

Roadmap for the Development of Low Carbon Hydrogen in Uzbekistan

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Executive summary

7. Uzbekistan is a natural resource processor and exporter for which low-carbon hydrogen would be a rare opportunity to grow, diversify, and decarbonize its economy. **Natural gas is the lifeblood of the Uzbek economy** and energy system. Accounting for its share in electricity, natural gas fuels around 85% of Uzbek final energy consumption. This creates a socioeconomic dependency on natural gas, as industries, transport, and buildings all run on it. To a lesser but significant extent, Uzbekistan also incurs a financial dependency on natural gas. Rents from natural gas add up to 20% of GDP and around 15% of total exports by value. Uzbekistan exports 20% of its natural gas production to China, Kazakhstan and Russia via pipelines running from Turkmenistan through Uzbekistan and Kazakhstan. This unique geographic layout makes Kazakhstan, Turkmenistan, and Uzbekistan economically interdependent.

8. Uzbekistan's dependency on natural gas poses risks to its economy and energy security, but it also threatens Uzbekistan's role in the global energy transition. Gas importing countries will gradually switch to cleaner sources of energy and aim at discontinuing their natural gas dependency. This risk is smaller in the short to medium-term with Uzbekistan's main gas offtakers, China, Russia, and Kazakhstan. China for instance is still transitioning out of coal and expects its natural gas demand to grow by 5% annually from 370 bcm today to 600 bcm by 2030. However, beyond that horizon, China's renewable energy and hydrogen ambitions could threaten Uzbek natural gas exports. The **long-term risk of natural gas import demand shrinking due to energy transition policies** is the same with Russia and Kazakhstan. Kazakhstan for instance has implemented a CO_2 emission trading scheme and could be switching to low-carbon and renewable energy including hydrogen.

9. The context of a global energy transition should also shape the Uzbek energy strategy and markets from the inside, as **the country has started to express significant climate ambitions[1], as in its updated Nationally Determined Contribution (NDC) and its "Strategy for Transition to Green Economy by 2030"[2]**. This renewed policy momentum settles the floor for considering the development of low-carbon hydrogen in the country as a real alternative, cascading into other policies that set targets and the required regulatory framework. In particular, the Uzbek presidential office released a resolution "*On measures for the development of renewable and hydrogen energy in the Republic of Uzbekistan*". The resolution sets up institutions like the Research Center for Hydrogen Energy, calls for the preparation of a National Strategy for Development of Renewable and Hydrogen Energy, for a regulatory and incentive framework, and for pilot hydrogen projects. Importantly, the resolution also calls for international cooperation agreements, which could form the foundation of the future Uzbek low-carbon hydrogen trade network. Low-carbon hydrogen would be a new industry in Uzbekistan, but the country has ample experience with its end-use industries like ammonia, and which would be aligned with the recent turn of the country to prioritize the production of added-value products rather than exporting raw materials.

[1] Recent insights are discussed presented at: https://blogs.worldbank.org/climatechange/uzbekistan-policy-dialogue-builds-momentum-transition-green-economy

[2] The strategy is available at: https://policy.asiapacificenergy.org/node/3927#:~:text=The%20Strategy%20of%20the%20Republic,the%20principles%20of%20the%20%22green%22

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10. Low-carbon hydrogen could play a major role in decarbonizing and supporting the development of the Uzbek economy. **This report aims to evaluate the potential of low-carbon hydrogen in Uzbekistan through a scenario-based analysis**. Five scenarios are tested: a central scenario, two scenarios of high and low hydrogen demand (cf., Figure 1), and two scenarios of high and low natural gas availability (cf. Figure 24). The purpose of these scenarios is to guide the reader through corridors of possibilities, knowing that the determinants of hydrogen demand and resource availability to supply it, both encompass many uncertainties. This report acknowledges and discusses other modelling limitations and uncertainties. The economically rational trade model employed could inaccurately predict the outcomes of an added layer of geopolitical interplay between Uzbekistan and China or Turkmenistan. Infrastructure also remains a major source of uncertainty, both in terms of feasibility and true costs. Finally, uncertain water scarcity projections raise risks on low-carbon hydrogen production, but also to any economic activity entailing water consumption, and should be the focus of further research.

11. The central scenario of this report considers an annual growth of 7% from 2030 to 2050 for domestic hydrogen demand, reaching 2 MtH_2 per year by 2050. domestic hydrogen demand grows by over 7% annually from 2030 to 2050 and exceeds 2 MtH_2 per year in 2050. As figure 1 shows, demand for low-carbon hydrogen is subject to a myriad of uncertain factors that make confidence intervals necessary for some analyses. This report focuses on the results of a central scenario but also provides alternative scenarios exploring the impact of key dimensioning factors impacting the future of hydrogen in the country. The development of low-carbon hydrogen in Uzbekistan would likely follow a "hydrogen valley" (cluster) approach like it is currently the case in other geographies, relying on existing assets and industries to minimize the cost of building new ones and to secure offtake.

12. **Low-carbon hydrogen is not a silver bullet** that can single-handedly cut all greenhouse gas (GHG) emissions, but it can be used to deeply decarbonize the hard-to-abate sectors of the economy. Economic forces dictate the order in which low-carbon hydrogen can penetrate demand sectors. **Unabated hydrogen feedstock replacements would come first, followed by light refurbishments and finally capital-intensive asset replacements**. As such, economic theory dictates that energy-intensive industries makes up the lion's share of hydrogen demand in Uzbekistan, while heavy-duty road transport provides a lower but significant share of demand. In addition, even if the mining sector would only represent a marginal share of total demand for hydrogen and which most likely would be fulfilled onsite, it can be seen as a first-mover sector in adopting hydrogen technologies[3] due to the lower competitivity gap between using conventional fuels such as diesel for transport and other activities[4], in particular for high added-value minerals taking place in isolated sites with good renewable energy potential. As such, it can be considered as a test bed for scaling up the hydrogen industry in the country.

[3] Further details available at: https://www.accenture.com/us-en/blogs/chemicals-and-natural-resources-blog/mining-hydrogen-economy and https://www.mining.com/green-hydrogen-key-to-decarbonising-mining-report/

[4] Mining industry experts believes that "the industry is just "four or five years away from getting to TCO parity for heavy-duty trucks on mines that have to bring diesel to site by ship or truck" (Alfred Wong, Asia Pacific Managing Director at fuel cell provider Ballard Power Systems). Further information available at: https://hydrogen.energyandmines.com/files/hydrogens-role.pdf

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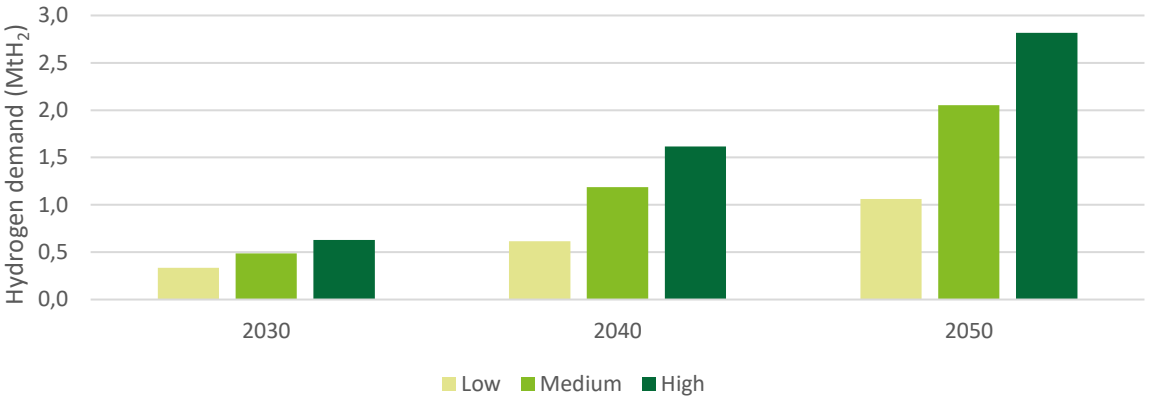
Figure 1. Scenarios of domestic low-carbon hydrogen demand in Uzbekistan



13. The economic "merit order" of hydrogen penetration is precisely what shapes low-carbon hydrogen demand in our results. Low-carbon hydrogen demand for methanol production reaches 760 ktH_2 per year in 2050, about 40% of total domestic demand. Methanol presents the double benefit of accepting low-carbon hydrogen as a plug-and-play input and of being a high-value and diverse product. Low-carbon hydrogen-based ammonia is another important plug-and-play source of demand, totaling 371 ktH_2 per year in 2050 in our medium scenario, or about 17% of total hydrogen demand in Uzbekistan. Ammonia is a high-value product for the Uzbek economy, being the essential component of fertilizers, which are then exported or used to enhance valuable crops. Industries that use low-carbon hydrogen for heating are another important source of local demand. The steel sector is a prime example of it: by 2050, hydrogen accounts for 30% of energy used in steel production in Uzbekistan, representing about 50 ktH_2 per year in 2050. Aggregating all other industrial heating end-uses yields a demand of 732 ktH_2 per year in 2050, or 34% of total demand in Uzbekistan in 2050. Regarding transport, half of road freight activity switches to hydrogen by 2050, resulting in low-carbon hydrogen demand of 140 ktH_2 per year.

14. Low-carbon hydrogen supply in Uzbekistan is promising thanks to the country's resources in renewable energies and gas. Abundant solar irradiation and strong wind potential in certain regions are suitable for the deployment of electrolysis-based hydrogen. Available gas fields and underground storage make a good business case for natural gas reforming with carbon capture and storage (CCS) or pyrolysis. Consequently, the highest in-situ levelized cost of low-carbon hydrogen shrinks from US $ 3/kgH_2 in 2030 to US $ 2/kgH_2 in 2050. However, the future of low-carbon hydrogen from natural gas will be defined by the trends of competitive uses of natural gas and by its potentially limited availability as a feedstock. Water scarcity also looms over the prospects of electrolysis-based hydrogen and natural gas reformers. Finally, hydrogen-ready transport infrastructure enables Uzbekistan to trade hydrogen with its neighbors and to export to the Chinese market, which is a massive commercial opportunity.

15. The Uzbek hydrogen market grows rapidly over time, after an initial push fueled by a rapid rise of domestic hydrogen demand, which incentivizes domestic production. Production growth spurs demand, which loops and snowballs over time into increasing hydrogen deployment rates. As shown in table 1 below, capacity starts to grow around 2030. Wind and PV capacity additions required up to 2030 are comparable to the official capacity targets for the power sector in the same time horizon, namely 5 GW of solar PV and 3 GW of wind. Blue hydrogen appears

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particularly competitive in our scenarios[5]. As such, the share of blue hydrogen in total demand is higher when total demand is lower. This shows that natural gas is used as a baseload energy source in the hydrogen mix: the role of blue hydrogen is to prop up the Uzbek market.

Table 1. **Production capacity additions per time period**

Technology	Unit	Up to 2030	2031-2040	2041-2050
Solar PV	GW	0	4 – 18	4 – 29
Onshore wind	GW	1 – 4	0.3	1 – 4
Electrolyzers	GW	1 – 3	3 – 11	6 – 33
GHR + CCS	GW	1	0.4 – 0.6	1 – 2.5
Pyrolysis	GW	0.1	0 – 0.1	0.2 – 0.3
SMR (in plans)	GW	1.7	0	0

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16. Beyond the domestic market, international trade of Uzbek low-carbon hydrogen takes time to ramp up. Over time, China's expected booming demand for low-carbon hydrogen will enable Uzbekistan to export part of its production at competitive prices. Around 2030, Kazakh, Uzbek and Turkmen will remain focused on their domestic markets respectively. By 2040, regional trade starts to develop and seems to be relevant for clusters near the border. However, it remains marginal at around 0.2 MtH_2 in 2050, and mainly occurs between Turkmenistan and Uzbekistan. Large-scale exports truly begin in 2040, when a repurposed line of the Central Asia – China pipeline is assumed to come online. This line enables Kazakhstan, Uzbekistan, and Turkmenistan to export hydrogen to the booming Chinese market. In 2050, exports reach more than 2.6 MtH_2, with nearly 0.9 MtH_2 from Uzbekistan, which is a third of his production and are enough to turn the trading balance positive, reaching an export value of about US $ 2 billion by 2050 as shown in the figure below.

[5] The scenarios assume official natural gas reserve figures, decreasing natural gas demand in other uses (mainly for power generation), rather stable production levels and decreasing exports, which are preconditions ensuring the natural gas availability for LCH production. Further details are presented in section 2.2.2.

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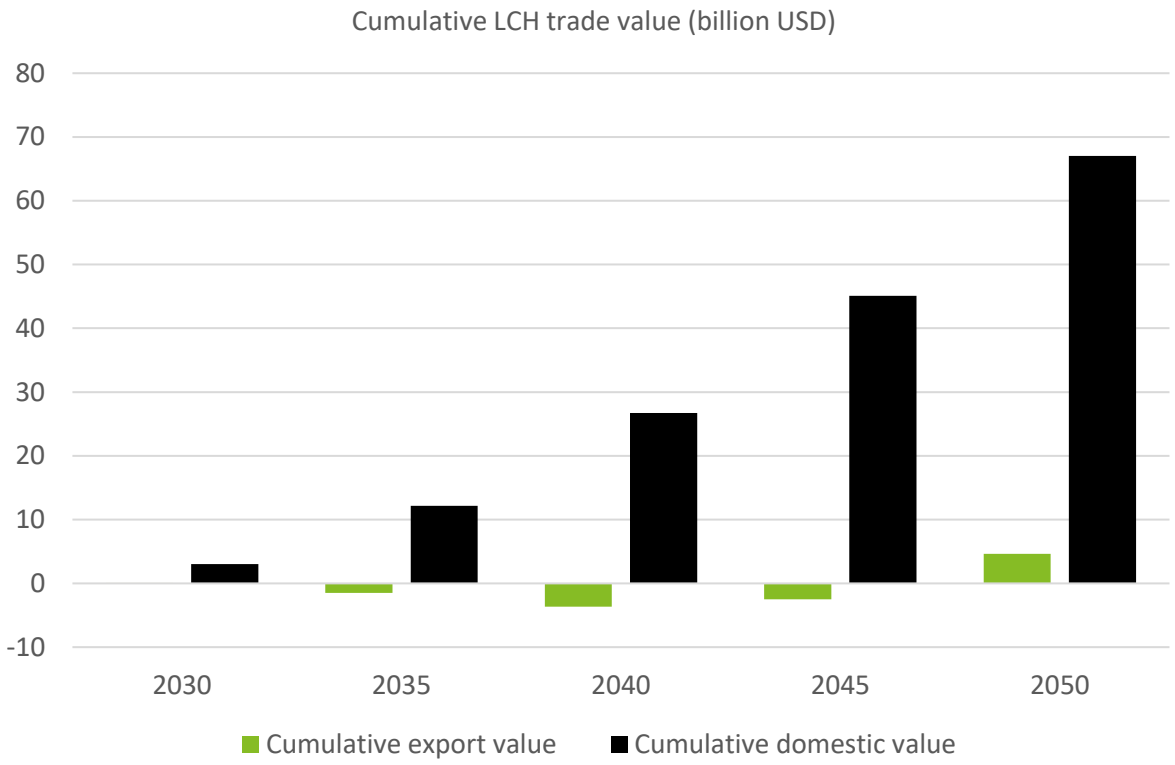
Figure 2. Value of domestic and export hydrogen markets for Uzbekistan, 2030-2050



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17. Low-carbon hydrogen exports are thus a long-term possibility for Uzbekistan, whereas the domestic market brings the most economic value until 2050. Nonetheless, developing LCH exports as a long-term strategic plan still means that the country should encourage hydrogen exports-related projects long before 2050. Interregional trade is possible and beneficial early-on, and local demand will grow together with overall supply. Infrastructure will also take significant time and funding to be commissioned. Similar than for the natural gas industry, a close strategic coordination around LCH topics with China and other trading partners must also be put into the agenda.

18. In the central scenario there are nearly US $ 45 billion of investments over 25 years in hydrogen production alone in Uzbekistan. This requires actions from policymakers and private investors alike to lower the cost of financing hydrogen projects and make them come online timely.

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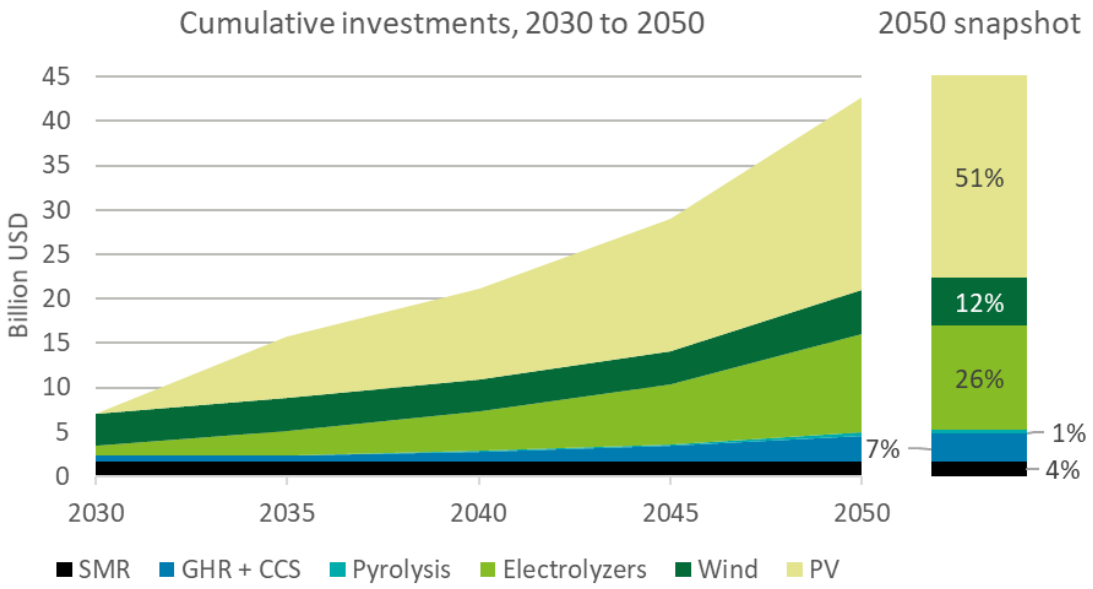
Figure 3. Cumulative investments required in hydrogen production technologies and dedicated renewable power generation in Uzbekistan, in billion USD and CAGR, 2030-2050



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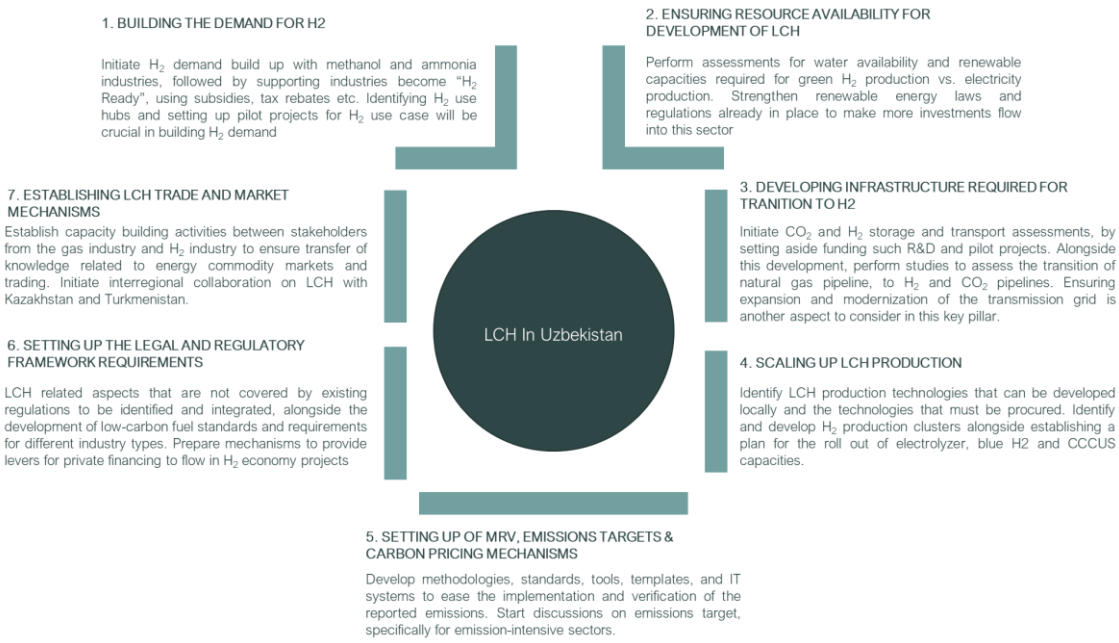
19. Based on the findings of the contextual and modelling parts of this report, we provide a roadmap for the development of low-carbon hydrogen in Uzbekistan, built around key recommendations. Figure 4 summarizes the key recommendations and pillars required for the development of LCH in Uzbekistan.

Figure 4. Key pillars for the development of LCH in Uzbekistan



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- **Building demand for hydrogen within Uzbekistan:** demand pilots should begin with methanol and ammonia production industries, followed by scale-up in in the hard-to-abate sectors. Supporting pilot projects will help make industries "hydrogen-ready" faster.

- **Ensuring resource availability for the development of low-carbon hydrogen:** Low-carbon hydrogen production would increase freshwater consumption by 6.77.3 Mt by 2030, while Uzbekistan is already water-stressed, requiring an in-depth assessment of water availability prospects. Likewise, a detailed evaluation of the country's huge renewable energy potential and a regulatory overhaul would ensure that targets and policies live up to this potential.

- **Developing the infrastructure required for enabling transition to hydrogen:** the first step towards transitioning from grey to LCH is the development of knowledge on CO_2 and hydrogen storage and transport. As of today, there's no detailed assessment on CO_2 storage potential and locations in Uzbekistan. Funding must be set aside for a thorough analysis of CO_2storage potential in the country. The first step would be the development of a CO_2 storage atlas for Uzbekistan. Broader scope can include the neighboring countries: Kazakhstan and Turkmenistan. The atlas will show total CO_2 storage capacity available in the country(s) and indicate the locations most suitable for it.

- **Scaling up low-carbon hydrogen production in Uzbekistan:** Uzbekistan has experience with various technologies comprising the LCH value chain. Most of the capabilities come from the oil and gas and energy sectors. As a starting point it is important to identify LCH production technologies that can be developed locally and the technologies that must be procured. The country can utilize its existing knowledge from the grey hydrogen production to develop the required capacity within the production of blue hydrogen. The government should establish a plan for the roll out of electrolyzer technology as well. As for blue hydrogen production it should be organized through public-private projects taking the technology from the laboratory to the commercial scale. Based on the results of the study the government should facilitate the development of pilot hydrogen production clusters with the objective to test the entire LCH value chain (hydrogen production, transport, use and storage). Capacity building programs for local workforce and industry stakeholders to improve knowledge and competences in LCH energy projects and skills needs to be considered to enable scale-up of LCH production in the country.

- **Setting up MRV, emission targets and carbon pricing mechanisms:** considering the liquid oil and gas market and the subsidies existing in the market, the cost of LCH is considerably higher than using fossil fuels directly. Carbon pricing mechanisms should be considered to push for the use and production of low carbon fuels such as LCH. In the short term, carbon tax on certain high emitting sectors could be beneficial to test the taxing mechanisms and to eventually include other sectors to the plan. The underlying system required for introducing carbon pricing mechanisms in a country would be the establishment of a monitoring, reporting and verification system (MRV). The setting up of an MRV system will require the development of methodologies, standards, tools, templates, and IT systems to ease the implementation and verification of the reported emissions by different sectors. Alongside the development of the MRV system, conversations on emissions target, specifically in emission-intensive sectors should be initiated. Support required for implementation of decarbonization plans in the form of climate finance, capacity building and technology transfer should be established.

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- **Setting up the legal and regulatory framework requirements:** following the laws and regulations targeting renewable energies in the country, elements related to LCH value chain should be included within the existing rules. Incentives, tax rebates and dedicated funding to stimulate investments in R&D for LCH technologies, and developments along the LCH value chain are factors to be considered while developing the legal and regulatory framework to support the hydrogen development; The government of Uzbekistan should facilitate the development of hydrogen safety codes and standards as they are critical for the commercialization of hydrogen-based products and systems. In addition, creating technical standards for all parts of LCH value chain (production, transport, storage, distribution, conversion) is necessary. Establishing international cooperation frameworks to foster these matters would be beneficial for the country.
- **Establishing low-carbon hydrogen trade and market mechanisms:** trading hydrogen with Turkmenistan and Kazakhstan will be a strategic advantage for the three countries. To prepare for that, interregional collaboration in the field of LCH should be established. As Uzbekistan is a land locked country, it has historically developed trading relations with neighboring Kazakhstan and Turkmenistan, which can form a solid base for the cooperation on LCH. It is important to develop milestones for interregional hydrogen trade based on the LCH production potential and demand in each country. This can be achieved through the dialog between relevant stakeholders in the region, in particular with those sharing similar climate ambitions. At the same time, dialogs and coordination with China should also be put into the agenda since it is likely to be the natural trading partner of LCH for the three countries as it currently is for natural gas.

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List of acronyms and symbols

ATR	*Auto-Thermal Reforming*
BAU	*Business As Usual*
Bcf	*Billion Cubic Feet*
Bcm	*Billion Cubic-Meter*
Bcm	*Billion Cubic Meter*
CBAM	*Carbon Border Adjustment Mechanism*
CCS	*Carbon Capture and Storage*
CCUS	*Carbon Capture, Utilization and Storage*
CO_2	*Carbon Dioxide*
CO_{2e}	*Carbon Dioxide equivalents*
US $	*U.S. dollar*
DRI	*Direct reduced iron*
EAF	*Electric arc furnace*
EBRD	*European Bank for Reconstruction and Development*
ETS	*Emissions Trading System*
GDP	*Gross domestic produc*
GHG	*Greenhouse gas*
GHR	*Gas Heating Reforming*
GTL	*Gas-to-Liquids*
GW	*Gigawatt*
H_2	*Hydrogen*
IFI	*International Financial Institutions*
km^2	*Square kilometre*
kt	*Kilo-tonne*
kWh	*Kilowatt hour*
LCH	*Low Carbon Hydrogen*
MoU	*Memorandum of Understanding*
MRV	*Monitoring Reporting and Verification*
Mt	*Million tonne*
NDC	*Nationally Determined Contribution*
NH_3	*Ammonia*
PMR	*Partnership for Market Readiness*
R&D	*Research and Development*
SMR	*Steam Methane Reforming*
tkm	*Tonne kilometer*

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Introduction

The government of Uzbekistan has initiated an ambitious transition to clean energy under the impulse of the 2015 Paris Agreement to contain increasing temperatures below +2°C by 2100. Upon signing the Paris Agreement, Uzbekistan and other United Nations Framework Convention on Climate Change agreed to reach Net Zero CO2 emissions by 2050. Two years later, in April 2017, Uzbekistan released its Intended Nationally Determined Contribution (NDC). The Uzbek NDC pledges a reduction of greenhouse gas (GHG) emissions per unit of GDP by 10% by 2030 against 2010 levels. Between the end of the Soviet era and 2010, the country's GHG emissions increased by only 10% while its GDP grew by nearly 200%. To that end, the Uzbek NDC's 10% target aims to reconcile the dual objectives of maintaining sufficient economic growth while reducing emissions.

In May 2021 the World Bank framed the potential for the development of a hydrogen economy in Uzbekistan. Its analysis concluded that hydrogen could be on par with fossil fuels by 2030 and advised developing a Hydrogen Development Strategy and Roadmap as a way forward.

Hydrogen, as a flexible energy carrier that produces zero-emissions when combusted, is widely seen as a key element of the global decarbonization effort to reach the Paris Agreement targets. Hydrogen has several pathways of production including conventional production from natural gas (grey hydrogen), production from natural gas but with CO_2 capture, storage or utilization (blue hydrogen), methane pyrolysis (turquoise hydrogen) and production using renewable-powered electrolysis (green hydrogen). Only low-carbon hydrogen (LCH) technologies, such as blue, turquoise, and green hydrogen, are consistent with the Paris Agreement targets, and then only when emissions associated with the entire natural gas and renewable supply chains are also addressed. This study assesses the technical potential for LCH in the country by modelling the role of LCH to enable a sustainable and resilient economy in line with climate mitigation commitments and the Paris Agreement. The study proposes develop a roadmap with the actions and milestones of the country level.

This report is a collaboration effort from Deloitte, Carbon Limits and the World Bank to analyze the potential of low-carbon hydrogen in Uzbekistan in the aforementioned context of the Uzbek clean energy transition. Focusing on Uzbekistan, the core of our combined analyses pays attention to geographical details. Nonetheless, as for natural gas, international trade of low-carbon hydrogen or derived products can be of interest and play a role in the country strategy. The international market of low-carbon hydrogen is an integral part of this analysis, albeit under a less granular lens. To that end, we assess the interplays of Uzbekistan's hydrogen-related value chains with those of neighboring CIS countries but also with other possible trading partners. Moreover, the study assesses different pathways to understand key aspects for the development of low-carbon hydrogen in the country and set goals for making the industry operational towards 2050.

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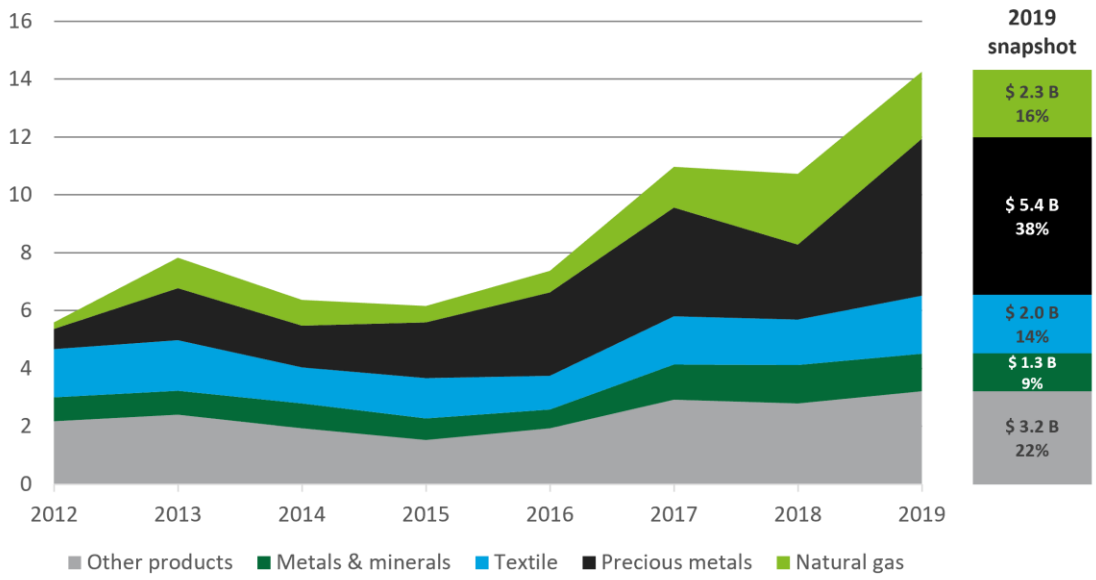
1 The energy sector in Uzbekistan and the role of low-carbon hydrogen

1.1 Energy profile of Uzbekistan

21. Uzbekistan's economy is largely based on the extraction and exports of minerals and fossil fuels. As figure 5 shows, gold is the top export product of the country, representing about US $ 5.4 billion in 2019, or nearly 40% of total exports by value that year. Throughout the 2010s, the main buyers of Uzbek gold have been Switzerland, Russia and the UK[6]. The Uzbek export industry is also highly specialized in textile, clothing, and related articles, which make up the bedrock of the country's export revenues with a yearly stream of US $ 1.5 to 2 billion. Around 10% of the country's export revenues come from the sale of copper, zinc, lead, molybdenum and other metals and minerals, though most of them are sold raw, i.e., non-finished. The remaining trade revenues come from a mix of sectors ranging from the agroindustry to chemicals and car-making. Overall, total Uzbekistan export value has increased by 2.5 times between 2012 and 2019 (see figure 5), making trade a vital aspect of its economy.

Figure 5. Uzbek exports by product, 2012 – 2019 (billion USD)



Deloitte 2022, based on data from the Observatory of Economic Complexity

22. In many ways, natural gas is an anchor of the Uzbek energy system and a key driver of its economic growth. Natural gas rents add up to 20% of GDP and around 16% of total exports by value, as figure 5 shows. However, its public revenue-generation role is overshadowed by its importance in the Uzbek domestic energy system. The figure 6 representing the share of natural gas in the Uzbek energy shows that the shares of natural gas in primary energy supply and in

[6] Source for export revenue statistics cited in this paragraph: Observatory of Economic Complexity (OEC).

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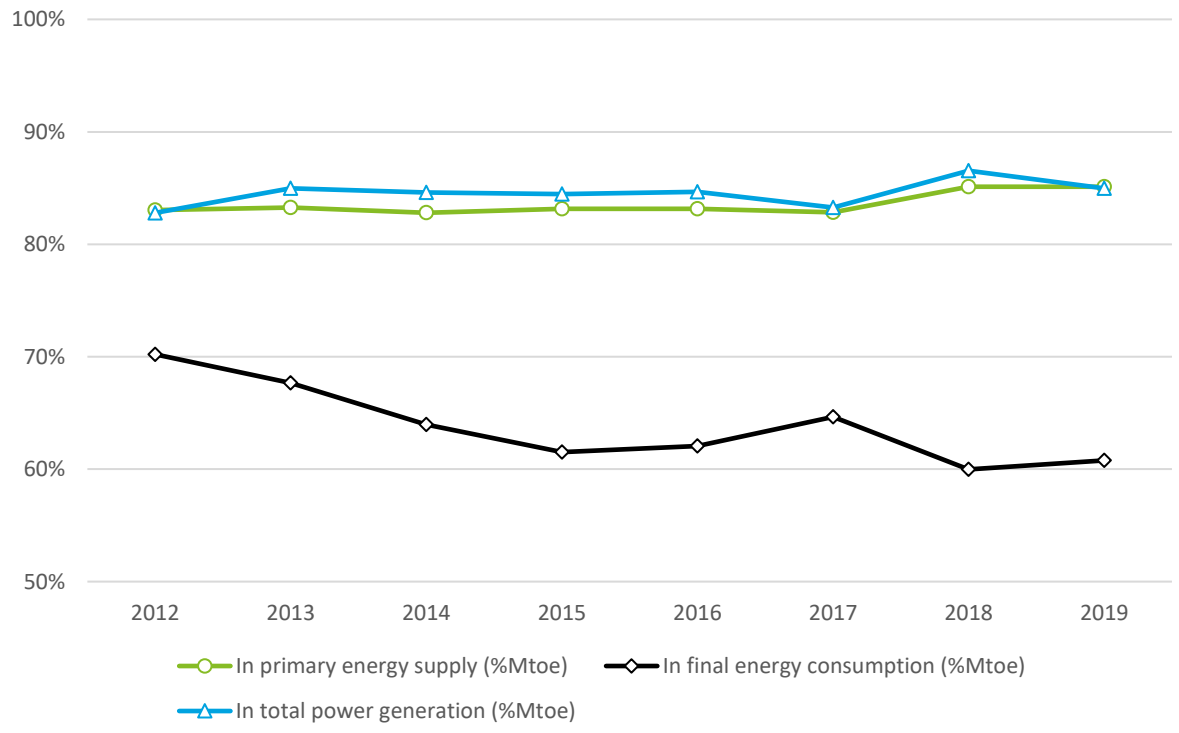
power generation hover around 85% from 2012 to 2019. Uzbek energy exports -exclusively natural gas- account for less than 20% of its total production and imports of energy, compared to 60% for Kazakhstan and Turkmenistan, which sell both oil and gas. Uzbekistan's less aggressive natural gas export strategy compared to its neighbors is in part explained by the role natural gas plays in its system and by its relatively limited reserves[7]. Uzbekistan runs on natural gas, but does not have a lot to spare for exports.

23. Nonetheless, 20% of Uzbek natural gas production is exported, mainly to China, Kazakhstan, and Russia. As a landlocked country with no shared border with China and Russia, Uzbekistan must send its gas through other countries. Fortunately for its natural gas exports, Uzbekistan stands astride a vast network of gas pipelines. The largest pipeline is the Central Asia – China gas pipeline, which connects Turkmenistan to the West – East Chinese pipeline via Uzbekistan and Kazakhstan. This unique geographic layout makes Kazakhstan, Turkmenistan, and Uzbekistan economically interdependent.

Figure 6. Share of natural gas in the Uzbek energy



Deloitte 2022, based on IEA and OEC data

[7] Official sources report proven Uzbek natural gas reserves stood at 2.24 tcm in 2019 and are estimated to last for another 30 years, or 40 years at current production rates of 49.3 Mtoe/year ("*Government of the Republic of Uzbekistan 2018, Gazeta Uz 2019"*, IEA Sankey 2020). Furthermore, the government has plans to explore unconventional gas potential in the country in partnership with the USGS agency. Further details available at: https://eurasianet.org/uzbekistan-us-to-lend-helping-hand-in-shale-gas-exploration

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1.2 Challenges and opportunities of Uzbek's energy industry

1.2.1 Energy security and diversification

24. Natural gas being the lifeblood of the Uzbek energy system it exposure to supply disruptions or long-term depletion raises concerns for the entire economy. Moreover, being heavily dependent on natural gas export revenues (16% of total exports as shown in figure 5), Uzbekistan is exposed to considerable socioeconomic and financial risks related to commodities' "boost and burst". As the COVID pandemic and the Ukraine war in Europe has shown, commodity prices can be fickle in times of geopolitical uncertainty. Moreover, with increasing concerns on decarbonization in key economies, in the longer-term, fossil fuel market prospects could be at risk.

- With 18.2 Mtoe of final energy supplied from natural gas out of 30 Mtoe, a disruption in gas supply could lead to shortages that would cripple entire chunks of the Uzbek economy, as displayed in figure 7. Half of the transport sector and two-thirds of the industry and buildings sectors would be on pause. Moreover, accounting for the natural gas used to produce 7.42 Mtoe of electricity and heat, up to 83% of final energy consumption could be compromised by gas shortages[8]. This level of dependency on a single source of energy bears serious risk on the core functioning of the Uzbek economy.

- The global energy transition poses threats to gas offtakers progressively switching to cleaner sources of energy and aiming at discontinuing their natural gas dependency. This risk is smaller with Uzbekistan's main gas buyers, China, Russia, and Kazakhstan[9]. China for instance is still transitioning out of coal and expects its natural gas demand to grow from 370 bcm today to 600 bcm by 2030, a 5% compound annual growth rate[10]. However, beyond that horizon, China's renewable energy and hydrogen ambitions could threaten Uzbek natural gas exports. The long-term risk of shrinking markets in the face of the transition is the same with Russia and Kazakhstan. Kazakhstan for instance has implemented a CO_2 emission trading scheme[11] and could be switching to low-carbon and renewable energy including hydrogen.

- Increased competitiveness of other sellers of natural gas, or alternative products, raises the risk of Uzbekistan losing grip on its current customer base. For example, Russian gas could be rerouted to internal uses or to China in response to the EU's boycott of Russian imports. In such cases, branching out to other countries is difficult given Uzbekistan's location[12]. The European market could be reached through, among other routes, Iran then Turkey or Kazakhstan then Russia, but this could prove politically challenging. Open seas are too far to make Japan a profitable market for Uzbek natural gas. European and Japanese natural gas demand is also likely to shrink rapidly as they switch to clean energies. Lastly, Afghanistan has no operational gas pipelines and blocks the way into Pakistani or Indian gas markets.

25. These risks call for economic diversification and heightened security of supply, both of which can be brought about with the emergence of a low-carbon hydrogen economy in Uzbekistan. Moving to low-carbon hydrogen would also help decarbonize domestic demand as gas reserves wane

[8] Source: own calculations based on data from the IEA (2020).
[9] See for instance the 2021, 2020, 2019, and 2018 editions of BP's Statistical Review of World Energy.
[10] Source: National Energy Administration of China, *Natural Gas Development Report* (2021).
[11] Source: World Bank blog (available online, 17 June 2021).
[12] For an overview of global gas pipeline networks, see Snam's global natural gas pipeline atlas.

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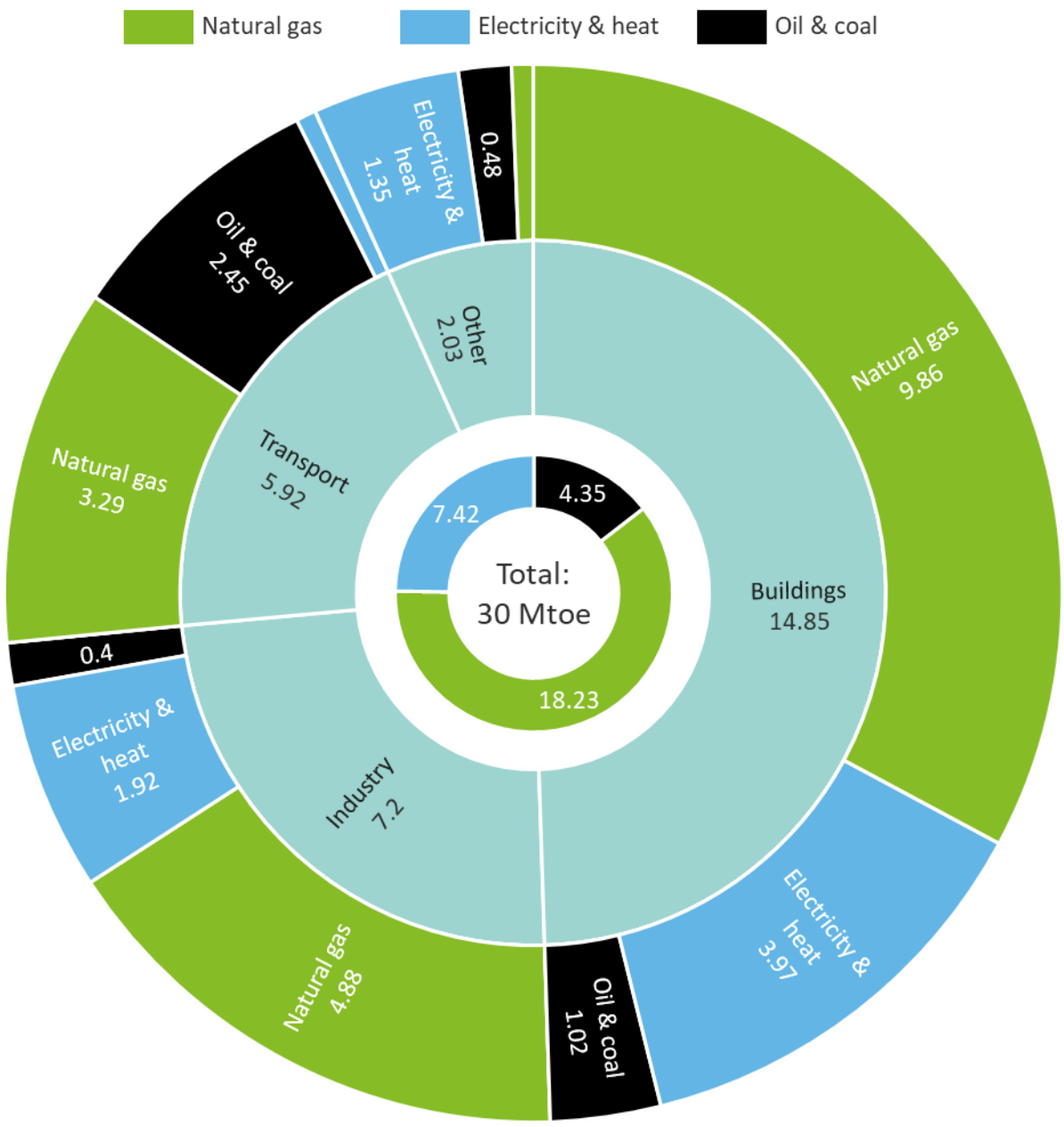
over the next 30-40 years[13]. To grow fast enough, not only an important development of renewables and electrolyzers would be required, the buildup of the hydrogen economy could entail some hydrogen made from natural gas, whose availability is within the control of Uzbek policymakers. This control means natural gas-made low-carbon hydrogen can be a viable alternative to ramp-up the hydrogen market while transitioning out of using waning natural gas reserves.

Figure 7. Final energy consumption of Uzbekistan in 2019



Deloitte 2022, based on data from the IEA (2020)

[13] Assuming historical gas consumption levels remains steady.

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1.2.2 Climate ambitions

26. Uzbekistan joined the United Nations Framework Convention on Climate Change (UNFCCC) in June 1993 and the UN Paris Climate Agreement in April 2017. In September 2021, the country reconfirmed its commitment to achieving the Paris Agreement goal. In its second Nationally Determined Contributions (NDC) Uzbekistan increased its commitments more than 300 percent, with plans to reduce greenhouse gas emissions per unit of GDP by 35% of 2010 levels by 2030, compared to the 10% reduction stated in the first NDC [14] An overview of 2030 NDC targets by the area of interest are presented in the table below.

Figure 8. Key climate targets for Uzbekistan

Sector covered	Sub-sector	Target	Source document
Whole economy	All	10% reduction in tCO_2/GDP by 2030 against 2010 baseline	Uzbekistan Nationally Determined Contribution (last update 30 Oct 2021)
Whole economy	All	50% reduction in energy intensity of GDP by 2030	Presidential Decree PP-4477 (October 2019)
Electricity	All	Net zero electricity sector across the country by 2050	A carbon-neutral electricity sector in Uzbekistan (February 2021)
	Renewables	35 new hydropower plants (HPPs) totaling 1537 MW	Concept note for ensuring electricity supply in Uzbekistan 2020-2030 (April 2020)
		27 modernized HPPs adding an extra 186 MW of capacity	
		3 GW of wind power by 2030	
		5 GW of solar power by 2030	
Energy	Gas	Zero routine gas flaring by 2030	World Bank Zero Routine Flaring initiative (2021)

Summary based on the documents listed in the table

27. The power sector produced about 57.5 TWh in 2019[15] out of which 89% comes from fossil fuels and 11% from hydro in 2020. In the way for a power sector with net-zero emissions by 2050, the country's official targets in terms of installed capacity are presented in figure 9. The mid-term ambitions of the country are significant, they consist of expanding renewable and natural gas capacity while retiring old coal-fired power plants. More specifically, by 2030 the country aims at installing between 5 GW and 7 GW of new solar power, between 3 GW and 5 GW of wind, about 1.9 GW of hydro and about 4.9 GW of natural gas-fired power plants. This represents a compound

[14] Republic of Uzbekistan, Updated Nationally Determined Contribution, 2021, Retrieved from: https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Uzbekistan%20First/Uzbekistan_Updated%20NDC_2021_EN.pdf, on 1 April 2022

[15] Based on IRENA country profile statistics. Retrieved from: https://www.irena.org/IRENADocuments/Statistical_Profiles/Asia/Uzbekistan_Asia_RE_SP.pdf

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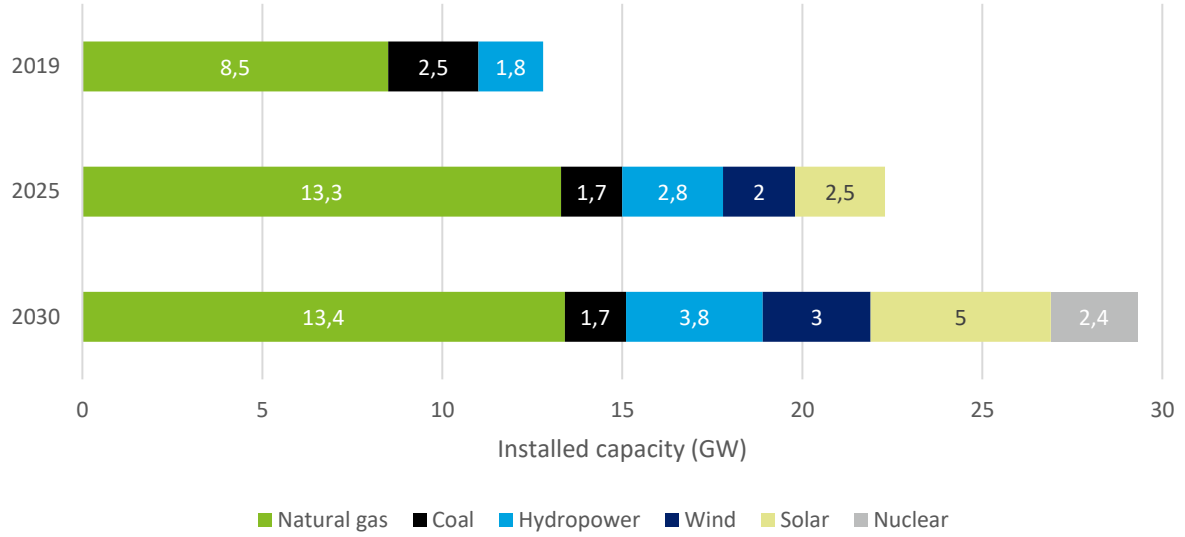
growth rate of at least 8% over the period which would require significant reforms and steady investments in the sector.

Figure 9. Targeted electricity mix in Uzbekistan



Source: Concept note for ensuring electricity supply in Uzbekistan 2020-2030 (April 2020)

28. The country's NDC indicates that Uzbekistan is focused on tackling climate change and keen on introducing environmentally friendly sources into the country's energy mix. The country has also signed a memorandum of understanding with the ERBD to elaborate long-term strategies compatible with the Paris Agreement[16]. Granted that it will lead to further incentives and laws to encourage the energy transition, the NDC is a solid base for developing low-carbon hydrogen (LCH) in the country. Hydrogen production, transport and storage can take various forms taking advantage of the best available resources in the country. The following section introduces the hydrogen production pathways, hydrogen transport and storage and costs based on relevant and recent sources.

29. Overall, the business case for the development of low-carbon hydrogen in Uzbekistan is strong. First, this business case stems from the needs to promote economic diversification and bolster energy supply security in a country with a strong socioeconomic dependency on natural gas. This argument is reinforced by waning natural gas reserves, which call for diversification -though some natural gas will be used to prop up the nascent low-carbon hydrogen industry. Second, this business case rests on the need to contribute towards the country's current and future climate goals, at country-level but also more specifically in its hard-to-abate sectors. As such, this business case depends to a large extent on the Uzbek policy framework for hydrogen. Incentives will be required to switch to hydrogen, be they carrot (hydrogen subsidies) or stick (CO_2 pricing). In addition to setting up incentives, policymakers must reduce developmental barriers. Low-carbon hydrogen answers a need for economic diversification, security of supply, and geopolitical relevance, but it requires policy actions, the likes of which are described hereafter in this report.

[16] Further information available at: https://www.ebrd.com/work-with-us/projects/tcpsd/15822.html

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1.3 Hydrogen as a promising alternative industry for the country

1.3.1 Hydrogen classification: production pathways, color shades and CO_2 intensities

30. With the expected growing demand for hydrogen at the global level, several hydrogen production pathways are being explored[17]. As of today, not all production pathways allow hydrogen production in significant quantities (see table 2) and cost reduction could be achieved with increasing maturity and economies of scale. Another important aspect to consider is the CO_2 emission footprint associated with each technology. In the context of climate change mitigation, it is important to look at the overall energy and GHG intensity of the hydrogen produced, to assess how much abatement can be effectively achieved by shifting energy uses to hydrogen. In addition, the water intensity of each of the production processes is also relevant. Water consumption should be carefully assessed since water resources are likely to become rarer in the future.

31. While several hydrogen production pathways and technologies are still under development, a they use to be categorized by colours. The colour spectrum reflects the feedstock used for the hydrogen production process and is considered a 'code-name' to describe different 'types' of hydrogen. This classification might change by country and may change over time. Table 2 describes the most common 'color-codes' for hydrogen.

Table 2. Hydrogen colour classification

	Colour	Fuel Used	Technologies	Description[18]	Max. scale of plant in operation as of 2022
1	Grey hydrogen	Coal or Natural Gas	Typically, uses thermochemical processes	Fossil fuels such as natural gas or coal are used for the production process, and the CO_2 generated is not captured or treated. Typically uses thermochemical processes such as steam methane reforming (SMR) and autothermal reforming (ATR), gasification for production of hydrogen. Typically, when black coal is used as fuel, this hydrogen is referred to as **black** hydrogen, and **brown** hydrogen when brown coal is used. This category of hydrogen has the highest direct CO_2 emissions associated with the production process.	>300 ktH_2/y

[17] Further detail on hydrogen production technologies is provided in appendix 6.

[18] H2 Bulletin, H2 colour codes, Retrieved from: https://www.H2bulletin.com/knowledge/hydrogen-colours-codes/#:~:text=These%20codes%20are%3A%20green%2C%20blue,emission%20during%20the%20production%20process., on 23 October 2021.

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	Colour	Fuel Used	Technologies	Description[18]	Max. scale of plant in operation as of 2022
2	 Blue hydrogen	Natural Gas, Biomass	Typically, uses thermochemical processes	The production pathway is similar to grey (or brown / black) hydrogen, but most of the CO_2 is captured, stored or utilised making the blue hydrogen process low carbon. **Blue** hydrogen has lower CO_2 emissions compared to grey category hydrogen, due to the combination with carbon capture and storage (CCS) technologies. As for grey hydrogen with natural gas, the emissions along the natural gas value chain need to be considered while assessing the emissions from blue hydrogen. The blue hydrogen presented in this study has 'net-zero' emissions, as the direct emissions after CCS application and the emissions along the gas value chain have been economically offset.	300 ktH_2/y[19]
3	 Turquoise hydrogen	Natural Gas	Typically, uses thermochemical processes	When natural gas pyrolysis is used for hydrogen production, this hydrogen is referred to as **turquoise** hydrogen. The byproduct of the pyrolysis process is gaseous hydrogen and solid carbon, known as carbon black. The CO_2 emissions associated with this process depend on the source of heat for carrying out the pyrolysis process.	5 ktH_2/y[20]
4	 Green hydrogen	Solar, Wind, Hydro	Typically, electrolysis is used, solar water splitting could be included in the future	Electrolysis of fresh water is used, involving electrochemical reactions. The production process requires electricity supply, provided using renewable energy sources such as solar and wind electricity. Green hydrogen has zero to near zero direct CO_2 emissions during the production process.	~3 ktH_2/y[21]

[19] Government of Canada, Shell Canada Energy Quest Project, Retrieved from: https://www.nrcan.gc.ca/science-and-data/funding-partnerships/funding-opportunities/current-investments/shell-canada-energy-quest-project/18168, on 27 January 2022.
[20] Recharge, Turquoise hydrogen leader awarded $1bn US government loan to expand commercial facilities tenfold, Retrieved from: https://www.rechargenews.com/energy-transition/turquoise-hydrogen-leader-awarded-1bn-us-government-loan-to-expand-commercial-facilities-tenfold/2-1-1139660, on 27 January 2022.
[21] Hatch, Bécancour green hydrogen plant, Retrieved from: https://www.hatch.com/Projects/Energy/Becancour-Green-Hydrogen-Plant, on 27 January 2022.

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	Colour	Fuel Used	Technologies	Description[18]	Max. scale of plant in operation as of 2022
5	Pink hydrogen	Nuclear [22]	Typically, electrolysis is used	Uses electrolysis for hydrogen production, however the source of electricity is nuclear energy. Pink hydrogen is also referred to as **red, yellow, or purple** hydrogen. The direct GHG emissions are zero.	~ 0.004 ktH_2/y[23]

Source: H_2 Bulletin, H_2 colour codes, 2021

1.3.2 Understanding the hydrogen supply chain

32. All in all, the levelized cost of hydrogen is highly dependent on the production pathway, transport route and storage type. It is important to get an overall picture of the hydrogen supply chain, to identify the best possible routes for the development of a hydrogen economy in each geography. For domestically produced blue or green hydrogen, the production process can happen centrally, or de-centrally, each with its own infrastructure requirements and emissions along the value chain. Table 3 summarizes the two production pathways.

Table 3. Centralized and decentralized hydrogen production

	Centralized hydrogen production	Decentralized hydrogen production
Description	Hydrogen is produced in large quantities at natural gas production sites or locations where renewable energy is installed and transported as hydrogen via pipelines.	Hydrogen is produced at use site, using natural gas transported to the site or on-site renewable energy capacity installed.
Infrastructure	Hydrogen pipelines and storage to be developed	No or very limited hydrogen pipelines required. Well-connected natural gas pipelines and electricity grid lines required.
	Hydrogen pipelines to be developed from production site to storage site in case of blue hydrogen production	CO_2 pipelines to be developed from every blue hydrogen production site to storage site
	Fewer hydrogen production facilities with large production capacity required	Several hydrogen production facilities with low production capacity required
Production potential	Centralized and close to gas production site or locations with high renewable energy capacity	Highly dependent on resource availability in the region

[22] It is worth noticing that since Uzbekistan have no yet nuclear capacity installed, it is highly uncertain to establish a date by when it could enter in operation and whether its production would be grid oriented or hybrid (electricity and hydrogen), this assessment doesn't include this technology.

[23] Recharge, World first for nuclear-powered pink hydrogen as commercial deal signed in Sweden, 2021, Retrieved from: https://www.rechargenews.com/energy-transition/world-first-for-nuclear-powered-pink-hydrogen-as-commercial-deal-signed-in-sweden/2-1-1155202, on 27 January 2022.

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Emissions along the value chain	Upstream CO_2 and CH_4 emissions are relevant in case of blue and turquoise hydrogen production. Energy and material flow emissions for green hydrogen production equipment are relevant.	Emissions along the entire gas value chain are relevant in case of blue and turquoise hydrogen production. Energy and material flow emissions for green hydrogen production equipment are relevant.

Source: Carbon Limits assessment using several references

33. The information presented in the previous sub-sections highlight the myriad of supply chain possibilities for hydrogen, from its production to its end use. While optimization is possible for every trade and domestic route, it is difficult to standardize the supply chain requirements worldwide. The life-cycle CO_2 footprint, water footprint, and energy intensity from production to end use are among the important parameters to understand the relevance of the said hydrogen supply chain.

34. **Defining low-carbon hydrogen and its variants**

35. In this report, we consider low-carbon hydrogen to include green (renewable-based electrolysis), blue (methane reforming with CCS), turquoise[24] (methane pyrolysis) and pink (nuclear) hydrogen[25].Owing to the different definitions for hydrogen, the EU recently adopted the CertifHy emissions thresholds as a starting point to classify low-carbon hydrogen production[26]. CertifHy, has the following categories of classification for hydrogen:

    (a) CertifHy green hydrogen: Uses renewable source of energy during the production process and has a life-cycle emission less than 36.4 g CO_2 per MJ of hydrogen produced.
    (b) CertfiHy low-carbon hydrogen: Uses non-renewable source of energy during the production process and has a life-cycle emission less than 36.4 g CO_2 per MJ of hydrogen produced.
    (c) Non-CertifHy hydrogen: Life-cycle emissions are greater than 36.4 g CO_2 per MJ of hydrogen produced.

36. Using this categorization, blue hydrogen, turquoise, and pink hydrogen can be classified as CertifHy low-carbon hydrogen[27]. As more hydrogen roadmaps and bilateral agreements get developed, there is a possibility that the definition of low-carbon hydrogen could evolve. The ultimate goal is to use fuels with the lowest possible carbon footprint both in its use and production. An important factor to note in blue and turquoise hydrogen production is the GHG emissions along the natural gas value chain, and more particularly the methane emissions. Box 1 presents the methane emissions along the gas value chain in Uzbekistan, and the potential reduction if best available technologies are applied along the gas value chain.

[24] As explained in (Timmerberg, Kaltschmitt, and Finkbeiner 2020): "Under the global natural gas supply chain conditions, hydrogen from methane decomposition still causes significant GHG emissions between 43 and 97 g CO2-eq./MJ. The bandwidth is predominately determined by the energy source providing the process heat, i.e. the lowest emissions are caused by the plasma system using renewable electricity. This configuration shows lower GHG emissions compared to the "classical" SMR (99 g CO2-eq./MJ) but similar emissions to the SMR with CCS (46 g CO2-eq./ MJ)"

[25] Appendix A.1 provides further details on hydrogen production technologies.

[26] S&P Global, *EC set to decide hydrogen taxonomy emissions threshold by April 21: RHC*, 2021, Retrieved from: https://www.spglobal.com/platts/en/market-insights/latest-news/coal/040721-ec-set-to-decide-hydrogen-taxonomy-emissions-threshold-by-april-21-rhc, on 28 October 2021.

[27] CertifHy, *Definition of Green Hydrogen* Retrieved from: https://www.certifhy.eu/wp-content/uploads/2022/06/CertifHy_H2-criteria-definition_V2.0_2022-04-28_endorsed_CLEAN-1.pdf

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Box 1. : GHG emissions along the natural gas value chain in Uzbekistan.

Along the natural gas value chain, there are several sources of GHG emissions. The table below presents the emission sources, the type of GHG emissions from the source, the decarbonization options available and a qualitative assessment of the costs.

	Main emission sources	GHG	Main decarbonization options	Abatement cost (qualitative)
Upstream	Energy production	CO_2	Changing power sources, electrifying equipment, renewable energy, CCUS	$$$
	Routine gas flaring	CO_2 and CH_4	Gas export, on-site gas utilization	$ - $$
	Non-routing gas flaring	CO_2 and CH_4	Flare Gas Recovery Systems (FGRS), optimizing during start up, preventive maintenance. Ensure back-up of critical equipment and components	$ - $$$
	Fugitives	CH_4	Leak Detection and Repair (LDAR), Vapor Recovery Unit (VRU), Blowdown management, replace compressor seals	$ - $$
Mid-stream	Transport	CO_2	Fuel change, electrification	$$$
	Hydrogen production – SMR	CO_2	Green hydrogen CCUS	$$$
	Energy production	CO_2	Fuel switching, electrification, renewable energy, CCUS	$ - $$$
Transmission	**Fugitives**	**CH_4**	**LDAR, VRU, blowdown management, replace compressor seals**	$ - $$
	Energy production	CO_2	Fuel switching, electrification, renewable energy, CCUS	$ - $$$

Carbon Limits, 2021

Methane emissions are a result of fugitive emissions, intentional venting, and incomplete flares. According to the IEA Methane Tracker 2021, methane emissions from the natural gas value chain amounted to 1.0 $MtCH_4$, for Uzbekistan, out of which about 0.3 Mt CH_4 are associated with the downstream sector[28].

As per the IEA methane tracker, several abatement options are available to reduce the methane emissions along the oil and gas value chain. Replacing existing equipment with instrument air systems or electric motors can bring about significant emissions reduction. Another highly significant abatement option is frequent leak detection and repair (LDAR)[29]. More in-depth analysis of the natural gas value chain in Uzbekistan is required to understand the scope of CH_4 emissions reduction and the costs associated with it. Worldwide, best available technologies are readily available to reduce the methane emissions, which in turn can increase the volume of natural gas available for use or trade. As per IEA estimates, around 0.5 $MtCH_4$ can be abated at no net cost[30].

[28] IEA, Methane Tracker Database, 2022, Retrieved from: https://www.iea.org/articles/methane-tracker-database, on 03 May 2022

[29] IEA, *Methane Tracker Database*, 2021, Retrieved from: https://www.iea.org/articles/methane-tracker-database, on 11 October 2021.

[30] IEA, *Methane Tracker Database*, 2021, Retrieved from: https://www.iea.org/articles/methane-tracker-database, on 11 October 2021.

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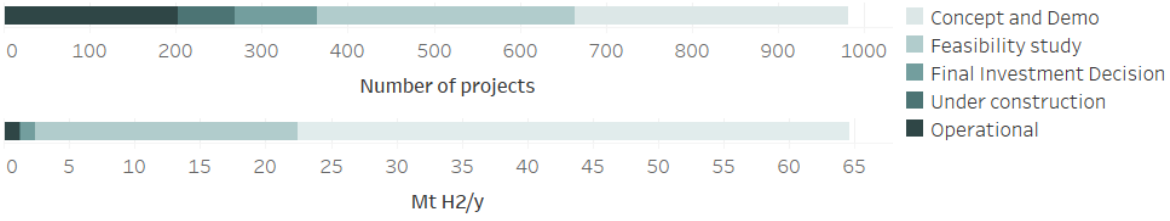
1.3.3 Hydrogen roadmaps and projects as of today

37. The hydrogen momentum is promising and gaining more and more interest worldwide. The IEA hydrogen project database from 2021, mentions 990 hydrogen related projects[31] worldwide at different levels of development[32,33]. Out of those 990 projects, 618 are currently under feasibility assessment, concept, or demo level and 364 are operational, under construction or received final investment decision. Most projects are small green hydrogen projects, estimated to produce close to 52 MtH_2 per year. On the other hand, the number of blue hydrogen projects are significantly lower (52), the production from these projects is estimated to be close to 12 MtH_2 per year. Figure 10 shows hydrogen related projects based on project progress, and figure 11 shows the hydrogen production projects currently operational and planned as of November 2021.

Figure 10. Number of hydrogen projects across the world, and their projected production quantities



Source: IEA Global H2 database, 2021.

[31] Include hydrogen, ammonia, synfuel, methanol and other fuel production

[32] Decommissioned, Concept, DEMO, Final Investment Decision (FID), Under Construction, Operational, and Unknown

[33] IEA Hydrogen Projects Database 2021.

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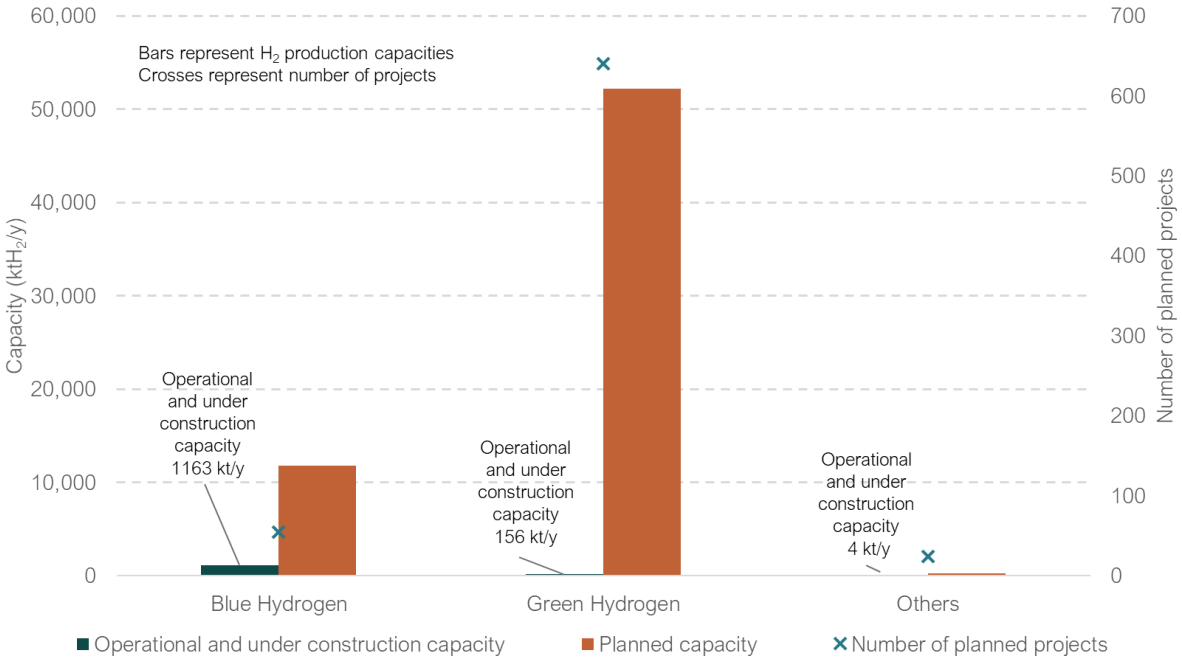
Figure 11. Operational and hydrogen production capacities under construction vs planned hydrogen production Current and planned hydrogen projects by type of production



Source: IEA Global H_2 database, 2021.

38. The largest green hydrogen project operational as of mid-2022 is hydro-powered PEM plant, producing over 8 tonnes of green hydrogen per day. Located in Quebec, Canada, this 20 MW PEM electrolyzer is the largest membrane-based hydrogen production unit in the world.[34] China is currently in the second phase of building one of the largest onshore wind powered hydrogen production facility, with an electrolyzer capacity of 10 MW. While the first phase of the project is operational as of 2021, the second phase expansion is expected to be operational by 2022. This project is expected to produce around 4 tonnes of green hydrogen per day.[35] Shell Canada's Quest project is currently the largest blue hydrogen production facility in the world. The facility captures over 1 Mt of CO_2 per annum and produces over 300 kt of hydrogen per year.[36]

39. The hydrogen for net zero report from the World Energy Council (2021a) estimates the hydrogen demand projections in different scenarios. In the optimistic scenario (<1.8°C heating), global hydrogen supply is projected to reach 690 Mt by 2050[37], ten times the demand in 2020. In the

[34] Air Liquide, *Air Liquide inaugurates the world's largest low-carbon hydrogen membrane-based production unit in Canada*, Retrieved from: https://www.airliquide.com/mainland-china/air-liquide-inaugurates-worlds-largest-low-carbon-hydrogen-membrane-based-production, on 13 December 2021

[35] Upstream Online, *China set to fire up wind farm-linked hydrogen scheme with Winter Olympics in its sights*, Retrieved from> https://www.upstreamonline.com/energy-transition/china-set-to-fire-up-wind-farm-linked-hydrogen-scheme-with-winter-olympics-in-its-sights/2-1-927148, on 13 December 2021

[36] Government of Canada, *Shell Canada Energy Quest Project*, Retrieved from: https://www.nrcan.gc.ca/science-and-data/funding-partnerships/funding-opportunities/current-investments/shell-canada-energy-quest-project/18168, on 13 December 2021

[37] Hydrogen council forecasted demand to be 660 Mt, retrieved from IEA net-zero scenario. 690 Mt is total supply in the optimistic scenario for 1.8°C. Retrieved from: https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero_Full-Report.pdf, on 17 November 2021

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medium scenario (1.8°C to 2.3°C heating), demand is forecasted at 213 Mt.[38] These numbers have pushed governments to be in the forefront of this sector, for both environmental and economic benefits. More than seventy countries worldwide have hydrogen strategies either published, or under review. The roadmaps mainly highlight the required hydrogen infrastructure and set up of institutions and policies to make hydrogen economy fully operational. The two main regions with significant hydrogen targets and roadmaps are Europe and East Asia (Japan and South Korea). Europe is leading the momentum with its hydrogen strategy issued in mid-2020[39], and with most of western European countries having published their hydrogen strategies[40]. Table 4 presents some of the targets set in different regions and the allocated investments as of mid-2021.

Table 4. **Example of national target and estimated investments in developed countries.[41]**

Region / Country	Targets (2030)	Type of hydrogen	Investments (Billion USD)
Europe [a]	Production Capacity: 27.4 GW EU production goal: 10 Mt of renewable hydrogen per year by 2030	Green & Blue	*23.4
Australia	N/A	Green & Blue	1.05
Americas [b]	Production capacity 69 GW Demand: 5.5 MtH_2 per year	Green & Blue	**2.569
MENA	Planned hydrogen production projects	Green & Blue	44[42]
East Asia [c]	Demand: 4.94 MtH_2 per year	Green & Blue	8.7
India	Production: 5 Mt of renewable hydrogen per year by 2030[43]	Green	***75[44]
Russia	Exports: 0.2 MtH_2 per year by 2024 2 MtH_2 per year by 2035	Green & Blue	****0.1 in 2022-2024[45]
China	Production: 1 Mt to 2 Mt of green H_2 per year by 2025[46]	Green	-

[a] Europe: Czech Republic, France, Germany, Hungary, Netherland, Norway, Portugal, Spain, and United Kingdom.
[B] Americas: USA, Canada, Chile.
[c] East Asia: Japan and South Korea.

[38] Hydrogen on the Horizon
[39] "A strategy for a climate-neutral Europe", available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301
[40] National Hydrogen Strategies
[41] IEA Global Hydrogen Review
[42] Energy Live News, *Middle East plans $44bn hydrogen investment*, Retrieved from: https://www.energylivenews.com/2021/11/26/middle-east-plans-44bn-hydrogen-investment/, on 04 March, 2022
[43] Bloomberg News, *India Unveils Hydrogen Plan to Speed Shift From Fossil Fuels*, Retrieved from: https://www.bloomberg.com/news/articles/2022-02-17/india-unveils-hydrogen-roadmap-to-speed-shift-from-fossil-fuels, on 04 March 2022
[44] Gulf News Business, *Ambani's $75 billion plan aims to make India a hydrogen hub*, Retrieved from: https://gulfnews.com/business/energy/ambanis-75-billion-plan-aims-to-make-india-a-hydrogen-hub-1.85305162, on 04 March 2022
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[46] Recharge News, *China unveils national 2025 target for green hydrogen and new strategies for further H_2 growth*, Retrieved from: https://www.rechargenews.com/energy-transition/china-unveils-national-2025-target-for-green-hydrogen-and-new-strategies-for-further-h2-growth/2-1-1189877, on 13 July 2022

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** In addition to $ 4.3 billion committed by the European Union*
*** United States' Budget is assumed constant after 2020 budget*
**** Businessman Ambani plans to invest $ 75 billion on developing hydrogen hubs in India*
***** Conversion rate used 1 USD =76.76 ₽ (data on 22 February)*

1.3.4 Status of hydrogen development in Uzbekistan

40. Uzbekistan recognizes the need to develop efficient, environmentally sound economy in the face of climate change and that one of the components of this economy can become LCH[47]. The government shows interest in its development and taking the first steps in that direction.

41. Three existing large energy project investors in Uzbekistan (Air Products, Siemens Energy and ACWA Power) have preliminarily agreed to extend their partnership with authorities to consider pilot hydrogen project in the country. In March 2020, the three companies signed a set of power purchase and investment agreements with the government, covering the construction of a 1,500 MW combined cycle gas turbine power plant in the Sirdarya region. The contract also includes the building of two wind power schemes in the region of Bukhara and Navoy with a total generation capacity of around 1,000 MW[48]. The three companies have also committed to organize capacity building for personnel that will be involved in the LCH operations.

42. In April 2021 the government has approved presidential resolution "*On measures for the development of renewable and hydrogen energy in the Republic of Uzbekistan*". The resolution implies the establishment of National Research Institute for Renewable Energy Sources. The institute is created under the Ministry of Energy and includes the Research Center for Hydrogen Energy and the Laboratory for Testing and Certification of Renewable and Hydrogen Technologies[49].

43. The resolution adopts an integrated approach focusing on:[50]

- The preparation of **National Strategy for Development of Renewable and Hydrogen Energy**
- **Capacity building**: starting from the 2021 - 2022 academic year the country has planned to increase the number of students in the LCH field, and from the 2024 - 2025 academic year, it plans to launch a master's program in "Hydrogen energy and technology"
- **International cooperation**: the plan is to promote cooperation in the academic field and with companies leading in LCH development

[47] Resolution on measures for the development of renewable and hydrogen energy in the Republic of Uzbekistan, 2021, Retrieved from: https://lex.uz/ru/docs/5362035, on 1 April 2022
[48] Upstream, Uzbekistan calls on World Bank to assess hydrogen production options, 2021, Retrieved from: https://www.upstreamonline.com/energy-transition/uzbekistan-calls-on-world-bank-to-assess-hydrogen-production-options/2-1-1114100, on 1 April 2022
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[50] IEA, Resolution No. PP-5063 "On measures for the development of renewable and hydrogen energy in the Republic of Uzbekistan", 2021, Retrieved from: https://prod.iea.org/policies/13432-resolution-no-pp-5063-on-measures-for-the-development-of-renewable-and-hydrogen-energy-in-the-republic-of-uzbekistan?page=4&sector=Education%2COffices%2CBuildings%2CHydrogen%20production%20and%20supply , on 1 April 2022

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- Development of **pilot hydrogen projects**
- Development of **incentives necessary to initiate the hydrogen industry development**.

44. While the hydrogen industry in Uzbekistan is in its infancy, the country has significant experience with producing and handling natural gas and ammonia (a hydrogen carrier). Ammonia production projects are presented in table 5.

Table 5. **Ammonia production projects in Uzbekistan**

	Facility	Company	Partners	Start of operation	Capacity (kt/year)
1	Ammonia and urea production complex at Navoiy[51]	Navoiyazot	Mitsubishi Heavy Industries Ltd	2021	660 of ammonia; 577 of urea
2	Ammonia based fertiliser plant in Yangiyer[52]	Ferkensco Management Limited	Enter Engineering Pte Casale SA	2025	495 of ammonia; 594 of urea
3	Chemical complex in Fergana[53]	Farg'onaazot		1964	475 of ammonia

[51] World Fertilizer Magazine, Urea production begins at Uzbekistan's new $958 million industrial complex, 2021, Retrieved from: https://www.worldfertilizer.com/special-reports/06012021/urea-production-begins-at-uzbekistans-new-us958-million-industrial-complex/, on April 6

[52] Chemical Industry Digest, Casale Collaborates With Partners for Ammonia Project in Uzbekistan, 2022, Retrieved from: https://chemindigest.com/casale-collaborates-with-partners-for-ammonia-project-in-uzbekistan/, on April 6

[53] Farg'onaazot, Retrieved from: https://azot.uz/en/, on April 6

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2 Potential supply and demand of low-carbon hydrogen in Uzbekistan

46. To grasp the full potential of the low-carbon hydrogen economy in Uzbekistan, an assessment of how much low-carbon hydrogen the country can produce and how much it can use is required. This is the concern underlying the following section of this report.

47. The modelling assessment for determining the LCH potential in Uzbekistan was conducted with the the **Hydrogen Pathway Explorer Model (HyPE)[54]. It** was used for assessing the domestic demand, production and export in Uzbekistan and the surrounding region. The objective of the HyPE model is to find the least cost pathways based on a set of assumptions with a 5-year time-step, considering the whole H_2 value chain. In importing countries, the imported H_2 needs to compete in price against potential local production.

48. The model uses a **combined geographical and techno-economic analysis**. Firstly, LCH production potential is estimated using resource, economic and topological data. This is followed by an assessment of the cost structure that considers domestic and international trade, along with the cost of conversion and reconversion steps to H_2 fuel. The least cost routes from production sites to domestic demand and import terminal are estimated considering the national and international transport constraints (point-to-point). Distances, costs of conversion and reconversion, production costs, transport costs and costs of offsetting residual emissions are all computed to build the least cost merit order curve based on the Levelized Cost of H_2 (LCOH).[55] Particular attention was dedicated to the representation of water use and costs, and associated emissions (direct and indirect) in each step of the value chain.[56]

Box 2. Model limitations

Model limitations

1. Cost minimization approach might lead to strategies based on the deployment of the single most competitive technology and not a risk diversification strategy.
2. Competition between gas and hydrogen are considered exogenously. This is tackled by natural gas availability scenarios that will be discussed further in the report.

Policy Uncertainties

1. No social-acceptability issues related to the deployment of blue or turquoise hydrogen was considered.
2. The scenarios assume efficient regulatory frameworks develop to set the floor for timely investments, access to project finance, etc.

Market uncertainties

[54] A model developed and maintained by Deloitte.

[55] The levelized cost of hydrogen (LCOH) is a methodology used to account for all of the capital and operating costs of producing hydrogen and therefore enables different production routes to be compared on a similar basis.

[56] Direct CO_2 emissions and indirect methane emissions from the production of LCH from natural gas are accounted for in CO_2e. Unabated emissions entail costs of economical offsetting given the carbon price trend assumed .(see appendix D).

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1. Uncertainty related to the development of CO2 prices, breakeven price of natural gas, carbon black prices and market size.
2. Cost evolution of renewables and electrolysers.

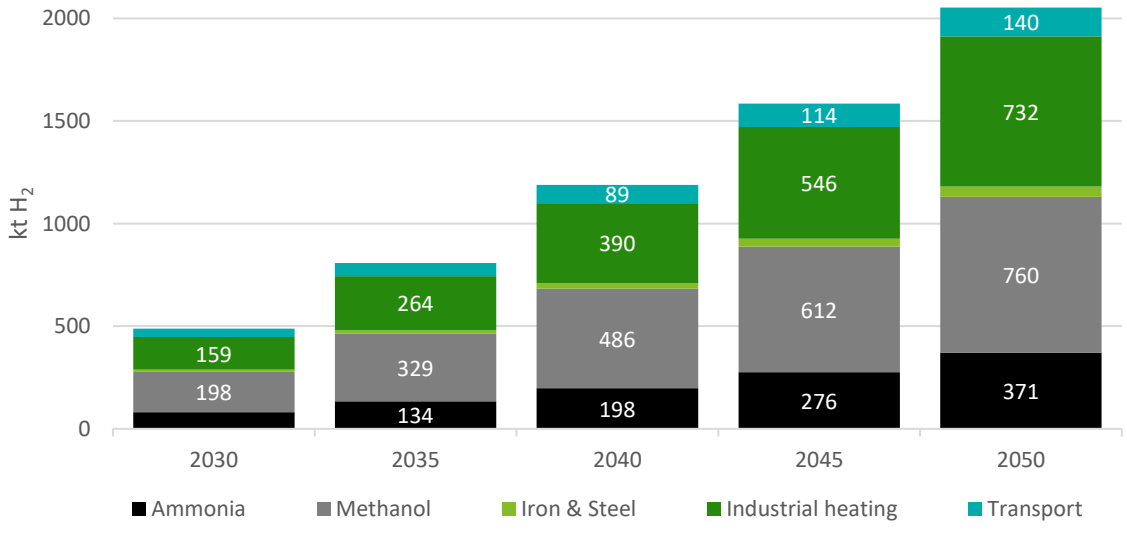
2.1 Low-carbon hydrogen demand by end-use sector

49. Uzbekistan has laid an array of decarbonization objectives in key policy documents as summarized in section 1.2.2. To that end, the country must reduce emissions stemming from, among other sectors, energy-intensive industries, and heavy-duty transport. Those sectors are good kicks-starters of the hydrogen economy because they often have relatively low switching costs or high technological readiness compared to other alternatives to hydrogen.

50. To assess low-carbon hydrogen demand in Uzbekistan, we model macroeconomic performance based on population growth and industrial activity growth coupled with assumptions on likely sectoral low-carbon technologies' adoption[57]. The projections assumed are based on the trends and ambitions adopted in first-mover countries targeting similar objectives[58]. Three scenarios are proposed to assess how Uzbekistan's low-carbon hydrogen demand can unfold towards 2050. The analysis first delves into the central scenario before presenting and discussing low and high demand scenarios.

2.1.1 Overview of low-carbon hydrogen demand

Figure 12. Annual domestic hydrogen demand by sector in Uzbekistan, 2030-2050 (medium demand scenario)



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[57] Industrial policies with deep foundations on climate neutrality ambitions would be necessary to foster technology adoption so creating a market for LCH. Section 4 further develops on them and provide guidelines for implementation.

[58] The sectoral methodology follows that proposed by Guidehouse (2021) for the European Hydrogen Backbone.

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51. Low-carbon hydrogen can play a major role in decarbonizing and supporting the Uzbek economy. In the central scenario, annual domestic hydrogen demand grows by over 7% annually from 2030 to 2050 and exceeds 2 Mt in 2050, as figure 12 shows. An initial phase of rapid growth brings clean hydrogen demand to half a million tonnes by the end of this decade. This increase is largely driven by first movers from the industrial sectors like the ammonia and methanol production and other industrial heat end-uses. Demand for low-carbon hydrogen in the transport sector grows past 100 kt/year in the 2040s and reaches 140 kt/year in 2050. The steel sector shows promises, but its relatively small size in the Uzbek economy means its demand represents a small share of the total under the current policy horizon. Energy-intensive industries account for over 1900 ktH_2/year in 2050, nearly 95% of total low-carbon hydrogen demand in Uzbekistan.[59]

52. Geographically, low-carbon hydrogen demand in Uzbekistan comes from defined industrial clusters dotted around the south and east of the country. The southern clusters concentrate around 75% of low-carbon hydrogen demand in 2050, and the eastern clusters 25%. In addition to having sizeable demand potential for low-carbon hydrogen, those regions are also endowed with a dense network of high-capacity gas transmission lines. The Bukhara area is the largest cluster by hydrogen demand in volume, thanks to a large existing methanol plant. Relying on existing assets and industries minimizes the cost of building new ones and secures offtake. This is precisely the “hydrogen valley” or cluster approach that other regions of the world have started to follow. Legacy industrial plants differ from cluster to cluster in Uzbekistan, which explains the variations in the distribution of hydrogen demand across clusters observed in figure 13. Converting road transport to hydrogen requires building new infrastructure. This explains the even distribution of hydrogen demand for transport in absolute value across sectors.

[59] The mining sector in Uzbekistan, which is a mining-intensive country, should also be considered in decarbonization pathways. In particular, low-carbon hydrogen could be used as low-carbon fuel for haul trucks and trains or to store and restitute clean electricity for powering processing plants in microgrids. As such, a part of this low-carbon hydrogen demand is already being addressed in the heavy-duty transport. In the other hand, it should also be noted that the technologies developed in this sector are a niche and are at early stages of development. The prospects of hydrogen in the mining are very site specific. Moreover, most advanced countries in the matter such as Australia are still at the first stages of developing a roadmap for low-carbon hydrogen in the mining sector. These are the reasons why this sector has been considered out of the scope for this study.

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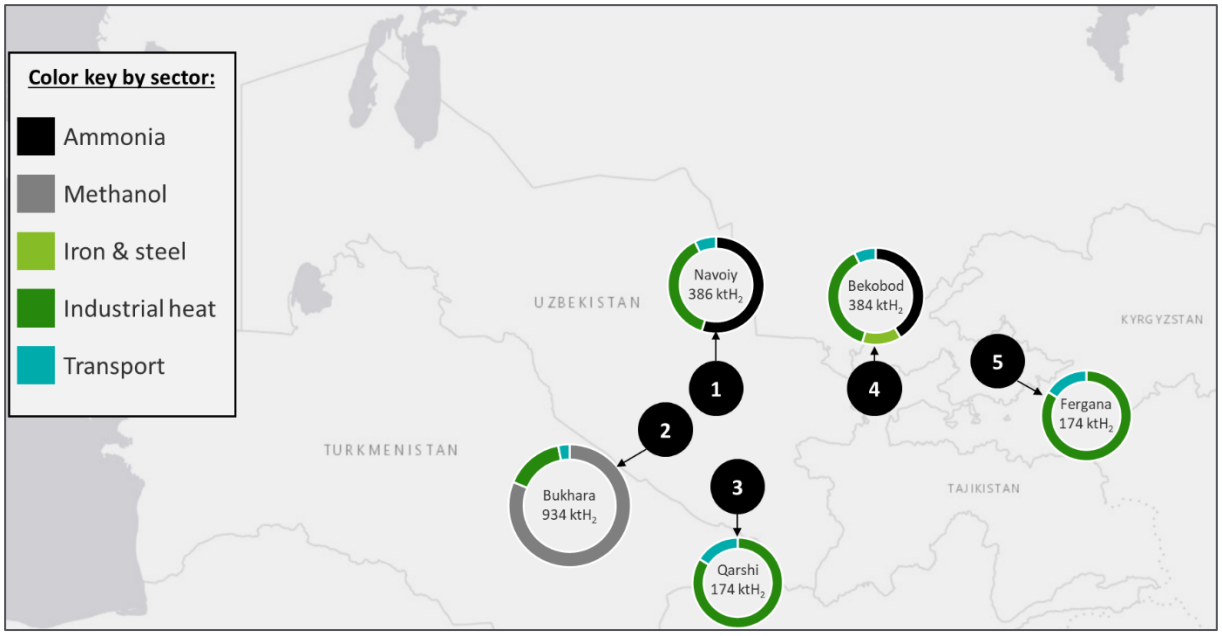
Figure 13. Distribution of hydrogen demand in Uzbekistan across clusters and sectors in 2050 (medium demand scenario)



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53. Low-carbon hydrogen is not the silver bullet that will single-handedly decarbonize the entire economy. However, it is a key alternative within the toolbox of solutions, together with direct electrification and carbon capture utilization and storage (CCUS), to replace significant amounts of non-abated fossil fuels used in hard-to-abate sectors. Those applications are particularly well-suited for competitively shifting to low-carbon hydrogen. For instance, we estimate that low-carbon hydrogen will account for 75% of steel production and 50% of heavy-duty road freight in Uzbekistan in 2050. This makes delving into the details of hydrogen penetration by industrial sector necessary to fully grasp the potential of hydrogen in Uzbekistan. We develop a sectoral analysis in the subsequent sub-sections. As a rule of thumb, low-carbon hydrogen penetrates markets by order of switching cost. Unabated hydrogen feedstock replacements come first, followed by light refurbishments and finally capital-intensive asset replacements.

2.1.1.1 Low-carbon methanol and ammonia production

54. Methanol could be the single largest demand sector for low-carbon hydrogen in Uzbekistan. Production pathways for methanol do not necessarily require low-carbon hydrogen, but blue and green methanol both need low-carbon or renewable hydrogen, as displayed in figure 14. The CO_2 and syngas hydrogenation routes are among the most promising ways of producing low-carbon methanol and derivatives, and multiple routes should be developed altogether. Thus, the share of hydrogen-based methanol has been considered reaching 20% in 2030 and 50% in 2050 in the central scenario, leaving room for other pathways. Total methanol production in Uzbekistan grows steadily from 4939 kt_{MeOH}/year in 2030 to 7596 kt_{MeOH}/year in 2050 in the medium demand scenario (see figure 15). This represents a 2.2% compound annual growth rate. Such a sustained growth could appear ambitious over the entire period, given the scale of standard plants the addition of a new plant would be more than enough to satisfy the trend. There is a steep increase in the share of low-carbon methanol based on low-carbon hydrogen in total methanol production by 2050. As a result, low-carbon hydrogen demand from the methanol sector starts by 2030 with

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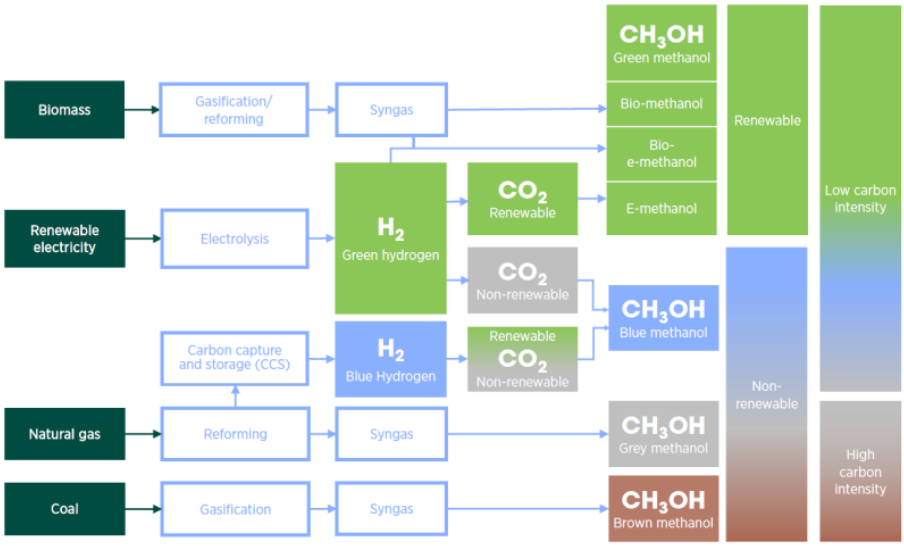
about 200 ktH_2/year and grows by 7% annually to 760 ktH_2/year in 2050. Methanol accounts for 40% of total low-carbon hydrogen demand in Uzbekistan across the outlook period, the largest share of any sector covered here. Methanol is not only a high-value energy product but a suitable platform to producing low-carbon polymers (i.e. methanol to olefins, MTO), which are very relevant for country revenues but that are currently based on fossil feedstock. Hence, the value of low-carbon methanol could further increase as the way through decarbonization progresses. Investing in greenfield low-carbon methanol production projects could be a way for Uzbekistan to diversify and sophisticate its exports while securing domestic low-carbon hydrogen offtake. The higher cost of renewable methanol could be matched with the higher willingness-to-pay of the aviation sector, which will increasingly look for renewable fuels.

Figure 14. Methanol production pathways



Source: IRENA (2021)

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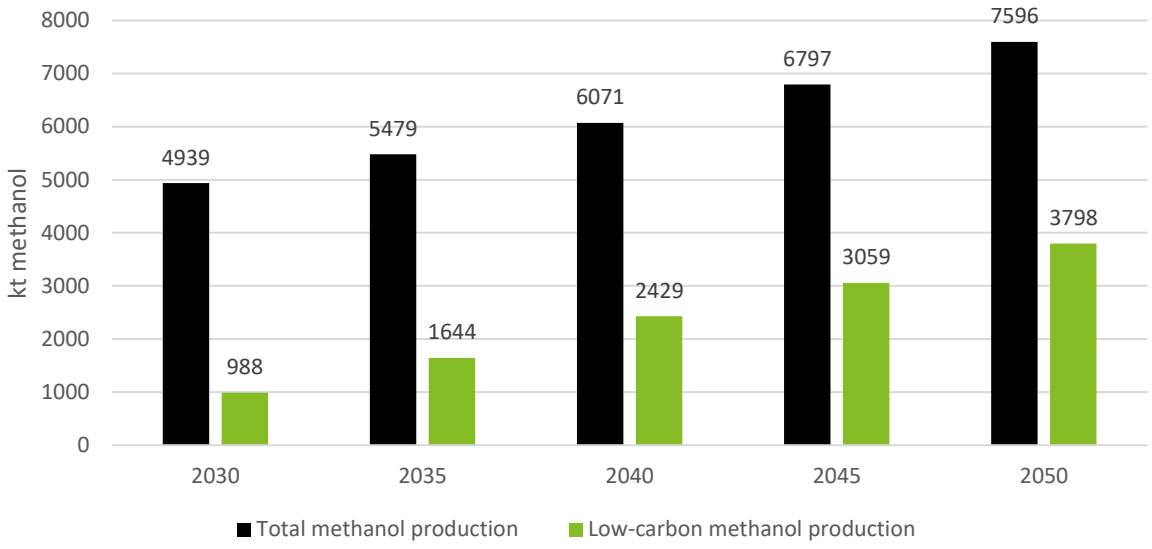
Figure 15. Total and low-carbon methanol production in Uzbekistan, 2030-2050 (medium demand scenario)



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55. Ammonia and methanol production are the powerhouse of the growth of low-carbon hydrogen demand in Uzbekistan. Such sectors where hydrogen can be used directly as feedstock in production processes for valuable products are low-hanging fruits for merchant hydrogen producers. Moreover, chemical plants are typically well-connected with gas or even hydrogen infrastructure[60] that delivers the required feedstock and energy inputs and outputs, which lowers switching costs. In our analysis, ammonia and methanol plants are located in the Navoiy, Bukhara, and Bekobod clusters, along the densest gas infrastructure nodes in the country[61].

[60] To handle hydrogen as a captive intermediate or by-product.

[61] This assumes that industrial spillovers would the industry develop around current locations within the country. Depending on the national industrial development strategies of the country, capacity could be developed in different locations.

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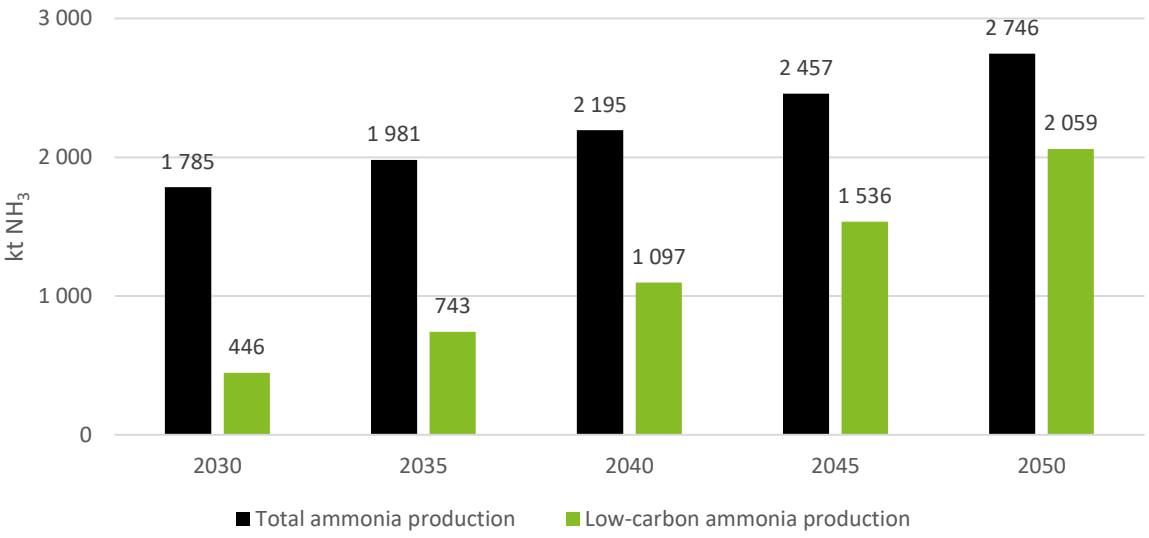
Figure 16. Total and low-carbon ammonia production in Uzbekistan, 2030-2050 (medium scenario)



Deloitte, FAO

56. Ammonia-making is particularly well-suited to accommodate to low-carbon hydrogen: all it requires is shifting from the unabated "grey" hydrogen feedstock. The medium scenario, shown in figure 16, foresees ammonia production growing by 2.2% annually from nearly 1785 $ktNH_3$ in 2030 to 2745 $ktNH_3$ in 2050. In the meantime, low-carbon ammonia production ramps up by 7.9% annually from 445 $ktNH_3$ in 2030 to 2060 $ktNH_3$ in 2050. Three-quarters of ammonia produced in Uzbekistan is low-carbon by 2050, up from 25% in 2030. Consequently, the overall CO_2 intensity of ammonia production shrinks by two-thirds in 2050 compared to 2030 levels. Low-carbon hydrogen demand for ammonia is thus 371 ktH_2 in 2050, up nearly fivefold or 8% per year from 80 ktH_2 in 2030. Ammonia's share in total low-carbon hydrogen demand in Uzbekistan hovers around 17% throughout the outlook period. This is consistent with the prominence of agriculture in the Uzbek economy, which would spur demand for fertilizers, of which ammonia is an essential component[62]. Furthermore, investments in greenfield ammonia plants could be encouraged by success stories of low-carbon hydrogen use in the sector and increase these numbers drastically.

[62] See data from the Observatory of Economic Complexity (webpage on Uzbekistan, last accessed July 2022).

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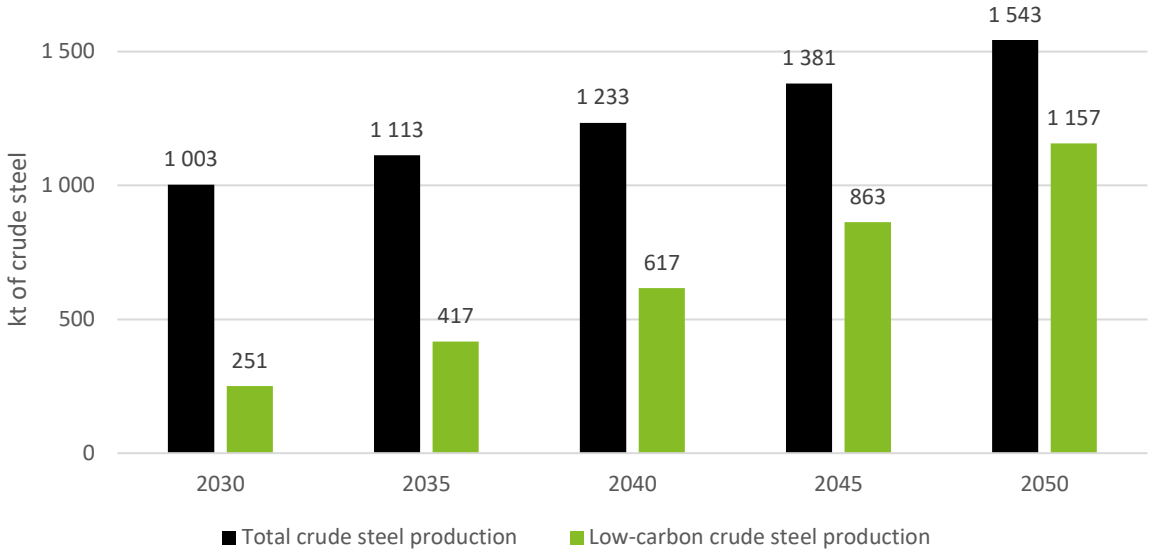
2.1.2 Industrial heating and steel production

2.1.2.1 Steelmaking

Figure 17. Total and low-carbon crude steel production in Uzbekistan, 2030-2050 (medium demand scenario)



Deloitte 2022, based on data from the World Steel Association

57. Despite its relatively small size in the economy, the Uzbek steel industry boasts ample potential for decarbonization, largely due to being ripe for the uptake of low-carbon hydrogen. The projection of total crude steel production in Uzbekistan in figure 17 shows that total crude steel production in Uzbekistan is projected to increase from 1003 kt in 2030 to 1545 kt in 2050. This corresponds to a 2.2% compound annual growth rate from 2030 to 2050. In the same period, low-carbon steel production quickly grows by 10.7% annually to be just shy of 1200 kt/year in 2050. The share of low-carbon crude steel in total production reaches 25% by 2030 and 75% by 2050. This is ambitious, but consistent with changes happening elsewhere in the world. For instance, the European Commission aims to decarbonize 30% of EU crude steel production by 2030[63]. The growth of low-carbon steelmaking halves the CO_2 emissions intensity of Uzbek crude steel production between 2030 and 2050.

58. In this context, low-carbon hydrogen plays a growingly important role as an input for steel production in Uzbekistan throughout the outlook period. Low-carbon hydrogen can decarbonize steelmaking by being used in direct reduced iron (DRI) processes. Low-carbon hydrogen-based DRI processes paired with electric arc furnaces (EAF) powered by low-carbon electricity can make low-carbon steel. As a result, the combined share of hydrogen and electricity in energy demand from steel production in Uzbekistan increases from 25% in 2030 to 75% in 2050. This amounts to over 50 kt of hydrogen demand per year, about 30% of energy demand in steel. However, as said above, the Uzbek steel industry is relatively small. The iron and steel sector accounts for less than 3% of total hydrogen demand in Uzbekistan in 2050. Nonetheless, should they prove successful, investments in low-carbon steel today could create blueprints for future greenfield projects.

[63] Source: European Commision (2022)

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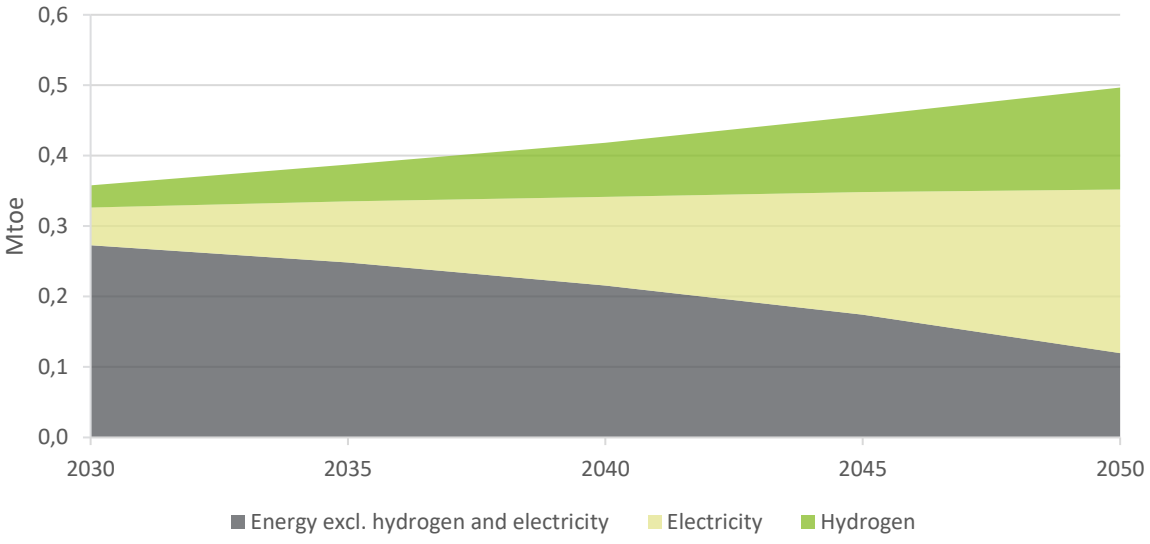
Potential future expansions of the Uzbek steel industry would thus adopt DRI + EAF technologies and thereby increase hydrogen demand in the sector (see figure 18).

Figure 18. Energy mix of steel production in Uzbekistan, 2030-2050



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2.1.2.2 Other industries

59. Natural gas remains the bedrock of the energy mix for industrial heating[64], but hydrogen and electricity gradually take on an increasing role as the sector grows. This might happen despite expected energy efficiency gains, which partly mask the true penetration of low-carbon hydrogen into the sector. As presented in figure 19, the share of hydrogen in industrial heat rises across the outlook period from 5% in 2030 to 15% in 2050, and the share of electricity mirrors this relative increase. Thus, demand for low-carbon hydrogen in industrial heating grows by 8% annually from 159 ktH_2 in 2030 to 732 ktH_2 in 2050. Industrial heating oscillates around 34% of total low-carbon hydrogen demand in Uzbekistan between 2030 and 2050. This makes it the second largest demand for low-carbon hydrogen after methanol by a slim margin of about 30 ktH_2/year in 2050.

60. However, unlike methanol, which is a clearly defined sector, industrial heating is an aggregate of many different industrial sector and uses, some of which are better suited for hydrogen than others. As explained above, low-carbon hydrogen penetration follows the ascending order of marginal switching cost, which is mainly determined by overall process efficiency. The efficiency of low-carbon hydrogen industrial heating technologies is greater for high-temperature applications than for lower or medium temperature uses. Low-carbon hydrogen will therefore be more competitive in high-temperature heat applications. High-temperature industrial heating applications are diverse, ranging from cement and lime to pulp and paper manufacturing. Due to their high energy consumption, those industries are located within the hydrogen consumption clusters identified in this report.

[64] In this study, the use of hydrogen as a feedstock is distinguished from the use of hydrogen for as a fuel for high temperature heating.

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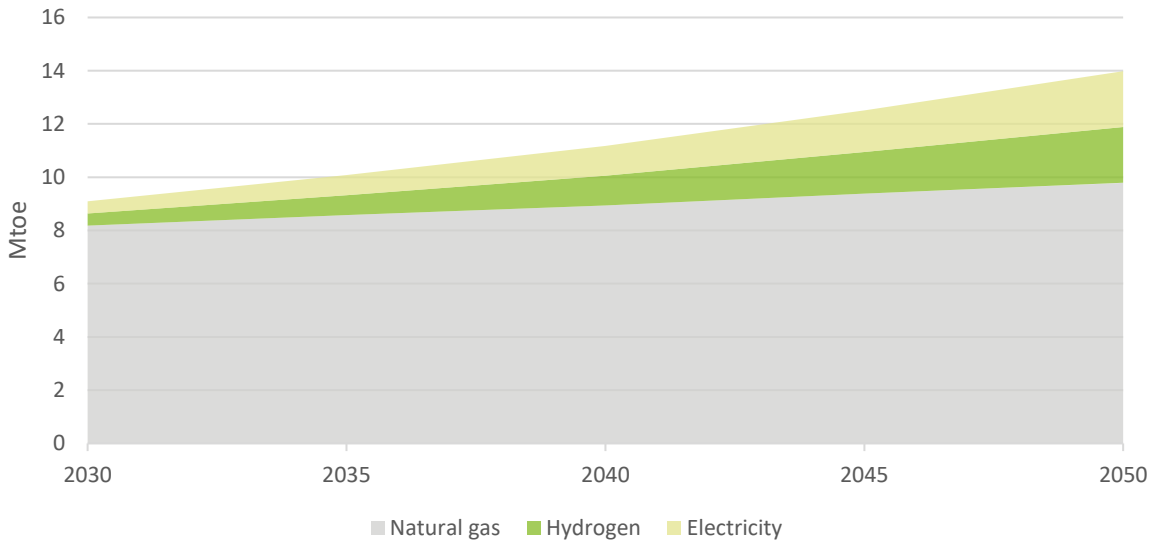
Figure 19. Energy mix of other Uzbek industries (heating purposes), 2030-2050



2.1.3 Road freight

61. Road transport could generate significant demand for low-carbon hydrogen in Uzbekistan. Passenger cars and light or medium-duty vehicles are better suited for electric batteries. The market for hydrogen-fueled cars would most likely be niche towards 2050. However, physical constraints limit the role of batteries in decarbonizing heavy-duty road transport, give a chance to hydrogen. Under currently available technologies, battery weight and size increase disproportionately with vehicle weight, reducing available cargo weight and space. Heavy road vehicles would also use batteries of over 300 kWh[65], drawing lots of power from the grid over long charging times that would cut fleet operators' profit margins. These physical constraints make electric battery solutions often improper to decarbonize heavy-duty transport, namely buses and heavy-duty trucks. Hydrogen fuel cells do not suffer from similar weight and charging time constraints and thus provide a viable alternative for heavy-duty trucks and buses. In Uzbekistan, the bus sector is far less economically and energetically significant than the road freight (trucks) sector, and it shows similar hydrogen uptake patterns. Therefore, we concentrate the subsequent analysis on the road freight sector.

62. As depicted in figure 20, road freight activity grows by 2% annually from 26 billion tkm in 2030 to 40 billion tkm in 2050. Like in other demand sectors covered in this report, low-carbon alternatives quickly catch up. The Uzbek road freight sector is slated to move away from a fossil fuel-dominated mix towards a multi-fuel mix where hydrogen is the leading fuel, shown in figure 21. In particular, hydrogen-fueled road freight grows by 6% annually from 3 billion tkm in 2030 to 20 billion tkm. By 2050, half of Uzbek road freight activity is fueled by low-carbon hydrogen. Total low-carbon hydrogen demand from transport is therefore 29 ktH_2 in 2030 and 140 ktH_2 in 2050. This is similar in order of magnitude to the Qarshi or Fergana clusters and their demands of 174 ktH_2 each in 2050.

[65] See for instance the eActros truck from Mercedes-Benz or Renault's 16t electric trucks.

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63. The single biggest barrier to developing hydrogen-fuel road freight is often the infrastructure required. Trucks need to refuel, and refueling stations need to be supplied frequently with low-carbon hydrogen. This entails the development of a hydrogen distribution network, which can be seen as a challenge to hydrogen growth or as an opportunity to build a hydrogen network.

Figure 20. Road freight projections for Uzbekistan, 2030-2050

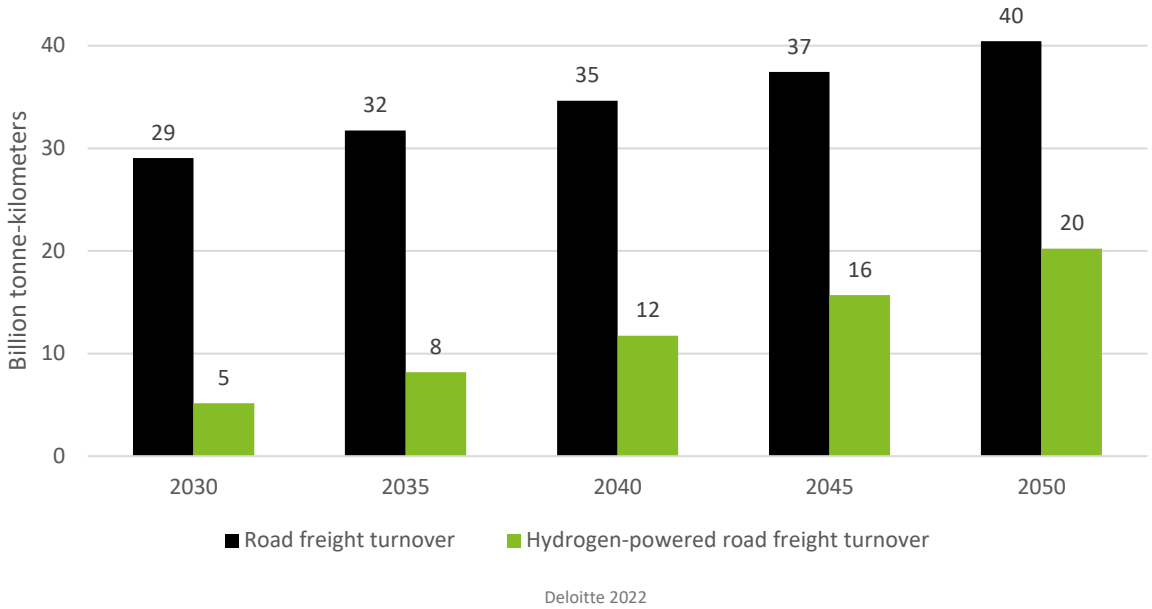

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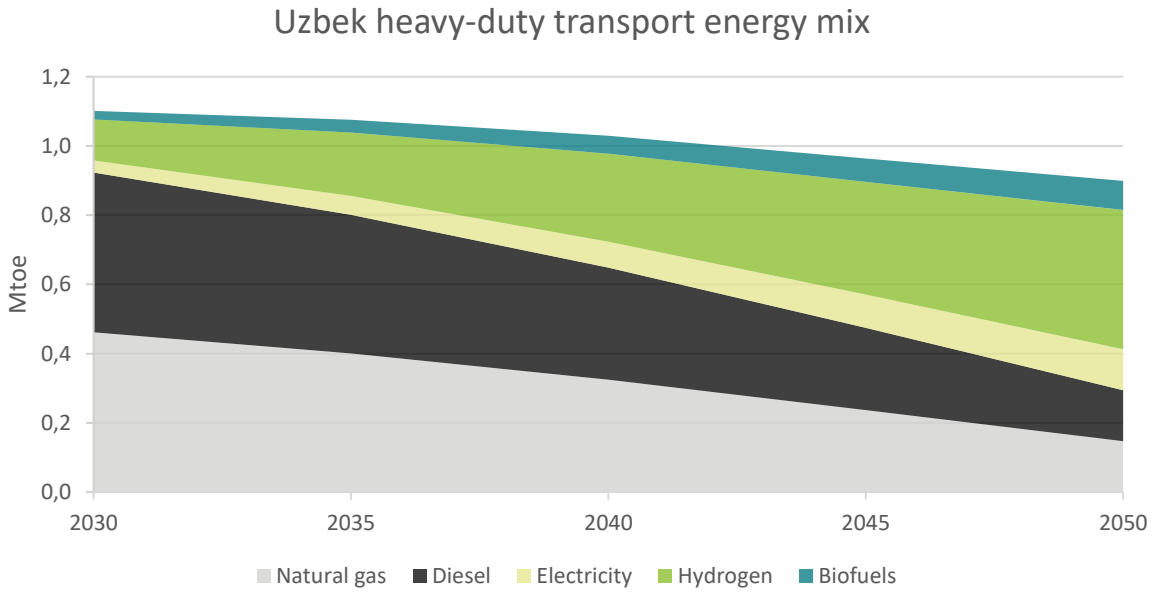
Figure 21. Energy mix of trucks and buses in Uzbekistan, 2030-2050



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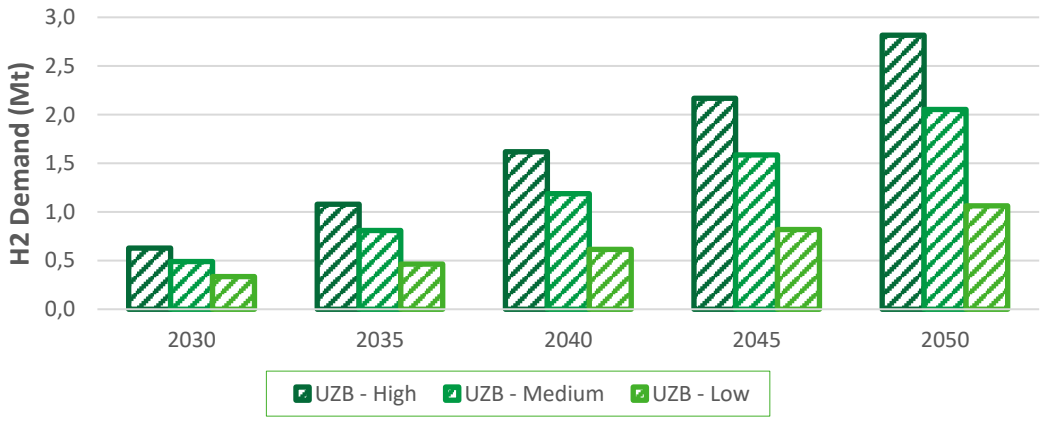
2.1.4 Uncertainties on the evolution of hydrogen demand

64. The medium demand scenario presented above focuses on a middle of the road estimate on the development of local hydrogen demand on a scenario compatible with deep decarbonization by 2050. LCH demand is mainly carried by methanol, industrial heating, and ammonia production. . In addition, even if the mining sector would only represent a marginal share of total demand for hydrogen and which most likely would be fulfilled onsite, it can be seen as a first-mover sector in adopting hydrogen technologies[66] due to the lower competitivity gap between using conventional fuels such as diesel for transport and other activities[67], in particular for high added-value minerals taking place in isolated sites with good renewable energy potential. As such, it can be considered as a test bed for scaling up the hydrogen industry in the country.

65. The development of the national hydrogen market is uncertain as it depends on the pathway to achieve long-term climate ambitions and on what actions are taken in other sectors. It is indeed closely dependent to the decarbonization of the power sector that will shape the electricity price and carbon intensity, and the economics and availability of natural gas in the country. It also depends on the deployment of technologies such as carbon capture and storage. Also, significant changes could be brought by pace of adoption of hydrogen-based technologies in end-use sectors. These uncertainties could have far reaching consequences and draw different pathways for the future hydrogen market in the country. In order to account for such uncertainties, two additional demand scenarios have been assessed: a low-demand scenario and a high-demand scenario. Both alternative scenarios follow the same rationale than the medium scenario to define demand estimates in each key sector. They provide a range that LCH could follow towards 2050. The corresponding evolution of demand over time is presented in figure 22.

Figure 22. Hydrogen demand scenarios: high, medium, and low.



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[66] Further details available at: https://www.accenture.com/us-en/blogs/chemicals-and-natural-resources-blog/mining-hydrogen-economy and https://www.mining.com/green-hydrogen-key-to-decarbonising-mining-report/

[67] Mining industry experts believes that "the industry is just "four or five years away from getting to TCO parity for heavy-duty trucks on mines that have to bring diesel to site by ship or truck" (Alfred Wong, Asia Pacific Managing Director at fuel cell provider Ballard Power Systems). Further information available at: https://hydrogen.energyandmines.com/files/hydrogens-role.pdf

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2.2 Low-carbon hydrogen supply by production pathway

66. Low-carbon hydrogen supply in Uzbekistan is promising thanks to its resources in renewable energies and natural gas. Good solar irradiation and strong wind potential in certain regions are suitable for the deployment of electrolysis-based hydrogen. Available gas fields and underground storage sites make a good business case for natural gas reforming with carbon capture and storage (CCS) or pyrolysis. However, the future of LCH from natural gas would be defined by competitive uses and limited availability. Water scarcity issues also looms over the prospects of electrolysis-based hydrogen and natural gas reformers. At last, pink hydrogen, powered by nuclear energy, isn't considered in the modelling due to the absence of nuclear reactors in the country, its complexity, uncertainties around their commissioning and operations (e.g. baseload electricity supply), and high investments needs.

2.2.1 The levelized cost of hydrogen (LCOH) of low-carbon hydrogen technologies

67. The future of low-carbon hydrogen production relies on multiple technologies that will be complementary with one another. However, the ratio of each technology in the production mix of Uzbekistan will highly depend on the relative competitivity of the different production pathways. Figure 23 summarizes the evolution of the in-situ production costs of low-carbon hydrogen technologies over time in Uzbekistan modelled for this study. There is evidence of the unmatched competitivity of natural gas-based hydrogen pathways. Blue and turquoise are particularly competitive since the country is endowed with competitive natural gas resources[68], also these technologies do not suffer much from the increasing carbon prices as much CO_2 is either stored or not created but either replaced by a valuable coproduct, carbon black, when using methane pyrolysis. This way, the levelized cost for these technologies is driven by the breakeven price of the feedstock leading to a LCOH expected to remain almost stable, reaching 1.3 US $/kg$H_2$ by 2050. For grey hydrogen however, competitivity is strongly penalized by the carbon prices applied to the CO_2 emitted by the process.

68. On the other side of the spectrum, green technologies start with significantly higher levelized costs, estimated at 2 US $/kg$H_2$ for wind based and 3 US $/kg$H_2$ for solar PV based hydrogen in the best locations of the country. However, cost reductions are expected when it comes to renewable electricity assets and electrolyzers driven by technology progress and spillover effects. This drives down the LCOH, at 1.6 US $/kg$H_2$ for onshore wind and 1.9 US $/kg$H_2$ for solar PV based hydrogen towards 2050. These prices are still higher than those of blue and turquoise hydrogen under current assumptions but become much more competitive than grey hydrogen. In case of unavailability of natural gas for hydrogen production, these technologies will be able to fill the gap at a price becoming more interesting over time.

69. However, to complete the picture, to these production costs should be added the transport costs whose structure depends on the type of transport and the distance between the production and the consumption sites. Technologies that are more suitable for a local production and use should face less transport costs.

[68] The LCOH for natural gas-based LCH uses average breakeven gas prices as feedstock cost for such technologies. Unlike market prices that result from demand and supply equilibrium, breakeven price is the price level over which the production of natural gas breaks even.

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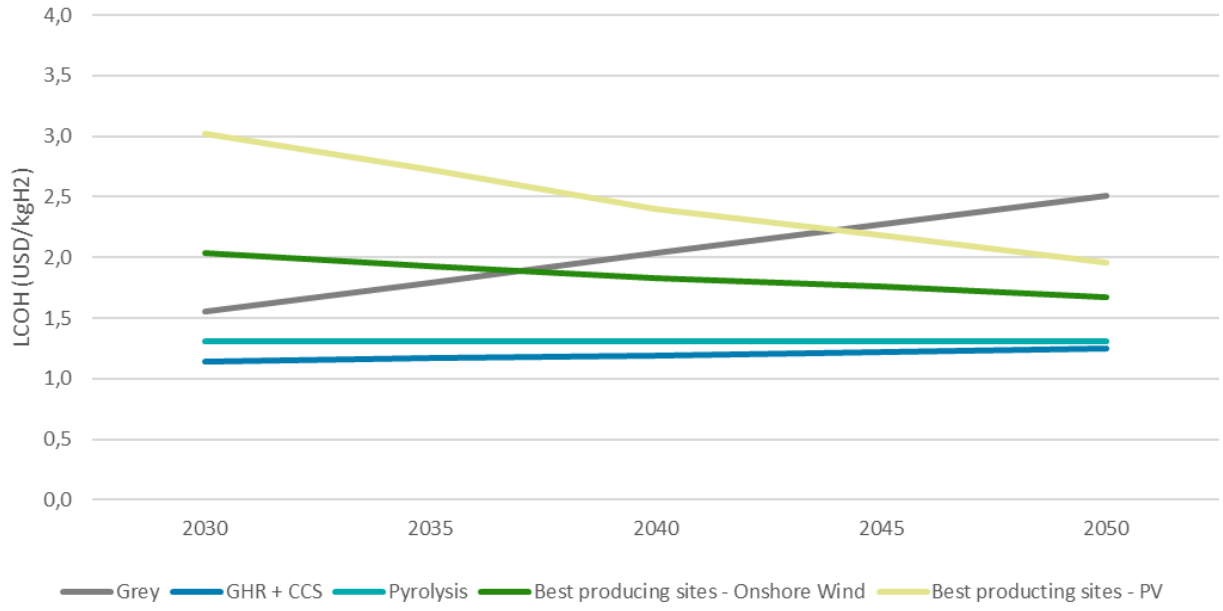
Figure 23. In-situ levelized cost of hydrogen (LCOH) in Uzbekistan, by technology



Deloitte 2022 based on data from BP statistical review, ERA5 GlobalSolarAtlas, H2 4EU (Deloitte, IFPEN, and SINTEF 2021),

Note: grey hydrogen is based on steam methane reformers (SMR) without CCS. GHR+CCS is an advanced methane reformer with enhanced heat efficiency and carbon capture rates of 90% (blue hydrogen). Pyrolysis stem for turquoise hydrogen with heat supplied by natural gas burners. Wind and PV stand for dedicated off-grid facilities and includes onsite electrolyzer costs with optimal dimensioning. An increasing carbon price is applied to all the technologies over unabated emissions (see appendix D).

2.2.2 Natural gas-based low-carbon hydrogen

70. The current economic and energy model of Uzbekistan relies to a large extent on the production, export and use of natural gas. Hence, natural gas could underpin the Uzbek low-carbon hydrogen production. Natural gas-based low-carbon hydrogen is often the cheapest production route. Figure 23 shows that the levelized cost of hydrogen for blue and turquoise hydrogen never exceeds 1.3 US $/kg$H_2$, compared to 1.6 US $/kg$H_2$ for the cheapest renewable hydrogen available in 2050. This is because of synergies with existing assets and minimal conversion costs for brownfield projects that only require the addition of carbon capture and storage (CCS) modules. Uzbekistan's legacy gas infrastructure provides a steady, affordable, and abundant supply of natural gas. Depleted natural gas fields also offer a possible solution for storing large quantities of hydrogen or captured CO_2.

71. Uzbekistan's natural gas endowments allow it to produce low-carbon hydrogen via methane pyrolysis or via methane reforming coupled with CCS. However, the relatively finite nature of natural gas production and reserves, together with other incumbent uses in the country will determine how much Uzbekistan could actually be dedicated to the production of low carbon hydrogen. To capture possible prospects on the natural gas availability to produce low carbon hydrogen in the country, three availability profiles are described below and in table 6[69].

[69] The scenarios are to be considered equiprobable. Scenarios results are built over these assumptions. Any variation affecting the reserve levels or the factors defining the natural gas availability in the country outside of this rage might lead to a different technology mix.

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- The high availability scenario assumes ambitious decarbonization policies in the short term together with expansion of production capacity, reducing the uses of unabated natural gas and increasing its availability for other uses[70]. Towards 2050, the production reaches a plateau but the trend in consumption continues leading to progressively higher amounts of natural gas for LCH production.
- The medium scenario assumes a decarbonization of the power sector by 2050 and a slight increase of production by 2030. However, in the demand side, incumbent uses of natural gas follows a slower decrease towards 2050, leading to middle of the road estimate.
- The low gas availability scenario is less optimist on the long-term production growth of natural gas and on its direct uses.

Table 6. Natural gas availability scenarios

Availability Scenario		Gas production		Gas consumption		Gas trade balance	
		Until 2030	After 2030	Until 2030	After 2030	Sign	Trend
1	**High**	**+**	**=**	**+**	**---**	**+**	**↘**
2	**Medium**	**+**	**=**	**+**	**--**	**+**	**↘**
3	**Low**	**+**	**-**	**+**	**-**	**+**	**↘**

72. The natural gas availability profiles presented in figure 24 show significant availability of natural gas for hydrogen production by 2030 thanks to early decarbonization policies assumed in the high availability scenario, while in the low availability scenario, the longer lasting reliance of end uses on natural gas reduces its availability for new uses such as LCH production. The medium availability scenario falls in between.

[70] Following the "Presidential Decree No. PP-280 (Decree)" adopted in June 2022, the gas availability scenarios are built on the assumption that the country start to correct supply-side inefficiencies. (see https://www.dentons.com/en/insights/articles/2022/june/23/new-decree-puts-focus-on-natural-gas-market-reforms-in-uzbekistan). It was also assumed official figures of natural gas reserves, that Uzbekistan progressively start decarbonizing the power sector, a key consumer of natural gas in the country, to achieve its net-zero ambitions by 2050, and that the country achieves its declared goals of expanding natural gas production towards 2030.

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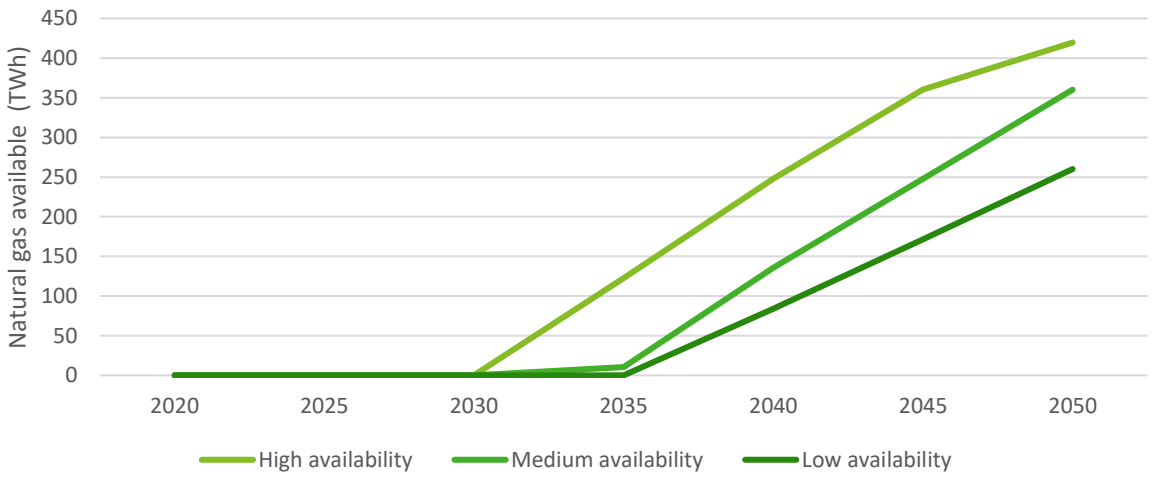
Figure 24. Scenarios of natural gas availability for low carbon hydrogen production in Uzbekistan



Own elaboration based on BP statistical review and GECF global gas outlook

2.2.3 Electrolysis-based renewable hydrogen

73. The cost decreases of green hydrogen technologies and the relevant renewable energy potential of the country seem promising to complete the market. Two potential challenges stand in the way of developing this production route: water scarcity, and the ability of the country foster deployment of renewable energy capacity for hydrogen production and for feeding the electricity grid.

2.2.3.1 LCH from solar PV

74. Uzbekistan has good solar irradiation, which confers it good solar photovoltaic (PV) potential and thereby makes hydrogen from solar PV-to-electrolysis viable. The best regions for producing solar PV are in the south-east of the country, nearby its domestic demand clusters as shown in figure 25. The availability of large flat non-arable land areas in Uzbekistan makes solar PV particularly appealing. Indeed, solar PV power plants require non-negligible dedicated land per MW installed[71]. Finally, the Uzbek government's plan to increase solar PV capacity to 2.5 and 5 GW by 2025 and 2030 will support the installation of the underlying solar PV capacity.

75. Overall, solar PV-to-X hydrogen production costs in Uzbekistan are expected to decrease to an average of 2 US $/kgH2 by 2050, with locations performing at 1.9 US $/kgH2. Moreover, the proximity of the best areas for hydrogen production from solar PV to the demand clusters makes it competitive as it can be produced nearby demand with limited transportation costs.

[71] An average of 85 MW/km² has been considered in this study

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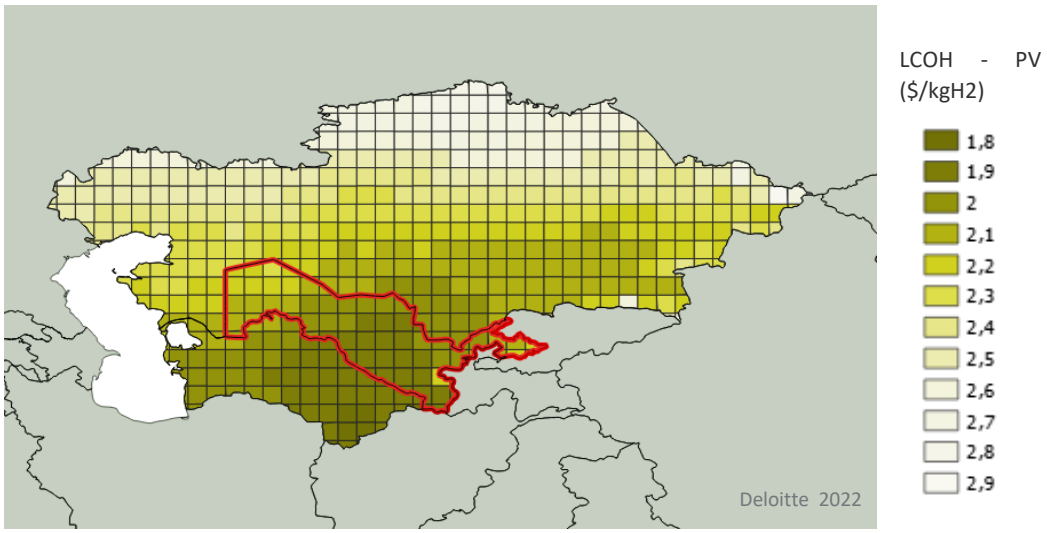
Figure 25. LCOH for solar PV-to-electrolysis hydrogen production in 2050 for Uzbekistan and neighboring countries



Deloitte 2022, based on data from ERA5 and GlobalSolarAtlas

2.2.3.2 LCH from onshore wind

76. Uzbekistan has some onshore wind potential, though this potential is somewhat smaller and less homogeneously distributed than that of solar PV. As presented in figure 26, mountain ranges shield the eastern regions from the wind, which hinders the potential of this route in those regions. However, a high speed and density wind blows on the open plains of the west, making them a prime region for the production of hydrogen based on onshore wind. The government also aims to install 2 and 3 GW of wind capacity by 2025 and 2030. Like for solar PV, this government target will help to get the ball rolling in terms of renewable energy deployment.

77. A small proportion of the territory could produce hydrogen from wind at a very competitive cost, around 1.6US $/kg$H_2$ by 2050. On average, wind-to-X projects could be developed with a levelized cost of hydrogen around 1.9 US $/kg$H_2$, on the western side of the country by 2050. This is cheaper than solar PV, but more expensive than blue hydrogen, which at this time will stand at 1.3 US $/kg$H_2$. However, the best locations for onshore wind are far from the demand cluster which are located on the south and east of the country. This implies higher transport costs for hydrogen based on wind power, that reduces the competitivity of wind over solar PV.

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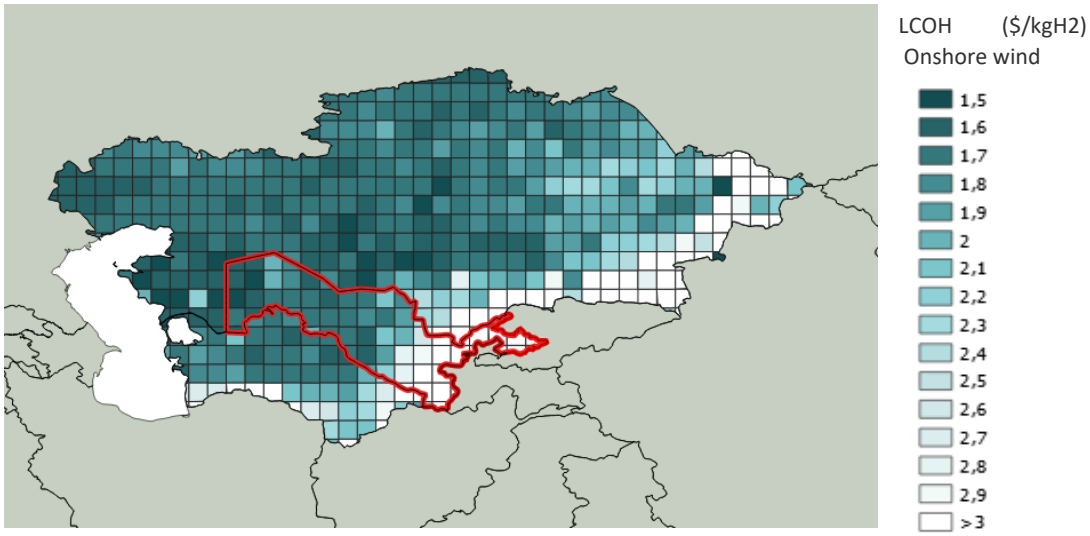
Figure 26. LCOH of onshore wind-to-electrolysis hydrogen production in 2050 for Uzbekistan and neighboring countries



Deloitte 2022, based on data from ERA5 and GlobalSolarAtlas

2.2.4 Land availability

78. From a technical perspective, land availability does not represent an issue in the country. After assessing land uses, waterways and protected area in the modelling, we estimate that more than 60% of land of the country (around 300 000 km²) remain available for new uses. Assuming that only 5%[72] of this area can be dedicated to renewables due to other concurrent uses of land, this is about 15 000 km² for renewable production. On the other hand, as it is discussed in section 3, most pathways would require less than 1000 km² to be dedicated to renewables for LCH production (about 0.3% of total available land). In addition to that, a gross area of 2500 km² would be required to produce the 97GW of renewable electricity assessed as a realistic strategy to reach net zero emissions in the power sector by 2050 ("A Carbon Neutral Electricity Sector in Uzbekistan - Summary for Policymakers", 2019) under the same assumptions.

79. The location of green hydrogen facilities is also considered in the modelling. The country is divided in cells where renewable potential, land use and distances to hydrogen demand areas are assessed. Figure 27 shows the share of land available across the country. The regions with very little land available are the Aral Sea area, those were lakes and mountains are located, and the urban areas, most of which are located on the south east of the country. On the other hand, most land available is located on desertic areas in the middle and in the western side of the country. This spatial distribution means that, although well-endowed with available land, Uzbekistan strategies relying on renewables should consider the transport infrastructures that will be required to transport power, or the product of this power -here, hydrogen- to the clusters of consumption or trade.

[72] JRC assumes 3% for solar pv in Europe, but more than 6% is has already been reached in the USA according to Great Plains Institute

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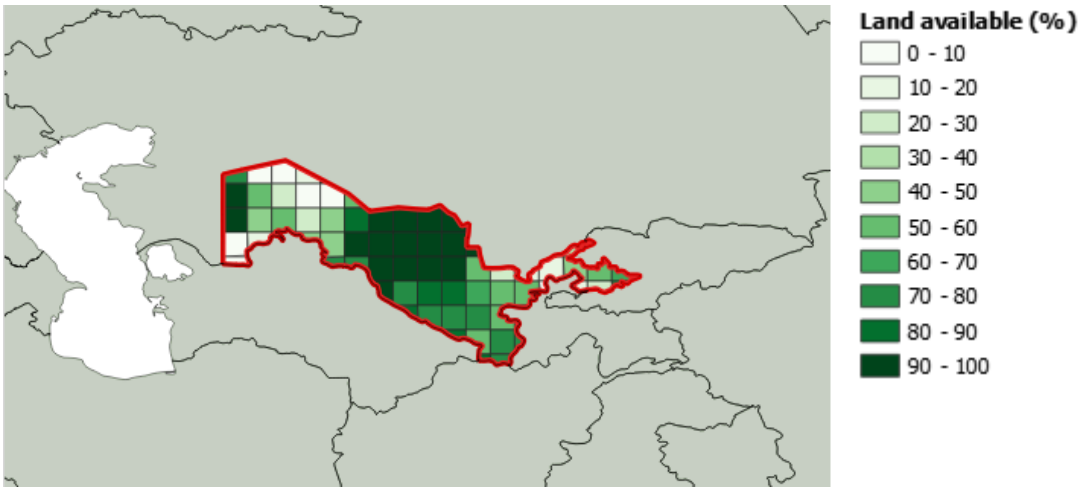
Figure 27. Land available in Uzbekistan



Deloitte analysis based on OpenStreetMap data

2.2.5 Developing hydrogen infrastructure

80. A vast network of hydrogen-ready pipelines could be developed to support the domestic market and the exports of hydrogen. In the short to mid-term, new pipelines built for hydrogen transport may not be the optimal solution, as it requires significant investments and a certain critical mass of demand size, so road transport or blending into the existing natural gas pipelines could represent a better opportunity. These pipelines are not currently fit to transport high concentrations or pure hydrogen due to technical constraints like embrittlement. Small hydrogen molecules can penetrate microscopic interstices in the pipeline wall and build up pressure, causing damage. However, they can be repurposed to transport hydrogen. Repurposing pipelines means replacing parts and installing an internal coating layer designed for hydrogen transport (ACER 2021)[73]. That cost increases with the length and diameter of the pipeline. Other investments to be considered are correspond the replacement of the compressor that puts the system in motion and upgrading the security equipment. About three times the compression power used for natural gas is needed to transport the same energy as hydrogen. This investment also depends on the length of the pipeline, which determines the compression power needed to send the hydrogen to its destination[74].

81. Concerning the export of hydrogen, table 7 provides the list of the pipelines candidates assumed to be repurposed in the scenarios assessed. Together, repurposed pipelines add up to nearly 2500 km, representing a CAPEX of over US $ 1.8 billion for line A of the Central Asia – China pipeline and about US $ 0.7 billion for the Bukhara – Almaty link according to our central estimate[75]. Shymkent (Kazakhstan) will be the most critical node outside of Uzbekistan's control, because Uzbekistan needs it to send hydrogen to Khorgos (China). The link from Shymkent to Khorgos

[73] See "Repurposing Existing Gas Infrastructure to Pure Hydrogen" (ACER, 2021).
[74] For the pipelines considered in this report, repurposing pipelines alone would cost around US $ 400 M/1000 km and reconversion of compression stations would add up about US $ 330 M/1000 km.
[75] This estimate includes the coating of the pipeline and the replacement of the compressor, with a methodology similar as the that of the Hydrogen Backbone - https://ehb.eu/files/downloads/ehb-report-220428-17h00-interactive-1.pdf

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could transport nearly 14 MtH_2/year[76], which is amply sufficient for Uzbek exports. Due to the considerable amount of project planning and works that must take place, those pipelines are assumed to become available only by 2040 in a best case scenario, which in turn would allow access to the Chinese market by that horizon[77].

Table 7. Hydrogen infrastructure development assumptions

Pipeline	Start	End	Length (km)	Line (if any)	Capacity (bcm natural gas)	Hydrogen-ready
Central Asia - China	Saman-Depe (TKM)	Olot (UZB)	383	A	15	From 2040
	Olot (UZB)	Shymkent (KAZ)	140	A	15	From 2040
	Shymkent (KAZ)	Khorgos (CHN)	1310	A	15	From 2040
Bukhara -Almaty	Bukhara (UZB)	Shymkent (KAZ)	600		22	From 2040

Deloitte 2022, scenario assumptions

82. The assumption of repurposing the Central Asia – China line A is very dimensioning and significant. It would requiresMaking it real would require a strong coordination between Kazakhstan, Uzbekistan, Turkmenistan, and China. Whereas the first two countries might be interested in exporting hydrogen through these pipelines, Turkmenistan interests, which is the main exporter of natural gas through this pipeline, is much more uncertain. HoweverHowever, since recently Uzbekistan and Kazakhstan exports to China are expected to shrink progressively in the coming years, and that line D of the Central Asia – China pipeline is under construction, it can be expected some capacity can be free up inthat this corridor will have idle capacity according to current trends.

83. On the other hand, the buildup of a hydrogen network for the domestic transport is a complex topic. The strategy for managing the competition and complementarities between natural gas and hydrogen transport in the country at an optimal cost is out of the scope of this current report. We have thus considered a worst-case scenario considering no national pipelines are available so only road transport is available in the domestic market[78].

84. Infrastructure needs go beyond transmission pipelines and pipeline nodes. Hydrogen storage, distribution and refueling infrastructure will be necessary for the hydrogen economy to grow. Fortunately, the development of the hydrogen economy around industrial clusters (“hydrogen

[76] Conversion based on the 15 bcm capacity of the Shymkent – Khorgos line, taking higher heating values (HHV).
[77] We estimate the spare capacity to be about 14 bcm in a scenario that Uzbek and Kazakh gas exports to China significantly reduces and line D comes online by 2030. Therefore, by considering a period of 7-10 years for repurposing the spare capacity of the pipeline to become hydrogen-ready, we assume that line A could become active for hydrogen trade by 2040.
[78] This is a conservative assumption since road transport is more expensive than transport via pipeline. It might bias the model results towards producing LCH nearby consumption since it gives a cost penalty to production sites far from the demand and clusters but were a hydrogen pipeline could be an option.

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valleys") minimizes the distance between production and consumption, and thereby investments and transport costs. Nonetheless, the development of local infrastructure remains a complex problem in itself. Safety becomes even more paramount and sometimes even a political barrier around populated areas. Hydrogen transport and logistics would require case specific assessments. As such, business models are still being tested everywhere in the world and it is therefore difficult to quantify the required investments in local hydrogen infrastructure with precision.

2.3 Low carbon hydrogen scenarios in Uzbekistan

85. In this analysis, two set of three scenarios have been introduced in sections 2.1.4 and 2.2.2. These variations around low-carbon hydrogen demand and natural gas availability lead to differences in the behavior of the main actors of the markets and in the optimal low-carbon hydrogen production strategy for Uzbekistan. The results of the model, considering each scenario separately, are interpreted in the following sections.

2.3.1 Balancing the future demand of low-carbon hydrogen

86. Based on the assumptions that the key policy and regulatory enablers are put in place in our scenarios[79], **domestic hydrogen demand is the main driver of the sector, kickstarting the development of hydrogen production capacity from the early stage of the market**.

87. Figure 28 shows the trade balance of hydrogen from Uzbekistan over the period 2030-2050 in the high, medium and low hydrogen demand scenarios. It can be seen a much faster growth in the development of production facilities in the high demand scenarios, compared to that of the low hydrogen demand scenario. In this scenario, it is assumed that the **higher domestic hydrogen demand gives higher incentives for national production to grow making higher deployment rates possible due to spillover effects**. **On the other hand, a low hydrogen demand traduces into a smaller national market which is less attractive for investments and develops at a slower pace**. Consequently, the capacity available to produce hydrogen to export is higher in the high demand scenario. In this case, exports reach more than 1.3 Mt of hydrogen in 2050 to compare with 0.86 Mt in the central scenario and 0.25 Mt in the low demand scenario.

[79] See section 4 for further development on these enablers.

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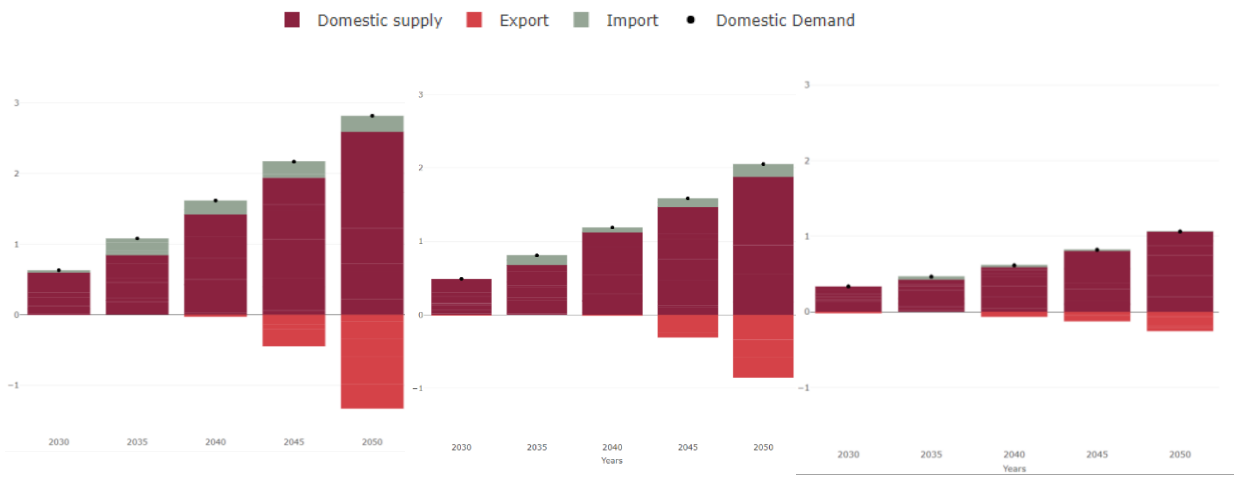
Figure 28. Low-carbon hydrogen market in Uzbekistan in the high, medium, and low hydrogen demand scenarios



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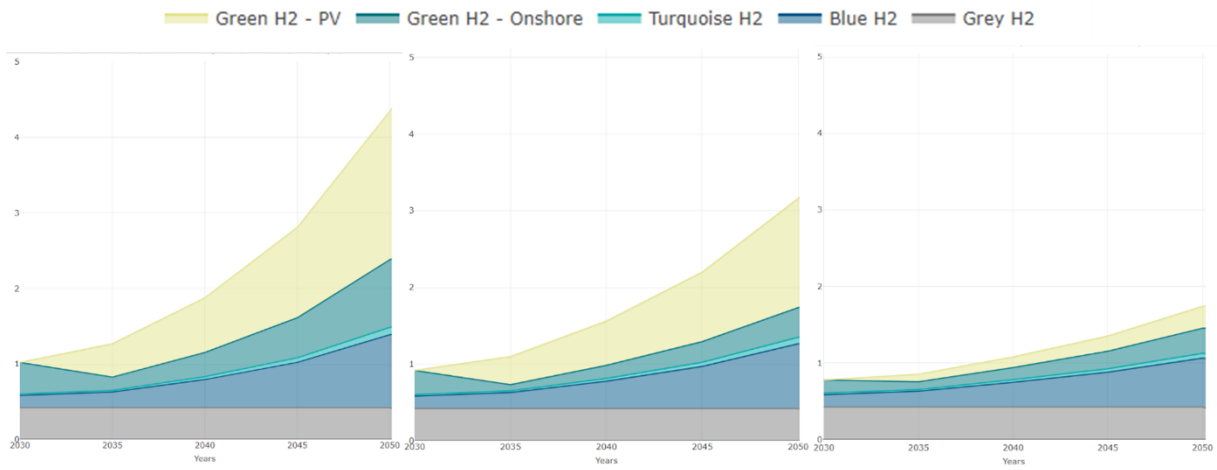
88. Since LCH from natural gas seems particularly competitive in the scenarios assessed**, the lower the hydrogen demand the higher the shares that can be met with blue hydrogen only. This is reflected in the share of blue hydrogen in the national production mix which is higher when the demand is low and *vice versa***. The extent of it can be seen in figure 29 where the share of blue hydrogen increases to 48% in the low demand scenario instead of 30% in the central scenario, in 2050 (grey hydrogen excluded). In the high demand scenario, the share of blue hydrogen in the mix in 2050 falls down to 25% (grey hydrogen excluded).

Figure 29. Production mix of low-carbon hydrogen in Uzbekistan in the high, medium, and low hydrogen demand scenarios



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89. The three scenarios require different volumes of water and natural gas to be fulfilled[80]. The production of renewable energy between the different demand scenarios can vary by a factor six, having a different impact on land use. In the low demand scenario, the capacities of renewable

[80] Further details on feedstock use are available in appendix E

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energy required amounts to 1.7 GW in 2030 and 9.9 GW in 2050, when they reach 4.3 GW in 2030 and 54.9 GW in 2050 in the high demand scenario. These capacities require an area of 170 km² to 430 km² in 2030 and 390 km² to 1361 km² by 2050 to be developed.

2.3.2 Assessing the impact of natural gas availability

90. As there are trade-offs to be considered for shifting from natural gas to LCH, and since blue hydrogen seems to become the most competitive way to produce it for the coming decades, **the future of low-carbon hydrogen in the country is closely tied to the prospects of the natural gas industry**. However, new natural gas end-uses are in harsh competition against incumbent domestic uses in industry and in the transport sector, and as a revenue stream from its exports. Therefore, its availability for LCH production is defined by complex supply/demand balance considerations, the evolution of the O&G upstream sector and other market incentives. As presented in section 2.2.2, three scenarios have been considered to assess the influence of natural gas availability in the hydrogen market development in Uzbekistan.

91. As shown in figure 30, **in the central scenario there is room for hydrogen production from natural gas with a share of blue hydrogen representing around one-third of the hydrogen production mix in Uzbekistan, from 2030 to 2050**. Some small amounts of turquoise hydrogen, and more than 0.4 Mt of grey hydrogen are also produced, which all use natural gas as feedstock. The scenarios assume natural gas becomes progressively available for new uses due to progressive shifts towards clean electrification driven by climate objectives which leads to significant decrease of unabated natural gas consumption. This situation enables a sufficient production to meet the domestic demand and to export hydrogen by 2040, also due to the development of green hydrogen technologies.

92. In the scenario assuming high availability of natural gas, the shares of blue hydrogen in the production mix are much larger. **The share of natural gas-based LCH (grey excluded) ramps up to 63% in the high availability scenario**. Such an increase is the result of the lower levelized cost of hydrogen of blue hydrogen against green-based hydrogen in the country. This scenario assumes very ambitious actions targeting the rational use of natural gas and the will to develop this blue hydrogen technologies in such a fast pace.

93. **Figure 30 also shows that investing in blue hydrogen technologies would be at the expense of the development of green hydrogen technologies over the period** due to the progressive development of the domestic demand. Given path dependencies due to industrial specialization, green hydrogen technologies have harder time catching up the levels attained in the central scenario. This results in a situation where there is less green hydrogen capacity deployed in the country all over the period. **This is particularly relevant when exports to China become possible since it leads to a limited amount of LCH that can be produced since the natural-gas based LCH is constrained by the available feedstock and the green hydrogen industry finds itself on a earlier stage of development**. **All in all, this leads to lower amounts of hydrogen exports by the end of the period** as shown in figure 31.

94. **In the case when not enough natural gas is available for LCH production, green hydrogen technologies are able to take over in terms of volume of hydrogen produced provided capacities are deployed timely**. **In the low natural gas availability scenario, the green hydrogen production takes about 68% of the mix while blue hydrogen falls to 18%**. This scenario requires more investments in renewables and electrolyzers from the beginning of the period, even if they are not the most competitive options, to progressively build up the industry. The key drawback of

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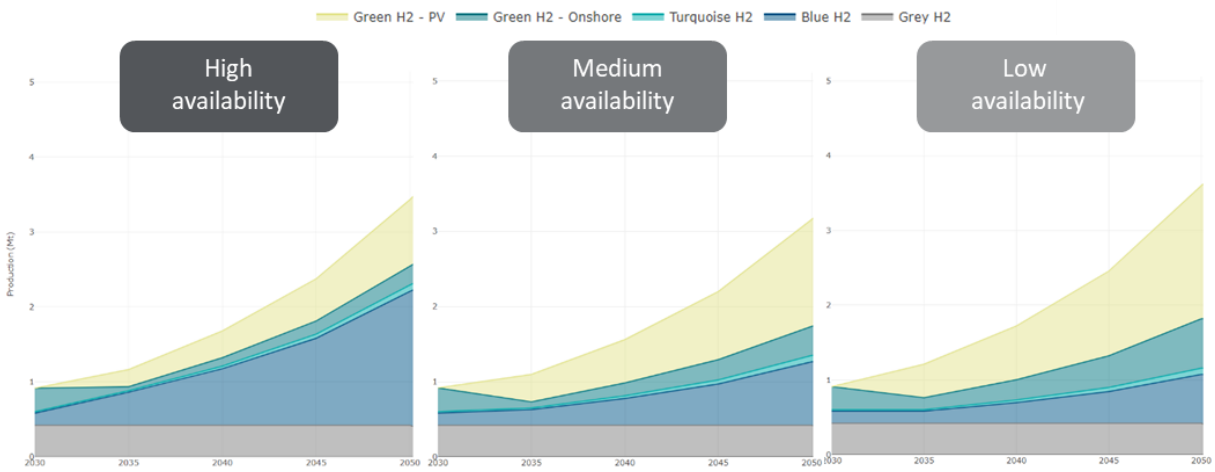
this pathway is the higher cost of hydrogen supply over the period, given the relatively lower cost competitivity of green and blue hydrogen technologies mentioned above. Although this results in slightly higher market prices in the country, **limited natural gas availability should not hamper Uzbekistan from exporting hydrogen to China** as presented in figure 31.

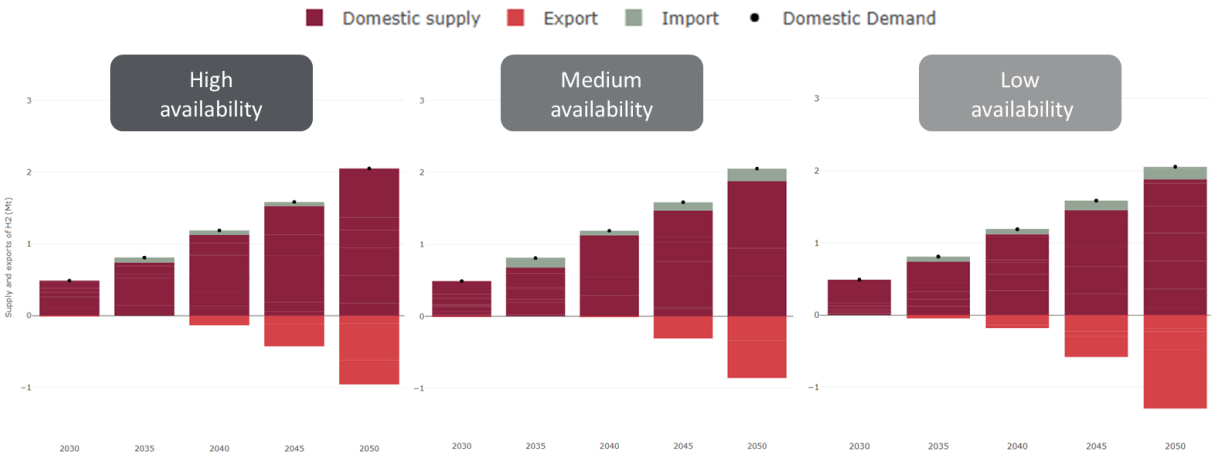
Figure 30. Low-carbon hydrogen market in Uzbekistan in the high, medium, and low natural gas availability scenarios



Source: Deloitte 2022

95. There is a direct impact of natural gas availability on the mix of production of low-carbon hydrogen. This also implies different land use, as the renewable energy is more intensive in land. Between the scenarios of high and low availability of natural gas, the land required for renewable energy dedicated to hydrogen production varies from 484 to 1116 km². This area range is centered around the 760 km² needed for renewable energy facilities in the central scenario.

Figure 31. Production mix of low-carbon hydrogen in Uzbekistan in the high, medium and low natural gas availability scenarios.



Source: Deloitte 2022

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Box 3. Interregional considerations on the LCH market strategy

Kazakhstan has made sign on its will to develop into a similar direction with regards to clean power and LCH, by reinforcing its NDCs and its will to diversify its economy. And since in such a pathway the country's natural gas industry would face similar challenges, it can be expected that the country would share a similar pathway with respect to low-carbon hydrogen development.

However, Turkmenistan can be seen as a wildcard with respect to the LCH industry in the region due to its colossal natural resource endowment, and its uncertain stance on climate ambitions and economic diversification plans. A prominent natural gas industry confers Turkmenistan the potential to produce vast quantities of affordable low-carbon hydrogen via methane reforming coupled with CCS. This plentiful and cheap hydrogen potential could displace Uzbekistan's hydrogen in the interregional merit order. In that case, some Uzbek buyers could turn to cheaper Turkmen hydrogen imports, provided investments take place, which would disincentivize domestic Uzbek production. Cheaper Turkmen hydrogen could get prioritized by Chinese importers, thereby smothering Uzbek hydrogen exports to China. While there is little doubt that Turkmenistan has the potential to displace its neighbors on LCH supply, its stance on hydrogen matters is uncertain. The Turkmen government has not shown strong signs of pursuing hydrogen production, let alone trade. Uzbekistan should therefore plan its hydrogen economy without counting on Turkmen hydrogen, but also be ready to adapt its plans if Turkmenistan makes a move on this market.

3 Market forces and prospects for low-carbon hydrogen in Uzbekistan

3.1 Capturing the evolution of a rapidly changing market

96. With the key policy and regulatory enablers in place, the scenarios show the hydrogen market in the country grows rapidly and see substantial changes over time. Table 8 shows the ranges of capacity additions per period and technology for the different scenarios. **As early as 2030, capacity starts to be developed. Wind and PV capacity additions required up to 2030 are comparable to the official capacity targets for the power sector in the same time horizon, namely 5 GW solar PV and 3 GW of wind**. Moreover, between 1 - 3 GW of electrolyzers and about 1 GW of blue hydrogen capacity are also required, on the top of the steam methane reforming (SMR) capacity already in plans.

Table 8. Production capacity additions per time period

Technology	Unit	Up to 2030	2031-2040	2041-2050
Solar PV	GW	0	4 – 18	4 – 29
Onshore wind	GW	1 – 4	0.3	1 – 4
Electrolyzers	GW	1 – 3	3 – 11	6 – 33
GHR + CCS	GW	1	0.4 – 0.6	1 – 2.5
Pyrolysis	GW	0.1	0 – 0.1	0.2 – 0.3

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SMR (in plans)	GW	1.7	0	0

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97. Figure 32 presents the flows of hydrogen at a regional scale over time, and the evolution of the prices and volumes of hydrogen traded in the market. The Sankey diagrams show the flows of hydrogen between the producing countries (on the left) and the consuming countries, by demand cluster, on the right. The merit order charts (right hand-side) show the supply curve of hydrogen traded in Uzbekistan (for exports and domestic supply), specifying the technology and destination (internal or trade).

98. International trade of LCH takes time to ramp up into a large-scale market, but eventually Uzbekistan can export significant volumes to China. In 2030, the Sankey diagram (left-hand side) reveals that **Kazakh, Uzbek, and Turkmen markets are mainly oriented towards their domestic markets respectively**, regional trade accounting for less than 0.1 MtH_2. By 2040, regional trade starts to develop and seems to be relevant for the clusters nearby the frontiers. However, it remains marginal at around 0.2 MtH_2 in 2050, and mainly occurs between Turkmenistan and Uzbekistan. Large-scale exports truly begin in 2040, when a repurposed line of the Central Asia – China pipeline is assumed to come online. This line enables Kazakhstan, Uzbekistan, and Turkmenistan to export hydrogen to China and its potentially massive market**. In 2050, exports reach more than 2.6 MtH_2, with nearly 0.9MtH_2 from Uzbekistan, which is a third of his production**. Overall, the domestic hydrogen market of Uzbekistan is comparable in size to its neighbors'. In 2050, the Uzbek market is two thirds the size of the Kazakh market in 2050[81].

99. **Natural gas-based hydrogen is the most cost-efficient technology throughout the outlook period, but hydrogen made from renewables, particularly from solar PV, becomes increasingly competitive**. This is depicted on the right-hand side of figure 32: reforming with CCS remains cheaper than its alternatives throughout the period. Then comes hydrogen from pyrolysis, renewable hydrogen from onshore wind, and, starting in 2040, the renewable hydrogen from solar PV. Total yearly production volumes increase over time. The right-hand side of figure 32 shows total yearly production volumes increasing over time, propelled by a skyrocketing volume of solar PV-based hydrogen. By 2050, it represents more than 1.4 MtH_2 which is almost half of the low-carbon hydrogen production of the country[82] [83].

[81] These scenarios assume Kazakhstan undertakes its energy transition driven by strong climate commitments.
[82] These results are consistent with the LCOH shown in Figure 23, which presents only in-situ LCOH, whereas the LCOH at demand site are shown here comprising domestic transport costs, which typically hover around $ 0.50/kgH_2. As such, costs are always higher for exported hydrogen than for domestically used hydrogen.
[83] The need of renewable energy resources to produce low-carbon hydrogen comes on top of the need for renewable energy to decarbonize the power sector. The strategy to decarbonize the power sector in Uzbekistan presented in a study lead by a consortium of consulting firms[83], foresees an annual deployment rate of renewables of 13% between 2030 and 2050. This is to be compared with the deployment rate of 9% assumed for this study. When adding the capacities together, the foreseen deployment rate between 2030 and 2050 does not increase, as volumes in 2030 are a little bit increased. Besides, synergies could also be found, and the country could benefit from costs reductions on the overall production cost and deployment rate of renewables due to learning by doing. Overall, the renewable sources for low-carbon hydrogen production represent a quarter of the renewables installed in the country by 2050. At last, the complexity of adding off-grid renewable capacities for green hydrogen is less stringent as it requires less network infrastructure.

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Figure 32. Evolution of the flows and merit order of low-carbon hydrogen in Uzbekistan from 2030 to 2050

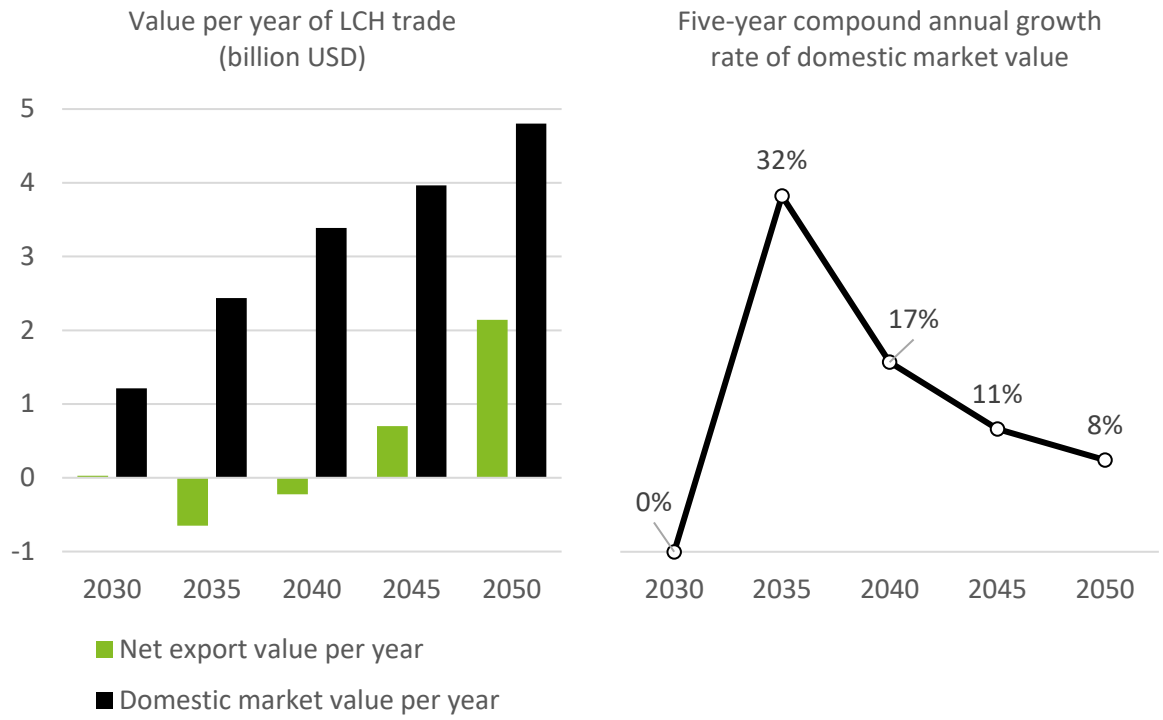


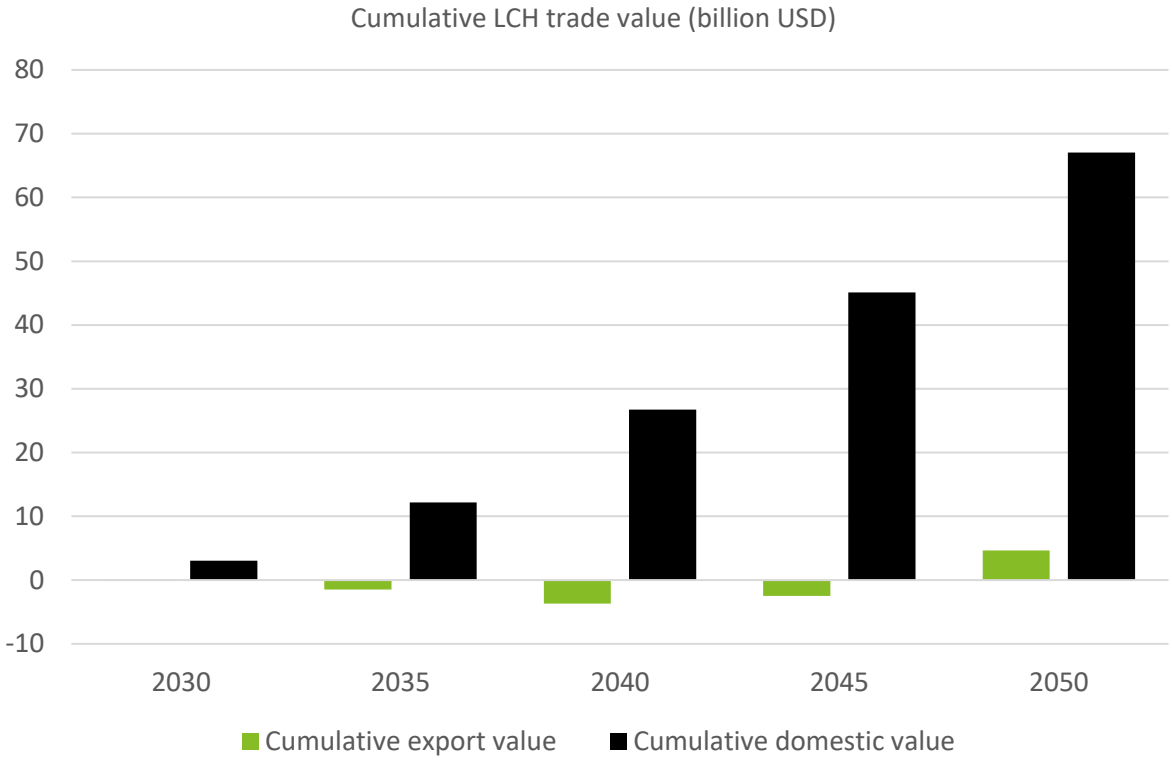
Source: Deloitte 2022

3.2 Economic value of the Uzbek low-carbon hydrogen market

100. The domestic market provides the most economic value for Uzbekistan throughout the outlook period, but access to the Chinese market in 2040 onwards quickly makes for a non-negligible source of revenue. Figure 33 shows the cumulative domestic market value growing by 17% annually from US $ 3 billion in 2030 to US $ 67 billion in 2050. In 2030, the domestic market is valued at US $ 1.2 billion per year. In 2050, the value of the domestic market is US $ 4.8 billion per year. As discussed above, the domestic market has a strong demand potential, in particular for feedstock uses in methanol, and ammonia and in industrial heat supply. The domestic market thus provides a solid revenue basis for the Uzbek low-carbon hydrogen value chain. The picture is slightly different for the export market. Until 2040, when a link with China become hydrogen-ready, Uzbekistan's trade balance is negative as interregional imports outweigh exports. Cumulative net export market value becomes positive only by the end of the period, reaching US $ 2.1 billion by 2050. **Low-carbon hydrogen exports are thus a long-term possibility for Uzbekistan, whereas the domestic market brings the most economic value until 2050. Nonetheless, developing LCH exports as a long-term strategic plan still means that the country should encourage hydrogen exports-related projects long before 2050**. Interregional trade is possible and beneficial early-on, and local demand will grow together with overall supply. Infrastructure will also take significant time and funding to be commissioned. **Similar than for the natural gas industry, a close strategic coordination around LCH topics with China and other export partners must also be put into the agenda**.

Figure 33. Value of domestic and export hydrogen markets for Uzbekistan, 2030-2050





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Box 4. Water stress and LCH production in Uzbekistan

Water scarcity is another risk factor for low-carbon hydrogen production in Uzbekistan. This constraint hinders electrolyzers but also steam methane reformers, though pyrolysis plants are not subject to it. An electrolyzer needs around 18 kg of water for every kilogram of hydrogen produced. With reformers and electrolyzer production reaching 0.8 MtH_2/year and 1.8 MtH_2/year by 2050 respectively, a corresponding 41.3 MtH_2O/year are required, or about 0.07% of current freshwater consumption[84]. This is a small share, but it can be significant given that the UN estimates Uzbekistan to be the most water-stressed landlocked developing country in the world (FAO 2021). Without access to the sea, desalination of water is not an option like it is in Saudi Arabia or other countries facing water scarcity issues and considering to become hydrogen exporters. Multiple solutions are being studied over the world to ensure a long and stable source of water for hydrogen production, such as desalination of brackish groundwater or of water aquifers. There also exist promising pilot studies to produce hydrogen from wastewater, through regular pathways or using biological reactions to produce hydrogen, the latter remaining at their infancy[85]. Managing water feedstock will most likely be one of the key challenges of sustaining Uzbekistan's low-carbon hydrogen economy. Should climate change heighten Uzbekistan's water stress levels as the IPCC reports (2019)[86], large-scale electrolysis would become an unviable production pathway. A full assessment on water production could be done in a future analysis.

3.3 Financing the ramp-up of the Uzbek low-carbon hydrogen market

101. Developing a hydrogen economy in Uzbekistan will entail significant investments in production capacity for hydrogen production and in renewable power generation dedicated to electrolyzers. **In the scenarios assessed, cumulative required investments total US $ 43 billion by 2050, growing by 9% annually from 2030 to 2050** (see Figure 34 below). This ramp-up can be divided into three phases. First, an initial US $ 15.7 billion push between today and 2035 enables in particular the growth of solar PV and electrolyzers. Second, investments in the decade spanning 2036 to 2045 add up to US $ 8.1 billion in solar PV, US $ 4 billion in electrolyzers, and US $ 1.1 billion in gas-heated reformers with CCS. The decade from 2036 to 2045 is the slowest growth period in the projection. One explanation is the lack of opportunities in the Chinese market, which is unavailable until 2040. Finally, in 2045-2050, investments bound back up to US $ 13.6 billion in 5 years, including US $ 8 billion in dedicated renewables, US $ 4.3 billion in electrolyzers and US $ 1.3 billion in methane-based low-carbon hydrogen.

[84] Based on data from the World Development Indicators database, retrieved from: https://datacatalog.worldbank.org/indicator/3e7b27df-bdce-eb11-bacc-000d3a596ff0/Annual-freshwater-withdrawals--total--billion-cubic-meters-

[85] (Islam et al. 2021)

[86] Source: IPCC, *Special report on climate change and land*, chapter 3 (available online).

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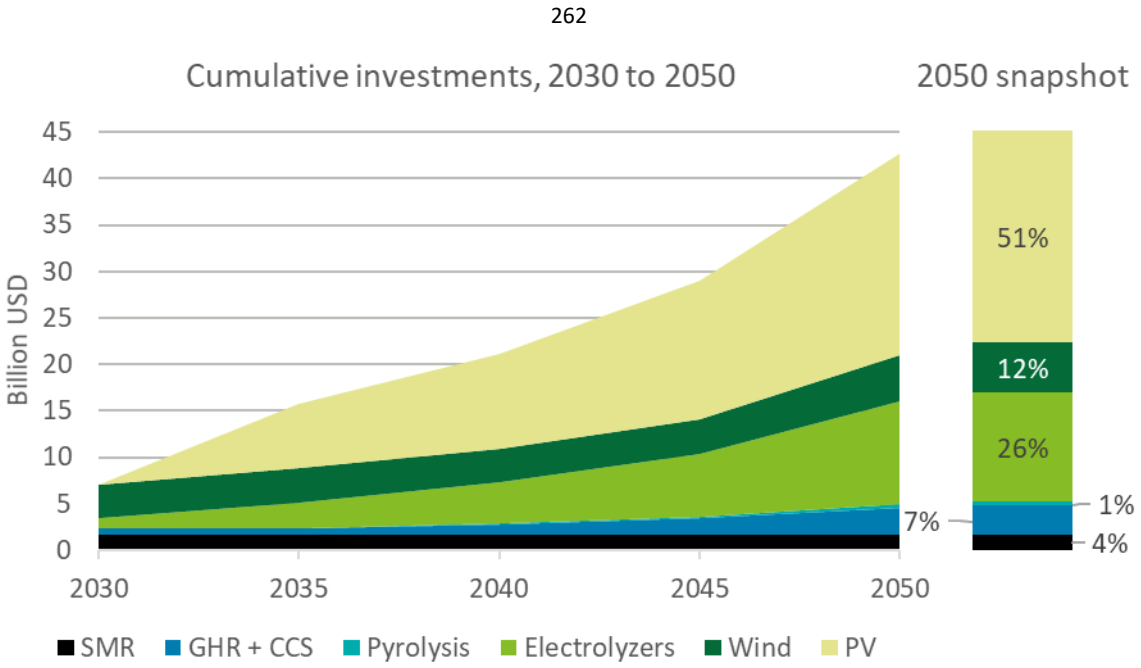
Figure 34. Cumulative investments required in hydrogen production technologies and dedicated renewable power generation in Uzbekistan, in billion USD and CAGR, 2030-2050



102. The slight acceleration observed in 2045 is largely driven by increased investments in renewable hydrogen production, i.e., electrolyzers, solar PV and wind power. Figure 34 shows investments in wind, electrolyzers, pyrolysis and gas heating reformers (GHR) with CCS accelerating in 2045-2050. Investments in wind power increase particularly sharply. Decreases in production costs making renewable hydrogen production projects more economically viable can partly explain this acceleration. Another part of the explanation is Uzbek producers' reaction to the opening of the vast but competitive Chinese market. A large chunk of Uzbek-made low-carbon hydrogen is rerouted to China to compete with cheap Central Asian or Chinese low-carbon hydrogen. This would leave room for new renewable hydrogen projects to satisfy domestic or Chinese demand, thanks to cost reductions in renewables and electrolyzers. Finally, electrolyzers installed early-on in the outlook period should also be renewed[87]. The accelerated trend in 2045 is therefore due to the cumulation of investments in new electrolyzers growing as fast as in 2035-2045, plus investments in renewed electrolyzers.

103. Experience from the first pilot projects in other regions of the world shows that for an effective way of incentivizing investments both the public and private sectors should be mobilized. Hydrogen projects, particularly infrastructure and renewable-based hydrogen production, are capital-intensive by nature. This often makes final investment decisions hinge on the availability of affordable and sufficient funding. Both the public and private sectors have a role to play. On the public side, grants, investment cost subsidies, and contracts for difference that cover investment costs can help reduce the cost of financing. Private investors can use financing models that incorporate sustainability criteria. **In the central scenario nearly US $ 45 billion of over 25**

[87] A typical electrolyzer's lifespan is 20 to 25 years. Electrolyzers installed in 2025 to 2030 will therefore need replacement starting in 2045.

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years are invested in hydrogen production alone in Uzbekistan. This requires actions from policymakers and private investors alike to lower the cost of financing hydrogen projects and make them come online timely.

4 A roadmap for developing low-carbon hydrogen in Uzbekistan

104. In May 2021, Uzbekistan signed a Memorandum of Understanding (MoU) with the European Bank for Reconstruction and Development (EBRD) to cooperate towards achieving carbon neutrality by 2050. The country is still predominantly dependent on fossil fuels (97% of energy mix) for its energy needs. Hence, significant efforts are required to reduce dependence on fossil fuels and decarbonize the country's economy.

105. As assessed in the previous sections, low-carbon Hydrogen (LCH) could play a very important role in achieving Uzbekistan's climate ambitions. However, there are several barriers to the development of LCH in Uzbekistan, owing to the technical, policy and financial developments required to support the LCH economy.

4.1 Barriers for the development of LCH in the country

106. **Technical/infrastructure barriers** include challenges related to water scarcity, slow growth of renewables, and the need for development of H_2 and CCS technologies. Water is a crucial resource for the LCH development. Green H_2 production and steam methane reforming are water intensive processes. In the central scenario, LCH production would require about 7.3 Mt of freshwater per year by 2030. As the demand for H_2 increases, the demand for freshwater will increase annually. Uzbekistan is located in a semi-arid region. It has less than 10% arable lands while the rest is covered by deserts and mountains[88].Currently, the country experiences critical load on its water resources. It consumes 169% of its water reserves[89] . The growing population and climate change are challenges exacerbating the situation. With increasing temperatures around the world, freshwater is expected to be scarcer in the future. Considering that Uzbekistan is a land-locked country, the possibility of having sea-water desalination facilities will represent a challenge.

107. Another challenge is associated with the capabilities of financing and deploying the required renewable energy capacity in the country. To produce LCH, renewable capacity should match the target electrolyzer capacity. Uzbekistan plans to generate around 25% of its electricity from renewable sources by 2030[90]. It is important to ensure the adequate pace of renewable energy development to reach that goal. As green H_2 production will go in parallel with the expansion

[88] The Diplomat, Uzbekistan's Impending Water Crisis,2019, Retrieved from: https://thediplomat.com/2019/09/uzbekistans-impending-water-crisis/, on 01 July 2022

[89] Food and Agriculture Organisation of the United Nations, *Water use in Uzbekistan and Turkmenistan has reached a critical level,* Retrieved from: https://news.un.org/ru/story/2021/08/1408882, on 01 July 2022

[90] Republic of Uzbekistan, Updated Nationally Determined Contribution, 2021, Retrieved from: https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Uzbekistan%20First/Uzbekistan_Updated%20NDC_2021_EN.pdf, on 01 July 2022

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of renewables for the electricity sector, a coordinated approach should be put in place to guarantee the successful development of both industries.

108. All these technologies are capital intensive which can pose deployment challenges. Additional challenge is associated with keeping an adequate pace of implementation to ensure that H_2 production targets are met. The pace at which renewable energies and other technologies required in the LCH supply chain can be deployed determines to a large extent the pace of adaption of hydrogen technologies and the LCH production mix. Since capacity cannot realistically be built overnight, to achieve the long-term LCH potential in the country significant year-on-year deployment rates are required over the period assessed. Since the demand scenarios show a growth rate of about 6-7% on average, the deployment rate in the supply-side should be at least equal or higher for it to be able to balance domestic and export demand. Securing such steady growth should not be taken from granted[91].

109. As the LCH industry in Uzbekistan is to be built from ground zero a crucial barrier that has to be addressed is associated with policy development. **Policy barriers** involve implementation of emission targets, carbon pricing mechanisms, development of relevant LCH regulations and standards.

110. Uzbekistan has set a target of reducing specific GHG emissions per unit of GDP by 35% below 2010 levels by 2030[92]. To build up LCH economy in the country industry specific targets have to be set. Oil and gas sector and heavy industry decarbonization could be the priority sectors to begin with.

111. Uzbekistan does not currently have any carbon pricing mechanisms in place which could be beneficial for boosting LCH developments as they drive the investments in clean technologies.

112. As LCH is a new and unexplored sector for Uzbekistan, it is associated with the **lack of necessary capacities**. As mentioned in Section 1.3.4 in April 2021 the government has approved presidential resolution "*On measures for the development of renewable and hydrogen energy in the Republic of Uzbekistan*". The resolution implies the establishment of a National Research Institute for Renewable Energy Sources which includes the Research Center for Hydrogen Energy and the Laboratory for Testing and Certification of Renewable and Hydrogen Technologies[93]. To succeed in the LCH development in addition to technical capacity building, it is important to address regulations, project development, financing, trade, among other related aspects.

113. Another significant barrier for the development of low-carbon hydrogen is the cost gap between hydrogen and unabated fossil fuels. There is significant potential to cut costs of LCH implementation through technology innovation and deployment instruments. But to ensure that, the government should develop **financial mechanisms** to finance the development of all

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[91] The central scenario assumes that LCH technologies cannot grow faster than 9% per year, which means doubling every 8 years approximately which is a typical value for a rapidly growing industry.

[92] Republic of Uzbekistan, Updated Nationally Determined Contribution, 2021, Retrieved from: https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Uzbekistan%20First/Uzbekistan_Updated%20NDC_2021_EN.pdf, on 01 July 2022

[93] IEA, Resolution No. PP-5063 "On measures for the development of renewable and hydrogen energy in the Republic of Uzbekistan", 2021, Retrieved from: https://prod.iea.org/policies/13432-resolution-no-pp-5063-on-measures-for-the-development-of-renewable-and-hydrogen-energy-in-the-republic-of-uzbekistan?page=4&sector=Education%2COffices%2CBuildings%2CHydrogen%20production%20and%20supply , on 1 April 2022

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aspects associated with low carbon hydrogen. Early mover projects will require extensive financial support but would allow to collect massive know-how to be harnessed for future undertakes.

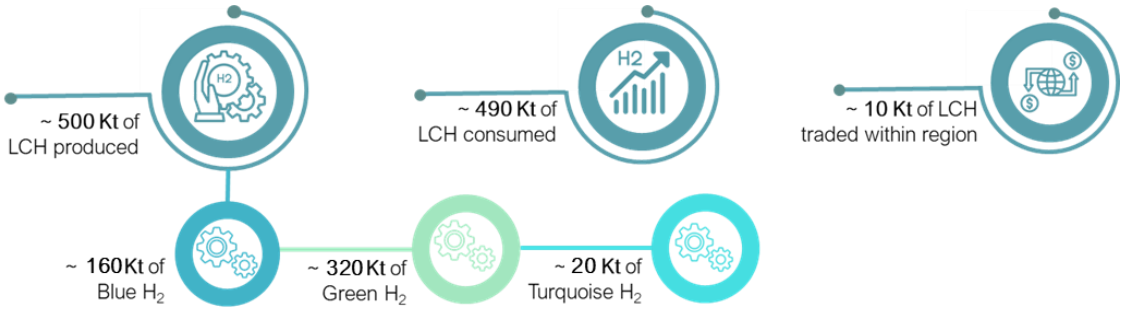
114. **Finally, barriers in LCH trade include** Turkmenistan having competitive advantage over Uzbekistan when it comes to blue H_2 cost. Due to ample natural resources Turkmenistan can produce vast quantities of affordable low-carbon hydrogen via methane reforming coupled with CCS. Provided Turkmenistan develops its LCH sector, it has the potential to outcompete exports from Uzbekistan to China.

115. The development and upscale of any technology will have barriers similar to those presented for the LCH development. Ample planning and target development can help improve the pace of LCH development. The roadmap developed for LCH in Uzbekistan aims to provide operational guidelines to the government of Uzbekistan to kickstart the LCH economy. This first sub-section of the roadmap presents the key milestones to be achieved by 2030, as obtained from the quantitative assessment presented in sections 2 and 3. The subsequent sub-sections focus on the key actions and priorities to meet the milestones for 2030. The roadmap pays particular attention to the enablers to put in place during the very early stage of this industry, specifically actions to be prioritized from 2022 to 2030, to achieve the milestones.[94]

4.2 Milestones for developing LCH in Uzbekistan

116. The identified milestones for developing LCH in Uzbekistan are based on the key qualitative findings related to hydrogen production and consumption volumes, infrastructure requirements, use of natural resources, and investments. The estimated H_2 volumes and the key requirements are shown in figure 35 to figure 38 below.

Figure 35. LCH production, domestic use and trade within the region (Uzbekistan - Turkmenistan - Kazakhstan), for the year 2030



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[94] It is to be noted that local and international demand for low carbon hydrogen this roadmap is based on the medium scenario results from the HyPE model. The values are subject to uncertainty.

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Figure 36. Infrastructure to be deployed by 2030 for the development of LCH in Uzbekistan

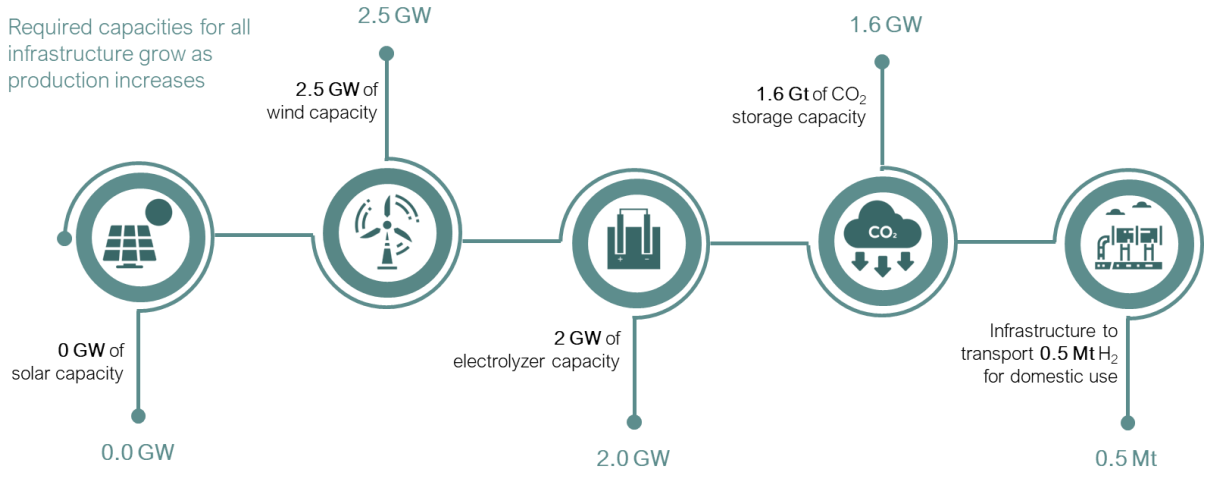

Figure 37. Natural resources required until 2030 for the development of LCH in Uzbekistan



Figure 38. CO2 price assumed until 2030 and total investments required by 2030 for the development of LCH in Uzbekistan



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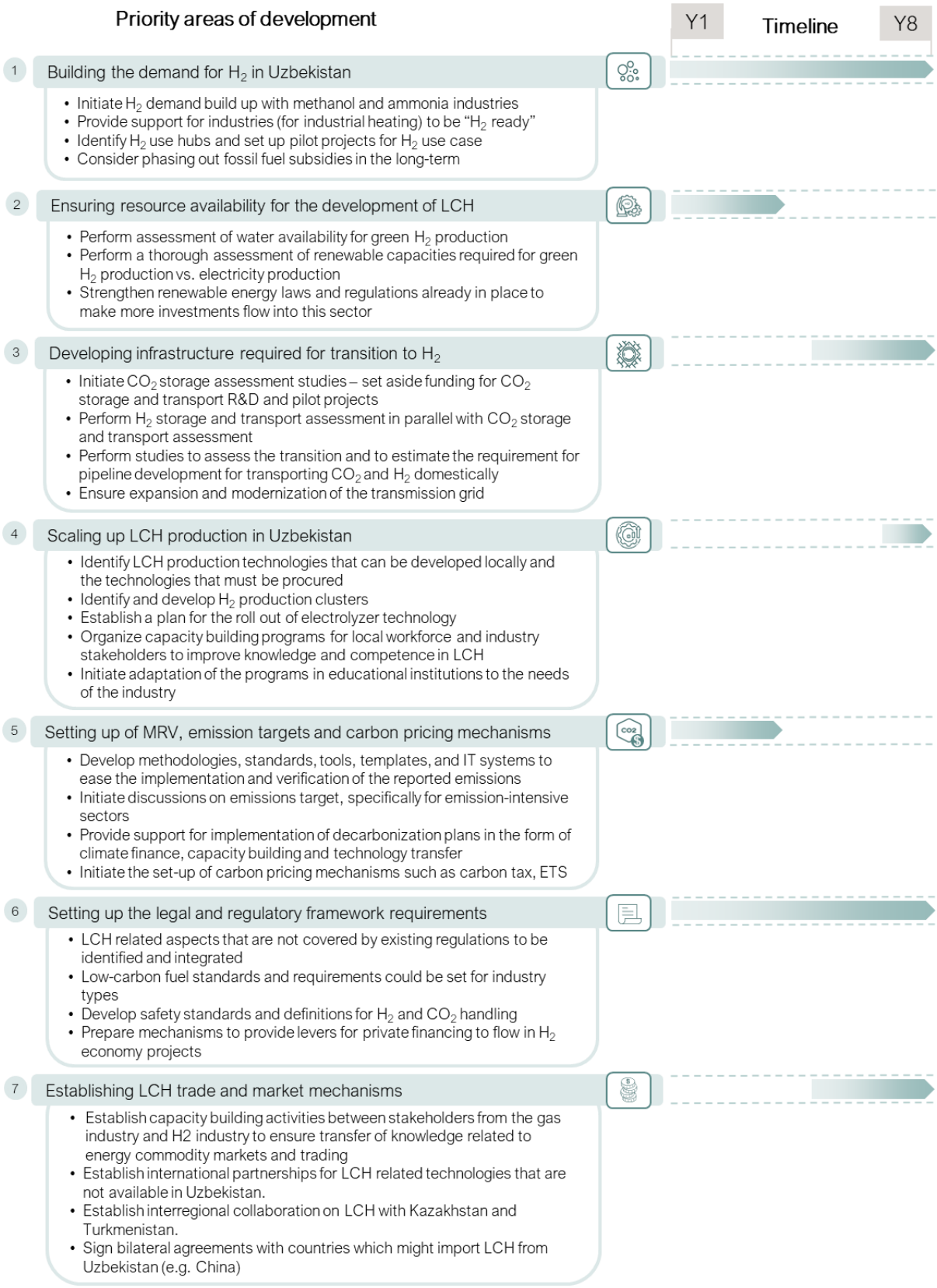
Table 9. Key pillars for the development of LCH in Uzbekistan



117. Before assessing the key pillars and actions, one of the most important aspects when it comes to technological transition in countries is collaboration with stakeholders within the country, and

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with international stakeholders with expertise in such transition. Part of having a clear transition goal is to make it easy to approach and have "one-stop" center or department to attend to all hydrogen related matters - for establishing any technical, regulatory, and financial protocols for hydrogen development, and being the main entity assessing viability, definition of hydrogen production, storage, and transport, etc. This helps build confidence among investors, industry, citizens, and other countries. Using the milestone and modelling results of the current and other H_2 modeling assessments done for Uzbekistan, building a collaborative hydrogen strategy that highlights the country's goals, targets and projected plans can be very impactful in improving international collaboration and trade possibilities. Alongside the establishment of such an entity, Uzbekistan's efforts to initiate the development of LCH in the country can be categorized into seven key pillars. The goal and actions to be taken under each key pillar are described in the following sub-sections.

4.2.1 Key Pillar 1: Building the demand for LCH within Uzbekistan

118. To promote a well-defined and liquid market for hydrogen, both supply and demand need to be scaled up. Investments in hydrogen will flow when there is a quantifiable demand for hydrogen, proving the presence of consumers, for the eventual sale of hydrogen. Due to the versatile nature of hydrogen, it can be used in several different sectors, however, considering that the cost of LCH is higher than fossil fuels as of today, government action would be required to make a case for it. **The focus of the demand build up should begin sectors already using H_2 as part of their production processes, followed by the hard-to-abate sectors and energy-intensive industries.** In Uzbekistan, methanol and ammonia production industries could be early adopters of LCH. Both production processes use H_2 as a feedstock. Currently gray H_2 is utilized, hence prioritizing the transition to LCH in these industries can kickstart the demand for LCH in industries.

119. **Another aspect of building the demand for LCH is to support the targeted hydrogen end-users to become 'H_2 ready'**. To begin with, a scoping study would be required to prepare a list of high energy consuming stakeholders from the industrial and oil and gas sector. Additionally, **an assessment of high hydrogen consumption areas** needs to be performed within Uzbekistan. Industries with potential to use hydrogen that are clustered within a specific area can play a crucial role in developing the first few H_2-hubs for the hydrogen economy. This would be the targeted hydrogen users to focus on by policymakers, both to initiate pilot projects and to understand the type of policies and financial support required to these sectors to become hydrogen-ready. For each category of industries, the equipment required for the transition from use of fossil fuels to hydrogen must be assessed. For example, industries with new 'hydrogen-ready' boilers/burners, or with the possibility to retrofit existing ones would be ready to shift to LCH instead of natural gas. Having focus group discussions with the stakeholders from the hard-to-abate sectors will help understand the magnitude of changes required. **For the pilot and demonstration projects to illustrate hydrogen use in different sectors, government funds and subsidies, along with private investments would be required.** International collaboration, memorandum of understanding (MoUs) with large development banks and other modes of financing could be discussed for launching pilot projects. **These projects can help demonstrate the transition required and make it accessible for smaller players in the sector**. This will also help to tailor the mode of support better adapted to each stakeholder or end-use, either in the form of tax rebates, subsidies or other financial instrument.

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120. **Phasing out of fossil fuel subsidies** is a strategy that can significantly boost the demand for low-carbon hydrogen. As of today, Uzbekistan ranks amongst the 25 top fossil fuels subsidy providers in the world.[95] Around US $ 2.2 billion were provided in subsidies for natural gas in Uzbekistan as of 2020.[96] However, Uzbekistan recently announced to delay the raising of electricity and gas tariffs. Hence reduction of fossil fuel subsidies for boosting low-carbon hydrogen should be a long-term strategy for Uzbekistan, focusing on enabling a smooth transition towards the low-carbon fuel. As a long-term strategy, the focus should be on converting existing fossil fuel subsidies to LCH relevant subsidies. For example, SMR, GHR and ATR production pathways for hydrogen use natural gas as feedstock. Natural gas production or processing companies could be the first movers in implementing hydrogen production facilities. **These subsidies could be transitioned to foster the development of LCH production facilities**. **Development of CO_2 storage facilities is another area of interest for transitioning fossil fuel subsidies.** Depleted oil and gas facilities are one of the proven areas for potential CO_2 storage. Collaborating with natural gas production facilities familiar with these sites and using the subsidies to aid the development of CO_2 storage will be beneficial for the development of blue hydrogen.

4.2.2 Key Pillar 2: Ensuring resource availability for the development of LCH

121. Success of LCH development in Uzbekistan largely depends on the availability of resources required for LCH production: water, renewable electricity produced from solar and wind resources.

122. Water is a crucial resource for the LCH development. As described in Section 4.1 and Box 3 green hydrogen production and steam methane reforming are water intense processes and Uzbekistan is located in the semi-arid region. Currently, the country experiences critical load on its water resources. **In-depth assessment of water availability and dependence on these resources must be performed to understand the bottlenecks and prepare for different scenarios**. Water efficient systems and recycling of water are important aspects to consider. Collaboration with countries in similar climatic conditions and dependence on freshwater could be beneficial for arriving at solutions catering to the problem.

123. In contrast, solar and wind potential in Uzbekistan to produce green hydrogen is significant. Uzbekistan has set a target to generate around 25% of its electricity from renewable sources by 2030.[97] The country does not plan to stop there and investigates opportunities fully decarbonize the power sector[98]. Though Uzbekistan has set targets for solar and wind energy development, green hydrogen production might compete with country's electricity needs. **A thorough assessment of renewable energy deployment potential would be required for developing a plan which ensures that projects are progressing in both directions.** Such a plan should be developed in close cooperation with the power sector.

[95] IEA, *Energy Subsidies*, Retrieved from: https://www.iea.org/topics/energy-subsidies on 03 July 2022.
[96] ibid
[97] Republic of Uzbekistan, Updated Nationally Determined Contribution, 2021, Retrieved from: https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Uzbekistan%20First/Uzbekistan_Updated%20NDC_2021_EN.pdf, on 01 July 2022
[98] European Bank for Reconstruction and Development, *A carbon-neutral electricity sector in Uzbekistan*, 2021

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124. In May 2019 Uzbekistan enacted its first comprehensive renewable energy law On Use of Renewable Sources of Energy[99]. The law supports investment in renewable energy generation by providing tax, customs and other benefits and preferences to producers of renewable energy and equipment used in the renewable energy sector. Other legal and regulatory reforms in the sector include a regulation for the connection of private sector electricity manufacturers to the national electricity grid[100]. Two other laws are on Public-Private Partnerships[101] and the Law on Investment and Investment Activities.[102] Even though these laws are broad in nature and cover several aspects of Uzbekistan's economy, they provide regulatory frameworks and support for the implementation of renewable energy projects. **Strengthening of renewable energy laws and regulations already in place would be beneficial to make more investments flow into this sector**.

125. Availability of land for LCH projects is another aspect that has to be considered. Solar and wind capacities would require around 250 km^2 by 2030 and around 750 $km^2$by 2050. **Extensive planning of LCH projects is necessary to ensure efficient use of the resources, including land**. Preferably the projects should be realised in hubs where hydrogen production facilities are in close vicinity to hydrogen demand areas, and vice-versa for future industrial development. In case the production and demand zones are far apart, hydrogen transport and potentially storage should be assessed. This production-transport aspect has been further described in key pillar 3.

4.2.3 Key Pillar 3: Developing infrastructure required for enabling transition to hydrogen

126. Uzbekistan has a significant potential for production of both blue and green hydrogen. While some grey hydrogen production facilities exist in Uzbekistan, CO_2 capture, and storage are currently lacking. There are some clear early steps to be taken in Uzbekistan for developing the infrastructure for LCH in the country.

127. Uzbekistan has blue hydrogen capacity for satisfying the country's domestic needs, and for exporting blue hydrogen quantities. **The first step towards transitioning from grey to blue hydrogen is the development of CO_2 storage sites. As of today, there's no detailed assessment on CO_2 storage potential and locations in Uzbekistan. Funding must be set aside for a thorough analysis of CO_2storage potential in the country. The first step would be the development of a CO_2storage atlas for Uzbekistan**. Broader scope can include the neighboring countries: Kazakhstan and Turkmenistan. **The atlas will show total CO_2 storage capacity available in the country(s) and indicate the locations most suitable for it.** This knowledge will allow for better planning of future blue hydrogen projects. Collaboration between the government, academia and CO_2 emitting intensive industries would be crucial in making this successful. For investments to flow into development of blue hydrogen, some push from the government would be required, in the form of funding or private-public collaboration to test CO_2 storage and assess the financial requirements for developing such projects. **Pilot CO_2 storage projects in Uzbekistan will help with assessing (1) feasibility of CO_2 storage at studied locations (2) extent of CO_2 transport infrastructure that would be required from high emissions areas to CO_2 storage sites (3)**

[99] The Government of Uzbekistan, *Law No. ZRU-539 On Use of Renewable Sources of Energy, 2019*, Retrieved from: https://policy.asiapacificenergy.org/node/3925, on 01 July 2022
[100] Vinson & Elkins LLP, *The Energy Transition in Central Asia: Drivers, Policy and Opportunities*, 2021, Retrieved from: https://www.ibanet.org/energy-transition-central-asia, on 01 July 2022
[101] The Government of Uzbekistan, Law No. ZRU-537 On Public-Private Partnership, 2019, Retrieved from: https://lex.uz/ru/pdfs/4329272, on 01 July 2022
[102] The Government of Uzbekistan, Law No. ZRU-598 On Investment and Investment Activities, 2019, Retrieved from: https://lex.uz/ru/docs/4751834, on 01 July 2022

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financial support and market mechanisms that could support the development of CO_2 infrastructure. Furthermore, the CO_2 storage assessment could be a topic of collaboration with Turkmenistan and Kazakhstan on aspects. Combined CO_2 pipelines to transport CO_2 from high emission hubs to nearest CO_2 storage sites will be beneficial for the entire sub-region.

128. **Hydrogen storage and transport assessment can be done in parallel with CO_2 storage and transport assessment**. Involving stakeholders from academia, industry and oil and gas sector, for timely studies, R&D and pilots in storage and transport assessment will help with making Uzbekistan hydrogen-ready.

129. In terms of transport of hydrogen and CO_2, there are existing natural gas pipelines for domestic use within Uzbekistan. Planning for the transition of natural gas pipelines to CO_2 or hydrogen transport pipelines is required, based on the expected utilization factors for this infrastructure. Studies must be done to assess the transition and estimate the requirement for more pipeline development for transporting CO_2 and hydrogen domestically.

130. To produce 0.2 Mt of green hydrogen in 2030, Uzbekistan will need 2.6 GW of installed wind capacity. Green hydrogen with the use of solar energy will come online by 2040, but to achieve 14 GW of solar capacity required to produce 2.6 Mt of green hydrogen with solar PV systems in 2040, the installations will have to be planned in this decade. In addition to new renewable capacities for hydrogen production the country will use renewables for electricity system decarbonisation. In this context expansion and modernisation of the transmission grid is a key requirement. Solar and wind power differ from traditional power sources like coal, natural gas, or hydropower. The latter can produce power on demand, but solar and wind power are variable in nature. When large intermittent capacities connect to the grid, it becomes harder for the operators to manage grid variability. It is crucial to start planning and development of grid projects ahead of the new renewable capacity's commissioning. Uzbekistan can leverage from EU and US experience in integrating large amounts of renewables into their grids, and sector coupling with hydrogen can be of help.

131. In terms of the investments required for the infrastructure development, Uzbekistan should focus initially on public-private partnerships, to begin R&D and pilot projects. Combination of public funds alongside international loans (for private or public entities), concessional financing would be required to establish these projects. Initial government support will help establish a testbed for these projects. Based on the findings and returns from the projects, more private sector investments could flow in.

4.2.4 Key Pillar 4: Initiating and scaling up LCH production in Uzbekistan

132. In the central scenario Uzbekistan produces around 500 kt of LCH using blue (160 kt), green (320 kt) hydrogen production routes and pyrolysis (20 kt). These capacities will have to be built up from scratch, as the country currently does not have any LCH projects in operation.

133. Uzbekistan has experience with various technologies comprising the LCH value chain. Most of the capabilities come from the oil and gas and energy sectors. As a starting point it is important to **identify LCH production technologies that can be developed locally and the technologies that must be procured** (for example solar panels, and wind turbines, electrolyzers, etc.). For the technologies that can be developed locally a technology qualification plan should be established, describing steps that must be taken to bring the technology to the commercial scale. As of today, Ministry of Energy of Uzbekistan pledged US $ 0.9 million of financial support for the

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development of LCH production, transmission, and storage technologies. Hydrogen production technology which was announced to be developed as part of this support are nano catalysts for hydrogen production and electrolysis based on solar energy.[103]

134. Uzbekistan has an important advantage when it comes to blue hydrogen. **The country can utilize its existing knowledge from the grey hydrogen production to develop the required capacity within the production of blue hydrogen**. In 2022 Uzbekistan a gas-to-liquid (GTL) plant commissioned hydrogen production facility able to produce 300 million m^3 of hydrogen annually.[104] To convert grey hydrogen into blue, CCS is required. **The country must develop the knowledge on the entire CCS value chain** (CO_2 capture, CO_2 transport and CO_2 storage). It can be done through pilot projects and international collaboration. **Early movers will naturally be stakeholders from the oil and gas sector, or current grey hydrogen producers.** The first projects should be developed in public-private partnerships with the government providing required incentives.

135. Currently there is no electrolyzer capacity in Uzbekistan. It will have to be built up to 2 GW by 2030. Several laboratory studies are being performed to develop electrolyzers in Uzbekistan[105]. As a next step, sing the findings of the studies being performed, t**he government should establish a plan for the roll out of electrolyzer technology**. **As for blue hydrogen production it should be organized through public-private projects taking the technology from the laboratory to the commercial scale**. To succeed it is essential to establish international collaboration on the subject. It can be done through EBRD and/or the World Bank since the country already has established relations with these institutions.

136. Half a million tonnes of LCH is required to cover Uzbekistan's domestic demand in 2030 in the central scenario. To meet this demand in the most efficient way it is recommended to **identify and develop hydrogen production clusters**. They would typically imply closely locating hydrogen consumption and production facilities. As part this study five high hydrogen demand clusters in Uzbekistan have been identified. All of them are located in the southern part of the country. **As a follow up it is recommended to perform a study to cross-validate potential cluster locations.** The study will include additional iteration on the identification of high hydrogen demand clusters, hydrogen production possibilities based on the good access to natural gas, water and renewable energy resources. **Based on the results of the study the government should facilitate the development of pilot hydrogen production clusters with the objective to test the entire LCH value chain (hydrogen production, transport, use and storage).**

137. Workforce management is another crucial aspect when developing a sector from scratch. This requires developing newly trained personnel and enabling the existing workforce to migrate into the hydrogen field by way of enhanced industry coordination and workforce readiness initiatives. Training, education, and international collaboration are required to make this possible. Current producers of grey hydrogen and stakeholders from the oil and gas sector could be the first category of workforce trained to become skilled on hydrogen topics. **Organize capacity building for local workforce and industry stakeholders to improve knowledge and competences in LCH energy projects and skills.** It is important to build a trained workforce on

[103] Uzbekistan Ministry of Energy, *Strategy: on the path towards the development of H_2 economy*, 2022, Retrieved from: https://t.me/minenergy_uz/4608, on 1 June 2022
[104] Uzbekistan Ministry of Energy, *Uzbekistan GTL launches hydrogen production facility*, 2022, Retrieved from: https://www.youtube.com/watch?v=JQvOz-kKD2M, on 1 June 2022
[105] World Bank, *Low Carbon Hydrogen in Uzbekistan Workshop,* 23 June 2022

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all aspects of the LCH value chain, including transition to LCH, LCH production, hydrogen storage and transport, and safety aspects associated with each step of the value chain. **To ensure that sufficient workforce is available, it is important to initiate adaptation of the programs in educational institutions to the needs of the industry.** Educational institutions can participate in the development of LCH projects to understand the areas where existing education programs can be strengthened or if new ones are required.

4.2.5 Key Pillar 5: Setting up of MRV, emission targets and carbon pricing mechanisms

138. Considering the liquid oil and gas market and the subsidies existing in the market, the cost of LCH is considerably higher than using fossil fuels directly. **Carbon pricing mechanisms should be considered to increase the demand and increase production of low carbon fuels such as LCH**. The underlying system required for introducing carbon pricing mechanisms in a country would begin with the establishment of a monitoring, reporting and verification system (MRV). It is fundamental for both the development of a domestic market and participation in the international carbon markets. The MRV system will be useful for collecting GHG emission data which is crucial for implementing carbon pricing mechanisms.

139. **The setting up of an MRV system will require the development of methodologies, standards, tools, templates, and IT systems to ease the implementation and verification of the reported emissions by different sectors**. This process is sector specific, hence emission-intensive sectors could be the priority in this deployment. Focus group meetings and workshops are required to develop the methodologies, and train stakeholders from government and participating sectors for the development of the MRV. The crucial discussions and initial implementation projects should help establish legislations to help implement and execute the MRV.

140. **Alongside the development of the MRV system, conversations on emissions target, specifically in emission-intensive sectors should be initiated**. Oil and gas sector and heavy industry decarbonization could be the priority sectors to begin with. Set targets and action plan to reduce and decarbonize the oil and gas sector, to enable the transition to blue hydrogen. Assess the effectiveness of existing policies and make new policy decisions on how to support higher mitigation actions and enable policy decisions on mitigation planning to reach the country's targets. **Support required for implementation of decarbonization plans in the form of climate finance, capacity building and technology transfer should be established**.

141. Alongside these developments, discussions on carbon pricing mechanisms such as carbon tax per unit of emissions or beyond a certain cap, or Emissions Trading System (ETS) or participating in international carbon markets must be considered. **In the short term, carbon tax on certain high emitting sectors could be beneficial to test the taxing mechanisms and to eventually include other sectors to the plan**. A carbon price of US $ 75 per tCO_{2e} is expected to be in place by 2030 to support Uzbekistan's carbon reduction targets. Several countries have established carbon pricing mechanisms to decarbonize their economies[106]. The main aspects to consider while establishing carbon tax are the (1) initial price per tonne of CO_{2e} (2) initial sectors to focus on (3) greenhouse gases considered in the tax (4) acceleration of tax until the target of 2030 is achieved. International collaboration for knowledge and technology transfer can be beneficial for Uzbekistan. Considering the gas and electricity trade contracts existing between Kazakhstan,

[106] Citizens Climate Lobby, *Carbon Prices as of April 2021*, Retrieved from: https://citizensclimatelobby.org/wp-content/uploads/2021/06/36.CPricesWorld.R3.Figs_.pdf, on 08 July 2022

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Uzbekistan and Turkmenistan, a collaborative carbon pricing mechanism could also be considered. Kazakhstan, for example, has already implemented a domestic carbon crediting mechanism which serves to promote the adoption of GHG mitigation projects for gases and in sectors which are not covered by its ETS. International partnerships on CO_2 pricing mechanisms could also help the individual countries with market liquidity issues in case of implementing cap and trade systems.

4.2.6 Key Pillar 6: Setting up the legal and regulatory framework requirements

142. One of the key enablers of the renewable energy boost came from dedicated renewable energy laws and regulations. Uzbekistan has concrete laws and decrees aimed at increasing the renewable energy capacities in the country. They contribute to increasing the number of renewable energy projects in the country. Similarly, for LCH, **elements related to LCH value chain within the existing rules and regulations should be identified**. **LCH related aspects that are not covered by the existing regulations (for example, hydrogen fueled transport) should be identified and the value chain should be comprehensively integrated into the regulations**. Having documents detailing all the permits and consents required for developing different aspects of the LCH value chain can help provide a clear idea to project developers and reduce the barriers to entry. These decrees and laws should ideally cover (1) accelerating permit processes for hydrogen related project development (2) development of consistent standards covering quality, GHG intensity, safety, and technology (3) bring clarity on available financing mechanisms for hydrogen related projects.

143. **Incentives, tax rebates and dedicated funding to stimulate investments in R&D for LCH technologies, and developments along the LCH value chain are factors to be considered while developing the legal and regulatory framework to support the hydrogen development**. As part of the development plan, incentives, or tax rebates for (1) R&D of LCH technologies – (pilot and demonstration projects), (2) to stimulate production capacity for LCH technologies and (3) for development of LCH related infrastructure. Uzbekistan recently set up the Research Center for Hydrogen and the Laboratory for Testing and Certification of Renewable and Hydrogen Energy Technologies under the Ministry of Energy. Ensuring the application, selection and certification of projects happen in collaboration with the centers will help **strengthen the research center's collaborations and support it as the "one-stop" center for hydrogen related discussions**. The discussions on incentives, tax rebates and funding aspect should be done in collaboration with the research centers.

144. As the demand and supply of LCH develops, **low-carbon fuel standards and requirements could be set for industry types.** As discussed in Pillar 1, methanol and ammonia could be first movers in using low-carbon hydrogen. The standards could begin with the methanol and ammonia industries, followed by industrial heating and other sectors. A follow up from incentives, tax rebates to low-carbon fuel requisites will help mature the hydrogen economy.

145. **The government of Uzbekistan should facilitate the development of hydrogen safety codes and standards** as they are critical for the commercialization of hydrogen-based products and systems. Studies are required to understand and estimate the safety protocols and standards required for safe transport and storage of hydrogen. Several international organizations have progressed on the development of hydrogen safety standards, for example, International Standards Organization (ISO) Technical Committee 197 "Hydrogen Technologies", International Electrotechnical Commission (IEC) Technical Committee 105 "Fuel Cell Technologies", European Industrial Gases Association (EIGA), the Compressed Gas Association (CGA), National Fire

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Protection Association (NFPA). Their work can be taken as a basis for the development of safety standards in Uzbekistan.

146. In addition to safety standards, **creating technical standards for all parts of LCH value chain (production, transport, storage, distribution, conversion) is necessary**. Lack of adequate information is often a barrier when it comes to project development. Having a clear structure for the development of LCH value chain helps the stakeholders understand the aspects to consider in project development and shows the government's commitment towards the industry development. The technical standards must cover (1) LCH production including GHG emission thresholds (2) LCH use and transport of hydrogen derivatives (ammonia, synthetic fuels), including the GHG emission limits. All standards should be harmonized with the international requirements.

147. Furthermore, international cooperation is essential in the establishment of the new industry. **Parties through sharing can build on their experience within the development of regulations, standards, incentives, technologies, projects, etc**. To succeed in the development of LCH industry in Uzbekistan it is important to (1) establish cooperation with countries leading in H_2 development; (2) establish cooperation with leading research organizations focusing on the LCH value chain; (3) participate in international organizations focusing on H_2 related subjects; (4) promote knowledge exchange internationally by participating in H_2 related workshops, international conferences and joining organizations as prominent members.

148. A factor combining international collaboration and local development is the preparation of financial mechanisms to finance the development of all aspects associated with low carbon hydrogen. **In the nascent phases, significant public investments would be required, to initiate public-private partnerships in H_2 production, transport and storage, and end use**. This could be provided in the form of contract-for difference (CfD) models[107], setting up tenders for H_2 production and utilization or temporary subsidizing of some investments required to kick start projects. Alongside this development, mechanisms to provide levers for private financing need to be considered for the next phase. Factors highlighted in Key Pillars 1 to 7 such as development of H_2 hubs, setting up low-carbon fuel standards, carbon pricing mechanisms, etc; could act as crucial levers in increasing private financing while transitioning from pilot to commercial scale deployment. **On the set up of some public-private pilot and demonstration projects in each H_2 chain aspect[108] equity-based financing involving large industries and potential venture capitalists could be expected**. As the development progresses, financing in the form secured / unsecured debt should be encouraged. **While the direct involvement of financing from the government might be low, the H_2 related policies and the H_2 economy**

[107] At its most basic, a contract for difference is essentially an agreement between two parties whereby one party agrees to pay the other party the difference between the actual value of a commodity at a point in time – the market price – and a value which the parties agreed at the point the CfD was entered into. The UK Government recently launched its first consultation on low-carbon hydrogen, to develop a Hydrogen Business Model that will provides revenue support mechanism for low-carbon hydrogen. It is proposing a bespoke contracts-for-difference (CfD) model to support hydrogen through its key barriers of high cost, technological and commercial risk, demand uncertainty, lack of regulatory structures, and lack of available infrastructure. Through the CfD model, low-carbon hydrogen operators will be invited to apply for contracts at competitive auction, with the UK government providing subsidies through a reference to strike price differential payment.

[108] Projects covering (1) H_2 demand – end use case (2) H_2 supply chain – transport and storage (3) H_2 production – blue and green

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development will significantly change the risk aspects of the projects, encouraging more private finance. Governments can provide the necessary overall enabling environment by bearing risks linked to market development.[109]

4.2.7 Key Pillar 7: Establishing LCH trade and market mechanisms

149. Our estimates show that hydrogen export to China from Uzbekistan will not happen until 2040. In 2040, exports are expected to reach 0.3 Mt of hydrogen and 0.9 Mt in 2050. Interregional trade with Kazakhstan and Turkmenistan also takes place over the period. Uzbekistan has a well-established natural gas pipeline network in the region and exports gas to Russia (currently halted[110]) and China. This network can potentially be repurposed for trade. In addition to the reuse of the physical infrastructure, the LCH industry can gain from the knowledge collected through the years of natural gas trading. **Capacity building activities between stakeholders from the gas industry and hydrogen industry should be established**.

150. The hydrogen trading market (including derivatives like ammonia) is not yet widespread but starting to evolve. Standards, certification, qualification of hydrogen properties, product definition, trading principles, policies, legislation, etc, are currently discussed internationally. It is important to **follow international hydrogen market development** to be able to smoothly integrate into this market later. International collaboration and participation in hydrogen conferences will highlight Uzbekistan's interest and open opportunities for collaboration on all LCH aspects.

151. Some of the hydrogen related technologies (i.e. solar and wind energy, electrolyzers, CO_2 capture technologies, etc.) are going to be developed or are already available within the country. At the same time, several technologies and components will have to be sourced internationally. These **technologies** must be identified and **trading agreements with relevant countries should be established**. There are currently several MoUs signed between countries, on various levels of collaboration. For example, Belgium and Oman signed an MoU to work on the implementation of standards for green certification and the interaction between universities, scientific research institutes and the private sector of both countries, to develop green hydrogen in their respective regions[111]. In 2017, Japan and Australia began collaborating on technologies to transport between Australia and Japan. Japan developed basic technologies with Australia to demonstrate a "liquified hydrogen supply chain" paving the way for commercialization. This strategy led to the successful development of a ~300 million US $ pilot transport project, Suiso Frontier, funded by the Japanese and Australia governments, studying the viability of liquid hydrogen transport.[112]

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[109] NATIXIS, Financing green hydrogen's development, 2021, Retrieved from: https://gsh.cib.natixis.com/our-center-of-expertise/articles/financing-green-hydrogen-s-development, on 31 August 2022

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152. Trading hydrogen with Turkmenistan and Kazakhstan will be a strategic advantage for the three countries. To prepare for that, **interregional collaboration in the field of LCH should be established**. As Uzbekistan is a land locked country, it has historically developed trading relations with neighboring Kazakhstan and Turkmenistan, which can form a solid base for the cooperation on LCH. It is important to develop milestones for interregional hydrogen trade based on the LCH production potential and demand in each country. **This can be achieved through the dialog between relevant stakeholders in the region, in particular with those sharing similar climate ambitions**. Dutch-Danish cooperation MoU to accelerate the green transition[113] and Belgium-Oman MoU for Cooperation in Green Hydrogen production[114] can serve as examples of collaboration in LCH field.

153. To promote LCH trade Uzbekistan should sign **bilateral agreement with countries which will import hydrogen.** As mentioned above, Uzbekistan has currently established trading agreement on natural gas with China. Discussions between two countries on LCH should be initiated in time to prepare for trading of 0.3 Mt H_2 by 2040. Alongside this, additional potential markets for H_2 should be evaluated. Examples of LCH trading cooperation are Green Hydrogen Export MoU between Rotterdam and Chile[115] and Germany-Australia agreement on hydrogen supply chain projects.[116]

154. Key pillars 1 to 7 identify the priority actions the government should focus on for the development of LCH in Uzbekistan. However, several iterations of the mentioned actions and key pillars would be required, as the development progresses. LCH production, consumption and export will increase between 2030 and 2050. Hence the establishment of the preliminary aspects of development must be accelerated, keeping in mind the progress required for achieving Uzbekistan's 2050 targets. The set of actions to be developed beyond 2030 must focus on (1) improving LCH economics, (2) enable LCH market liquidity, (3) ensure sufficient availability of LCH supply technologies (renewables, electrolyzer, desalination facilities, etc.), (4) ensure necessary infrastructure is in place to support the growing LCH demand, (5) guarantee regulations are in line with internationally agreed definitions, and (6) support LCH development.

155. Uzbekistan is currently accelerating its goals and plans for decarbonizing its emissions-intensive sectors. As highlighted in the key pillars, international and regional collaboration will be very beneficial for the LCH development in the country. However, international organizations, development banks and financial institutions can play a major role in enabling these collaborations.

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[113] IEA, *Dutch-Danish cooperation MoU to accelerate the green transition*, 2021, Retrieved from: https://www.iea.org/policies/11983-dutch-danish-cooperation-mou-to-accelerate-the-green-transition, on 08 July 2022

[114] IEA, *Belgium-Oman MoU for Cooperation in Green Hydrogen*, 2022, Retrieved from: https://www.iea.org/policies/14752-belgium-oman-mou-for-cooperation-in-green-hydrogen, on 08 July 2022

[115] IEA, *Green Hydrogen Export MoU with Rotterdam*, 2021, Retrieved from: https://www.iea.org/policies/13221-green-hydrogen-export-mou-with-rotterdam, on 08 July 2022

[116] Ministers for the Department of Industry, Science and Resources, *Australia-Germany to support hydrogen supply chain projects*, 2021, Retrieved from: https://www.minister.industry.gov.au/ministers/taylor/media-releases/australia-germany-support-hydrogen-supply-chain-projects, on 08 July 2022

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Box 5. Role of International Financial Institutions (IFIs) in LCH development

Considering the involvement of IFIs in technology developments in other countries, IFIs can play a big role in enabling knowledge sharing between Uzbekistan and other countries with similar development portfolios. The most significant impact IFIs' support in the short term could be on developing policies and incentives, as they are the base for the development of the LCH industry. Using their broad international experience and extensive knowledge, IFIs can help Uzbekistan develop sound and consistent regulations with practical enforcement mechanisms in place. The table below presents the potential areas of assistance the IFIs could provide Uzbekistan, to enable the development of LCH in the country.

Building the demand for H_2	IFIs can assist the countries with the (1) development of the plan for phase-out of fossil fuel subsidies; (2) perform collaborative studies on ideal LCH targets for key industrial and transport sectors; (3) enable international collaboration and funding mechanisms for R&D and pilot projects for identifying H_2 demand hubs
Ensuring resource availability for the development of LCH	Using the broad experience working with climate change impacts on countries, IFIs can assist and fund studies for (1) assessing the freshwater availability and impacts of technological development and climate change on the water resources; (2) similar studies on availability of land area for LCH development and its impacts on the country's ecosystem
Developing infrastructure required for enabling transition to H_2	Enable international collaborations and support with identifying financing mechanisms for the (1) identification of CO_2 storage potential and development of country-specific CCS roadmaps; (2) developing H_2 storage and transport strategies; finance pilot CCS projects/pilot CCS hubs; (3) studies on the potential reuse of oil and gas pipelines
Initiating and scaling up LCH production in Uzbekistan	Help the governments to establish a robust financial support scheme for LCH projects. Finance the studies and pilot projects on the development of electrolyzer technology, and blue, turquoise, and green H_2 projects. Support the countries with mapping high renewable energy capacity regions against H_2 demand in the country.
Setting up of MRV, emission targets and carbon pricing mechanisms	IFIs could focus on (1) assisting with setting targets for the decarbonization of the oil and gas value chains through capacity building on the subject; (2) financing the studies on emissions inventories, identification of mitigation options; and assessing tis readiness for the development of MRV and carbon pricing mechanisms (such as the Partnership for Market Readiness (PMR))
Setting up the legal and regulatory framework requirements	Use international work experience to (1) assist the government in the development of LCH and CCS regulations and incentives; (2) help establish interoperable and consistent H_2 standards covering quality, GHG intensity, safety, and technology. Using their international network, (3) IFIs can help with capacity building for local LCH stakeholders.
Establishing LCH trade and market mechanisms	(1) Finance country-specific studies on H_2 trading hubs; (2) assist with defining LCH market design and operating rules for H_2 trading; (3) support international cooperation on aligning technical and emissions standards for LCH and enable MoUs with potential H_2 importing countries and technology providing countries.

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Conclusions

156. Uzbekistan's economy is heavily reliant on natural gas for primary energy supply and for exports. That level of structural dependency comes from a legacy of industrial specializing geared towards the extractive industries. However, the over reliance on the exploitation of natural resources poses significant threats for the economy in the long run given their non-renewable nature and due to the exacerbating concerns on climate and energy independence issues worldwide.

157. The assessment of low carbon hydrogen potential in the country is promising. It levers on the renewable and fossil resources of the country, and at the same time would be suitably aligned with its economic development objectives and climate ambitions. In the way towards deep decarbonization, adopting LCH in hard-to-abate sectors show particularly relevant. Sectors such as ammonia, methanol, heat supply and heavy-duty transport are the most suitable to switch to hydrogen, for which putting in place carbon pricing mechanisms is a necessary condition.

158. On the supply-side, the country's natural gas and renewable potential would allow blue and green hydrogen to complement each other to balance demand. On one hand, blue hydrogen appears to be slightly more cost-competitive than green, particularly at the beginning of the period, but the gap reduces over time. On the other, blue hydrogen production depends on the availability of natural gas as a feedstock at low prices and on the development of CCUS solutions which brings important industrial risks to be carefully assessed. Both green and blue hydrogen production requires access to water which is already limited in the country and that is expected to become even more scarce in future years. Hence, access to feedstock is a key factor that would shape the future of the industry and for which policies fostering their rational use would be highly relevant.

159. Moreover, green hydrogen production is capital-intensive and its development would require capacity additions of solar PV and wind comparable to what is currently been targeted for the power sector to decarbonize but that would be on the top of it due to the additionality considerations. Therefore, putting in place innovative financing mechanisms to reduce risks and cost of capital would be key, as well as building local capabilities in the sector.

160. LCH is also promising in terms of interregional and international trade. Uzbekistan can benefit from synergies with neighboring countries to supply its domestic demand at lower costs while furthering revenues from exporting LCH to China provided the hydrogen-ready infrastructure is available. By assuming the repurposing of a line of the Central Asia-China by 2040, Uzbekistan, Turkmenistan and Kazakhstan progressively start exporting to China who becomes its key trading partner as it currently is for natural gas. Uzbekistan export value to China has the potential to reach about US $ 2 billion by 2050 which is comparable to the current value of total natural gas exports (US $ 2.3 billion in 2019). This sheds light to the potential of the country to become a net exporter of hydrogen, as well as the opportunities for coordination between the concerned countries on infrastructure development matters for enabling wider trading partnerships in the region.

161. The future of this new industry is shaped progressively. Setting up the enabling conditions around the key pillars are required from now for kickstarting and reach the milestones identified by 2030. The key pillars consist of building up the demand-side, supporting the supply-side, setting up a legal, regulatory and policy framework for enabling LCH trade, planning and implementing for the development of the required infrastructure, as well as implementing measures to ensure access to resources and feedstock.

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Appendix

A. Hydrogen costs across the value chain

A.1 Review of hydrogen production costs

162. The production pathways summarized in table 10 present the energy intensity and life cycle emissions associated with the production of hydrogen. These emissions are highly dependent on the country and supply chain arrangements.[117]

[117] For blue and turquoise hydrogen, the life cycle emissions are highly dependent on the source of natural gas and the emissions along the gas value chain (Bauer et al. 2022; Howarth and Jacobson 2021; Kerscher et al. 2021; Sadeghi, Ghandehariun, and Rosen 2020). High variability in methane leaks along the gas value chain can be observed around the world (Bauer,2022) and up to 90% of the lifecycle emissions of these fossil-based technologies can be attributed to the operation of the plant and the natural gas supply chain (Sadeghi et al. 2020). Life cycle emissions for green hydrogen arise primarily from indirect emissions, energy or material flows associated with the manufacture and construction of renewable-electrolysis plants (Sadeghi et al. 2020).

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Table 10. Hydrogen production pathways (mature and lab-scale technologies are shown[118])

	Process Name	Fuel and input	Technology Maturity[119]	Energy Use per kgH_2	Life cycle GHG emissions[120]	Process Description
Thermochemical	Steam Methane Reforming (SMR)	Natural gas (Heat)	Mature Technology	175 MJ to 216 MJ	8 kg to 14 kg of $CO_{2,e}$ per kgH_2[121]	Methane reacts with steam in the presence of a catalyst, to produce hydrogen and carbon monoxide (CO). The CO produced further reacts with steam, in the presence of a catalyst to produce CO_2 and H_2. Around 95% of the hydrogen produced today use the SMR production process. Around 3 kg CH_4[122] and 15 kg of water[123] is consumed per kg of hydrogen produced.

[118] Due to the uncertainties on costs and commercial availabilities, only technologies deemed "mature" and "mature at small scale" where considered in the assessment of Uzbekistan. The only exception is biomass gasification which was excluded due to the lack of data on feedstock availability.

[119] A mature technology is a technology that has been in use for long enough that most of its initial faults and inherent problems have been removed or reduced by further development**.** It also refers to technology that has not seen widespread use, but whose scientific background is well understood.

[120] Note that literature on life cycle GHG emissions of hydrogen production pathways is scarce and for some controversial due to the assumptions taken.

[121] Rocky Mountain Institute, *Hydrogen's Decarbonization Impact for Industry*, 2020, Retrieved from: https://rmi.org/wp-content/uploads/2020/01/hydrogen_insight_brief.pdf on 28 October 2021
.The upper bounder corresponds to a methane emission rate (gram CH_4 emitted per gram of natural gas delivered) along the gas supply chain of 4% (US upper boundary) (Bauer et al. 2022).

[122] Including CH_4 used in the process and CH_4 used for providing energy to facilitate the process (Budsberg et al. 2015).

[123] Water Smart Solutions, *Water for H2 economy*, Retrieved from: https://watersmartsolutions.ca/wp-content/uploads/2020/12/Water-for-the-Hydrogen-Economy_WaterSMART-Whitepaper_November-2020.pdf, on 11 November 2021

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	Process Name	Fuel and input	Technology Maturity[119]	Energy Use per kgH_2	Life cycle GHG emissions[120]	Process Description
Thermochemical	Auto/Thermal Reforming (ATR) and Gas Heating Reforming (GHR)	Natural Gas (Heat)	Mature at small scale[124]	160 MJ to 200 MJ[125]	7 kg – 14 kg $CO_{2,e}$ per kgH_2[125]	Both ATR and GHR processes involve methane reforming, in a process similar to the SMR. In ATR, the feed-gas (natural gas and steam) are partially combusted to generate heat for the endothermic reforming process. The gas mixture then undergoes steam reforming over a fixed catalyst bed. The GHR system works in conjunction with a SMR or ATR facility. The GHR and ATR/SMR work in a counter-flow setup, with the steam and natural gas mixture being pre-heated in the GHR, before getting converted to syngas (CO + H_2 mixture) in the SMR or ATR chamber. Combining the two helps reduce the heat requirements, the water footprint of the plant (between 10 kg to 15.5 kg water used in GHR combined process) and associated CO_2 emissions.[126]

[124] Technology Readiness Level between 6 and 8. Hyfindr, *Technology Readiness Leve*l, Retrieved from: https://hyfindr.com/technology-readiness-level/, on 17 November 2021

[125] Patwardhan et. Al, *Optimized hydrogen production using steam reforming*, Retrieved from: https://www.digitalrefining.com/article/1000841/optimised-hydrogen-production-by-steam-reforming-part-2#.YaEe1NDMI2w, on 26 November 2021

[126] Johnson Matthey Process Technologies, *Reforming (ATR, GHR, SMR),* Retrieved from: http://davyprotech.com/what-we-do/licensed-processes-and-core-technologies/core%20technologies/refiningdistillation/specification/#tab-content-1, on 26 November 2021.

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	Process Name	Fuel and input	Technology Maturity[119]	Energy Use per kgH_2	Life cycle GHG emissions[120]	Process Description
Thermochemical	SMR / ATR / GHR + Carbon Capture & Storage (CCS)	Natural Gas (Heat)	Mature at small scale	180 MJ to 240 MJ[127]	2 kg to 6 kg of $CO_{2,e}$ per kgH_2[128] *(in this study direct CO_2 and CH_4 emissions along the value chain are economically offset)*	When SMR, ATR and/or GHR production pathways are combined with carbon capture and storage with capture rates of 90-95%, hence the resulting hydrogen has low direct CO_2 emissions associated with the production process. While some CO_2 emissions exist, in this study, the remaining CO_2 emissions are economically offset, leading to a 'net-zero' production process. The addition of CCS to the production process leads to higher initial investment costs and requires higher energy to operate.

[127] Assuming 9 kg CO_2 is produced per kgH_2, and 90% of the CO_2 is captured by the CCS facility. Energy required per tonne of CO_2 captured is 2.5 GJ.

[128] Low methane emission rate and high CO_2 removal rate are key to lower the lifecycle emissions of blue hydrogen production as mentioned in (Bauer et al, 2021). The upper bounder corresponds to a methane emission rate (gram CH_4 emitted per gram of natural gas delivered) along the gas supply chain of 4% (US upper boundary) (Bauer et al. 2022; Kerscher et al. 2021).

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	Process Name	Fuel and input	Technology Maturity[119]	Energy Use per kgH_2	Life cycle GHG emissions[120]	Process Description
Thermochemical	Methane pyrolysis *(Also called methane decomposition)*	Natural gas (Heat)	Mature at small scale	200 MJ to 230 MJ[129]	2 kg to 6 kg $CO_{2,e}$ per kgH_2[130] *(in this study direct CO_2 and CH_4 emissions along the value chain are economically offset)*	In pyrolysis, methane is decomposed, in the absence of oxygen (O_2), to produce hydrogen and solid carbon as by products. Water is not a required input for the pyrolysis process. Widely used technologies for pyrolysis include (a) molten metal reactors (b) plasma reactors and (c) gas reactors with or without catalysts. The energy consumption and CO_2 emission vary by technology.[131]
Thermochemical	Biomass Gasification	Biomass (Heat)	Mature at small scale	6.2 MJ[132]	Low GHG emissions predicted.[133] More in-depth assessment required	Biomass is gasified using O_2, to produce Syngas. Similar to the SMR process, this syngas is reacted with steam in the catalyst's presence, to produce hydrogen and CO. The CO produced reacts further with steam, in the presence of a catalyst to produce CO_2 and H_2.[134] The process uses 7.0 and 13.5 kg biomass (for the gasification process) per kg of hydrogen produced.[135]

[129] From Bhaskar, Assadi, and Somehsaraei (2021). Energy requirements are provided per ton of liquid steel (tls) produced. This was converted to per kgH_2 prodcued, using the conversion factor presented in the same report (59.25 kgH_2 per tls)
[130] From Kerscher et al.(2021)
[131] Timmerberg, Kaltschmitt, and Finkbeiner (2020).
[132] From Mehmeti et. Al (2018).
[133] Emitted CO_2 is $BioCO_2$:
[134] Office of energy efficiency and renewable energy, *Hydrogen production: Biomass gasification*, Retrieved from: https://www.energy.gov/eere/fuelcells/hydrogen-production-biomass-gasification, on 28 October 2021.
[135] From Mehmeti et. Al (2018).

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	Process Name	Fuel and input	Technology Maturity[119]	Energy Use per kgH_2	Life cycle GHG emissions[120]	Process Description
Thermochemical	Biomass derived liquid reforming *(Also called biomass pyrolysis)*	Biofuel (Heat)	Pilot Projects	Low energy Potential	Low GHG emissions predicted. More in-depth assessment required	Thermal decomposition of biomass in the absence of O_2 produces hydrogen and other hydrocarbon by-products. Depending on the number of reactors involved in the decomposition process, the catalyst and the temperature used in the process, the volume of hydrogen produced and the energy intensity change. Pyrolysis process can breakdown the biomass directly to gas, to bio-oil or to char. Catalytic cracking and steam reforming can be used to produce hydrogen from gasified biomass and bio-oil.[136] Between 10 kg and 30 kg of biomass could be required to produce 1 kg of hydrogen. This is highly dependent on the type of biomass used and the process implemented for the pyrolysis process.[137] More in-depth assessment is required to understand the energy requirements and CO_2 emissions from the different pyrolysis processes.

[136] International Energy Agency, *Hydrogen from biomass gasification*, 2019, Retrieved from: https://www.ieabioenergy.com/wp-content/uploads/2019/01/Wasserstoffstudie_IEA-final.pdf, on 28 October 2021.
[137] (García et al. 2015).

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	Process Name	Fuel and input	Technology Maturity[119]	Energy Use per kgH_2	Life cycle GHG emissions[120]	Process Description
Electrolysis	Solid Oxide Electrolysis (SOEC)	Pure Water (Heat and electricity)	Pilot Project[138]	60 MJ[139,140]	1 to 3.5 kg $CO_{2,e}$ per kgH_2[141] emissions if renewable electricity Up to 30 kg $CO_{2,e}$ per kgH_2 if grid electricity	In this type of electrolysis solid ceramic material is used to separate the anode and the cathode. It operates at high temperature (700°C to 850°C). This helps reducing electricity required for splitting the water molecules, by providing part of the energy for separation. Waste Heat can be used to provide the heat required for this electrolysis process.

Carbon Limits assessment using multiple references, 2021

163. As of today, grey hydrogen is the most common type of hydrogen used since it is the most competitive in terms of costs among the other available options. With the incorporation of carbon taxes, Carbon Border Adjustment Mechanisms (CBAM) and decarbonisation targets set up by countries, the incentives to shift to low-carbon hydrogen technologies increases. As a result, supporting low carbon footprint hydrogen production will be beneficial at the national level. Table 11 presents some high level hydrogen costs, as presented in the IEA (2021), Hydrogen Council (2021b) and Kearney (2020) reports. Grey hydrogen costs are the lowest as of today, owing to its wide scale deployment and low to no carbon taxes associated with the emissions during production. With the introduction of carbon taxes, technology progress and improving economies of scale for CCS infrastructure and renewable energy, green and blue hydrogen levelized cost of hydrogen (LCOH) are expected to decrease in future years. Several international cost assessments show green hydrogen becoming competitive with blue hydrogen prices between 2030 and 2050[142].

[138] IRENA, *Green Hydrogen Cost Reduction*, 2020, Retrieved from https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf, on 29 October 2021

[139] 3.37 kWh per Nm^3, converted to MJ per kgH_2 for consistency of units throughout the report.

[140] Helmeth, *High Temperature Electrolysis Cell (SOEC)*, Retrieved from http://www.helmeth.eu/index.php/technologies/high-temperature-electrolysis-cell-soec, on 29 October 2021

[141] Timmerberg, Kaltschmitt, and Finkbeiner (2020) and Kerscher et al.(2021).

[142] World Bank, Low-Carbon Hydrogen: An Alternative Pathway to Decarbonisation,

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Table 11. H_2 production price (US $ per kgH_2) projections by type.

Type of Hydrogen	Source	2020	2030	2050
Grey Hydrogen	IEA	0.5 – 2.1	0.8 – 4.1	1.0 – 6.4
	Hydrogen Council	0.6 – 1.9	0.8 – 2.1	0.8 – 4.9
	Kearney	0.9 – 2.1	0.9 – 2.1	No Data
Blue Hydrogen[143]	IEA	1.0 – 2.8	1.0 – 2.3	1.0 – 2.4
	Hydrogen Council	1.0 – 2.2	1.0 – 2.1	0.8 – 4.9
	Kearney	1.5 – 2.5	1.3 – 1.9	No Data
Green Hydrogen	IEA	3.0 – 8.3	1.3 – 4	1.0 – 3.2
	Hydrogen Council	3.7 – 6.1	1.8 – 2.7	0.9 – 1.9
	Kearney	2.6 – 9.6	1.6 – 2.2	No Data

Sources: (Kearney 2020, 6–7; IEA 2021, 113; Hydrogen Council 2021b, 8)

Note: These numbers are only indicative and provide an order of magnitude on the expected cost decrease by technology type. The assumptions in terms of price of natural gas, solar and wind potential etc. behind those numbers are unknown and as such these numbers are generic and not necessarily valid for the context of this study. Refer to (Deloitte, IFPEN, and SINTEF 2021) for more information on the costs assumed in this study.

A.2 Review of hydrogen transport and storage costs

164. Alongside developing hydrogen production technologies, transmission, distribution, and storage of hydrogen are key factors to be considered when assessing LCH potential in a region. Connecting the demand centers with regions with abundant LCH production potential requires substantial initial investment, pushed forward by appropriate legal and regulatory framework, incentives, and policies.

165. H_2 can be transported as gaseous H_2, via pipelines and tube-trailers, in liquefied form in cryogenic tanks or as liquid organic hydrogen carriers (LOHCs), that can be reconverted to gaseous hydrogen at the demand sites. Several reports summarizing the infrastructure requirements and transport methods to enable hydrogen transport both in short and long distances. Table 12 summarizes the different transport options documented as of today.

[143] Data retrieved from IEA report. Natural Gas and Coal as a fuel for both blue and Grey Hydrogen.

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Table 12. Summary of hydrogen transportation pathways

Hydrogen Form	Mode of transportation	Description
Gaseous Hydrogen	Pipelines	As of today, depending on the transport capacity, pipelines are generally the most cost-efficient mode of transport for distances below 1,500 km to 3,000 km.[144,145] There are existing hydrogen pipeline networks in the United States, Germany, France and Belgium (approximately a total of 5,000 km). Most networks are currently operated by merchant hydrogen producers.[146] Transmission pipelines for hydrogen are very similar to those used for natural gas. The natural gas transmission pipelines are generally high-pressure steel pipes operated at pressure around 20 to 100 bar onshore.[147] The low volumetric energy density of hydrogen means that, to deliver a given amount of energy, the flow rate through the pipeline must be higher by a factor of 2.8 than that of natural gas.[148] The specific properties of hydrogen should be accounted for when designing or repurposing a pipeline network. At high pressures, hydrogen can over time cause embrittlement of steel. Before reusing a pipeline to transport hydrogen, integrity assessment should be carried out.[149] According to the Re-Stream study, in Europe, most of the existing oil and natural gas pipes can be reused for hydrogen transport considering the state of knowledge/standards as of 2021.[150] As for natural gas pipelines, hydrogen pipelines are high upfront investment projects.

[144] International Energy Agency, The Future of Hydrogen, Retrieved from: https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf on 5 November 2021

[145] International Energy Agency, *Global Hydrogen Review*, 2021, Retrieved from: https://www.iea.org/reports/global-hydrogen-review-2021, on 28 October 2021

[146] Rödl, Anne, Christina Wulf, and Martin Kaltschmitt. 2018. "Assessment of Selected Hydrogen Supply Chains—Factors Determining the Overall GHG Emissions." Hydrogen Supply Chains. Elsevier. https://doi.org/10.1016/b978-0-12-811197-0.00003-8

[147] European Hydrogen Backbone, 2020, How a dedicated hydrogen infrastructure can be created. Retrieved from: https://gasforclimate2050.eu/wp-content/uploads/2020/07/2020_European-Hydrogen-Backbone_Report.pdf on 7 November 2021

[148] Takahashi K., 2009, Energy carriers and conversion systems – vol. II - Transportation of hydrogen by pipeline – p 153

[149] From European Hydrogen Backbone, (2021), Analysing future demand, supply, and transport of hydrogen.

[150] Carbon Limits / DNV, 2021. Re-Stream – study on the reuse of oil and gas infrastructure for hydrogen and CCS in Europe. Retrieved from: https://www.carbonlimits.no/wp-content/uploads/2021/10/Re-stream-report-October-2021.pdf on 7 November 2021

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		New hydrogen pipelines could cost 1.1 to 1.5 times more than similar diameter natural gas pipelines.[151] The European Hydrogen Backbone study estimates the capital expenditure of new hydrogen pipelines to be between US $ 1.6 million and US $ 3.9 million (€ 1.4 million to € 3.4 million) per km depending on the pipe diameter. As for repurposed pipelines, capital expenditure could vary from US $ 0.2 million to US $ 0.7 million (€ 0.2 million to € 0.6 million) per km. Hence, re-use of the existing pipelines can lead to significant cost reduction.[152] As a transition solution and for hydrogen production near existing gas pipelines and without access to dedicated hydrogen infrastructure, blending of hydrogen could play an important role for initiating the market. There are some important safety aspects to consider in the case of handling gaseous H_2. hydrogen has an almost invisible flame; increased ignition risk; and produces a very hot flame. Storage of hydrogen at extremely low temperatures is a safety hazard; and needs to be stored at high pressure. Hence its compressors present a potential explosion risk greater than Liquified Petroleum Gas (LPG) bullets. However, there are extensive codes and standards established for safe handling and storage of hydrogen, but they need to be adopted across countries.
	Tube trailers *(Via road)*	As for compressed natural gas, hydrogen can be compressed into long cylinders (pressure between 180 bar and 250 bar) and stacked in a trailer to be transported by a truck. Such heavy-duty trailers can carry around 380 kgH_2, however vessels capable of carrying between 500 kgH_2 and 900 kgH_2 are currently under development.[153]
Liquefied Hydrogen	Tube trailers *(Via road)* and ships *(seaway)*[154]	In the absence of pipelines, hydrogen is commonly transported in the liquid form in trucks.[155] Liquid hydrogen (LH_2) is a cryogenic liquid that boils at around -253°C (20K). It is an attractive way to store hydrogen on account of its density compared with gaseous H_2 (the volumetric energy density is increased by a factor above 10 compared to

[151] International Energy Agency, *Global Hydrogen Review*, 2021, Retrieved from: https://www.iea.org/reports/global-hydrogen-review-2021, on 28 October 2021

[152] European Hydrogen Backbone, 2021, Extending the European Hydrogen Backbone. Retrieved from: https://gasforclimate2050.eu/wp-content/uploads/2021/06/European-Hydrogen-Backbone_April-2021_V3.pdf on 7 November 2021

[153] Office of energy efficiency and renewable energy, *Hydrogen Tube Trailers*, Retrieved from: https://www.energy.gov/eere/fuelcells/hydrogen-tube-trailers, on 28 October 2021.

[154] There are currently no ships that can transport pure hydrogen. Liquefied hydrogen transport by ship is similar to LNG tankers apart from the fact that better insulation is required to keep the hydrogen cool over long distances. Hydrogen that is unavoidably evaporated may be used as fuel on board.

[155] Office of energy efficiency and renewable energy, *Liquid Hydrogen delivery*, Retrieved from: https://www.energy.gov/eere/fuelcells/liquid-hydrogen-delivery, on 28 October 2021.

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		gaseous hydrogen at 80 bar).[156] However, there are some limitations to consider. a) The liquefaction process uses considerable amount of energy. Theoretically, about 10 kWh of energy is required per kgH_2[157], although, the actual requirement will vary depending on the scale of operation. For large liquefaction plants (>1,000 kgH_2 per hour), the energy input is roughly equivalent to 30% of the energy value of H_2.[153] b) The cryogenic equipment to liquefy and contain the hydrogen is sophisticated and costly. c) Despite having good insulation, such as multi-layer vacuum super-insulation, the boil-off rate[158] of LH_2 can be high (0.3%/day).[157] Liquefied hydrogen can present challenges such as leakages of low temperature material that can fracture steel structures, while transient heavier-than-air hydrogen vapours present fire and asphyxiation risk;
Conversion to other products: Liquid organic hydrogen carriers (LOHC)[159]	Ships *(seaway)*	LOHCs are a potentially safe and convenient form of storing and transporting hydrogen over long distances. hydrogen is incorporated into the LOHCs through catalytic hydrogenation and hydrogen is released by catalytic dehydrogenation (at optimal temperature and pressure).[160] Their properties are like those of crude oil and oil products, and they do not require cooling to be transported as liquids. Toluene could be one of those carriers. As of today, the hydrogenation and dehydrogenation processes are very energy intensive, requiring large quantities of heat energy (35% and 40% of the hydrogen itself).[161] To be considered as a low-carbon or green hydrogen, this heat energy must come from a low emission energy source, to ensure no carbon emissions are incurred. Furthermore, transportation is required to carry the hydrogenated LOHC to the area of use, and the

[156] European Hydrogen Backbone, 2021, Analysing future demand, supply, and transport of hydrogen. Retrieved from: https://gasforclimate2050.eu/wp-content/uploads/2021/06/EHB_Analysing-the-future-demand-supply-and-transport-of-hydrogen_June-2021_v3.pdf on 7 November 2021

[157] Decker, 2019, Linde. Liquid hydrogen distribution technology. Retrieved from: https://www.sintef.no/globalassets/project/hyper/presentations-day-2/day2_1105_decker_liquid-hydrogen-distribution-technology_linde.pdf on 7 November 2021

[158] The amount of liquid that is evaporating from a cargo due to heat leakage and expressed in % of total liquid volume per unit time.

[159] Including naturally occurring hydrocarbons, other organic molecules (e.g. methanol), metal alloy hydrides and liquid ammonia. Except for ammonia and metal alloy hydrides, all these candidate compounds contain carbon.

[160] Rao and Yoon (2020)

[161] International Energy Agency, The Future of Hydrogen, Retrieved from: https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf on 5 November 2021

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		dehydrogenated LOHC must be transported back to its original location for renewing the process. There are also toxicity considerations to take note of, in the case of LOHCs. The toxicity and safety requirements for LOHCs are highly dependent on the type of LOHC being transported. International standards need to align on the safety requirements for LOHC transport.
Conversion to other products: Ammonia (NH_3)	Ships *(seaway)*	There are a few advantages of converting hydrogen to ammonia for transport: (1) Unlike LOHCs, there is no 're-transport' required (2) Ammonia is a product that is traded at a global scale as of today. Trade routes of ammonia today include transport from the Arabian Gulf and Trinidad and Tobago to Europe and North America. The familiarity with the product makes it easier to explore as a viable long-term transport option for hydrogen. (3) Ammonia is easy to liquefy compared to hydrogen (it liquefies at -33°C) and has physical properties similar to liquified petroleum gas (LPG), providing an opportunity to use existing storage, transport and terminal equipment. However, similar to LOHCs, significant amount of energy is required for the conversion of hydrogen to ammonia, and its reconversion back to hydrogen (between 14% and 36% of the energy contained in the hydrogen).[162] Considering ammonia's toxicity, there could be significant safety considerations if large scale ammonia transport is explored as a hydrogen transport pathway though there has not been any incident reported for small scale NH_3 transport.

IEA Global Hydrogen Review 2021, and other references

166. Each transport option has its own set of advantages and disadvantages. The cost variability is very high, depending on the quantity of H_2, and the distance over which hydrogen is transported. A case-by-case assessment is required to estimate the transport cost of hydrogen relevant for the country and industry where this hydrogen will be used.

167. In the International Energy Agency's (IEA) Net zero Emissions Scenario, international trade of hydrogen and hydrogen based fuels cover ~15% of global demand in 2030. According to their latest hydrogen review report, the costs vary drastically by the mode of transport and the transport distance. The key take-aways are summarized below:[163]

    1. Transporting gaseous hydrogen by pipelines is competitive with other modes of transport within 500 km (pipeline capacity: 100 tonnes per day), 2,000 km (pipeline capacity: 500 tonnes per day) and within 3,000 km (pipeline capacity: 1,000 tonnes per day). The costs in these cases vary

[162] International Energy Agency, The Future of Hydrogen, Retrieved from: https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf on 5 November 2021

[163] IEA, *Global H2 Review*, 2021, Retrieved from: https://www.iea.org/reports/global-hydrogen-review-2021, on 28 October 2021

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between US $ 0.5 and US $ 1.2 per kgH_2. Beyond these distances, converting hydrogen to another hydrogen-based molecule such as ammonia or LOHC is more cost competitive.

2. Transporting gaseous hydrogen via road, using tube trailers has very steep cost to distance profile. It could be competitive within 500 km, hence suitable for local distribution. The cost varies between US $ 0.5 and US $ 1.2 per kgH_2.
3. Transport of liquid hydrogen by pipeline, and ammonia and LOHC by ships have a similar cost profile, over distances between 500 km and 5,000 km. The costs vary between US $ 1 to $ 2 per kgH_2, including the cost of reconversion at the use site.

168. As with oil and gas, hydrogen storage facilities will be required as a buffer between supply and demand across a variety of timescales. The following storage options are available for hydrogen:

1. Geological storage: hydrogen can be stored underground in depleted oil and gas fields, salt caverns, etc. Salt is extracted from the salt formations in some areas by dissolution of the rocks and the resulting caverns in the rock are sufficiently inert to store hydrogen in a safe manner. hydrogen has been stored primarily underground in salt caverns, which are not available in all geographies. Depleted fields and aquifers are theoretically the next best large-scale solutions for hydrogen storage. However, large scale testing and demonstration is required to assess the safety and feasibility of storing hydrogen in depleted gas fields and reservoirs. Building the hydrogen storage capacity is needed for the large-scale development of LCH. However, this will require overcoming potential public opposition due to safety concerns, subsidence, and induced seismicity.
2. Pressure vessels: Industrial customers of hydrogen sometimes use above-ground storage in vertical rows or horizontal stacks of cylinders at pressures in the range of 20 MPa up to a maximum of 80 MPa. For portable and mobile applications (e.g., fuel for road vehicles), both weight and volume are vital considerations, and it is desirable to have energy and volumetric densities as high as possible. The highest costs in this case come from the energy required to operate the compressors[164]. It has been estimated that the electricity required to compress hydrogen to 20 MPa is equivalent to over 7% of the energy content of hydrogen. The figure rises to 10% for compression to 80 MPa.
3. Material based storage: This technique uses materials – solids or liquids – that can absorb or react with hydrogen to bind it, due to their chemical attributes. Ammonia and LOHCs described in appendix A.2 offer easier storage opportunities in liquid storage tanks. However, there are costs associated with the conversion and re-conversion of hydrogen, and safety concerns based on the toxicity of the LOHC being used for storage.

169. Whilst small storage facilities may be constructed independently of geography, large scale storage facilities are anticipated to rely on access underground formations, such as salt formations or depleted oil and gas fields[165]. As highlighted by Guidehouse[166], the development time of a hydrogen storage site can take between 1 and 7 years (when repurposing an existing gas storage), and between 3 and 10 years (for a new storage site) from pre-feasibility, hydrogen injection test, to becoming operational.

170. Hydrogen storage costs are challenging to generalize, due to the different storage options, volume and type of storage, the location of storage site and the form in which hydrogen is stored.

[164] Note - the compression process could be reduced, or eliminated altogether, if the hydrogen was supplied from pressurized electrolyzers and this is a prospect for the future

[165] (Caglayan et al. 2020)

[166] Guidehouse for GIE, Picturing the value of underground gas storage to the European hydrogen system, June 2021

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Indications for the levelized cost of storage for hydrogen are summarized in table 13. However, more in-depth and case by case studies are required to estimate the costs at a higher confidence level.

Table 13. Hydrogen storage costs

	Levelized cost of hydrogen storage (US $ per kgH_2)
Salt Cavern	0.2 – 1.35
Depleted Gas fields	~ 1.2 – 1.9
Aquifer	~ 1.2
Pressurized Containers (gaseous hydrogen)	~ 0.2
Liquid hydrogen	~ 4.6

Note: the numbers are generic based on assumptions not detailed in the report.

Gas Infrastructure Europe, Guidehouse, 2021 /KPMG, 2021

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Box 6. Ammonia (NH_3) insights

Ammonia has been gaining significant attention in relation to the hydrogen economy, to ease transport and storage of hydrogen. The advantage of ammonia over pure hydrogen, is the higher volumetric energy density and liquefication temperature. These characteristics make ammonia transport and storage more competitive than gaseous or liquefied hydrogen. Ammonia trade infrastructure is already developed, reaching a quantity of 20 Mt traded globally in 2020[167]. Green ammonia costs are still high today at US $ 970 per tNH_3, with more than one third dedicated to electricity cost for electrolysis. Sources forecast a huge reduction to around US $ 300 per tNH_3, in 2050, in the net zero emissions scenario[168]. Blue ammonia production have a cost advantage at US $ 650 per tNH_3. Grey ammonia remains the cheapest today at US $ 450 per tNH_3.

Around 7.8 Mt of low-carbon ammonia production projects have been announced until 2030, with a focus on electrolysis, and also CCS coupled technology. This is driven by the rising world demand for ammonia, with total estimated demand projected to be over 200 Mt in 2050[169].

[167] IEA, Ammonia Technology Roadmap, 2021, Retrieved from: https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf, on 2 November 2021

[168] IEA, *Global H2 Review*, 2021, Retrieved from: https://www.iea.org/reports/global-hydrogen-review-2021, on 28 October 2021

[169] IEA, *Hydrogen Projects Database*, 2021, Retrieved from: https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database, on 28 October 2021

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B. Hydrogen demand assumptions

Table 14. Macroeconomic drivers

Parameter	Unit	Source	2030	2040	2050
Population	inhabitants	[3] and [4}	37,000,000	38,950,000	40,950,000
GDP	Current Bn. USD	[1]	107	125	146
GDP per capita	Current USD		2890	3212	3570
Agriculture	% of GDP	[3]	14%	13%	10%
Industry	% of GDP	[3]	41%	42%	45%
Services	% of GDP	[3]	46%	45%	45%

Table 15. LCH demand for ammonia production assumptions

Parameter	Unit	Source	2030	2040	2050
Ammonia capacity	Thousand metric tons	2019: Source[170] Forecast: estimated	1,785	2,194	2,754
Increase in ammonia capacity	% over a ten-year period	Estimated from agriculture share in GDP	100%	23%	25%
Ammonia production from LCH – Low scenario	% of total ammonia production	Own assumptions	10%	25%	50%
Ammonia production from LCH – Medium scenario			25%	50%	75%
Ammonia production from LCH – High scenario			50%	75%	100%

Table 16. LCH demand for methanol production assumptions

Parameter	Unit	Source	2030	2040	2050

[170]Further information available at Nitrogen Fertilizer Production in Uzbekistan (nationmaster.com)

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Methanol capacity	Thousand metric tons	2025: Sources[171], [172] Forecast: estimated	4,939	6,071	7,596
Increase in methanol capacity	% over a ten-year period	Estimated from industry share in GDP	100%	23%	25%
Methanol production from LCH – Low scenario	% of total methanol production	Own assumptions	10%	10%	10%
Methanol production from LCH – Medium scenario			20%	40%	50%
Methanol production from LCH – High scenario			25%	50%	75%

Table 17. LCH demand for iron & steel production assumptions

Parameter	Unit	Source	2030	2040	2050
Steel capacity	Thousand metric tons	2025: Sources[173] Forecast: estimated	1,003	1,233	1,543
Increase in steel capacity	% over a ten-year period	Estimated from industry share in GDP	100%	23%	25%
Steel production using LCH – Low scenario	% of total steel production	Own assumptions	10%	25%	50%
Steel production using LCH – Medium scenario			25%	50%	75%
Steel production using LCH – High scenario			50%	75%	100%
H2-DRI/EAF share		Own assumptions	75%	75%	75%

Table 18. LCH in transport assumptions

Parameter	Source	Description
Buses	Own assumptions	Linear increase in share from 0% in 2019 to 40% in 2050

[171] Further information available at https://www.azernews.az/region/140119.html#:~:text=South%20Korean%20company%20GS%20Engineering,at%20the%20end%20of%202022

[172] Further information available at https://globuc.com/news/uzbekistan-to-develop-a-2-5-billion-gas-chemical-complex-by-2023/

[173] © 2022 World Steel Association https://www.worldsteel.org/

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Freight – road transport	Own assumptions	Linear increase in share from 0% in 2019 to 50% in 2050
Passengers' turnover of buses (bln. Pass-km)	UZB stat	These data are used to calculate energy needs
Road freight turnover (bln. Ton-km)	UZB stat	These data are used to calculate energy needs
Energy efficiency per transport type (MJ/pass-km or MJ/ton-km)	PotenCia and own calculation	Energy efficiency of each transport type over the years to calculate hydrogen needs
GDP growth	Own assumptions	It's considered that GDP and population growth will affect passenger transport and industry and agriculture GDP growth will affect freight transport

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Table 19. Other industries and heating assumptions

Parameter	Source	Description
Energy consumption	IEA World Energy Balances[174]	Used energy consumption per sector in 2019 to calculate the total energy consumption of the industrial sector
Energy intensity of GDP	IEA World Energy Balances	Took the values of historical years from IEA. Considered that for the rest of the period the country achieves a reduction by twofold of energy intensity in 2010 stated in NDC
Hydrogen share – Low demand scenario	Own assumptions	Considered 5%, 7.5% and 10% of natural gas consumption in other industry and heating is replaced by hydrogen in 2030, 2040 and 2050 respectively.
Hydrogen share – Medium demand scenario	Own assumptions	Considered 5%, 10% and 15% of natural gas consumption in other industry and heating is replaced by hydrogen in 2030, 2040 and 2050 respectively.
Hydrogen share – High demand scenario	Own assumptions	Considered 5%, 15% and 20% of natural gas consumption in other industry and heating is replaced by hydrogen in 2030, 2040 and 2050 respectively.

[174] IEA World Energy Balances https://www.iea.org/data-and-statistics/data-product/world-energy-statistics-and-balances

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C. Hydrogen supply model assumptions

The data presented in the following tables were collected as part of the assessment done for the H_2 for EU project, drafted by Deloitte France, IFPEN, and SINTEF.[175]

Table A. 1: H_2 production technologies – Cost data. All cost data is provided in the lower heating value (LHV)

Technology	Investment costs [€/kW H_2]			Fixed O&M [€/kW H_2]			Variable O&M [€/GJ]			Source
	2020	2030	2050	2020	2030	2050	2020	2030	2050	
SMR, large size, centralized	805	805	805	37.8	37.8	37.8	0.08	0.05	0.05	1, 9
SMR + CO_2 capture, large size, centralized	1487	1204	1133	44.6	36.1	34.0	0.53	0.07	0.07	1, 9
ATR + CO_2 capture, large size, centralized	800	700	700	24.0	21.0	21.0	0.53[176]	0.07[185]	0.07[185]	8, 9
GHR + ATR + CO_2 capture, large size, centralized	830	750	750	24.9	22.5	22.5	0.53[185]	0.07[185]	0.07[185]	8, 9
PEM electrolyzer	1750	-[177]	-[185]	52.5	45	-[185]	0.15[178]	0.06[187]	0.06[187]	2, 3, 7, 9, 10
Alkaline electrolyzer, large size, centralized	1250	-[185]	-[185]	18.8	15	-[185]	0.15	0.06	0.06	2, 3, 7, 9, 10
Molten media methane pyrolysis, large size	778	778	778	64.9	64.9	64.9	-	-	-	11

Table A. 2: H_2 production technologies – Technological Data

Technology	Typical size [MW]	Fuel Efficiency [PJ/PJH_2] (LHV)				Lifetime			Source
		Fuel	2020	2030	2050	2020	2030	2050	
SMR + CO_2 capture, large size, centralized	1502	Natural gas	1.38	1.38	1.38	25	25	25	1, 8, 9
SMR, large size, centralized	1530	Grid electricity	0.01	0.01	0.01	25	25	25	
ATR + CO_2 capture, large size, centralized	1260	Natural gas	1.36	1.36	1.36	25	25	25	8, 9
		Grid electricity	0.04	0.04	0.04				
GHR + ATR + CO_2 capture, large size, centralized	1260	Natural gas	1.28	1.20	1.20	25	25	25	8, 9
		Grid electricity	0.06	0.05	0.05				
		Grid electricity	0.08	0.08	0.08				

[175] Full report can be found here: https://www.hydrogen4eu.com/

[176] The variable O&M costs for *GHR + ATR* and *ATR* are based on the reported values for *SMR + CO_2 capture* as they are mostly related to process water, cooling water, and catalyst replacement.

[177] Future costs in water electrolysis are highly uncertain and are be calculated through learning by doing in the model Integrate Europe.

[178] The variable O&M costs for *PEM electrolyzer* are based on *Alkaline electrolyzer, large size* as they are mostly related to process and cooling water.

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Technology	Typical size [MW]	Fuel Efficiency [PJ/PJH_2] (LHV)				Lifetime			Source
Molten media methane pyrolysis, large size	420	Natural gas	2.05	2.05	2.05	20	20	20	11

Sources for Table A. 1 and Table A. 2:

1. IEA 2019: The Future of Hydrogen
2. Blanco H., Nijs W., Ruf J., Faaij A., 2018a, Potential for hydrogen and Power-to-Liquid in a low-carbon EU energy system using cost optimization, Applied Energy 232, pp. 617-639
3. Blanco H., Nijs W., Ruf J., Faaij A., 2018b, Potential of Power-to-Methane in the EU energy transition to a low carbon system using cost optimization, Applied Energy 232, pp. 323-340
4. Sgobbi A., Nijs W., De Miglio R., Chiodi A., Gargiulo M., Thiel C., 2016, How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system, International Journal Hydrogen Energy 41, pp. 19-35
5. Bolat P., Thiel C., 2014a, Hydrogen supply chain architecture for bottom-up energy systems models. Part 1: developing pathways, International Journal Hydrogen Energy 39, pp. 8881-8897
6. Bolat P., Thiel C., 2014b, Hydrogen supply chain architecture for bottom-up energy systems models. Part 2: techno-economic inputs for hydrogen production pathways, International Journal Hydrogen Energy 39, pp. 8898-8925
7. Schmidt O., Gambhir A., Staffel, I., Hawkes, A., Nelson, J., Few, S., 2017 Future cost and performance of water electrolysis…, International Journal of Hydrogen Energy 42, pp. 30470-30492
8. Information provided by partners
9. H_2 North of England Report (2018)
10. NREL Technical Report NREL/TP-560-46267 September 2009 and NREL Technical Report NREL/TP-6A10-60528

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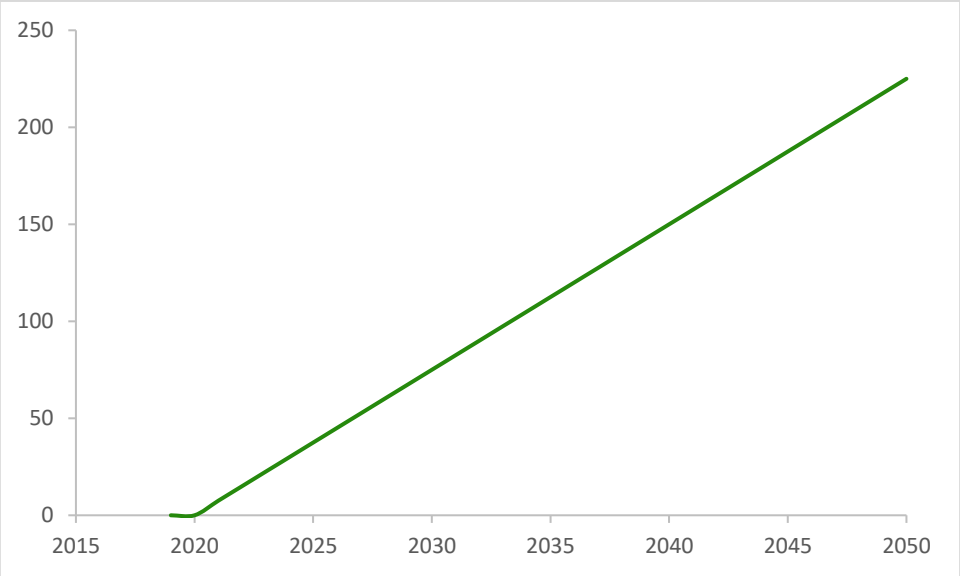
D. Carbon pricing assumptions

Carbon price has a critical influence on the cost of production of hydrogen. It discriminates between the most effective pathways by applying a penalty to carbon-intensive processes. The assumption assumed for Uzbek carbon prices in this model is a steady increase from now on until 2050 where it will reach 250 US $/tCO$_2$.

Figure 39. Carbon pricing assumptions (in US $/tCO$_2$)



Source: World Bank 2022

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E. Feedstock consumption per scenario

Table 20. Feedstock consumption per scenario for low-carbon hydrogen production only

Scenario	Year	2030	2040	2050
Natural gas consumption (Bcm)				
Central		0.8	1.8	4.2
Low NG availability		0.8	1.4	3.4
High NG availability		0.8	3.5	8.3
Low H2 demand		0.8	1.6	3.2
High H2 demand		0.8	1.9	4.8
Water consumption (MtH_20)				
Central		7.3	17.1	41.3
Low NG availability		7.2	20.7	50.6
High NG availability		7.3	16.2	39.0
Low H2 demand		4.8	8.7	17.6
High H2 demand		9.2	22.7	61.5
Captured CO_2 (cumulative. in $MtCO_2$)				
Central		1.1	15.2	49.7
Low NG availability		1.1	13.7	39.7
High NG availability		1.1	26.0	99.2
Low H2 demand		1.1	15.0	44.0
High H2 demand		1.1	15.3	52.9

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