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Global Hydrogen Diplomacy

The role of green hydrogen in the energy transformation of fossil fuel exporters

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Executive summary

Executive summary

Study goals

This study aims to generate insights into how countries that are currently heavily reliant on fossil fuel exports might be affected by a declining demand for fossil fuels and the resulting losses of export revenues as well as further macro-economic and associated employment effects in the future. The study further analyses how the anticipated global demand for carbon-neutral green hydrogen and its derivatives (such as green ammonia and methanol) could stimulate sustainable economic development and diversification and thereby offsets part of the losses in the fossil fuel sector. Thereby, the study investigates three exemplary case study countries, namely Saudi Arabia, Kazakhstan and Nigeria.

Projections for the future global demand for fossil fuels foresee drastic decreases in global demand of up to 75% until 2050

There is a broad consensus that, against the backdrop of the global efforts to combat climate change, the global demand for fossil fuels will decline drastically over the next decades. Various scenarios, e.g. published by the European Commission, the International Energy Agency, BP and Shell, project that, for the most ambitious scenarios (i.e. consistent with the Paris Agreement) a decline of the fossil fuel demand of around 75% until 2050 can be expected compared to the 2019/20 base year. This shift necessitates a strategic response in particular by nations reliant on fossil fuel exports, urging them to explore economic diversification options.

Power-to-X (PtX) products, such as green hydrogen and its derivatives, hold the potential to partially mitigate the consequences of diminishing fossil fuel exports. Nonetheless, it is important to recognize that the anticipated future demand for hydrogen and e-fuels is poised to be considerably lower than the current demand for oil and natural gas. Even the most ambitious scenarios by the IEA (2022b) and the EU JRC (2021) project that the share of hydrogen and e-fuels in 2050 will remain well below one-fourth of today's final energy demand for oil and gas. Therefore, the international market for hydrogen and e-fuels will likely be significantly smaller in terms of energy volumes compared to the current fossil fuel market. This emphasizes the need for strategic diversification and development of technological capacities and trade relationships in countries with a high dependency on fossil fuel exports.

Targeted and tailored diversification strategies are needed in countries currently relying on the export of fossil fuels

Fossil fuel exporting countries feature varying degrees of economic dependency on the export of oil and gas, and they differ in their framework conditions for economic diversification and trade. Therefore, understanding the country-specific economic characteristics and identifying promising areas for branching out and broadening the economic basis is crucial for being able to craft tailored, sustainable development and diversification strategies.

In the case of the three case study countries, as of today, all three countries are highly dependent on the export of fossil fuels. However, they feature different characteristics in terms of their competitive position on the global fossil fuel market as well as regarding potential areas for economic diversification.

In Kazakhstan, the trade of oil and gas accounted for about half (47%) of the export revenues in 2021. Thereby, the majority of the crude oil is exported to the EU, in particular to Germany (13%) as well as to China (9.6%). For refined oil, the USA is the main trade partner (46.2%), whereas natural gas was traded mainly to China (53.8%) and Ukraine (11.7%). With vast oil resources and marginal production costs of crude oil well below the global average, Kazakhstan will likely remain a competitive supplier of crude oil on the world market, especially for the growing markets in Asia, in which the demand will likely remain higher compared to Europe. Besides oil and gas, Kazakhstan possesses vast resources of coal and various metal ores as well as notable reserves of uranium and a well-developed metal mining industry, which offers further trade diversification potentials.

Saudi Arabia's economic dependency on the production and export of fossil fuels is reflected by a share of 23.7% of the national GDP stemming from oil rents and a total share of 56.6% of the net export revenues based on the trade of crude oil and oil products in 2021. The marginal cost of oil production in the country is among the lowest globally, thus making the country highly competitive on the world market. Saudi Arabia's main trade partners are primarily the fast-growing economies in Asia. The main export destination for crude oil in 2021 was China (23.6%) followed by Japan (15%), South Korea (13%) and India (12%). The majority of petroleum gases was exported to India (54.7%) as well as China (12.8%) and Indonesia (10.9%). It can thus be expected that Saudi Arabia will remain a highly competitive supplier of fossil fuels, especially for the Asian market. Besides the export of fossil fuels, Saudi Arabia's economy has already begun a shift towards a higher degree of diversification, notably based on the development of the chemical industry sector, which shows further development potential.

In Nigeria in 2021 crude oil and natural gas accounted for over 90% of the country's net export budget, with crude oil accounting for almost 77% of the export revenues and 6.2% of the national GDP. In 2021, Nigeria held a market share of 5% in the global crude oil market, with the main trade partners being India (19%) and Spain (13%). Refined petroleum oils in the past have been exported mainly to the USA. However, the export of refined oil has declined significantly over the past years and currently does not play a relevant role in the national export profile anymore. The cost of crude oil production in Nigeria is well below the global average and very competitive on the world market. However, the country currently faces massive challenges due to increasing oil theft from its pipelines, which causes significant economic losses in the range of several billion dollars annually in the oil industry.

Besides losses in export revenues, a globally declining fossil fuel demand implies relevant secondary effects on the economies of fossil fuel exporting countries

The declining demand for fossil fuels will have a drastic impact on the economies of fossil fuel exporters, not only in terms of lost export revenues, but also regarding secondary economic effects in various sectors such as value added and employment. To analyze and quantify the extent of the impact following a 75% reduction in fossil fuel exports, an Input-Output Analysis (IOA) was conducted, which allows to examine the interactions between different sectors of an economy and to assess potential effects on upstream and downstream sectors.

The findings of the analysis for the three case studies highlight that, based on the breakdown of value added by economic sector, fossil fuel industries are among the most important economic sectors in all three countries. In 2018, the shares in gross output were 20.22% in Saudi Arabia, 10.57% in Kazakhstan and 6.88% in Nigeria. Generally, the impact of the assumed decline in exports on gross output is strongest in the sector ‘Mining and quarrying of energy products’ itself. However, due to domestic up- and downstream interlinkages between economic activities, such as wholesale and retail trade; repair of motor vehicles or other types of secondary services, further effects on other economic sectors can be observed which can have significant impacts on overall value added and employment. On the other hand, despite the high relevance in terms of overall economic output and exports, the number of employed workers in the energy mining sector is comparatively low in all three countries. Consequently, the decline in employment as a result of declining fossil fuel exports, is less pronounced. The findings thus indicate that especially countries with a dominance of labor-intensive industries with a comparatively low output per worker and strong domestic upstream and downstream linkages may be particularly affected by the decline in fossil fuel exports in terms of job losses. Such potential secondary employment effects should not be neglected when developing strategies for economic diversification. In Saudi Arabia, most economic effects of energy extraction occur within the country, but only contribute a small fraction to the overall economy. If fossil fuel exports decline, the main impact will be on the fossil fuel industry itself, with a 70% reduction. However, this sector employs only a small portion of the workforce, and other sectors will follow general trends based on their vulnerability. In Kazakhstan, a significant share of the economic effects of energy extraction is domestic, mainly due to the need for pipeline transport. The majority of the output is exported, affecting downstream activities mainly abroad. The energy mining sector is expected to see a 72% reduction in output, with indirect effects on 'Basic metals.' The decline in employment follows the reduction in the energy mining sector's output. In Nigeria, a substantial portion of economic effects attributed to energy extraction occur outside the country, resulting in a higher upstream impact on other countries. A significant portion of the output is exported, impacting domestic downstream activities. The primary industry affected by the reduction is the energy mining sector, which is set to see a 64% decrease in output. While it affects a relatively small share of the workforce directly, there will be indirect effects on sectors like agriculture and food-related services, which are vital to the Nigerian economy.

The export of PtX products offers significant economic opportunities but strongly depends on the competitiveness of local production

The opportunities of current fossil fuel exporting countries to develop export-oriented PtX industries are affected by a number of economic and non-economic framework factors. Besides the availability of renewable energy resources and required infrastructures and the associated techno-economic potential for the production of green hydrogen, a number of political and socio-economic factors will have an influence on the competitiveness of the PtX sector. Important framework factors in this regard comprise the maturity of the renewable energy market as well as the existence of strategies and targets for the future development of the energy sector and for covering the domestic energy demand. The overall environment for business development and project implementation is a further factor that affects the competitiveness of green hydrogen exports, in particular through its impact on the financing conditions and the resulting Weighted Average Costs of Capital (WACC) for renewable energy projects. As the WACC have a significant impact on the resulting cost of the PtX product, especially countries facing high financing risks due to political instability or administrative barriers for project development might not be able to fully develop their potentials even if renewable energy resources are abundant. Against this background, addressing the regulatory and political framework conditions for renewable energy development and the general environment for business development and project financing will be crucial for countries aspiring to become PtX exporters, in order for them to be able to develop a competitive advantage.

Further, the production and export of PtX products should be soundly embedded in the national energy and climate strategy and aligned with the targets for meeting the domestic energy demand as well as national decarbonization targets in order to avoid potential resource conflicts and public opposition. In addition, countries may face different types of political and financial risks which can significantly impact the economic viability of PtX projects. Political and economic instability, reflected by high inflation rates and an elevated risk of corruption, will drive the cost of capital and enhance project implementation risks in general. This can currently be considered a relevant barrier, for example, in Nigeria but also Kazakhstan is faced with relatively high inflation and interest rates. But even if the national political and economic system is more stable, such as in Saudi Arabia, the implementation of green energy projects can be hampered, for example, if there is a lack of transparency with regard to relevant administrative procedures and regulations for project development (e.g. regarding land acquisition, environmental impact assessments or cross-border trade). Addressing these factors will thus be key to increase the competitiveness of local PtX industries.

All three case study countries still heavily rely on fossil fuels for their own electricity generation, with renewables shares of 11% (KAZ), 0.5% (SAU) and 17% (NGA) with large shares of hydro power in Kazakhstan and Nigeria. The development of non-hydro renewables has only picked up recently. Nevertheless, all three countries have stated goals for developing green hydrogen and ammonia projects and intend to become PtX product exporters in the future. Saudi Arabia has even initiated first trade relationships for blue ammonia with Japan and South Korea.

In all three of the case study countries the techno-economic potential for green hydrogen production is high with notably high solar potentials in Saudi Arabia leading to potential LCOH as low as 40 USD/MWh in 2050. In Kazakhstan especially the wind potential is promising, implying LCOH at around 80 USD/MWh in 2030 and as low as 50 USD /MWh in 2050. Nigeria exhibits high potentials for solar-based hydrogen production, even though the land area is limited due to the high population density. The LCOH-Solar PV for the year 2030 range from approximately 120 to 150 USD/MWh (4-5 USD/kg). However, until 2050, costs can be expected to decrease further, nearly halving to around 60 USD/MWh (2 USD/kg).

Regarding transport infrastructure, in Saudi Arabia the repurposing of existing gas pipelines for green hydrogen export would be an additional competitive advantage through lowering transport costs to neighboring countries. In Nigeria, transport and pipeline infrastructure is generally more developed in the south of the country even though expansion plans for additional gas pipelines exist. Kazakhstan is currently improving its Caspian Sea maritime infrastructure, notably in ports like Aktau and Kury, to enhance trade and shipping. Generally, the development of maritime transport routes will be important to increase the competitiveness in the international trade of green hydrogen derivatives.

Export potentials for PtX products have to be seen in the context of local energy demand, energy capacity expansions and transport costs

To derive an estimation of the export potential for green hydrogen and its derivatives, the development of the local energy demand must be taken into account. Kazakhstan is projected to experience low local energy demand which is expected to decrease further in the future. In Nigeria is likely to see a substantial increase in final energy demand due to rapid population growth. In all three countries, the electricity consumption is expected to increase strongly in the future. Rapid expansion of renewable electricity generation is therefore critical for all countries even when not specifically addressing the export of green hydrogen and downstream products. The theoretical potential for the export of PtX products in all three countries is very high and exceeds both the local final energy demand and the expected global demand for hydrogen and e-fuels. However, the technically feasible potential is likely much lower and, especially in the earlier years, the ramp-up of production facilities might be challenging in all three countries. In this context, factors such as domestic production and installation capacities will have a limiting effect, but also social acceptance and land use conflicts will likely play a relevant role. As transporting gaseous hydrogen via pipelines is considerably less expensive than shipping liquid hydrogen, especially for shorter distances of less than 5000km, the analysis shows that Kazakhstan has a strong competitive advantage for the export of gaseous hydrogen to Asia and Europe. For Saudi Arabia and especially Nigeria, where potential markets in Europe and Asia are distant and unlikely to be supplied via pipelines, this means that marine transport of liquefied PtX products would be a more likely option.

In absence of an established market, estimating potential future export revenues for PtX products is challenging

Predicting future hydrogen market prices is a complex task that depends on several key factors such as market size, competition among market participants, and individual willingness to pay. Strategic behaviors and geopolitical preferences play a significant role, as some nations may pay premium prices for PtX products to advance strategic goals, such as energy supply diversification or forging strategic partnerships. As of today, the global hydrogen industry is based on a mostly localized supply, often directly on-site by those enterprises using the hydrogen, without significant trading activities. Consequently, no public hydrogen market, with mechanisms of price formation based on the emergence of an equilibrium of supply and demand, exists yet (Wietschel et al. 2021). With increasing hydrogen demand in the future it can be expected, though, that hydrogen trade will increase strongly, thus leading to some type of market based price formation.

Against the background of the high relevance of transportation costs of hydrogen, it is likely that, in the medium term, the majority of hydrogen trade will take place regionally via pipeline where this is possible (e.g. in Europe). Maritime transport of liquid hydrogen is likely to remain more expensive, also in the longer term. It is therefore likely that, initially, the trade of green hydrogen will be based on bilateral contracts building on strategic and geopolitical partnerships. At a later stage, regional markets might evolve, likely driven by the availability of transport infrastructure, in particular maximum distances for the transport of hydrogen via pipelines (i.e. distances <5,000km). This could lead to the emergence of regional markets and price zones, similar to regional gas markets. A global price convergence is rather unlikely in the medium to long term against the background of the relevance of transportation costs as well as the high relevance of the multitude of factors on national level (e.g. policies, regulations).

The willingness to pay for green hydrogen, as a basis for appraising potential export revenues, can be estimated based on analyses of the price dependent demand for hydrogen, in competition with other technology options, such as direct electrification. To better understand the pricing of green hydrogen, Germany was selected as an exemplary import market that can be representative for other industrialized countries with ambitious decarbonization targets. Techno-economic modelling of the sector-specific energy demand in Germany assuming carbon neutrality until 2045 carried out by Wietschel et al. (2023), indicates that a robust (i.e. price independent) baseline demand can be expected for sectors in which hydrogen will inevitably be needed for decarbonization in lack of other technology options (e.g. for production of ammonia, chemicals or steel, as a fuel for air and ship transport). For the case of Germany, this baseline demand is estimated to amount to ca. 250 TWh/a in 2045. A price-dependent demand is expected for use cases for which hydrogen competes with alternative decarbonization technologies, such as direct use of electricity. This applies, for example, to applications for energy storage and electricity supply and industrial heat provision. This price-dependent hydrogen demand significantly drops at price levels >90€/MWh (>3€/kg) and decreases to the baseline demand at levels >120€/MWh. At higher price levels, other technology options will be more competitive for most use cases.

Using these estimations as a baseline for assessing the potential export revenues for green hydrogen export of the three case study countries, it becomes apparent that the profits derived from potential hydrogen exports will likely not suffice to fully compensate for fossil fuel profits, as both, volumes and margins of the PtX products, can be expected to be significantly lower. Nevertheless, significant export profits could theoretically be realized, amounting to 6 billion $US for Saudi Arabia (per 200 TWh of exports at a price level of 120 USD/MWh), which would correspond to 6.5% of the countries' 2021 crude oil export profits. For Nigeria, a price level higher than 120 USD/MWh would be required for a profitable trade, thus indicating that export to Germany would only be lucrative given a higher willingness to pay for the product. For Kazakhstan, potential export profits up to 7 billion $US were assessed, assuming a price of 120 USD/MWh and based on an export volume of 200 TWh. This potential profit would correspond to up to 87% of the 2021 crude oil export profits. Obviously, these estimates can only serve as perspectives for a hypothetical development as actual price levels and export volumes strongly depend on individual national agreements, trade relationships and strategic preferences. Also, it should be noted that trade with countries other than Germany could be profitable at the given production costs, depending on the respective transportation costs, local market conditions and price levels in the importing country.

Additional economic opportunities related to the development of a domestic green hydrogen and PtX sector could help compensate for export losses

To assess the broader macro-economic impacts of a potential development of PtX sectors in the three case study countries, another Input-Output Analysis was performed. The analysis focused on the potential economic activity and job creation that could be stimulated by generation of 1 TWh of a certain PtX product (liquid or gaseous H2, NH3, MeOH) and the related activities along the upstream and downstream value chains. The results of the analysis indicate that for the different PtX products, more than half of the required macroeconomic output per TWh of PtX product would be associated with wind turbines and PV systems, meaning that the RE industry would attribute for the majority of the economic impulses. In contrast, the impact of the added electrolyzer capacity on the national gross output and induced employment effects would be relatively less important. Nevertheless, further economic impulses would also occur in other economic sectors not directly related to RE or PtX, such as wholesale and trade activities. Such second order effects could further contribute to compensating for economic losses caused by declining fossil fuel exports.

Economic diversification potentials should be developed timely and strategically

To broaden the economic basis and enhance the resilience of the economy of fossil fuel exporting countries in the frame of a declining demand for fossil fuels in the future, it is crucial to diversify national production and export while building on established sectors and competitive advantages. An analytical tool for assessing the level of economic diversification and identification of further potentials in this regard is the product space approach. Thereby, export goods of a country are represented in the so-called product space, which graphically depicts the relatedness of different products, thus indicating in which fields an economy is more advanced than in others and where further potentials could be developed building on existing know-how. Comparing the product space for different years (here for the years 2006 and 2021) further provides an indication of the trends in regard to economic diversification and a perspective for potential future developments.

For the case of Saudi Arabia, a successful diversification into new industries could be observed, notably in the chemical industry sector. Between 2006 and 2021 a total of 24 new products have been added to the export profile with a comparative advantage, 14 of them in the chemical industry. The analysis suggests that the acquired know-how in this sector could be transferred to green chemical products in the future. This includes basic chemicals such as methanol and ammonia, but also downstream products such as fertilizers and plastics. The electronics and mechanical engineering sectors, however, are less developed and could be targeted by supportive strategies to enhance local value and job creation in the context of an emerging PtX industry.

Also, for Kazakhstan a notable diversification trend could be observed with 23 new products added to the export profile since 2006. Especially the metal processing industry could be a key sector offering opportunities to boost the local demand for hydrogen and to potentially establish green steel and sustainable steel products as new export commodities. Further value creation potential could be exploited domestically by extending local metal processing capabilities instead of exporting raw materials. Furthermore, the metal industry has particular relevance as an important upstream value chain segment of the wind energy industry, which will gain importance with the expected installation of large numbers of wind turbines in the coming years. In addition, the transformation of the existing fertilizer production to green ammonia could be an opportunity, both for use in local agricultural production and for the export of the product.

In Nigeria the diversification of the economy has progressed rather slowly since 2006, with the most important export goods remaining basic goods, namely fossil fuels and agricultural products. However, one strategic field for diversification could be to target local fertilizer production, where green ammonia could be used in the future. On this basis, strategic efforts could be made to gradually develop a more diversified chemical industry sector. The export of green methanol or Fischer-Tropsch fuels could further contribute to this development, provided that long-term partnerships with fixed purchase guarantees are established to create investment security.

01

Introduction

1 Introduction

1.1 Context

The Paris Agreement's goal of limiting global warming to under 2°C has led many countries to adopt decarbonization strategies in pursuit of climate neutrality. Notably, recent declarations from fossil-fuel exporting countries, like Saudi Arabia's aim to achieve carbon neutrality by 2060, demonstrate the recognition among leading fossil fuel exporters of the importance to transition toward a climate-friendly energy and economic paradigm. This shift poses significant challenges, in particular, to countries that are heavily dependent on the export of fossil-fuels. These nations must transition to clean energy to maintain their fuel trade relationships with demand centers such as the EU and East Asia. Thus, carbon-neutral hydrogen produced from renewable energy emerges as a compelling alternative to both sustainably manage their energy sector and compensate for some of the economic losses resulting from a declining global demand for fossil fuels in the future. Thereby, the development of local value chains for green hydrogen and its derivatives, such as green ammonia or methanol, could offer opportunities for economic diversification and job creation in future-oriented economic sectors. However, the shift away from strongly fossil fuel-based economies and export profiles towards a higher degree of diversification also comes with risks and challenges for the concerned countries.

1.2 Scope and goals of the study

This project aims to provide support to fossil-fuel-exporting countries in comprehending the potential effects of declining demand for fossil fuels and the anticipated global demand for carbon-neutral hydrogen as a catalyst for sustainable economic development. Thereby, the primary focus countries of the study are three countries that currently rely on the export of fossil fuels to different degrees, namely Saudi Arabia, Kazakhstan, and Nigeria. A successful decarbonization effort in these nations necessitates harmonizing the interests of the fossil fuel sector with climate policy objectives to facilitate a climate-resilient and low-risk economic transformation. Hydrogen and its derivative products hold the potential to propel the expansion of renewable energy sources within these countries while also partially offsetting projected declines in fossil fuel revenues. In this context, the study aims to analyze the dual impact of declining oil and gas demand and the potential benefits of diversification through exports of green hydrogen and its derivatives, enhancing long-term economic resilience. The focus is on Saudi Arabia, Kazakhstan, and Nigeria, exploring the unique aspects of each.

To this end, as a first step, the implications of the decline in the global demand for oil and gas products resulting from existing decarbonization scenarios on the respective economies will be examined. Next, the techno-economic potential and relevant political and economic framework conditions will be identified and evaluated to assess the extent to which these countries could be suitable as green hydrogen suppliers in the future. Finally, the macroeconomic export potential of hydrogen and its derivatives for each country will be assessed to point out to which extent the countries might be able to offset the losses caused by declining fossil fuel exports.

1.3 Structure of this report

Following this introduction, the report is structured into three main chapters, followed by a conclusion.

The second chapter delves into the consequences of a global decline in fossil fuel consumption, encompassing an examination of future global demand projections, an assessment of the extent of dependence for the three case study countries, and the economic consequences stemming from diminishing exports of fossil fuels.

The third chapter then focuses on the potentials associated with the development of green hydrogen value chains by assessing the competitiveness of green hydrogen producers, evaluating political and socio-economic framework conditions for the development of local PtX industries, analyzing the techno-economic potentials and infrastructure capabilities for renewable energy development, and deriving the export potential for PtX products.

The fourth chapter is dedicated to the analysis of macroeconomic export potentials for PtX products, encompassing an exploration of potential export revenues concerning PtX products based on export costs. It also investigates broader macroeconomic effects associated with the development of the PtX sector and its potential role in economic diversification.

Lastly, the concluding chapter five summarizes the insights gleaned from the study.

02

Consequences of a globally declining fossil fuel demand

2 Consequences of a globally declining fossil fuel demand

2.1 Projections for the future global demand for fossil fuels

Against the backdrop of global efforts to combat climate change, there is a consensus that the global demand for fossil fuels will decline drastically over the next decades. However, various studies and scenarios projecting the future demand development show a wide spectrum of possible development corridors. To derive a balanced analysis of possible development pathways for the global demand for fossil fuels until 2050, we analyzed the latest energy outlooks from various publishers. In order to get a balanced picture, the analysis comprised international organizations (IEA 2022b; Keramidas et al. 2022) as well as energy companies with a stronger focus on fossil energy sources (bp 2023; Shell 2023). The different scenarios were classified into "reference scenarios", "medium ambitious scenarios", and "most ambitious scenarios".

Table 1 presents the relative change in global demand for oil and gas by 2050 compared to the reference year 2020 and 2019, respectively, for each study and scenario. While the demand sometimes increases or decreases in the reference scenarios, depending on the publisher and energy source, a clear decrease is projected in all other scenarios. For the medium ambition levels, the decrease ranges from -34% (IEA 2022b) to -70% (Keramidas et al. 2022). For the most ambitious scenarios, the level of reduction varies from -73% to -83% for BP, IEA, and EU JRC, with only Shell projecting smaller reductions of -43% (oil) and -54% (gas). However, Shell has published only two scenarios and, therefore, does not present a medium ambition scenario.

Table 1 Overview of the relative evolution of global final energy demand for oil and natural gas in 2050 compared to the 2019/2020 baseline for the different publishers and ambition levels in their latest energy outlooks

Oil / Natural gas	IEA	EU JRC	BP	Shell
Reference scenarios	+19% / +19%	-36% / +14%	-26% / +14%	+5% / -1%
Medium scenarios	-35% / -34 %	-70% / -66%	-58% / -42%	X / X
Ambitious scenarios	-75% / -77%	-78% / -83%	-79% / -73%	-43% / -54%

In view of the Paris climate agreement and the resulting need for a rapid and strong reduction in CO_2 emissions, the focus hereafter is on the ambitious scenarios in particular. The development of historical and projected global demand for oil and gas for these scenarios is shown in Figure 1 and Figure 2. For further analysis of the macroeconomic effects of the declining fossil fuel demand, a reduction of 75% by 2050 is assumed, based on the forecasts of the IEA and bp.

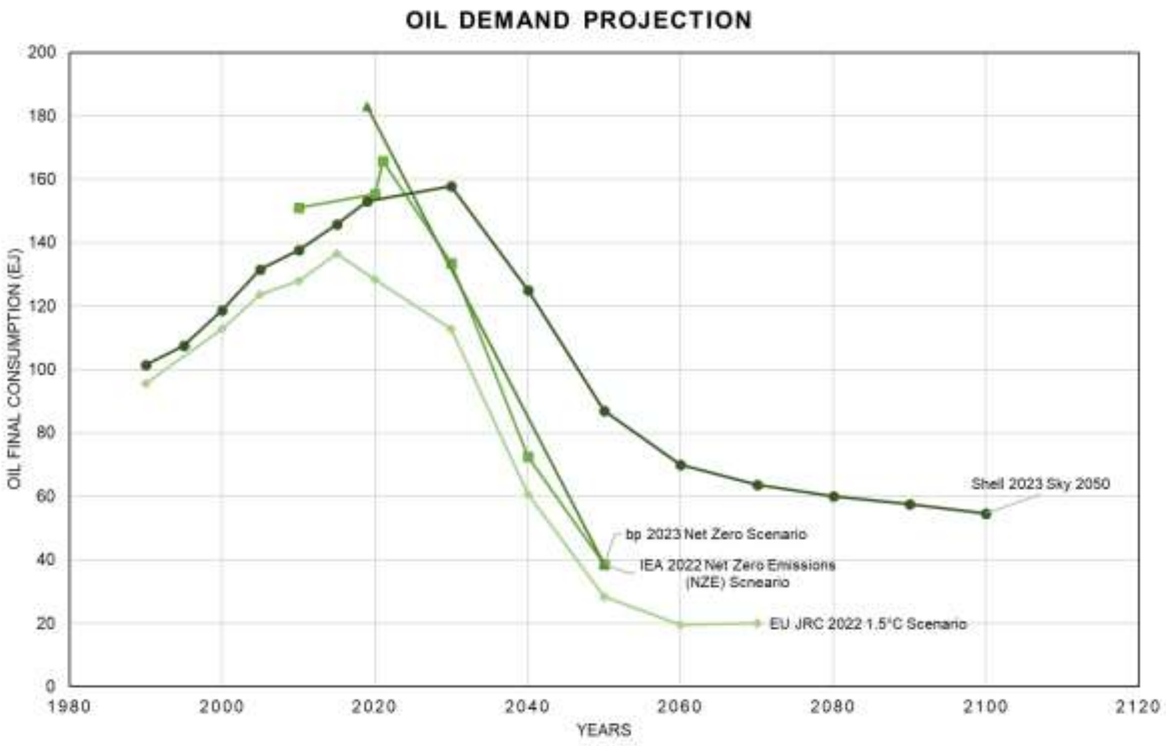


Figure 1 Comparison of the most ambitious scenarios of the latest international energy outlooks for global final energy consumption of oil between 1990 and 2100 in EJ

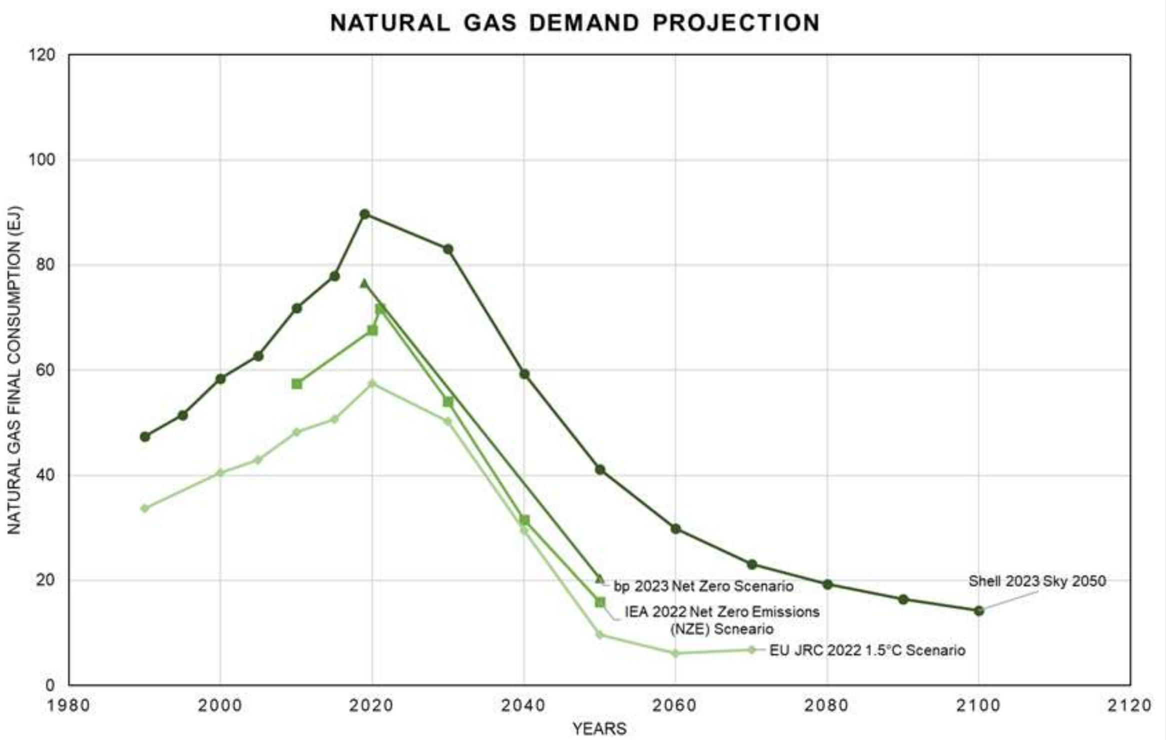


Figure 2 Comparison of the most ambitious scenarios of the latest international energy outlooks for global final energy consumption of natural gas between 1990 and 2100 in EJ

Besides the expected future decline in the demand for fossil fuels, the analyzed scenarios also offer relevant insights into the extent to which fossil fuels will be replaced by carbon-neutral fuels such as green hydrogen and e-fuels, Figure 3, therefore, compares the projected demand for oil and gas to the expected demand for their potential substitutes, namely green hydrogen and e-fuels, for the years 2030 and 2050. The analysis compares the most ambitious scenarios of (IEA 2022b; Keramidas et al. 2022). The figures clearly show that the expected future demand for hydrogen and e-fuels will be much lower than today's demand for oil and natural gas, even in the long term. In 2030, it is anticipated that the demand for fossil oil and gas (totaling 163-188 EJ) will continue to surpass the demand for hydrogen and hydrogen-based e-fuels (totaling 2.6-4.7 EJ) significantly. With ambitious global decarbonization efforts, the demand could increase strongly after 2030, reaching about 29-43 EJ (combined) by 2050. Nevertheless, the share of hydrogen and e-fuels in 2050 still remains well below one-fourth of today's final energy demand for oil and gas in both scenarios. This reveals that energy efficiency and direct electrification will be the key factors for decarbonization and that the international market for hydrogen and e-fuels will likely remain much smaller in terms of energy volumes compared to the current fossil fuel market. This is further underscored by the fact that, unlike fossil fuels, renewable hydrogen can, in principle, be produced anywhere and is, therefore, likely to be traded less internationally.

IEA 2022 – Net Zero Emission Scenario
E-Fuels-H_2 vs. Oil-Natural Gas (EJ)

EU JRC 2022 -1,5°C Scenario
E-Fuels-H2 vs. Oil-Natural Gas (EJ)

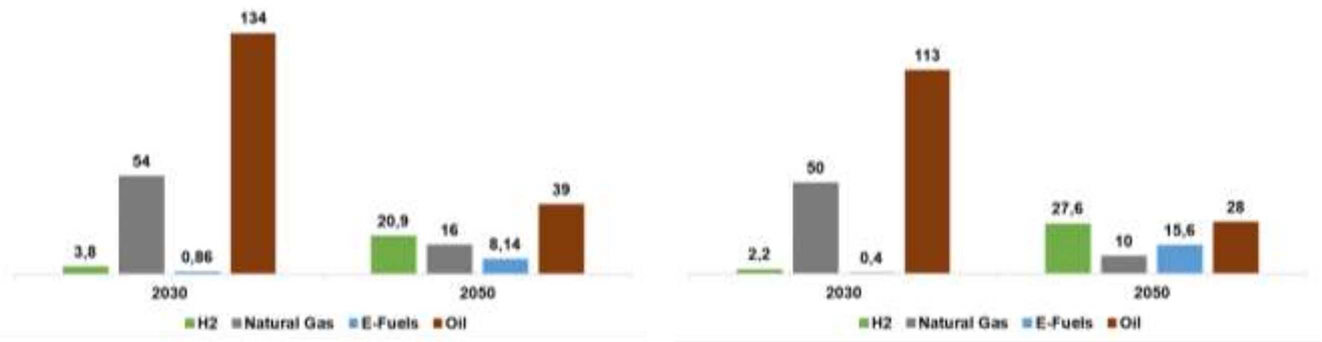


Figure 3 Comparison of the latest, most ambitious scenarios of IEA (left side) and EU JRC (right side) for final consumption of hydrogen, natural gas, e-fuels, and oil for the years 2030 and 2050

2.2 Degree of dependency of fossil fuel exporting countries

All three of the case study countries are, to varying degrees, strongly dependent on the export of fossil fuels but show varying characteristics in terms of their competitive position on the global fossil fuel market as well as their economic diversification potentials. The following analysis thus investigates key indicators such as the percentages of export revenues and GDP stemming from the oil and gas industry as well as the competitiveness on the world market in terms of production costs and diversification of trade partners.

Kazakhstan

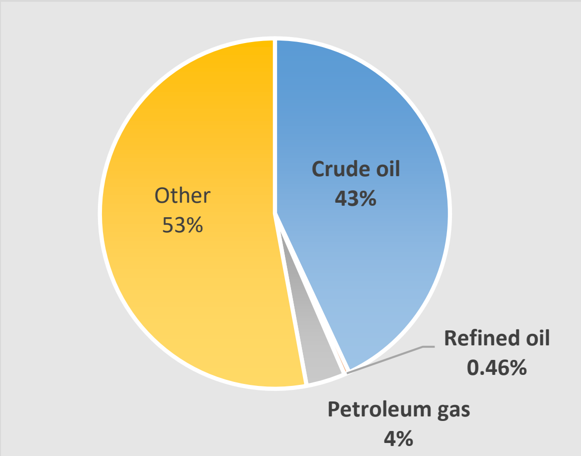
In 2021, the trade of oil and gas accounted for over 47% of Kazakhstan's export revenues. Thereby, the majority of the crude oil was exported to Germany (13%) and to various other European Member States as well as to China (9.6%). Refined oil was mostly exported to the USA (46.2%), to the Netherlands (18.5%) and Uzbekistan (11.2%), whereas natural gas was traded mainly to China (53.8%) and Ukraine (11.7%) with vast oil resources and marginal production costs of crude oil well below the global average (cf. Table 8 in Annex). Kazakhstan will likely remain a competitive supplier of crude oil on the world market, especially for the markets in Asia.

Besides petroleum oil and natural gas, the country is rich in resources of coal, iron ore, manganese, chrome ore, nickel, cobalt, copper, molybdenum, lead, zinc, bauxite, gold and uranium. Kazakhstan is currently the world's largest uranium producer and presumably holds more than 20% of the world's uranium reserves (International Trade Administration 2022). The countries' richness in various natural resources is also reflected in some degree of **diversification** in its export profile. Especially metals and metal products (such as copper ores, refined copper and copper alloys, and ferroalloys), gold, silver and uranium are further relevant export goods (Harvard Growth Lab 2023).

Based on its current level of economic diversification, especially in the metal mining and processing sector, employment in the oil and gas sector can be considered of comparatively low relevance for the overall national labor force.

Table 2 provides a synopsis of some key indicators for the degree of Kazakhstan's economic dependency on the export of fossil fuels.

Table 2 **DEGREE OF DEPENDENCY – FACT SHEET KAZAKHSTAN**

NATIONAL EXPORT SHARES (Harvard Growth Lab 2023)		
Crude petroleum oil export (net national export budget share, 2021)	43.0%	
Refined petroleum oil export (net national export budget share, 2021)	0.46%	
Petroleum gas export (net national export budget share, 2021)	3.06%	
Total share of oil and gas in national export budget (2021)	47.1%	
Oil rent as share of GDP (2021)(World Bank Open Data 2023a)	14.8%	Total net exports (2021): 54.5 billion US$
GLOBAL MARKET SHARES (Harvard Growth Lab 2023)		
Global crude oil export share (% of global net exports, 2021)	2.96%	Main trade partners: **Germany**, China, Italy, Greece, France, South Korea, Spain, Netherlands
Global refined oil export share (% of global net exports, 2021)	0.1%	Main trade partners: **USA, Netherlands, Uzbekistan**, Russia
Global petroleum gas export share (% of global net exports, 2021)	0.6%	Main trade partners: **China, Ukraine**, Tajikistan, Russia, Turkey, Algeria
Marginal upstream production cost of crude oil	Below global average (range: 5.3-27.8 US$/bbl)[1]	
EMPLOYMENT[2]		
Overall employment in oil and gas sector	Ca. 155,000	
Share of oil & gas workers in overall labor force (%)	Ca. 1.78%	

[1] Sources: see Table 6 in Annex
[2] Cf. Section 2.3.2 on national employment structure

Saudi Arabia

Saudi Arabia's economy is strongly based on the production and export of fossil fuels, with 23.7% of the national GDP based on oil rents and a total share of 56.6% of the net export revenues stemming from the trade of oil and gas in 2021. The marginal cost of oil production is among the lowest globally, thus making the country highly competitive on the world market (cf. Table 8 in Annex). With 14.9% of the 2021 global crude oil exports originating in Saudi Arabia, the country is one of the leading suppliers, serving mostly the fossil fuel demand in the fast-growing economies in Asia. The main export destination for crude oil in 2021 was China (23.6%), followed by Japan (15%), South Korea (13%) and India (12%). The majority of natural gas was exported to India (54.7%) as well as China (12.8%) and Indonesia (10.9%). It can be expected that Saudi Arabia will remain a highly competitive supplier of fossil fuels, especially for the Asian market.

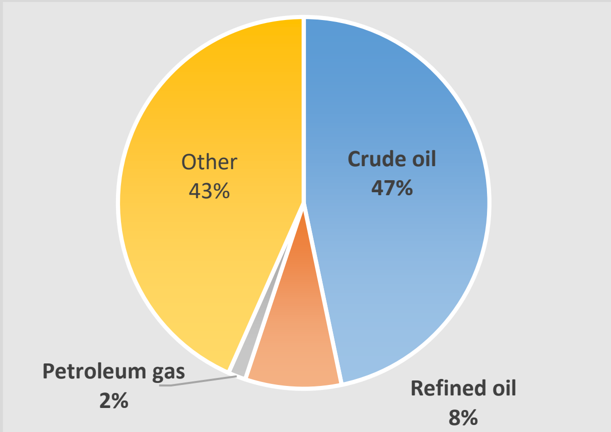
However, over the past decade and against the background of declining crude oil exports, the economy has already begun a shift towards a higher degree of **diversification**, notably based on the development of the chemical industry sector. Major export goods, such as polymers of ethylene, propylene, acyclic alcohols, but also ammonia and fertilizers, play a growing role in the Saudi Arabian economy. In 2021, Saudi Arabia accounted for 1.38% of the global trade in chemical industry products. (Harvard Growth Lab 2023)

Besides some of the world's largest proven reserves of petroleum oil and gas, Saudi Arabia also possesses gold, bauxite, copper, iron ore and phosphate resources. Phosphate is mined in particular for fertilizer production.

Employment in the oil and gas industry can be considered as relevant for the national labor force, with over 300,000 people (ca. 1.9% of the labor force) employed in the sector in 2022 (Saudi Arabia open data platform 2022).

Table 3 provides a synopsis of some key indicators for the degree of Saudi Arabia's economic dependency on the export of fossil fuels.

Table 3 **DEGREE OF DEPENDENCY – FACT SHEET SAUDI ARABIA**

NATIONAL EXPORT SHARES (Harvard Growth Lab 2023)		
Crude petroleum oil export (net national export budget share, 2021)	46.7%	
Refined petroleum oil export (net national export budget share, 2021)	8.4%	
Petroleum gas export (net national export budget share, 2021)	1.5%	
Total share of oil and gas in national export budget (2021)	56.6%	
Oil rent as share of GDP (2021) (World Bank Open Data 2023a)	23.7%	Total net exports (2021): 254 billion US$
GLOBAL MARKET SHARES (Harvard Growth Lab 2023)		
Global crude oil export share (% of global net exports, 2021)	14.9%	Main trade partners: **China, Japan, South Korea, India**, USA
Global refined oil export share (% of global net exports, 2021)	7.9%	Main trade partners: Egypt, UAE, France, USA, Italy, Djibouti
Global petroleum gas export share (% of global net exports, 2021)	1.2%	Main trade partners: **India, China, Indonesia**, Egypt
Marginal upstream production cost of crude oil	Among lowest globally (range: 2.9-9.9 US$/bbl)[3]	
EMPLOYMENT[4]		
Overall employment in oil and gas sector	300,090 (2022)	
Share of oil & gas workers in overall labor force (%)	Ca. 1.9%	

[3] Sources: see Table 6 in Annex
[4] Source: 2022 employment data from (Saudi Arabia open data platform 2022)

Nigeria

Nigeria's economy is strongly dependent on the export of fossil fuels. In 2021, crude oil and natural gas accounted for over 90% of the countries' net export budget, with crude oil making up almost 77% of the export revenues and 6.2% of the national GDP. The cost of crude oil production in Nigeria, with an estimated marginal production cost of between 5.3 and 28.9 US$/bbl, is well below the global average and can be considered very competitive on the world market (cf. Table 8 in Annex).

In 2021, Nigeria held a market share of 5% in the global crude oil market, with its main trade partners being India (19%) and Spain (13%). Refined petroleum oils have been exported mainly to the USA. However, the export of refined oil has declined over the past years and currently does not play a significant role in the national export profile. For petroleum gas, the major trade relationships are established with countries in Asia and Europe, with 17.5% of exports going to China, 15.4% to Spain and 10.04% to India in 2021 (Harvard Growth Lab 2023).

It can be expected that, based on the global climate policy landscape, the demand for fossil fuels will likely decline more readily in Europe compared to the fast-growing economies in Asia, which would sustain the fossil fuel export opportunities to these markets for longer.

Besides the export of fossil fuels, the Nigerian export economy exhibits a rather low level of **diversification** with some agricultural products, special function vessels (floating platforms), nitrogenous fertilizers and precious and non-precious metals as further but much less relevant export goods (Harvard Growth Lab 2023).

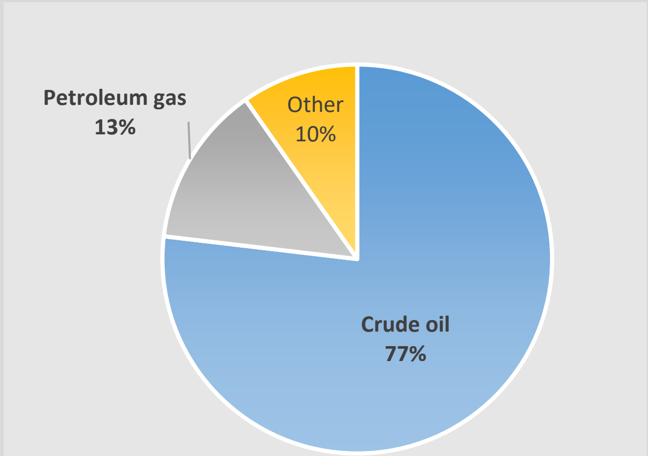
However, the country is rich in various other natural resources such as metals and minerals (such as gold, lead, zinc, manganese, iron-ore, graphite, limestone, bentonite, marble, and various gemstones), which have not been exploited to their full extent yet (Ministry of Foreign Affairs of Nigeria 2022).

The relevance of the oil and gas sector for **employment** in Nigeria can be considered as rather low, with an estimated number of 80,000 people employed in the sector in 2021 (Statista 2023a), which would translate to only about 0.11% of the overall national labor force.

Furthermore, the share of foreign nationals working in the oil and gas sector, especially in high-level engineering positions, is known to be high, and the lack of skilled workers has been an issue acknowledged by the Nigerian government through setting up funds, institutions and programs to enhance the availability of trained work force and to increase the share of Nigerian nationals in the up- and downstream sectors (National Assembly of the Federal Republic of Nigeria 2010). For example, in 2017, a strategic 10-year roadmap was developed to increase the local content in oil and gas activities to 70% by 2027 and to create over 300,000 direct jobs in the sector (NCDMB 2020).

Table 4 provides a synopsis of some key indicators for the degree of Nigeria's economic dependency on the export of fossil fuels.

Table 4 **DEGREE OF DEPENDENCY – FACT SHEET NIGERIA**

NATIONAL EXPORT SHARES (Harvard Growth Lab 2023)		
Crude petroleum oil export (net national export budget share, 2021)	76.9%	
Refined petroleum oil export (net national export budget share, 2021)	0.0%	
Petroleum gas export (net national export budget share, 2021)	13.4%	
Total share of oil and gas in national export budget (2021)	90.3%	
Oil rent as share of GDP (2021) (World Bank Open Data 2023a)	6.2%	Total net exports (2021): 51.9 billion US$
GLOBAL MARKET SHARES (Harvard Growth Lab 2023)		
Global crude oil export share (% of global net exports, 2021)	5.04%	Main trade partners: **India, Spain**, USA, France, South Africa, Indonesia, Italy, Canada
Global refined oil export share (% of global net exports, 2021)	0.0%	Main trade partners: **USA**, Germany, UK, Netherlands, Belgium, Brazil, Benin
Global petroleum gas export share (% of global net exports, 2021)	2.06%	Main trade partners: **China, Spain, India**, France, Portugal, Japan, Taiwan, Thailand, South Korea
Marginal upstream production cost of crude oil	Well below global average (range: 5.3-28.9 US$/bbl)[5]	
EMPLOYMENT		
Overall employment in oil and gas sector (Statista 2023a)	Ca. 80,000 (2021)	
Share of oil & gas workers in overall labor force (%)	Ca. 0.11% (2021)	

[5] Sources: see Table 6 in Annex

2.3 Economic effects of declining fossil fuel exports

2.3.1 Input-Output Analysis

Input-output analysis (IOA) is an economic method for studying the interactions between different sectors of an economy. Thereby, the analysis is based on tables that represent the interwoven structure of the economy by providing data on the monetary flows of goods and services between sectors and final consumers, covering imports and exports, the produced value-added and primary inputs such as labor. It is applied to quantify the impact of economic change and to identify interdependencies within an economy. [6] An IOA was conducted to assess the implications of a 75% decrease in fossil fuel exports in the three case study countries based on the OECD Intercountry Input-Output (ICIO) tables (OECD 2021, 2023). In the most recent version, the OECD offers IO data for 76 countries with 45 economic sectors following the ISIC Rev. 4 classification. The decline in exports corresponds to the ambitious scenario presented in section 2.1 and targets the exports of the economic sector 'Mining and quarrying of energy products'. The scenario is considered as an upper-bound estimate to demonstrate the effects that a substantial demand reduction could have. The OECD tables represent the year 2018 as a base year for the analysis. The results should be interpreted as counterfactual what-if scenarios that change the economic structure of the countries in 2018. Therefore, apart from the sectors that are changed in the impact assessment, consumption patterns, inter-industry interactions and foreign trade are assumed to be stable throughout the scenario. Nevertheless, the changed sectors cover large parts of the economies presented and thus a great extent of the economic interactions. Employment data was added as an extension to the ICIO tables based on available data from the Bureau of National Statistics Kazakhkstan (2023), the International Labour Association (2023) for Nigeria and the OECD (2021) for Saudi Arabia. Data adjustments were necessary for Kazakhstan and Nigeria due to a higher level of aggregation in terms of sectors in the employment data compared to the IO data. The employment data was disaggregated based on the share of wages in value added. Furthermore, the estimation of employment per sector was conducted with available employment data in units of thousands of formal workplaces. This limits the comparability between sectors and countries by omitting possible effects of part-time work, wage differences and differences due to high shares of informal work. Uncertainty should therefore be taken into account when interpreting employment results. The employment impact assessment also relies on the assumption of proportional effects underlying the IO model approach.

2.3.2 Macroeconomic structure and impacts of fossil fuel export reductions

In this chapter, the effects of the modelled export decline in the primary sector 'Mining and quarrying of energy products', are highlighted with respect to total outputs and the employment for the most affected industries in each country. The results are placed in the context of the economic structures of the three countries, represented by 44 macroeconomic sectors based on the distribution of gross output sectors (*Figure 4, Figure 7, Figure 10*)[7] and employment. Sorted by the absolute value of product equivalents,

[6] For comparability of products across sectors, products are quantified by monetary units, e.g. the "dollars worth of products".
[7] Due to missing data, the sector 45 "private households" is not displayed

these figures underline that 'Mining and quarrying of energy products' is a main contributor to the national economies of all three countries.

2.3.3 Macroeconomic and employment effects by country

Kazakhstan

The share of the sector ‘Mining and quarrying of energy products’ in the gross total output of Kazakhstan is 10.57% (see *Figure 4*). The industry contributes 44.4% to the country's total exports and is, by a wide margin, the largest export sector of the economy. The remaining primary production in Kazakhstan contributes further 8.28% to the total output, with ‘Agriculture, hunting, forestry’ (4.45%) and ‘Mining and quarrying, non-energy producing products’ as the main industries. The industries in the secondary sector of the economy contribute with 22.89% to the economy-wide output, with ‘Construction’ (7.46%), ‘Basic metals’ (4.94%) and ‘Food products, beverages and tobacco’ (3.24%) being the largest industries. The services in the tertiary sector contributed with 58.2% to the economy-wide output with an emphasis on the ‘Wholesale and retail trade; repair of motor vehicles’ (13.57%) and ‘Land transport and transport via pipelines’ (6.22%) and ‘Real estate activities’ (6.1%).

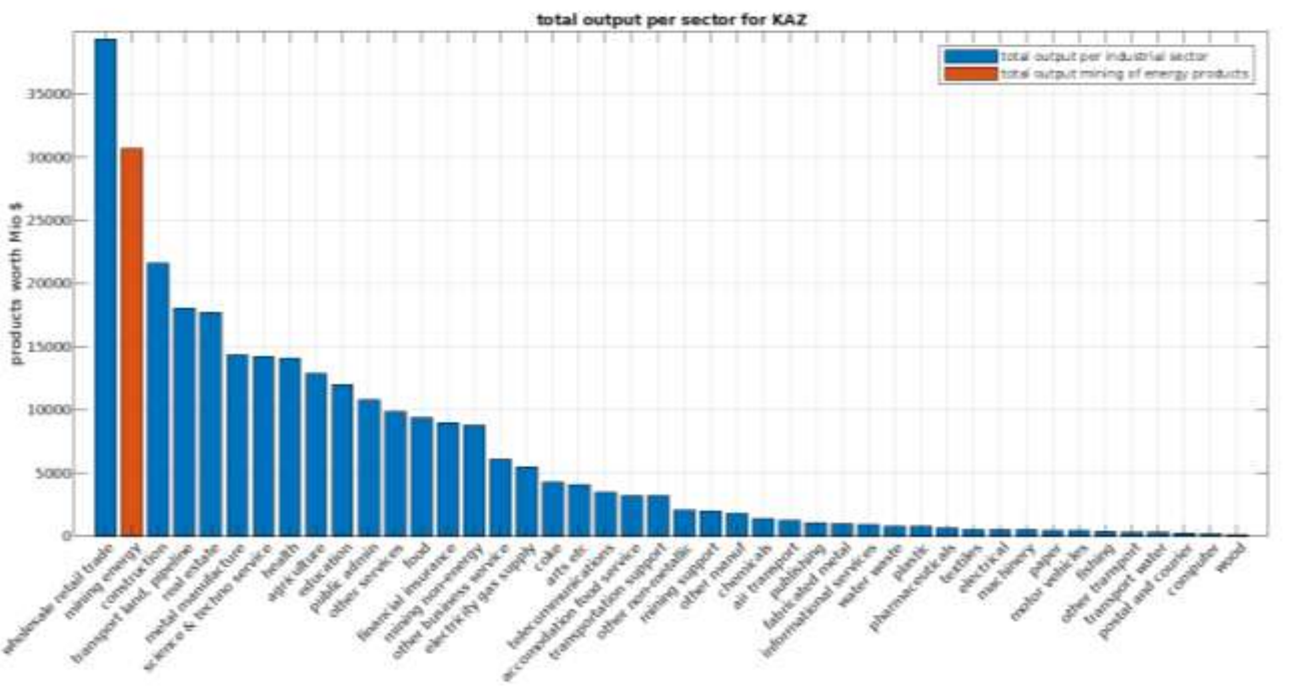


Figure 4: Gross output per macro-economic sector in Kazakhstan in 2018 based on OECD (2021).

The gross output of 'Mining and quarrying of energy products' was $30.658 billion in 2018, and 97% of this was exported across borders. A decline in exports is therefore broadly equivalent, but not identical, to a decline in sectoral gross output. The reduction of exports in mining and quarrying of energy products by 75% mainly affects the sector mining of energy products itself: Here, a reduction of product equivalents of $23 billion, corresponding to 72% of the initial gross output of the sector, can be observed (see *Figure 5*).

The industrial upstream linkages of 'Mining and quarrying of energy products' are based on domestic production with a share of 82% ($6.484 billion). The remaining inputs are imported. The most relevant upstream activity in this context is ‘Land transport and transport via pipelines’ with a contribution of 19.3% of the domestic upstream activity of 'Mining and quarrying of energy products'. ‘Mining support service activities’ contributed 15.7%, and ‘Professional, scientific and technical activities’ with 12.7% to the production inputs of the sector. Overall, upstream activity accounts for 2.24% of the total output. The sector's domestic downstream industrial activity totals $816.7 million (2.66% of the sector's output). With a reduction of one-third of its initial output, the second most affected sector is ‘Basic metals’, which is highly energy-intensive, in particular in upstream processes, and constitutes the most important manufacturing industry in terms of gross output of the country (cf. section 3.2.1). Due to their overall strong extent of interlinkages within the economy and their contribution to the sector of energy mining in upstream processes, ‘Agriculture, hunting, forestry’ and ‘Wholesale and retail trade, repair of motor vehicles’ are affected by reductions by about 20%. Sectors of ‘Mining and quarrying, non-energy products‘, as well as ‘Food products, beverages and tobacco’ and ‘Accommodation and food service activities’ are still affected by more than 8%. This is attributable to their consumption stemming from 'Mining and quarrying of energy products' in higher tiers and their contribution to higher levels of the value chain of the sector.

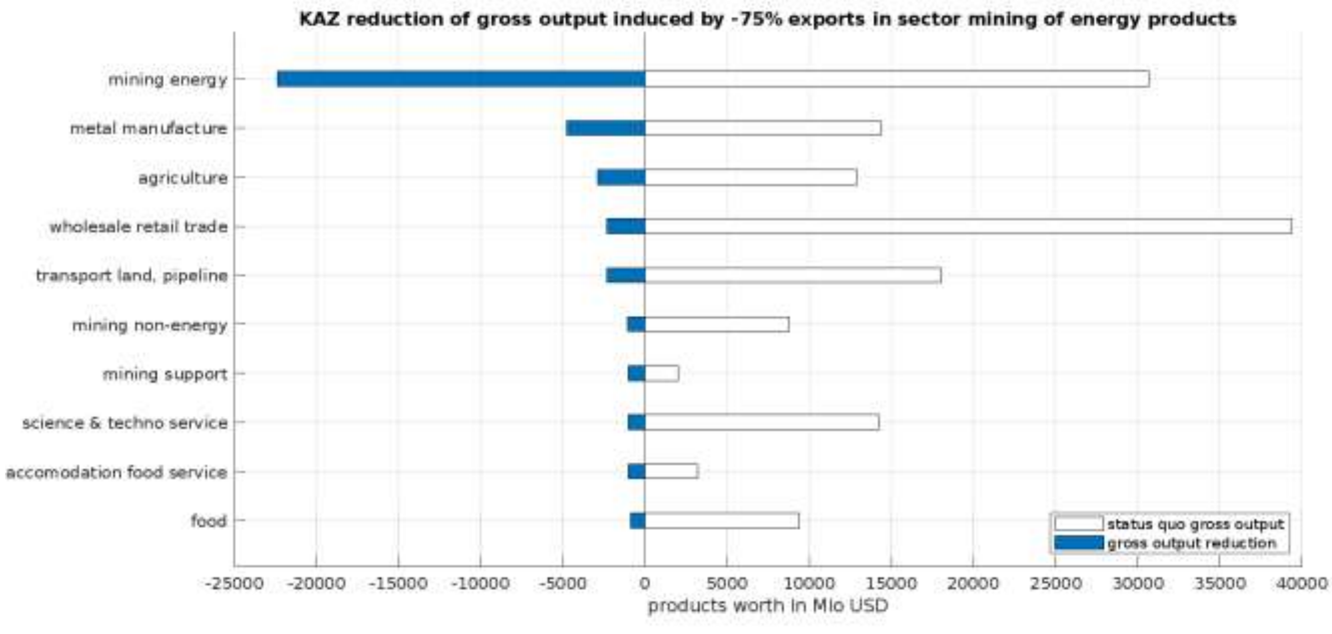


Figure 5: Sectors most affected by a 75% reduction in exports in energy mining in Kazakhstan.

In terms of employment, the share of ‘Mining and quarrying of energy products’ of the employed working force is marginal with 1.78%. This underlines the high productivity in the sector, with a high level of total output being produced by a small work force. The remaining employment in the primary production is dominated by ‘Agriculture, hunting, and forestry’ with a share of 14.01% of the national workforce. The secondary sector employs 16.57% of the local workforce, with ‘Construction’ being the most labor-intensive industry (7.24%). Employment in Kazakhstan is largely dominated by the services in the tertiary sector with 66% and ‘Wholesale and retail trade; repair of motor vehicles’ (16.06%) as well as

‘Education’ (12.06%) being the most labor-intensive sectors. Employment effects induced by the decline of -75% of exports in ‘Mining and quarrying of energy products’ (see *Figure 6*) also manifest in the sectors with highest effects in the output displayed in *Figure 5*. The potential employment decline in 'Land transport and transport via pipelines' and 'Professional, scientific and technical activities' can be attributed to the upstream linkages of the industry, while the employment demand of ‘Mining and quarrying of energy products’ itself could be reduced by two thirds of its 154000 jobs. Labor-intensive sectors that employ a high share of the population (1.2 million in ‘Agriculture, hunting, forestry’ and 1.4 million in ‘Wholesale and retail trade; repair of motor vehicles’) are affected substantially with up to 20% or 6% reductions, respectively. They display comparatively lower levels of produced output per worker, leading to a higher sensitivity. This is also the case for ‘Accommodation and food services’. In metal manufacturing, a third of employment demand could be lost through the modelled decline in fossil fuel exports. This sector shows vulnerability due to the high level of interlinkages with other industries in the economy.

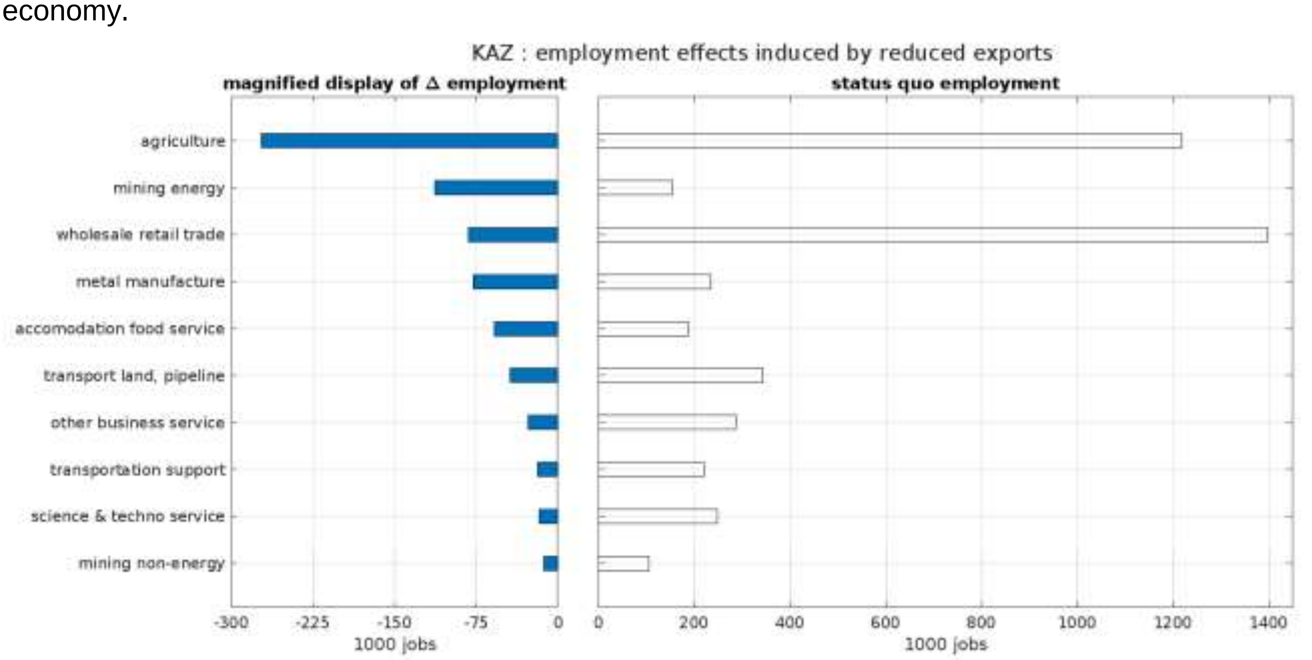


Figure 6: Employment effects induced by a 75% reduction of exports in energy mining in Kazakhstan.

Saudi Arabia

The share of ‘Mining and quarrying of energy products' in the economy-wide output of Saudi Arabia is 20.2% (see Figure 7). The sector contributes 73.84% to the country's total exports and is, by a wide margin, the largest export sector of the economy. The remaining primary production in Saudi Arabia contributes a further 2.64% to the total output, with agriculture as the main sector. The industries in the secondary sector contribute 30.18% to the economy-wide output, with ‘Construction’, ‘Coke and refined petroleum products’ and ‘Chemical and chemical products’ being the largest industries. The tertiary sector contributes 46.97% to the economy-wide output with an emphasis on the services ‘Wholesale and retail trade; repair of motor vehicles’ and ‘Public administration and defense; compulsory social security’.

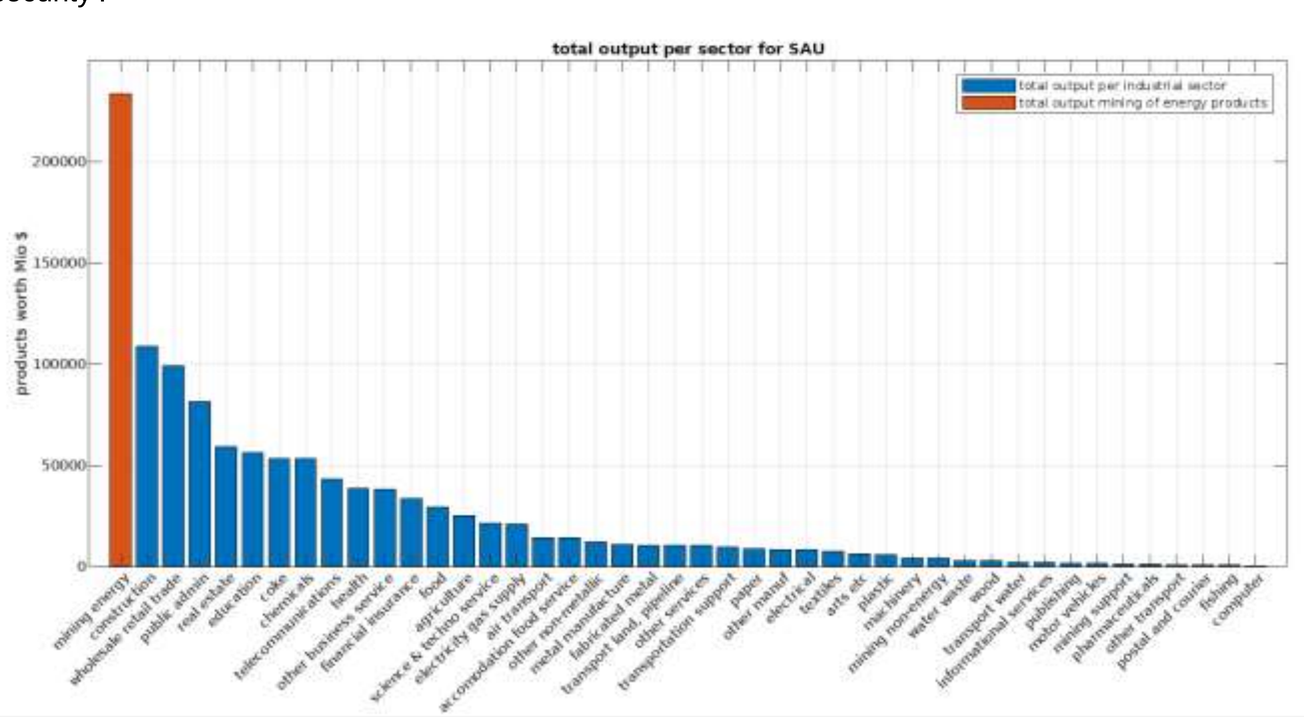


Figure 7: Gross output per macro-economic sector in Saudi Arabia in 2018 based on OECD (2021).

The gross output of 'Mining and quarrying of energy products' was $233.455 billion in 2018, and 93% of this output was exported across borders. A decline in exports is therefore broadly equivalent, but not identical, to a decline in total sector gross output. The reduction of exports in mining and quarrying of energy products by 75% mainly affects the sector mining of energy products itself: Its output is reduced by product equivalents of $165 billion, which corresponds to a reduction of 70% of the initial value. *Figure 8* displays the effects in the ten economic sectors most affected by the reduction in exports in relation to the status quo scenario.

The industrial upstream linkages of 'Mining and quarrying of energy products' are based on domestic production with a share of 86.66%. The remaining inputs are imported. The domestic upstream activity accounts for $5.626 billion worth of products, about 0.56% of the economy wide output. In terms of downstream linkages, $16 billion worth of the industries output is consumed by other domestic sectors in Saudi Arabia (6.9% of the total sector output). The effects on the other industrial sectors shown in

Figure 8 experience reductions of less than $9 billion, which is less than 5% of the losses observed in the sector of 'Mining and quarrying of energy products'. This can be attributed to the limited interrelations of the industry with other sectors. As a primary sector, the upstream interlinkages of the energy mining sector are limited and on the downstream side, most of the production is exported to other countries. The effects on the presented sectors are due to second-order effects found in the service sectors and manufacturing of final products that feature strongly interrelated value chains (such as ‘Food products, beverages and tobacco’, ‘Accommodation and food services’, ‘Wholesale and retail trade; repair of motor vehicles’), but also energy intensive production sectors, including the chemical and textile industries as well as the production of electrical equipment as downstream activities.[8]

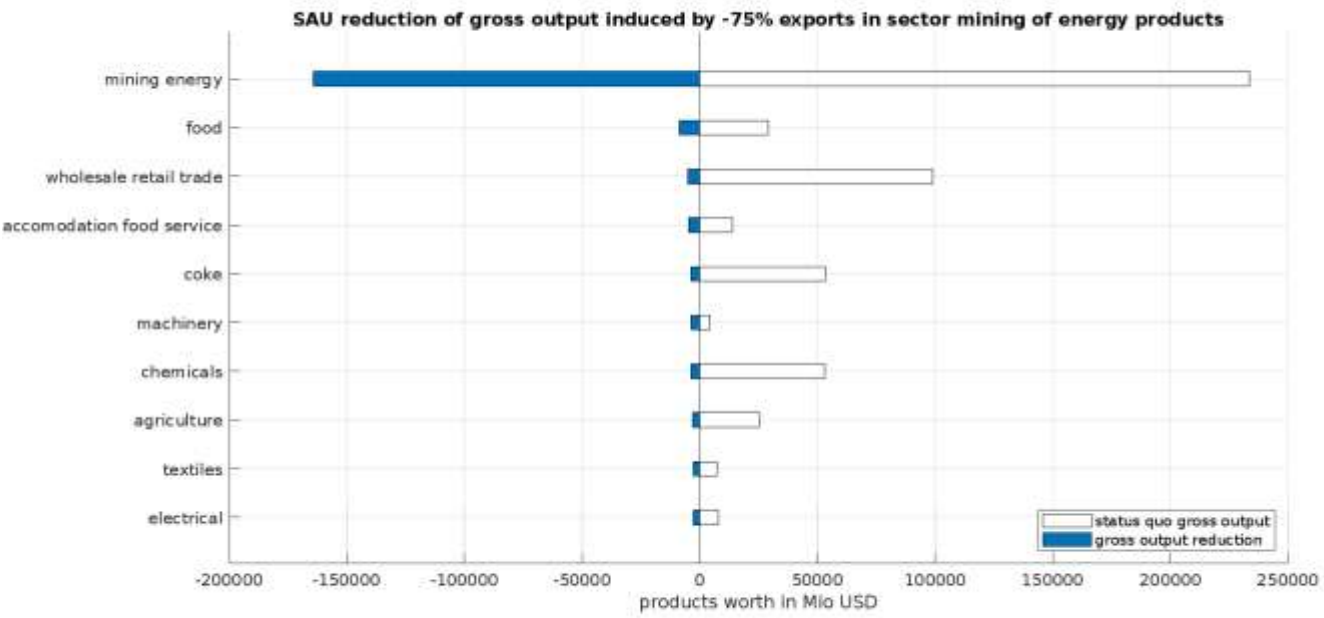


Figure 8: Sectors most affected by a 75% reduction in exports in energy mining in Saudi Arabia.

In terms of employment, the share of ‘Mining and quarrying of energy products’ in the employed working force is marginal with 0.81%. This underlines the high productivity in the sector, with a high level of total output being produced by a small workforce. The remaining employment in the primary production of Saudi Arabia is dominated by ‘Agriculture, hunting, forestry’ with a share of 4.6% of the national workforce. The secondary sector employs 23.05% of the local workforce, with construction being the most labor-intensive industry (14.16% of the total workforce). However, employment in Saudi Arabia is largely dominated by the services in the tertiary sector with 71% and ‘Wholesale and retail trade; repair of motor vehicles’ (13.79%) as well as 'Public administration and defense; compulsory social security’ (14.85%) being the most labor-intensive sectors.

Reductions in total output are more likely to affect sectors where large numbers of workers are needed to produce output, implying a comparatively lower productivity per worker. It has to be noted, though,

[8] The influence of the reduction on the sector ‘mining support services’, whose reduction of 700 Mio USD is low compared to the reductions of other within the entire economy (cf. Figure 4), is still considerable in relative terms and corresponds to a shrinking of that sector to 1/3 of its initial volume.

that without data on part-time work, the comparability between sectors is limited. Therefore, conclusions about productivity and the impact on the labor force have to be seen in this context. The effects that were identified on output reductions due to the decline of fossil fuel exports in Saudi Arabia are particularly visible at the level of employment effects in sectors with high labor intensity and comparably lower productivity per worker. The sector 'Accommodation and food services' displays one of the lowest outputs per worker in the overall economy, leading to the high sensitivity of the employment to a reduction in the sector's output. Sectors employing large numbers of workers, such as "Agriculture, hunting, forestry", 'Construction' and 'Wholesale and retail trade; repair of motor vehicles', also operate with comparatively lower output per worker and are therefore among the main sectors affected by the reduction in fossil fuel exports.

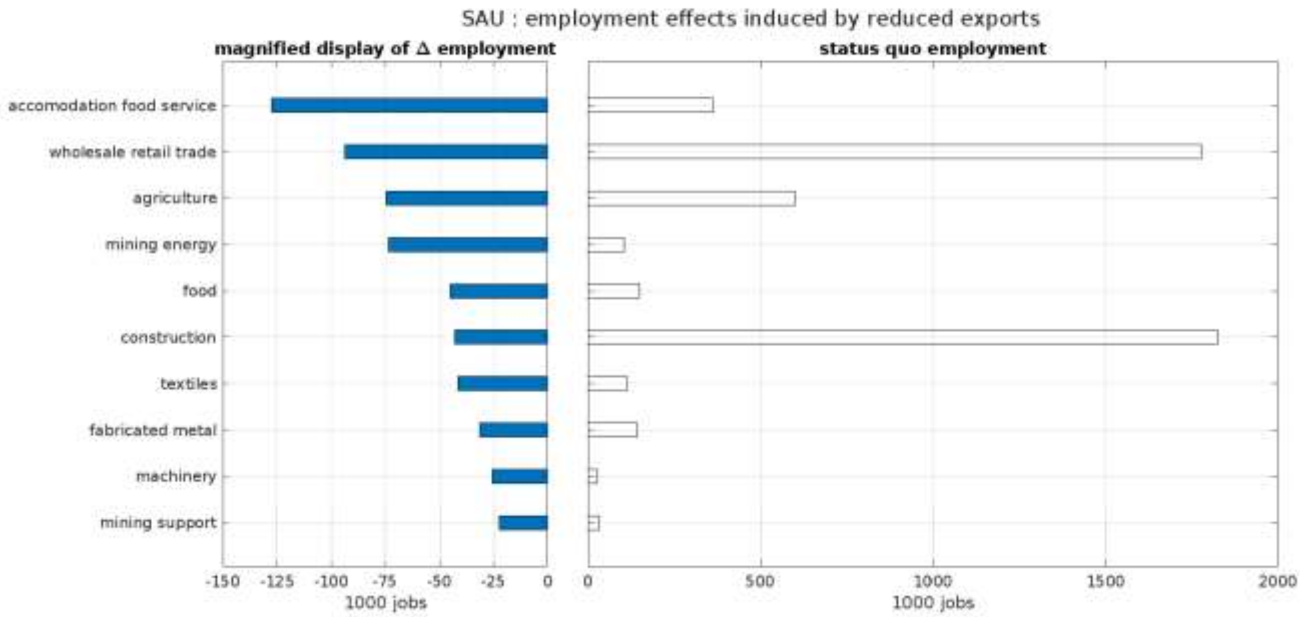


Figure 9: Employment effects induced by a 75% reduction of exports in energy mining in Saudi Arabia.

Nigeria

The share of ‘Mining and quarrying of energy products’ on the gross output of Nigeria is 6.88% (see Figure 10). The industry contributes 68.8% to the country's total exports and is by far the largest export sector of the economy. The remaining primary production in Nigeria contributes a further 17.09% to the total output, with ‘Agriculture, hunting, forestry’ (16.5%) being the main industry. The secondary sector contributes 18.96% to the economy-wide output, with ‘Construction’ (5.92%) and ‘Food products, beverages and tobacco’ (6.34%) being the largest industries. The tertiary sector contributes 57.06% to the economy-wide output with an emphasis on the services ‘Wholesale and retail trade; repair of motor vehicles’ (18.71%) and “Telecommunications” (5.67%) and ‘Real estate activities’ (5.15%).

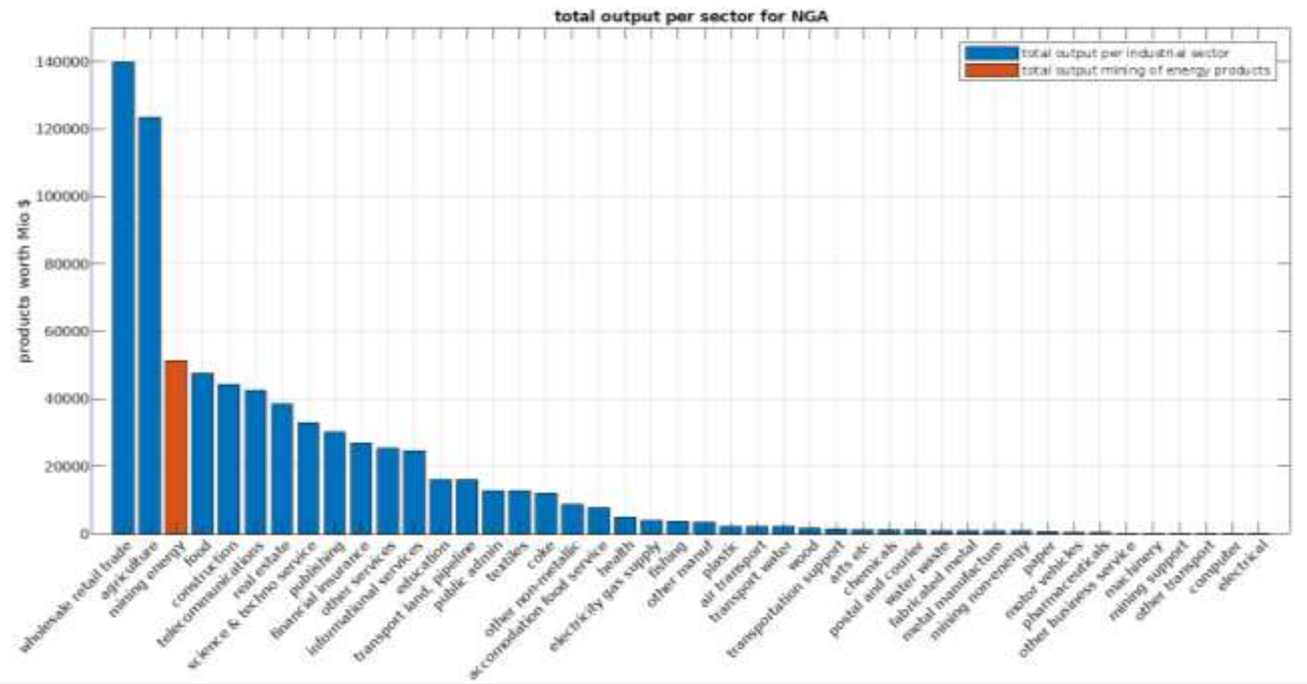


Figure 10 Gross output per macro-economic sector in Nigeria in 2018 based on OECD (2023).

The gross output of 'Mining and quarrying of energy products' was \$51.419 billion in 2018, and 84.26% of this output was exported across borders. A reduction in exports is therefore broadly equivalent, but not identical, to a reduction in total sector gross output, and the decline by 75% induces a 64% reduction of total output within this sector (see Figure 11). The industrial upstream linkages of the sector 'Mining and quarrying of energy products' are, by a small margin, mainly based on imports with a share of 50.55% (\$3.824 billion), the remaining inputs being produced domestically. Thereby, the most important upstream industry is ‘Water transport’ with a contribution of 36.6% of the domestic upstream activity of 'Mining and quarrying of energy products'. ‘Air transport’ contributes with 15.55% and intra-sectoral trade within 'Mining and quarrying of energy products’ with a further 18.11% to the production inputs of the sector. Overall, the upstream activity accounts for 0.5% of the economy-wide output. The sector's domestic downstream industrial activity totals \$8071.6 billion (15.7% of the sector's output). It is thereby primarily used in the production of ‘Coke and refined petroleum products’ (\$7056.3 billion worth of product equivalents).

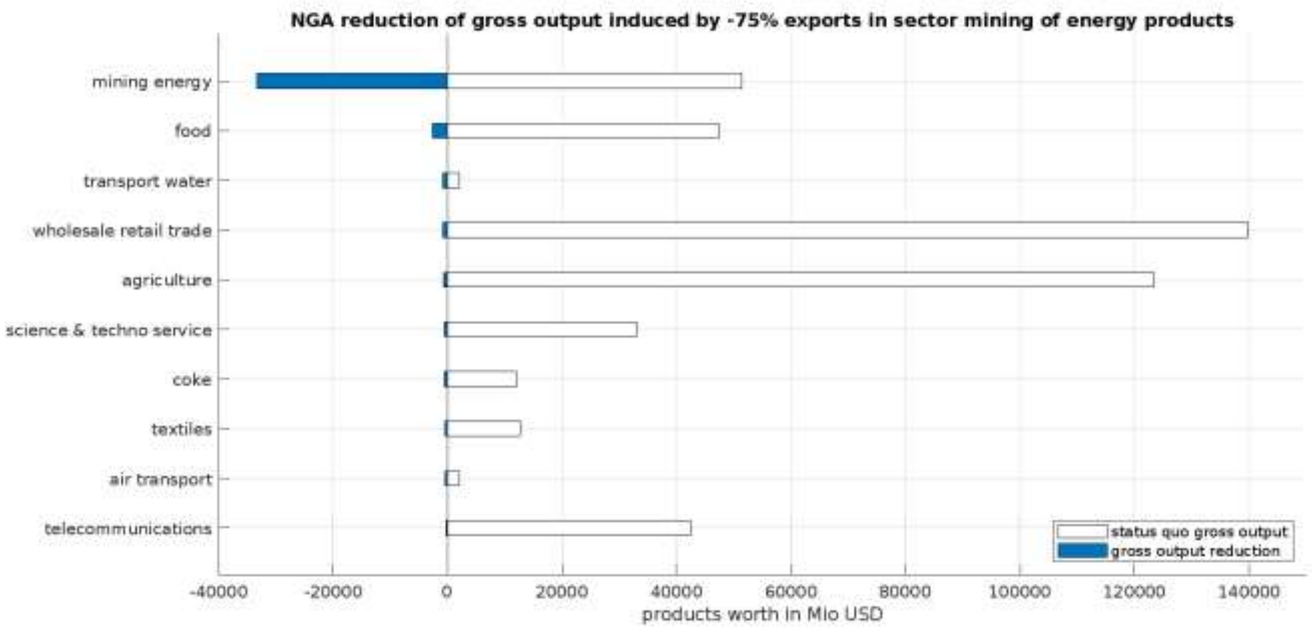


Figure 11: Sectors most affected by a 75% reduction in exports in energy mining in Nigeria.

In terms of employment, the share of 'Mining and quarrying of energy products' of the employed working force is small at 2.54%. This underlines the high productivity per worker in the sector in Nigeria, with high levels of total output being produced by a small work force. The remaining employment in primary production is dominated by 'Agriculture, hunting, and forestry' with a share of 36.08% of the national workforce. The secondary sector employs 13.45% of the local workforce, with 'Food products, beverages and tobacco' (4.87%) being the most labor-intensive industry, followed by 'Construction' (2.23%). Employment in Nigeria is largely dominated by the services in the tertiary sector with 47.59% and 'Wholesale and retail trade; repair of motor vehicles' (22.21%), 'Other business activities' (5.78%), 'Financial and insurance activities' (3.7%) as well as 'Land transport and transport via pipelines' (3.01%) being the most labor-intensive sectors.

With the export reductions, the employment effects in Nigeria are distributed between primary production (agriculture and energy mining), secondary production (food, textiles, pharmaceuticals and other manufacturing) and services in the tertiary sector (other business services, wholesale and retail trade, air and water transport) as displayed in Figure 12. The high vulnerability to the fossil fuel export decline is due to the production being based on a larger share of workers with relatively low productivity in terms of output and a higher share of domestic industrial linkages. This leads to an estimated decline in employment in the displayed sectors. The high level of industrial interlinkages between the sectors of agriculture, food production, textile production and 'Wholesale and retail trade; repair of motor vehicles', combined with comparatively low output per worker, led to a decline in these sectors. All of these sectors are, to different extents, upstream or downstream activities of 'Mining and quarrying of energy products' and the interlinkages between these sectors lead to a further decline due to secondary effects of the reduction.

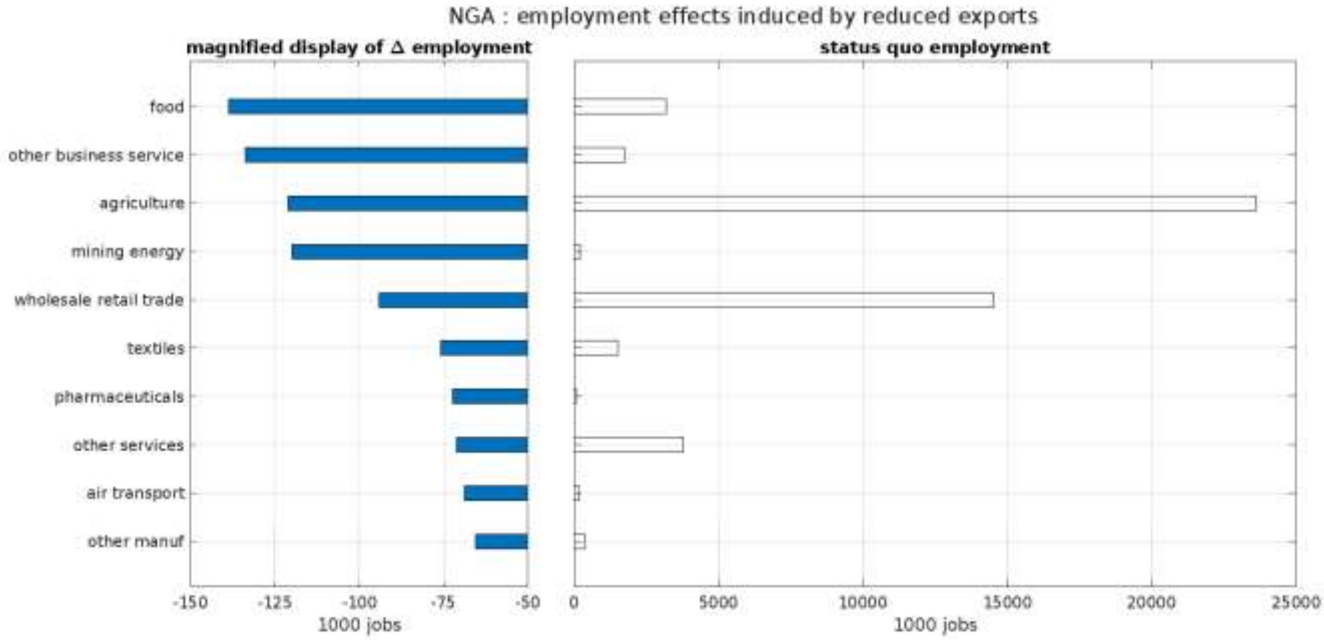


Figure 12: Employment effects induced by a 75% reduction of exports in energy mining in Nigeria.

Summary

The economic sector 'Mining and quarrying of energy products' is central in all three of the economies and contributes a large share to the exports. Overall, the decline in the economy-wide output is mainly limited to the energy mining industry itself, with reductions up to 72%. This is attributable to limited domestic upstream linkages as a primary sector and most of the downstream activity taking place outside of the country due to high export shares. The remaining impact on other domestic industries can be attributed to second-order effects of highly interrelated sectors, such as, 'Wholesale and retail trade repair of motor vehicles' in all three of the countries. Despite its high relevance in terms of output and exports, the number of employed workers in 'Mining and quarrying of energy' is marginal in all of the three countries. As a result, the demand for employment in other industries is more affected in all three countries, but the industry itself remains one of the four sectors with the largest reductions. The findings show that employment in sectors with lower output per worker and a high share of domestic upstream and downstream linkages is more sensitive to the decline in fossil fuel exports.

In **Kazakhstan**, the industry 'Mining and quarrying of energy products' produced a total output of $30.658 billion worth of product equivalents (10.57% of the total economy-wide output) in 2018. The exports constitute 97% of the industries' downstream activity. The industrial upstream linkages of 'Mining and quarrying of energy products' are based on domestic production with a share of 82% ($6.484 billion). The remaining inputs are imported. The amount of upstream activities required as production inputs is comparatively higher in Kazakhstan (2.24% of economy-wide output), including 'Land and pipeline transport'. In addition to a 72% reduction in the industry itself, other industries affected include the manufacturing of 'Basic metals', agricultural production and 'Wholesale and retail trade, repair of motor vehicles’, among others. This shows an increased sensitivity to impacts outside of the industry itself due to high industrial interlinkages and upstream activities. The impact on employment is sensitive to domestically strongly interdependent industries and to those with lower productivity per worker.

'Mining and quarrying of energy products' constituted $233.455 billion, about 20.2% of the gross output of **Saudi Arabia** in 2018. The industrial upstream linkages of 'Mining and quarrying of energy products' are based on domestic production with a share of 86.66% ($5.626 billion). The remaining inputs are imported. The domestic production inputs remain limited, with a contribution of 0.56% to the economy-wide output. The downstream activity is dominated with 93% by exports to other countries, while the upstream activity remains limited. The reduction in economy-wide output in Saudi Arabia due to a decline in fossil fuel exports is therefore largely confined to 'Mining and quarrying of energy products' itself. The effects on other industries remain below 5% but highlight the diversified economic structure of Saudi Arabia with effects on the primary, secondary and tertiary sectors, and this effect can also be observed in terms of employment.

In **Nigeria**, the industry 'Mining and quarrying of energy products' produced a total output of $51.419 billion worth of product equivalents (6.88% of the total economy-wide output) in 2018. The share of domestic production in the upstream activity of the industry is the lowest of the three focus countries (49.45%). Domestic upstream activities contribute 0.5% to total economic output, which is the lowest among the countries covered. The exports constitute 84.26% of the industries’ downstream activity. The reduction in gross output is primarily limited to the industry itself, as in the other case study countries. The remaining effects are distributed between closely linked sectors such as agricultural production, the manufacturing of processed food and beverages, as well as wholesale and retail services. Other distributional services, such as the transport sectors, remain among the most affected, as well as downstream activities such as ‘Coke and refined petroleum’. This is reflected in the estimated development of employment. In terms of sensitivity, it follows the same trends as the other countries.

It has to be noted that the modelling approach has limitations, and that the scenario analysis should be considered as upper-range estimates. Furthermore, the comparability of the results between sectors could be increased by adding data on the average working time in each industry to assess full-time equivalents rather than workers in units of thousands. Due to a lack of detail in the employment data, the data were adjusted on the basis of the wage share in value added for Kazakhstan and Nigeria. In addition, an estimation of the wage share was conducted for Nigeria as a prerequisite for the data analysis, which was performed with available data for countries based on geographical proximity. This adds uncertainty to the employment data, and ongoing research with improved data quality and sensitivity testing would be beneficial to increase the accuracy of the analyses. The impact assessment also builds on the assumption of proportional effects that is inherent to the IO model approach.

03

Competitiveness of green hydrogen producers

3 Competitiveness of green hydrogen producers

This section presents an analysis of some of the key factors that determine the opportunities of the three case study countries to develop national PtX industries as a basis for the assessment of their competitiveness for exporting PtX products in the future. Besides the availability of renewable energy resources and required infrastructures and the associated techno-economic potential for the production of green hydrogen, this also includes various political and socio-economic framework factors that affect the competitiveness of the sector.

3.1 Political and socio-economic framework conditions

Important framework factors affecting the feasibility and competitiveness of a developing PtX industry comprise the maturity of the renewable energy market represented, besides others, by the current share and past deployment of renewable energy technologies, as well as the existence of strategies and targets for the future development of the energy sector. These parameters can serve as indicators for how realistic and feasible the required future rollout in the frame of the development of a PtX industry would be, also with regard to the availability of local know-how for the implementation of future PtX projects (section 3.1.1). In a broader context, also the overall environment for business development and project implementation is a relevant factor that affects the competitiveness of green hydrogen exports, in particular through its impact on the financing conditions and the resulting costs of capital (section 3.1.2).

3.1.1 Electricity generation mix, renewable energy capacity development and energy sector targets

Kazakhstan

Today's electricity generation energy mix in Kazakhstan is dominated by coal with up to 60% (see Figure 13) (Ember 2023; IRENA 2023a). In 2021, renewable energy accounted for 11% of electricity generation, while its share in generation capacity reached 20.7% by 2022. Large hydroelectric power plants are the primary contributors to the renewable energy share, while wind and solar power contribute with less than 4% of the overall generation capacity.

The historical development of renewable energy capacities (cf. Figure 14) shows that solar photovoltaic (PV) and wind energy growth has been relatively sluggish until recently, with significant installations only gaining momentum since 2019. Wind energy, for instance, has seen average capacity additions of over 250 megawatts per year, reflecting a remarkable annual growth rate of 42%. Similarly, solar PV has shown an average capacity addition of over 230 megawatts per year, representing a notable annual growth rate of 31% over the past four years (IRENA 2023a). These trends indicate a promising shift towards cleaner and more sustainable energy sources in electricity generation and a stepwise maturing of the renewable energy market, which is, however, still in its early development stages.

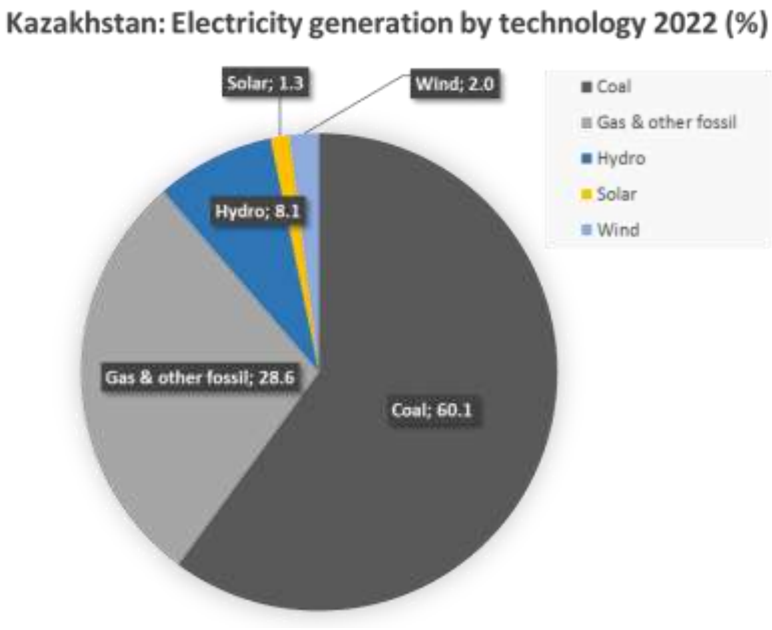


Figure 13: Kazakhstan's electricity generation by technology in 2021 (Ember 2023; IRENA 2023a)

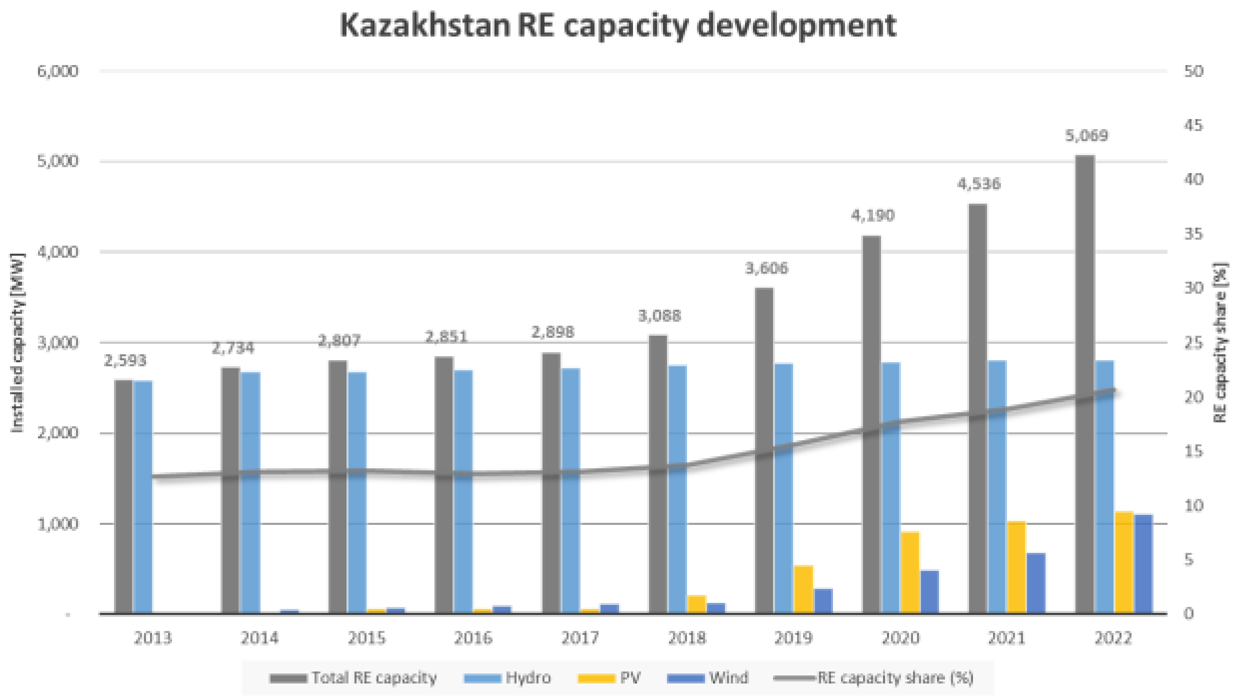


Figure 14: Kazakhstan 2013-2022 renewable energy capacity development (IRENA 2023a)

Kazakhstan's strategy for the future development of the energy sector is laid out in the "Strategy Kazakhstan 2050", which defines the target to increase the share of alternative fuels to 15% by 2030 and to 50% by 2050 (Ministry of Energy of the Republic of Kazakhstan 2023a; Ministry of Foreign Affairs of Nigeria 2022; Republic of Kazakhstan 2013). However, besides renewable energy sources (RES) this share may also include nuclear power which implies that renewable energy deployment may remain limited. The strategy further foresees a 15% reduction in CO2 emissions by 2030 and 40% by 2050, mainly through switching to RES and shifting away from coal, as well as by increasing the overall energy efficiency (i.e. reducing the energy intensity of the GDP by 30% in 2030 and 50% in 2050 compared to 2008 values). Until 2060, the country strives for carbon neutrality. Besides RES, natural gas is still a major pillar of the national energy strategy and laid out in the 2014 “General Scheme of Gasification of the Republic of Kazakhstan for 2015-2030”, which foresees enhanced access for private households to the national gas network through substantial public investments in gas infrastructure. It is envisaged that the ‘Green Economy Transition’ will require investments of 1% of the GDP per year (52bn in the RE and gas sector until 2050) but that in the long-term, it will increase the countries’ GDP by 3% and create 500,000 new jobs (Republic of Kazakhstan 2013).

Also, the production and export of green hydrogen is part of Kazakhstan’s green economic transition, and with the HYRASIA ONE project, the country is currently developing its first wind and solar-powered production site for green hydrogen and green ammonia in cooperation with the Swedish-German ‘Svevind Energy Group’ (HYRASIA 2022). The project is located in the Mangystau region in the Southwest of the country, with excellent wind resources (cf. section 3.2.1). The project is envisaged to become operational by 2030 and to reach its full production capacity of up to 2 million tons of green H2 per year by 2032. The project is expected to create up to 3,500 jobs during the construction period and up to 1,800 permanent jobs as soon as the facilities become fully operational (Bulatkulova 2022b).

Kazakhstan seeks to strengthen its strategic partnerships for the export of green hydrogen to the EU and thus signed an agreement on establishing financial and technological cooperation in the field of raw materials, batteries and green hydrogen with the EU at the COP27 in Egypt in Nov 20 (Bulatkulova 2022a). Besides the export of fuels and mining products, notably, uranium of which the country currently provides about 40% of the global production (Ministry of Energy of the Republic of Kazakhstan 2023c), Kazakhstan aims at further development of its petrochemistry sector and the production of high-value chemicals (such as polymers, polypropylene, polyethene, methanol and olefins) as high-value export goods (Ministry of Energy of the Republic of Kazakhstan 2023b).

Saudi Arabia

Saudi Arabia's current electricity generation energy mix is predominantly composed of fossil fuels, with oil and natural gas being the primary energy sources, Figure 15 (Ember 2023; IRENA 2023c). As of 2022, the RES share in the overall installed generation capacity remains notably low at 0.5%. Remarkable advancements in the realm of renewable energy have primarily transpired since 2021, exemplified by a substantial 75% increase in PV capacity, amounting to an additional 330 MW between 2020 and 2021, as well as a surge of 400 MW in wind energy capacity from 2021 to 2022, The solar energy landscape predominantly comprises PV technology, except for a 50 MW Concentrated Solar Power (CSP) project established in 2018. Furthermore, there is an ongoing construction of another CSP project, boasting a capacity of 43 MW, projected to commence operations in 2023 (IRENA 2023c). By the conclusion of 2021, a noteworthy milestone was achieved by operationalizing the inaugural commercial-scale wind farm, boasting a substantial 400 MW capacity known as Dumat Al Jandal (Ministry of Energy of Saudi Arabia 2021b).

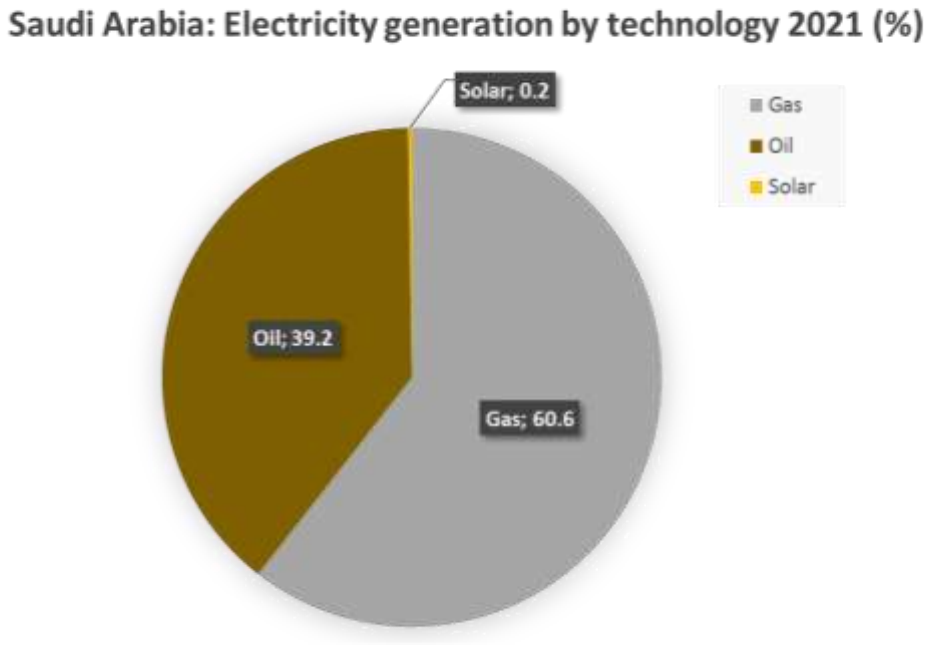


Figure 15 Saudi Arabia's electricity generation by technology in 2021 (Ember 2023; IRENA 2023c)

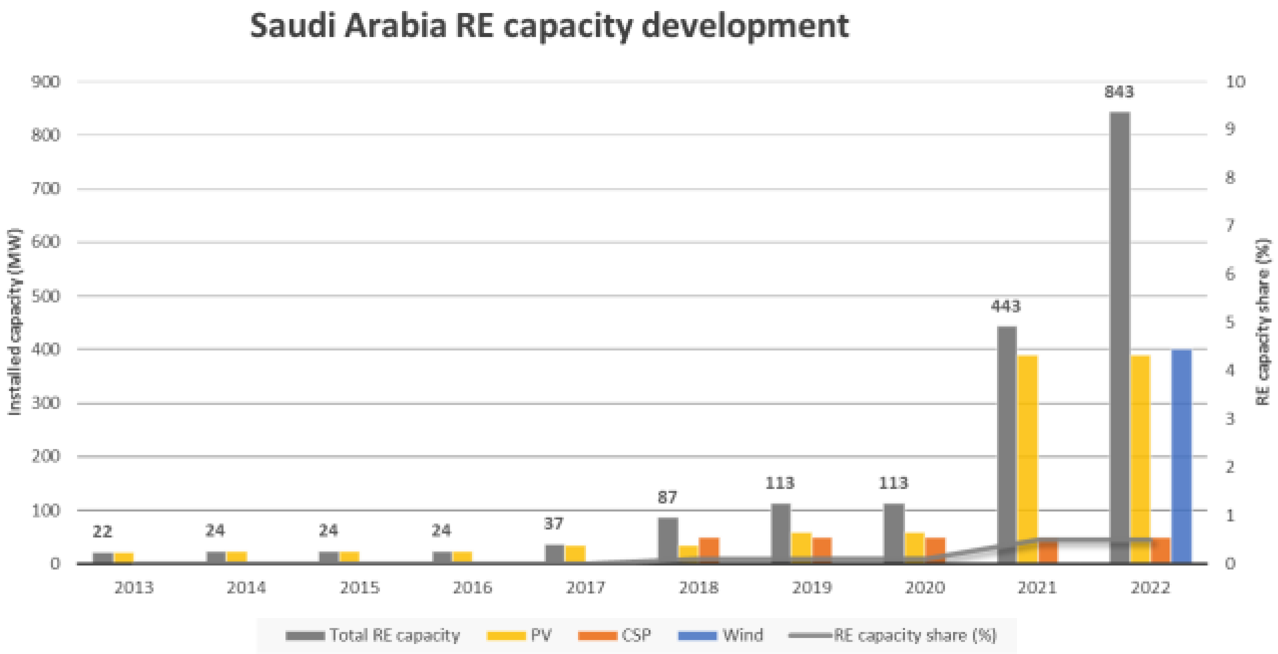


Figure 16 Saudi Arabia 2013-2022 renewable energy capacity development (IRENA 2023c)

The national renewable energy strategy as part of the "*Saudi Vision 2030*" foresees a renewable energy share in the countries' electricity generation mix of ca. 50% until 2030 and aims at full carbon neutrality until 2060 (Ministry of Energy of Saudi Arabia 2021b). Key pillars of the strategy, besides a massive rollout of renewable energy technologies, are the replacement of liquid fuels with natural gas (by 2030) as well as the widespread implementation of carbon capture use and storage (CCUS) technologies as part of the national circular carbon economy program (Ministry of Energy of Saudi Arabia 2021a). Besides the latest wind energy developments in Dumat Al-Jandal, various PV projects with an aggregated capacity of over 3GW (3,270 MW) are currently in the pipeline for development in the near term (Ministry of Energy of Saudi Arabia 2023). Against the background of the latest RE capacity increases (cf. Figure 16) as well as the proclaimed ambitious deployment plans, it can be expected that the Saudi Arabian renewable energy market will experience a stark development push in the coming years.

The development of the PtX sector plays a major role in the Saudi Arabian strategy for economic diversification, and the country strives to become a globally leading supplier of green hydrogen and PtX products on the market as a reaction to the declining global crude oil demand. By 2030, Saudi Arabia aims at a production of blue (based on natural gas combined with CCUS) and green hydrogen of 2.9 million tons per year and 4 million tons per year by 2035. The country's flagship project, Neom City, will feature a green hydrogen project with a renewable energy capacity of 4GW for the production of 1.2 million tons of green ammonia per year, which will make it the largest green hydrogen facility in the world. The 8.4 billion US$ project is expected to commence production by the end of 2026 (NEOM 2023). As part of its circular carbon economy program, the country can also build on its experience in the field of carbon capture and storage (CCS) and CO2 to chemicals, which has been proven in various projects, such as the Jubail CCUS facility, which captures CO2 from an ethylene glycol production facility from which it is transported via pipeline and used for methanol, urea and polycarbonate production (Rizvi 2022). Further, CCUS facilities are currently under development in Jubail, which will become a major CCUS hub in the eastern part of Saudi Arabia. The project is expected to capture up to 9 million tons of CO2 annually after its completion in 2027 (ARAMCO 2023). The expertise in the field of CCUS can be considered highly relevant for the development of a PtX sector.

Also, initial strategic partnerships for the trade of PtX products exist, for example, with Japan, which received its first shipment of 40 tons of independently certified blue ammonia in 2020 or with South Korea, which received its first shipment of blue ammonia in 2022 (ARAMCO 2023). In 2021, a partnership agreement on green hydrogen has also been signed with Germany. However, no specific targets for the trade of PtX products have been formulated yet (Staff 2021).

Nigeria

Nigeria's energy mix in the electricity sector predominantly relies on fossil fuels, specifically oil and natural gas (see Figure 17). The country does possess some hydropower capacity (IRENA 2023b). In 2022, RES accounted for 17% of the installed capacity in the region. This area's primary RE source is derived from large-scale hydroelectric power generation. Notably, there is an absence of grid-connected wind energy infrastructure in the region. The development of grid-connected photovoltaic capacities has been limited and characterized by slow progress over the past decade, with an average annual growth rate of +30% in installed capacity from 2014 to 2022 and a more recent average of +13 MW per year, equating to a +24% annual increase (IRENA 2023b). The region also features small-scale biomass power plants, primarily utilizing materials such as bagasse and other agricultural waste products. In rural areas, off-grid RE capacity is predominantly harnessed through solar-powered mini-grids and standalone PV modules, with a lesser presence of biomass-based power generation facilities (IRENA 2023b).

Nigeria's national decarbonization strategy is laid out in the Nigeria Energy Transition Plan (ETP), which defines the target of reaching carbon neutrality by 2060 (Government of Nigeria 2022). One of the core objectives of the ETP is, in particular, the elimination of diesel generators for both centralized and decentralized power generation until 2050. The key strategy to achieve the shift away from fossil fuels is the massive expansion of solar PV in combination with battery storage. However, in addition to renewable energy, natural gas is seen as an important transition fuel to ensure the reliable provision of baseload power, implying increasing gas-based generation capacities until 2040. The electricity demand in the centralized power grid is projected to grow significantly from 61 TWh/a in 2020 to over 532 TWh/a by 2050, whereas the decentralized electricity demand is expected to grow moderately from 15 TWh/a in 2020 to 24 TWh/a in 2050. In order to meet this strongly growing electricity demand and to reach the target of universal electricity access for the growing population by 2030, massive generation capacity increases will be required. It is expected that 6.3 GW of decentralized renewable capacity and 42 GW of overall operational grid capacity will be needed to ensure universal electricity access by 2030. For 2050, 197 GW of installed solar PV capacity is projected to replace all diesel generators. By 2060, the ETP foresees 250 GW of PV and 112 GW of storage capacity (Government of Nigeria 2022).

In light of the observed moderate PV capacity developments over the past decades (cf. Figure 18), the massive capacity additions needed to reach the targets stated in the ETP seem challenging. The Nigerian government estimates the investment volumes required for the energy transition at 1.9 trillion US$ until 2060 (10 billion US$ annually), with most of the investments needed for ramping up power generation and grid infrastructure development. In the course of the transition, the ETP also projects a job creation potential of up to 340,000 jobs by 2030 and up to 840,000 jobs by 2060 (Government of Nigeria 2022). In addition to the challenges related to ensuring universal electricity access for the growing population, Nigeria faces massive difficulties due to the theft of increasing volumes of crude oil from its pipelines (Eboh 2022; George 2022). The oil theft causes substantial losses of export revenues in the range of several billion US$ per year and, in recent years, even puts the country in danger of failing to meet its OECD export quotas (Orjinmo 2022). The situation is further aggravated as oil companies are starting to completely shut down production facilities due to the massive financial losses (Al Jazeera 2022). This further exacerbates the issue of economic dependency on revenues from oil exports and highlights the need for economic diversification.

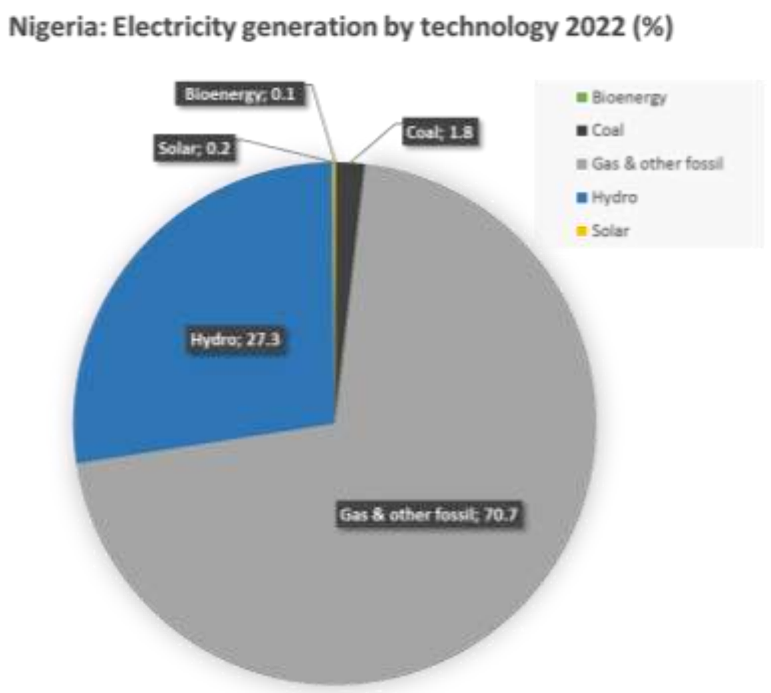


Figure 17 Nigeria's electricity generation by technology in 2022 (IRENA 2023b)

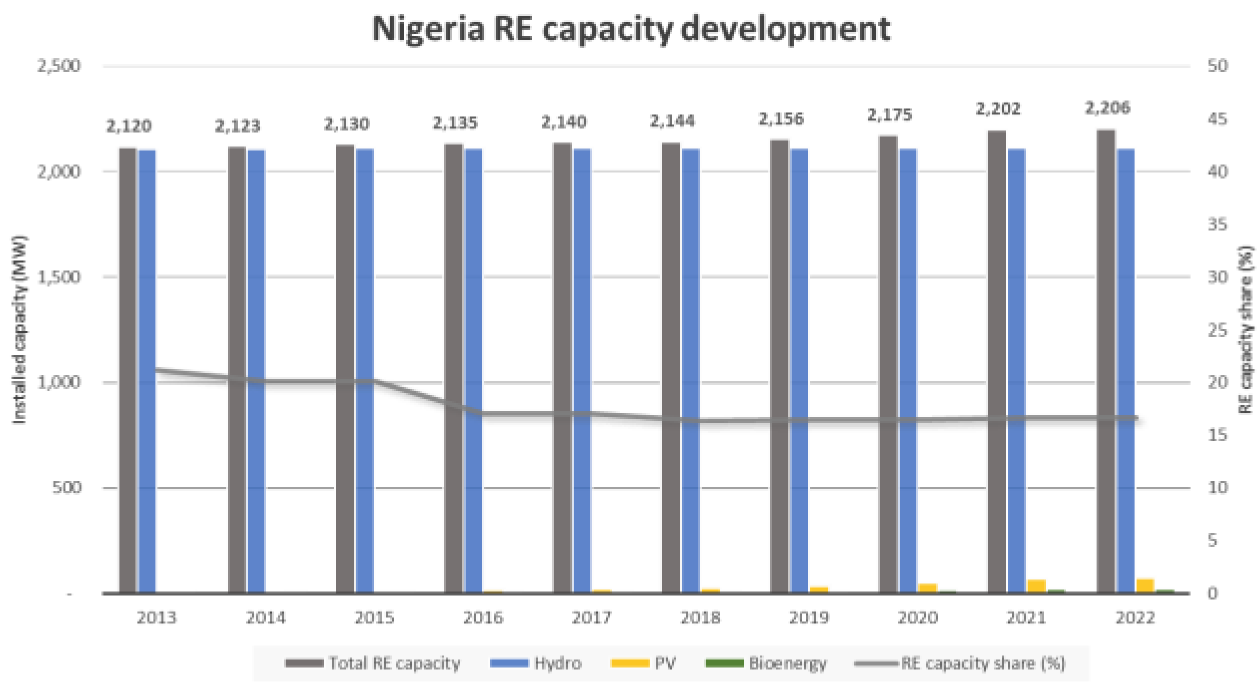


Figure 18: Nigeria 2013-2022 renewable energy capacity development (IRENA 2023b)

Nigeria has not published a designated strategy, however, in the Energy Transition Plan, it has set targets for green hydrogen and blue hydrogen. Hydrogen is foreseen as a storage technology in combination with solar PV with a target electrolyzer capacity of 5 GW until 2040 and 22 GW until 2050. Until 2050, a local demand of 46 TWh of hydrogen is foreseen (9 GW of hydrogen production capacity by 2040, 34 GW of hydrogen production capacity by 2050) (Government of Nigeria 2022). Generally, Nigeria’s mid- and longer-term economic strategy still strongly builds on the further development of the oil and gas sector and foresees the support of investments in the oil and gas sector in order to maintain and create employment opportunities in the sector (Federal Republic of Nigeria 2016; Middle East Monitor 2022; NCDMB 2020). In October 2022, the country signed a Memorandum of Understanding (MoU) for the construction of the Nigeria – Morocco gas pipeline project, which is expected to offer new opportunities for the export of natural gas along the coast from Nigeria, Benin, Togo, Ghana, Côte d’Ivoire, Liberia, Sierra Leone, Guinea Bissau, Gambia, Senegal and Mauritania to Morocco and from there to Europe. The construction of the pipeline is expected to take about 25 years (Middle East Monitor 2022). Another planned project is the Trans-Sahara Gas Pipeline, which runs from Nigeria to Algeria, where it could be connected to the existing pipelines to Europe. A new MoU was signed in 2022 after an earlier agreement from 2009 was not realized due to safety concerns (Global Energy Monitor 2023b). A hydrogen cooperation agreement has been established with Germany in the frame of the existing energy partnership between the countries. A hydrogen office was inaugurated in Abuja in 2021 but no specific targets or measures have been published in the frame of this cooperation yet (Nigerian Investment Promotion Commission 2022). On a regional level, the Economic Community of Western African States (ECOWAS) has published and adopted a 'Green Hydrogen Policy and Strategy Framework' for its 14 Member States in July 2023 which emphasizes the region's abundance in competitive renewable energy resources and states a regional production target of at least 0.5 million tons of green hydrogen per year by 2030 and 10 million tons/year by 2050. The study also highlights the potential for the local use of green hydrogen in the domestic industries present in the Member States, such as the chemical and petrochemical industry, fertilizer production and iron and steel industries in Nigeria. The ECOWAS strategy foresees the development of at least 3 green hydrogen clusters in the region until 2025 implying the implementation of at least 5 green hydrogen production projects in these clusters by 2026. (ECOWAS 2023)

3.1.2 Broader socio-economic framework conditions affecting the development of a future PtX sector

The conditions for renewable energy project development and project financing are further influenced by a range of factors that impact the risks associated with the project implementation and thereby affect the cost of financing and, thus, the economic competitiveness of the projects. Particularly relevant factors in this regard are general political and regulatory risks, currency risks and inflation rate, as well as risks associated with administrative procedures (e.g. related to permitting and land acquisition) and the general business environment (cf. also Table 9 in the Annex). A selection of some of the key indicators is compiled in Table 5.

Table 5 Selected indicators for political stability and conditions for economic activities in the case study countries

Indicator	Nigeria	Saudi Arabia	Kazakhstan
Political Stability Index (2023) 9 (Haken et al. 2023)	Score 98 (alert)	Score 65.3 (warning)	Score 60.6 (warning)
Corruption Perceptions Index (2022) 10 (Transparency International 2022)	Score 24 (fairly high level)	Score 51 (medium level)	Score 36 (high to medium level)
National credit rating (S&P) (Trading Economics 2023a)	B- (highly speculative)	A (upper medium grade)	BBB- (lower medium grade)
National Bank interest rate (2023)	18.75% (CBN 2023)	6% (Trading Economics 2023b)	16.75% (National Bank of Kazakhstan 2023)
Ease of Doing Business Index 11 (2020) (World Bank 2020)	Rank 131 (Score 56.9)	Rank 62 (score 70.9)	Rank 25 (score 79.6)
Inflation, annual, consumer prices (2022) (The World Bank 2023)	18.8%	2.5%	8%
GDP (current US$, 2022)(The World Bank 2023)	477.39 bn US$	1,108.15 bn US$	220.62 bn US$
GDP per capita (current US$, 2022) (The World Bank 2023)	2,184.4 US$	30,436.3 US$	11,243.7 US$
GDP growth (% per year, 2022) (The World Bank 2023)	3.3%	8.7%	3.2%

The indicators show that all three countries face some challenges when it comes to the framework conditions for business development. Particularly high political and economic risks can be observed, especially in Nigeria, which are reflected in less favorable conditions for economic activities in general and for financing in particular. According to the Central bank of Nigeria, the prime lending rate to the private sector in July 2023 was 13.98% (CBN 2023). Kazakhstan also faces some difficulties when it comes to financing but has slightly better conditions for overall business development. Saudi Arabia is characterized by comparatively stable economic conditions reflected in lower capital costs.

The above trends are further supported by data published on Weighted Average Costs of Capital (WACC) for renewable energy projects globally reported by IRENA (2023d) and IEA (2022a). For example, IRENA (2023d) indicates a WACC (based on 2019-2021 data) of 12.2% for Ukraine (as a country comparable to Kazakhstan) 9.7% for Egypt and 10.7% for Tunisia, 9.1% for Morocco and 9.6% for Yemen. A regional average for the Middle East and Africa is given as 7% for wind energy and 8.5% for PV. The country specific WACCs used for the subsequent modelling are given in Table 11 in the Annex.

9 Note: Score between 0 and 120, maximum score of 120 indicating a highly fragile and unstable situation
10 Note: perceived level of public sector corruption, a score of 100 means “very clean” a score of 0 means “highly corrupt”
11 Note: The score evaluates the general business climate based on a variety of indicators measuring the framework conditions for starting and operating businesses. The score ranges from 0-100 and ranks 190 countries.

3.2 Techno-economic potential and infrastructure for renewable energy deployment

The assessment of generation potential and infrastructure in the three focus countries involves a structured methodology consisting of three key steps. First, an evaluation of renewable energy potential is conducted using GIS data sets, such as the Global Solar Atlas (2023) and the Global Wind Atlas (2023). These datasets provide valuable information, including the full load hours (FLH) of PV and wind (class IECIII at 100 meters), measured in MWh/MW per year. When assessing the results, it should be noted that the data sets may have some local inaccuracies due to their global coverage. In particular, the wind potential data used may overestimate wind speeds, see (Duc et al. 2022) and FLH to some extent. Secondly, infrastructure analysis is undertaken, encompassing critical components like transportation networks (roads and ports), desalination plants, power facilities, and pipelines. To support this analysis, data is sourced from the World Bank Open Data (2023b) and the Global Energy Monitor (2023a). The third step involves the identification of excluded areas based on selected specific criteria, including high population density exceeding 100 inhabitants per square kilometer, steep terrain with slopes greater than five degrees, specific land cover types (e.g., forests, urban areas, water bodies), and the presence of protected areas. These datasets are collected from sources such as the US Geological Survey USGS (2023), information on protected areas, Copernicus Global Land Service (2023) data, and WorldPop (2023) population data. This methodological framework ensures a comprehensive assessment of both renewable energy potential and the existing infrastructure while also considering exclusion criteria based on geographic and environmental factors.

3.2.1 Renewable energy potentials

Kazakhstan

The study of Kazakhstan's renewable energy potential shows notable solar potential in lower-medium ranges and wind energy exhibiting above-average potential. Solar PV potential is at its peak in southern Kazakhstan, where it reaches around 1500 MWh/MW per year. In contrast, the highest wind potential is found along the Caspian Sea coast, with full load hours of around 4500 MWh/MW per year (Figure 19 and Figure 20).

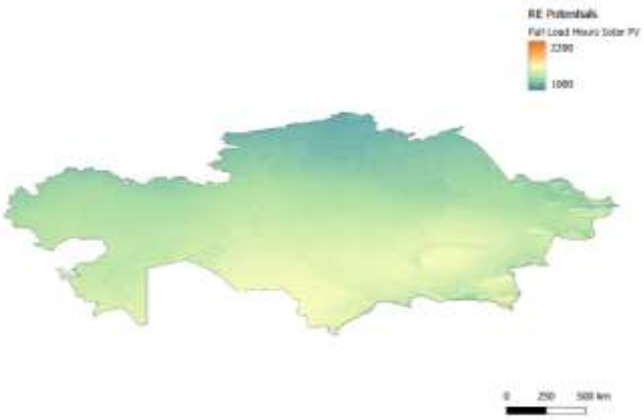


Figure 19: Solar energy potential in Kazakhstan in MWh/MW per year (Global Solar Atlas 2023)

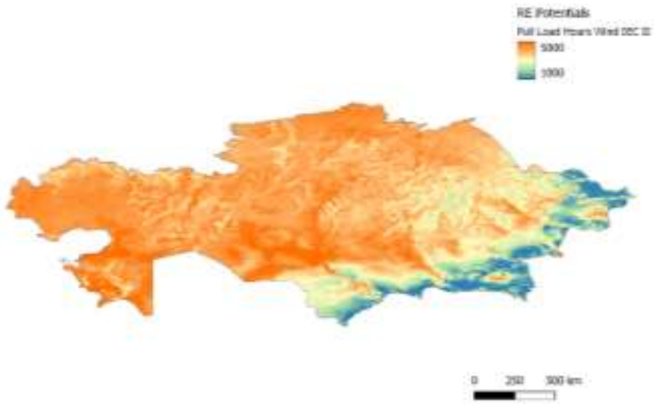


Figure 20: Wind energy potential in Kazakhstan in MWh/MW per year (Global Wind Atlas 2023)

Saudi Arabia

The solar potential in the region largely surpasses the global average, showcasing an abundance of sunlight. Solar-PV potential is highest in the north of Saudi Arabia in Tabuk and Al Jouf regions, where the annual solar exposure can reach 2200 MWh/MW per year (Figure 21). The highest wind potential is situated in the western and southwestern areas, along the Red Sea coast, the Red Sea coastline and parts of the Asir Province. These areas experience strong and consistent winds, making them suitable for wind energy generation, which has the potential to reach above 3000 MWh/MW per year (Figure 22).

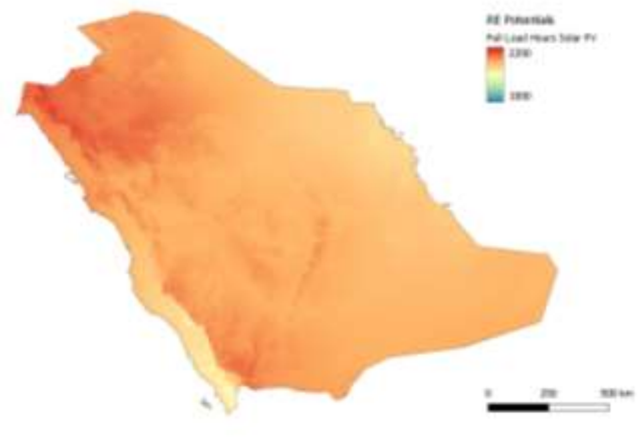


Figure 21: Solar energy potential in Saudi Arabia in MWh/MW per year based on (Global Solar Atlas 2023)

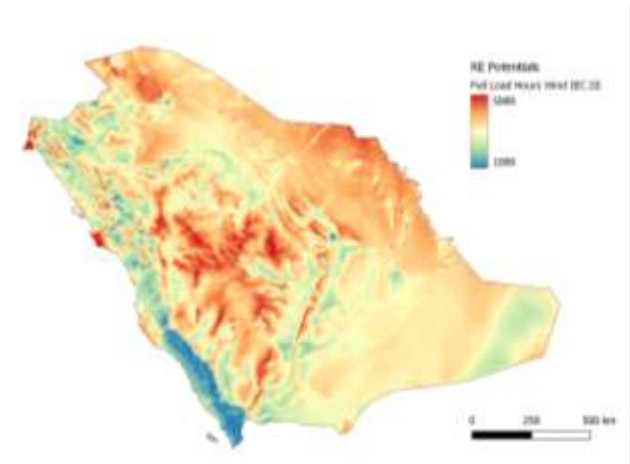


Figure 22: Wind energy potential in Saudi Arabia MWh/MW per year based on (Global Wind Atlas 2023)

Nigeria

Nigeria exhibits a comparatively high solar potential, boasting ample sunlight for solar energy generation in the north and central north regions, with FLH reaching 2000 MWh/MW per year (Figure 23). Wind potentials are overall rather low, with some exceptions in the northern regions such as Sokoto, Kano, and Borno, where they can reach up to 3000 MWh/MW per year (Figure 24). In Nigeria, hydro and geothermal power could also serve as a complementary renewable baseload option. However, this was not included in the GIS analysis due to a lack of available data to spatially quantify the potential. In addition, there are concerns about the sustainability of largescale hydropower projects, which should not be neglected, especially with regard to the export of green PtX products.

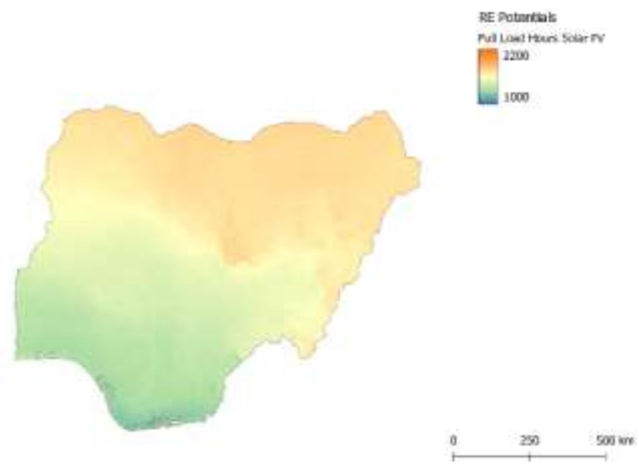


Figure 23: Solar energy potential in Nigeria in MWh/MW per year (Global Solar Atlas, 2023)

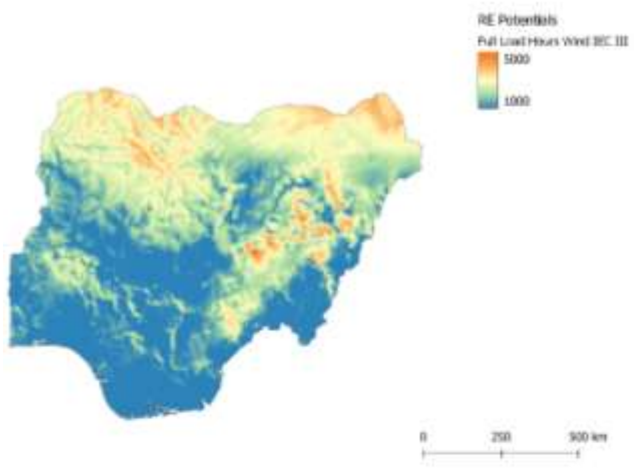


Figure 24: Wind energy potential in Nigeria

A GIS analysis was conducted to better assess the wind and solar energy generation potential and energy infrastructure. It consisted of three steps designed to determine suitable areas for renewable energies and PtX expansions. The analysis will eventually be utilized in the estimation of the Levelized Cost of Electricity (LCOE) and Levelized Cost of Hydrogen (LCOH) per technology per country. Based on the analysis of renewable energy potential, the study will specifically concentrate on solar-PV energy generation for Saudi Arabia and Nigeria, while wind energy potential will be the primary focus for Kazakhstan.

3.2.2 Infrastructure and excluded areas

Kazakhstan

Potential hydrogen infrastructure development in Kazakhstan involves repurposing established natural gas pipelines. Kazakhstan is actively improving its maritime infrastructure, especially in the Caspian Sea region. Notably, ports like Aktau have seen significant upgrades to facilitate trade and shipping. The excluded areas are situated in the southeast regions (Figure 27).

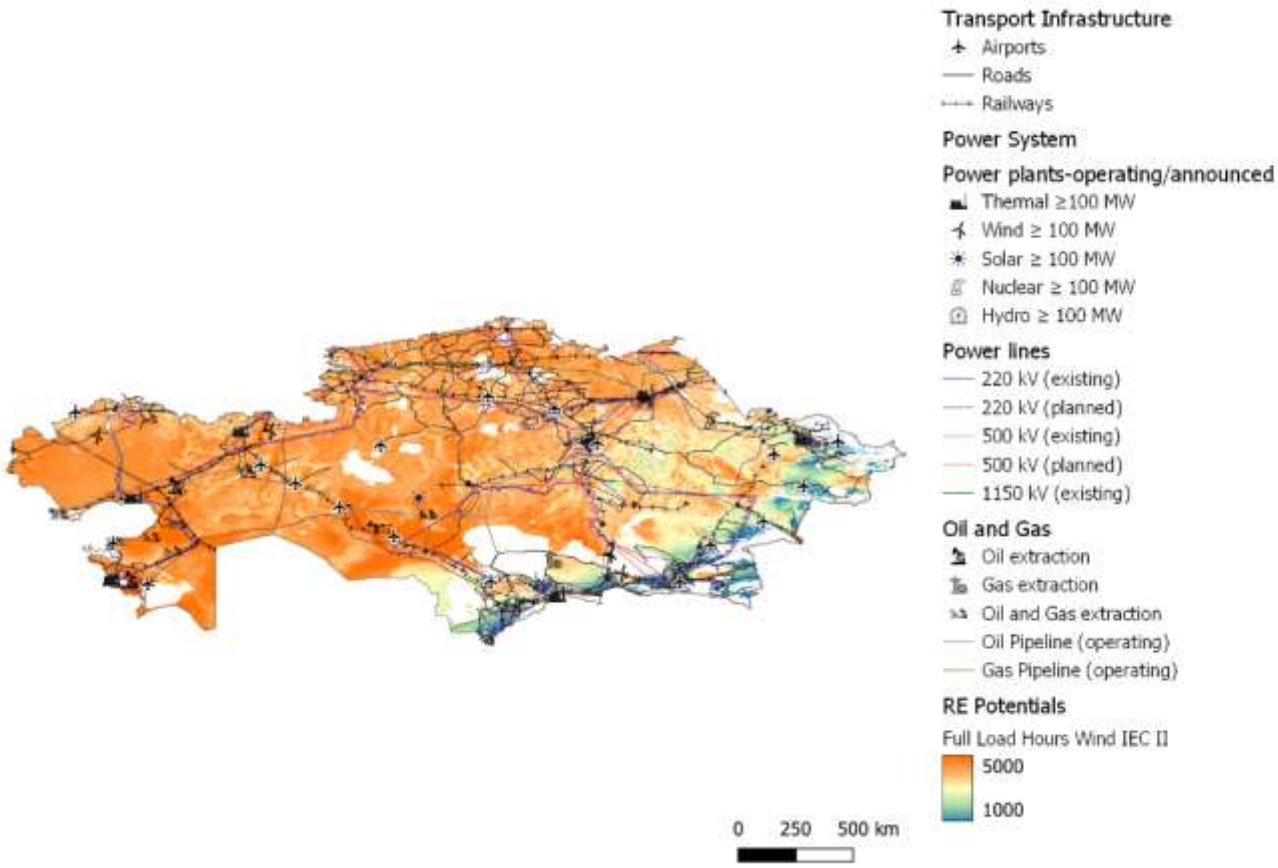


Figure 25: GIS analysis-Wind FLH-Excluded area-Kazakhstan

Saudi Arabia

Saudi Arabia has a well-established and extensive inland network of pipelines for transporting natural gas, which might be repurposed for transporting hydrogen. The country boasts well-developed ports, such as those along the Red Sea and the Persian Gulf and has an extensive network of highways and roads that facilitate the efficient movement of goods and materials. The excluded areas are sited in the north due to protected areas, and along the coast due to slope restriction and highly dense urban areas with more than 100 habitants per km² (Figure 26).

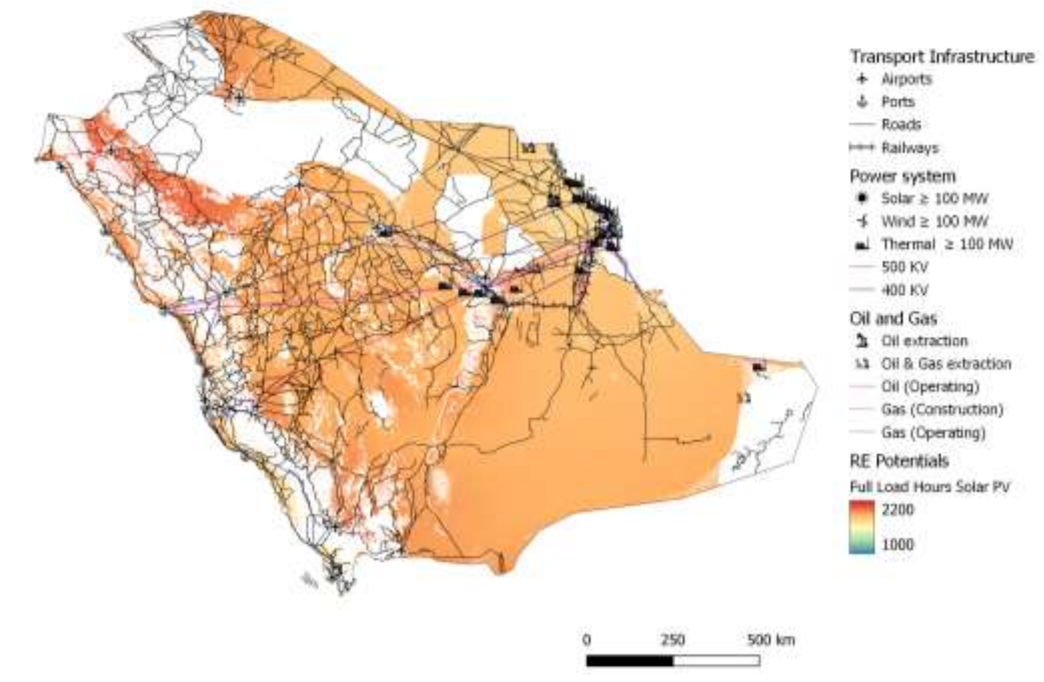


Figure 26: GIS analysis-Solar FLH-Excluded-Saudi Arabia

Nigeria

In Nigeria, the current infrastructure is more developed in the south, though expansion plans for the gas and electricity sectors are in place, including in the north of the country. Thermal power plants are mainly in the south, while significant hydropower facilities are in the central and western regions. However, constraints like land cover, population density, protected areas, and terrain slope limit renewable energy expansion especially in the south of the country (Figure 27).

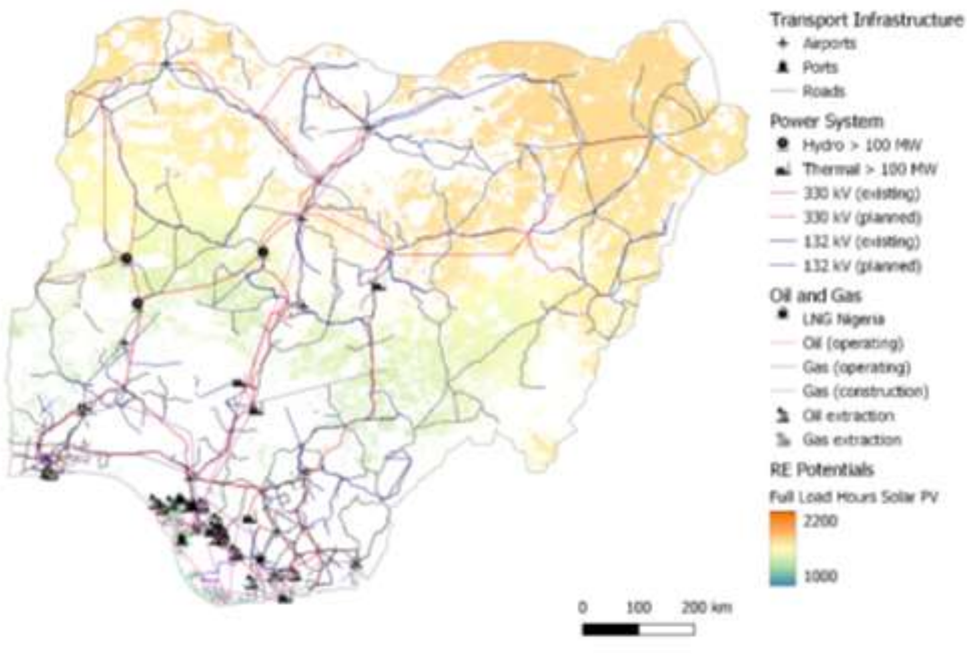


Figure 27: GIS analysis-Solar FLH-Excluded area-Nigeria

3.3 Generation costs for renewable electricity and PtX products

3.3.1 PtX product export costs and transport options – Modelling Tool

By the help of a modelling tool the analysis of landing costs, including generation and transport, across different fuels, generation technologies, and timeframes is possible. The impact of input parameter variations (CAPEX, lifetime, WACC, and efficiency, with the option to use default values or customize parameters as needed) was explored. The tool calculates total landing costs in 2021 USD/MWh for various fuels: gaseous hydrogen (GH2), liquefied hydrogen (LH2), methanol (MeOH), and ammonia (NH3) with projections for 2030 and 2050. Key inputs include full load hours for PV and wind, WACC, total transmission distance, and the percentage of new pipelines built versus repurposed pipelines, if applicable.

Utilizing the modelling tool, the LCOE for Hydrogen across various technologies was determined, accounting for different default sensitivities. The Optimistic scenario is defined by a +20% CAPEX, a reduction of 5 years in lifetime, a -3% WACC, and a +3% efficiency improvement. Conversely, the Pessimistic scenario is characterized by a -20% CAPEX, a reduction of 5 years in lifetime, a -3% WACC, and a -3% efficiency decrease.

Kazakhstan

The LCOH-Wind values, as determined through GIS analysis, hover at approximately 80 USD/MWh in 2030 and 50 USD /MWh in 2050. These costs are generally consistent across most of Kazakhstan, with the exception of the southeast region, where costs are notably higher. This disparity aligns with the area's lower wind potential compared to the rest of the country. The values used for calculating the total landing costs of various fuels in Kazakhstan include FLH for solar PV at 1533 h/year, FLH for Wind at 4680 h/year, a WACC of 11%, and a distance of 5500 km assuming pipeline transport for gaseous hydrogen. Notably, the costs are lower for wind technology when compared to solar PV.

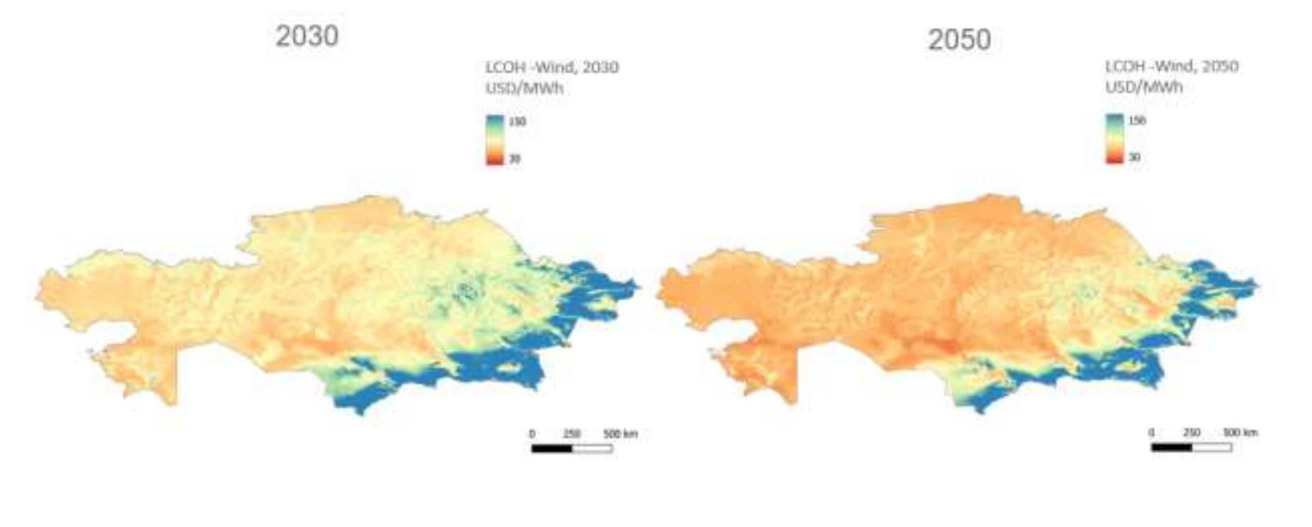


Figure 28: LCOH-Wind maps for KAZ in 2030 and 2050

In the scenarios for 2030 and 2050, MeOH-PV exhibits the highest costs at 249 USD/MWh and 143USD/MWh, respectively. Conversely, GH2-Wind demonstrates the lowest costs at 130 USD/MWh for 2030 and 101 USD/MWh for 2050. These costs are attributed to factors such as transport, hydrogen generation, and electricity generation (see Figure 29).

A summary of the LCOE-hydrogen-wind under pessimistic and optimistic scenarios for 2030 and 2050 is presented in Figure 30. The base cost for 2030 is around 80 USD/MWh, and it is around 45 USD/MWh in 2050.

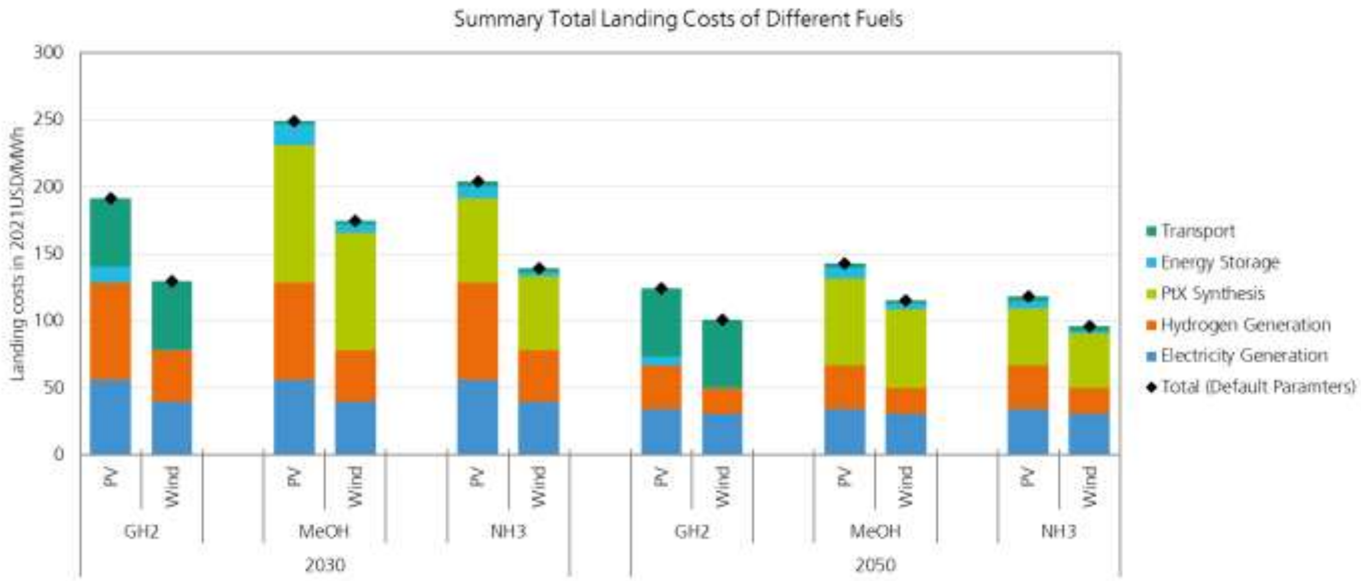


Figure 29: Summary total landing costs of different fuels in KAZ

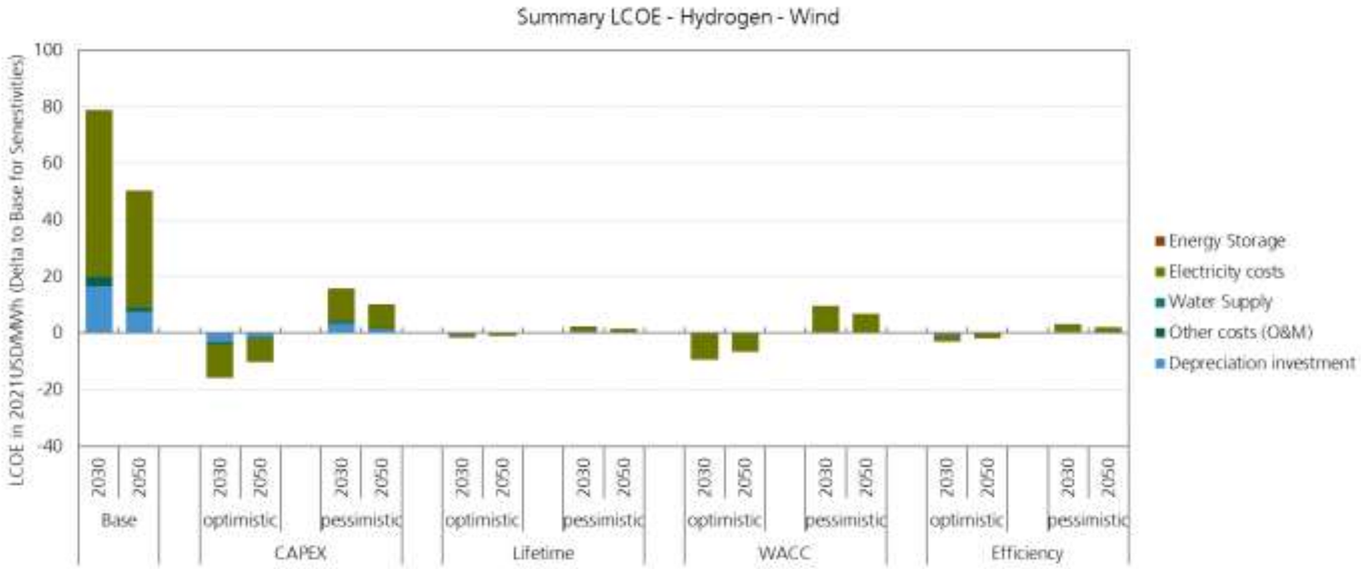


Figure 30: Summary LCOE-Hydrogen-Wind in KAZ

Saudi Arabia

The GIS analysis, Figure 31, shows the evolution of LCOH-Solar PV from 2030 to 2050. During this period, it decreased strongly, starting at approximately 80 USD/MWh and eventually stabilizing at around 40 USD/MWh.

To estimate the landing costs of LH2, MeOH, and NH3 in Saudi Arabia, based on the GIS analyses, the FLH for solar PV was set at 2070 h/year and for wind at 3100 h/year. We employed a WACC rate of 7% specific to Saudi Arabia and assumed a shipping distance of around 7800 km[12]. Notably, the costs are lower using solar PV. The analysis revealed that NH3 using PV for electricity generation represented the most cost-effective option, with a landing cost of 117 USD/MWh for the 2030 scenario, while the highest cost was associated with MeOH production using wind turbines as a power source at 195 USD/MWh. Similarly, in the 2050 scenario, NH3 maintained its cost advantage at 69 USD/MWh, with MeOH following at 129 USD/MWh, Figure 32.

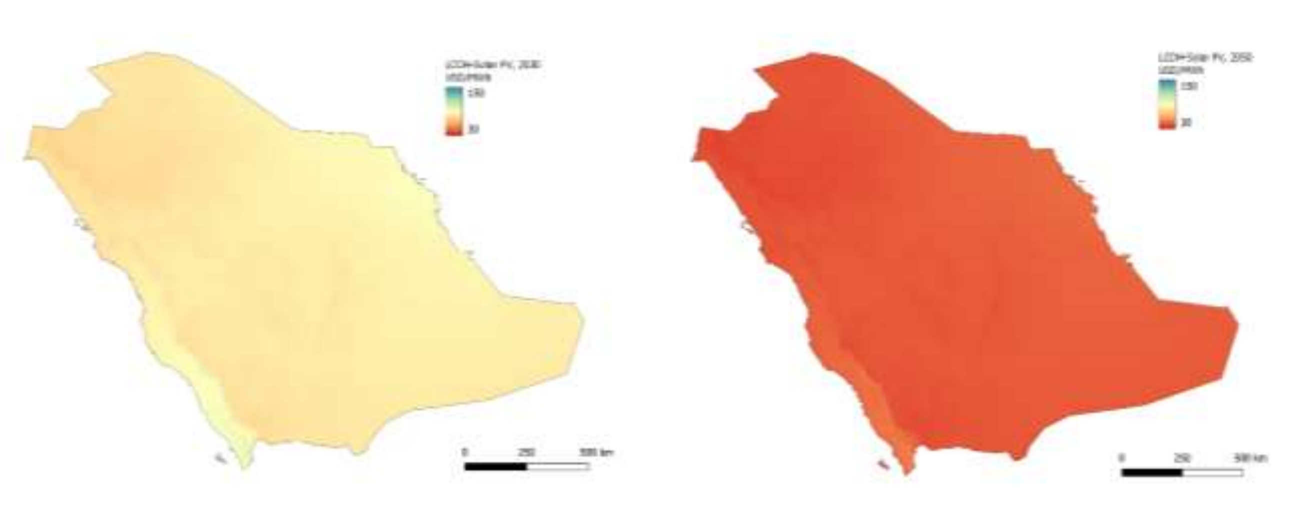


Figure 31: LCOH-Solar PV maps for SAU in 2030 and 2050

Figure 33 shows that changes in CAPEX and WACC have the most significant impact on LCOE. Electricity costs are the biggest component of LCOE for most scenarios. The LCOH values align with those presented in the GIS analysis depicted in Figure 31.

12 Distance from Dschidda to Brunsbüttel derived from https://sea-distances.org/

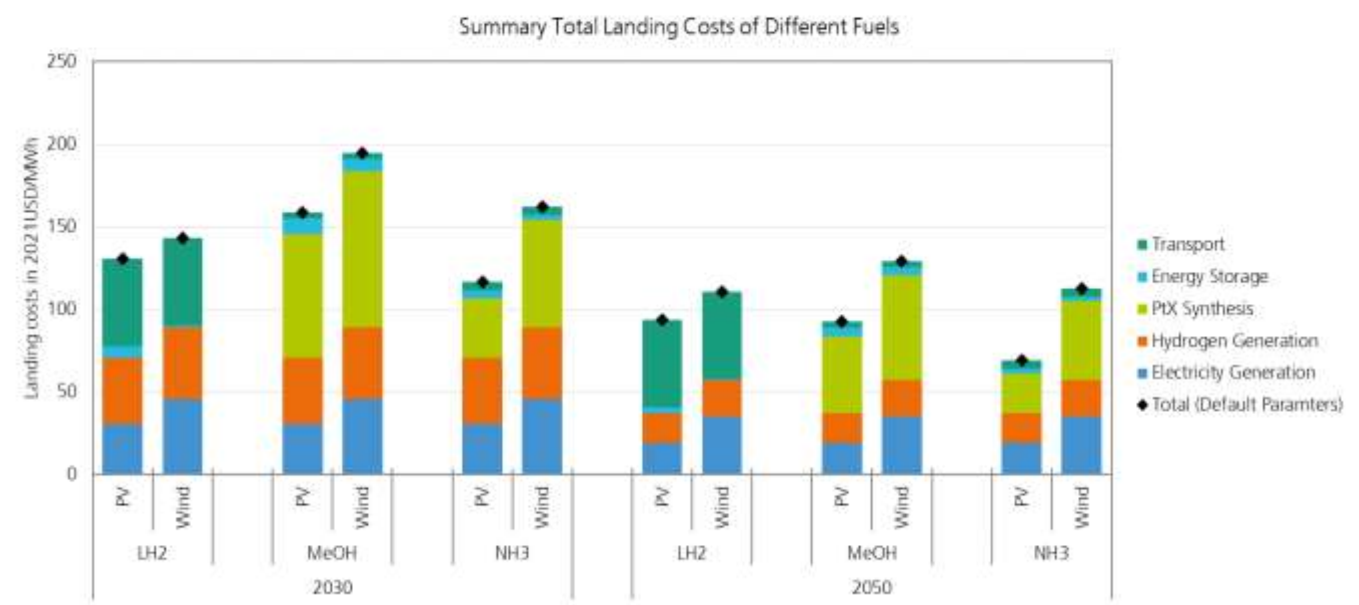


Figure 32: Summary of total landing costs of different fuels in SAU

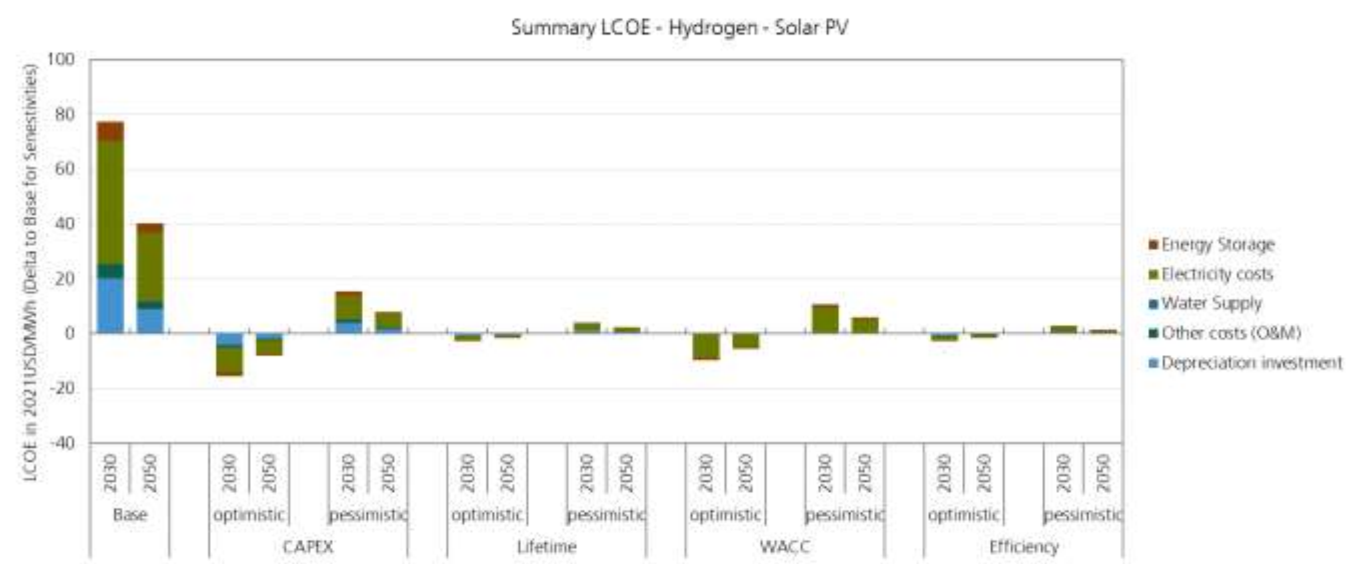


Figure 33: Summary LCOE-Hydrogen-Solar PV in SAU

Nigeria

In Nigeria, the LCOH-Solar PV for the year 2030 falls within the highest bracket, ranging from approximately 120 to 150 USD/MWh. However, in the 2050 scenario, costs decrease strongly, nearly halving to around 60 USD/MWh. Notably, the LCOH is lower in the northern regions of the country, Figure 34. In the Nigeria analysis, the inputs applied in the tool for computing landing costs include a solar PV potential of 2000 h/year, 3000 h/year for wind power, a WACC of 13%, and a shipping distance of 8126 km. Given the current extensive use of biomass for energy purposes in Nigeria, it is assumed that the resulting biogenic CO2 can be used for methanol production at a cost of 15-30 USD/tCO2, as indicated by IEA (2020). This potentially gives Nigeria a competitive advantage for methanol production in contrast to SAU and KAZ, where the cost of direct air capture is estimated to be much higher at 90-150 USD/tCO2.

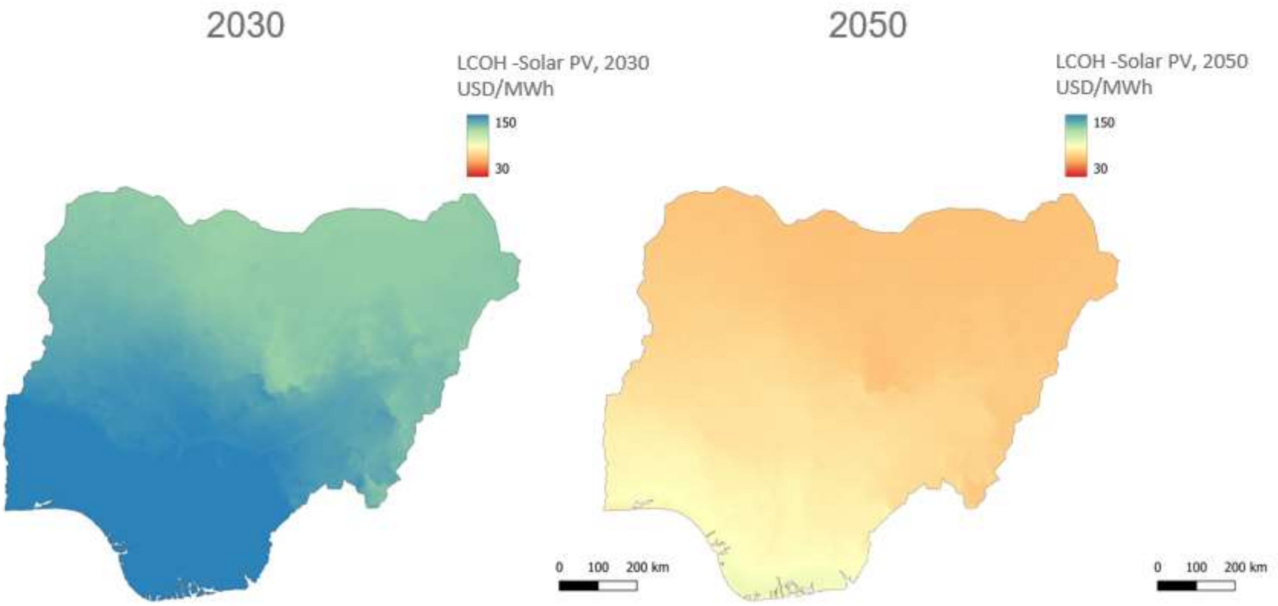


Figure 34: LCOH-Solar PV maps for NGA in 2030 and 2050

Landing costs of different fuels for Solar-PV technology are generally cheaper than those generated with wind technology. MeOH-wind and NH3-wind are the costliest, around 244 USD/MWh, while LH2-PV is the least expensive at 176 USD/MWh in 2030. In the 2050 scenario, NH3-PV is the most affordable at 105 USD/MWh. Transport costs strongly impact LH2 costs, while PtX synthesis is crucial for MeOH and NH3. The base LCOE-Hydrogen using solar PV technology in 2030 is around 120 USD/MWh. By 2050, the LCOE is reduced to almost 65 USD/MWh.

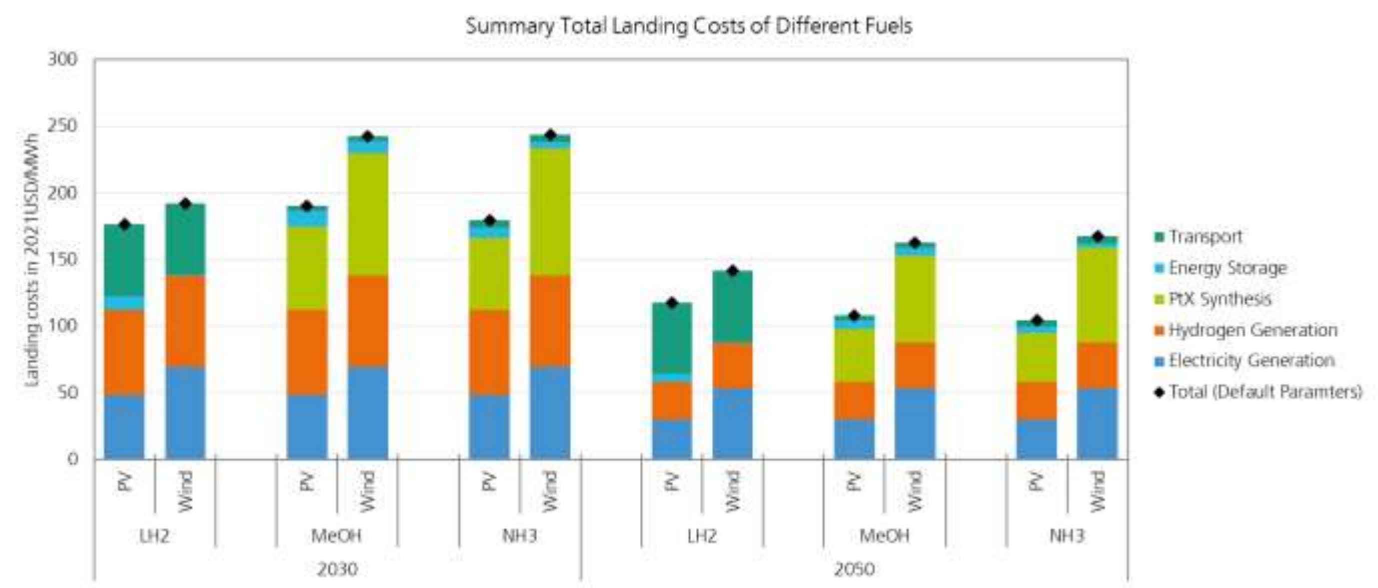


Figure 35: Summary total landing costs of different fuels in NGA

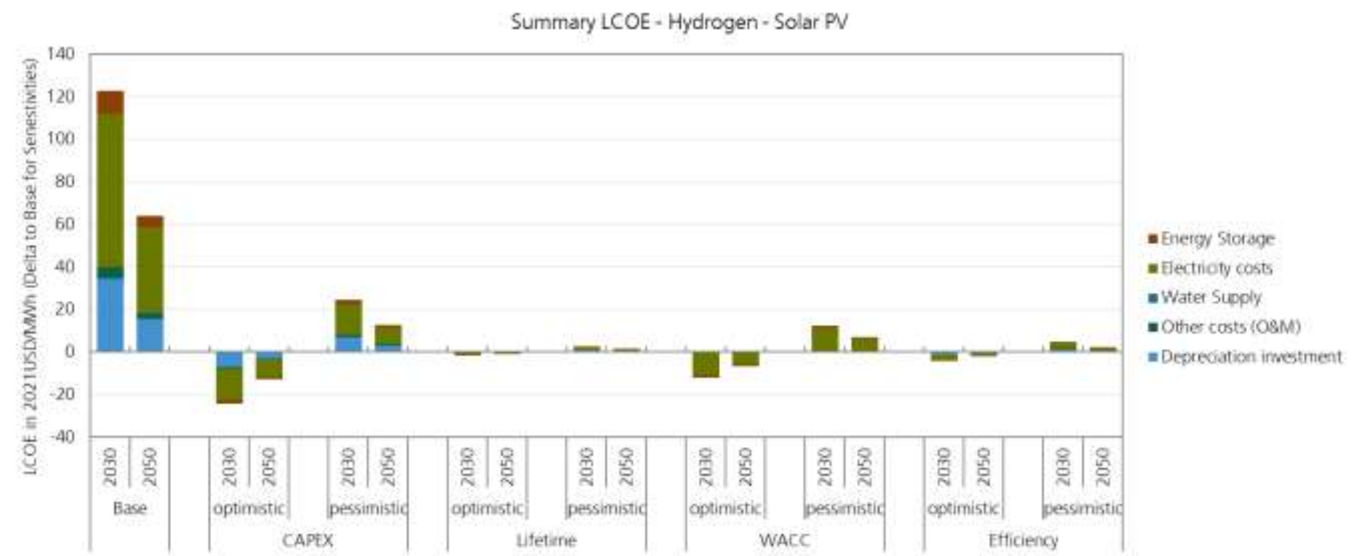


Figure 36: Summary LCOE-Hydrogen-Solar PV in NGA

3.4 Export potentials for PtX products

3.4.1 Projection of future energy demand

To derive an estimation of the export potential for green hydrogen and its derivatives, the development of the local energy demand in the respective production countries must be taken into account. For this purpose, projections are derived based on a top-down approach using historical statistics and forecasts for the development of key factors affecting the national energy demand. The development of the national GDP is regarded as the main driver of the energy demand. For this analysis, the GDP forecasts from the "sustainable development" scenario of the "Shared Socioeconomic Pathways" (SSP) (Koch et al. 2022) are used. Further key factors comprise the development of the energy intensity and the shares of fuel types used for energy generation. Here, historical data on final energy consumption are based on data published by the International Energy Agency (IEA 2023). Future projections of energy intensity and fuel share draw on the "net zero emissions" scenario of the latest World Energy Outlook (IEA 2022b). The methodology does not include a detailed bottom-up representation of the different sectors and processes. The results are, therefore, to be seen as a rough estimate.

Kazakhstan

Final energy demand in Kazakhstan declined sharply after the end of the Soviet Union (1990-2000) and then increased again until 2010. Over the last 10 years, it has remained at a similar level of about 450 TWh. By 2050, the final energy demand could decrease by almost 18% to about 390 TWh due to energy efficiency improvements. Coal has been an important energy source in Kazakhstan in the past (38.6% in 2010) and needs to be replaced by renewable fuels as soon as possible to reduce CO2 emissions. Electricity accounted for 14.9% (70 TWh) of final energy consumption in 2020 and could increase to 55% (213 TWh) by 2050. After 2030, hydrogen could also be used as a substitute for fossil fuels in certain sectors, although its role in national energy consumption is likely to remain small.

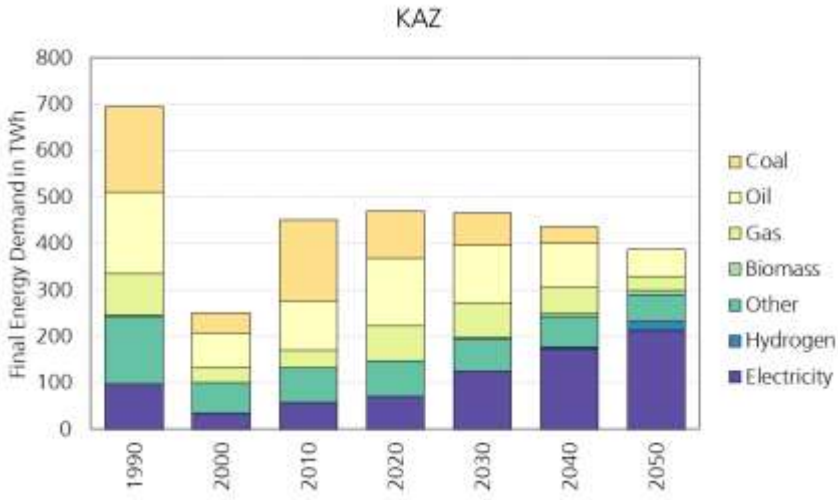


Figure 37 Development of national final energy demand in Kazakhstan by fuel (historical data from IEA (2023), future projections based on own estimates)

Saudi Arabia

Final energy demand in Saudi Arabia increased strongly to almost 2000 TWh between 1990 and 2015 but then declined moderately in recent years to 1770 TWh in 2020. By 2050, final energy demand could decrease by another 29 % to 1249 TWh. To date, oil (66.2 % in 2020) remains the most important final energy source in Saudi Arabia. However, the share of electricity in final energy consumption has steadily increased to 17.1 % (303 TWh) by 2020, overtaking gas (16.7 %) as the second most important energy source. By 2050, electricity demand could increase to almost 750 TWh, representing a 60 % share. Hydrogen could also play an increasing role in decarbonization after 2030 (5 % of final energy demand in 2040; 10 % in 2050).

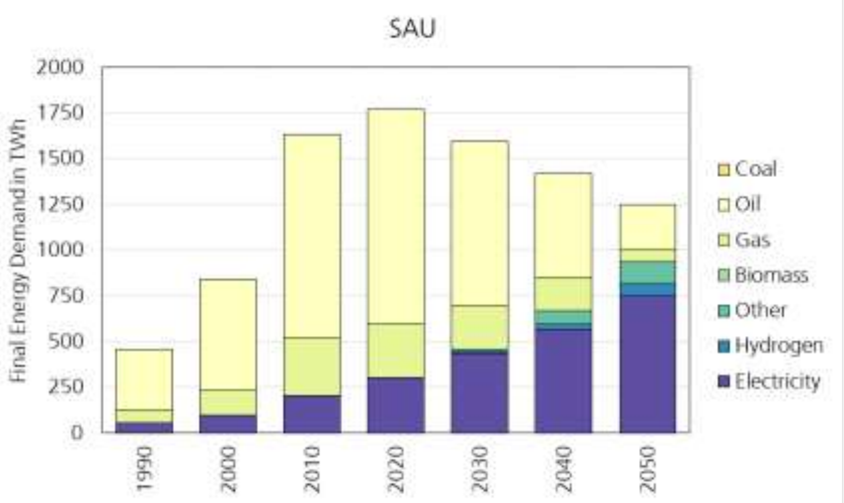


Figure 38 Development of national final energy demand in Saudi Arabia by fuel (historical data from IEA (2023) future projections based on own estimates)

Nigeria

Final energy demand in Nigeria has increased from 690 to 1586 TWh between 1990 and 2020 and could increase by another 80% to about 2850 TWh by 2050. Biomass was and is the most important final energy source in Nigeria, accounting for over 80% in 2020. In contrast, electricity accounted for only 1.8% of final energy consumption in 2020. By 2050, the share of electricity in final energy consumption could increase to 45%, which would be close to 1300 TWh, indicating how challenging the expansion of the electricity sector in Nigeria will be in the coming years. Hydrogen, on the other hand, is expected to play only a very minor role in Nigeria's energy mix by 2050.

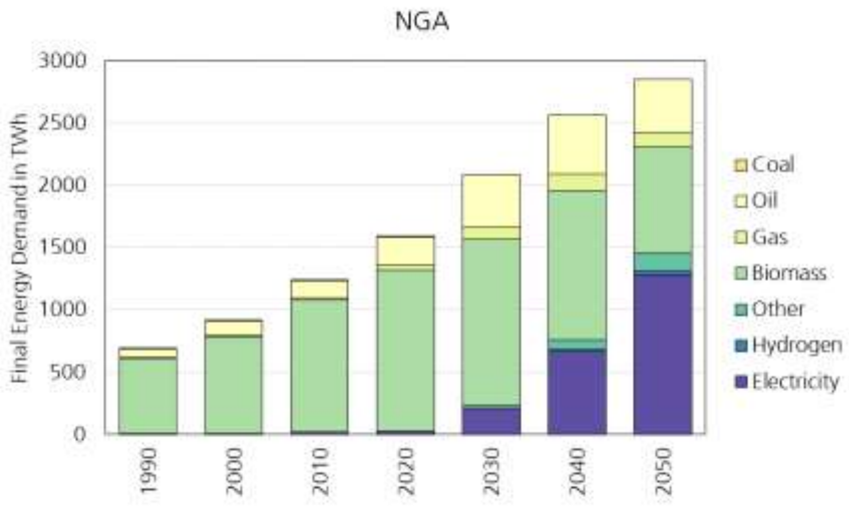


Figure 39 Development of national final energy demand in Nigeria by fuel (historical data from IEA (2023), future projections based on own estimates)

The comparison of the three countries shows the similarities, but also the differences and the resulting country specific challenges. In all countries, electricity consumption will increase strongly in the future, while renewable energies currently play only a very minor role in the electricity sector, with the exception of hydropower (cf. Section 3.1.1). Therefore, rapid expansion of renewable electricity generation is crucial for all countries, even without considering exports of green hydrogen and downstream products. However, local energy demand in Kazakhstan is already the lowest among the three countries and is expected to decline further in the future, potentially mitigating some of the conflicts between domestic renewable energy use and potential hydrogen exports. Saudi Arabia is characterized by a higher final energy demand compared to Kazakhstan but also shows a declining trend. Although the country's electricity generation is currently largely based on fossil fuels, it has increasingly implemented large-scale renewable energy projects in the last two years and defined ambitious targets for a future decarbonization of the energy system. Nigeria, on the other hand, is likely to face significant challenges with regard to the domestic electricity supply. On the one hand, final energy demand is expected to continue to increase strongly in the coming years, and on the other hand, electricity has so far played only a minor role in overall energy consumption. The combination of these two factors means that there is a particularly strong need to expand renewable power plants, which indicated potential difficulties in view of the limited expansion rates of the past.

3.4.2 Estimation of the total theoretical production potential

To estimate the theoretical production potential for green hydrogen and divide it into cost intervals, we build on the GIS analyses presented in section 3.2. The respective LCOH are combined with the maximum hydrogen production volumes resulting from the product of the electrolyzer efficiency, the RE full load hours, and the land use factors for PV (40.8 MW/km2) and wind (3.85 MW/km2).

To keep the results concise, only the cheapest production technology is used for each country. This is solar PV for Saudi Arabia and Nigeria and wind energy for Kazakhstan. In addition to RE potential, transportation costs and WACC also play an important role in the total supply cost of hydrogen. Therefore, the results of three different scenarios are presented and discussed. Scenario 1 examines the cost potential for pure generation costs in the production country with country-specific WACC. Scenario 2 additionally considers the transportation costs for hydrogen. Here, Germany is exemplarily taken as the target country, although the results would also be transferable to other consumers. Due to the lack of infrastructure and the greater distances to potential consumers, the transport of liquid hydrogen by ship is assumed for Saudi Arabia and Nigeria, while the transport of gaseous hydrogen by pipeline is considered for Kazakhstan. Scenario 3 builds on this but assumes the same WACC of 7% for all three countries. The purpose of this scenario is to highlight the importance of financing and investment conditions for the total supply costs.

Overall, it should be emphasized that the estimated theoretical potential for all countries considered is very high and exceeds both the local final energy demand and the global demand for hydrogen and e-fuels. However, the technically feasible potential is likely to be much lower and especially in the earlier years, the ramp-up will be challenging. Factors such as production and installation capacities have a limiting effect, but social acceptance also plays a role. This in turn, is strongly related to conflicts of use, both in terms of land use in general (e.g. power generation vs. agriculture) and in terms of local demand versus export.

Figure 40 shows that in terms of the pure generation costs analyzed in Scenario 1, Saudi Arabia offers a large potential at low cost. Kazakhstan has also sites with excellent wind potential where costs could be very competitive, although site-specific studies would be needed to assess this more accurately. Due to high country-specific WACC and given PV irradiation conditions the LCOH are higher for Nigeria. Under the given techno-economic assumptions, it can be assumed that, realistically the most favorable generation cost will be above 65 USD/MWh in 2030 and above 35 USD/MWh in 2050.

If, as in scenario 2, transport costs are also taken into account in addition to production costs, the supply costs for hydrogen increase considerably. For the results presented here, 53 USD/MWh are assumed for ship transport from Nigeria and Saudi Arabia, respectively, and 45 USD/MWh for pipeline transport from Kazakhstan. These values are based on estimated transportation distances and literature values. The specific transport costs differ depending on the source and underlying assumptions. In particular, for pipeline transport, the exact routing and resulting transport distance as well as the share of repurposed and new-build pipeline sections play an important role. However, the overall consensus is that transporting gaseous hydrogen via pipelines is considerably less expensive than shipping liquid hydrogen, especially for shorter distances of less than 5000 km. More detailed analyses comparing the costs of different transport options can also be found in recently published studies such as Agora Industrie (2023) and Kreidelmeyer et al. (2023).

For Saudi Arabia and especially Nigeria, where potential markets in Europe and Asia are distant and unlikely to be supplied via pipelines, this means cost disadvantages compared to competitors with more favorable locations and transportation infrastructure, even in the long term. This is also reflected in the supply costs shown (including transport costs), where Kazakhstan, based on the input data and the assumptions made, could reach cost levels of 85-90 USD/MWh in 2050. For Saudi Arabia, values range from 90-95 USD/MWh result and for Nigeria the most favorable potentials are at 120-125 USD/MWh. The costs shown are to be regarded as a lower cost range, since they do not include any domestic distribution costs and the full load hours given in the Global Wind Atlas in particular, appear to be quite optimistic compared to real existing projects.

The last scenario with the same WACC for all three countries clearly shows the influence these have on the total costs. By reducing the WACC by 4% in the case of Kazakhstan and even 6% in the case of Nigeria, the potential for both countries shift into considerably cheaper areas compared to the previous scenario. The cost advantage of Kazakhstan compared to the other two countries would thus increase, while the supply costs for Nigeria would approach those of Saudi Arabia but remain slightly more expensive due to the smaller PV potentials.

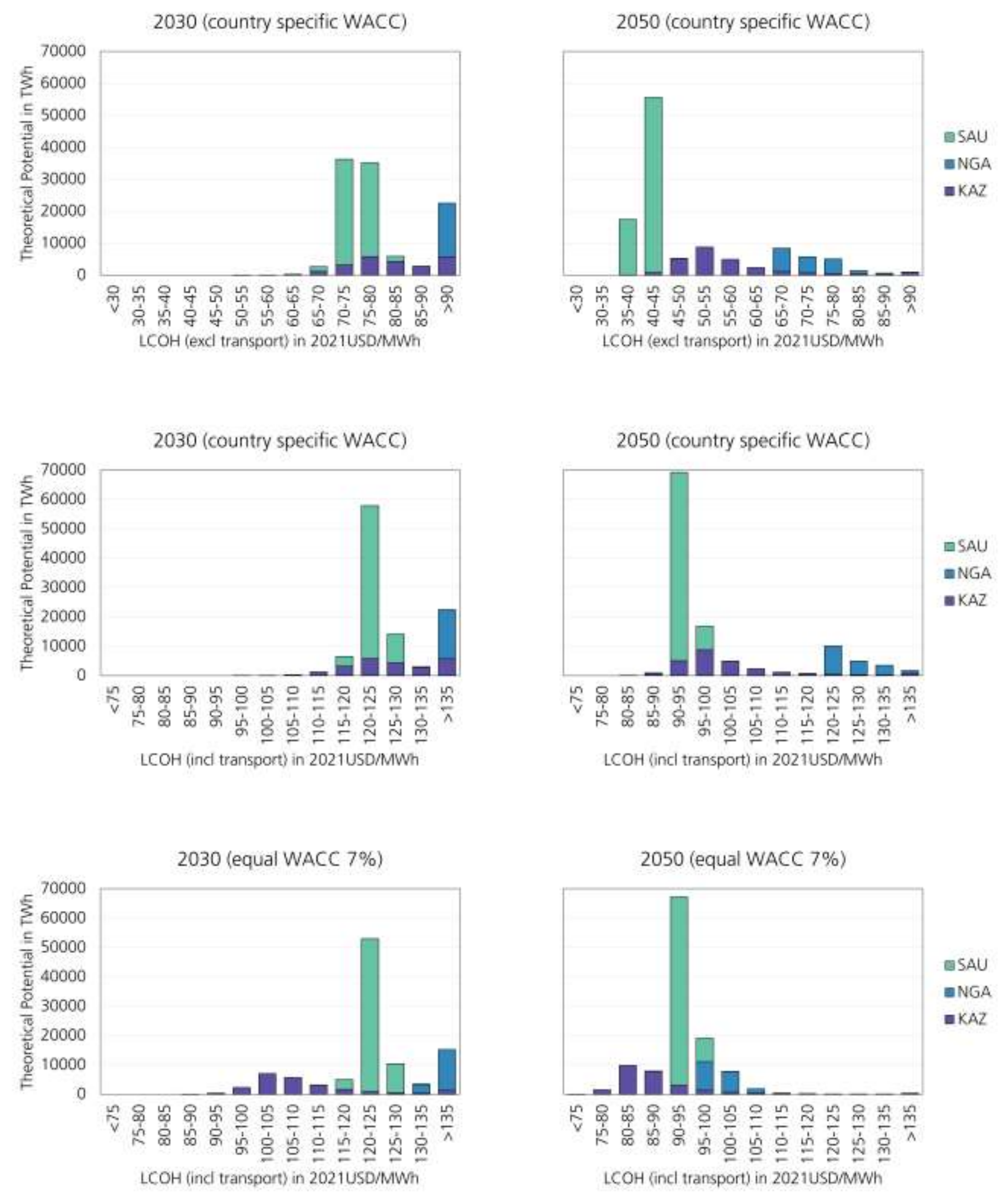


Figure 40: Overview of estimated theoretical hydrogen supply potentials per cost interval and country for different scenarios (excluding/including transport costs and assuming different capital costs) in 2030 (left side) and 2050 (right side)

04

Macro-economic export potentials for PtX products

4 Macro-economic export potentials for PtX products

4.1 From export costs to export revenues for PtX products

4.1.1 Export costs for PtX products

As discussed in the previous section, transportation costs are one of the core factors affecting the total cost of exporting hydrogen. However, as of to date, there are no existing projects for hydrogen transport on a large scale and thus no real-life cost data exists. However, sound estimates can be based on literature values and respective techno-economic models (cf. (Agora Industrie 2023; Brändle et al. 2021; Keramidas et al. 2022; Kreidelmeyer et al. 2023; Staiß et al. 2022).

As far as the future costs for different supply options for green hydrogen are concerned, it can be assumed that the transport of gaseous hydrogen via pipeline will be the cheapest mode of transportation. This particularly applies to short transport distances and in cases where existing gas pipelines can be retrofitted for the transport of hydrogen. However, building the necessary infrastructure implies some latency. The expected implementation horizon for retrofitting a pipeline is estimated at 3-5 years and 8-10 years for new construction, respectively (Agora Industrie 2023). This lead time should be taken into account when talking about transport options and associated costs in the medium-term (e.g. in 2030).

An alternative PtX product that is being discussed for export purposes is green ammonia. Ammonia is particularly suitable for transport over long distances and for applications directly as a material in the destination country. Due to the high technological maturity of ammonia tankers and terminals, a short-term implementation horizon of 2 years seems feasible (Agora Industrie 2023). Due to the lower conversion and transport losses, ship transport of ammonia is more cost-effective than that of liquid hydrogen. However, if hydrogen and not ammonia is required at the export destination, implying that cracking would be required, the picture could change in favor of liquid hydrogen (Kreidelmeyer et al. 2023). That said, since both ammonia crackers and liquid hydrogen tankers are not yet in commercial use, cost estimates for this transport option are more difficult, so further studies and pilot projects are needed to be able to derive more reliable cost estimates.

With regard to methanol and Fischer-Tropsch fuels, the same applies as for ammonia, and export by tanker makes sense if the product itself is needed in the target country, since the share of transport costs in the total export costs is relatively low in this case. In contrast, other alternatives such as Liquid Organic Hydrogen Carriers or Synthetic Methane are likely to remain more expensive compared to the previously mentioned marine transport options (Agora Industrie 2023; Kreidelmeyer et al. 2023).

In summary, it seems most likely that in the medium term the majority of hydrogen trade will take place regionally via pipeline where this is possible (e.g. in Europe), due to lower transport costs. Maritime transport of liquid hydrogen is likely to remain more expensive. However, for reasons of diversification and energy security, certain quantities of hydrogen could be imported by ship, albeit at a higher cost, comparable to current LNG imports. Countries that are likely to import hydrogen but do not have a pipeline connection (e.g. Japan or South Korea) will have to cover all their hydrogen imports this way. For ammonia and liquid carbon-based fuels (methanol and Fischer-Tropsch), on the other hand, it is more likely that global trade will be established, since transportation costs account for a much smaller share of the total cost of the product. Importing these energy sources is particularly sensible if the products can be used directly as raw materials in the importing country.

4.1.2 Assumptions for future market prices for PtX products

As of today, the global hydrogen industry is based on a mostly localized supply, often directly on-site by the enterprises using the hydrogen themselves, without significant trading activities. By 2021, only about 5% of the global hydrogen demand were being transported and traded (Monopolkommission 2021). Consequently, no public hydrogen market, with mechanisms of price formation based on the emergence of an equilibrium of supply and demand, exists (Wietschel et al. 2021). However, against the background of ambitious global decarbonization targets and the growing number of applications for green hydrogen, it can be expected, that the global hydrogen demand will strongly increase in the future, leading to an enhanced international trade of the commodity. Various studies have pointed out that many countries such as, for example, Germany will depend on substantial imports of green hydrogen, as the national production potentials will not be sufficient to meet the projected demand for a full decarbonization of the economy (Riemer et al. 2022). For the case of Germany, estimates indicate that the majority (i.e. 50-70%) of the national hydrogen demand forecasted at 95-130 TWh by 2030 will need to be imported, implying potential import volumes of 45-90 TWh in 2030. For the timeframe beyond 2030, a further increase of these import volumes can be expected (NWS 2023).

As for any commodity, estimating future market prices for green hydrogen is very difficult, as a large number of factors influence the price formation mechanism. However, for the case of hydrogen, the level of uncertainty is particularly high, due to the early stage of market development and the high level of uncertainty attached to the parameters affecting both the supply and demand side.

Generally, besides the underlying production costs, especially the following parameters will affect the price formation mechanism (Wietschel et al. 2021):

- **Market size:** The market could either remain based mainly on bilateral contracts between individual countries or evolve into regional markets based on the existence of transport infrastructure or transportation distances similar to regional gas markets. The development of a global hydrogen market is theoretically possible but rather unlikely due to the high transportation costs for hydrogen over long distances.
- **Development of price zones:** As mentioned above, prize zones might evolve based on transportation distances and the availability of transportation and distribution infrastructure, in particular pipelines but also according to preferable shipping routes.
- **Level of competition:** It is currently unclear whether the PtX market will be dominated by a small number of leading suppliers or if a multitude of producers will compete on the market. The level of competition will be further affected by the level of differentiation of the various PtX products

(i.e. the role of green ammonia and methanol) and their applications and competing technologies (e.g. in industry, transport, etc.) and the formation of respective submarkets.

- **Global demand:** The future demand for PtX products is subject to a high level of uncertainty as the development of the demand for the various use applications depends on political measures, the development of costs for alternative decarbonization technologies as well as complex interactions between the various markets, in particular the hydrogen market and the markets for its derivatives.
- **Strategic behavior and geopolitics:** National or regional policy strategies and geostrategic decisions could lead to unpredictable developments and the formation of sub-markets based on the technological preferences and willingness to pay for specific products from specific suppliers.
- **Policies and regulations:** National policy measures, incentive schemes, regulations and taxation schemes will strongly affect the demand and supply side of green hydrogen and its derivatives on a national level.

Based on the above considerations, it is likely that, at an initial stage, the trade of green hydrogen will be based on bilateral contracts building on strategic and geopolitical partnerships. At a later stage, regional markets might evolve, likely driven by the availability of transport infrastructure, in particular maximum distances for the transport of hydrogen via pipelines. This could lead to the emergence of regional markets and price zones, similar to regional gas markets (see potential import and export hubs in Figure 41). A global price convergence is rather unlikely in the medium to long term against the background of the relevance of transportation costs as well as the high relevance of the multitude of factors on national level (policies, regulations, technological preferences, willingness to pay, etc.). Further discussion with regard to the stages of a future hydrogen market can also be found in Butzengeiger et al. (2023).

A recent study by Wietschel et al. (2023) highlights the importance of competitiveness and willingness to pay for green hydrogen, by analyzing the influence of the competition of various decarbonization technologies for different use cases for green hydrogen and the resulting price-elasticity of the demand (cf. Figure 42). The study shows that, assuming carbon neutrality in 2045, the total national hydrogen demand is highly price dependent:

- A robust (i.e. price independent) baseline demand can be expected for sectors in which hydrogen will inevitably be needed for decarbonization in lack of other technology options (e.g. for production of ammonia, chemicals or steel, air and ship transport). For the case of Germany, this baseline demand is estimated to amount to ca. 250 TWh/a in 2045.
- A price-dependent demand is expected for use cases for which hydrogen competes with alternative decarbonization technologies, such as direct use of electricity. This applies, for example, to applications for energy storage and electricity supply and industrial heat provision. This price-dependent hydrogen demand drops at price levels >90€/MWh.

For a number of sectors, direct electrification will likely remain more competitive compared to green hydrogen in most cases (e.g. passenger transport or space heating). It can be expected that only if hydrogen price levels would drop well below 90€/MWh, additional demand for hydrogen would occur in these sectors.

In the frame of this study, we use Germany as an exemplary case of an industrialized country with ambitious decarbonization targets and as a future importer of PtX products and thus as a potential target market for the three focus countries. Even though the above findings on technology competitiveness and price elasticity were derived for the German case, the corresponding trends and findings can also be applied to other potential importing countries.

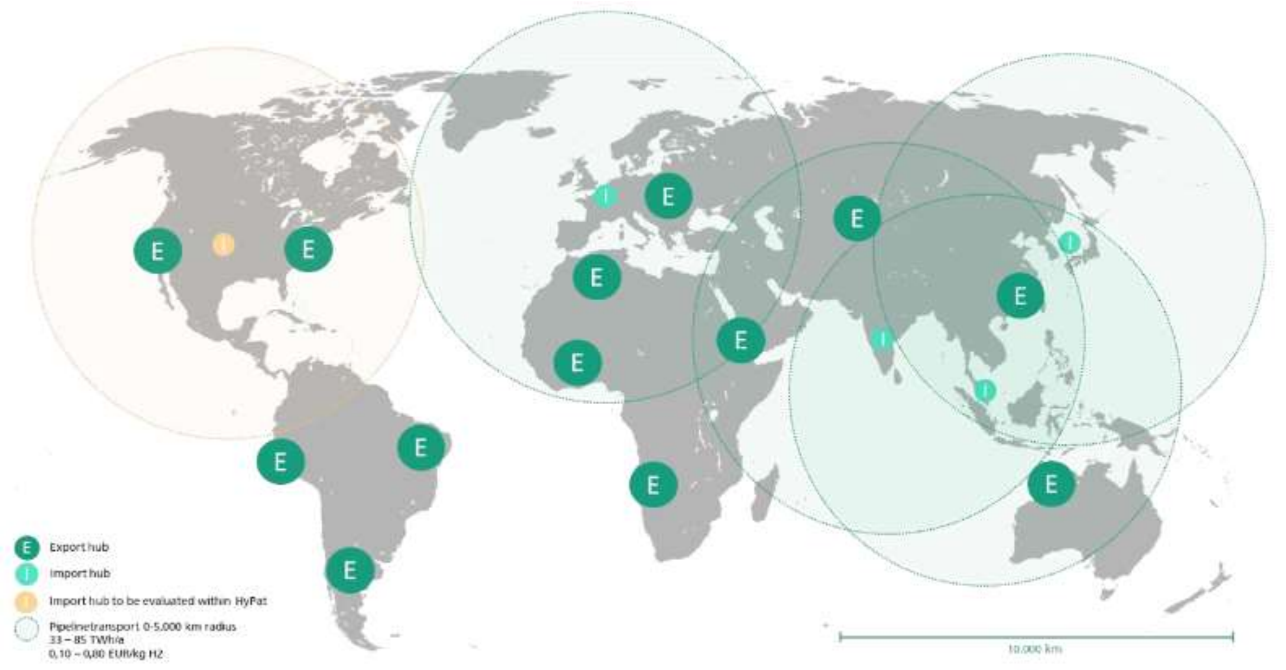


Figure 41 Qualitative illustration of potential import (I) and export (E) hubs for green hydrogen based on the availability of renewable energy potentials as well as the projected future demand and transport distances (Wietschel et al. 2021)

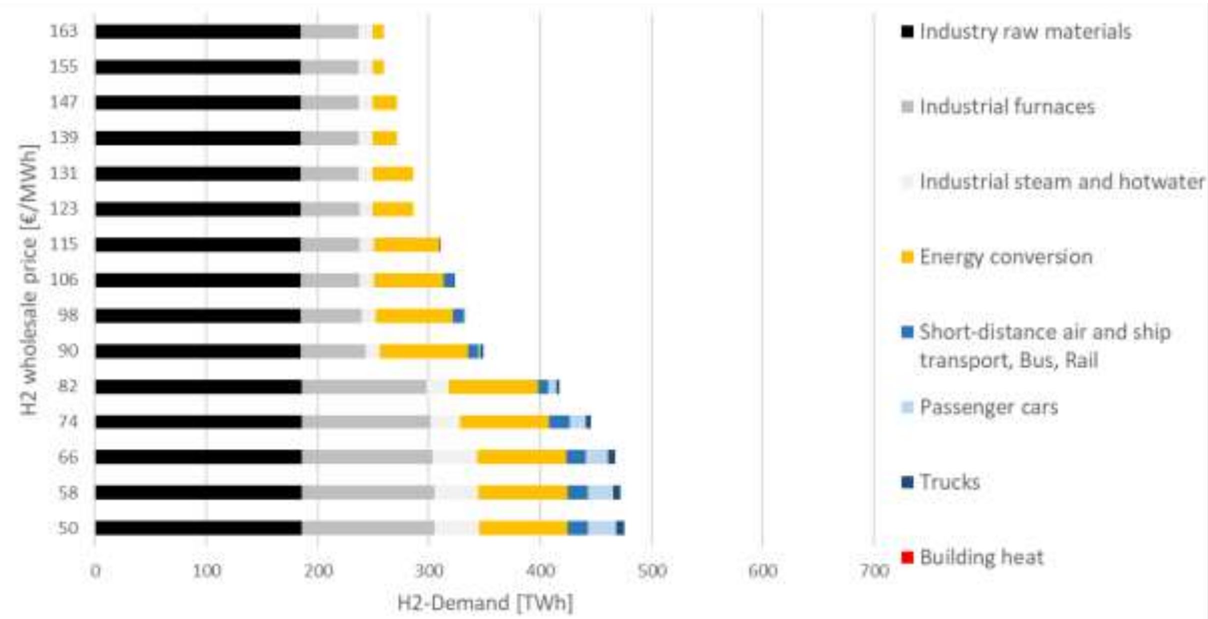


Figure 42 Price-dependent hydrogen demand in Germany in 2045 assuming carbon neutrality (Wietschel et al. 2023)

4.1.3 Estimation of potential export revenues

To allow for an estimation of potential export revenues for the three case study countries, we apply a simplified approach considering the production and transportation costs for green hydrogen and the assumed willingness to pay for the product. To this end, we use the case of Germany as an exemplary import country that could be representative for a potential future regional market price level in Central Europe. For the demand we assume two exemplary demand levels of 100 and 200 TWh, which would be in line with potential import volumes of green hydrogen to Germany in the timeframe after 2030 as indicated in the National Hydrogen Strategy (NWS 2023). In order to derive a rough estimation of potential future revenues from the export of hydrogen and how these compare to current revenues from the export of fossil fuels, the hypothetical export scenarios are contrasted with the actual oil exports of the three countries in 2021. For this purpose, the most favorable hydrogen supply costs for the year 2050 (Scenario 2 in Section 3.3.1) in each of the three countries are combined with to two different assumed price levels (90 and 120 2021USD/MWh) and the two exemplary export quantities (100 and 200 TWh). Thereby, a set of exemplary revenue levels and potential markup ranges can be derived. However, as these values are based on simplified assumptions and as actual prices and export volumes are influenced by a large number of unpredictable parameters (cf. previous section), they are subject to large uncertainties. Nevertheless, the results can serve as indicative ranges for possible magnitudes of revenues in contrast to current crude oil export revenues. Data for crude oil exports in 2021 are based in monetary terms on the Atlas of Economic Complexity and in energy units on OPEC data (Harvard Growth Lab 2023; OPEC 2023). Country-specific oil production costs are based on CNNMoney (2015) data retrieved from Statista (2023b) and converted to USD for 2021 using the consumer price index (World Bank Open Data 2023b).

In order to derive a rough estimation of potential future revenues from the export of hydrogen and how these compare to current revenues from the export of fossil fuels, the hypothetical export scenarios are contrasted with the actual oil exports of the three countries in 2021. For this purpose, the most favorable hydrogen supply costs for the year 2050 (Scenario 2 in Section 3.3.1) in each of the three countries are combined with to two different assumed price levels (90 / 120 2021USD/MWh) and the two exemplary export quantities (100 / 200 TWh). Thereby, a set of exemplary revenue levels and potential markup ranges can be derived. However, as these values are based on simplified assumptions and as actual prices and export volumes are influenced by a large number of unpredictable parameters (cf. previous section), they are subject to large uncertainties. Nevertheless, the results can serve as indicative ranges for possible magnitudes of revenues in contrast to current crude oil export revenues. Data for crude oil exports in 2021 are based in monetary terms on the Atlas of Economic Complexity (Harvard Growth Lab 2023) and in energy units on OPEC data. Country-specific oil production costs are based on CNNMoney (2015) data retrieved from Statista (2023b) and converted to USD for 2021 using the consumer price index (World Bank Open Data 2023).

Kazakhstan, on the other hand, features lower supply costs for hydrogen of USD 85/MWh and could thus achieve markups of between USD 0.5 and 7 billion through hydrogen exports, depending on the assumed price level and export volume (see Figure 43). By comparison, Kazakhstan exported crude oil worth USD 23.4 billion in 2021, with an estimated profit of about USD 8.1 billion. Export markups from green hydrogen could, therefore, offset between 6% and 87% of this amount, depending on the combination of assumed price levels and export volumes.

In 2021, **Saudi Arabia** exported 3,863 TWh of crude oil for a total of USD 118 billion (see Figure 44). Assuming production costs of USD 6.66/MWh, this results in a total markup of over USD 92 billion. In comparison, the potential cost of hydrogen supply of 90 USD/MWh would result in a markup of only 6 billion USD even in the most optimistic assumed case with future prices of 120 USD/MWh and 200 TWh of hydrogen exports. This represents only 6.5% of the crude oil export profits in 2021 and would be halved to USD 3 billion at the same prices and the lower export volume of 100 TWh. Given that the lower price level of USD 90/MWh corresponds exactly to the assumed specific supply costs, this would just result in break-even conditions for Saudi Arabia, offering only marginal profits. These figures clearly show that future export revenues from green hydrogen in Saudi Arabia will most likely compensate for only a small fraction of today's fossil fuel export revenues. This is due to the current combination of remarkably low production costs and high export volumes for crude oil. For hydrogen, on the other hand, export volumes will likely be lower, and production and transportation cost will be higher, resulting in both lower total revenues and markup.

Nigeria exported 988 TWh of crude oil worth USD 39.9 billion in 2021, assuming production costs of USD 21 billion (see Figure 45). Considering the comparatively high supply costs for green hydrogen of 120 USD/MWh, it would not be profitable for Nigeria to export hydrogen at a price level of 90 USD/MWh. Even assuming a higher price level of 120 USD/MWh, the export revenues would just balance out the production costs, indicating that lucrative markups from the export of green hydrogen seem rather unlikely for Nigeria under the given assumptions.

The presented estimates of potential export revenues show notable differences between the countries. For Nigeria, under the given assumptions and the comparatively higher hydrogen production costs, profitable hydrogen exports seem to be possible only at higher market price levels (>120 USD/MWh). For the case of Saudi Arabia, despite the relatively low hydrogen production costs which would allow for profitable trade based on the assumed price levels, the potential future revenues from hydrogen export still seem relatively small if compared to today's oil revenues, due to the currently much higher volumes and margins on the oil market. This picture might change in the case of significantly higher export volumes for hydrogen, though. In Kazakhstan, hydrogen exports via pipeline could, under favorable framework conditions, compensate for a relatively high share of today's oil export profits. Nevertheless, under the given assumptions even for the scenarios assuming the higher hydrogen price levels and higher exemplary export volumes, none of the three countries would be able to fully offset their current oil export profits with hydrogen exports. The targeted development of further economic diversification potentials will therefore be key in order to avoid economic losses in the context of declining fossil fuel exports. Especially for countries with longer transport distances to the respective destination countries, the export of PtX downstream products such as methanol or ammonia could be more profitable, as the transport costs for these products are significantly lower compared to the transport of hydrogen over long distances. In addition, the expansion of value creation along the downstream segments of the PtX value chain could result in further positive economic effects in terms of creation of revenues and jobs (cf. results presented in Section 4.2.1).

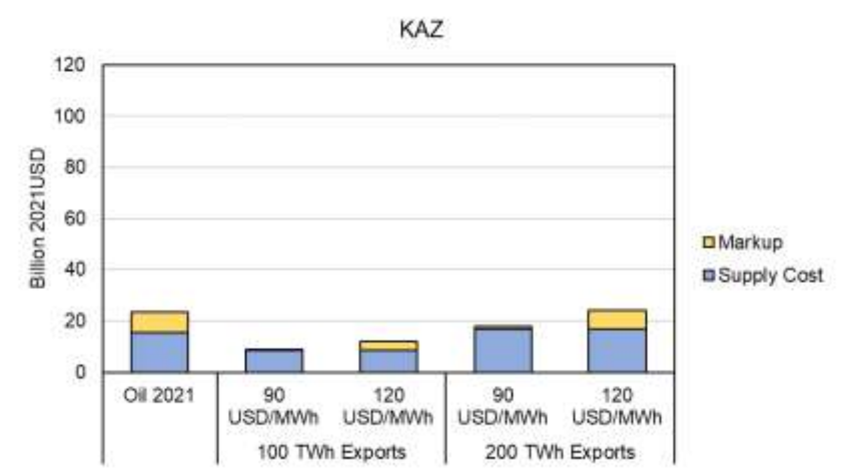


Figure 43 Comparison of 2021 oil export revenues with hypothetical green hydrogen export revenues at price levels of 90 USD/MWh and 120 USD MWh for exemplary export volumes of 100TWh and 200 TWh for Kazakhstan

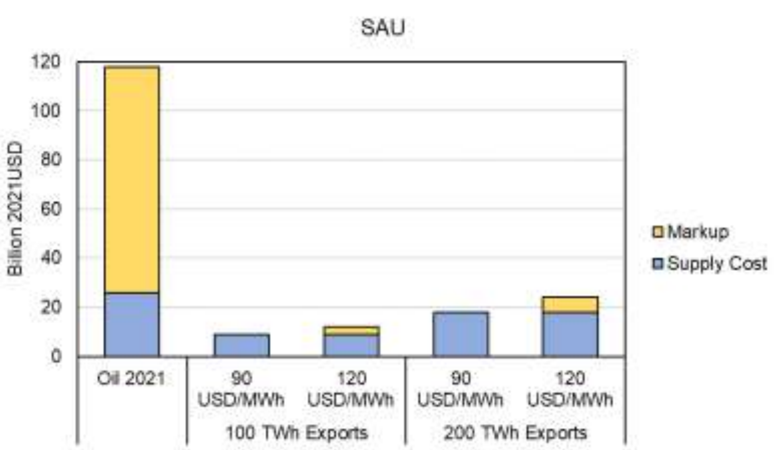


Figure 44: Comparison of 2021 oil export revenues with hypothetical green hydrogen export revenues at price levels of 90 USD/MWh and 120 USD MWh for exemplary export volumes of 100TWh and 200 TWh for Saudi Arabia

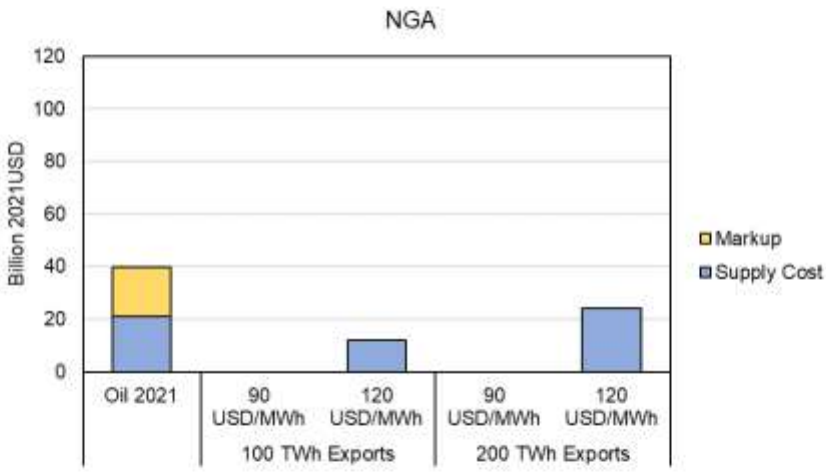


Figure 45: Comparison of 2021 oil export revenues with hypothetical green hydrogen export revenues at price levels of 90 USD/MWh and 120 USD MWh for exemplary export volumes of 100TWh and 200 TWh for Nigeria

4.2 Broader macro-economic effects of PtX sector development

Input-output analysis (IOA) was applied to estimate the impact of the production of hydrogen and other PtX products on the gross output and employment in the producing countries. For each country, two scenarios were analyzed, each focusing on different PtX value chains. One scenario examines basic green hydrogen production, while the other scenario focuses on a selected downstream PtX product that seems particularly suitable in the given country context. Table 6 presents an overview of the investigated scenarios. In line with the cost estimates in chapter 3.3, liquid hydrogen (LH2) is regarded for Saudi Arabia and Nigeria and gaseous hydrogen (GH2) for the case of Kazakhstan. For the PtX products, ammonia (NH3) is considered for Saudi Arabia, Kazakhstan and Nigeria. An additional scenario analyzing the case of methanol (MeOH) production in Nigeria is also included, as biomass is widely used within the country, providing the opportunity to benefit from potentially comparably low-cost biogenic sources of CO2. The exact plant configuration, i.e. which installed capacity of which technology would be required to produce the respective volume of product, is based on the optimization results of the PtX Atlas of Fraunhofer IEE (Fraunhofer IEE 2023). For power generation, wind turbines are assumed in the case of Kazakhstan, photovoltaics in Nigeria, and a hybrid configuration, consisting of a combination of both, for Saudi Arabia.

Table 6 Energy generation and P2X Product-combinations analyzed in scenarios

Country	KAZ	SAU	NGA
Scenario 1 (Green Hydrogen)	Wind GH2	Hybrid LH2	PV LH2
Scenario 2 (Downstream product)	Wind NH3	Hybrid NH3	PV NH3 / MeOH

As no PtX sector exists in the countries' economic structure yet, the economic interlinkages and sector interactions have to be implemented in the IO model. In order to analyze the impact of the production of the required technology components for electricity generation, electrolysis and PtX synthesis and the installation of the plants on the national economy, the assumed capital costs (CAPEX) are allocated to the sectors listed in the IO tables and used proportionally as input to the model. This methodology is based on publications by Garrett-Peltier (2017) and Dell'Anna (2021). Additional technology-specific literature (Böhm et al. 2019; Holst et al. 2021; Nyari 2019; Rouwenhorst et al. 2020) was used to allocate the components to the economic sectors. In each of the following analyses the impact of installing one TWh of PtX production capacity in the country is presented.[13]

As input-output analysis is an approach that uses retrospective data, all scenarios were conducted under the assumption that monetary and material flows within value chains and the overall structure within and between sectors of the economy remain stable relative to the base year 2018.[14] Investments

[13] Due to the linearity of the model, the effects of n TWh of P2X product could be calculated simply by multiplying with n.

[14] The stability of production recipes for products within one sector has often been shown, see Holub et al. 1994; Miller et al. 2022.

in the different PtX technologies have been included in the model as investment impulses that increase the final demand of the sectors. The total amount of investment required and its distribution across national industries is shown in Table 7. The results have to be interpreted under the assumption that all production and value added is attributed to the national economy of the country. The resulting macro-economic effects observed for the two scenarios per country are described in the following.

Table 7 Total investment impulses by PtX installation scenario and their distribution across industries.

Sectors	SAU Hybrid LH2	SAU Hybrid NH3	KAZ Wind GH2	KAZ Wind NH3	NGA PV LH2	NGA PV NH3	NGA PV MeOH
Total investment in 2021 million USD/TWh PtX output	753.7	1065.3	667.9	1102.8	979.9	1291.3	1430.3
Chemical and chemical products	0.6%	0.5%	0.8%	0.5%	0.9%	0.8%	0.7%
Rubber and plastics products	5.4%	4.1%	8.9%	6.6%	0.0%	0.0%	0.0%
Fabricated metal products	14.5%	12.0%	14.4%	11.2%	16.0%	14.2%	15.7%
Computer, electronic and optical equipment	4.6%	3.8%	6.0%	4.1%	6.7%	6.2%	5.6%
Electrical equipment	13.8%	10.9%	12.6%	8.8%	18.9%	16.4%	16.1%
Machinery and equipment, nec	36.3%	38.4%	30.7%	35.4%	38.6%	39.0%	42.0%
Manufacturing nec; repair & installation of machinery & equipment	1.8%	7.3%	2.4%	8.5%	2.6%	6.1%	4.0%
Construction	18.7%	19.9%	19.2%	21.1%	14.2%	15.4%	14.0%
Land transport & transport via pipelines	0.6%	0.5%	0.7%	0.5%	0.4%	0.3%	0.3%
Accommodation & food service activities	0.2%	0.2%	0.4%	0.3%	0.0%	0.0%	0.0%
Financial & insurance activities	0.4%	0.3%	0.4%	0.3%	0.4%	0.3%	0.3%
Real estate activities	2.9%	2.2%	3.7%	2.7%	1.4%	1.2%	1.2%

4.2.1 Macro-economic effects of PtX production

Kazakhstan

Figure 46 shows the results of input-output analysis for Kazakhstan for gaseous hydrogen (GH2) and the PtX product ammonia (NH3) based on wind energy.

In the GH2 scenario (Figure 47 a), the investments in wind turbines (blue bars) could have significant contributions in the machinery and construction sector with product equivalents of $182 million per TWh and $147 million per TWh, respectively, assuming that the value chain is established within the country. The investment impulse for wind also supports the sectors ‘Wholesale and retail trade; repair of motor vehicles’ with outputs of up to $73 million and the metal related sectors ‘Fabricated metal products’ and ‘Basic metals’ with outputs of $105 million, which are already well established in the country. Also, the production of ‘Rubber and plastics products’ (outputs worth $60 million), as well as ‘Real estate activities’ with more than $30 million could be generated due to investment into wind plant. The effects of electrolyzers (yellow bars) are smaller compared to those of wind turbines. They would particularly contribute to sectors of ‘Electrical equipment’ and ‘Computer, electronic and optical equipment’ with output worth $54 million and $40 million, respectively.

For the GH2 scenario, effects on employment would translate into a similar ratio as investment impulses, with the highest potential in job generation in the sectors of ‘Machinery and equipment, nec’ (5000 jobs), ‘Construction’ (4400 jobs) and, induced by the value chain, in the sector ‘Wholesale and retail trade; repair of motor vehicles’ (3580 jobs). The highest impact could be induced by wind turbines. The sectors for ‘Electrical equipment’ and ‘Computer, electronic and optical equipment’ would benefit from up to 1600 jobs by the installation of electrolyzer capacity.

For the NH3 scenario (Figure 46 b), the distribution of output effects into wind turbines and electrolyzers are comparable to the ones described for the GH2 scenario with about 8% higher investment required for wind power installations in NH3 production compared to GH2 (cf. Table 6). This is reflected in the outputs as well, as the principal sectors of machinery and construction have outputs of $223 million and $181 million of outputs, respectively (Figure 46 b, left). In addition to the GH2 scenario, the NH3 scenario requires a considerable amount of output for the synthesis of NH3, which would take about one fourth of the overall output required. NH3 synthesis capacity additions mainly induce outputs in the sectors of ‘Machinery and equipment, nec’ ($141 million), ‘Construction’ ($86 million), ‘Basic metals’, ‘Fabricated metal products’ and ‘Manufacturing nec; repair and installation of machinery and equipment’ (together 114 million). Induced output effects can be found in ‘Wholesale and retail trade; repair of motor vehicles’, but also in ‘Professional, scientific and technical activities’ with outputs of $45 million and $12 million, respectively. Employment effects for wind and electrolysis are similar to the ones described in the GH2 scenario, with main contributions in the production of machinery, construction and trade services. Smaller amounts are involved in ‘Manufacturing nec; repair and installation of machinery and equipment’, transport and technology services. Additionally, NH3 synthesis could generate jobs in machinery manufacturing (3650), construction (2500) and trade services (1600) and up to 3100 jobs per TWh of NH3 in the sector ‘Manufacturing nec; repair and installation of machinery and equipment’.

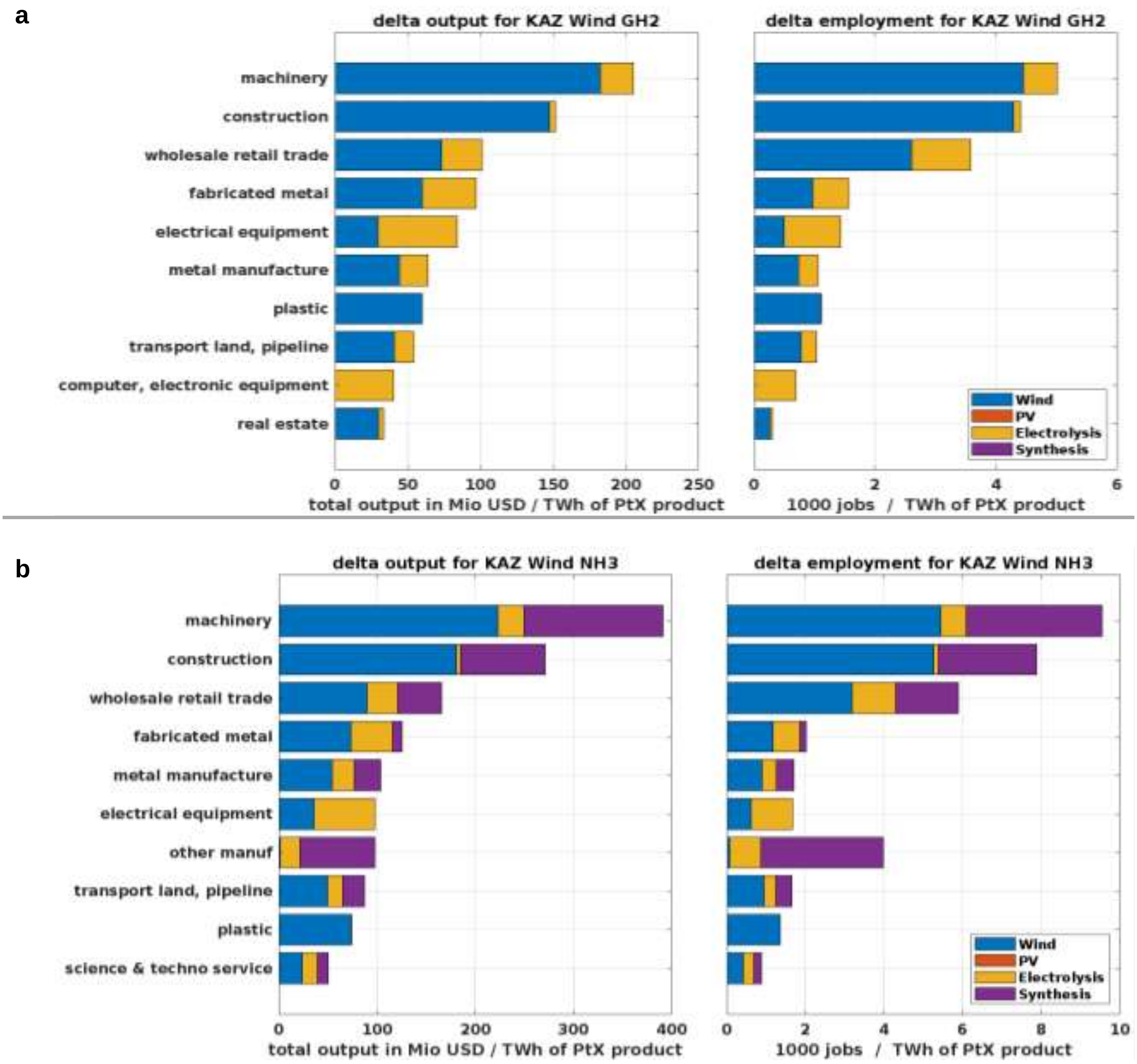


Figure 46: Macroeconomic impacts per TWh of NH3 production in Kazakhstan. a) GH2 scenario, b) NH3 scenario.

Saudi Arabia

In Saudi Arabia, the scenario of LH2 products generated with a hybrid electricity mix of solar PV and wind shows that main contributions to the total outputs of more than $1235 million per TWh LH2 are due to the installation of wind (blue bars in Figure 47) and PV plants (orange bars in Figure 47), mainly in the sectors of ‘Machinery and equipment, nec’ ($254 million) and ‘Construction’ ($188 million). ‘Fabricated metal products’ ($79 million) and ‘Electrical equipment’ ($58 million) also benefit from the installation of wind and PV plants. ‘Wholesale and retail trade; repair of motor vehicles’, ‘Coke and refined petroleum products’ and ‘Telecommunications’ are elements of the production chains for wind and PV plants that would benefit from the installation with an overall output of up to $116 million per TWh LH2. The impact of electrolysis capacity installation is lower compared to that of wind power and PV with an output of $47 million per TWh in the sector ‘Electrical equipment’, followed by ‘Computer, electronic and optical equipment’ as well as ‘Fabricated metal products’ with $35 million and $32 million, respectively (Figure 47 left).

In the PtX scenario with NH3 as a product (Figure 47b, left), similar sectors as in the previous scenario would be affected by the installation of NH3 infrastructure, particularly for wind power and PV installations. In its magnitude, synthesis of NH3 (purple bars) would have an impact comparable to PV installation in most sectors. Synthesis of NH3 would mainly contribute to manufacturing sectors, machinery and construction with outputs up to $115 million and $81 million/TWh of NH3, respectively.

Employment effects of NH3 production would affect the sectors mentioned above, with particular effects in the labor-intensive construction sector (Figure 47b, right), with a potential of 3570 jobs due to wind, PV plants and synthesis per TWh of PtX product, plus approximately 1300 in the scenario of NH3 synthesis. Jobs in ‘Machinery and equipment, nec’ and ‘Fabricated metal products’ would be required in either of the scenario options. The hybrid LH2 installation could additionally generate employment in sectors related to ‘Electrical equipment’, while some more employment opportunities would be generated in manufacturing sectors in the hybrid NH3 scenario.

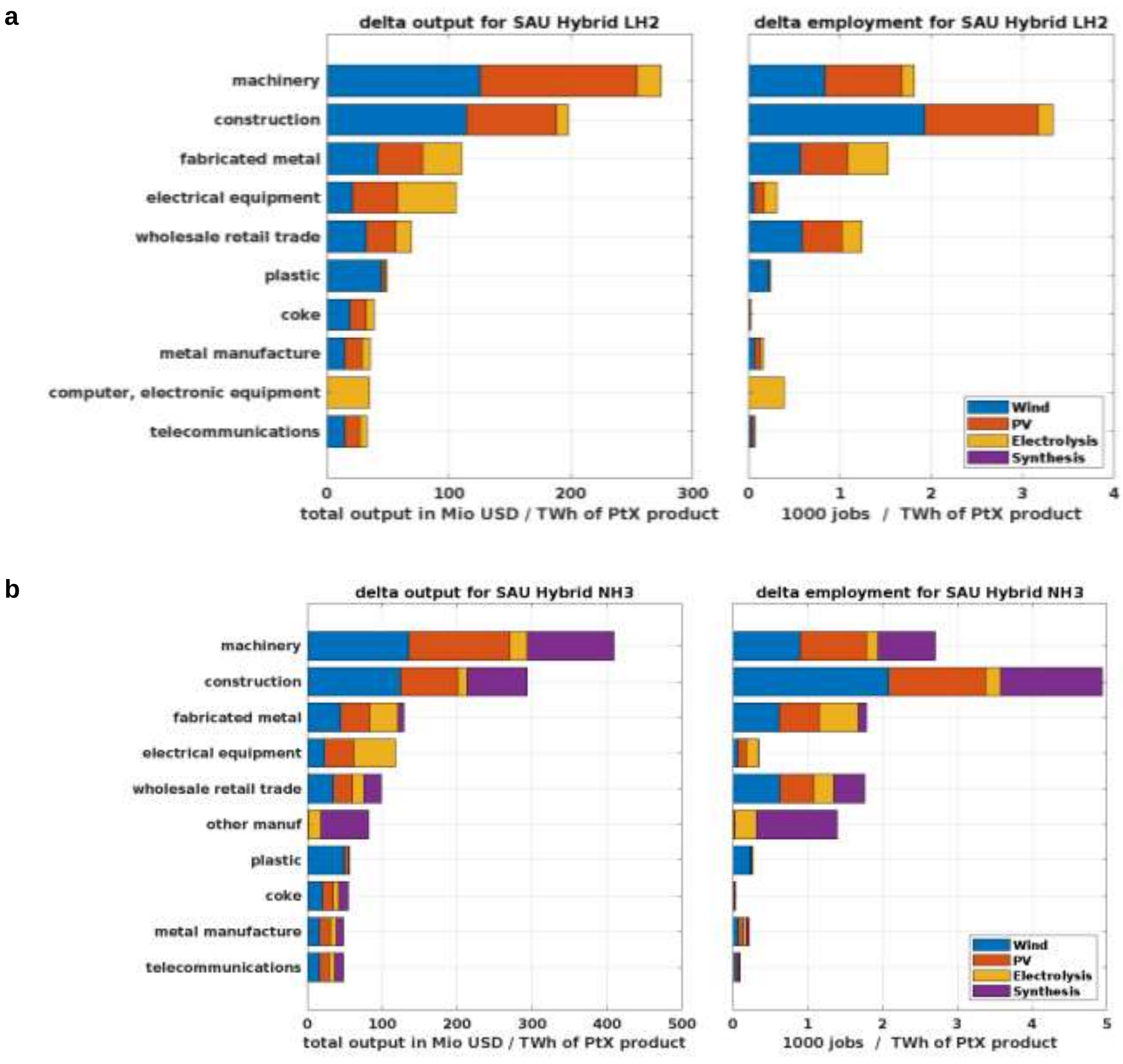


Figure 47 Macroeconomic impacts per TWh of LH2 production in Saudi Arabia. a) LH2 scenario. b) NH3 scenario. Left: output generated per TWh Right: employment effects per TWh of LH2.

Nigeria

For Nigeria, liquefied hydrogen (LH2) as well as ammonia (NH3) and methanol (MeOH) as possible PtX downstream products were compared, combined with an upstream value chain based on PV energy (Figure 48). As described for the other countries, main macroeconomic effects across sectors are induced by PV plants. The NH3 synthesis is more investment intensive than liquefied hydrogen, which is also reflected in the generated gross output. Outputs for PV (orange bars in Figure 48b, left) are mainly located in the sectors ‘machinery’ ($368 million), ‘fabricated metal products’ ($117 million), ‘electrical equipment’ ($105 million) and ‘construction’ ($150 million). Equally high investment requirements in these sectors are also visible in the MeOH scenario (Figure 48c). The required investments in both scenarios remain above those for LH2, where investment into the same sectors leads to outputs for PV in a range between $341 million for machinery and $139 million for construction and $108 million for 'Electrical equipment' (Figure 48a). The main contributions of electrolyzers are in the sectors of ‘Electrical equipment’ and ‘Computer, electronic and optical equipment’ in both scenarios, with a total of $212 and $80 million in the NH3 scenario and $188 and $128 million for MeOH, respectively. Contributions of NH3 synthesis (purple bars in Figure 48b, left) are mainly located in the sectors 'Machinery and equipment, nec’ ($90 million/TWh of NH3). Compared to this, about half of the output potential of $48 million/TWh is located in ‘Manufacturing nec; repair and installation of machinery and equipment’ and ‘construction’. Smaller effects between $11 and $25 million/TWh are seen in the sectors 'Wholesale and retail trade; repair of motor vehicles‘, 'Other non-metallic mineral products' and 'science and technology services'. Further contributions for MeOH are in the sectors of ‘fabricated metal products’, ‘Manufacturing nec; repair and installation of machinery and equipment‘, as well as ‘construction’ in the range of $25-30 million/TWh of MeOH. As described in previous scenarios, induced effects can be seen in the sector 'Wholesale and retail trade; repair of motor vehicles‘ in both Nigerian scenarios with $195 million in the case of MeOH and $135 million in the case of LH2.

Considering the potential for employment, macroeconomic effects in Nigeria appear to be higher compared to the other two countries. This has to be considered in the context of higher employment coefficients (i.e., employees required for a defined sectoral output) reported. As employment effects scale linearly with the employment coefficients, the actual employment potential might be lower than described here, in particular in the sectors ‘Machinery and equipment, nec’, ‘Fabricated metal products’, ‘Computer, electronic and optical equipment’ and ‘Electrical equipment’. The high value of the coefficients could be associated with a lower output per worker in the status quo. However, the tendency is that higher employment effects per TWh of PtX product are reported for the sectors. To prevent misinterpretation, the following analysis refers to relative references only.

For the NH3 scenario, similar to the previous scenarios, a main employment potential is generated in the sector of ‘Machinery and equipment, nec’, with 58% of potential jobs in the sector attributed to PV installation, 7.2% for the installation of electrolyzers and about 14.3% for the synthesis of the PtX product NH3.

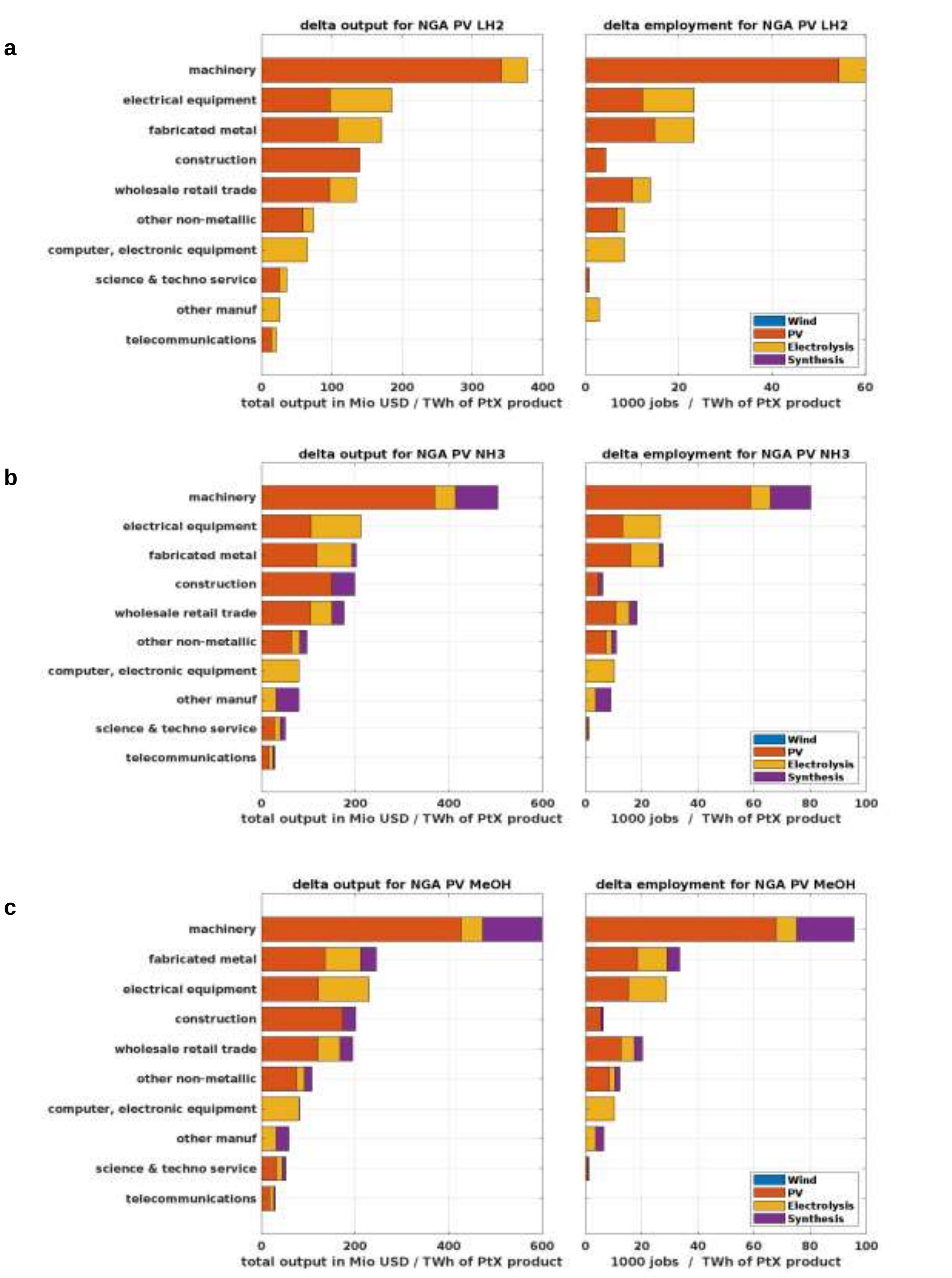


Figure 48: Macroeconomic impacts of PtX production in Nigeria (Results of input-output-analysis). a) LH2 scenario, b) NH3, c) MeOH scenario. Left: output generated per TWh of PtX product, right: employment effects per TWh of PtX product.

‘The industries 'Electrical equipment', 'Fabricated metal products' would generate an employment potential in particular for the installation of PV and electrolyzers, each with about 35% of the employment potential seen for ‘Machinery and equipment, nec’. For the MeOH scenario, a main employment potential is generated in the sector of ‘Machinery and equipment, nec’, with 75% of potential jobs in the sector attributed to PV installation, 2% for the installation of electrolyzers and about 21% for the synthesis of the PtX product MeOH. ‘The industries 'Electrical equipment', 'Fabricated metal products' and 'Other non-metallic mineral products' would generate an employment potential in particular for the installation of PV and electrolyzers, each with about 30% of the employment potential seen for ‘Machinery and equipment, nec’. As reported for in the other countries, electrolyzers bear some potential for related employment in the sector of ‘Computer, electronic and optical equipment’ and additionally in ‘Manufacturing nec; repair and installation of machinery and equipment’ in all scenarios. Across all sectors, 14% of the overall jobs could be generated for NH3 synthesis, in particular in the sectors ‘Machinery and equipment, nec’, ‘Fabricated metal products’, and ‘Wholesale and retail trade; repair of motor vehicles’. For the MeOH scenario, a main job source is 'Machinery and equipment, nec', with 75% of the potential jobs in this sector attributed to PV installation, 2% to electrolyzer installation and around 21% to the MeOH synthesis. The 'Electrical equipment', 'Fabricated metal products' and 'Other non-metallic mineral products' industries would generate employment potential in particular for PV installation and electrolyzers, each with around 30% of the employment potential seen for 'Machinery and equipment, nec'. For the LH2 scenario the employment effects that can be induced by PV and electrolyzers distribute similarly on the mentioned sectors, yet at a lower level than NH3 (-25%), due to the smaller initial investment into PV and electrolyzers for LH2 compared to the downstream PtX product NH3.

4.2.2 Overall discussion of scenario analysis

Scenarios for all three countries with two alternatives of hydrogen production and downstream PtX products were analyzed based on the cost estimates in chapter 3.3. In all cases, more than half of the required macroeconomic output per TWh of PtX products is required for the upstream parts of the value chain, i.e. wind turbines and PV systems. Compared to this, the impact of added electrolyzer capacity on the national gross output and induced employment effects is less important. Compared to wind and PV plants, electrolyzers, however, show effects in additional sectors, such as ‘Electrical equipment’ and ‘Computer, electronic and optical equipment’ and ‘Manufacturing nec; repair and installation of machinery and equipment’.

When interpreting the modelling results, the underlying assumptions need to be regarded: As status-quo domestic input-output tables, that represent the current cross-linking of value chains within the national economy, are used, it is assumed that the production structure remains stable and that investment impulses in technologies are used under the status quo mix of technologies. It is also assumed that all production takes place within the country. If import shares were considered, the corresponding share of the economic effect would be located outside the country and not be attributed to the countries' national account. Therefore, the results described in this section (Figure 47 to Figure 48) can be understood as an upper range for possible effects at a national scale.

Not only sectors receiving direct investments benefit from PtX installations, but also sectors that are part of the upstream or downstream value chain. These induced effects include in particular the sector ‘Wholesale and retail trade; repair of motor vehicles’ in all three countries, which is ranked third in output generation in the Kazakhstan scenarios and fifth in the scenarios for Saudi Arabia and Nigeria.

In Saudi Arabia, induced effects include the sector of ‘Coke and refined petroleum products’, which is prominent in the status quo economy of this country. ‘Professional, scientific and technical activities’, which is closely interlinked with other sectors of raw materials and manufacturing for the production involved into PtX is ranked among those which are indirectly affected by the investment impulse into PtX technologies.

The summary of employment effects is to be interpreted under the same conditions: In all scenarios, the sectors of ‘Machinery and equipment, nec’ and ‘Construction’ would experience job effects as the main investments go into these sectors. Metal- and electronics related sectors also bear a potential for job creation, assuming that the corresponding production would take place within the corresponding countries. In particular 'Electrical equipment' and ‘Computer, electronic and optical equipment’ is usually imported to a high share (e.g. in Kazakhstan 93.4% and 80.1%, respectively), so the values described in the analysis display upper estimates assuming domestically exploited employment potential. Due to the importance of the sector in all economies, 'wholesale and retail trade; repair of motor vehicles' would be one of the main sectors to benefit from PtX installations as an induced effect. This sector traditionally has a high domestic share (e.g. in Kazakhstan, 79.5% of the upstream activity is domestic).

Scenario analysis was conducted assuming a constant technology mix. Considering that countries will likely evolve over time, in particular concerning their portfolio of manufacturing and service sectors, it is possible that the contribution of different sectors at a national level could change, in particular if policy efforts were made at a national level, e.g. the contribution of sectors related to fossil energy, such as ‘Coke and refined petroleum’ might decrease and the importance of sectors closely interlinked to hydrogen-related technologies might increase within the country contributing to a higher share of domestic production.

4.4 Economic diversification potentials

4.4.1 Economic Complexity and Product Space Approach

As described in Müller et al. (2023), countries with higher shares of fossil exports often display lower levels of industrial diversification (see Figure 52 in the appendix). One explanation for this would be that the high revenues from fossil fuel exports hinder development in other industries because they are "not needed" from a revenue perspective. At the same time, the required machinery for fossil fuel extraction and often also the highly skilled labor force come from abroad. As a result, the development of local supporting industries is inhibited. Given the expected decline in exports of fossil fuels over the next few years, this poses challenges for fossil fuel exporting countries. It is, therefore, increasingly important to identify and promote strategic diversification potentials early on, in order to allow for a steady development of the respective sectors. In view of the exports of the focus countries and the development over the last few years, insights into existing know-how and possible new export opportunities and diversification potentials can be gained. Thereby, the representation of exports in the so-called product space (cf. Figure 49 - Figure 51) is a useful way to graphically depict the relatedness of different products in an intuitive way. In this representation, related products, which require similar know-how for their production are connected to each other and thus arranged closer together. Applying this to all traded products of a country results in a large network representation that contains a tightly interlinked core and a looser connected outer area. Thereby, the core of the network consists mainly of metal products, machinery, electronics and chemicals, while the periphery is characterized by agricultural products and natural resources (Hidalgo et al. 2007; Hidalgo et al. 2009).

The approach was applied to the three case study countries in order to further analyze the complexity of their economies, beyond the analysis of the dependency on fossil fuel exports presented in section 2.2. The economic complexity was derived for each country for the years of 2006 and 2021, to give an indication of the past trend in regard to economic diversification and a perspective for potential future developments.

In the case of **Kazakhstan**, 23 new products have been added to the export basket in the last 15 years (Harvard Growth Lab 2023). In addition to fossil fuels and agricultural goods, Kazakhstan also exports metals and metal products such as copper, zinc, aluminum, iron and steel. Especially the latter could be an opportunity to boost the local demand for hydrogen and to establish green steel and sustainable steel products as an export commodity. There is also further value creation potential for the other metals, as a large proportion of metals have so far been exported as raw materials and not processed further within the country. With regard to the upstream value chain of electricity and hydrogen production, wind energy in particular represents a potential target sector. Driven by the good wind energy potential and the resulting expected local installation of large numbers of wind turbines, more components could gradually be produced in Kazakhstan, which in turn, could have interlinkages with other sectors such as the metal industry for the tower and the machinery industry for bearings and gearboxes. In addition, the transformation of fertilizer production to green ammonia could be an opportunity, both for use in local agricultural production and for the export of the product.

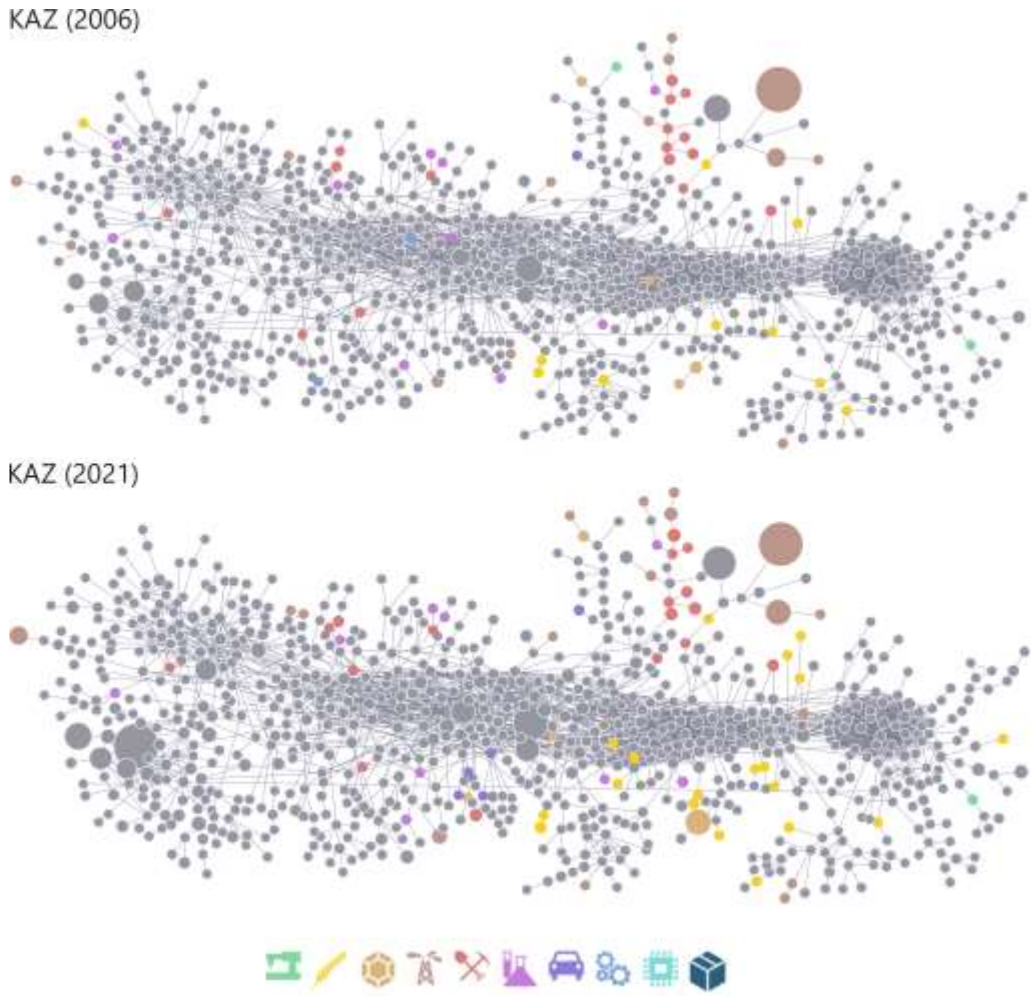


Figure 49: "Product space representation of the goods exported by Kazakhstan in 2006 and 2021 with a comparative advantage, colored by product category (own representation based on Harvard Growth Lab (2023))

Saudi Arabia represents an example of a successful diversification into new industries. Between 2006 and 2021, a total of 24 new products have been added to the export profile with a comparative advantage, 14 of them from the chemical industry (Harvard Growth Lab 2023). The acquired know-how could be transferred to green chemical products in the future. This includes basic chemicals such as methanol and ammonia, but also downstream products such as fertilizers and plastics. Converting existing refineries to renewable refineries and exporting Fischer-Tropsch fuels for shipping and aviation are also possibilities for economic diversification in this regard. By contrast, the electronics and mechanical engineering sectors, shown in the center of the product space, have been less developed to date, although these are precisely the sectors that are critical to the upstream value chain (e.g., PV and wind turbines and electrolyzers). In terms of technology components for the green hydrogen value chain, Saudi Arabia is so far rather poorly positioned, see (Müller et al. 2023). The targeted development of local production capacities and their promotion, for example through quotas, could be another way to boost the development of new industries.

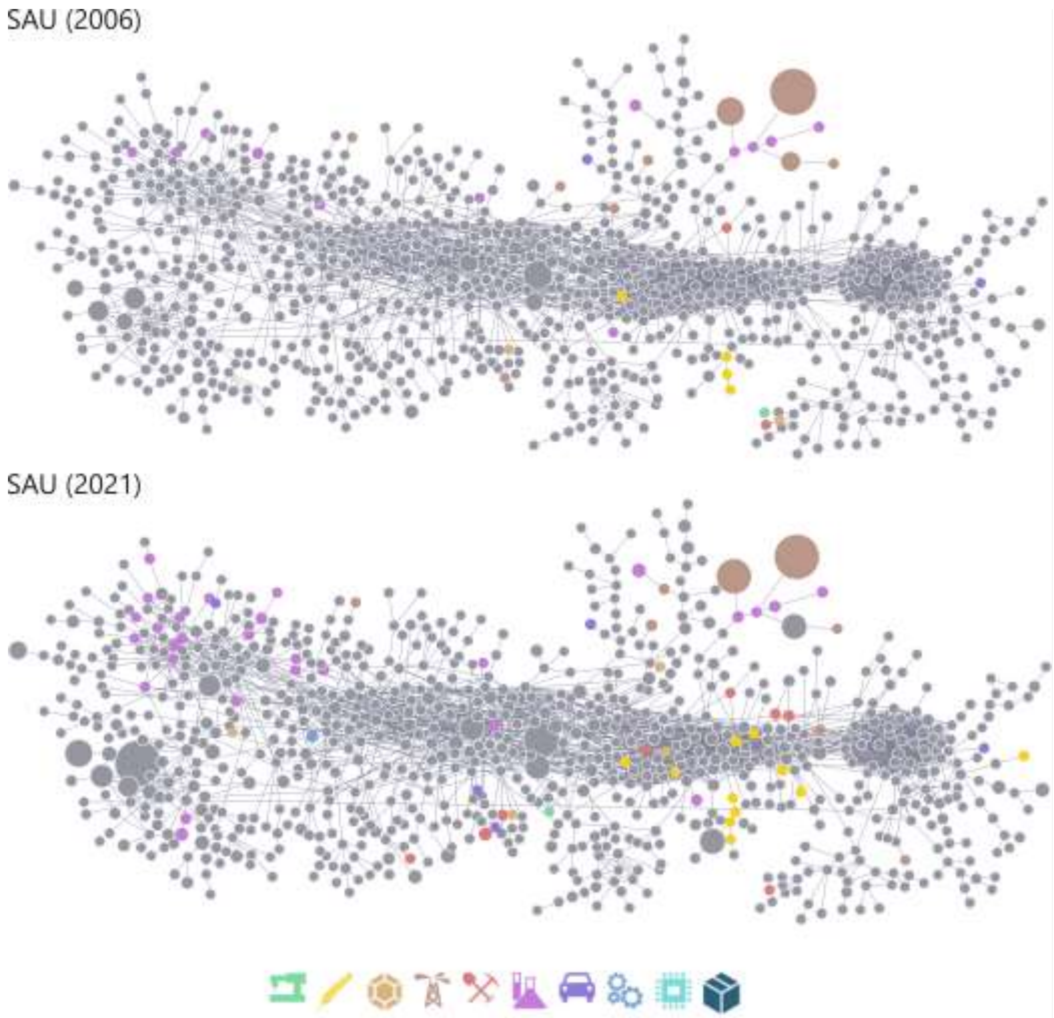


Figure 50: "Product space representation of the goods exported by Saudi Arabia in 2006 and 2021 with a comparative advantage, colored by product category (own representation based on Harvard Growth Lab (2023))

In the case of **Nigeria**, industrial diversification appears particularly challenging. Between 2006 and 2021, the country added only 7 new products to its export profile with a comparative advantage, indicating a rather slow diversification process (Harvard Growth Lab 2023). However, the most important export goods currently remain fossil fuels and agricultural products. In international comparison, it has one of the least complex export baskets. An important factor could therefore be local fertilizer production, where green ammonia could be used in the future. Based on this, strategic efforts could be made to gradually develop a more diversified chemical industry similar to that in Saudi Arabia. The export of green methanol or Fischer-Tropsch fuels could further contribute to this, provided that long-term partnerships with fixed purchase guarantees are established to create investment security.

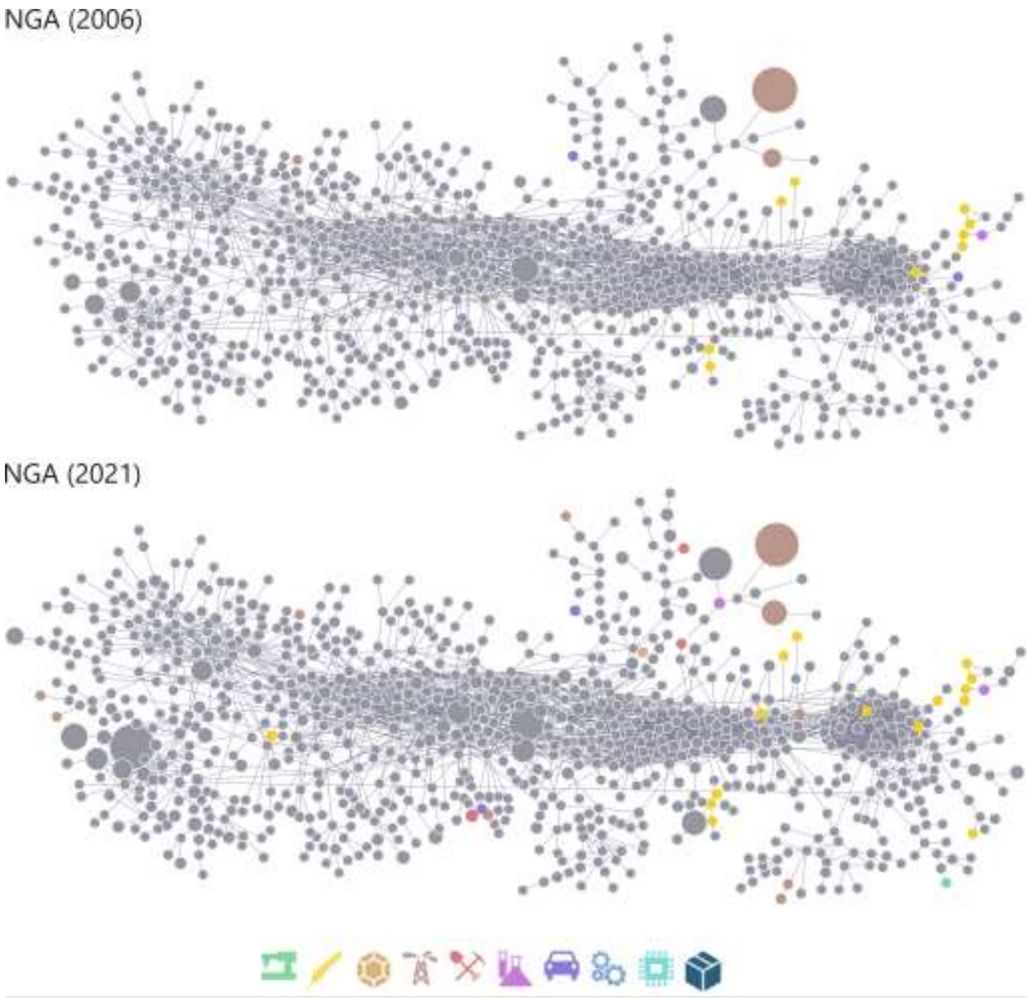


Figure 51: Product space representation of the goods exported by Nigeria in 2006 and 2021 with a comparative advantage, colored by product category (own representation based on Harvard Growth Lab (2023)

05

Conclusion

5 Conclusion

There is a consensus that the global demand for fossil fuels will decline drastically over the next decades. However, the various studies and scenarios projecting the future demand development (e.g. by the European Commission, International Energy Agency, BP and Shell) show a wide spectrum of possible development corridors ranging from 35% up to 75% decline in fossil fuel demand by 2050.

As of today, all three countries in focus of this study are strongly dependent on the export of fossil fuels but show varying characteristics in terms of their competitive position on the global fossil fuel market as well as their current economic structures and diversification potentials. This implies that they will be affected differently by the expected declining fossil fuel demand. The effects will manifest, not only in terms of lost export revenues, but also regarding secondary economic effects on the output in various economic sectors as well as on employment.

The economic sector 'Mining and quarrying of energy products' is central in all three countries' economies and contributes a large share to their exports. Overall, the 75% decline in fossil energy exports would mainly affect the energy mining industry itself, with reductions in output of up to 72%. This is due to the limited integration of the sector with upstream sectors and as also most of the downstream activities are located outside of the country. This low level of economic diversification and vertical sector integration is a typical phenomenon in economies heavily reliant on the export of fossil fuels (cf. Figure 52). The remaining impact on other domestic industries can be attributed to second-order effects on highly interrelated sectors, such as, 'Wholesale and retail trade repair of motor vehicles' in all three of the countries. Regarding employment effects, it is notable that, despite its high relevance in terms of economic output and export shares, the workforce employed in 'Mining and quarrying of energy' is rather marginal compared to the overall workforces, in all three countries. In this context it should also be regarded that especially the highly skilled workforce in the oil and gas industry (especially the highly paid engineering positions) is often hired from abroad, e.g. from the US or Europe, and therefore employment effects will not primarily affect the local workforce (as is the case in particular for Nigeria and to a lesser extent for Saudi Arabia).

The theoretical potential for the export of PtX products in all three countries is very high and exceeds both the local final energy demand as well as the expected global demand for hydrogen and efuels. The level to which an exploitation of these potentials and a competitive international trade of PtX products will be possible, though, depends on a large variety of factors. Besides the limiting effects of domestic capacities for producing and installing the required renewable energy installations and putting the required infrastructure in place, also social acceptance and land use conflicts as well as potential conflicts with reaching the national energy sector targets (in Nigeria notably the targets for enhancing electricity access for the population) will likely play a relevant role in this regard.

Generally, the techno-economic potential for green hydrogen production is notably high in all three countries with particularly high solar potentials in Saudi Arabia leading to potential LCOH as low as

40 USD/MWh in 2050. Additionally, the availability of existing gas pipelines that could be repurposed for green hydrogen export would be an additional competitive advantage through lowering transport costs to neighboring export countries. In Kazakhstan especially the wind energy potential is promising with associated LCOH at around 80 USD/MWh in 2030 and 50 USD /MWh in 2050. New port infrastructure around the Caspian Sea as well as pipelines to neighboring countries could offer favorable transport options for PtX products. Nigeria features high potentials for solar-PV based hydrogen production, even though the available land area is highly restricted due to the high population density, which is expected to increase further in light of the strong population growth in the future. LCOH for Solar PV for 2030 could range from 120 - 150 USD/MWh and 60 USD/MWh in 2050. Transport and pipeline infrastructure in Nigeria is currently unevenly distributed and more developed in the south of the country even though expansion plans for additional gas pipelines exist.

The political and economic framework conditions bear relevant risks in all three countries and are reflected in higher capital costs which, again, significantly affect the competitiveness of green hydrogen exports. Besides political risks also various barriers for business development and access to financing persist in all three countries. Addressing these factors and further reducing the cost of capital for RE projects should be a key measure to increase the competitiveness of local PtX industries.

The strong impact of local capital costs is also underlined when comparing potential export revenues for green hydrogen export of the three case study countries based on estimates of the price-elastic demand for green hydrogen in Germany, exemplary for the willingness to pay in a Central European country. Assuming price levels of 90 or 120 €/MWh potential profits derived from hydrogen exports would likely not suffice to fully compensate for the losses of fossil fuel profits in any of the three focus countries, as both volumes and margins can be expected to be significantly lower.

Nevertheless, significant export profits could theoretically be realized, especially if transport costs can be minimized. For Kazakhstan, for example, potential hydrogen export profits up to 7 billion $US could theoretically be realized, assuming a price of 120 € MWh and based on an export volume of 200 TWh. This potential profit would correspond to up to 87% of the 2021 crude oil export profits. For countries with higher production and transportation costs, such as Nigeria, exports would be less lucrative and would likely only be profitable in case of a higher willingness to pay for the PtX product, for example, in the frame of a strategic bilateral agreement.

In addition to the potential revenues directly generated through the export of green hydrogen or its derivatives, broader macro-economic impacts of the development of PtX sectors can be expected, notably economic impulses and job creation in upstream sectors of the PtX value chain. In comparison the economic impact of the electrolyzer capacity on the national gross output and employment will be rather small. Creating a favorable environment for the development of domestic wind and solar energy industries (with the related metal processing and mechanical and electrical engineering sectors) could therefore be a key strategy to maximize the economic benefits of PtX sector development. Further, positive second order-effects can be expected in sectors such as wholesale and trade, adding to compensating economic losses caused by declining fossil fuel exports.

The above results underline the pivotal importance of strategic economic diversification of the economies in order to enhance resilience and maximize a sustained domestic value creation.

Saudi Arabia is successfully developing its position as a global supplier of chemicals and realized a remarkable degree of diversification in this field over the past decade. The know-how in this sector could be transferred to green chemical products in the future and the government has already set targets for the production of blue and green ammonia for international trade. Targeted strategies should be developed for the evolution of the domestic electronics and mechanical engineering sectors, as these are currently much less developed but could become a major source of local value creation in the future against the background of the ambitious national renewable energy deployment targets.

For Kazakhstan particularly a further diversification in the metal processing sector could be a key strategy offering opportunities to boost the local demand for hydrogen and to potentially establish green steel as a new export commodity, for example to Europe. Similarly, green ammonia could be used to produce fertilizers for the European market. With the expected strong deployment of wind energy in the coming years, the development of a strong steel/metal industry could further maximize local value creation through supply of upstream products for the wind energy industry.

In Nigeria the economy diversification needs to be prioritized strongly, as besides the declining demand for fossil fuels also the corruption, i.e. oil theft, in the sector is causing significant economic damage to the country. Besides the increased exploitation of the various natural resources available in the country, a strategic field for diversification could be to target local fertilizer production, where green ammonia could be used in the future. This could, in the future, be a nucleus for the development of a more diversified chemical industry sector. The export of green methanol or Fischer-Tropsch fuels could be part of this strategy, in case that long-term partnerships with lucrative purchase guarantees could be established to create investment security.

06

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Appendices

Appendices

Table 8 Overview - Marginal cost of crude oil production cited by different sources

Definition	Unit	SAU	NGA	KAZ	Source
Upstream marginal cost of production	**2015 USD/bbl**	**2.9**	**5.3**	**5.3**	(Masnadi et al. 2021)
Total production cost	**2015 USD/bbl**	**9.9**	**31.6**	**27.8**	(CNNMoney 2015)
Operational expenditure	2015 USD/bbl	5.4	15.3	11.5	(CNNMoney 2015)
Capital expenditure	2015 USD/bbl	4.5	16.2	16.3	(CNNMoney 2015)
Total production cost	**2016 USD/bbl**	**8.98**	**28.99**	-	(Friedman 2016)
Production cost	2016 USD/bbl	3	8.81	-	(Friedman 2016)
Capital spending	2016 USD/bbl	3.5	13.1	-	(Friedman 2016)
Administrative/ transportation costs	2016 USD/bbl	2.49	2.97	-	(Friedman 2016)
Gross Taxes	2016 USD/bbl	0	4.11	-	(Friedman 2016)

Table 9 Overview of indicators for the regulatory framework for doing business in the three countries (World Bank 2020)

	Nigeria	Saudi Arabia	Kazakhstan
Overall "Ease of Doing Business"	**Rank 131 (Score 56.9)**	**Rank 62 (Score 70.9)**	**25 (Score 79.6)**
Starting a business	**105 (86.2)**	37 (93.1)	22 (94.4)
Dealing with construction permits	55 (73.6)	28 (78.3)	37 (76.5)
Getting Electricity	**169 (47.4)**	18 (91.8)	**86 (81.6)**
Registering property	**183 (29.5)**	19 (84.5)	24 (82.4)
Getting credit	15 (85)	**92 (55)**	25 (80)
Protecting investors	28 (72)	3 (86)	7 (84)
Paying taxes	**159 (53.7)**	62 (78.7)	64 (78.2)
Trading across borders	**179 (29.2)**	**86 (76)**	**105 (70.4)**
Enforcing contracts	73 (61.5)	51 (65.3)	4 (81.3)

Table 10 Assumptions and key numbers for the final energy demand projections

KAZ	GDP	FEI	FED
	billion 2017$PPP	kWh/ 2017$PPP	TWh
1990	220	3.15	694
2000	153	1.64	251
2010	339	1.33	451
2020	476	0.99	469
2030	715	0.65	464
2040	967	0.45	435
2050	1107	0.35	387

SAU	GDP	FEI	FED
	billion 2017$PPP	kWh/ 2017$PPP	TWh
1990	672	0.68	459
2000	867	0.97	841
2010	1208	1.35	1633
2020	1544	1.15	1770
2030	1784	0.90	1605
2040	2180	0.65	1417
2050	2497	0.50	1249

NGA	GDP	FEI	FED
	billion 2017$PPP	kWh/ 2017$PPP	TWh
1990	310	2.22	690
2000	364	2.50	911
2010	782	1.58	1237
2020	1014	1.57	1586
2030	1542	1.35	2082
2040	3015	0.85	2563
2050	5694	0.50	2847

Table 11 Baseline assumptions for country specific financing costs for RE projects

As explicit data on the cost of capital for renewable energy projects in the three case study countries is not publicly available, we have made the following baseline assumptions regarding the country specific WACC for renewable energy projects:

Nigeria: 13%

Kazakhstan: 11%

Saudi Arabia: 7%

The baseline assumptions are used for calculations of the techno-economic potential.

Table 12 Assumptions for assessment of potential export revenues

Scenarios:

- 2 cost levels 90 USD/MWh vs. 120 USD/MWh
- 2 levels of export volumes: 100 TWh vs. 200 TWh

Country specific supply cost in 2050 based on GIS analysis in 2021USD/MWh:

- KAZ 85 (wind + pipeline)
- SAU 90 (pv + LH2 ship)
- NGA 120 (pv + LH2 ship)

Oil total production cost per country from CNNMoney (2015) in 2021USD/MWh (converted using consumer price index from World Bank Open Data (2023b):

- KAZ 18.70
- SAU 6.66
- NGA 21.25

Comparison with 2021 Oil Exports

- KAZ 821 TWh (OPEC 2023) resp. 23.4 billion 2021 USD (Harvard Growth Lab 2023)
- SAU 3863 TWh (OPEC 2023) resp. 118 billion 2021 USD (Atlas of Economic Complexity)
- NGA 988 TWh (OPEC 2023) resp. 39.9 billion 2021 USD (Atlas of Economic Complexity)

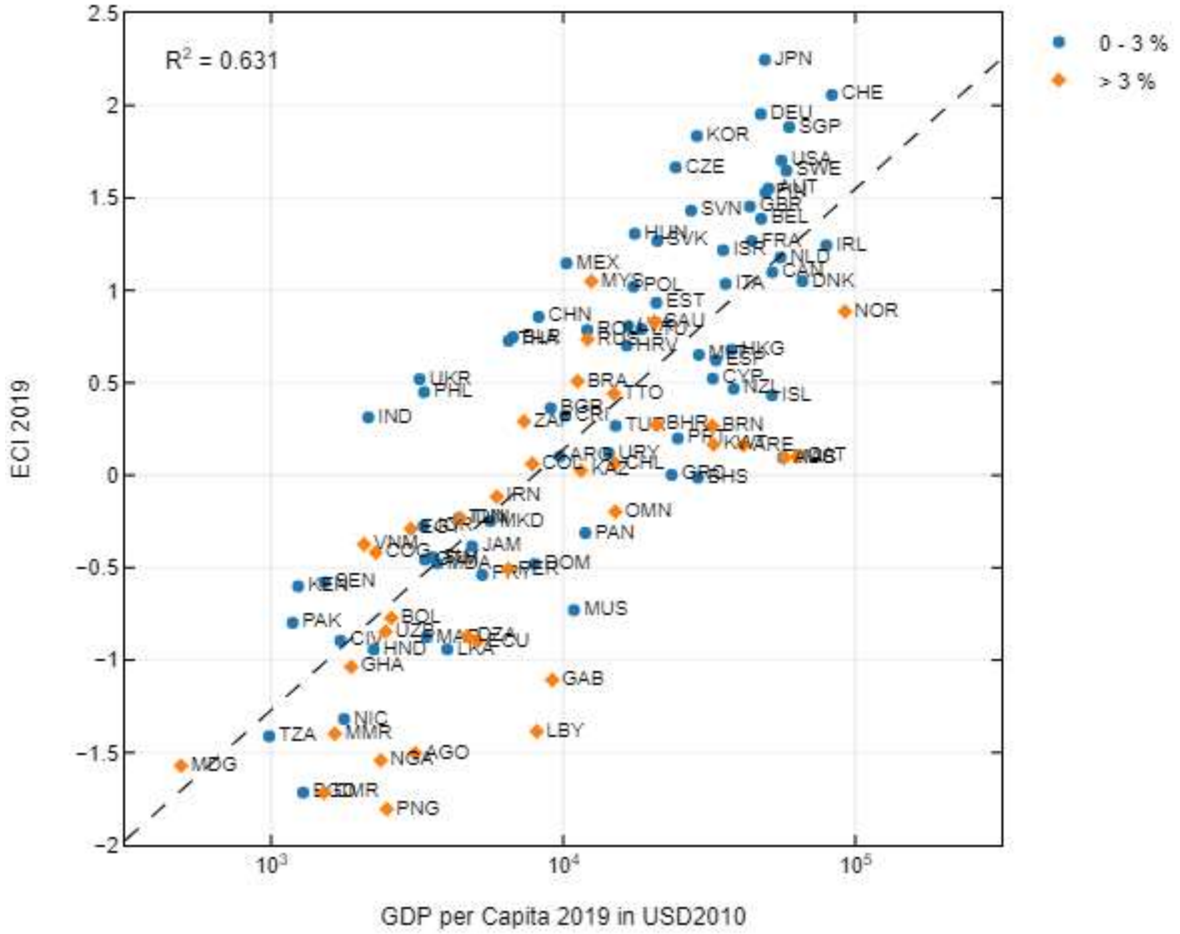

Figure 52: GDP per Capita 2019 in USD 2010 (Harvard Growth Lab 2023; Müller et al. 2023)

List of abbreviations

CAPEX	Capital expenditure
CBN	Central Bank of Nigeria
CCUS	Carbon capture use and storage
CSP	Concentrated Solar Power
ETP	Nigeria Energy Transition Plan
EU JRC	EU Joint Research Centre
FLH	Full load hours
GDP	Gross domestic product
GH2	Gaseous Hydrogen
ICIO	Intercountry Input-Output
IEA	International Energy Agency
IOA	Input-output analysis
IRENA	International Renewable Energy Agency
ISIC	International Standard Industrial Classification
KAZ	Kazakhstan
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Hydrogen
LH2	Liquid Hydrogen
MeOH	Methanol
NGA	Nigeria Energy Transition Plan
NH3	Ammonia
OECD	Organization for Economic Cooperation and Development
OPEC	Organization of the Petroleum Exporting Countries
OPEX	Capital expenditure
PtX	Power-to-X
PV	Photovoltaic
RE	Renewable energy
RES	Renewable energy sources
SAU	Saudi Arabia
SSP	Shared Socioeconomic Pathways
USGS	US Geological Survey
WACC	Weighted Average Costs of Capital