Synthetic fuels on the Arabian Peninsula

Potential applications, production economics and international trade aspects

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EXECUTIVE SUMMARY

Green synthetic fuels such as hydrogen have received enormous attention in recent years as a possible cornerstone of the global transition to renewable energy sources. For countries on the Arabian Peninsula, these fuels present an opportunity in two ways:

- There are many potential **applications for synthetic fuels** in the region (see chapter 2);
- The Arabian Peninsula has very attractive conditions to **produce synthetic fuels**, putting it in a good position to become a global renewable fuel supplier (see chapter 3).

To establish international markets for hydrogen and other synthetic fuels though, some requirements beyond pure economics will likely need to be fulfilled (see chapter 4). Stakeholders from governments and companies in potential production and consumption regions should therefore enter a dialogue to create a mutual understanding and develop strategies on some pressing open questions, including:

- When demand for synthetic fuels will reach scale (see chapter 2.4);
- Which synthetic fuel production technologies are most promising (see chapter 1.1);
- How to transport synthetic fuels (see chapter 1.2);
- How to share costs and benefits of synthetic fuel markets (see chapter 4.1);
- Which sustainability criteria to set (see chapter 4.2).

Bilateral partnerships such as the Emirati-German Energy Partnership and the Energy Dialogues between Germany and Saudi Arabia and Oman are ideal platforms to discuss these questions – through high-level political exchange, expert workshops or study tours, for instance.

1 TECHNOLOGY OVERVIEW

1.1 Production of synthetic fuels

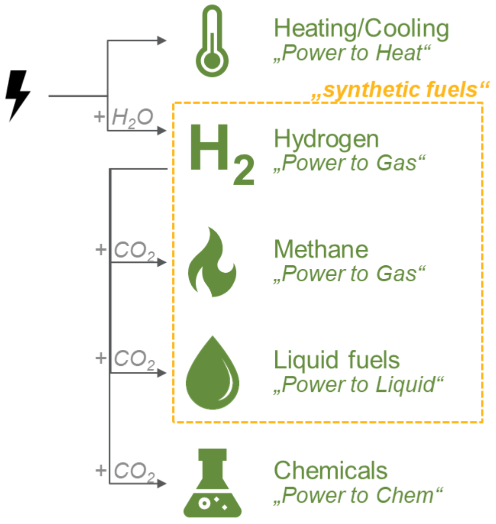

Figure 1: Schematic depiction of Power-to-X production pathways. Source: Own illustration

„Power-to-X” (PtX) is a term commonly used to describe electricity-based fuels. As Figure 1 shows, this is somewhat misleading since PtX covers also technologies like Power-to-Heat (e.g. electrical boilers) or Power-to-Chem (e.g. making complex molecules from CO_2 and electricity). The more concise term “synthetic fuels” covers only molecular, electricity-based energy carriers. Most prominently, these include:

- **Hydrogen** can be produced through water electrolysis. It is the platform molecule for all other synthetic fuels – therefore its production is highly relevant, even if it is not used as an energy carrier for end uses. Hydrogen is today already produced at industrial scale, but mostly from fossil feedstocks for industrial purposes. It is not used as an end energy carrier at significant scale yet. “Blue” hydrogen means the production from fossil sources with subsequent carbon capture and storage (CCS).

- **Methane** can be produced with hydrogen and CO_2 as feedstocks. If it is to count as carbon neutral, the CO_2 feedstock must be renewable (see chapter 4.2). Since natural gas consists largely of methane, electricity-based methane can be transported and used like natural gas.
- **Liquid fuels** are liquid, electricity-based hydrocarbons like gasoline, diesel or kerosene. As methane, they require CO_2 feedstock but can be transported and used like their fossil-based equivalents.

An issue is that every conversion step shown in Figure 1 is associated with energy losses. Producing hydrogen through water electrolysis typically entails 30% energy losses, power-to-liquid even around 50%.[1] As a consequence, large amounts of electricity are needed for the production of synthetic fuels.

Details on synthetic fuel production economics and scalability on the Arabian Peninsula can be found in chapters 3.1 and 3.2, respectively. More general information on synthetic fuel production can be found in a number of recent publications e.g. by IRENA[2], IEA[3] or Navigant[4].

1.2 Long-distance transport of synthetic fuels

If synthetic fuels were to be traded internationally, long-distance transport of these energy carriers would be required. This chapter briefly introduces the two main technology options for this – shipping and pipelines. There is still high uncertainty how long-distance transport of synthetic fuels could be arranged in order to create a basis for international synthetic fuel markets. Addressing this will hence be the task of international energy cooperation platforms.

Pipelines

Much like natural gas, gaseous synthetic fuels like hydrogen or methane can be transported via pipelines. The advantage of this is that energy losses, e.g. for compression, and hence costs are relatively low.[5] The downside is that pipelines by nature require large upfront investments. This leads to a first-mover-problem, where infrastructure investments are only attractive when there is high-volume trade of synthetic fuels – on the other hand, international trade becomes only economical once infrastructure for it is provided.

While there are numerous gas pipelines from Russia or North Africa to Europe, pipeline projects from the Arabian Peninsula such as the Qatar-Turkey pipeline have not been realised, partly due to geostragic reasons. To enable global synthetic fuel markets, pipelines could however be an important element for low-cost supply. This underlines the necessity for international collaboration in the field of synthetic fuels.

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[1] Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018): The Future Cost of Electricity-Based Synthetic Fuels. Available online: https://www.agora-energiewende.de/fileadmin2/Projekte/2017/SynKost_2050/Agora_SynKost_Study_EN_WEB.pdf

[2] IRENA (2018): Hydrogen from Renewable Power. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf

[3] IEA (2019): The Future of Hydrogen. Available online: https://www.iea.org/publications/reports/thefutureofhydrogen/

[4] Navigant (2019): Gas for Climate. Available online: https://www.gasforclimate2050.eu/files/files/Navigant_Gas_for_Climate_The_optimal_role_for_gas_in_a_net_zero_emissions_energy_system_March_2019.pdf

[5] IEA (2019): The Future of Hydrogen. Available online: https://www.iea.org/publications/reports/thefutureofhydrogen/

Shipping

The cost of pipeline transport roughly correlates with distance in a linear fashion as for every kilometer of distance, one kilometer of pipeline needs to be built. Costs for synthetic fuel shipping in contrast are less dependent on distance: the largest cost driver is the fuel conversion before shipping (e.g. hydrogen liquefication, ammonia conversion), while the cost for each kilometer of shipping is less relevant.[6] Consequently, shipping is more economical for longer distances while pipelines are attractive for shorter logistics.

An important parameter for shipping is the energy density of the synthetic fuel, as it dictates the amount of energy one ship can carry (see Table 1). Hydrogen has a lower energy density than other synthetic fuels – on the other hand, hydrogen has the least energy losses in its production because other synthetic fuels require additional conversion steps (see Figure 1). Choosing the best molecular carrier for transportation therefore depends on energy density, electricity availability and synthetic fuel end use requirements.

Table 1: Energy density of energy carriers.

	Liquid hydrogen	Liquid ammonia	Liquid methane	Diesel fuel
Energy density (MJ per L)[7]	8.5	11.5	22.2	38.6

If the Arabian Peninsula was to become a global supplier of synthetic fuels, pipelines could be a long-term option to supply less distant demand markets at high volumes and low cost. For the short-term, lower volumes and also more distant destinations, shipping could also be pursued. Shipping however also requires infrastructure investments and is therefore connected to similar issues as discussed above for pipelines. As an upside, technology innovations such as liquid organic hydrogen carriers[8] could reduce the cost of shipping in the future.

2 SYNTHETIC FUEL USE CASES ON THE ARABIAN PENINSULA

The main use case of synthetic fuels is to use them as renewable energy carriers in applications where direct usage of renewable electricity is challenging, such as heavy industries or transport. They can also facilitate the transition of the electricity system towards very high shares of renewables.

2.1 Industry

The industrial sector is today the largest consumer of fossil-based hydrogen and could also in the future lead demand due to new applications of hydrogen and its derivatives as decarbonization option.[9] The main use cases – steel manufacturing, base chemicals and refining processes – and their potentials on the Arabian Peninsula are described in more detail below.

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[6] Ibid.

[7] Ronnie Belmans (2019): No molecules, no energy transition. Working Paper.

[8] Molecules which can be “loaded” with hydrogen, then shipped and “unloaded” in the target country – researched e.g. by Hydrogeneous: https://www.hydrogenious.net/index.php/en/hydrogen-2-2/

[9] IEA (2019): The Future of Hydrogen. Available online: https://www.iea.org/publications/reports/thefutureofhydrogen/

Steel Manufacturing

The steel industry is responsible for 7 to 9% of global greenhouse gas (GHG) emissions, mostly stemming from the use of coking coal in the blast furnace process.[10] The necessity to decarbonize the economy has led the sector to increasingly investigate GHG-neutral processes, most prominently replacing coal by hydrogen and CCS. At electricity prices below USD ~50/MWh, hydrogen becomes a more attractive option than CCS[11] – such prices are already achieved in renewable energy tenders on the Arabian Peninsula today (see Table 3). Leading steel producers like ThyssenKrupp are also advocating hydrogen-based routes. However, even if hydrogen-based steelmaking is the most economical option for GHG-neutral steel, it is still more expensive than conventional, GHG-intensive processes. This means that governments will need to support hydrogen-based steelmaking initially. On the other hand, new investments in GHG-intensive steelmaking are probably risky because these assets could become increasingly uncompetitive in a global steel market under growing regulatory pressure to decarbonize.

Table 2 shows that there is already some conventional steel production in the UAE, Saudi Arabia, Oman and Qatar from companies like SABIC or Emirates Steel. This means that relevant steel supply chains are already in place in the region. Together with the very attractive hydrogen production potentials described in chapter 3, this could be an opportunity for these countries to become early adopters and global suppliers of GHG-neutral steel.

Table 2: Steel and refinery output in selected countries on the Arabian Peninsula.

	UAE	Saudi Arabia	Oman	Qatar
Crude steel production 2017 (Mt)[12]	3.3	4.8	2.0	2.6
Crude steel production 2017 (% of world total)	0.2%	0.3%	0.1%	0.1%
Refinery throughput 2018 (Thousand barrels daily)[13]	1044	2770	282	397
Refinery throughput 2018 (% of world total)	1.3%	3.3%	0.3%	0.5%

Refining processes

The use case of hydrogen in refineries is economically and technically very different to the applications in steel or chemicals. This is mainly because refineries are today already among the largest hydrogen consumers, using it mainly for hydrocracking and desulphurization. Consequently, using electricity-based "green" hydrogen does not require a fundamental change of production processes as it would be the case for chemicals or steel. Refineries could begin blending small amounts of green hydrogen into existing streams of fossil-based hydrogen, leaving all other processes unchanged. The

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[10] World Steel Association (2019): Steel's Contribution to a Low Carbon Future. Available online: https://www.worldsteel.org/en/dam/jcr:7ec64bc1-c51c-439b-84b8-94496686b8c6/Position_paper_climate_2019_vfinal.pdf

[11] McKinsey & Company (2018): Decarbonization of industrial sectors. Available online: https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/how%20industry%20can%20move%20toward%20a%20low%20carbon%20future/decarbonization-of-industrial-sectors-the-next-frontier.ashx

[12] World Steel Association Database. Available online: https://www.worldsteel.org/internet-2017/steel-by-topic/statistics/steel-data-viewer/P1_crude_steel_total/DEU/SAU/ARE/OMN/QAT

[13] BP (2019): BP Statistical Review of World Energy. Available online: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf

share of green hydrogen could then be increased over time. An early example for this strategy is the pilot plant by BP and Uniper in BP's refinery in Lingen, Germany.

Green hydrogen in refineries is also a more attractive business case due to existing regulations. The European Union's Renewable Energy Directive II[14] foresees that conventional fuel suppliers may count green hydrogen which is used as "intermediate product" to reduce the share of biofuel they are obliged to blend into their fuels. In cases where biofuels e.g. from food waste are not available, it might be more economical for fuel suppliers to use green hydrogen rather than more expensive biofuels. From the perspective of refinery operators on the Arabian Peninsula it could therefore be an opportunity to become suppliers of green hydrogen based conventional fuels for consumers in Europe. As companies like Saudi Aramco or ADNOC are already amongst the globally leading refinery operators (see Table 2), they could be in a strong position to seize this opportunity.

Organic Base Chemicals

As shown in Figure 1, synthetic fuels can also decarbonize the chemical industry by replacing current fossil oil-based feedstocks – mainly for plastics production. The main issue with the "power-to-chem" technology is its high costs: Abatement costs of over 250 €/tCO_2 are ten times higher than the 2019 industrial CO_2 price in the EU.[15] This means that recycling is economically much more attractive than power-to-chem. But even with drastically increased recycling, there would be a need for virgin base chemical production, e.g. through power-to-chem.[16]

The Arabian Peninsula could become a production hub for electricity-based chemicals not only because of the boundary conditions listed in chapter 3, but also because of its company landscape. The chemical industry is an intricate network of complex processes, so regions with existing chemical industries will have a competitive edge when adopting power-to-chem. Due to the availability of petrochemical feedstocks, the Arabian Peninsula already hosts some relevant chemicals production today. The most prominent example is SABIC in Saudi Arabia, the fourth largest chemical company in the world.[17] There are also plans in the UAE and Oman to increase petrochemical capacities.[18] In this light, pioneering power-to-chem could be an opportunity for countries on the Arabian Peninsula.

2.2 Transport

The transport sector is a large contributor to the Gulf region's GHG emissions. For instance, the sector accounted for 15% of the UAE's GHG emissions in 2016.[19] Green synthetic fuels could support

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[14] Directive (EU) 2018/2001, Article 25 (1) a)

[15] McKinsey & Company (2018): Decarbonization of industrial sectors. Available online: https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/how%20industry%20can%20move%20toward%20a%20low%20carbon%20future/decarbonization-of-industrial-sectors-the-next-frontier.ashx

[16] Energy Transitions Commission (2018): Mission possible. Available online: http://www.energy-transitions.org/sites/default/files/ETC_MissionPossible_FullReport.pdf

[17] Chemical & Engineering News (2018): C&EN's Global Top 50 chemical companies of 2017. Available online: https://cen.acs.org/business/finance/CENs-Global-Top-50-chemical/96/i31

[18] The National (2019): Middle East petrochemical push signals oil's future. Available online: https://www.thenational.ae/business/energy/middle-east-petrochemical-push-signals-oil-s-future-1.823480

[19] Environment Agency Abu Dhabi (2019): Greenhouse Gas Inventory. Available online: https://www.ead.ae/Publications/Greenhouse%20Gas%20Inventory%20For%20Abu%20Dhabi%20Emirate%202019/EAD5726_GREENHOUSE%20GAS%20INVENTORY%20REPORT_ENGLISH_FOR%20WEB.pdf

efforts to decarbonize the sector by substituting fossil fuels in passenger and freight transport on roads as well as in the maritime and aviation industry.

Road transport

Fuel cell electric vehicles (FCEV) produce electricity from hydrogen with water as the byproduct. Japan and China have set themselves ambitious goals for the market uptake of FCEVs and there are available models for fuel cell passenger and freight vehicles including busses, but FCEVs do not play a significant role in any country to date.

Passenger road transport is currently the only transportation mode in which synthetic fuel applications are being tested on the Arabian Peninsula, with several pilot projects in the UAE and Saudi Arabia. In the UAE, Abu Dhabi Police and the Dubai Taxi corporation are currently testing the Toyota Mirai for use in their fleet, with Abu Dhabi Police aiming to convert its entire fleet of police vehicles to FCEVs by 2057. [20] The first public hydrogen fueling station was opened in Dubai Festival City in October 2017 by Al Futtaim, the exclusive distributor of Toyota in the UAE in partnership with French industrial gases company Air Liquide.[21] Further fueling stations are planned in Masdar City in collaboration with ADNOC, Masdar and Al Futtaim[22] and on the EXPO 2020.[23] In Saudi Arabia, the first hydrogen fueling station was installed in June 2018 in the Dhahran Techno Valley Science Park by Saudi Aramco in cooperation with Air Products. Initially, the station shall fuel a fleet of six Toyota Mirai vehicles.[24] Besides the self-prescribed goal of Abu Dhabi Police to convert its fleet to FCEVs, there are no political targets related to FCEVs and the attention to the technology has been limited in the past years.

From an efficiency standpoint, it would make more sense to use FCEVs for larger vehicles like trucks and busses. For passenger transport, battery electric vehicles (BEVs) present a feasible and much more energy efficient option. Driving the same distance requires almost twice as many kWh with a FCEV compared to a BEV due to the conversion losses described in chapter 1.1. As a downside, energy consumption for vehicle cooling could reduce BEV ranges – however, with modern vehicle ranges of more than 350 km, even range reductions of up to 40% on the hottest days[25] could be handled.

For busses and trucks, BEVs are not as practical, as the heavy batteries significantly reduce the allowed load and it is challenging to provide large ranges for trucks with purely battery powered vehicles. Hydrogen and other synthetic fuels could mitigate these challenges. A study by Air Liquide and Al Futtaim in cooperation with Khalifa University suggested that in the early phases of using hydrogen as a fuel, there should be a focus on buses and trucks as well as other fleet vehicles including taxis.[26] A pilot project featuring FCEV busses fueled by green hydrogen from the Siemens electrolysis plant at the Mohammed Bin Rashid Al Maktoum Solar Park is planned for the EXPO in Dubai. Given that

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[20] Air Liquide, Al-Futtaim motors & Khalifa University (2018) Hydrogen Mobility. Available online: https://www.airliquide.com/sites/airliquide.com/files/2019/01/28/medium-to-long-term-development-of-hydrogen-mobility-in-the-uae.pdf

[21] Gulf News (2017) Region's first hydrogen refilling station opens in Dubai. Available online: https://gulfnews.com/uae/environment/regions-first-hydrogen-refilling-station-opens-in-dubai-1.2103976

[22] The National (2019) UAE in prime position as hydrogen power revolution accelerates. Available online: https://www.thenational.ae/business/energy/uae-in-prime-position-as-hydrogen-power-revolution-accelerates-1.831617

[23] Air Liquide, Al-Futtaim motors & Khalifa University (2018) Hydrogen Mobility. Available online: https://www.airliquide.com/sites/airliquide.com/files/2019/01/28/medium-to-long-term-development-of-hydrogen-mobility-in-the-uae.pdf

[24] Saudi Gazette (2019) Saudi Arabia gets first hydrogen fueling station. Available online: http://saudigazette.com.sa/article/569192

[25] Sgouris Sgouridis et. al (2017)

[26] Air Liquide, Al-Futtaim motors & Khalifa University (2018) Hydrogen Mobility. Available online: https://www.airliquide.com/sites/airliquide.com/files/2019/01/28/medium-to-long-term-development-of-hydrogen-mobility-in-the-uae.pdf

the public transport network is very limited in the Gulf region, long-distance heavy freight trucks present the more likely application in the medium term.

There are however several challenges to market uptake of FCEV vehicles, including limited model availability and lack of fueling infrastructure[27]. Model availability may improve in the next few years due to ambitious targets in East Asian countries. The construction of fueling infrastructure largely depends on political commitment, as private investors are unlikely to commit as long as the business case is not yet profitable. For the UAE, Air Liquide, Al Futtaim and Khalifa University argue that only 12 hydrogen fueling stations in total would cover hydrogen demand from road transport due to the centralized population in Abu Dhabi, Dubai and a few other cities.[28] While this assumption may be optimistic, it suggests that the necessary investment in hydrogen fueling infrastructure may not be prohibitively high. In comparison, there are currently over 70 charging stations in Germany (2019).[29]

Maritime and air transport

Synthetic fuels also have the potential to substitute fossil fuels in the shipping and aviation industries. Pure hydrogen is likely not a feasible option for these applications, as the energy density compared to kerosene or heavy oil is much lower, and hydrogen would hence necessitate very large tanks (see Table 1). The use of liquid synthetic fuels other than hydrogen is therefore the more likely option.

Globally, there are no pilot projects for commercial aviation and very few for the shipping industry. However, once the technologies become commercially viable, the Arabian Peninsula could become an important off-taker. The region features some of the world's most important ports, including Dubais Jebel Ali port (14.95 million TEU[30]/year), Saudi-Arabia's Jeddah port (4.12 million TEU/year), and Oman's Salalah (3.39 million TEU/year).[31] Similarly, there are major airports and several large airlines such as Etihad, Emirates, Oman Air and Qatar Airways.

2.3 Electricity system

Synthetic fuels – especially hydrogen – are currently discussed as a potentially important part of highly renewable electricity systems. Three more specific use cases which are most commonly named are discussed below. In this initial assessment, it seems that synthetic fuels could offer benefits for electricity systems on the Arabian Peninsula mostly through long-term storage (i.e. seasonal storage). More technical studies would be needed to validate this in depth.

Short term storage

Since countries on the Arabian Peninsula are expected to rely predominantly on solar energy, there will need to be solutions how electricity demand at night can be catered. Synthetic fuels could to this end be produced at daytime using solar electricity and be re-electrified at night. However, batteries as a competing technology offer round-trip efficiencies of around 90%, while electrolysis with fuel cell re-

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[27] Commercially available FCEVs include the Toyota Mirai, Honda Clarity and Hyundai Nexo

[28] Air Liquide, Al-Futtaim motors & Khalifa University (2018) Hydrogen Mobility. Available online: https://www.air-liquide.com/sites/airliquide.com/files/2019/01/28/medium-to-long-term-development-of-hydrogen-mobility-in-the-uae.pdf

[29] H2 (2019) H2 tanken. Available online: https://h2.live/

[30] Twenty-Foot Equivalent Unit (TEU) is a unit of cargo capacity for shipping

[31] World Shipping Council (2019) Top 50 World Container Ports. Available online: http://www.worldshipping.org/about-the-industry/global-trade/top-50-world-container-ports

electrification stands at approximately 40%.[32] For short-term storage with many charge-discharge cycles per year, batteries could therefore be more attractive in most cases. Also, countries on the Arabian Peninsula are starting to deploy solar thermal plants as addition to solar photovoltaics (PV) because this technology can readily incorporate thermal storage for electricity production at night.[33]

Long term storage

A crucial point of long-term storage economics is that there are in many cases only very few charge-discharge cycles per year. This means that in contrast to short-term storage, investment costs per unit of storage capacity are an important cost driver besides conversion efficiencies. Synthetic fuels, like their fossil counterparts today, can be stored in high volumes at low cost in caverns or tanks.

A question that would need further assessment is the magnitude for seasonal storage needs in high-renewable electricity systems on the Arabian Peninsula. Seasonal electricity demand in this region is relatively aligned with renewable generation, since space cooling demand correlates with solar irradiation. Therefore, the demand for long-term storage could be smaller than e.g. in Germany, where energy demand is higher in winter due to space heating.

Reducing the need for electricity lines

In most regions, the investment cost of electricity lines is typically by a of factor 2-10 more expensive than for gas pipelines.[34] It could in some cases therefore be attractive to convert renewable electricity to hydrogen or methane and transport it through a pipeline rather than building an electricity line. The downside of this are the high conversion losses of hydrogen or methane production (see chapter 1.1). As a consequence, using power-to-gas is only competitive against electricity transmission under the following conditions:

- If energy needs to be transported over longer distances – In Germany, using power-to-gas instead of electricity transmission is discussed for the North Sea, where offshore wind power needs to be transported more than 600 km to load centers in southern Germany. In the UAE, this is less of an issue: The Mohammed Bin Rashid Al Maktoum Solar Park for example is located less than 100 km away from Dubai city; Noor Abu Dhabi solar park is around 100 km away from Abu Dhabi city. For countries with larger territories like Saudi-Arabia, there might however be cases where renewable energy needs to be transported over longer distances.
- If there are special obstacles to electricity grid expansion – In Germany, high population density and extensive agriculture have led to difficulties with the construction of power lines. On the Arabian Peninsula, these issues are not as prevalent though (see Table 4).

Using power-to-gas as a substitute for electricity transmission lines therefore seems not to be a promising major application case for the Arabian Peninsula.

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[32] Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018): The Future Cost of Electricity-Based Synthetic Fuels. Available online: https://www.agora-energiewende.de/fileadmin2/Projekte/2017/SynKost_2050/Agora_SynKost_Study_EN_WEB.pdf

[33] E.g. at the Mohammed Bin Rashid Al Maktoum Solar Park in the UAE (under construction) or Shagaya CSP in Kuwait

[34] Saadi et. al. (2018): Relative costs of transporting electrical and chemical energy. Available online: https://pubs.rsc.org/en/content/articlelanding/2018/ee/c7ee01987d#!divAbstract

2.4 Exports

Besides the domestic applications of synthetic fuels described in the previous chapters, producing these fuels for international markets could be very attractive for some countries on the Arabian Peninsula:

- The region has a competitive advantage globally for synthetic fuel production because of cheap renewable electricity resources (see chapter 3.1) and availability of land (chapter 3.2).
- Most economies in the region currently rely heavily on fossil energy exports. Synthetic fuels could be the corresponding export commodity in a globally renewable era.

Synthetic fuel exports could indeed to some extent compensate the decline of fossil fuel export revenues. Saudi Arabia for example is the largest oil producers on the Arabian Peninsula with oil export revenues of USD 183 billion in 2018.[35] If these revenues where to be replaced by hydrogen exports in the long-term, this would be in the order of magnitude of 92 Mt of hydrogen.[36] This in turn would correspond to approximately 750 GW electrolyser capacity – ten times larger than the total electrical capacity in Saudi Arabia 2017.[37] This proves that from today's view, synthetic fuels will not be able to fully replace fossil fuel revenues and economic diversification strategies are hence crucial. On the other hand, GW-scale renewable capacity additions on the Arabian Peninsula in recent years show that synthetic fuel production could in the long-term still replace some of today's fossil fuel exports.

A main obstacle for international synthetic fuel markets is the so-called "chicken-egg-problem": potential producers will only start investing if there are secure demand markets, but potential consumers will only commit to significant synthetic fuel usage if they are confident that there will be cheap, large-scale supply. Governments across the world should hence enter a dialogue to create a mutual understanding on the timing and scale of potential synthetic fuel demand.

3 PRODUCTION POTENTIALS IN GULF COUNTRIES

Countries on the Arabian Peninsula have significant competitive advantages for synthetic fuel production both from a cost per unit perspective as well as for absolute production volumes. The factors driving this advantage are explained in this chapter.

3.1 Cost of synthetic fuel production

The dominating cost component of synthetic fuel production is the electricity feedstock. In hydrogen electrolysis for example, electricity costs account for more than half of total costs if the electrolyser is operated at around 5000 full load hours.[38] Generation costs of renewable electricity are therefore a main cost driver of synthetic fuel production, followed by cost of capital.[39] Transport costs are a major additional cost component, as discussed in chapter 1.2.

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[35] Daniel Workman (2019): Crude Oil Exports by Country. Available online: http://www.worldstopexports.com/worlds-top-oil-exports-country/

[36] Assuming 2 $/kg$H_2$ as target price from Navigant (2017): Making the MENA Region a World Leader in Green Hydrogen

[37] Assuming 4000 electrolyser full load hours. Source of KSA capacity: IRENA (2019): Renewable Energy Market Analysis: GCC. Available online: https://www.irena.org/publications/2019/Jan/Renewable-Energy-Market-Analysis-GCC-2019

[38] Own calculation based on 800 $/kW Capex, 15 year lifetime, 6% WACC, 40 $/kW fixed Opex, 30 $/MWh electricity price

[39] Capex is also an important cost component, but can be assumed to be very similar across countries.

Recent renewable electricity auctions have demonstrated that the Arabian Peninsula offers extremely low-cost renewable electricity (see Table 3), meaning that synthetic fuels can also be produced cheaply. The large price difference to Germany can be attributed to a number of reasons:

- Better natural resources, especially solar irradiation
- More attractive tender design, e.g. pre-development of site by government
- Generally favorable economic conditions, e.g. taxation and labor cost

Table 3: Renewable energy tender results in selected countries on the Arabian Peninsula and Germany (for reference).

	Germany[40]	UAE[41]	KSA[42]	Oman	Qatar
Wind onshore auction results (€ / MWh)	38 – 63	*No auctions*	19	*No auctions*	*No auctions*
Solar PV auction results (€ / MWh)	39 – 84	15 – 22	21	*Not disclosed*	*No auctions*

Besides the electricity cost per unit of energy, it is also crucial that electricity is supplied for at least approx. 4000 hours per year – otherwise, the fixed cost of synthetic fuel production per unit of fuel are too high to be competitive. This means that while PV – which offers the lowest cost per unit of energy – will likely need to be complemented by other electricity sources as it has load factors of only around 22%.[43] Complementary renewable electricity sources could include:

- Wind onshore – there are very attractive potentials for example in Saudi Arabia (see Table 3), Kuwait or Oman. Wind speeds are furthermore often the highest when solar irradiation is lower, making it well suited to be paired with PV.
- Concentrated Solar Power (CSP) – As this technology generates electricity thermally, it can store heat as an intermediate energy carrier and dispatch electricity very flexibly. As a downside, it is currently significantly more costly than PV. For example, the auction for Phase IV of Dubai's Mohammed bin Rashid Al Maktoum Solar Park in 2017 yielded results of 24 $/MWh (22 €/MWh) for PV and 73 $/MWh (66 €/MWh) for CSP.

3.2 Potential production volume

Apart from the production cost per unit of synthetic fuel, the potential for countries to become competitive synthetic fuel exporters also depends on the absolute production volume that could be achieved. This chapter discusses main factors driving absolute production potentials.

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[40] EEG auction results October 2017 to October 2019. Source: Bundesnetzagentur.

[41] Noor Abu Dhabi (upper bound) and MBR solar park phase V (lower bound).

[42] Dumat al Jandal wind farm and Sakaka solar park.

[43] IRENA (2016): Renewable Energy Market Analysis, the GCC Region. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Market_GCC_2016.pdf

Land availability

Renewable energy and synthetic fuel production require significant amounts of land – this can be a limitation for synthetic fuel production. In Germany for example, the technical potential for renewable electricity production is estimated at 7.800 TWh, with constraints mainly due to population density and agricultural land usage leading to a realistic potential of approximately 800 TWh.[44] While these estimates require dedicated technical studies, some initial hypotheses for the Arabian Peninsula can be derived from the basic land availability parameters from Table 4:

- The renewable electricity potential of Saudi Arabia could exceed 10.000 TWh due to the large territory and few constraints from settlements or agriculture. This could lead to a massive potential for synthetic fuel production.
- Oman might also present large synthetic fuel production potentials due to a land area similar as Germany, but few restrictions through competing land uses.
- The UAE have less territory available than Saudi Arabia and Oman and have a higher population density. Most of the population however is concentrated in Dubai, Abu Dhabi, Sharjah and few other cities so that there could still be significant production potentials, also for exports.
- Qatar probably offers less absolute potential than the aforementioned countries due to its significantly smaller territory. Its population is however concentrated mostly at the east coast around Doha and Al Rayyan. Hence, there may still be relevant synthetic fuel production potentials.

Table 4: Indicators for synthetic fuel production potential constraints.

	UAE	Saudi-Arabia	Oman	Qatar	Germany
Land area (km^2)[45]	71,020	2,149,690	309,500	11,610	349,360
Population density (persons per km^2)[46]	117	16	16	244	240
Arable land (% of land area)[47]	0.5%	1.5%	0.1%	1.1%	34.1%
Forest (% of land area)[48]	3.8%	0.5%	0%	0%	31.8%
Water stress level[49]	Extremely high	Extremely high	Extremely high	Extremely high	Medium-high

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[44] The Boston Consulting Group (2018): Klimapfade für Deutschland. Available online: https://bdi.eu/publikation/news/klimapfade-fuer-deutschland/

[45] World Bank Database (2018): Land area. Available online: https://data.worldbank.org/indicator/ag.lnd.totl.k2

[46] Ibid. and UN DESA (2019): World Population Prospects 2019. Available online: https://population.un.org/wpp/

[47] Source: CIA World Factbook. Available online: https://www.cia.gov/library/publications/the-world-factbook/fields/288.html

[48] Ibid.

[49] World Resources Institute (2019): Aqueduct Global Maps 3.0 Data. Available online: https://www.wri.org/resources/data-sets/aqueduct-global-maps-30-data

Water supply

Synthetic fuel production requires water as a feedstock, most prominently green hydrogen which is produced by electrolysing water. This leads to a potential challenge for countries on the Arabian Peninsula which are, mainly due to their arid climate zone, exposed to very high water stress levels (see Table 4).

The difficult water situation must however not necessarily lead to a competitive disadvantage for the Arabian Peninsula in synthetic fuel production. First, water consumption of synthetic fuel production is comparable to that of other industrial processes, e.g. gasoline production, and does therefore not lead to disproportionately large water demand.[50]

Second, many attractive synthetic fuel production sites on the peninsula are located near the sea. This enables producers to source water via seawater desalination, for instance using reverse osmosis (RO) technology. The cost of installing and operating RO facilities would be a very small part of overall synthetic fuel productions costs.[51] Legal requirements could however be introduced to ensure sustainable water supply for “green” synthetic fuels. This could include obligations to use renewable energy for desalination and regulations of environmental impact from discharge water.

Lastly, some regions on the Arabian Peninsula are not exposed to water stress, e.g. Asch-Scharqiyya in Oman or Asir in Saudi Arabia.[52] Corresponding site choices, at least for pilot projects, could therefore reduce the challenge.

4 REQUIREMENTS FOR INTERNATIONAL SYNTHETIC FUEL MARKETS

Although the case for international trade of synthetic fuels as described in chapter 3 seems clear economically, there still needs to be strong political alignment internationally to establish these markets. The required buy-in from political stakeholders will likely depend on a number of factors. From today’s view, two early requirements are particularly important:

- For exporting countries, it will be important to translate synthetic fuel production into a fair share of **local value creation**.
- For importing countries, it will be important to have evidence for the **sustainability** of the fuels – since this is the motivation to use them in the first place.

4.1 Local value creation

While it is obviously important to producing countries to retain value add in their countries, politicians in importing countries such as Germany will likely also need to present some economic advantages from synthetic fuel production. This is because synthetic fuels are more expensive than their fossil

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[50] Argonne National Laboratory (2016): Life-Cycle Analysis of Water Consumption for Hydrogen Production. Available online: https://www.hydrogen.energy.gov/pdfs/review16/sa039_elgowainy_2016_o.pdf

[51] Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018): The Future Cost of Electricity-Based Synthetic Fuels. Available online: https://www.agora-energiewende.de/fileadmin2/Projekte/2017/SynKost_2050/Agora_SynKost_Study_EN_WEB.pdf

[52] World Resources Institute (2019): Aqueduct Global Maps 3.0 Data. Available online: https://www.wri.org/resources/datasets/aqueduct-global-maps-30-data

counterparts and have no advantages besides being carbon-neutral – the price premium will hence be more justifiable for importing countries if there are also economic benefits.

Shared value chains for synthetic fuels could hence be the target model for international markets. The company landscape today along the synthetic fuel value chain shows that this is already partially the case today:

- **Synthetic fuel production asset manufacturing and plant installation:** There are a number of leading companies from Germany, e.g. Siemens, ThyssenKrupp or sunfire. Companies from the Arabian Peninsula have not yet appeared as prominent examples in this technology.
- **Renewable electricity production:** There are some very successful renewables project developers on the Arabian Peninsula. Most notably, ACWA Power from Saudi Arabia and Masdar from Abu Dhabi have won several large-scale renewable auctions on the Arabian Peninsula and beyond.[53] There are also some equipment manufacturers like Qatar Solar Energy or Noor Solar Technology, however the larger share of equipment is imported.[54]
- **Synthetic fuel production operations, transmission and distribution:** Since this market does not exist at scale yet, it is difficult to assess the company landscape. One conceivable scenario is that current industrial gas players such as Linde will use their strong position today and retain high market shares at least for hydrogen. Another possible scenario is that oil & gas companies leverage their extensive hydrocarbon infrastructure for synthetic fuels – this could be an interesting opportunity for players like Saudi Aramco, Petroleum Development Oman, ADNOC, ENOC or Qatargas.

Potential producing countries on the Arabian Peninsula would therefore be in a good position to access value pools especially for renewable electricity supply and synthetic fuel logistics – these already account for a significant share of the total synthetic fuel value pool.[55]

Synthetic fuel production at scale could unlock even more local value creation for producing countries. For example, large renewable capacity additions, triggered by synthetic fuel demand, could lead to a situation where the business case for PV cell and module manufacturing on the Arabian Peninsula becomes more attractive. Also, if large capacities of electrolysers are installed in the region, manufacturing of electrolysers could also be localised at least to some extent.

Finally, it must be noted that while there are some mature synthetic fuel technologies, more research on existing technologies and development of new technologies such as high-temperature electrolysis is needed. This could be an opportunity for the Arabian Peninsula to attract R&D for promising, clean technologies.

4.2 Sustainability

Synthetic fuels are not by nature more sustainable than their fossil counterparts. Especially the sources of electricity and carbon are important to ensure that these fuels actually provide emissions savings.

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[53] Navigant (2019): Neue Entwicklungen bei erneuerbaren Energien in den Ländern des Golfkooperationsrats. Report for BMWi.

[54] IRENA (2019): Renewable Energy Market Analysis: GCC. Available online: https://www.irena.org/publications/2019/Jan/Renewable-Energy-Market-Analysis-GCC-2019

[55] Navigant project experience.

Green electricity

Due to the high energy losses in their production (see chapter 1.1), synthetic fuels can cause significant GHG emissions depending on the emission intensity of the electricity used. In Germany for example, the average GHG intensity of electricity generation is relatively high at 474 gCO_2 per kWh – if synthetic diesel was produced from this electricity, it would lead to more than three times higher GHG emissions than using fossil diesel in the first place.[56] On the Arabian Peninsula, power generation is largely based on natural gas power plants which have emission factors of 300 – 557 gCO_2 per kWh, leading to a similar problem as for Germany.[57]

To avoid that synthetic fuels cause increased GHG emissions, legislators in the European Union are developing criteria. These criteria are not yet in force; however the Renewable Energy Directive II already outlines some guiding principles for renewable synthetic fuels:[58]

- They must be made only from renewable energy sources.
- There must be an “element of additionality” to the renewable electricity input – meaning that new renewable electricity capacities must be built for synthetic fuel production.
- There must be a “temporal and geographical correlation” between renewable electricity generation and synthetic fuel production.
- If there is a “direct connection” between renewable electricity generation and synthetic fuel production and grid electricity is not used, it may be counted as renewable.

These principles will be translated into a detailed, legally binding methodology by the EU in the coming years. Potential producers of synthetic fuels should participate in the dialogue on these regulations to ensure that they safeguard sustainability and are practical for producers at the same time.

Green carbon

As described in chapter 1.1, some synthetic fuels like methane or liquids require carbon input. There are broadly three options to source this carbon, with varying impacts on the carbon footprint:

- Bio-based carbon. This carbon would be counted as “green” but would likely be subject to further sustainability criteria as for biofuels.
- Direct air capture. CO_2 can be filtered from ambient air and would also be counted as “green” provided the energy required for the process is renewable. This technology is however still at an early stage and very expensive.
- Carbon captured from fossil sources, e.g. cement kiln or power plant exhausts. This pathway is not compatible with long-term decarbonization as it still entails quarrying and ultimately emitting fossil carbon. In the short-term, the technology could however be employed if double counting of emission savings is avoided. Prolonging the lifetime of fossil emitters due to carbon capture also needs to be avoided. There is currently no comprehensive policy framework globally or in the EU for accounting and requirements of recycled carbon fuels.

As for green electricity, regulations on carbon feedstocks for synthetic fuels will be developed in the near future – parties that have an interest in these regulations should participate in the dialogue to create a clear and sustainable framework.

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[56] Oeko-Institut (2019): Kein Selbstläufer: Klimaschutz und Nachhaltigkeit durch PtX. Available online: https://www.oeko.de/fileadmin/oekodoc/Impulspapier-soz-oek-Kriterien-e-fuels.pdf

[57] European Commission Joint Research Center (2017): Greenhouse gas emissions from fossil fuel fired power generation systems. Available online: https://pdfs.semanticscholar.org/d666/1a01ee6a54f86fad283e4650e1074c795b7b.pdf

[58] Directive (EU) 2018/2001