.org/publications/bioresources-within-a-net-zero-economy/.

First Abu Dhabi Bank. 2023. “Sustainable Finace Report 2022-2023.” https://www.bankfab.com/-/media/fabgroup/home/about-fab/esg/reports-policy-frameworks/pdfs/sustainable-finance-report-2023.pdf?view=1.

Getting to Zero Coalition. 2021. https://www.globalmaritimeforum.org/content/2021/11/The-Next-Wave-Green-Corridors.pdf.

Global Carbon Project. 2020. “Supplemental Data of Global Carbon Project 2020.” Version 1.0. With Pierre Friedlingstein, Matthew Jones, Michael O’Sullivan, et al. Global Carbon Project, October 1. MS Excel. https://doi.org/10.18160/GCP-2020.

Global CCS Institute. 2022. “Global Status of CCS 2022.”

“Global Solar Atlas.” n.d. Accessed October 26, 2023. https://globalsolaratlas.info/global-pv-potential-study.

GMI. 2023. “Glass Manufacturing Market Size | Industry Report 2023-2032.” Global Market Insights Inc. https://www.gminsights.com/industry-analysis/glass-manufacturing-market.

Gnana, Jennifer. 2021. “Adnoc Signs 10-Year Gas Supply Agreements with Emirates Steel and Arkan.” The National, May 25. https://www.thenationalnews.com/business/energy/adnoc-signs-10-year-gas-supply-agreements-with-emirates-steel-and-arkan-1.1229761.

Gray, Diana. 2023. “What Does EU ETS Mean For The Shipping Industry?” Nautilus Labs, August 2. https://nautiluslabs.com/resources/what-does-eu-ets-mean-for-the-shipping-industry/.

Harvard Growth Lab. 2023. “The Atlas of Economic Complexity by @HarvardGrwthLab.” https://atlas.cid.harvard.edu/explore?country=undefined&queryLevel=undefined&product=5748&year=2021&productClass=HS&target=Product&partner=undefined&startYear=undefined.

Hausmann, Ricardo, César A. Hidalgo, Sebastián Bustos, Michele Coscia, Alexander Simoes, and Muhammed A. Yildirim. 2014. *The Atlas of Economic Complexity: Mapping Paths to Prosperity*. The MIT Press. https://doi.org/10.7551/mitpress/9647.001.0001.

Hill, Joshua S. 2023. “UAE Awards Contract for Huge 1.8GW Solar Park Addition at Record Low Prices.” RenewEconomy, August 17. https://reneweconomy.com.au/uae-awards-contract-for-huge-1-8gw-solar-park-addition-at-record-low-prices/.

Hydrogen Council. 2023. “Hydrogen Insights 2023.”

IATA. 2023. “Net Zero 2050: Sustainable Aviation Fuels.” https://www.iata.org/en/iata-repository/pressroom/fact-sheets/fact-sheet---alternative-fuels/.

IEA. 2021a. “Net Zero by 2050: A Roadmap for the Global Energy Sector.” https://www.iea.org/reports/net-zero-by-2050.

IEA. 2021b. “The Role of Critical Minerals in Clean Energy Transitions.”

IEA. 2022. "Final List of Critical Minerals 2022." https://www.iea.org/policies/15271-final-list-of-critical-minerals-2022.
IEA. 2023a. "Aluminium." https://www.iea.org/energy-system/industry/aluminium#tracking.
IEA. 2023b. "Critical Minerals Market Review 2023."
IEA. 2023c. "Global Hydrogen Review 2023."
IEA. 2023d. "Hydrogen Production and Infrastructure Projects Database." https://www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database.
IEA. 2023e. "International Shipping." IEA. https://www.iea.org/energy-system/transport/international-shipping.
IEEFA. 2023. "MENA, a Potential New Hub for Green Steel and Green Iron Metallics." https://ieefa.org/resources/mena-potential-new-hub-green-steel-and-green-iron-metallics.
International Aluminium Institute. 2023. "Global Aluminium Cycle 2050." https://alucycle.international-aluminium.org/public-access/public-global-cycle/.
International Energy Agency. 2020. *World Energy Outlook 2020*. International Energy Agency.
King Abdullah University of Science & Technology. 2022. *Kingdom Takes Carbon Capture to Clean Heights through KAUST Partnership with ENOWA and SEC*. November 30. https://www.kaust.edu.sa/en/news/cryogenic-carbon-capture_mous_sgi.
Liu, Hengwei, Berenice Garcia Tellez, Tarek Atallah, and Murad Barghouty. 2012. *The Role of CO2 Capture and Storage in Saudi Arabia's Energy Future*. August 13. https://www.sciencedirect.com/science/article/abs/pii/S1750583612001934.
Maritime Executive. 2023. "The Decarbonization Tradeoffs for Ammonia, Methanol and H2." The Maritime Executive. https://maritime-executive.com/editorials/the-decarbonization-tradeoffs-for-ammonia-methanol-and-h2.
Mckinsey. 2023. "Green Cement and the Net-Zero Transition | Sustainability | McKinsey & Company." https://www.mckinsey.com/capabilities/sustainability/our-insights/Spotting-green-business-opportunities-in-a-surging-net-zero-world/transition-to-net-zero/cement.
Mehta, Angeli, and Angeli Mehta. 2023. "In the Voyage to Net-Zero, Which Green Shipping Fuel Will Rule the Seas?" Climate & Energy. *Reuters*, May 15. https://www.reuters.com/sustainability/climate-energy/voyage-net-zero-which-green-shipping-fuel-will-rule-seas-2023-05-15/.
Millet et al. 2023. "Technology and Market Power: The United States Cement Industry, 1974-2019." http://www.nathanhmiller.org/cementmarkups.pdf.
Ministry of Energy & Infrastructure. 2023. "National Hydrogen Strategy."
Mission Possible Partnership. 2022a. "Making Net Zero Aviation Possible."
Mission Possible Partnership. 2022b. "Making Net Zero Steel Possible." https://missionpossiblepartnership.org/wp-content/uploads/2022/09/Making-Net-Zero-Steel-possible.pdf.
Mission Possible Partnership. 2023. "Making Net-Zero Aluminium Possible."

Rahman, Fareed. 2022. "Emirates Steel Registers 50% Increase in Number of Export Markets amid Higher Demand." The National, March 17. https://www.thenationalnews.com/business/economy/2022/03/17/emirates-steels-registers-50-increase-in-number-of-export-markets-amid-higher-demand/.

Repsol. 2021. "Presentation on the V Med Hub." https://www.hubdaytarragona.com/.

Ritchie, Hannah. 2020. "Climate Change and Flying: What Share of Global CO2 Emissions Come from Aviation?" https://ourworldindata.org/co2-emissions-from-aviation.

SKYQUEST. 2023. "Cement Market Size, Share, Growth Analysis, By Type, Application - Industry Forecast 2022-2028." https://www.skyquestt.com/report/cement-market.

"Solar Energy | The Official Portal of the UAE Government." n.d. Accessed October 27, 2023. https://u.ae/en/information-and-services/environment-and-energy/water-and-energy/types-of-energy-sources/solar-energy.

Standard & Poor. 2023. *Sustainable Bond Issuance Will Return to Growth in 2023*. https://www.spglobal.com/esg/insights/featured/special-editorial/sustainable-bond-issuance-will-return-to-growth-in-2023.

The National News. 2022. *EGA Plans Shift to Nuclear and Solar for Aluminium Production as Demand Soars*. https://www.thenationalnews.com/business/energy/2022/04/15/ega-plans-shift-to-nuclear-and-solar-for-aluminium-production-as-demand-soars/.

"UAE Energy Strategy 2050 | The Official Portal of the UAE Government." n.d. Accessed October 27, 2023. https://u.ae/en/about-the-uae/strategies-initiatives-and-awards/strategies-plans-and-visions/environment-and-energy/uae-energy-strategy-2050.

UAE Ministry of Climate Change and Enviroment. 2021. "UAE Sustainable Finance Framework 2021-2031." https://www.moccae.gov.ae/assets/24b84d14/UAE_Sustainable_framework_21.pdf.aspx.

United Arab Emirates Ministry of Climate Change & Environment. 2023. "Accelerating Action Towards a Green, Inclusive and Resilient Economy." https://unfccc.int/sites/default/files/NDC/2023-07/Third%20Update%20of%20Second%20NDC%20for%20the%20UAE_v15.pdf.

University of Brighton. n.d. *Cryogenic Carbon Capture*. https://www.brighton.ac.uk/business-services/consultancy/cryogenics/cryogenic-carbon-capture.aspx.

US Department of Energy. 2023. "Alternative Fuels Data Center." https://afdc.energy.gov/fuels/sustainable_aviation_fuel.html.

Vilayanur Viswanathan. 2022. "2022 Grid Energy Storage Technology Cost and Performance Assessment." https://www.pnnl.gov/sites/default/files/media/file/ESGC%20Cost%20Performance%20Report%202022%20PNNL-33283.pdf.

WEF. 2022. "Power-to-Liquid Roadmap (UAE)." https://www3.weforum.org/docs/WEF_UAE_Power_to_Liquid_Roadmap_2022.pdf.

White House. 2021. “FACT SHEET: The United States and European Union To Negotiate World’s First Carbon-Based Sectoral Arrangement on Steel and Aluminum Trade.” The White House, October 31. https://www.whitehouse.gov/briefing-room/statements-releases/2021/10/31/fact-sheet-the-united-states-and-european-union-to-negotiate-worlds-first-carbon-based-sectoral-arrangement-on-steel-and-aluminum-trade/.

World Economic Forum. 2020. “Aluminium for Climate: Exploring Pathways to Decarbonize the Aluminium Industry.” https://www3.weforum.org/docs/WEF_Aluminium_for_Climate_2020.pdf.

World Economic Forum. 2022. “Power-to-Liquids Roadmap: Fuelling the Aviation Energy Transition in the United Arab Emirates.”

Zawya. 2016. “Emirates Global Aluminium, One of UAE’s Most Innovative Companies, Announces 2 More Patents during Innovation Week.” https://www.zawya.com/en/press-release/emirates-global-aluminium-one-of-uaes-most-innovative-companies-announces-2-more-patents-during-innovation-mcaatqv7.

Appendix

Methodological Explanation of Green Supply Chain Analysis

The analysis as shown builds on a mapping of the respective green supply chains based on reports from the Department of Energy and the International Energy Agency to products using the HS classification from the United Nations Statistical Division (COMTRADE). The application of economic complexity methods to arrive at the results shown in previous sections is based on the following steps:

1.) A within country z-score standardization of the following variables for all products: Complexity Outlook Gain (COG), Density, RCA, Growth Rate past 10 years (variables explained in box below). This ensures that all variables are expressed in the same unit (i.e. z-scores)

2.) Calculating the median of each variable by country and by supply chain – i.e. median COG for the Solar Supply Chain in the UAE

3.) Calculating a compositive Attractiveness and Feasibility Score, where:
   - Attractiveness: 0.75*COG + 0.25*Growth Rate past 10 years
   - Feasibility: 0.5*Density + 0.5*RCA

Complexity Outlook Gain (COG): This is a place-product measure that quantifies the extent to which a location could benefit in opening future diversification opportunities by developing a particular product. Complexity outlook gain quantifies how a new product can open links to more, and more complex, products. Complexity outlook gain classifies the strategic value of a product based on the new paths to diversification in more complex sectors that it opens up. Complexity outlook gain accounts for the complexity of the products not being produced in a location and the distance or how close to existing capabilities that new product is.

Distance: This is a place-product measure and corresponds to the sum of the proximities connecting a new good to all the products that country is not currently exporting. This value is normalized by dividing it by the sum of proximities between the new product and all other products. In turn, proximity is a product-product measure that is calculated as the minimum conditional probability that a country intensively exports one product given that it already intensively exports the other. Thus, if a country exports most of the goods connected to a product, then its distance to it will be short (close to zero). However, if the country only exports a small proportion of them, then its distance to it will be large (close to one). Density, in turn, is the inverse of distance (1-distance).

Revealed Comparative Advantage (RCA): This is a place-product measure that captures the relative importance of a product in a place. Following the methodology of Balassa (1964), it is usually calculated as the ratio between the proportion of the product in the export basket of a place and the proportion of the product in world trade. If this relationship is greater than one, the place has a "revealed comparative advantage" in that product, which is equivalent to saying that the place produces the product more intensively than the rest of the world.

The following tables show the top 10 products by overall score, attractiveness and feasibility for the UAE in the wind, solar and fuels & hydrogen (here for simplicity just referred to as hydrogen) supply chains. These supply chains were identify to be most strategic for the UAE given the tradeoff between attractiveness and feasibility. The results shown here should only be taken as indicative results since the measures require more testing given the novelty of the research in this context.

Table 8: Top 10 Products from Wind, Solar & Hydrogen Supply Chain by Overall Score

Product Name	Supply Chain	Attractiveness Score	Feasibility Score	Overall Score
Unwrought aluminum	Solar, Fuel Cells and Green Hydrogen	-1.07	4.31	1.62
Polymers of ethylene	Wind, Solar, Fuel Cells and Green Hydrogen	-1.06	1.93	0.43
Carbon articles for electrical purposes	Fuel Cells and Green Hydrogen	1.20	-0.37	0.42
Screws and similar articles of iron or steel	Fuel Cells and Green Hydrogen	1.36	-0.68	0.34
Measuring instruments	Fuel Cells and Green Hydrogen	1.23	-0.56	0.34
Laboratory, hygienic or pharmaceutical glassware	Fuel Cells and Green Hydrogen	1.40	-0.81	0.29
Platinum	Wind, Fuel Cells and Green Hydrogen	1.05	-0.47	0.29
Ion-exchangers based on polymers	Fuel Cells and Green Hydrogen	1.36	-0.78	0.29
Artificial graphite	Fuel Cells and Green Hydrogen	1.06	-0.50	0.28
Articles of stone or of other mineral substances	Fuel Cells and Green Hydrogen	0.95	-0.39	0.28

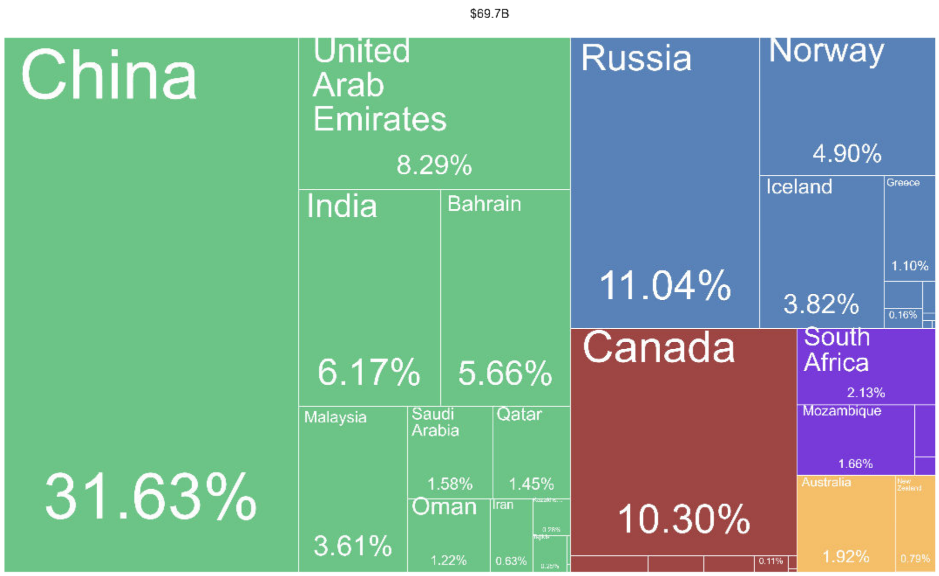
Table 9: Top 10 Products from Wind, Solar & Hydrogen Supply Chain by Attractiveness

Product Name	Supply Chain	Attractiveness Score	Feasibility Score	Overall Score
Laboratory, hygienic or pharmaceutical glassware	Fuel Cells and Green Hydrogen	1.40	-0.81	0.29
Screws and similar articles of iron or steel	Fuel Cells and Green Hydrogen	1.36	-0.68	0.34
Ion-exchangers based on polymers	Fuel Cells and Green Hydrogen	1.36	-0.78	0.29
Measuring instruments	Fuel Cells and Green Hydrogen	1.23	-0.56	0.34
Carbon articles for electrical purposes	Fuel Cells and Green Hydrogen	1.20	-0.37	0.42
Transmission shafts	Wind, Solar	1.18	-0.66	0.26
Instruments for physical or chemical analysis	Fuel Cells and Green Hydrogen	1.13	-0.61	0.26
Appliances for thermostatically controlled valves	Fuel Cells and Green Hydrogen	1.08	-0.79	0.15
Artificial graphite	Fuel Cells and Green Hydrogen	1.06	-0.50	0.28
Platinum	Wind. Fuel Cells and Green Hydrogen	1.05	-0.47	0.29

Table 10: Top 10 Products from Wind, Solar & Hydrogen Supply Chain by Feasibility

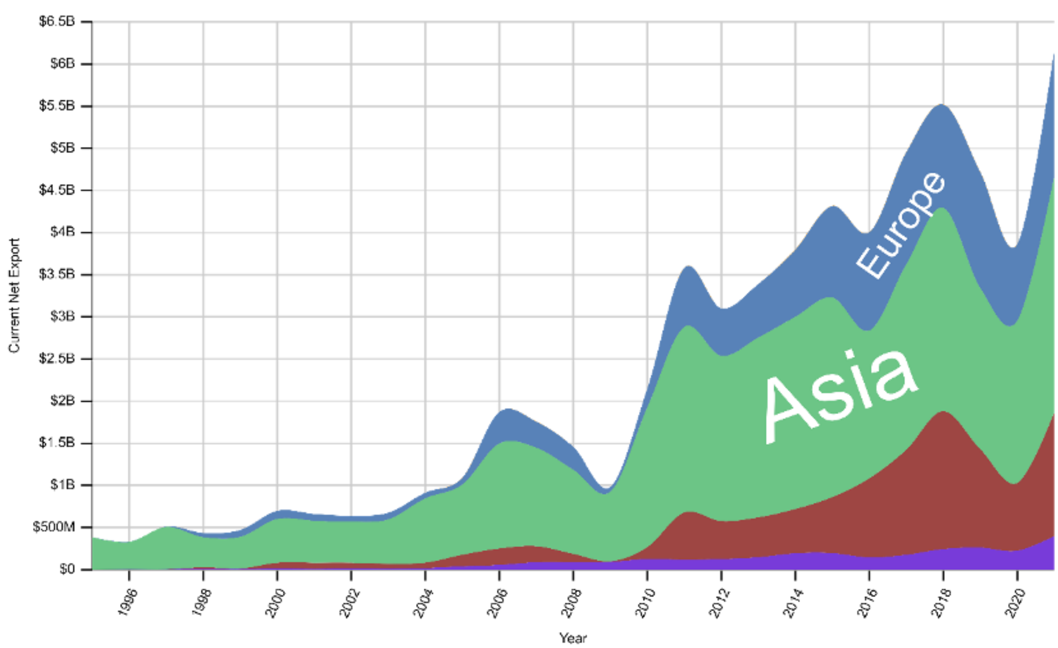
Product Name	Supply Chain	Attractiveness Score	Feasibility Score	Overall Score
Unwrought aluminum	Solar, Fuel Cells and Green Hydrogen	-1.07	4.31	1.62
Polymers of ethylene	Wind, Solar, Fuel Cells and Green Hydrogen	-1.06	1.93	0.43
Lead refined unwrought	Wind	-1.02	1.52	0.25
Copper bars, rods and profiles	Fuel Cells and Green Hydrogen	-1.18	1.21	0.02
Zirconium ore	Fuel Cells and Green Hydrogen	-1.54	1.03	-0.25
Manganese > 47% by weight	Fuel Cells and Green Hydrogen	-0.60	0.97	0.19
Other vessels	Wind	-1.44	0.94	-0.25
Chromium ore	Fuel Cells and Green Hydrogen	-0.88	0.81	-0.03
Other tubes, pipes and hollow profiles of iron or steel	Fuel Cells and Green Hydrogen	-1.08	0.81	-0.14
Structures and their parts, of iron or steel	Wind, Solar	-1.09	0.66	-0.21

Figure 29: Global Net Aluminum Exports - 2021



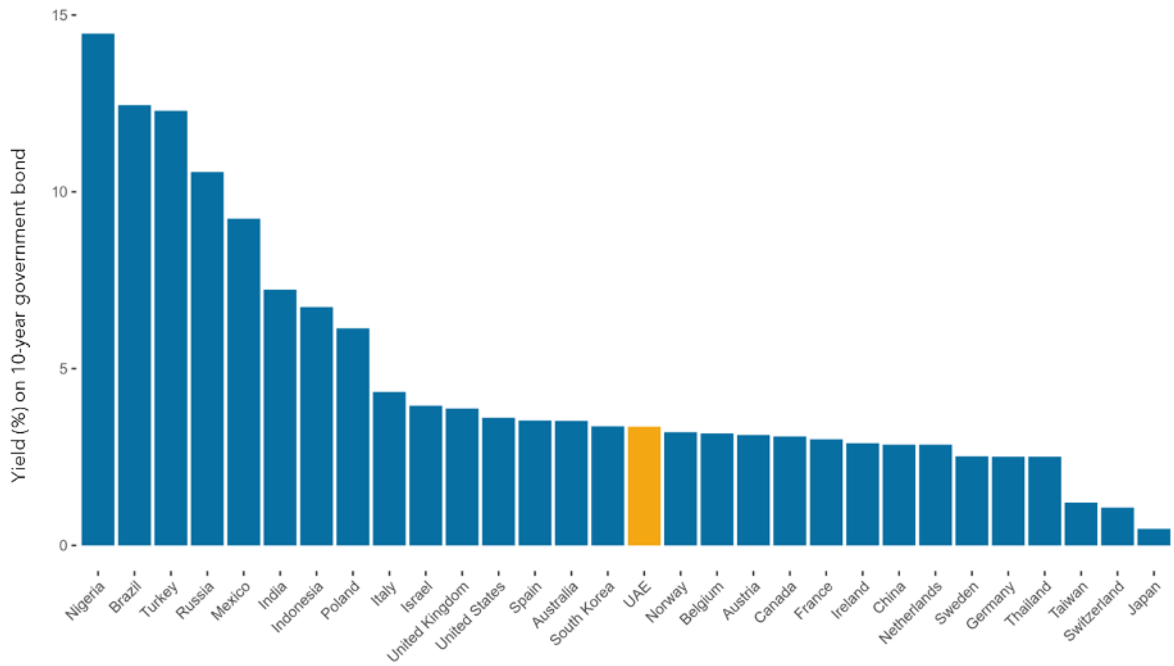
Source: Atlas of Economic Complexity 2023

Figure 30: UAE Net Aluminum Exports - 1990 to 20201



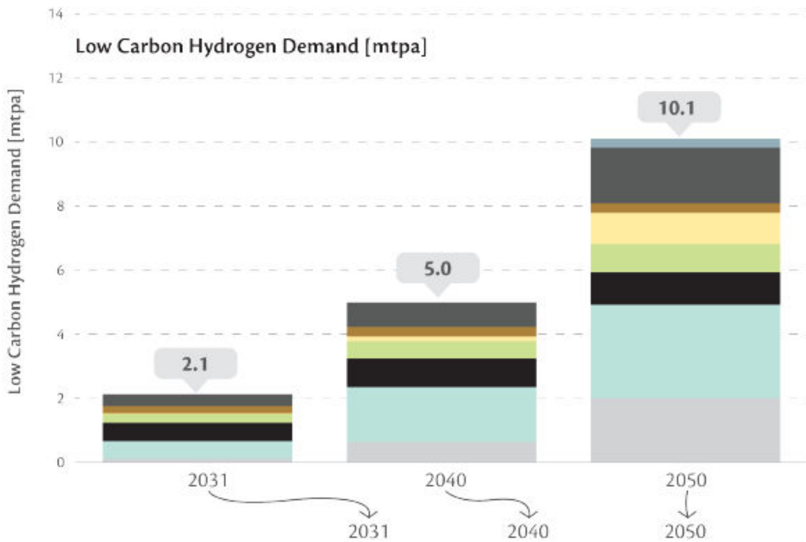
Source: Atlas of Economic Complexity 2023

Figure 31: Government bonds – Global Comparison February 2023



Source: Author's elaboration based on Statista and World Government Bonds & Capital IQ

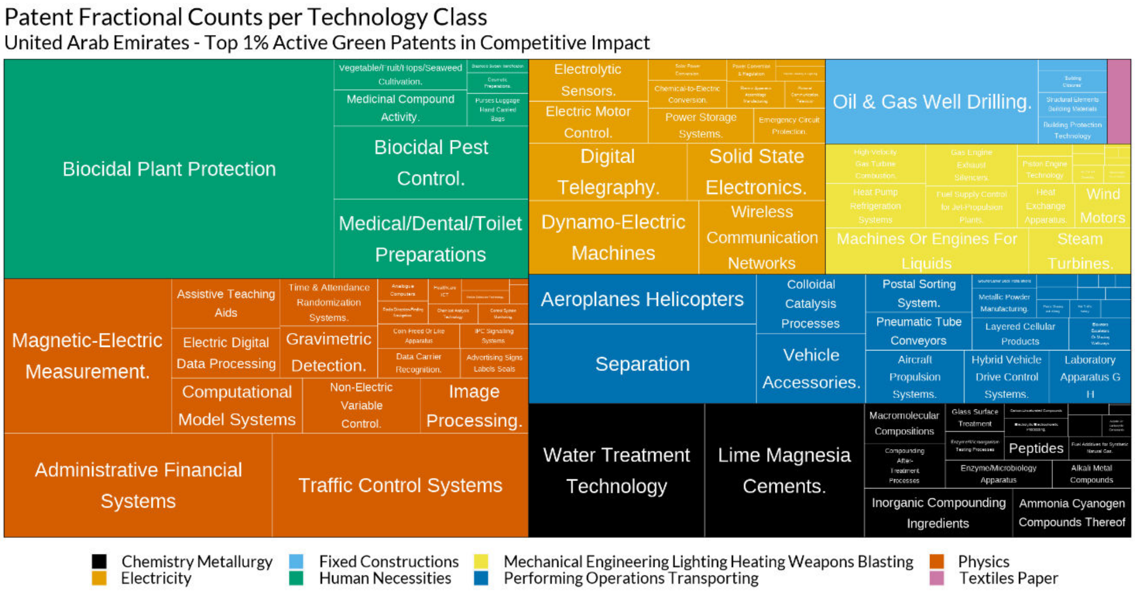
Figure 32: Low Carbon Hydrogen Demand in the UAE



	2031	2040	2050
Total	**2.1**	**5.0**	**10.1**
Grid Flexibility	0.0	0.0	0.3
Aluminium	0.4	0.8	1.7
Refineries	0.2	0.3	0.3
Transport	0.0	0.1	1.0
Fertilizers and chemicals	0.3	0.5	0.9
Iron and Steel	0.6	0.9	1.0
Shipping	0.5	1.7	2.9
Aviation	0.1	0.6	2.0

Source: Ministry of Energy and Infrastructure 2023

Figure 33: High Quality Green Patents from UAE by Technology Class



Source: Author's own elaboration based on WIPO & PATSTAT data

Table 11: Top 15 Green Patents Assignees - UAE (2017 - 2022)

ASSIGNEE	INDUSTRY	GREEN PATENTS
UPL	Professional, Scientific, and Technical Services	52 Patents
UNITED ARAB EMIRATES UNIVERSITY	Local University	39 Patents
KHALIFA UNIVERSITY OF SCIENCE AND TECHNOLOGY	Local University	28 Patents
GE (GENERAL ELECTRIC COMPANY)	Motor and Generator Manufacturing	11 Patents
ABU DHABI NATIONAL OIL COMPANY	Mining, Quarrying, and Oil and Gas Extraction	10 Patents
SHAHEEN INNOVATIONS HOLDING	Management of Companies and Enterprises	6 Patents
G & W ELECTRIC COMPANY	Wholesale Trade	5 Patents
HONEYWELL INTERNATIONAL	Administrative and Support and Waste Management and Remediation Services	5 Patents
SCHLUMBERGER TECHNOLOGY	Mining, Quarrying, and Oil and Gas Extraction	5 Patents
ABU DHABI POLYTECHNIC	Local University	4 Patents
ACCENTURE GLOBAL SOLUTIONS	Professional, Scientific, and Technical Services	4 Patents
ABU DHABI UNIVERSITY	Local University	3 Patents
GARGASH, ABDUL JABBAR ABDULLA ALI	Individual	3 Patents
MASTERCARD WORLDWIDE	Professional, Scientific, and Technical Services	3 Patents
VISA INTERNATIONAL SERVICE ASSOCIATION	Management of Companies and Enterprises	3 Patents

Source: Author's own elaboration based on WIPO & PATSTAT data