Potential demand for green hydrogen in Kenya

Green manufacturing TA support

June 2022

ANALYSIS

This programme is funded by UK aid from the UK Government; however, the views expressed do not necessarily reflect the UK government's official policies

Abbreviations and terminology notes

BEV	battery electric vehicle
BF-BOF	blast furnace - basic oxygen furnace
CAGR	compound annual growth rate
CAPEX	capital expenditure
CARB	California Air Resources Board
CCS	carbon capture and storge
CCUS	carbon capture, usage, and storage
CHP	combined heat and power
CO2	carbon dioxide
DAC	direct air capture
DRI	direct reduced iron
EAF	electric arc furnace
EJ	exajoule
EU	European Union
EV	electric vehicle
FCEV	fuel cell electric vehicle
GJ	gigajoule
GT	Gas turbine
GWh	gigawatt hour
H2	hydrogen
HDT	heavy duty truck
HFO	heavy fuel oil
HVO	hydrotreated vegetable oil
ICE	internal combustion engine
kg	kilogram
KWh	kilowatt hour
LCOE	levelized cost of electricity
M3	meters cubed
MDT	medium duty truck
MMBTU	metric million British thermal unit
Mn	million
MSD	medium speed diesel
MT	metric ton
MWh	megawatt hour
NAFTA	North American Free Trade Agreement
OEM	original equipment manufacturing
PSC	point-source capture
PtL	power to liquid
RFNBO	renewable fuels of non-biological origins
RoPax	roll-on passenger ferry
SAF	sustainable aviation fuel
SGR	Standard Gauge Railway
SMR	steam methane reforming
SOEC	solid oxide electrolyzer cell
SUV	sports utility vehicle
TCO	total cost of ownership
TWh	terawatt hour
USD	United States dollar
ZEV	zero-emissions vehicle

Green hydrogen/H2 is hydrogen produced with renewable electricity

Blue hydrogen/H2 is grey hydrogen but with carbon capture

Grey hydrogen/H2 is produced from natural gas and is not carbon-neutral

Fertilizer can be shown as nutrient or product tons. Nutrient only shows the amount of the specific nutrient (e.g. nitrogen) in the fertilizer. Product shows the weight of the end-product. For example, urea is a product, but is 46% nitrogen so 1 ton of urea product is 0.46 tons of nitrogen nutrient

Fuel cell electric vehicles and **hydrogen fuel cell** are used interchangeably in this document and mean the same thing

Contents

Executive summary

Deep dives per use case

Executive summary

Green hydrogen can be a major opportunity for decarbonization in the long-term globally, with 7,600 TWh of energy demand expected to be needed for hydrogen production by 2040. Globally, there are ~40 potential use cases for green hydrogen, either as a fuel (e.g., for transportation, power generation, or industrial heating), **or as a feedstock for industrial processes** (e.g., for green ammonia and green fertilizer). Typically, it is most likely to be used in industries that are hard to decarbonize through other means (e.g., heavy industry)

In Kenya, the use cases that have the highest technical feasibility include heavy duty transport, trains, aviation, stationary power generation, industrial heating, ammonia/fertilizer, and steel. This is based on criteria including assessing whether the sector itself will be large enough in Kenya in 2040, whether green H2 is likely to be the winning fuel technology, and technological availability. For example, heavy duty transport is hard to decarbonize via electrification due to charging requirements and therefore could transition to green hydrogen instead. For power, Kenya could consider transitioning remaining thermal power plants (constituting ~8% of energy consumption today) to green hydrogen, particularly among gas turbines that have already proven technology to transition to replace natural gas with green hydrogen

Use cases that have less technical feasibility in Kenya include some forms of light transportation, maritime fuel, and building heating. For example, for light transportation (e.g., passenger vehicles, buses, commercial fleet) electric vehicles are the winning technology globally, and the high availability of renewable electricity in Kenya favours EVs. For maritime, ships tend to refuel in major ports (e.g. Singapore, Rotterdam) along major shipping routes and not secondary ports like Mombasa (ships are also unlikely to divert off major shipping lanes to Kenya to refuel so making Kenya a refuelling hub unlikely)

The maximum potential Kenya domestic demand for technically feasible use cases is ~140-390k tonnes of green hydrogen in 2040. The majority (25-45%) of this demand could come from green ammonia/fertilizer, which would assume replacing 100% of imports with locally produced green urea. Next, 20-30% of this demand could come from aviation, specifically power-to-liquid (PtL) sustainable aviation fuel, assuming 5-10% of jet fuel demand transitions by 2040 (alongside other sustainable aviation fuels). The lowest demand may come from steel production, which can use green hydrogen in upstream and downstream production; however, there is limited upstream production in Kenya with only 1 plant currently operational, while downstream processing has low demand for hydrogen.

Use cases with potential for export might include green ammonia (i.e., for maritime fuel), but not steel, PtL fuels, or green urea, since the latter 3 use cases require CO2 or iron ore which are not available competitively in Kenya. **The overarching determinant of whether Kenya could be competitive for exports is based on green hydrogen production costs, and Kenya's costs are slightly higher than global estimates** for 2040 at ~USD 2.2-3.3 per kg, compared to ~2 USD globally. Additionally, infrastructure requirements for export have significant capex, and may not be technically feasible in all cases. It would require either a deep sea port for shipping – Mombasa port is deep but is congested, and has limited space for landside infrastructure (e.g., liquefaction plant, compressors and electrolysers) – or a pipeline to Saudi Arabia which would require significant volumes produced to be economical.

Overall, green hydrogen use cases are estimated to be more expensive in Kenya compared to conventional alternatives. For example, a green hydrogen fuel cell truck may have a total cost of ownership in 2040 of USD ~820-900k, compared to USD ~650k for a diesel truck. The cost difference is driven by higher costs of fuel, refueling infrastructure, and cost of vehicle capex

There are several enablers that could help to make green hydrogen adoption more attractive, including financial incentives to bring down the costs of green hydrogen adoption (e.g., tax rebates or credits), financial penalties to increase the costs of conventional alternatives (e.g., CO2 tax, however this could have significant implications for cost of living), or regulatory incentives to drive adoption of green hydrogen (e.g., mandates for blending aviation fuels to use PtL)

The global transition to using cleaner fuel/energy sources such as hydrogen will happen, and Kenya has two options going forwards. Either, Kenya can "lean forward" on green H2 production over the next 10 years, or wait out the global trend and re-evaluate after several years.

Existing work has been conducted by stakeholders on estimating the supply and demand of green hydrogen in Kenya

AS OF JUNE 2022 – NOT EXHAUSTIVE

▨ Focus of this report

	Focus	Status and insights	Contributors *(not exhaustive)*
Supply	Locations suitable for green H2 production	Analysis ongoing	CCG
	Cost of production of green H2	**Estimated costs for green hydrogen** could range from USD/kg 2-4 (compared to an international range of USD/kg 1.5 – 4) **Estimated costs for ammonia production** could range from USD/t 500-900 (compared to an international range of USD/t 400 – 600)	GIZ
	Regulations and policies	Analysis not yet identified	Not identified
Demand	Technical feasibility	**Identified high level potential use cases with high technical feasibility** may include fertilizer, steel production, some forms of transportation, H2 derivatives for industrial uses, aviation, and off-grid power. Estimated high level technical potential demand could be ~1,800–2,500 MW (electrolyser capacity)	GIZ, MoE, CCG
		▨ **Estimating detailed technical potential demand**	Manufacturing Africa
	Economic feasibility	**Estimated high level commercial potential demand** for green H2 could be ~120-660 MW (electrolyser capacity)	GIZ
		Conducting **economic feasibility analysis into fertilizer**	KfW
		▨ Conducting **detailed deep dives on economic feasibility**, and **sizing economically feasible demand**	Manufacturing Africa
	Roadmap to scaling green H2	Analysis ongoing	GIZ, EU

Manufacturing Africa focused on prioritizing demand use cases in Kenya and sizing the demand potential (including theoretical potential and economic feasibility)

The cost of hydrogen production is key to this analysis. Given existing work on this, we utilized the cost projections from GIZ in this analysis.

The intent of this document is to support actors interested in hydrogen development in Kenya in evaluation the total business case for this fuel

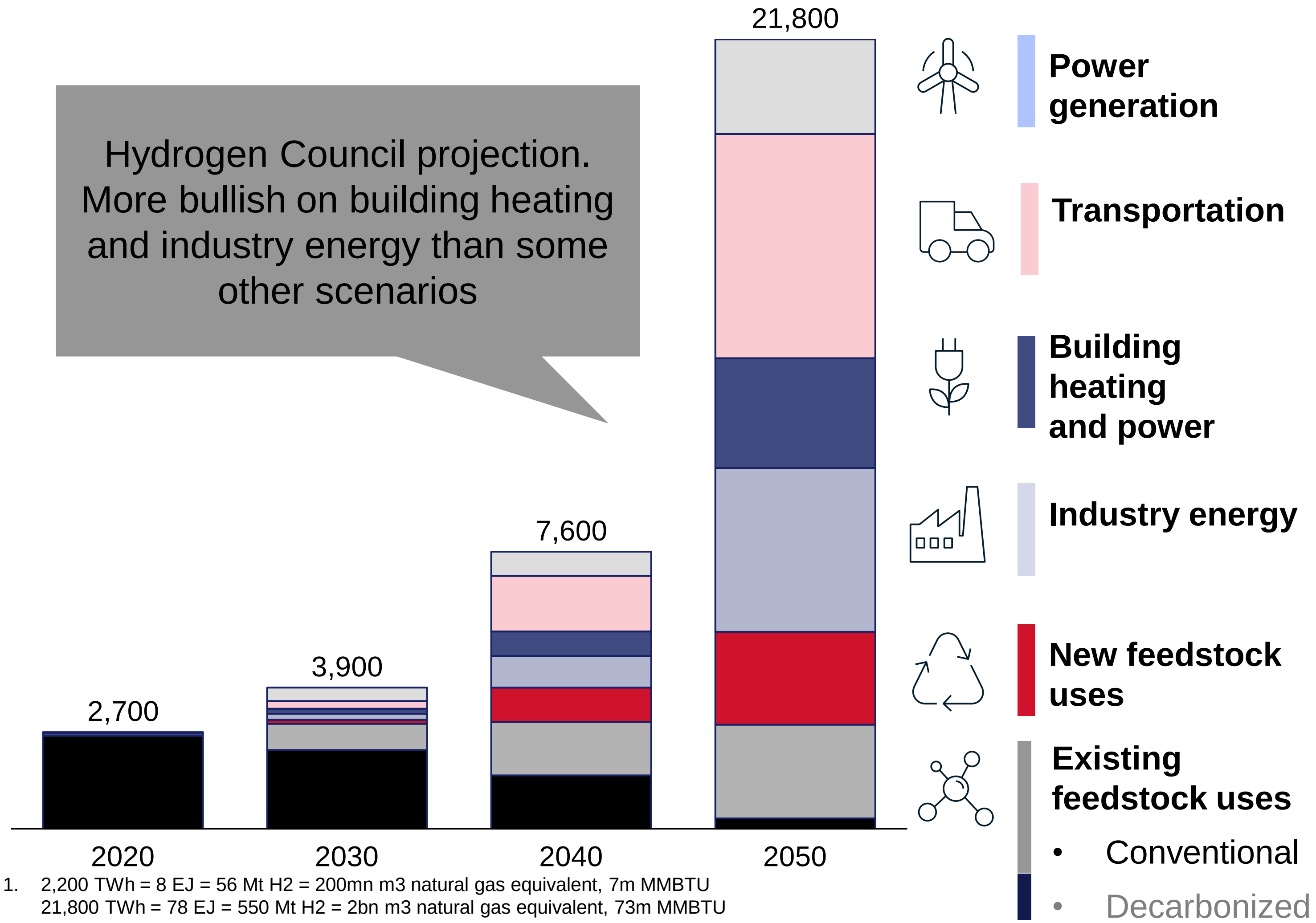
We followed a 3-step process in identifying demand use cases with high potential for scaling green hydrogen and potential market size

Steps for selecting priority sectors to scale green hydrogen in Kenya

	1. What demand use cases could be technically feasible in Kenya and what could be the theoretical market size?	**2. What is the economic feasibility of scaling these use cases?**	**3. What are the enablers to scale the priority use cases?**
Key questions addressed	What are the **main use cases for green hydrogen globally?** **Which of these use cases are technically feasible in Kenya** (and not likely to use alternate green energy such as renewable electricity instead of green H2)? What is the **hypothetical maximum demand for green H2 by 2040** in the technically feasible use cases in Kenya (incorporating expected sector growth)? **How feasible could exports be** for green H2 from Kenya?	**What is the feasibility of each use case based on the cost effectiveness** against conventional fuel sources by 2040?	**What enablers** could scale green hydrogen in Kenya in prioritized use cases?

1. Hydrogen can be a major opportunity in the long-term, but some uncertainties remain

Potential global energy demand supplied with hydrogen, TWh[1]



Hydrogen Council projection. More bullish on building heating and industry energy than some other scenarios

An aggressive **decarbonization constraint** (e.g. regulatory and/or financial constraints) is the decisive factor in scaling hydrogen demand given switching costs and economics of hydrogen versus conventional sources

The **demand in some industries is also uncertain due to competing technologies**:

- Industrial use, especially for heating where the decarbonization pathway could come through hydrogen or CCS (carbon capture & storage), depending on economics
- Transport (outside heavy duty), where battery technology is likely winning out over hydrogen
- Whether home-based heating will face a push for decarbonization

Short-term **cost competitiveness** is also key for deployment:

- 2 USD/kg green hydrogen production cost (required to break even with grey hydrogen[2]) – *expected by 2030-2040 globally, depending on scenario*
- -50% to -75% reductions in fuel cell and electrolyzer capex

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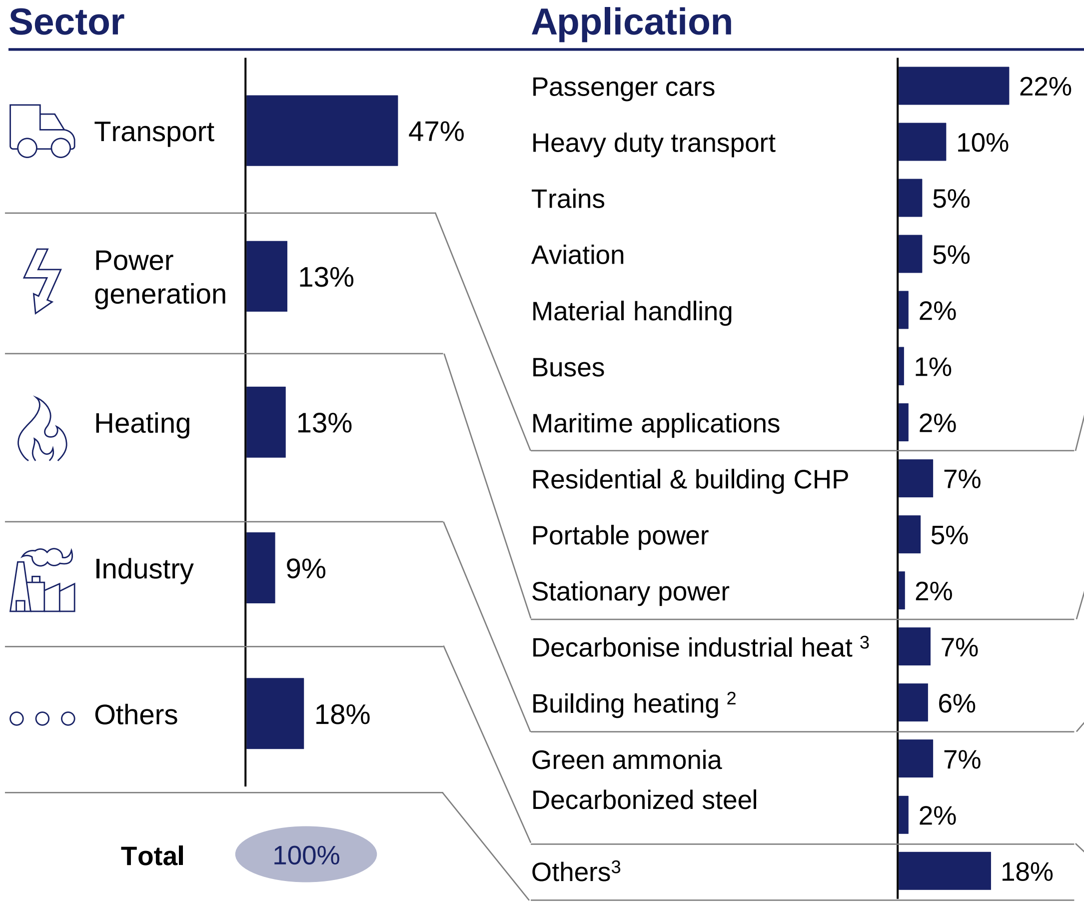
1. 2,200 TWh = 8 EJ = 56 Mt H2 = 200mn m3 natural gas equivalent, 7m MMBTU
   21,800 TWh = 78 EJ = 550 Mt H2 = 2bn m3 natural gas equivalent, 73m MMBTU
2. Hydrogen produced from natural gas / fossil fuels

Source: Hydrogen Council 2021

1. Globally, there are ~40 potential use cases for green hydrogen…

Proportion of theoretical green hydrogen demand by sector vs proportion of green hydrogen demand by application, 2030 (shown for the top use cases)



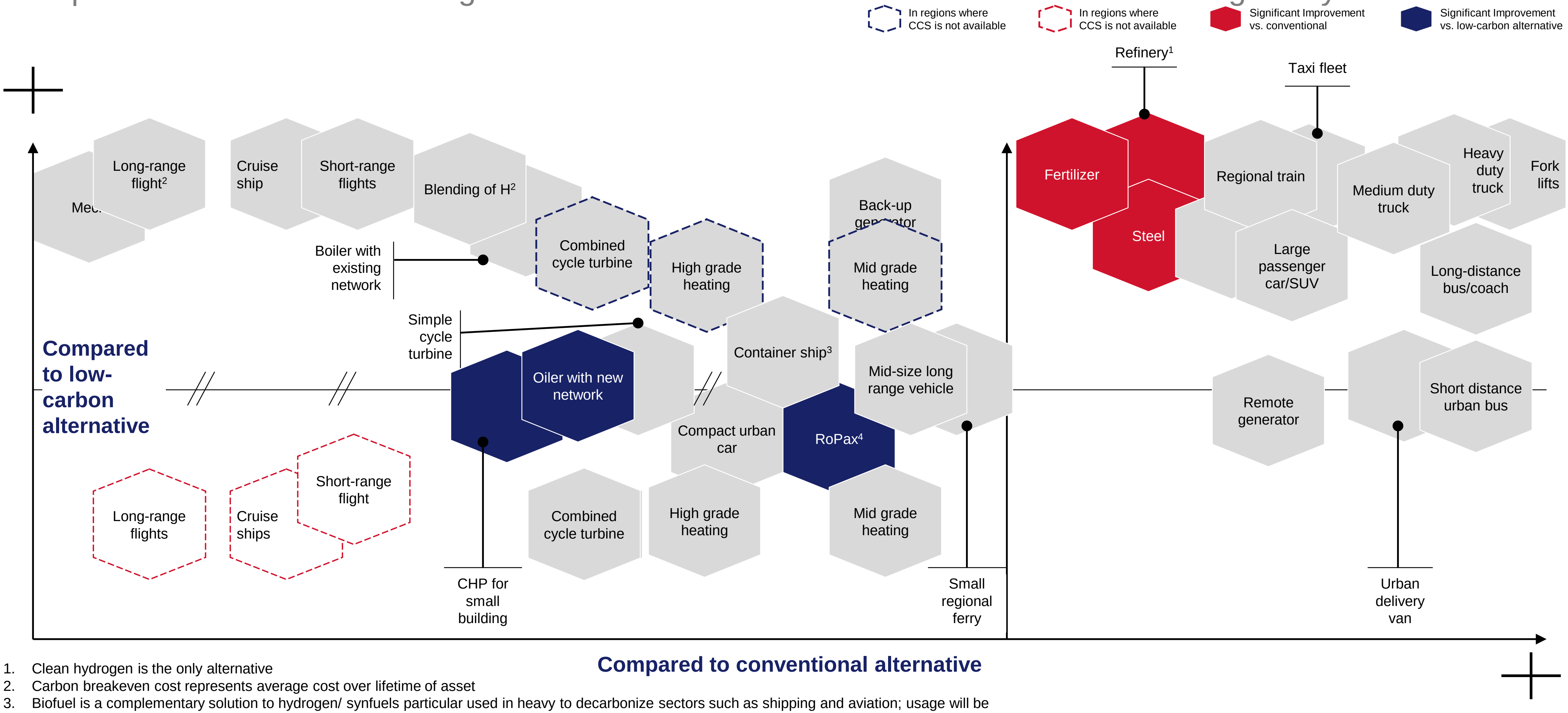
Advantages of using green hydrogen	Challenges of using green hydrogen
• Fast refueling, similar to internal combustion engines (ICEs) • Longer range than batteries • Long lifespan of fuel cells	• Initial high cost and low volume • Technology risk and safety perceptions • Dedicated infrastructure unavailable • Costs of vehicles
• Fuel cells are flexible and scalable • Seasonal storage of energy • Longer term: replacing natural gas with hydrogen for power generation	• Technology unpreparedness and scale of required investment • Lack of hydrogen delivery network • Current price of hydrogen
• Decarbonization of heat • Possibility of flexible scale-up in output and infrastructure • Enabling other hydrogen applications by contributing to reduction in the cost of hydrogen	• Possible retrofitting of appliances • Backing from governments is essential • Need for cost-effective green hydrogen and CCS at scale for blue hydrogen
• Existing hydrogen expertise and infrastructure • Large scale green hydrogen production could boost other sectors	• Absence of market for green products • Significant CAPEX commitments • Large amounts of new dedicated renewables required to produce green hydrogen via electrolysis

1. Deep reductions in greenhouse gas emissions from the generation of industrial process heat
2. Increase the temperature of space in buildings or industrial processes
3. Household grid

Source: IRENA, Hydrogen Council 2021

1…with specific use cases likely to be most economically feasible by 2030…

Competitiveness of use cases against conventional and other low-carbon alternatives globally



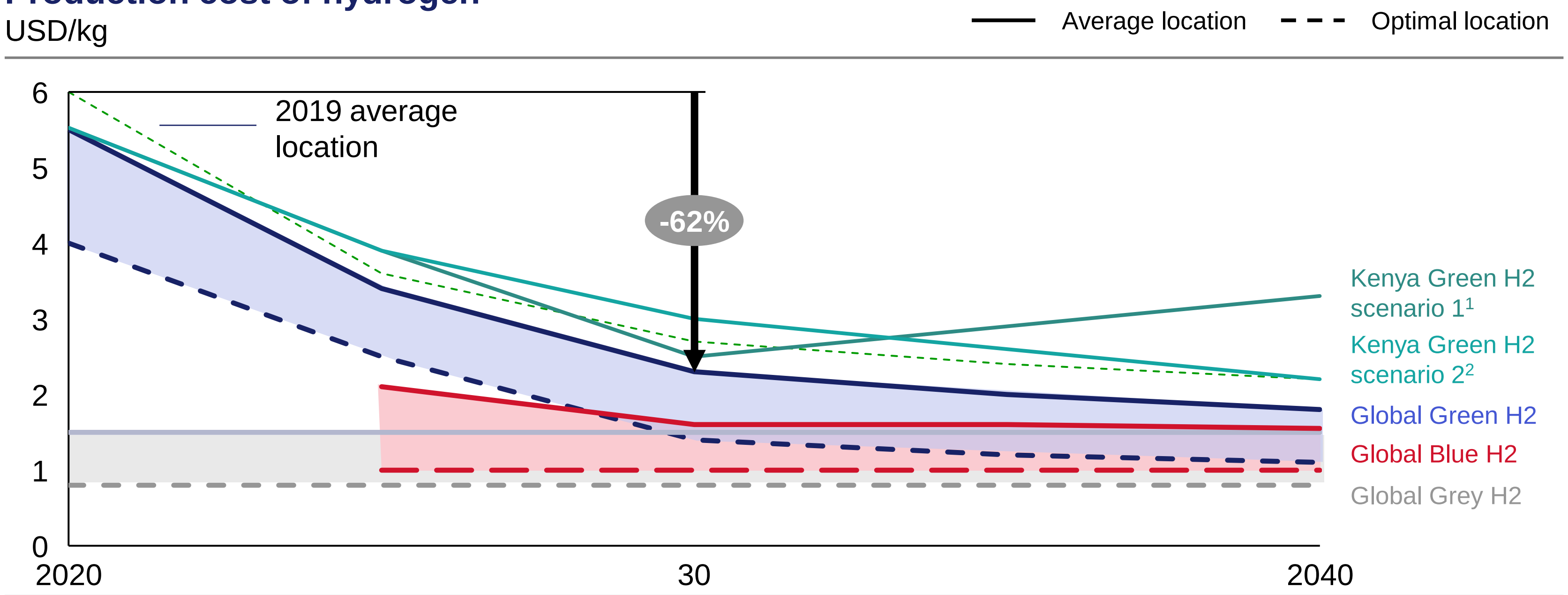
1. Clean hydrogen is the only alternative
2. Carbon breakeven cost represents average cost over lifetime of asset
3. Biofuel is a complementary solution to hydrogen/ synfuels particular used in heavy to decarbonize sectors such as shipping and aviation; usage will be subject to supply constraints
4. Ferries designed to transport vehicles, cargo, and passengers

Source: Hydrogen Council

1. …assuming a falling cost of hydrogen driven by large-scale investments

Production cost of hydrogen

USD/kg



Global Green hydrogen

- Dedicated renewable/electrolyzer system
- Fully flexible production
- Scale up of renewable hydrogen production
- Additional costs to reach end supply price

Key assumptions: Gas price 2.6-6.8 USD/MMBtu; LCOE USD/MWh 25-73 (2020), 13-37 (2030) and 7-25 (2050)

Global Blue hydrogen

- Development of CO2 pipelines and at-scale sites
- Scale-up of low-carbon hydrogen production
- Scale-up of CCS outside of hydrogen production

Kenya green hydrogen (scenarios 1 and 2)

- Scenario 1: Assumes hydrogen costs decline by 2030, and then increase slightly, using green H2 cost from GIZ's report Baseline Study on the Potential for Power-to-X in Kenya, 2022
- Scenario 2: Assumes hydrogen costs decline over time to 2040, by using green H2 costs from GIZ's report for 2025 and applying decline rate of estimated global costs from Hydrogen Council report

Globally, green hydrogen could break-even with grey hydrogen by 2030 in optimal regions

Reaching this cost-curve for green hydrogen assumes **significant global investments in electrolyzer capacity**, which brings down the cost of electroyzers. It also assumes **reduced renewable energy costs over time** as well as increased utilization of electrolyzers as demand increases

The Kenya **projected hydrogen production costs are somewhat higher than global projections, suggesting that the economic feasibility of many domestic use cases might be challenging**, particularly given that the break-even point for some large use cases like fertilizer are already on the borderline of the low-end of the global cost projections

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1. Uses cost of green H2 from 2025-2040 from GIZ's report Baseline Study on the Potential for Power-to-X in Kenya, 2022
2. Uses GIZ's costs of green H2 for 2025 from GIZ's report, Baseline Study on the Potential for Power-to-X in Kenya, 2022, and then applied the expected costs reduction to 2030-2040 based on global green H2 cost estimates from Hydrogen Council, Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, 2022

Source: : Hydrogen Council, Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, 2021; GIZ's report, Baseline Study on the Potential for Power-to-X in Kenya, 2022

1. For Kenya, we tested each global use case for technical feasibility and sized theoretical demand

We used 3 criteria to assess technical feasibility for use cases by 2040

Is the **sector itself large-enough in Kenya** for this use case in Kenya by 2040?

Is **green H2 likely to be the winning fuel technology** (e.g. instead of electricity)?

Will the **technology to enable adoption for this use case be available** by 2040 (e.g. cement kilns that can use hydrogen)?

We estimated potential demand based on industry-specific factors for each use case with 2 scenarios

Lower bound: Assumes an ambitious scenario of adopting green hydrogen by 2040, but focused more on market evolution and “low-hanging fruit” with government policy support

Upper bound: Assumes a highly ambitious scenario of adopting green hydrogen by 2040, with more aggressive government policies incentivizing purchase of green hydrogen-based products

Specific assumptions in each scenario vary by use case (described for each use case later on)

We identified 7 technically feasible use cases for Kenya:

- Heavy duty transport
- Aviation
- Stationary power
- Green ammonia & fertilizer
- Decarbonized steel
- Industrial heating
- Trains

Technical potential demand for Kenya (excl. exports) could be ~**140-390k MT green H2** annually by 2040

1. In Kenya, there are 7 technically feasible use cases: heavy duty transport, trains, aviation, power, industrial heating, fertilizer, and steel (1/2)

Technical feasibility assessment for demand use cases in Kenya

			Feasibility criteria					
Sector	**Use case**	**Application**	Is the **sector itself large-enough** for this use case in Kenya by 2040?	Is **green H2 likely to be the winning fuel technology** (e.g. instead of electricity)?	Will the **technology to enable adoption for this use case be available** by 2040?	**Techni-cally feasible in 2040?**	**Export potential?[1]**	**Rationale**
Tran-sport	Heavy duty transport	Replace diesel/petrol with green H2 via green H2 fuel cell	✓	✓	✓	✓		Long distance trucking less feasibility for electrification due to charging requirements; although EVs still being explored. **H2 could therefore be feasible heavy-duty trucks (HDT)** and medium-duty trucks (MDT); however, MDT more likely to transition to EV, hence we focus primarily on HDT
	Trains	Replace diesel with green H2 via green H2 fuel cell	✓	✓	✓	✓		Technically feasible to transition Kenyan train lines; **less likelihood of using renewable electricity** for SGR line due to **lack of costly catenary lines**
	Aviation	Replace fuel with either: • Power-to-liquid (PtL) synthetic aviation fuels (carbon and green H2) • New propulsion technologies (e.g., H2 fuel cell)	✓	✓	✓	✓		**PtL:** Potential by 2040, since technology available now; however, requires sustainable source of carbon in order to meet sustainability requirements (e.g. in Europe) which would need to be confirmed from one of the following: • Direct air capture (DAC) - technology is expensive and not at scale yet • Biogenic sources - require biogas plants which are very small-scale in Kenya • Industrial waste (e.g., geothermal production). could be used but would not be considered carbon neutral • New propulsion technologies: Potential based on technology for the new aircraft becoming available until ~2035

1. In Kenya, there are 7 technically feasible use cases: heavy duty transport, trains, aviation, power, industrial heating, fertilizer, and steel (2/2)

Technical feasibility assessment for demand use cases in Kenya

			Feasibility criteria					
Sector	**Use case**	**Application**	Is the **sector itself large-enough** for this use case in Kenya by 2040?	Is **green H2 likely to be the winning fuel technology** (e.g. instead of electricity)?	Will the **technology to enable adoption for this use case be available** by 2040?	**Techni-cally feasible in 2040?**	**Export potential?**[1]	**Rationale**
Power generation	Stationary power	Replace natural gas in gas turbines with green H2 and consider potential to retrofit HFO plants to green H2 plants	✓	✓	✓	✓		Potential to use green hydrogen for **power** substituting HFO and gas in thermal plants**.** Potential to convert gas turbines – constituting 56 MWh of Kenya's energy demand - to green H2, and retrofit HFO plants constituting 588 MWh of Kenya's energy demand to green H2 We assume that Kenya will continue to require thermal-equivalent plants in 2040 for grid stability
Heating	Industrial heating	Replace fossil fuels used for high grade heating	✓	✓	✓	✓		Potential to use in **sectors requiring high-grade heating** e.g., cement, aluminum. Cement is feasible but can only replace 2-20% of fossil fuels with green hydrogen
Industry	Ammonia/ fertilizer	Green ammonia and green fertilizer	✓	✓	✓	✓	✓	Potential to **substitute imports with production of green ammonia and green fertilizer** in Kenya
	Decarbonized steel	Use as a reductant in upstream processing or as a replacement for fossil fuels along the value chain (e.g., reheating)	✓	✓	✓	✓		Potential to use green H2 in 2 ways in Kenya: • As a **reductant for the DRI-EAF plant** for 1 plant doing upstream processing • As a **replacement for fossil fuels in heating** for remaining plants doing downstream processing only

1. In Kenya, use cases that may not be technically feasible include passenger or commercial vehicles, maritime, and building heating

Technical feasibility assessment for demand use cases in Kenya

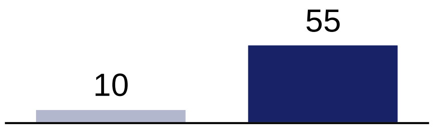
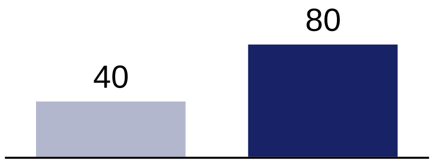
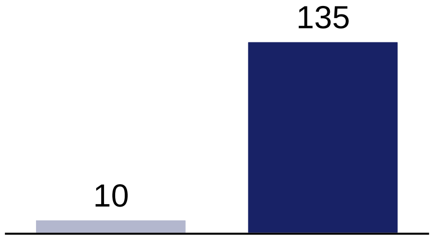
			Feasibility criteria					
Sector	**Use case**	**Application**	Is the **sector itself large-enough** for this use case in Kenya by 2040?	Is **green H2 likely to be the winning fuel technology** (e.g. instead of electricity)?	Will the **technology to enable adoption for this use case be available** by 2040?	**Techni-cally feasible in 2040?**	**Export potential?**[1]	**Rationale**
Transport	Passenger cars	Replace diesel/petrol with green H2 via green H2 fuel cell	✓	✗				**Electric vehicles are the winning technology globally** (few OEMs continuing to manufacture hydrogen fuel cell cars and government regulation driving EV adoption). High availability of renewable electricity in Kenya favors EV adoption as well
	Commercial fleet	Replace diesel/petrol with green H2	✓	✗				
	Buses	Replace diesel/petrol with green H2	✓	✗				
	Maritime applications	Replace diesel/petrol with pure green H2 or green ammonia	✗				✓	**Low demand for refueling ships in Kenya**, at only ~0.1% of total petroleum products consumed in Kenya. Ships tend to travel long-distances before needing to refuel and typically refuel at major ports (e.g. Rotterdam, Singapore) versus secondary ports such as those in Kenya **Potential to consider for export to those ports**
Power generation	Portable power	Replace diesel in portable generators with green H2 fuel cells	✓	✗				**Conversion of off-grid stations to full solar likely used ahead of green hydrogen** due to relatively small-size of the off-grid stations (<1% of all power generated) and plans to explore solar already
Heating	Residential & building heating	Residential & building heating	✗					There is **limited building heating in Kenya** due to warm temperatures

1. The potential demand for technically feasible use cases could be ~140-390k MT of green H2 in 2040 (1/2)

Estimated potential demand for green H2 in technically feasible use cases in Kenya

PRELIMINARY

■ Upper bound □ Lower bound

Sector	**Use case**	**Potential demand[1] in 2040,** 000’ MT green H2	**Rationale**
Transport	Heavy duty transport		**Lower bound:** Technical potential to **transition ~1,500 heavy duty trucks** to green H2 fuel cells by 2040, assuming that **~10% of sales** are green H2 trucks by 2040 (based on a 10-year lag compared to global uptake rates) **Upper bound**: Technical potential to **transition ~9,000 heavy duty trucks** to green H2 fuel cells by 2040, assuming that government policies encourage uptake of **~40% of sales** to green H2 trucks by 2040 (same as global uptake estimates) Requires replacing existing trucks with new trucks, that are expected to be on the market in Europe within 5 years, and could enter Kenyan market second hand within 10 years
	Aviation		**Lower bound:** Assumes **5% of all aviation fuel demand** in Kenya in 2040 is converted to PtL, with small proportion of small planes (<50 passengers) converted to hydrogen fuel cells **Upper bound**: Assumes **10% of all aviation fuel demand** in Kenya in 2040 is converted to PtL, with small proportion of small planes (<50 passengers) converted to hydrogen fuel cells For comparison, Europe aims to have ~8% of aviation fuel demand met by synthetic fuels by 2040
Power generation	Stationary power		**Lower bound:** Assumes **gas turbines are transitioned to green H2** by 2040 (constituting 56 MWh of total power consumption in Kenya today) **Upper bound**: Assumes **gas turbines are transitioned to green H2, and existing capacity of today from HFO and diesel plants** (making up 588 MWh of total power consumption today) is retrofitted to use green H2 by 2040

1. This does not include export potential

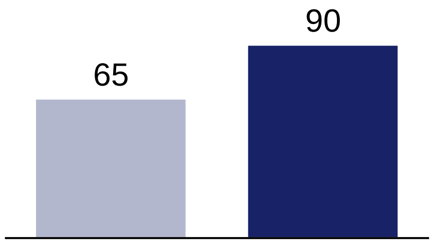
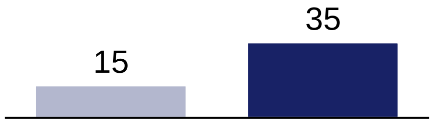
Source McKinsey’s Basic Materials model , Trademap, International Fertilizer Agency, Kenya Bureau of Statistics

1. The potential demand for technically feasible use cases could be ~140-390k MT of green H2 in 2040 (2/2)

Estimated maximum potential demand for green H2 in technically feasible use cases in Kenya

PRELIMINARY

■ Upper bound ■ Lower bound

Sector	**Use case**	**Potential demand in 2040,** 000' MT green H2	**Rationale**
Industry	Green ammonia (fertilizer)		**Lower bound**: Assumes **100% of fertilizer demand in 2040 is substituted for green fertilizer, based on demand projections using 2009-2018 CAGR**, reaching a total demand for nitrogen-based nutrients of ~300,000 MT in 2040. **Upper bound:** Assumes **100% of fertilizer demand in 2040 is substituted for green fertilizer, based on demand projections reaching 50kg/ha Abuja Declaration target**, which results in ~400,000 MT nitrogen-based nutrients. Since 100% of fertilizer is imported today, both scenarios assume replacing all imports with local production which would require setting up the production of ammonia and fertilizer granulation
	De-carbonized steel		**Lower bound**: Assumes that **green hydrogen is used to replace fossil fuels in downstream processing** (e.g., in the reheating furnace) **Upper bound**: Assumes that **green hydrogen is used to replace fossil fuels in downstream processing** (e.g., in the reheating furnace), **and in upstream processing** by replacing natural gas in DRI, and additional DRI plants (assuming 1-2 additional plants are opened, based on government incentives to increase local production)
Total *(excluding trains, industrial heating, other industrial uses e.g., cement, exports)*		~140-390k	

Demand for two technically feasible use cases not sized:

- Trains - assumed to be small demand given only one main train line in Kenya and expense of needing to convert that line to use catenary lines
- Industrial heating given small expected demand (e.g. can only replace 2-20% of fuel in cement) and as-yet unproven technology

1. Exports of green H2 from Kenya could be feasible, but might struggle on cost competitiveness

✓ Feasible ◌ Less feasible

Requirements	Feasibility in Kenya	Rationale
Cost competitiveness of green H2 compared to other countries	◌	**Kenya's production cost of green hydrogen per MT in 2040 is $2,200[1]-3,300[2], higher than the estimated average global cost** of $2,000
Transportation infrastructure for green H2 or renewable electricity from inland to coast	✓	This would **require a pipeline to transport green H2 or investment in a transmission line to transmit renewable electricity from the production site to the coast,** e.g., Mombasa. This is feasible but a pipeline could cost $2.2- 4.5 million per km to build
Deep sea port for exporting via shipping	◌✓	**Green H2 or green ammonia could be shipped in liquid organic hydrogen carriers. It would require landside infrastructure such as liquefaction plant, compressor, electrolyzers, and storage tanks** In order to make infrastructure investments viable, it would require shipments every 2 weeks (or ~700k MT ammonia or 130k ton of hydrogen per year production) Options could include either Mombasa or Lamu ports: • Mombasa port is deep (15m); however, it is congested and therefore would require expansion in order to start exporting additional goods. • Lamu Port is deep (17m); however, may be a longer distance from inland locations and has not yet been fully scaled as a port
Infrastructure for exporting via pipeline (alternative to shipping)	◌✓	Instead of shipping green H2, it can be exported via pipeline which is typically cheaper however requires significant investment to build. A potential pipeline could go from Mombasa to Saudi (which may then have additional pipelines to Europe); this would require agreements with neighboring countries such as Sudan and Ethiopia It is unlikely to be economically viable given investment required and volumes produced in Kenya

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1. Uses GIZ's costs of green H2 for 2025, and then applied the expected costs reduction to 2030-2040 based on global green H2 cost estimates from Hydrogen Council, Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, 2022
2. Uses cost of green H2 from 2025-2040 from GIZ's report Baseline Study on the Potential for Power-to-X in Kenya, 2022

Source: GIZ's report, Baseline study on the potential for power-to-x in Kenya (2022), Hydrogen Council report, Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, 2021 expert interviews

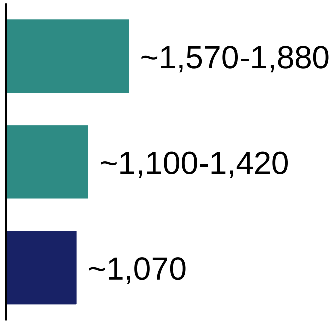
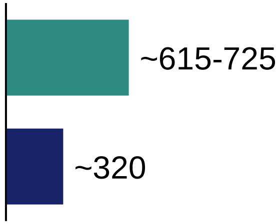
Use cases with potential for export might include green ammonia (i.e., for maritime fuel), PtL fuels, or green urea

The most important factor in estimating export potential is hydrogen production cost. In Kenya, this cost is marginally higher than estimated average global costs, which limits Kenya's competitiveness, particularly when considering likely high logistics costs

Hydrogen can be exported as liquid hydrogen or hydrogen organic compounds or ammonia. It can be exported via shipping or pipeline, both of which could be feasible but would require significant infrastructure investments

2. In Kenya, use cases of green hydrogen are more costly than the conventional alternative

🟩 Green H2 scenario[2] ■ Conventional alternative

Use case	Scope for 2040 use	Cost comparison in 2040, ($)	Rationale
Heavy duty transport	Transition 10-40% of new truck sales by 2040 to green hydrogen trucks	 TCO for green H2 fuel cell truck: ~820,00-900,000 TCO for diesel truck: ~650,000	High costs driven by cost of green hydrogen fuel (~50% of costs), vehicle capex (~21% of costs), and refueling infrastructure costs (~5% of costs),
Aviation	Transition 5-10% of jet fuels to Power-to-Liquid synthetic aviation fuel	 1MT PtL fuel using DAC[1]: ~1,570-1,880 1MT PtL fuel using industrial sources: ~1,100-1,420 1MT jet fuel: ~1,070	Low economic feasibility due to high cost of green hydrogen (~51% of costs) and CO2 from DAC (~30% of costs)
Ammonia/ fertilizer	Transition 100% of fertilizer imports to green urea in 2040	 1 MT of green urea (ex-factory): ~615-725 1 MT of conventional urea (landed cost): ~320	High costs driven mainly by green ammonia (~60% of costs), and CO2 feedstock from DAC (~20% of costs)

We analyzed the economics of 3 use cases – heavy-duty transport, aviation, and fertilizer

In all cases, even with declining hydrogen costs and compared against long-term price projections for conventional fuels, use of hydrogen is more costly than conventional alternatives. Therefore, policy interventions are likely required to bridge this gap

Aviation is closest in economics by 2040 and may be reinforced by blending mandates introduced in other parts of the world (e.g. Europe) that may encourage international airlines to use PtL

Trucking has the next greatest economic feasibility in the timeframe, but this would require **domestic logistics providers to move to hydrogen fuel cell trucks** plus significant investment in refuelling infrastructure and **would increase the cost of logistics without any incentives**

Fertilizer is the least feasible from an economic perspective. While it does have some additional benefits such as reducing imports and creating greater demand security, it may increase the cost of food to use green fertilizer

1. Direct air capture
2. The green H2 range is between using cost of green H2 from 2025-2040 from GIZ’s report, Baseline Study on the Potential for Power-to-X in Kenya, 2022 and using GIZ green H2 cost estimates for 2025 and apply the expected costs reduction to 2030–2040 based on global green H2 cost estimates from Hydrogen Council, Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, 2022

Source: Hydrogen Council, Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, 2021; GIZ’s report, Baseline Study on the Potential for Power-to-X in Kenya, 2022, World Bank, Energy Information Administration (EIA), Energy and petroleum statistics report, 2021

3. While economically challenging, three types of enablers could support adoption of hydrogen in Kenya…

Potential enablers used globally to scale demand of green hydrogen, not-exhaustive

Categories	Options	Relevant to which use case	Benchmark example	Potential implications for Kenya
Financial incentives to bring down costs of green H2 use cases	Tax rebates, exemptions, or credits	✈ 🚚 🫘	In the US, a bill is to be passed that will ensure hydrogen producers get green hydrogen tax credits of up to $3 a kilogram per production	
	Financial support mechanisms such as grants, fund and loans	✈ 🚚 🫘	In 2019, China government provided over $70million to national hydrogen and fuel cell research and development projects	
	Carbon contracts for difference	✈ 🚚 🫘	The German government is setting up the H2 Global initiative featuring a CfD[2] scheme that enables temporary compensation for the difference between the purchase price (production plus transport costs) and the sales price (currently the market price for fossil hydrogen) of renewable hydrogen and derived products	
Financial penalties to increase costs of conventional alternative	CO2 tax (e.g., on jet fuel or diesel)	✈ 🚚	In Canada, British Columbia increased the CO2 tax on diesel from $77 per MT in 2012 to $104 per MT in 2021	Could increase cost of living, such as the cost of food or transportation
	Removal of subsidies reducing costs of conventional alternatives (e.g., for jet fuel and diesel)	✈ 🚚		
Regulatory incentives that could drive adoption of green H2	Blending mandates for aviation fuel	✈	In 2019, Norway placed a 1% SAF[1] (PtL) blending mandate for any aircraft refueling in their territories	Must ensure affordable PtL and relevant infrastructure is in place before mandate is introduced
	Mandates for zero-emission vehicles	🚚	In California, the governor issued an executive order mandating that all new trucks sold by 2035 be zero-emission vehicles	May increase cost of second-hand vehicles in Kenya and put increasing pressure on availability of trucks for transporting goods
	Targets for decarbonization of the economy and national hydrogen strategies or roadmaps	✈ 🚚 🫘	In South America, Chile's Green Hydrogen Strategy from November 2020 sets the goals of producing the cheapest renewable hydrogen in the world by 2030 and becoming one of the three largest hydrogen exporters by 2040	Requires commitment from the government to offer both financial and non-financial support

1. Sustainable aviation fuel
2. Contracts for Differences

Source: Office of Governor Gavin Newsom: California will phase out gasoline-powered cars & drastically reduce demand for fossil fuels in California's fight against climate change, 2020, SKYNRG: 1% SAF MANDATE NORWAY, 2019, Hydrogen Council: policy toolbox for low carbon and renewable hydrogen, 2021, Holland Innovation Network China Bente Verheul: Overview of hydrogen and fuel cell developments in China, 2019, S&P global commodity insights

3. …with two options to consider going forward

The global transition to using cleaner fuel/energy sources such as hydrogen will happen

Investments from major production and demand centres will drive cost reductions for hydrogen production that will make the economics of various use cases more and more feasible

In this context, Kenya has two options going forward…

Option 1: “Lean forward” on H2 production in the next ~10 years

Given costs of production for hydrogen in Kenya plus the costs of other needed factors (e.g. DAC for fertilizer and PtL, infrastructure for fuelling stations and distribution), this would require either:

- significant economic and regulatory incentives to drive economic feasibility and avoid significant cost increases in downstream industries such as agriculture and transportation which would impact consumers; or
- a lower cost of power to drive break-even economics

While there are macroeconomic benefits to reduced import bill and job creation, this needs to be weighed against the expected increased cost to the consumer and cost to government for the needed economic incentives

Option 2: “Wait out” the global trend and re-evaluate

Wait-and-see how the global cost curve evolves as other major production centers make investments, bringing costs down for hydrogen as well as technologies such as DAC

This could allow adoption of production when costs are already lower on the cost curve, meaning the costs to consumers and government likely to be lower

Contents

Executive summary

Deep dives per use case

- **Heavy duty transport**
- Aviation
- Stationary power
- Green ammonia (fertilizer)
- Decarbonized steel

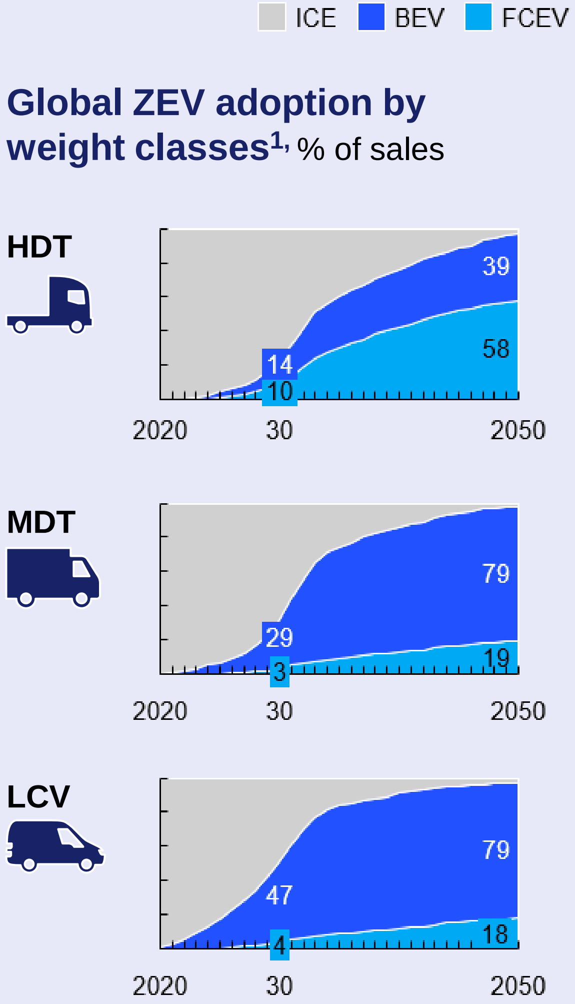
The global trend on zero-emission for trucks is driven by regulation, cost, supply and demand

Main drivers impacting ZEV[3] adoption

Regulation	**EU[2]**	EU[2] regulation mandates -15% and -30% CO$_2$ emissions by 2025 and 2030 respectively
	NAFTA	CARB states target ~30% zero-emission trucks by 2030, and ~100% by 2045 within 15 states
	China	CapEx Subsidies at a regional and national level for FCEVs and BEVs support the adoption of technology
Total cost of ownership (TCO)	**Battery costs**	Battery packs costs declines from ~250$/kWh to ~105$/kWh in 2030 for average eTruck player
	Hydrogen price	Hydrogen price at the pump declines from 10-12$/kg today to 4-5$/kg by 2030
	Powertrain costs	Fuel cell system costs decline more than 50% in the next decade, closing the gap with ICE engine
Supply and demand drivers	**FCEV and BEV supply**	35+ eTrucks model launched in US and EU through 2024; market launches expedited by SPACs in emerging players
	Large fleet investments	More than 10 large fleet operators have announced significant investments/purchases of ZEV trucks, pushing the initial adoption

There is still a debate over whether trucks will electrify or switch to hydrogen – is still unclear which technology will prevail

Global ZEV adoption by weight classes[1], % of sales



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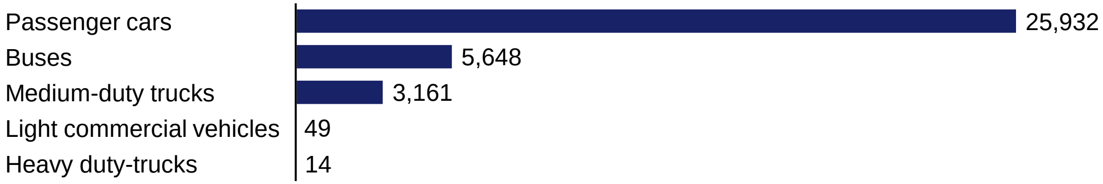
1. Weight class definitions: US: HDT: Class 8 (>15t), MDT: Class 4-7 (6-15t); LCV: Class 1-3 (<6t), excluding pick-up trucks below 3.5t; EU: HDT >16t, MDT: 7.5-16t , LCV: <7.5t; CN: HDT >14t, MDT: 6-14t , LCV: <6t
2. European union
3. Zero Emission Vehicles

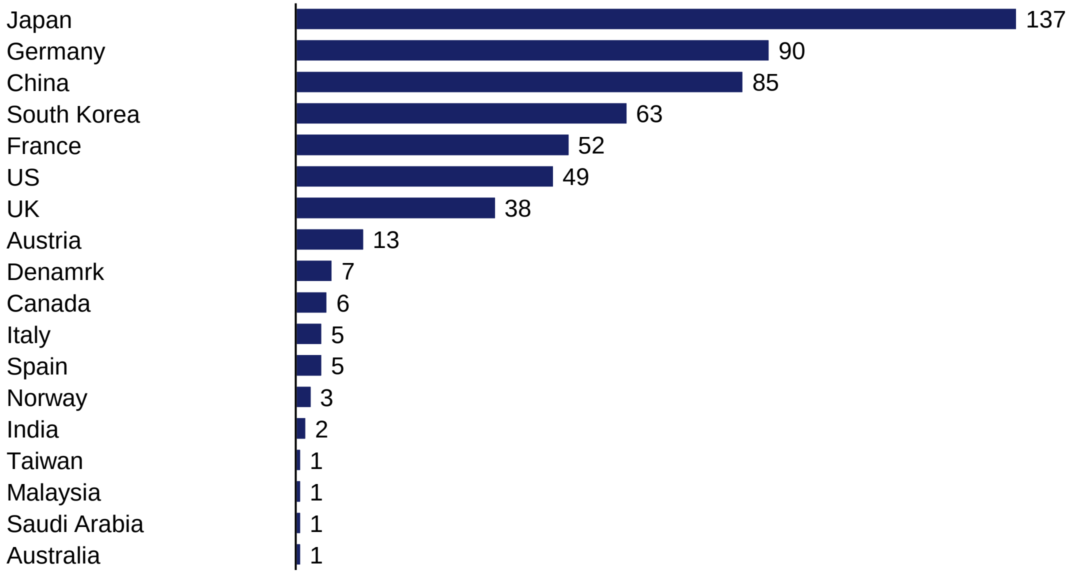
Hydrogen fuel cell technology and infrastructure for trucks is still nascent globally; however, major OEMs are making future commitments

Heavy trucks and hydrogen refueling infrastructure are still nascent

Number of vehicles using green hydrogen fuel cells, globally, 2022



Number of hydrogen refueling stations, end of 2020



Vehicle companies globally are already announcing H2 pilot and large-scale initiatives- expected to be in EU in 5 year's time

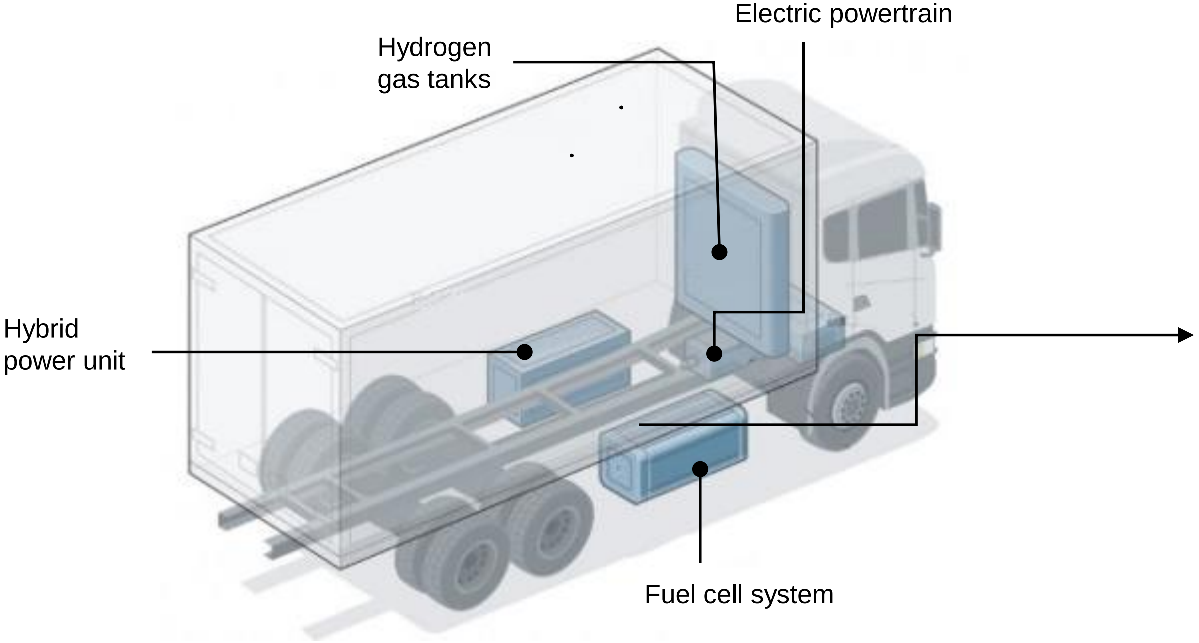
Company	H2 announcements
HYUNDAI	Hyundai Motor North America has reached an agreement with Equilon Enterprises LLC/Shell Hydrogen for a hydrogen refueling infrastructure in California. Referred to as Project Neptune, the partnership will construct 48 additional and two upgraded hydrogen refueling stations across the US beginning in 2021
HYZON	Hyzon Motors Australia has announced plans to build a green hydrogen refueling depot at their regional headquarters in Melbourne
Air Liquide	Air Liquide and IVECO collaborate to accelerate the development of hydrogen heavy-duty mobility in Europe
plug	Plug Power Inc. announced their new hydrogen fuel cell powered van, HYVIA hydrogen Renault Master Van H2-TECH prototype, a vehicle that produces no emissions and is able to provide a range over 300 miles. Renault Master Van is equipped with a 30kW fuel cell engine, based on Plug Power's ProGen technology platform

Source: IKEA Technology Collaboration Programme, Statista

Hydrogen fuel cell trucks have a different drive train from ICE trucks, and require refueling every ~600km

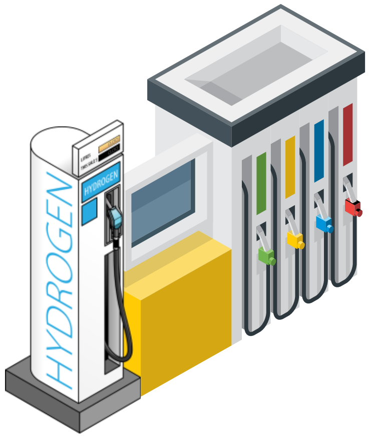
Green hydrogen fuel cell trucks have a different drive train and fuel cell from normal trucks

Components in the hydrogen truck



ICE trucks cannot be retrofitted to become green hydrogen trucks, due to the need for a hydrogen power tank, hydrogen gas tanks, and hydrogen fuel cell system which requires a new drive train. Therefore, they would need to be replaced entirely.

Hydrogen refueling stations are required every ~300km



Hydrogen can be transported to fueling stations either via a pipeline or via trucks

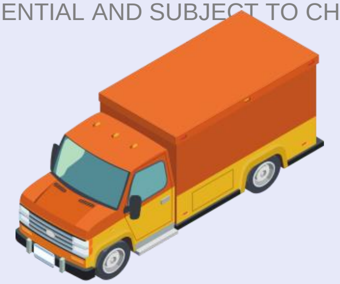
Source: Scania website

FCEVs have an electric powertrain that is "recharged" via a hydrogen fuel-cell

Current technologies are projected to require refueling every 600km

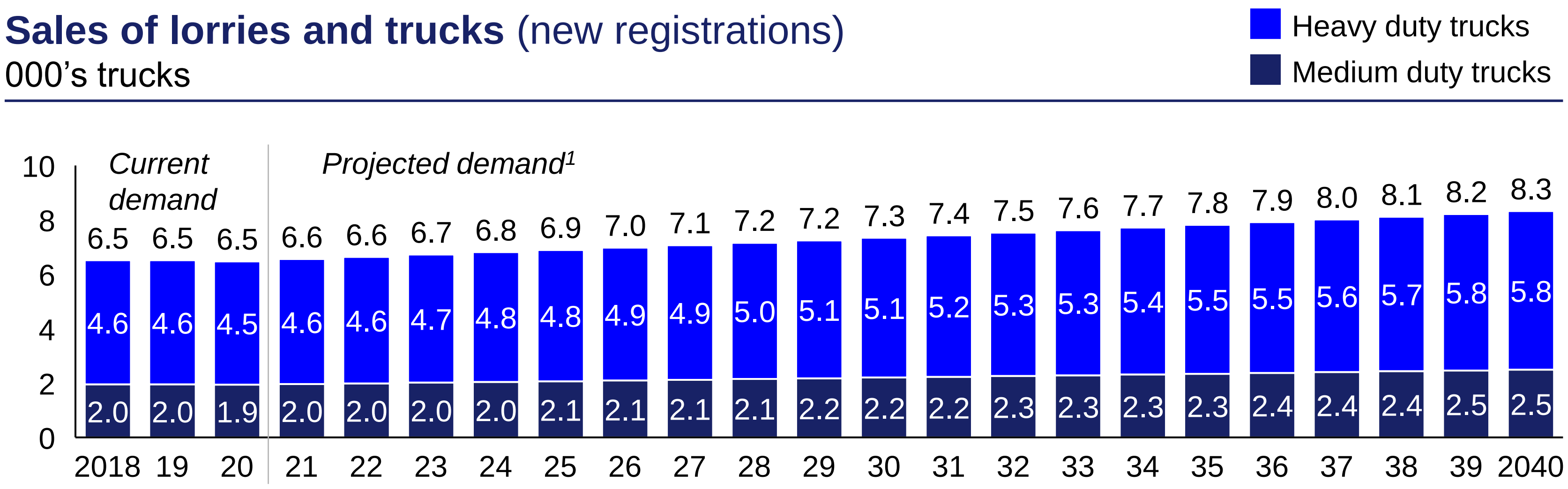
However, technology has not yet been commercialized at scale and electric trucks are still being explored in parallel

Heavy truck sales in Kenya may rise from ~5,000 in 2022 to ~6,000 in 2040 as a result of economic growth



Sales of lorries and trucks (new registrations)

000’s trucks



Vehicle segment	Average vehicle age	Top import destinations	Proportion of imported HDTs
Truck <7.5t	7	Japan	~36%
Truck 7.5t-12t	8	India	~19%
Heavy goods vehicles (HGV)	8	China	~10%

HDT have a higher potential for green H2 than MDT, given MDTs could potentially be run on renewable electricity. Therefore, we focus our analysis on HDTs

In order to transition HDTs to green hydrogen in Kenya, the existing truck fleet would need to be replaced with green hydrogen-powered trucks

Since the majority of trucks today are imported, green H2 trucks in Kenya would likely be imported

Green H2 trucks could be available in 5 years’ time in Europe, and therefore in ~10 years’ time in East Africa

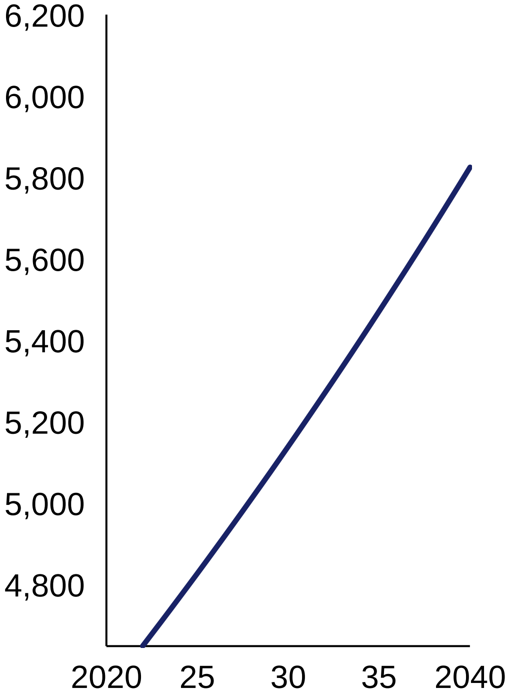
---

1. Estimated based on half of the CAGR from 2010-2020, a conservative estimate, assuming that increase in demand for trucks slows over time. Assumption that HDTs constitute ~70% of lorries and trucks

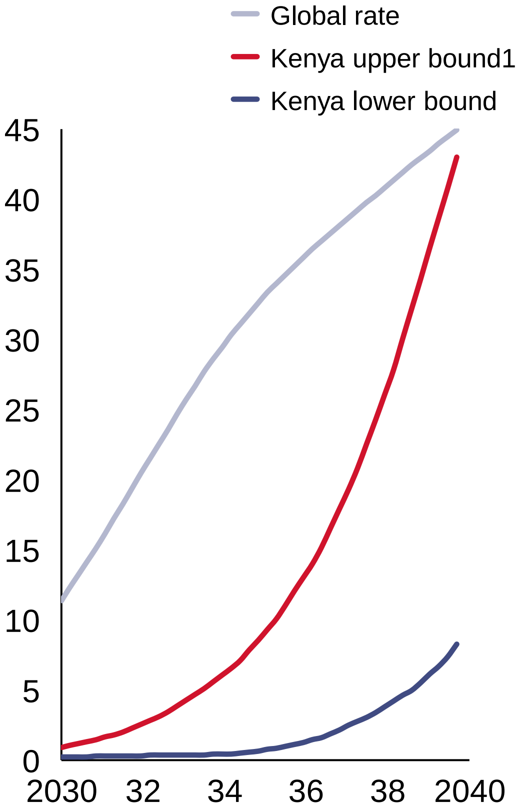
Source: CEIC, Kenya Bureau of Statistics

In Kenya, the number of hydrogen fuel cell HDTs could be ~1,000-9,000 by 2040 depending on scenario

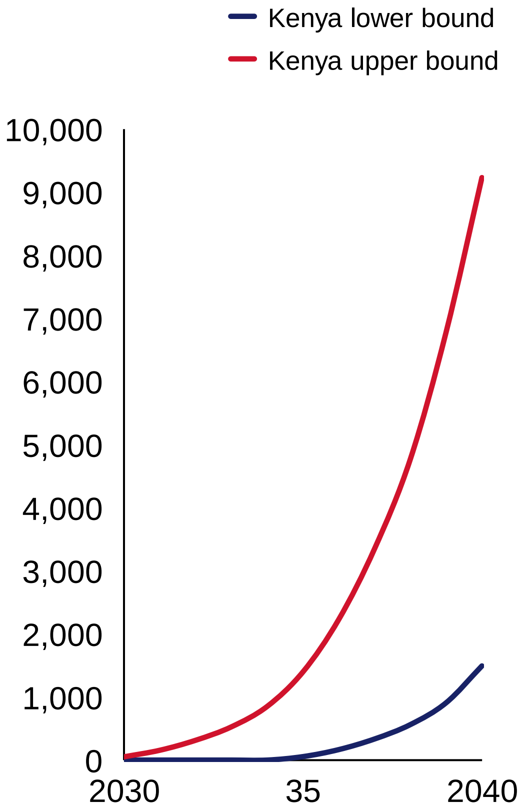
Sales of lorries and trucks
(new registrations)



Adoption curves
(% uptake of new sales)



Estimated green hydrogen truck parc
(No. of trucks)



There are 2 scenarios assumed:

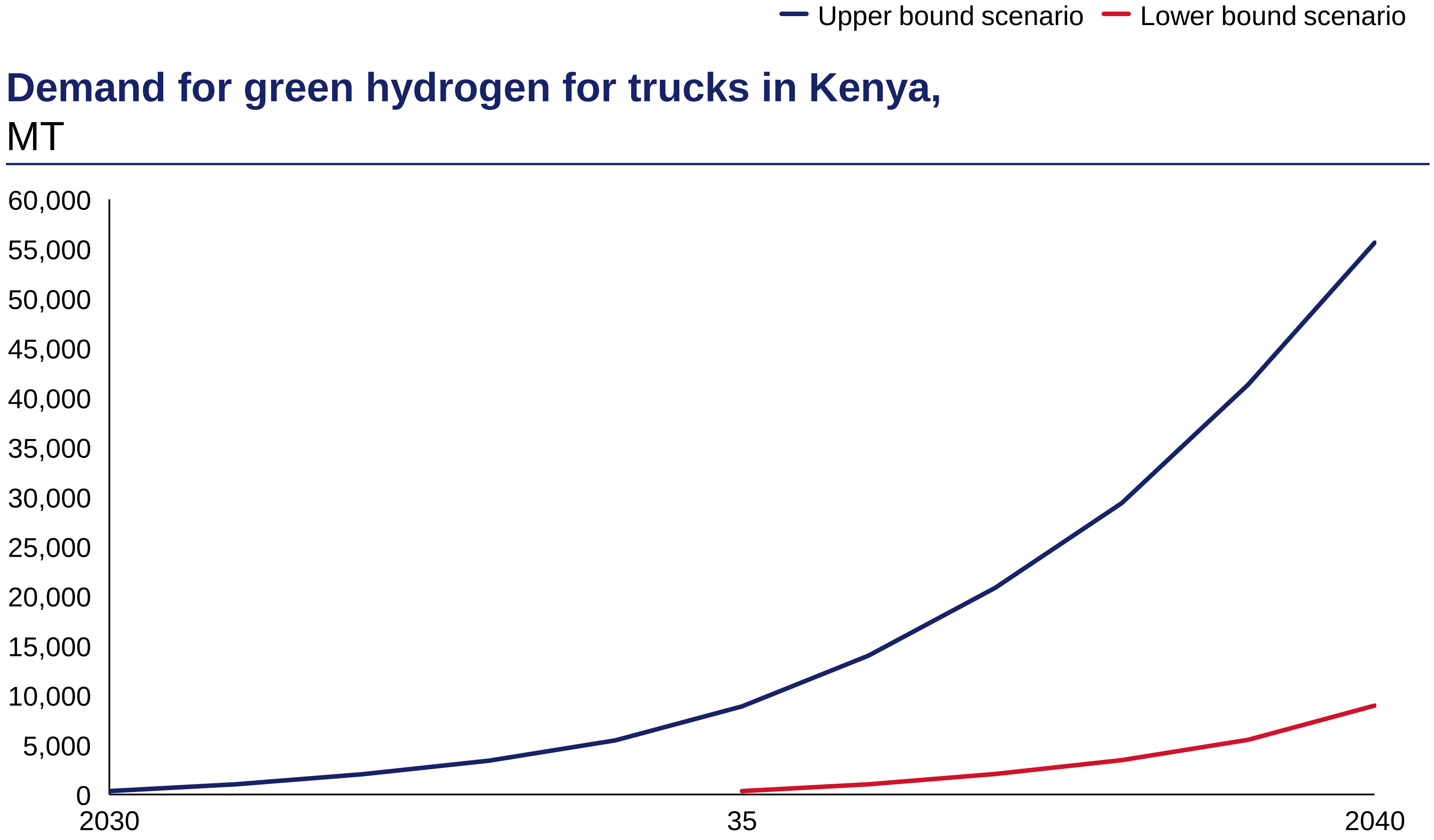
The **lower bound scenario** assumes that **adoption of green H2 trucks may follow a 10-year lag in Kenya** compared to the global projected uptake. This assumes 10% adoption by 2040 (compared to 42% in global scenario)

The **higher bound scenario for Kenya** assumes Kenya follows the global uptake curve, and has 1% adoption by 2030 and 42% adoption by 2040, assuming major policy interventions are introduced encouraging the purchase of green H2 trucks

Source: Kenya Bureau of Statistics, Global Energy Perspective

By 2040, this could result in ~10-55k MT of green hydrogen demand for hydrogen fuel cell HDTs

Demand for green hydrogen for trucks in Kenya,
MT



Source: Global Energy Perspective

This analysis assumes that green hydrogen fuel cell trucks travel 400km per day for 250 days per year, and the amount of green H2 required per km (in kg) is assumed to decrease over time due to efficiencies:

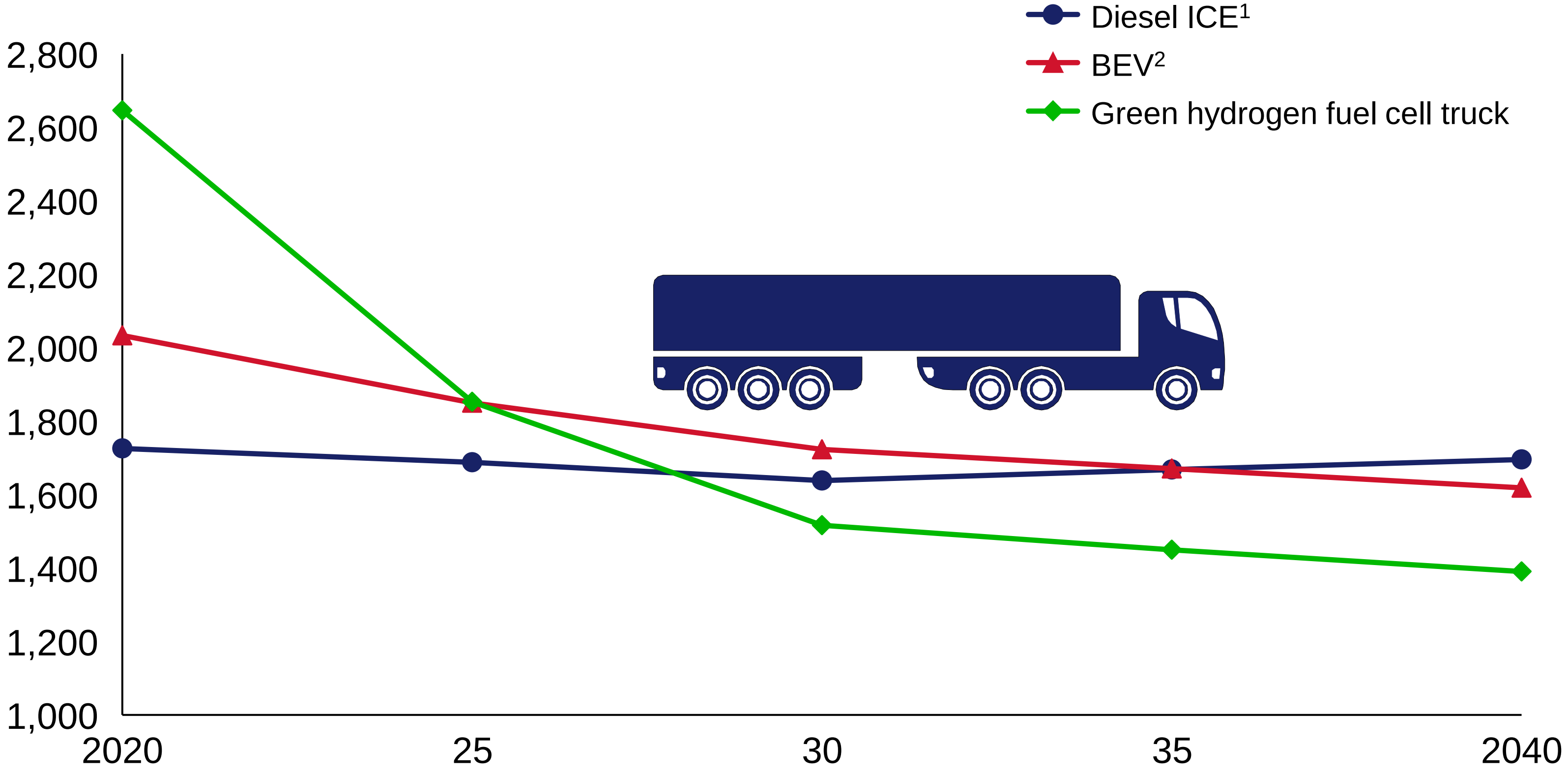
- 2020: 0.08
- 2030: 0.07
- 2040: 0.06

This would necessitate heavy infrastructure development, such as the construction of new hydrogen refueling stations every ~300km

Globally, the TCO for hydrogen fuel cell trucks may be cost competitive with diesel ICE or BEV by 2030

Total cost of ownership of a heavy-duty truck

000' USD



1. Internal combustion engine
2. Battery electric vehicles

Source: Hydrogen Council, Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, 2021

Hydrogen cost is expected to fall as a result of falling capital investment required for the technologies to produce hydrogen, e.g., electrolyzer cost

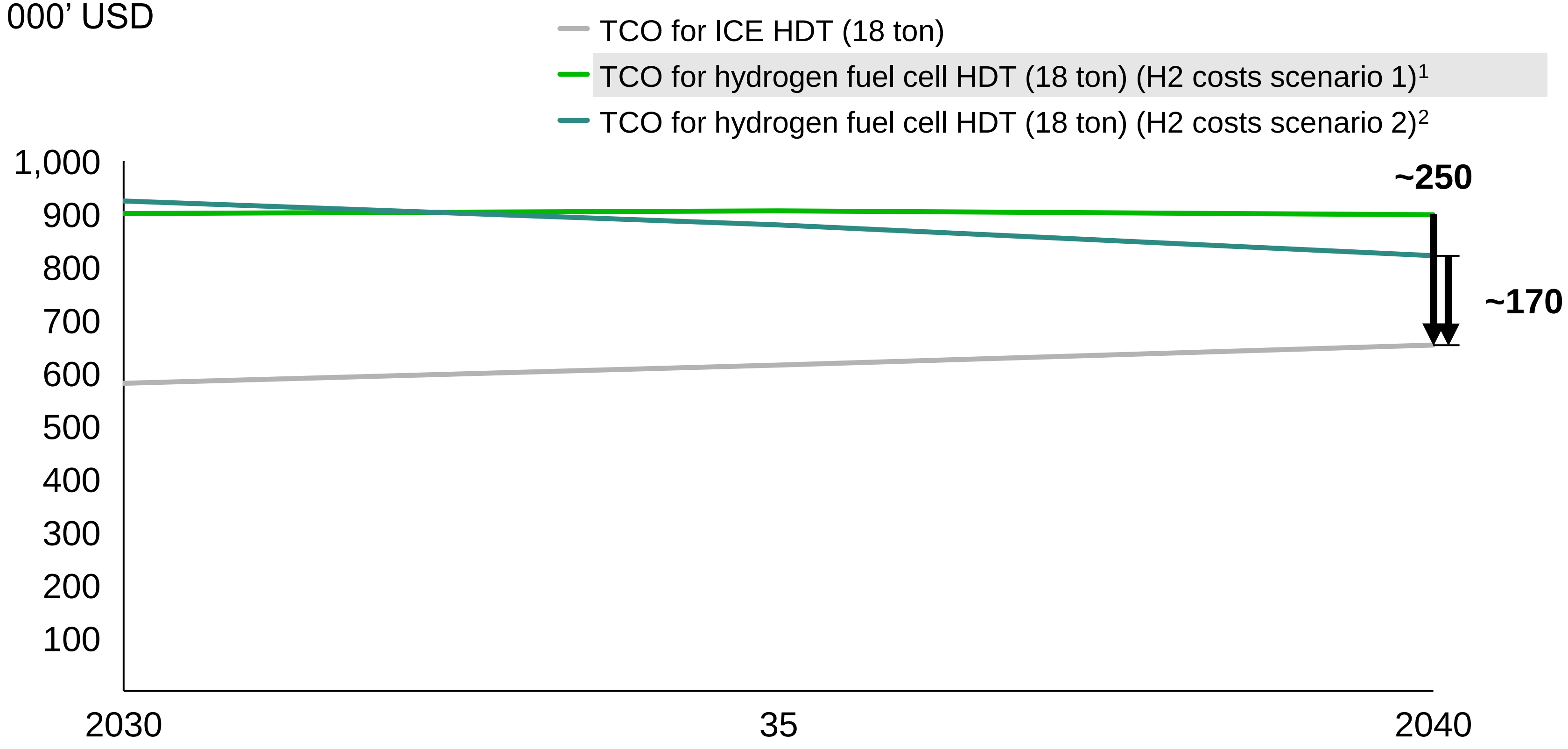
Equipment cost is expected to fall between 2020 and 2022, e.g., powertrain costs

However, in Kenya, the TCO for hydrogen HDTs is higher than for ICE HDTs

▨ Detailed next

Total cost of ownership for used ICE and green hydrogen fuel cell heavy duty trucks in Kenya

000’ USD



[1] Uses cost of CO2 from the GIZ’s report, Baseline Study on the Potential for Power-to-X in Kenya, 2022

[2] Uses GIZ’s costs of green H2 for 2025 from the GIZ’s report, Baseline Study on the Potential for Power-to-X in Kenya, 2022, and then applies a growth rate to 2040 based on global green H2 cost estimates from Hydrogen Council, Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, 2021

Source: Energy and petroleum statistics report, 2021, GIZ’s report, Baseline Study on the Potential for Power-to-X in Kenya, 2022, Hussein Basma, A meta-study of purchase costs for zero-emission trucks, 2022, truck dealers and truck owner interview, Hydrogen Council, Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, 2021; EIA

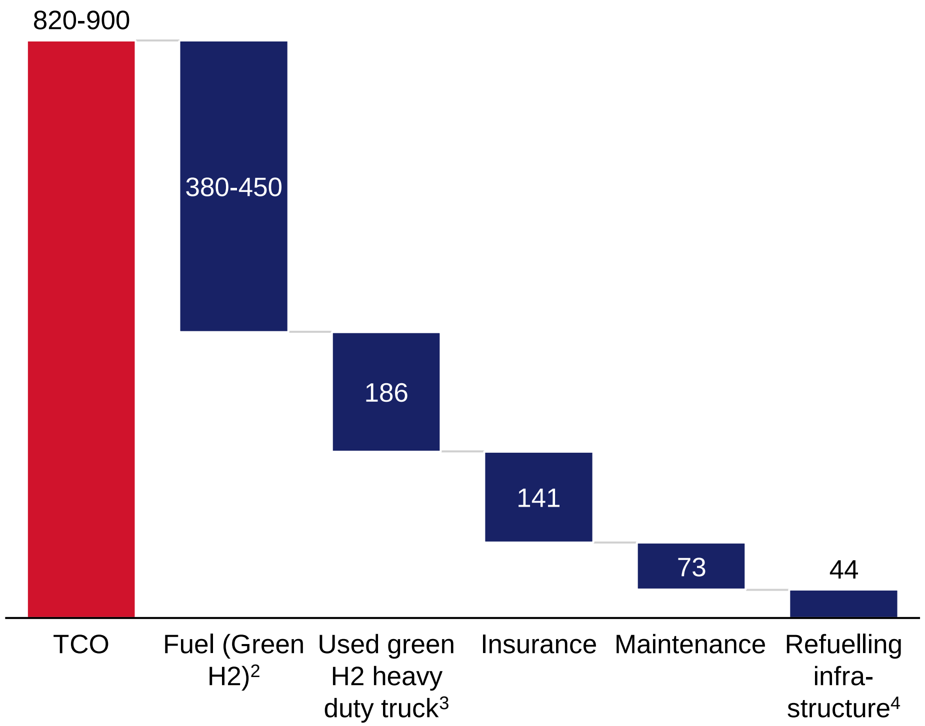
The TCO of a used hydrogen fuel cell truck could be ~USD 250-170,000 more expensive than an ICE (diesel) truck in 2040

We assumed that new green H2 fuel cell trucks would become commercially available around 2025-2027 globally, and that used ones would be available from ~2030, that could be imported to Kenya to replace sales of used ICE trucks

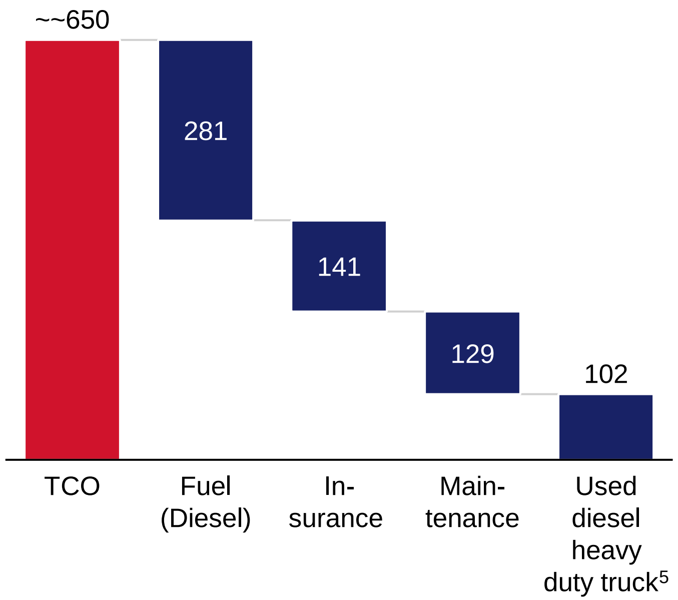
TCO for ICE (diesel) HDT factors in expected forecast for diesel pricing from EIA

Deep dive: TCO for used green hydrogen fuel cell HDT compared to ICE HDT

TCO[1] breakdown for used green hydrogen fuel cell truck, USD, 2040



TCO breakdown for used ICE heavy-duty truck, USD, 2040



The green hydrogen fuel cell truck scenario uses green H2 costs that decline in 2030 and then rise again by 2040 (based on GIZ's report, Baseline Study on the Potential for Power-to-X in Kenya, 2022)

The used ICE heavy-duty truck scenario does not include costs of diesel refueling infrastructure, which is assumed to be fairly minimal given:

- Diesel fueling infrastructure largely depreciated and new infrastructure leverages upon existing infrastructure
- Annual opex split across all ICE vehicles on the road (given diesel infrastructure somewhat shared with gasoline infrastructure)

1.Total cost of ownership
2. This includes green H2 and fuel distribution and compression. The range is between using cost of green H2 from 2025-2040 from GIZ's report, Baseline Study on the Potential for Power-to-X in Kenya, 2022 and using GIZ green H2 cost estimates for 2025 and apply the expected costs reduction to 2030–2040 based on global green H2 cost estimates from Hydrogen Council, Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, 2022
3. This includes the cost of green H2 truck, fuel stack replacement cost, and cost of capital
4. Includes capex, and labor costs and operations & maintenance costs of green hydrogen stations
5. Includes cost of capital

Source: GIZ's report, Baseline Study on the Potential for Power-to-X in Kenya, 2022, expert interview

Contents

Executive summary

Deep dives per use case

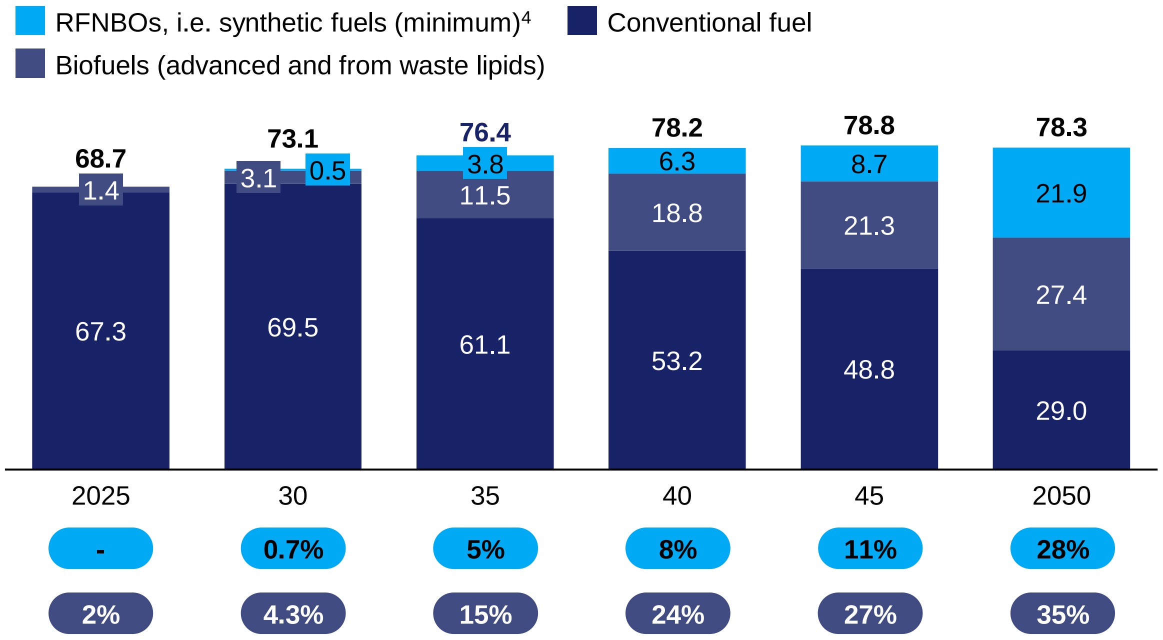
- Heavy duty transport
- **Aviation**
- Stationary power
- Green ammonia (fertilizer)
- Decarbonized steel

Global aviation players are making commitments to using hydrogen-based fuels

In the EU, synthetic fuels could make up ~8% of aviation fuel by 2030 and ~28% by 2050

SAF[1] ramp-up trajectory in the EU[2]

Composition of aviation demand[3] in Mt (in %)



Aviation companies globally are already announcing H2 pilot and large-scale initiatives

Company	H2 announcements
AIRBUS	Airbus announces that green hydrogen is expected to power its future zero-emission aircraft when it reaches the market by 2035
REGOURD AVIATION	The subsidiary of Regourd aviation, Paris-based Amelia, commits to purchasing three Universal Hydrogen conversion kits as the airline seeks to provide travelers with zero emissions solutions for domestic air travel
United Airlines	United aviation invest in zero-emission, hydrogen-electric engines for regional aircraft, the latest move toward achieving its goal to be 100% green by reducing its 100% of its GHG emissions by 2050, without relying on traditional carbon offset
Universal Hydrogen	Universal Hydrogen has signed LOIs with Icelandair Group (Iceland), Air Nostrum (Spain), and Ravn Air (Alaska) for aftermarket conversion of aircraft to hydrogen propulsion and for the supply of green hydrogen fuel using Universal Hydrogen's modular capsule
ZEROAVIA	ZeroAvia signed a memorandum of understanding with hydrogen fuelling firm ZEV Station on Monday to develop refuelling infrastructure for green hydrogen at airports in California in order to achieve zero-emission aviation by using hydrogen-electric power

1. Sustainable Aviation Fuels
2. 104 to 106 additional SAF plants need to be built in the EU by 2050 to cater for the necessary SAF production capacity
3. Aviation demand by region – McKinsey Energy Insights data
4. Renewable Fuels of Non- Biological Origin, this includes hydrogen-based fuels

Source: European Commission website, ReFuelEU Aviation Initiative, Press research

Aircraft can use PtL or new propulsion technologies; both could be feasible for Kenya in 2040

▨ Detailed further

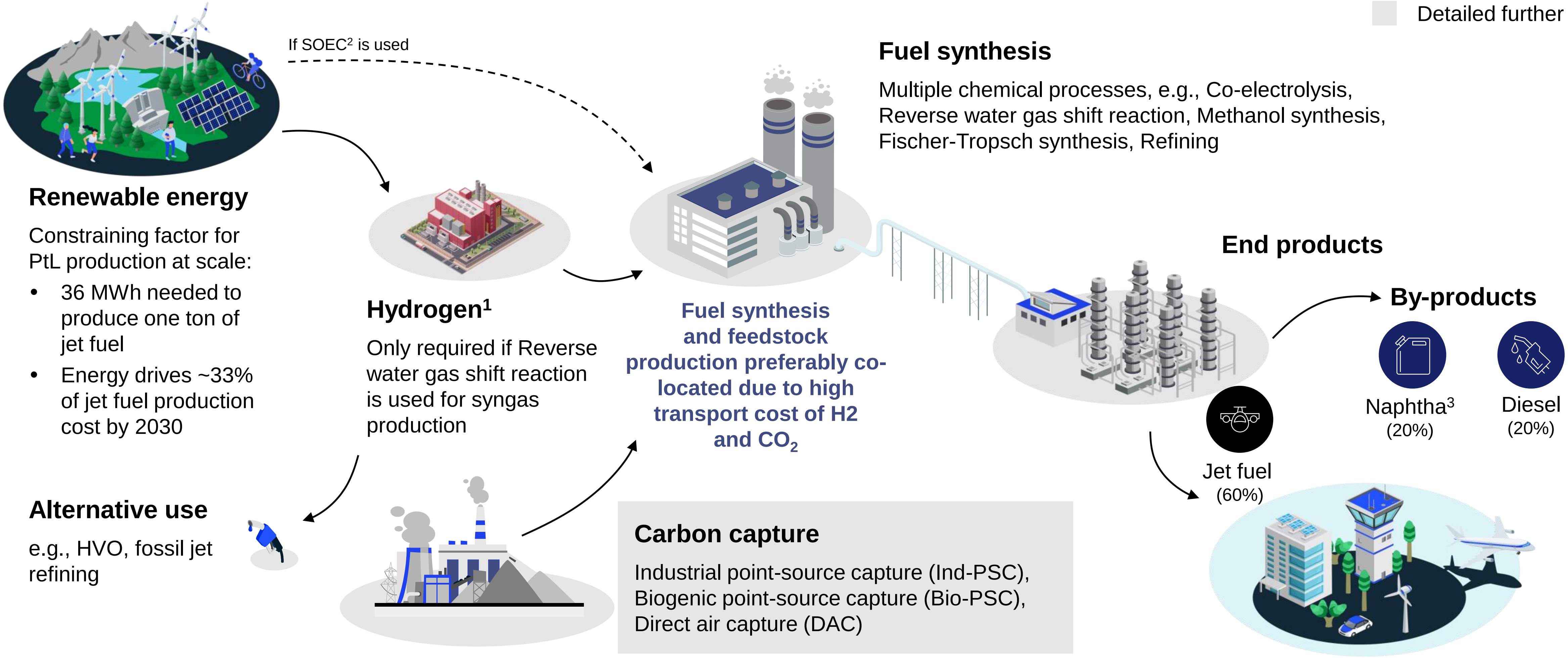
Fuel type	Description	Usage	Timeline	Technical feasibility in Kenya
Power-to-liquid (PtL) fuel	PtL is the combination of electrolysis + catalytic synthesis processes, which involves the electrolysis of water combined with captured CO_2 and synthesized by Fischer-Tropsch reaction into a mix of hydrocarbons The captured CO_2 can be sourced from one of: • Direct Air Capture (DAC) • Biogenic source • Industrial waste CO_2	For short and long-haul flights Can be used in existing aircraft	PtL available within next 5 years, however, requires sustainable source of CO2	✓ If a sustainable source of CO2 is available, then this could be feasible Potential sources of CO2 in Kenya include: • Direct air capture (DAC) – not available at scale until ~2035 and expensive • Industrial waste – potential to use e.g., CO2 from geothermal production; however, not carbon neutral Low potential sources include: • Biogenic sources - requires biogas plants which are only available on a small scale in Kenya
New propulsion technologies (e.g., H_2 fuel cell, turbines)	H2 fuel cell converts hydrogen to electricity to power the electric motor of the aircraft Hydrogen combustion in a turbine powers electric motors	For short-haul flights and small planes only Requires new aircraft, not yet available on the market	Technology for the new aircraft available in 2035 earliest	✓ Earliest availability for newly designed aircraft is ~2035. Technically feasible by 2040 in Kenya for small planes (<50 passengers)

PtL and new propulsion technologies could be feasible by 2040 in Kenya

PtL will be more applicable to more flights in Kenya since this can be used for medium- and long-haul flights, while new propulsion technologies are typically for short-haul only

The PtL value chain is based on renewable energy and recycled carbon, which is upgraded to synthetic fuels

▨ Detailed further



Renewable energy

Constraining factor for PtL production at scale:

- 36 MWh needed to produce one ton of jet fuel
- Energy drives ~33% of jet fuel production cost by 2030

Hydrogen[1]

Only required if Reverse water gas shift reaction is used for syngas production

Alternative use

e.g., HVO, fossil jet refining

Fuel synthesis

Multiple chemical processes, e.g., Co-electrolysis, Reverse water gas shift reaction, Methanol synthesis, Fischer-Tropsch synthesis, Refining

Fuel synthesis and feedstock production preferably co-located due to high transport cost of H2 and CO_2

Carbon capture

Industrial point-source capture (Ind-PSC), Biogenic point-source capture (Bio-PSC), Direct air capture (DAC)

End products

Jet fuel (60%)

By-products

Naphtha[3] (20%)

Diesel (20%)

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1. Blue hydrogen likely required until sufficient renewable energy is available to produce necessary amounts of green hydrogen
2. Solid oxide electrolyzer cell
3. Gasoline or chemical feedstock

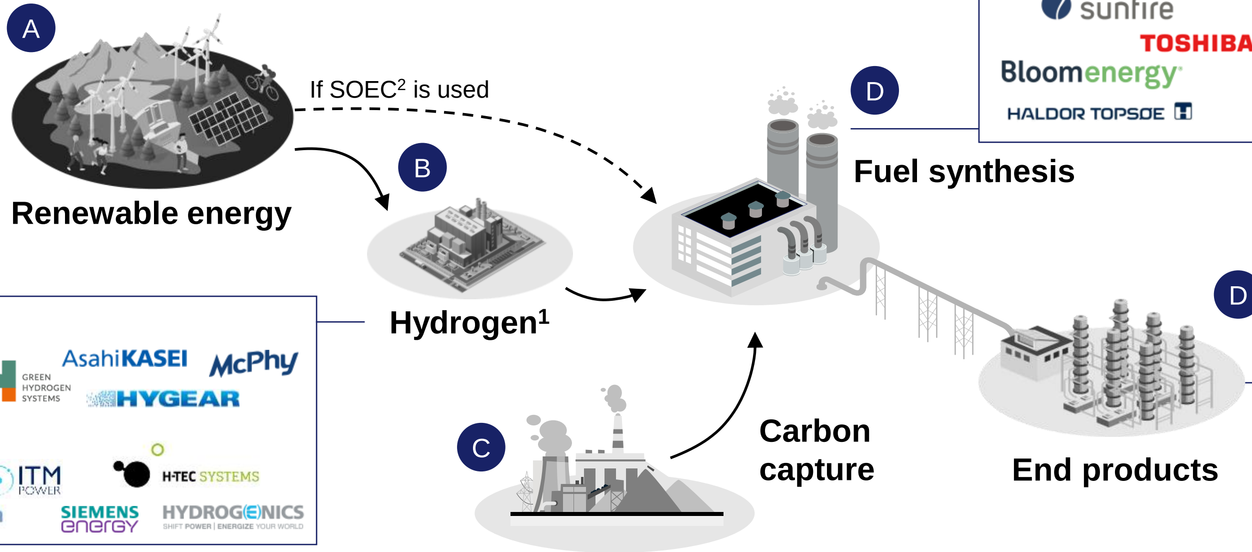
Source: Expert interviews, Web search

The PtL ecosystem is still evolving; new players with more integrated technologies are entering the field

Last update - July 2021

Non-exhaustive

Company deep-dives in backup



- ENGIE
- ENERTRAG
- Ørsted
- enel

AWE

- thyssenkrupp
- Green Hydrogen Systems
- AsahiKASEI
- McPhy
- HYGEAR

PEM

- nel
- ITM Power
- H-TEC SYSTEMS
- AREVA H₂Gen
- SIEMENS energy
- HYDROGENICS SHIFT POWER | ENERGIZE YOUR WORLD

Co-electrolysis

- sunfire
- TOSHIBA
- Bloomenergy
- HALDOR TOPSOE

Fischer-Tropsch

- INERATEC
- JM Johnson Matthey Inspiring science, enhancing life
- sasol
- RED ROCK BIOFUELS
- VELOCYS

CCU sources

- CEMEX
- TATA
- LafargeHolcim

CCU technology providers

- carbon clean
- MITSUBISHI
- AKER CARBON CAPTURE

Bio-CCU

- storaenso

DAC

- CLIMEWORKS
- Carbon Engineering
- global thermostat
- Carbon Collect

End products

- NESTE
- Enerkem
- SkyNRG
- norsk e-fuel
- RAFFINERIE HEIDE
- Synkero

New players with more integrated PtL technologies

- synhelion
- INFINIUM™
- CAPHENIA Turning CO₂ into fuel

Research institutions

- Fraunhofer ISE
- Bauhaus Luftfahrt Neue Wege.
- SRI International
- KIT
- ETH zürich
- The University of Chicago
- Chinese Academy of Sciences
- gti
- imdea
- DLR Deutsches Zentrum für Luft- und Raumfahrt

NGOs

- NOW
- Transport & Environment
- RSB
- ISCC
- aireg

Regulatory

Government, e.g., of Chile/Australia/Saudi (optimal renewable power locations), or Germany (actively developing SAF)

- IATA
- ASTM International

Finance

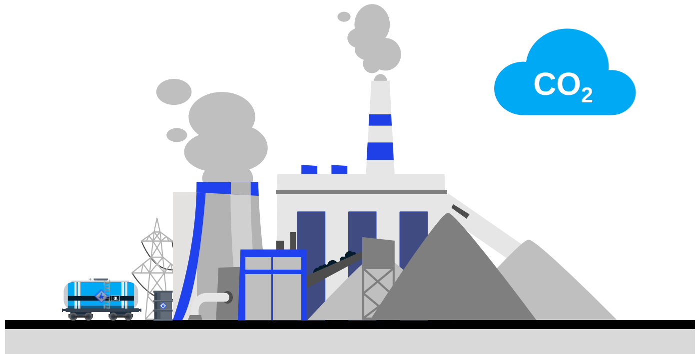
- The World Bank
- European Central Bank
- Quadrature Capital
- Breakthrough Energy
- United Airlines Ventures
- Fly Green Fund

1.Blue hydrogen likely required until sufficient renewable energy is available to produce necessary amounts of green hydrogen

2.Solid oxide electrolyzer cell

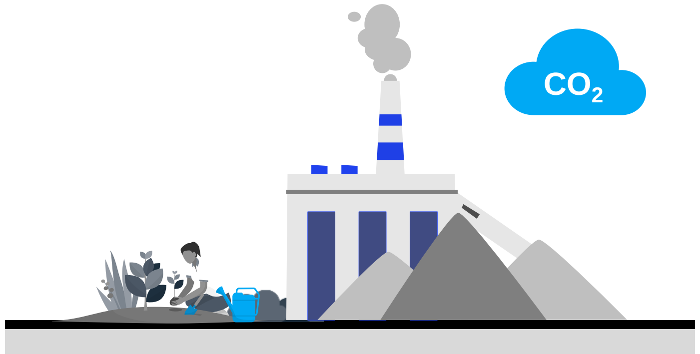
Source: Company websites, Expert interviews, Press releases, Web search

Typically, there are three CO_2 sources used for PtL production



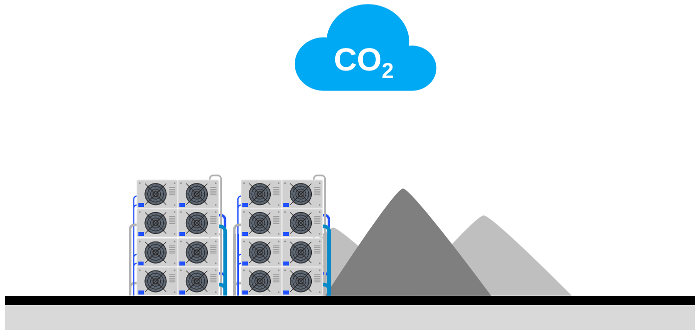
Industrial point-source capture (Ind-PSC)

Capture CO_2 from **industry sources** (e.g., cement, steel, limestone, coal generation plants) and transport it to the synfuel production



Biogenic point-source capture (Bio-PSC)

Capture CO_2 from exhaust gases released during **biomass conversion / biofuel combustion** (e.g., pulp, wood plants) and transport it to the synfuel production



Direct Air Capture (DAC)

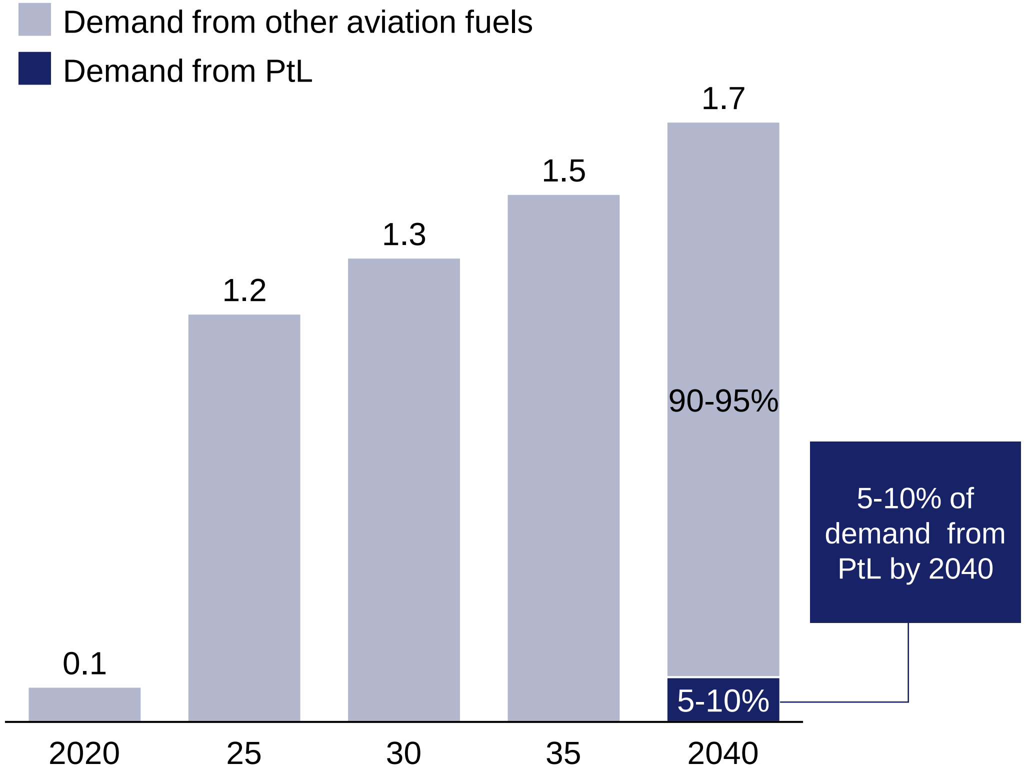
Up and coming technology which captures CO_2 on-site **directly form the air** through either high or low heat processes

Source: IEA (2020), CCUS in Clean Energy Transitions, Web search

In 2040, there could be ~40-80k MT of demand for green hydrogen for aviation in Kenya

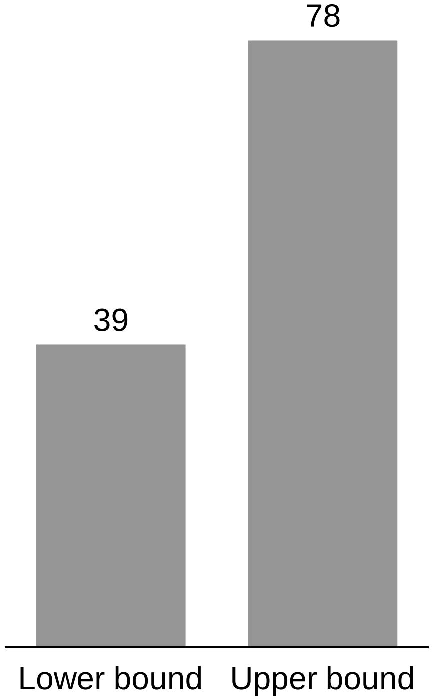
Potential demand for aviation fuel[1]

000’ MT



Potential demand for green hydrogen for fueling aviation using PtL

000’ MT



Assumption that 5-10% of aviation fuel (85-170k MT) demand in 2040 could be met by PtL. Europe is projected to have ~8% of aviation demand in 2040 met by synthetic fuels.

We used a conversion factor of 0.447t H2/MT PtL to estimate the potential demand for green hydrogen

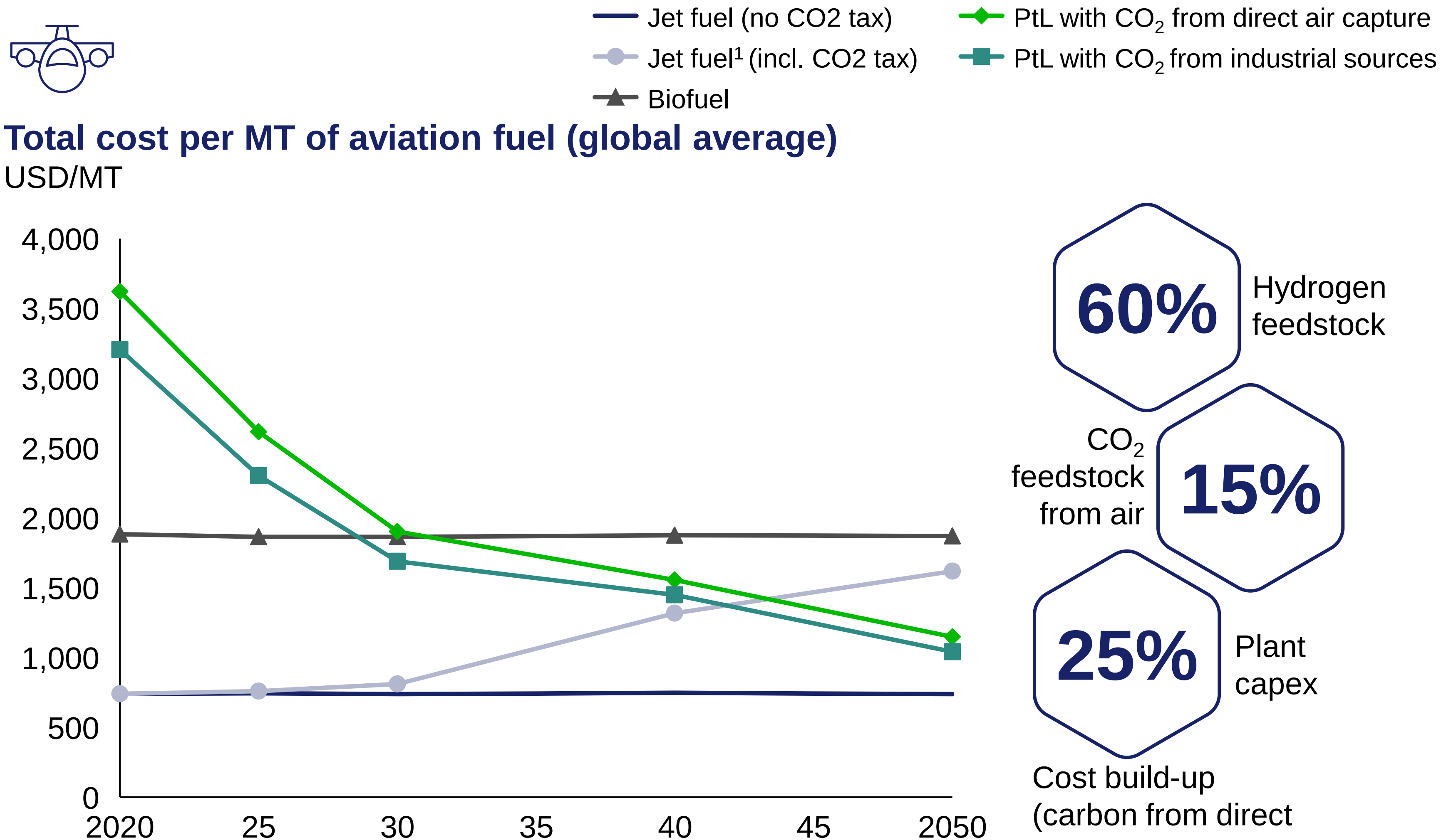
1. This was estimated using projected CAGR for Africa from McKinsey’s Global Energy Perspective 2022

Source: McKinsey Energy Insights Global Energy Perspective 2022

Globally, by 2050 PtL synthetic aviation fuel could be cost competitive with jet fuel and biofuel

Total cost per MT of aviation fuel (global average)

USD/MT



60% Hydrogen feedstock

15% CO_2 feedstock from air

25% Plant capex

Cost build-up (carbon from direct air capture) in 2030

From 2025, hydrogen cost is expected to fall as a result of falling capital investment required for the technologies to produce hydrogen

The cost of sustainable CO_2 is likely to fall from 2030 due to learning curves in higher-cost capital components, and reduction of capital and energy costs

Jet fuel costs could rise based on CO2 taxes

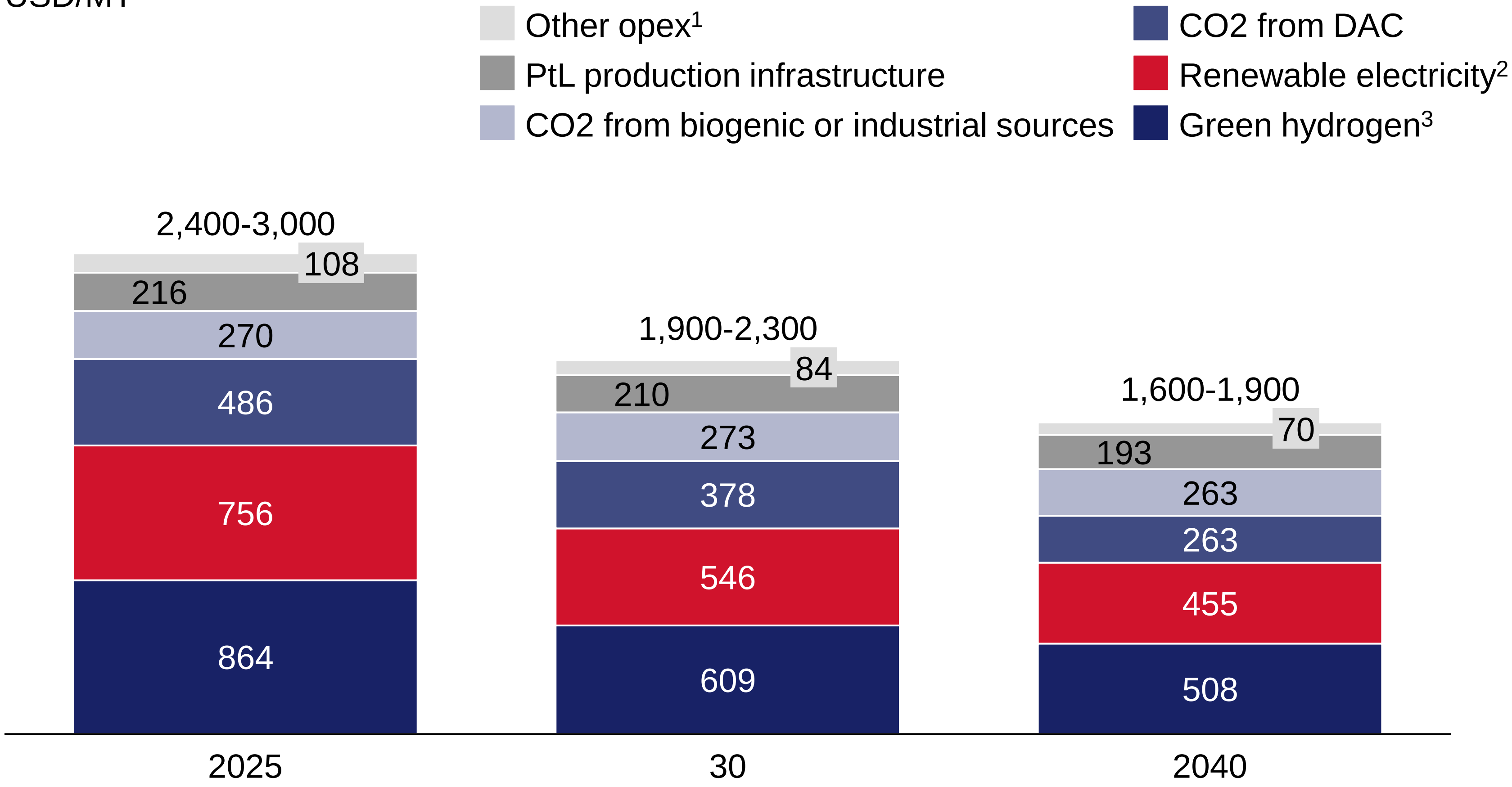
1. It is based on the YOY global growth rate of forecast jet fuel from EIA applied to the global price of standard jet fuel in 2020

Source: Hydrogen Council, Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, 2021, World Economic Forum, Delivering on the global Power-to-Liquid ambition, 2022

In Europe, hydrogen accounts for the highest cost in the production of PtL per MT

Breakdown of cost per MT of PtL synthetic aviation fuel (Europe average)

USD/MT



PtL cost reductions are driven by reduced hydrogen costs, expected reductions in the levelized cost of renewable electricity, and reductions in DAC technology costs due to learning curve

1. Includes utilities (heat) and labor cost
2. Renewable electricity includes the cost of electricity for producing green H2 (the majority of this cost) as well as the cost for producing PtL
3. Green hydrogen includes transportation and distribution cost of hydrogen

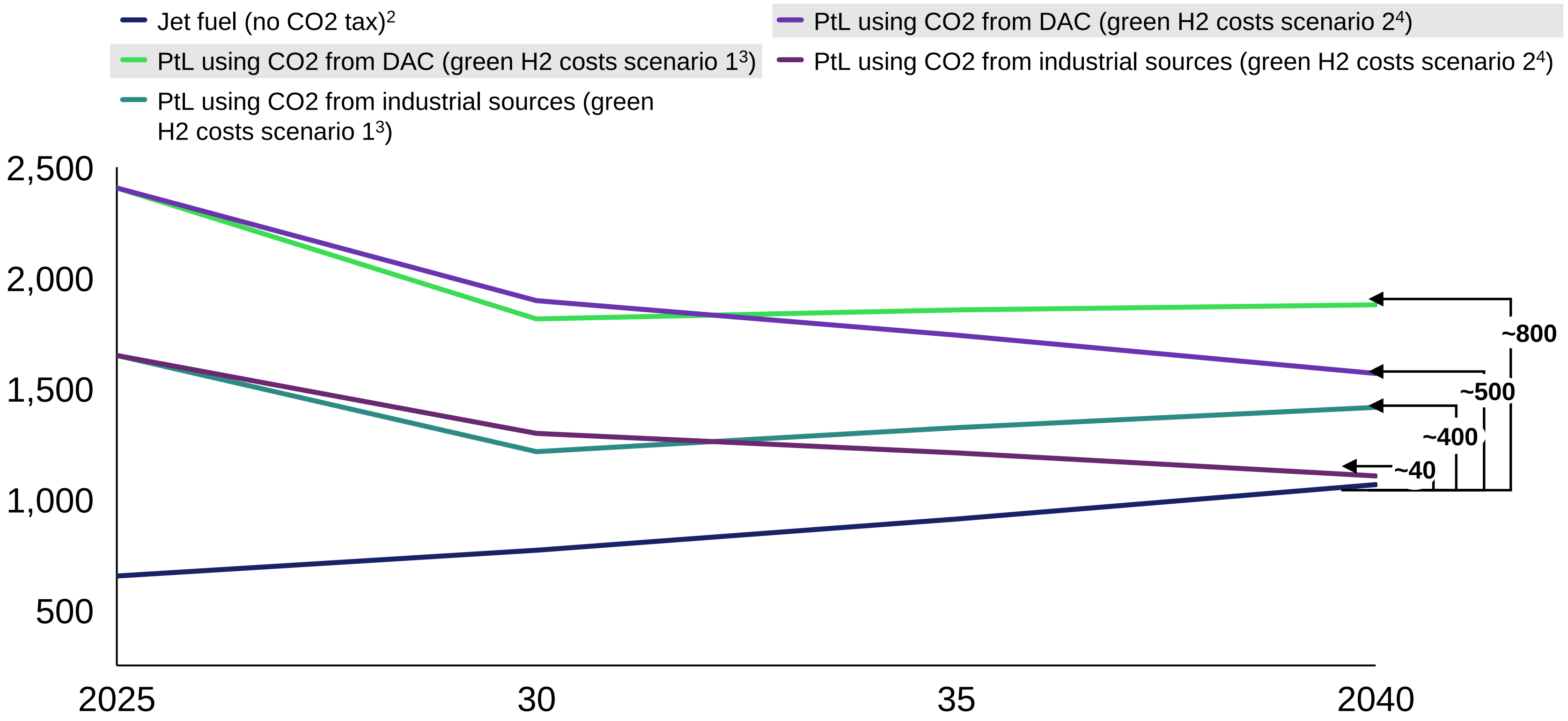
Source: World Economic Forum, Delivering on the global Power-to-Liquid ambition, 2022

In Kenya, cost of PtL per MT may decline by 2040 but is still likely to be more expensive than jet fuel

▨ Detailed next

Total cost per MT of aviation fuel in Kenya[1]

USD/MT



1. For PtL, we calculated Kenya values assuming: Kenya-specific green H2 costs (from GIZ's report Baseline Study on the Potential for Power-to-X in Kenya, 2022), Kenya's renewable electricity cost, European cost of CO2 from direct air capture and industrial sources, and European opex costs
2. Based on EIA global forecast for jet fuel in nominal terms
3. Uses cost of green H2 from 2025-2040 from GIZ's report, Baseline Study on the Potential for Power-to-X in Kenya, 2022
4. Uses GIZ's costs of green H2 for 2025 from GIZ's report, Baseline Study on the Potential for Power-to-X in Kenya, 2022, and then applies the expected costs reduction to 2030-2040 based on global green H2 cost estimates from Hydrogen Council, Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, 2022
5. Costs of other aviation fuels (e.g., HEFA) not shown here

Source: GIZ's report, Baseline Study on the Potential for Power-to-X in Kenya, 2022, World Economic Forum, Delivering on the global Power-to-Liquid ambition, 2022, World Economic Forum, Sustainable aviation fuels feasibility assessment insights, 2022, Hydrogen Council, Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, 2021, Energy Information Administration (EIA), Expert interviews

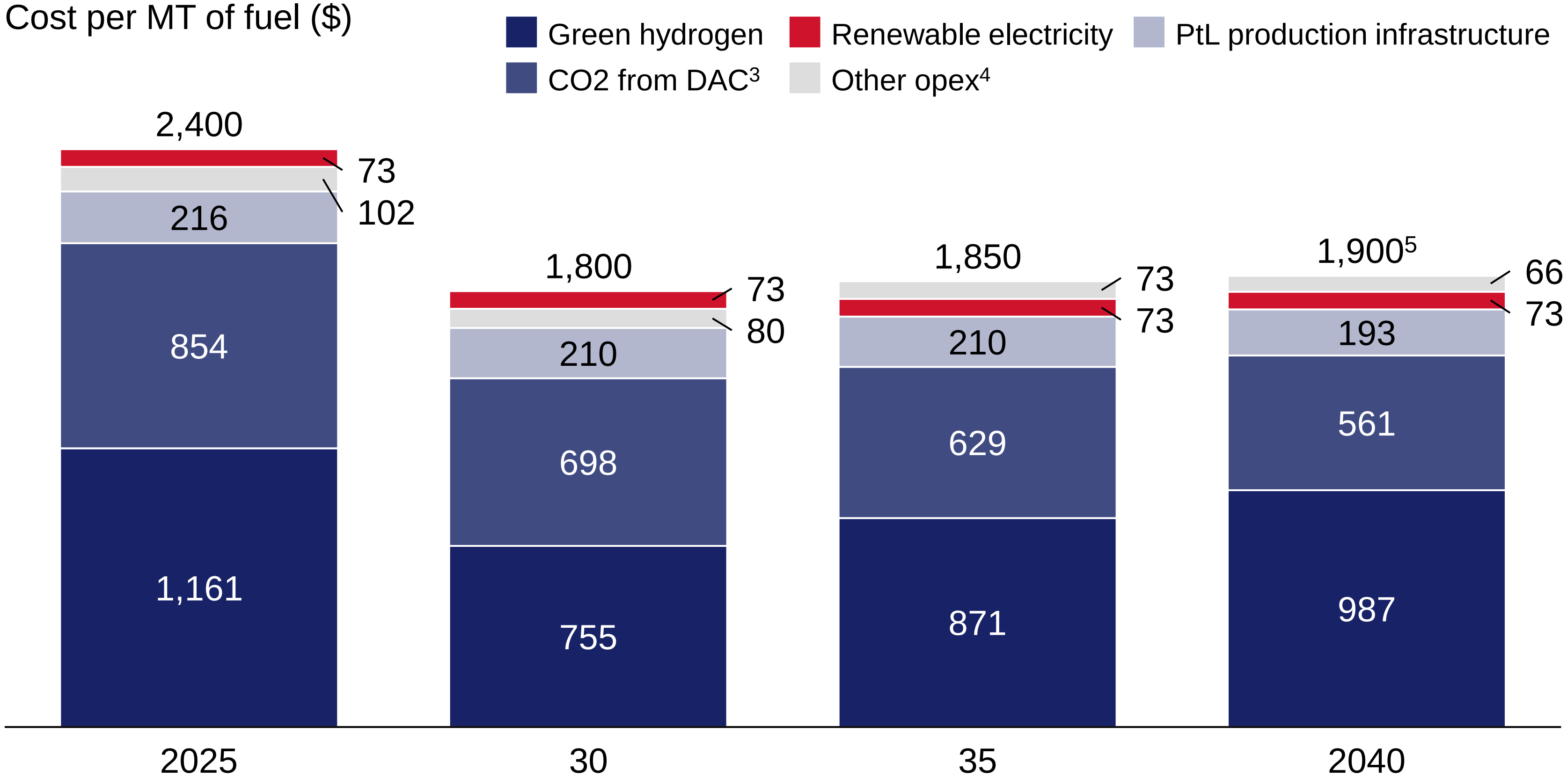
We assumed that by 2040, 5-10% of jet fuel could be converted to PtL, while the remaining fuel demand may be met by jet fuel or other sustainable aviation fuels[5]

PtL is estimated to be more expensive than jet fuel by ~$40-800, depending on whether CO2 is sourced from DAC or industrial sources, and depending on green H2 costs

Deep dive: Cost of PtL per MT using CO2 from DAC – green hydrogen costs, scenario 1

Total cost per MT of PtL fuel using CO2 from DAC[1] (Green hydrogen costs scenario 1)[2]

Cost per MT of fuel ($)



1. Direct air capture
2. Uses cost of green H2 from 2025-2040 from GIZ's report Baseline Study on the Potential for Power-to-X in Kenya, 2022
3. Green hydrogen includes transportation and distribution of green H2
4. Utilities (heat) and labor cost
5. Total numbers are rounded to the nearest 50s

Source: GIZ's report, Baseline Study on the Potential for Power-to-X in Kenya, 2022, World Economic Forum, Delivering on the global Power-to-Liquid ambition, 2022, World Economic Forum, Sustainable aviation fuels feasibility assessment insights, 2022

This scenario assumes CO2 is sourced from DAC and that green H2 costs decline by 2030 and then rise again by 2040 (based on GIZ's report, *Baseline Study on the Potential for Power-to-X in Kenya, 2022)*

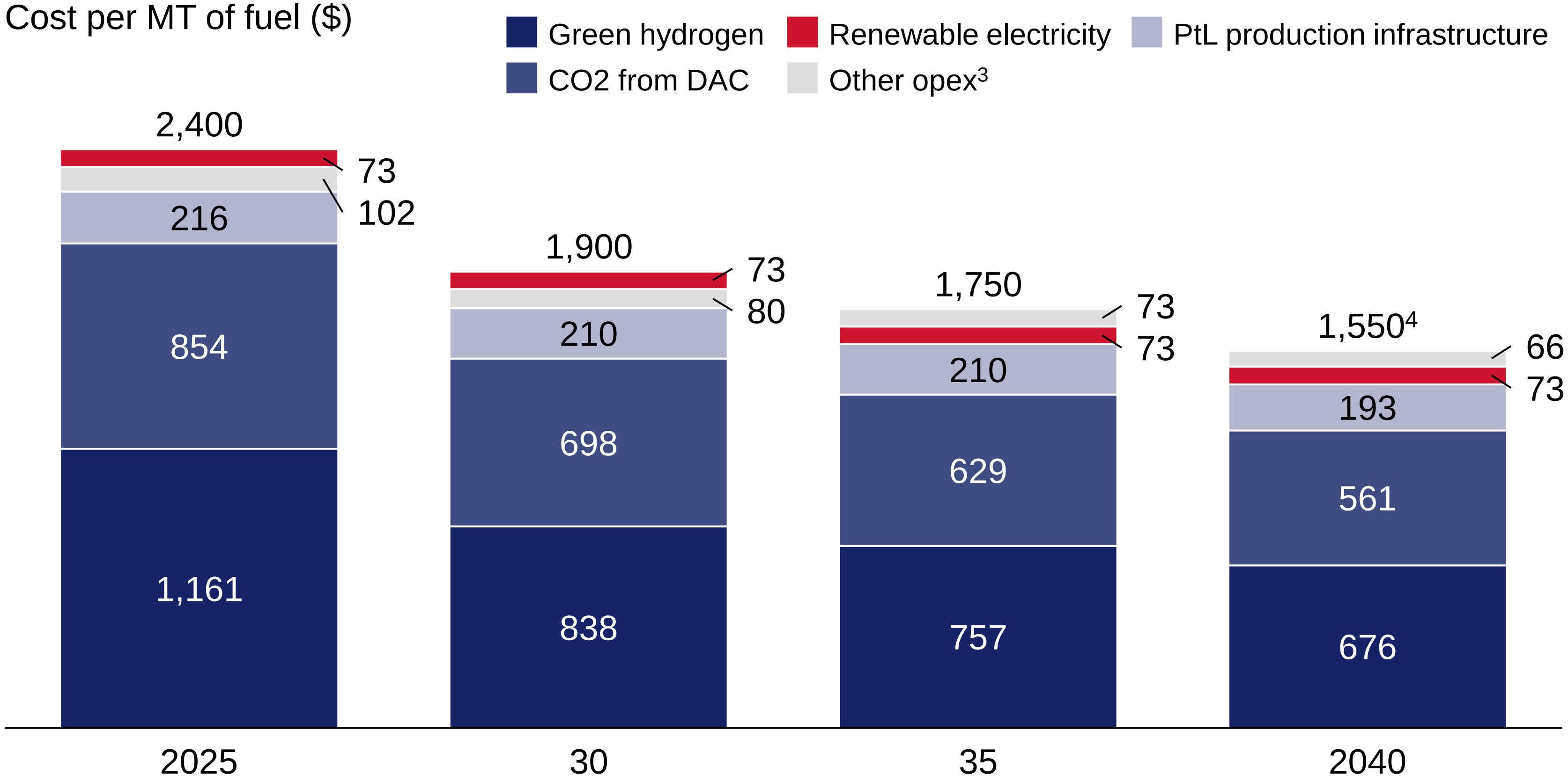
Green hydrogen accounts for the highest cost in the production of PtL

Other major cost drivers might fall from 2030, such as PtL production infrastructure cost, CO2 and electricity costs due to government involvement, the introduction of more innovative technology, incentives to reduce the cost of PtL, etc.

Deep dive: Cost of PtL per MT using CO2 from DAC – green hydrogen costs, Scenario 2

Total cost per MT of PtL fuel using CO2 from DAC[1] (Green hydrogen costs, scenario 2)[2]

Cost per MT of fuel ($)



1. Direct air capture
2. Uses GIZ's report, Baseline Study on the Potential for Power-to-X in Kenya, 2022, and then applied the expected costs reduction to 2030–2040 based on global green H2 cost estimates from Hydrogen Council, Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, 2021
3. Utilities (heat) and labor cost
4. Total numbers are rounded to the nearest 50s

Source: Baseline study on the potential for power-to-x in Kenya (2022), World Economic Forum, delivering on the global Power-to-Liquid ambition, 2022, Hydrogen Council, Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, 2021

This scenario assumes CO2 is sourced from DAC, and that green H2 costs decline over time (taking GIZ green H2 cost estimates for 2025, and applies the expected costs reduction from global green H2 costs based on Hydrogen Council, Hydrogen Insights: *A perspective on hydrogen investment, market development and cost competitiveness, 2021)*

Green hydrogen accounts for the highest cost in the production of PtL

The cost of PtL dips over time due to the decrease in the cost of major cost drivers such as hydrogen, electricity, and CO2 due to the introduction of more innovative technology, falling capital investment required for the technologies to produce hydrogen, incentives to reduce the cost of PtL

Contents

Executive summary

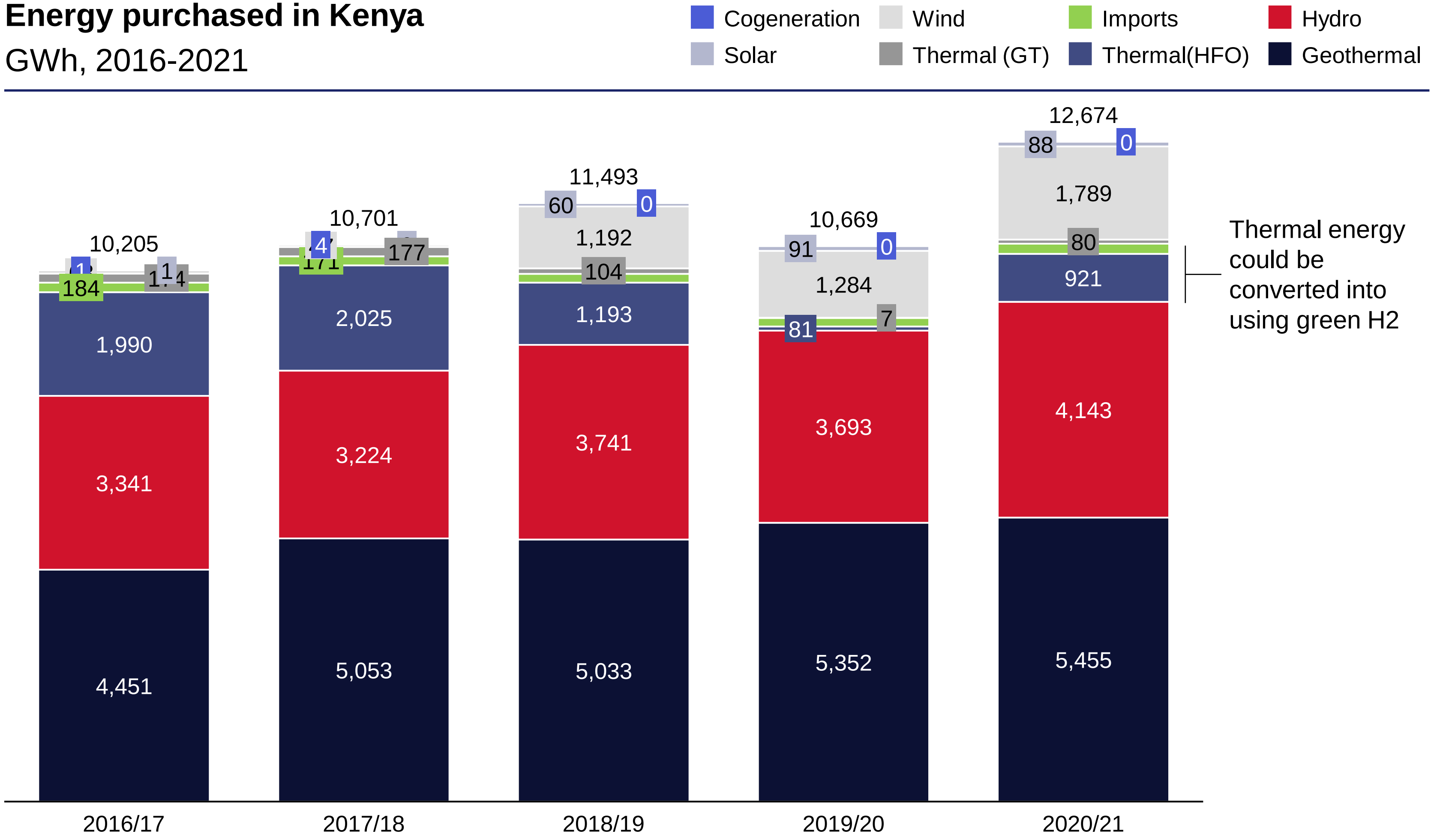
Deep dives per use case

- Heavy duty transport
- Aviation
- **Stationary power**
- Green ammonia (fertilizer)
- Decarbonized steel

Kenya consumes 8% of its power from thermal sources, that could have potential for green hydrogen

Energy purchased in Kenya

GWh, 2016-2021



Thermal energy could be converted into using green H2

Source: KPLC, Energy & Petroleum Statistics Report (EPRA), 2021

Today, 92% of energy consumed in Kenya is renewable

The remaining 8% is thermal, of which 0.7% is produced via gas turbines, and 7.3% is produced via HFO or diesel plants

Gas turbines can be transitioned to using green hydrogen by replacing natural gas, with some capex investment

HFO likely cannot be directly replaced with green hydrogen without a major retrofit, but technology is unclear and no existing examples of this happening

Our expectation is that thermal-equivalent plants will continue to be required in 2040 to support grid stability, particularly in certain parts of the country

Though the country is already looking into converting HFO plants to gas, going straight to H2 would be a "leapfrog" approach (since H2 is more similar to use in a gas turbine than an HFO plant)

Kenya has 9 thermal power plants, of which 7 are powered by HFO, 1 is MSD, and 1 is powered by gas turbines

Plant name	**Type**	**Location**	**Effective capacity** (MWh)	**Commissioned date**
Iberafrica Diesel	MSD	Nairobi, Kenya	~53	2004
Muhoroni GT	GT	Kipevu, Mombasa, Kenya	56	1999
Kipevu I Diesel	HFO	Mombasa port city, Kenya	60	1999
Tsavo Diesel	HFO	Mombasa, Kenya	74	2001
Gulf Diesel	HFO	Athi River, southeast of Nairobi	80	2014
Triumph Diesel	HFO	Kitengela, Athi River, close to Nairobi	83	2015
Thika Diesel	HFO	Rabai,Kilifi county, Mombasa	87	2013
Rabai Diesel	HFO	Rabai, Kilifi County, Kenya	~89	2009
Kipevu 3 Diesel	HFO	Kipevu, Mombasa, Kenya	115	2011

Source: KPLC, Energy & Petroleum Statistics Report (EPRA), 2021

Gas turbines can be retrofitted to use green hydrogen, and HFO plants would have to be redesigned to use green hydrogen

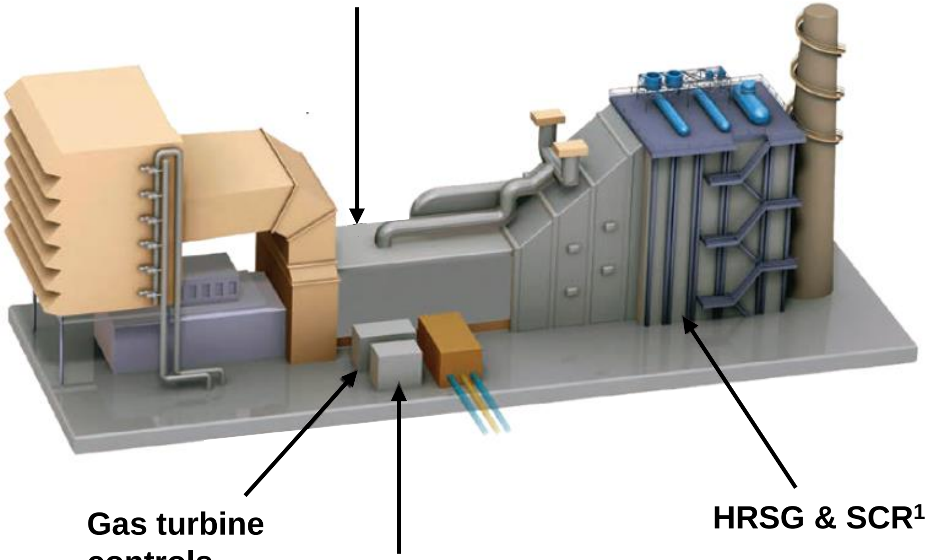
	How hydrogen is used	Timeline	Examples of companies transitioning to green H2
Gas turbines	Replaces natural gas (up to 0-20% or 20- 100%) and can be retrofitted to allow hydrogen-based fuel. But requires the retrofitting of burners, fuel nozzle and the addition of a gas content monitor	Technology is currently available globally for less than 100% blending 100% hydrogen-fueled plant will be available from 2024-2028	Florida Power & Light will complete a 20 MW green hydrogen plant by 2023. This hydrogen will be used in a 20% blend at FP&L's 1.75-gigawatt Okeechobee gas-fired plant Long Ridge Energy Terminal, located in Hannibal, Ohio, has announced plans to transition its 485 megawatts (MW) combined-cycle power plant – currently under construction – to run on green hydrogen Mitsubishi Power has announced its intention to convert JAC gas turbine power islands that are initially capable of operating on 30% green hydrogen to 100% green hydrogen New Fortress Energy is currently building new GE H-class gas turbines in its Hannibal, Ohio plant. The 485 MW plant will burn a 15-20% hydrogen and natural gas blend starting November 2021. New Fortress has plans to burn 100% hydrogen in the next decade German energy company RWE Generation SE (RWE) and Japanese comprehensive heavy-industry manufacturer Kawasaki Heavy Industries (Kawasaki) are planning to install a hydrogen-fueled gas turbine based on renewable green hydrogen in Lingen, Germany, which will be operational from 2024
HFO plants	HFO plant cannot be retrofitted, it will be completely redesigned into a hydrogen fuel cell/ hydrogen plant	No technology is available to transition HFO to green hydrogen pant	Wabash Valley Resources LLC announces operation with Honeywell UOP technologies to convert an old gasification plant (coal plant) to a hydrogen plant producing plant to generate power This is not HFO but an example of transitioning a thermal plant

Source: Gas turbines in the US are being prepped for a hydrogen-fuelled future, 2021, hydrogen for power generation, 2019

Gas turbines can operate on blending or pure hydrogen

Enclosure modifications:

- Piping for hydrogen gas, diluent, etc.
- Explosion proofing
- Hazardous gas detection
- Ventilation system
- Fire protection



Gas turbine controls

HRSG & SCR[1]

Accessory modules:

- High hydrogen fuel system
- Diluent injection module (if required)
- Air extraction modules (if required)

Potential impact of hydrogen fuel conversion on gas turbine systems

Gas turbines are capable of operating on a wide variety of fuels, including fuels with low (less than 20%), moderate (20-90%), and high (90-100%) levels of hydrogen

20% blending requires no change to the gas turbine while more than 20% requires changes to gas turbine accessories-limited controls updates along with new combustor fuel nozzles and the balance of the plant, but configuring a gas turbine to burn just hydrogen will require a thorough review of the plant

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1. Selective catalytic reduction and heat recovery steam generator

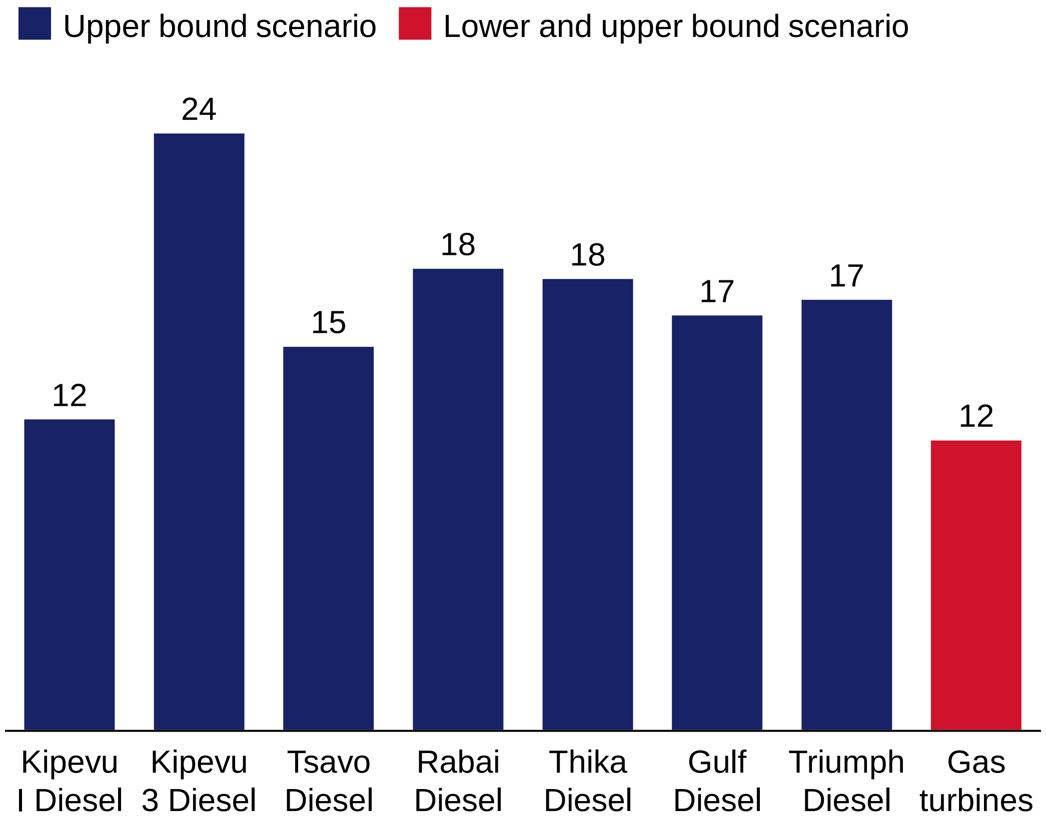
Source: Power to gas: hydrogen for power generation, February 2019

By 2040, Kenya may demand ~10-135k MT of green hydrogen for HFO plants and gas turbines

PRELIMINARY

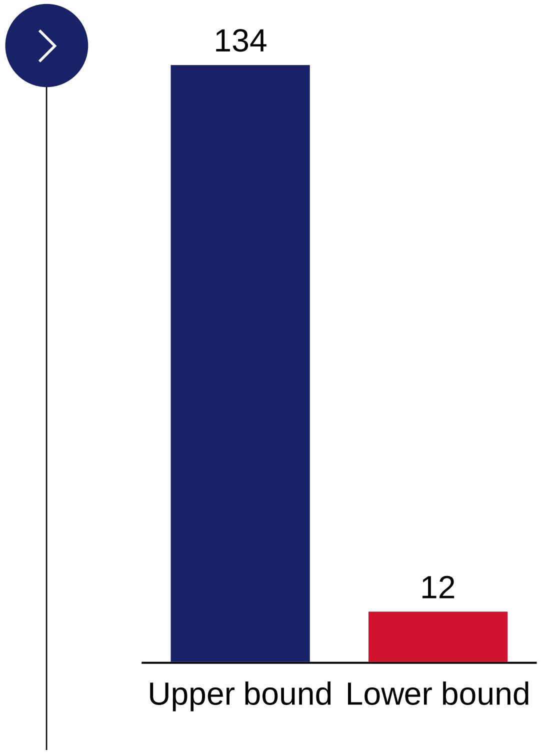
Demand for green hydrogen for HFO plants and gas turbines,

millions MT, 2040



Total demand for green H_2O for HFO plants and gas turbines

millions MT, 2040



Upper bound: is the amount of green hydrogen required for gas turbine (as calculated above) +the amount of green hydrogen required for HFO plants which is estimated by multiplying its MW with the load factor of 70% and annual energy output of 8769, then dividing by a turbine efficiency of 38% and multiplying by LHV[1] H2 of 33.33

Lower bound: is the amount of green hydrogen required for gas turbine which is estimated by multiplying its MW with the load factor of 30% and annual energy output of 8769, then dividing by a turbine efficiency of 38% and multiplying by LHV[1] H2 of 33.33

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1. Low heating value

Source: Expert interview, EPRA, 2021

Contents

Executive summary

Deep dives per use case

- Heavy duty transport
- Aviation
- Stationary power
- **Green ammonia (fertilizer)**
- Decarbonized steel

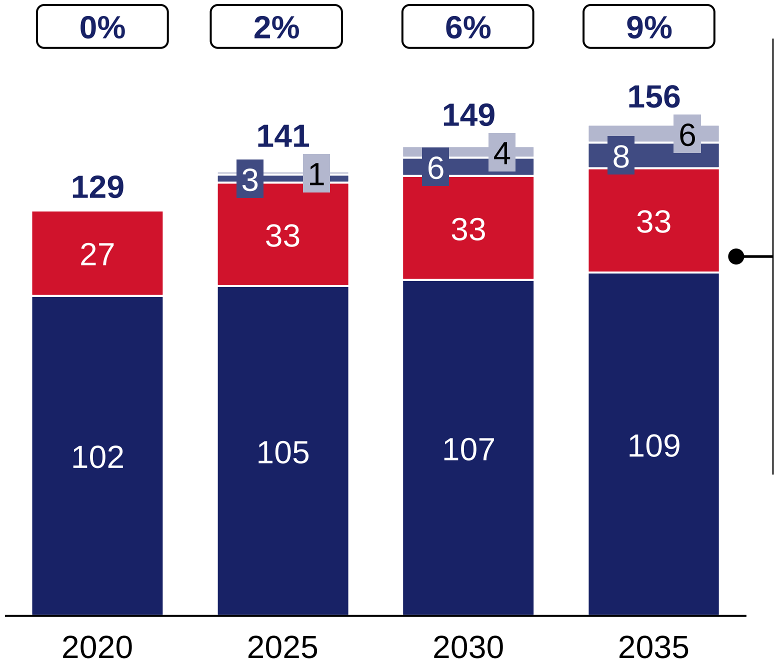
Global fertilizer producers have started expressing interest in producing green ammonia with green hydrogen

~9% of global fertilizer and industrial ammonia could be green by 2035

■ Fertilizer - Conventional ■ Fertilizer- green
■ Industrial - Conventional ■ Industrial- green

% **Share of green ammonia demand**, % of total demand

Global fertilizer and industrial ammonia market, excl. China, MT



Global average forecast – Higher green potential in geographies with more aggressive decarbonization regulations (e.g. EU FitFor55 proposed target of 50% renewable H2 for industry uses by 2030)

Fertilizer producers are communicating green ammonia ambition targets

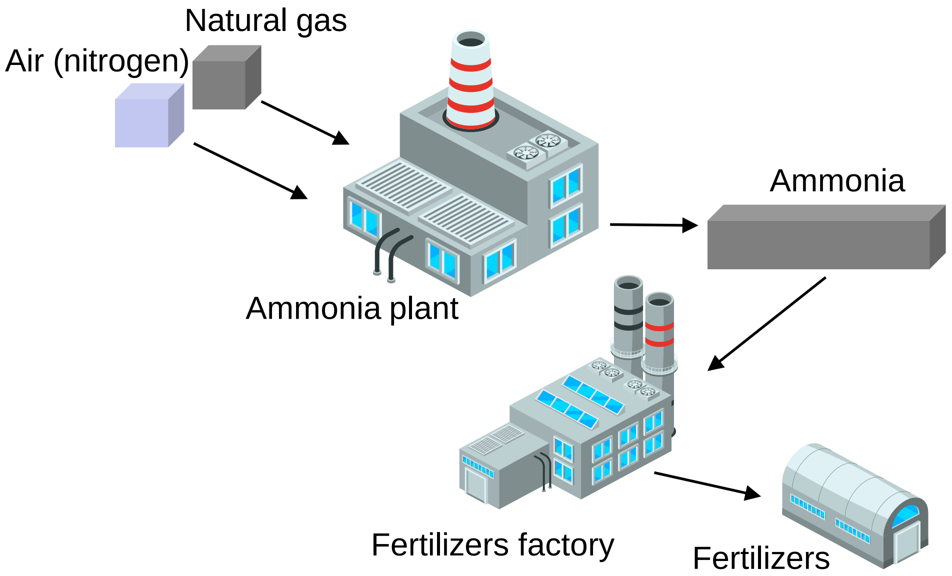
Company	Green ammonia ambition
YARA	Feasibility study for green NH3 with Engie in Pilbara (WA) Goal to become **market shaper in low-carbon fertilizer production,** with 2050 carbon neutral goal
Incitec Pivot	Production of **green ammonia nitrates for mining** clients Feasibility study at Moranbah facility in Australia
Wesfarmers	Feasibility study of 20ktpy green NH3 fertilizer production 2025 target to drive **emissions per unit below peers**
Ballance agri-nutrients	Green ammonia feasibility study in New Zealand
Fertiberia	Largest green hydrogen plant for **industrial use in Europe** announced to be operational in 2022-3 Hydrogen used to produce 200ktpy of green fertilizer
OCP	Green pilot plant in Germany
CF	20ktpy pilot project in Louisiana for 2024 **2050 carbon neutral target**

Source: Fertecon Ammonia Outlook 2021 – Base case; Expert and team analysis

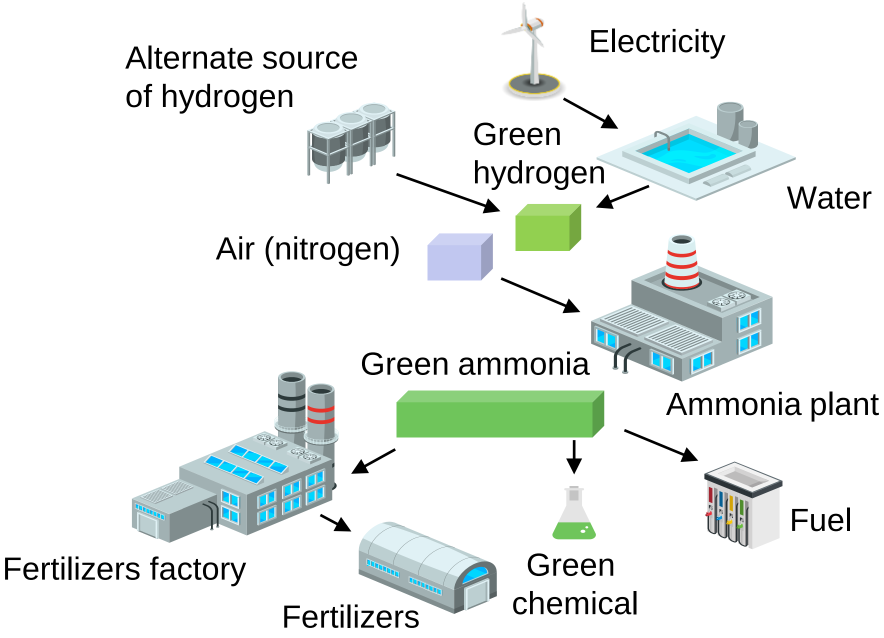
Producing green fertilizer requires replacing natural gas with green hydrogen to produce green ammonia

PRELIMINARY

Process for producing standard ammonia and fertilizer



Process for producing ammonia and fertilizer using green hydrogen



Producing green ammonia would require the replacement of natural gas with green hydrogen and the adoption of electrolysis instead of Steam Methane Reforming (SMR)

Hydrogen is produced by the electrolysis of water and is converted to ammonia using Haber–Bosch reactor like the conventional process

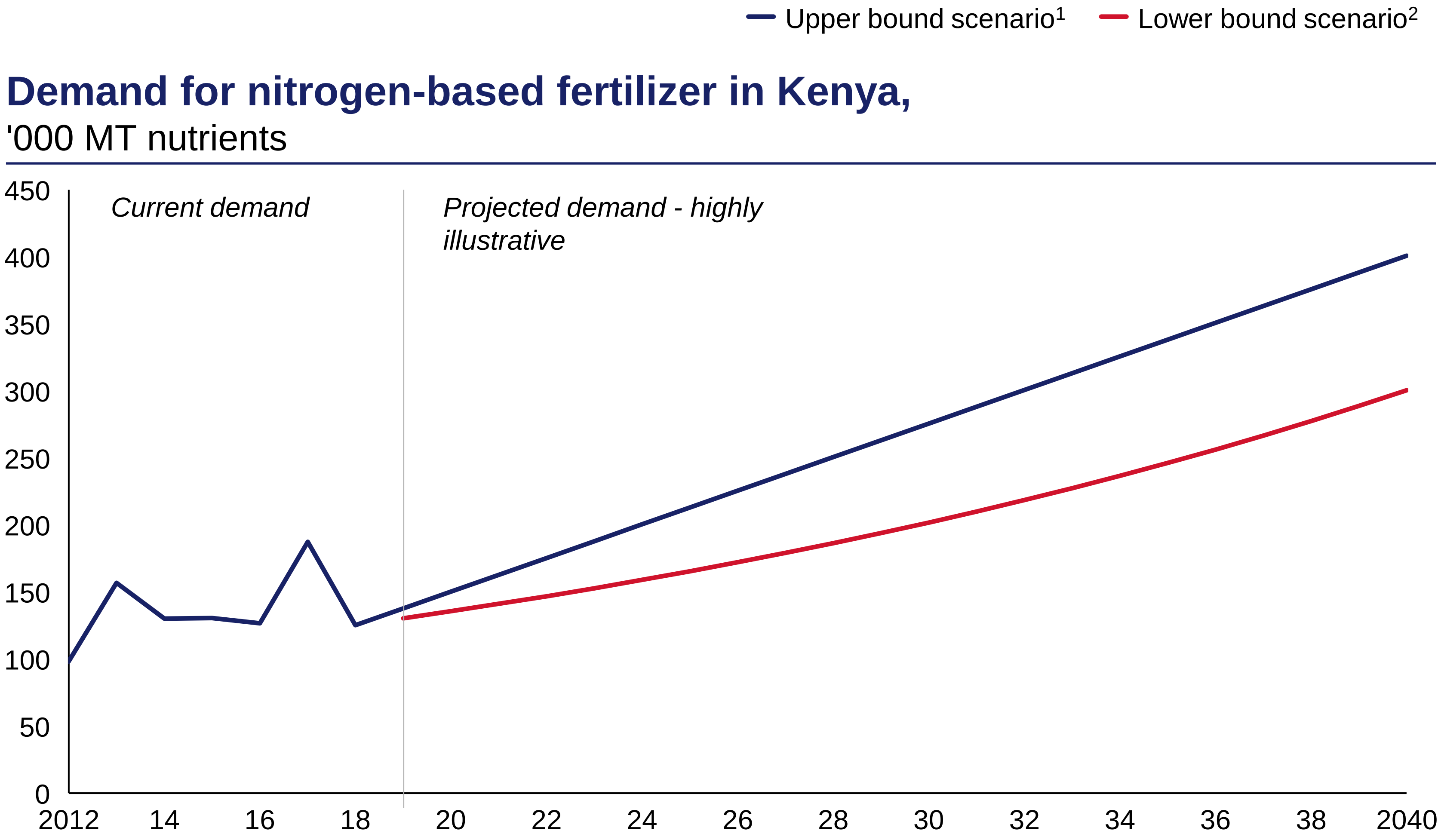
There is no fertilizer production facility in Kenya (only blending); therefore, both an ammonia and a fertilizer granulation facility would be required to be built in order to transition to producing green fertilizer

Source: Paving the way to green ammonia and low-carbon fertilizers

All nitrogen-based fertilizer in Kenya is imported, and demand will continue to grow

Demand for nitrogen-based fertilizer in Kenya,

'000 MT nutrients



Kenya's demanded ~125,000 MT of nitrogen nutrients in 2018, all in granulated form (e.g., Urea, NPKs). **By 2030, this may increase to ~400,000 MT of nitrogen fertilizer.** Our assumption is that fertilizer consumption will continue to be in granulated forms (while ammonia can be directly applied as fertilizer, this is only common in the US and requires specialty distribution and direct injection application into the soil using mechanization; unlikely to be scaled in Africa)

100% of this fertilizer is imported, and Kenya does not currently have any local fertilizer granulation capacity; however, there is some mechanical blending capacity

In order to produce green fertilizer, **Kenya would have to develop ammonia and fertilizer production**

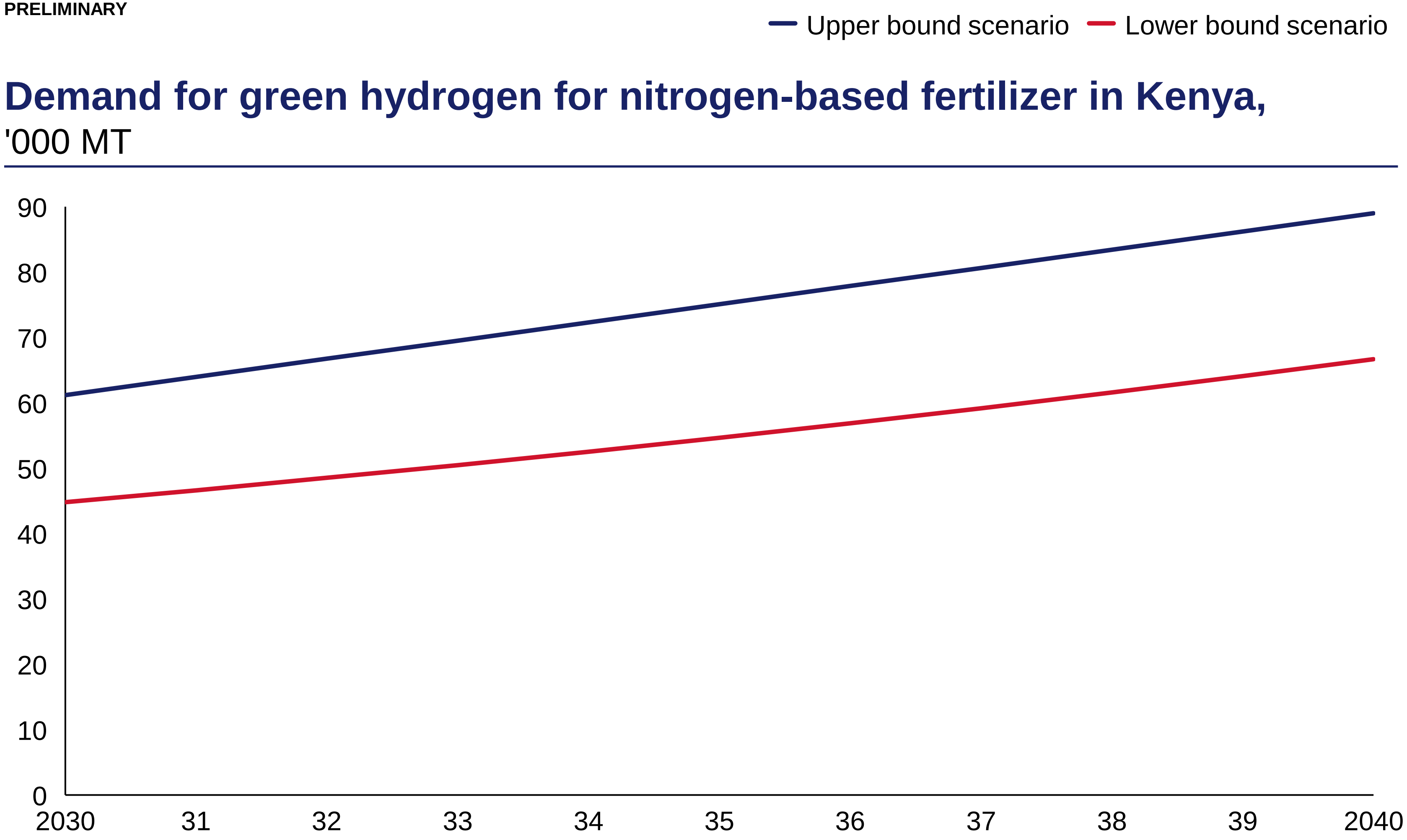
1. This assumes reaching the 50kg/ha Abuja Declaration target by 2040
2. Demand projections based on the 2009-2018 CAGR

Source: International Fertilizer Agency

There could be ~65-90k MT of green hydrogen demanded for nitrogen-based fertilizer by 2040

PRELIMINARY

Demand for green hydrogen for nitrogen-based fertilizer in Kenya,
'000 MT



Source: International Fertilizer Agency, expert interview

Total potential demand for green hydrogen for nitrogen-based fertilizer is based on replacing 100% of imports of nitrogen-based fertilizers

This is based on the assumption that if we have local ammonia production, we will no longer need to import, as is currently the case in nitrogen-producing countries

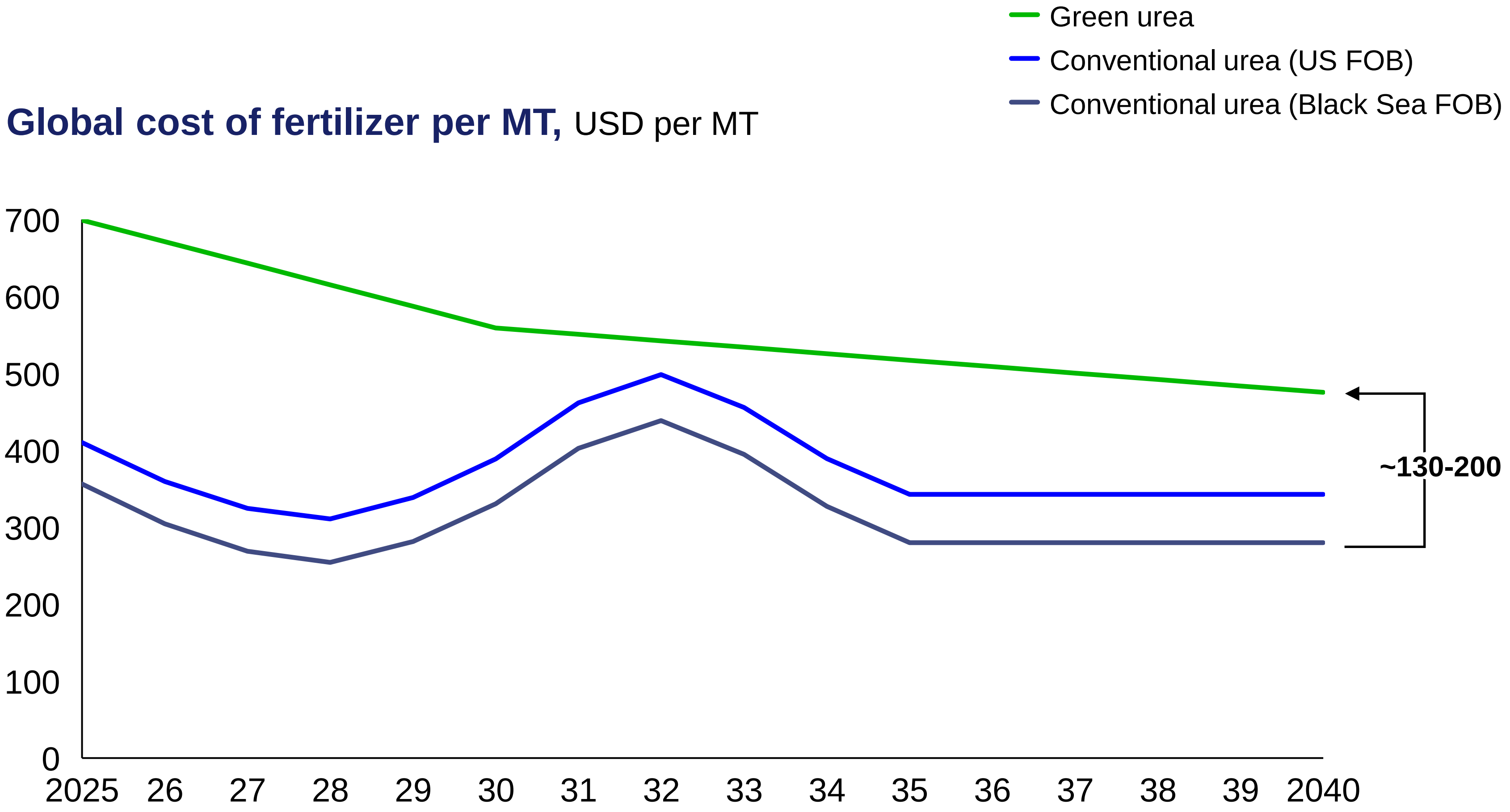
This would require setting up an ammonia and fertilizer granulation facility in order to transition to producing green fertilizer

---

Estimation of green hydrogen demand assumes that each ton of ammonia contains 82 percent nitrogen and that each ton of ammonia requires 0.182 tons of hydrogen

Globally, green urea could be USD ~130-200 more expensive per MT than conventional urea in 2040

Global cost of fertilizer per MT, USD per MT



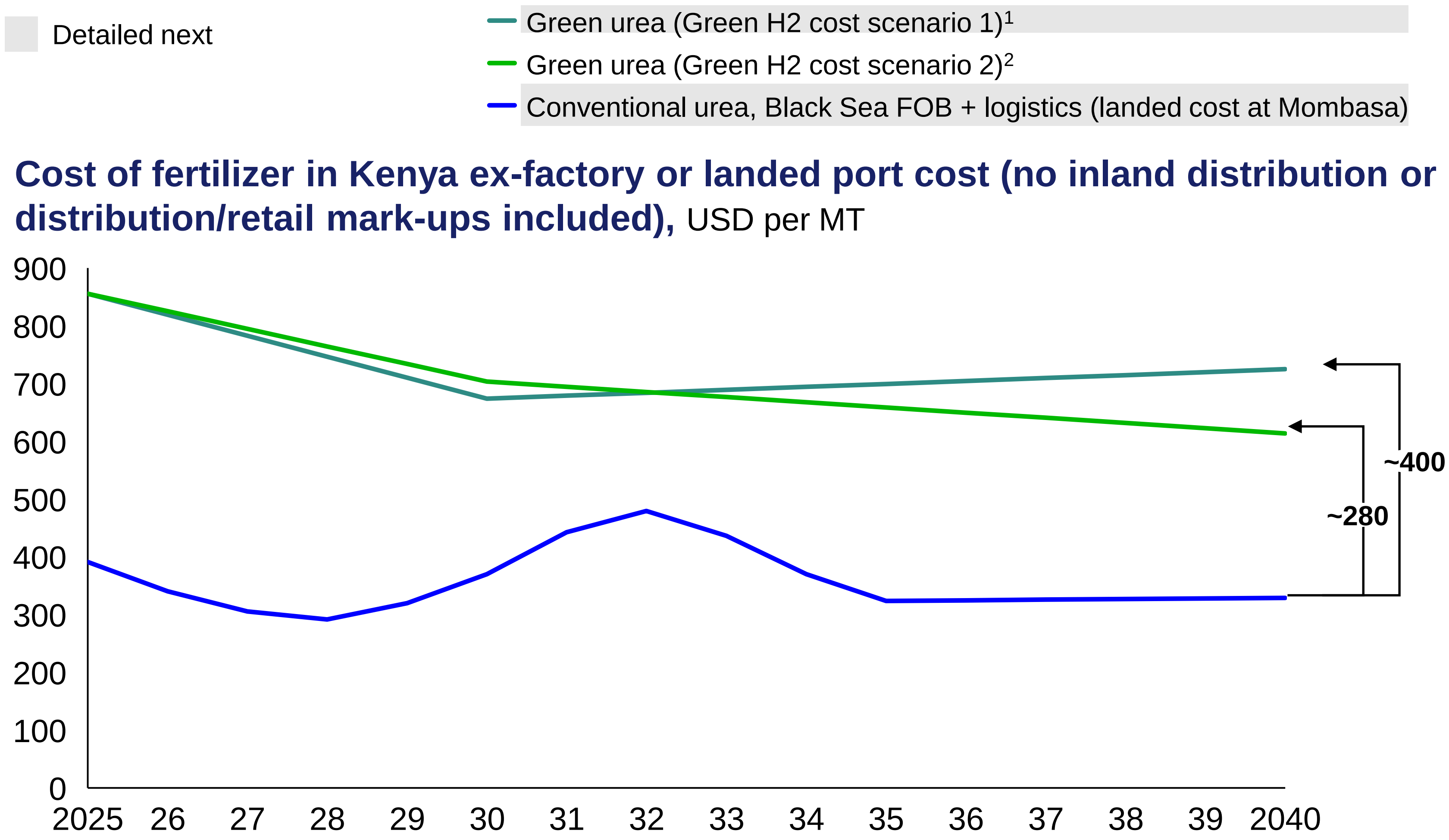
Conventional urea is currently in a price fly-up, but based on historical experience, this is expected to revert to lower levels in the next few years. There is some expected cyclicality shown here in the 2030s due to supply-demand imbalances that again are expected to level out

Green urea cost reductions are driven by declining green ammonia (which is driven by declining green H2) costs and reductions in DAC technology costs

Source: IHSM, Lloyds Register: Techno-economic assessment of low carbon fuels, 2020, IHSM, McKinsey Chemical Insights, Hydrogen Council, Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, 2021, World bank,

Green urea could be USD ~280-400 more expensive per MT than conventional urea in 2040

Cost of fertilizer in Kenya ex-factory or landed port cost (no inland distribution or distribution/retail mark-ups included), USD per MT



1. Uses cost of green H2 from 2025-2040 from GIZ's report Baseline Study on the Potential for Power-to-X in Kenya, 2022
2. Uses GIZ's costs of green H2 for 2025 from GIZ's report, Baseline Study on the Potential for Power-to-X in Kenya, 2022, and then applied the expected costs reduction to 2030-2040 based on global green H2 cost estimates from Hydrogen Council, Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, 2022, World bank

Source: IHSM, Lloyds Register: Techno-economic assessment of low carbon fuels, 2020, IHSM, McKinsey Chemical Insights, Hydrogen Council, Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, 2021, GIZ's report, Baseline Study on the Potential for Power-to-X in Kenya, 2022, World bank

In Kenya, several fertilizers incorporate nitrogen such as diammonium phosphate (DAP) and calcium ammonium nitrate (CAN) Urea is the highest volume nitrogen fertilizer so used here for comparison

Green urea could be USD ~280-400 more expensive per MT than conventional urea in Kenya, of which ~60% is driven by the cost of green ammonia made from green hydrogen

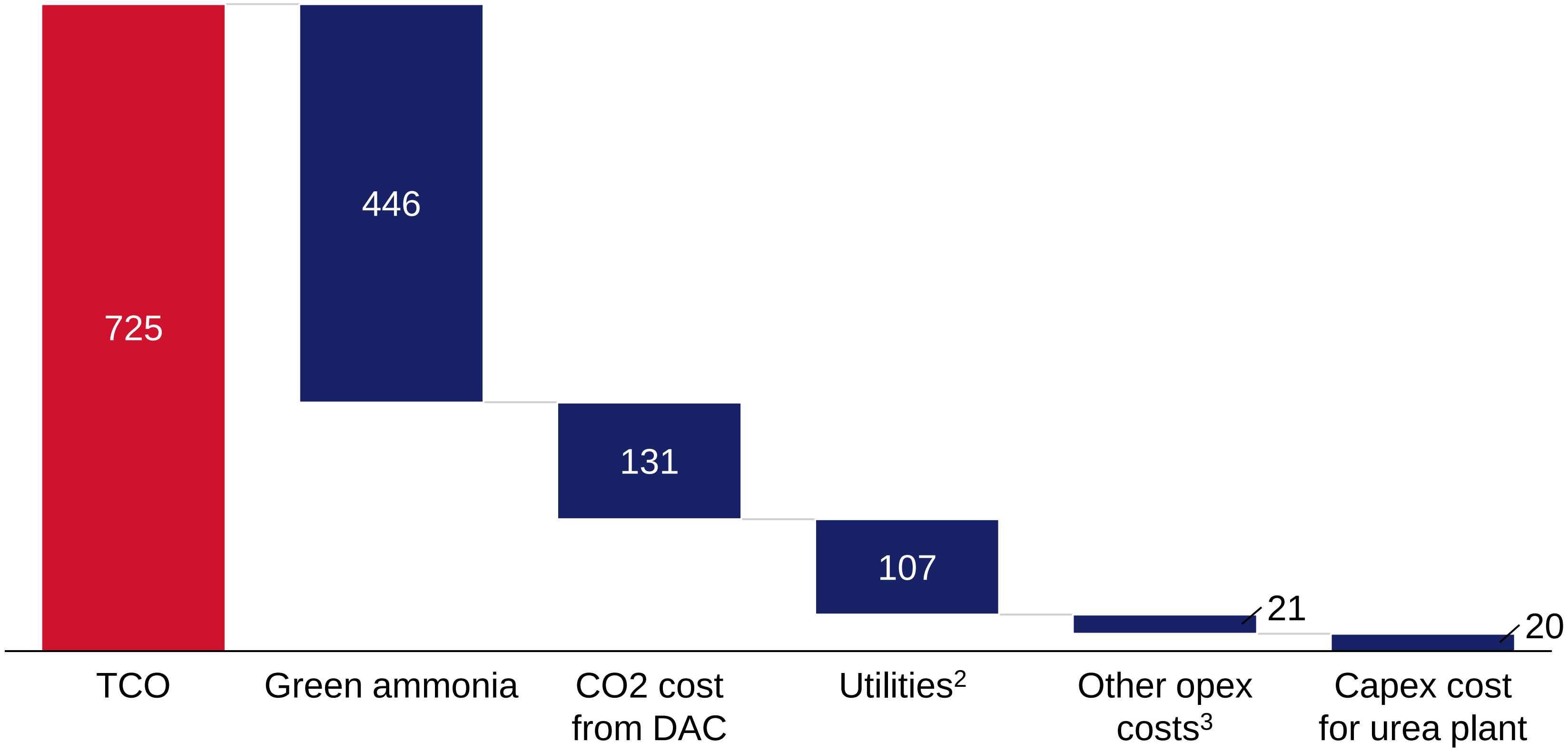
There are alternative types of green fertilizer that could be less expensive than green urea (not shown here), such as green ammonium nitrate, which is ~$280-300 cheaper than green urea mainly due to requiring less green ammonia and not requiring CO2 as a feedstock

However, ammonium nitrate is not currently consumed in Kenya and is lower in demand globally due to its explosive nature

Deep dive: Cost of green urea per MT in Kenya

Cost of green urea using direct air capture in Kenya (Green H2 cost scenario 1)[1]

Cost per MT, USD, 2040



~60% of the TCO is driven by green ammonia, with an additional ~20% driven by CO2 cost from direct air capture

The TCO could be reduced if using CO2 from an alternative source, such as industrial sources; however, this would not be carbon neutral

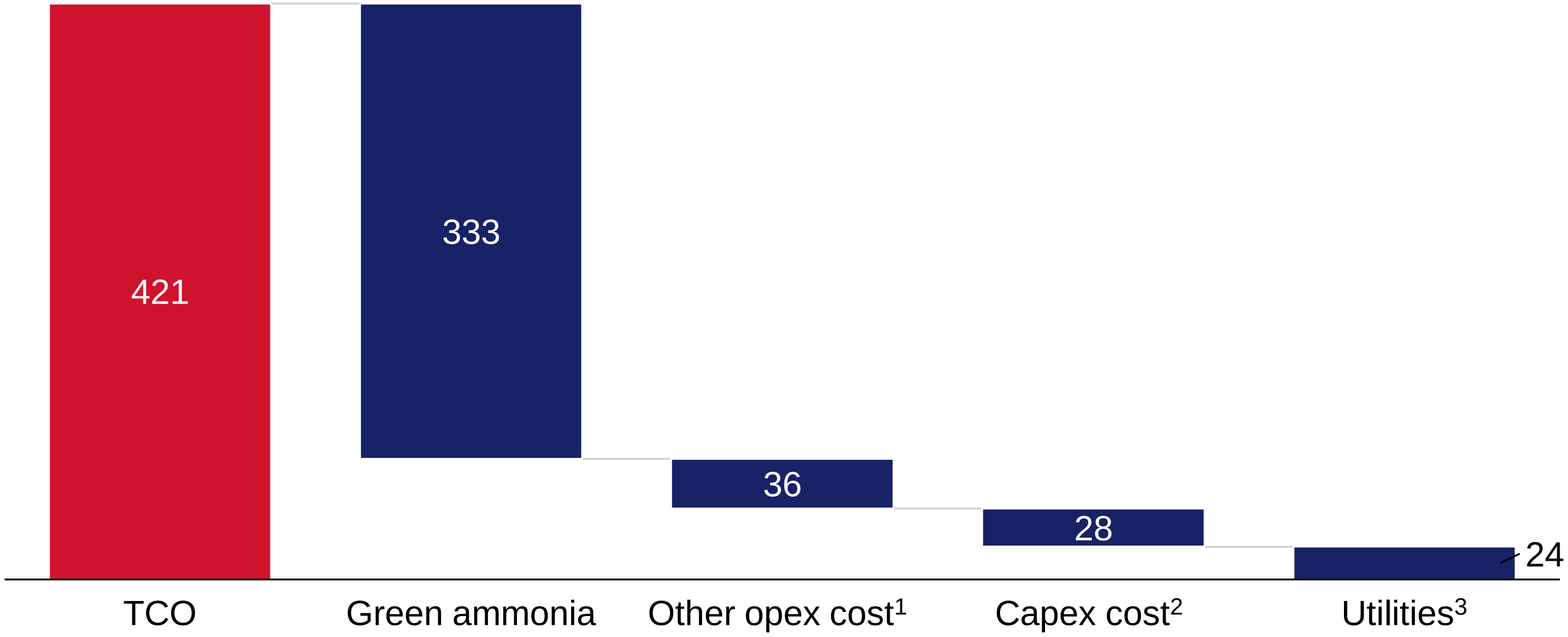
1. Uses cost of green H2 from 2025-2040 from GIZ's report Baseline Study on the Potential for Power-to-X in Kenya, 2022
2. Utilities include electricity (energy related) and non energy related
3. Overhead, maintenance, labor, selling, general and administrative expenses

Source: IHSM, Lloyds Register: Techno-economic assessment of low carbon fuels, 2020, IHSM, McKinsey Chemical Insights

Deep dive: Cost of green ammonia nitrate per MT

Cost of green ammonium nitrate using direct air capture in Kenya (Green H2 cost scenario 1)[1]

Cost per MT, USD, 2040



There is no demand for ammonium nitrate in Kenya today, principally because can be explosive therefore any adoption of green ammonium nitrate would require sufficient safety measures in place and a switch in behaviors of farmers

Green ammonia is the major cost driver, which accounts for ~80% of TCO per MT of ammonium nitrate

1. Overhead, maintenance, labor, selling, general and administrative expenses
2. Nitric acid plant and ammonia nitrate plant
3. Utilities include electricity (energy related) and non energy related

Source: IHSM, Lloyds Register: Techno-economic assessment of low carbon fuels, 2020, IHSM, McKinsey Chemical Insights

Contents

Executive summary

Deep dives per use case

- Heavy duty transport
- Aviation
- Stationary power
- Green ammonia (fertilizer)
- **Decarbonized steel**

Leading global players across industries are making commitments towards producing steel with green hydrogen

Steel-making companies globally are already announcing H2-DRI pilot and large-scale initiatives

Company	H2-DRI announcements
ArcelorMittal	Pilot plant in Hamburg with 100 kton DRI by 2025 Full-scale DRI to feed new EAF in Gijón and existing EAF in Sestao with 2.3 Mn MT DRI by 2025 Full-scale DRI and new EAF in Ontario for 2Mton by 2028
LIBERTY STEEL	Ascoval collaboration with SHS (incl. Dillinger) and SMS group to produce green H2 + DRI/HBI steel through Liberty Steel's existing EAFs in France
thyssenkrupp	Ambition to produce green H2 and green steel in Duisburg – feasibility study stage
SALZGITTER AG Stahl und Technologie	Ambition to produce 2Mn MT per year via DRI with green H2 – feasibility study stage
SSAB	Green H2 and DRI-EAF pilot project with test production started at limited scale in Luleå
LKAB	Longer term strategy to transition to green HBI production, with the first sites (Malmberget and Kiruna) to be converted by 2029 Green H2 used as input for new EAFs

Example: ArcelorMittal is building hydrogen-ready DRI units and EAF to replace blast furnace steelmaking

13 July 2021 13:45 CET

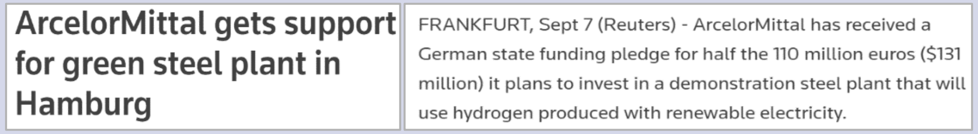
ArcelorMittal signs MoU with the Spanish Government supporting €1 billion investment in decarbonisation technologies

New DRI and EAF installations in Gijón will reduce carbon emissions at the company's Spanish operations by approximately 50%. The DRI installation in Gijón will also enable ArcelorMittal Sestao to be the world's first full-scale zero carbon-emissions[1] steel plant.

30 July 2021 16:00 CET

ArcelorMittal and the Government of Canada announce investment of CAD$1.765 billion in decarbonisation technologies in Canada

New DRI and EAF installations at ArcelorMittal Dofasco in Hamilton, Ontario will reduce carbon emissions by approximately 60%



ArcelorMittal gets support for green steel plant in Hamburg

FRANKFURT, Sept 7 (Reuters) - ArcelorMittal has received a German state funding pledge for half the 110 million euros ($131 million) it plans to invest in a demonstration steel plant that will use hydrogen produced with renewable electricity.

Green hydrogen can be used as a reductant in upstream steel production and to replace fossil fuels across the whole value chain

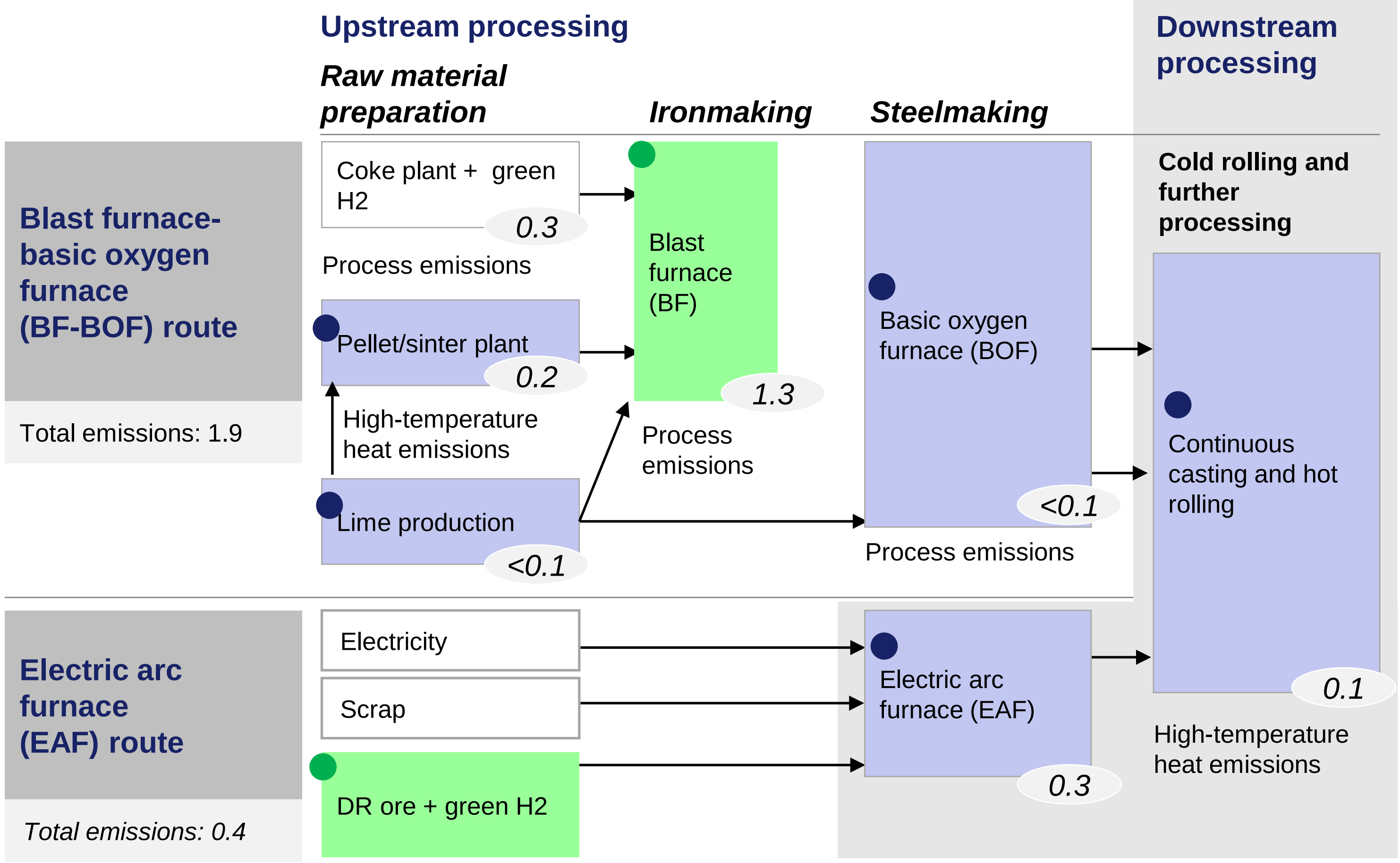
⬜ Main activities in Kenya 🟩 Areas where green h2 can be used as a reductant 🟦 Areas where green h2 can be used to replace fossil fuels along value chain x Emissions, tCO2/tsteel

Means of using green H2 in steel production

● As a reductant in upstream raw material preparation (e.g., via replacing 20% of coal in BOF, or replacing natural gas in DRI)

● Replacing fossil fuels along the whole value chain (e.g., replacing natural gas in EAF)

Main methods of producing steel incl where green hydrogen can be used



Upstream processing

Raw material preparation ***Ironmaking*** ***Steelmaking***

Downstream processing

Blast furnace-basic oxygen furnace (BF-BOF) route

Total emissions: 1.9

Coke plant + green H2 0.3

Process emissions

Pellet/sinter plant 0.2

High-temperature heat emissions

Lime production <0.1

Blast furnace (BF) 1.3

Process emissions

Basic oxygen furnace (BOF) <0.1

Process emissions

Cold rolling and further processing

Continuous casting and hot rolling 0.1

High-temperature heat emissions

Electric arc furnace (EAF) route

Total emissions: 0.4

Electricity

Scrap

DR ore + green H2

Electric arc furnace (EAF) 0.3

The two main approaches to producing steel with green hydrogen include

- Blast furnace-basic oxygen furnace (BF-BOF) route
- Electric arc furnace (EAF) route

For the BF-BOF route green hydrogen can replace ~20% coal, while on the EAF route green hydrogen can replace 100% natural gas

Green hydrogen can be used as a fuel throughout the value chain: It can be used to replace fossil fuels in the re-heating furnace for BF-BOF, EAF, Hot and cold furnace.

Most emissions happen upstream and therefore the opportunity to reduce carbon in Kenya, which imports semi-processed steel, is limited

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1. Direct reduced iron

Source: Material Economics, 2019

By end 2022 there will be 2 plants doing upstream processing, with the remaining doing downstream only

Major producers of steel products in Kenya

PRELIMINARY **NON-EXHAUSTIVE**

🟩 Areas where green h2 can be used as a reductant

🟦 Areas where green h2 can be used to replace fossil fuels along value chain

Type	Company	End products	Estimated capacity, MT, 2022	Type of plant	Green hydrogen application
Upstream processing	DEVKI DEVKI STEEL MILLS LTD.	- Billets (expected to become operational at end of 2022)	~250,000	Induction furnace	N/A – no potential for green H2 since induction runs on electricity
	AGI Abyssinia Group Of Industries	- Wire rods	~170,000	DRI + melting shop	🟩 As a reductant in DRI process
Downstream processing *(not exhaustive)*	DEVKI DEVKI STEEL MILLS LTD.	- Rebar - Wire rods - Plate and sections	~250,000[1]	EAF + imported scrap (no DRI)	🟦 As a replacement for natural gas used for the EAF, and replacing fossil fuels in re-heating furnace
	TARMAL THE STEEL PEOPLE	- Hollow sections - Power steel - Wire products	~120,000		
	AGI Abyssinia Group Of Industries	- Hot rolled products - Cold rolled products - Hoop iron - Zed purlins - Roofing and collated nails	~180,000	Transformation of billets or scrap without EAF	🟦 As a replacement for fossil fuels in re-heating furnace
	NYUMBA	- Galvanized and pre-painted - roofing sheets - Ridges and gutters - Hollow sections and wire products - Bitumen products	~250,000		
	MRM MABATI ROLLING MILLS	- Coated roof sheeting - Hot roll coil - Hot dip galvanized sheets - Cold rolled steel	~390,000		

In terms of upstream processing, Kenya today has one plant with an additional one coming online at end of 2022

Remaining production is all downstream processing

Therefore, **green hydrogen's only potential applications in Kenyan steel production** are:

- Using it **as a reductant in upstream processing**: to replace natural gas in the 1 plant that does upstream processing using DRI (or additional 1 or 2 plants based on government incentives to increase local production)
- As a **replacement for fossil fuels in downstream processes** for all plants - during the reheating process

Source: Company websites

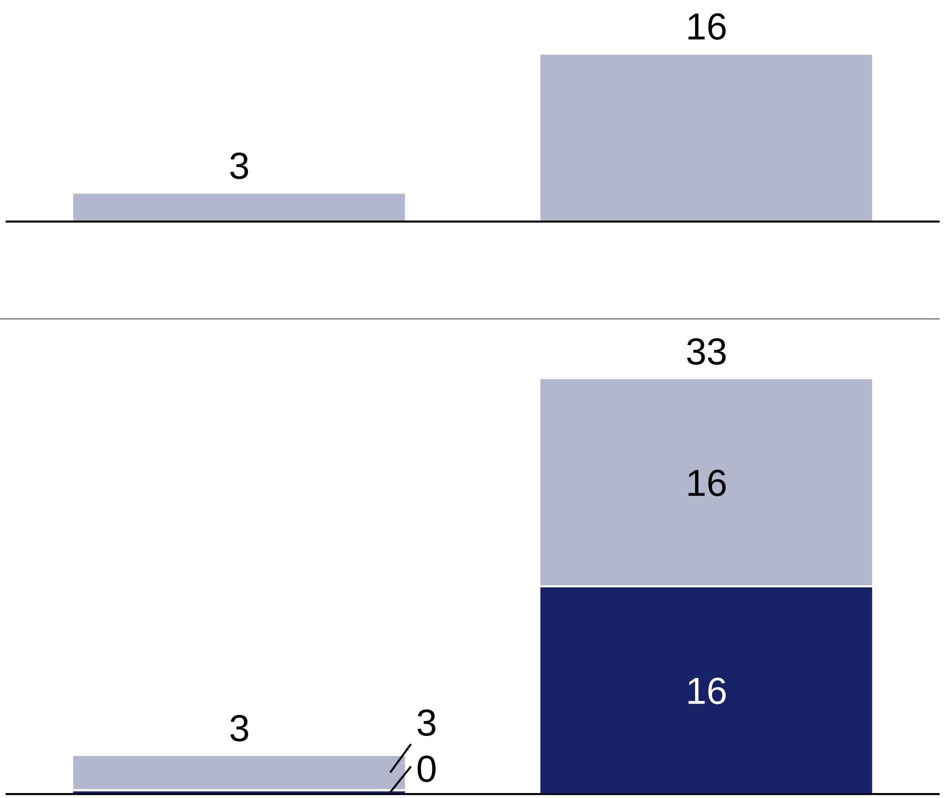
The maximum potential demand for green H2 could be ~15-35k MT in 2040

PRELIMINARY

Scenario	Description
Lower bound	A Green hydrogen replaces fossil fuel for downstream reheating processing
Upper bound	A Green hydrogen replaces fossil fuel for downstream reheating processing B Green hydrogen replaces 100% of natural gas in DRI processing

Potential MT of steel processed in 2040 Millions MT

Potential demand for green H2 000, MT



Lower bound: Assumes that green hydrogen is used in downstream processing only, e.g., to replace heat in reheating furnace

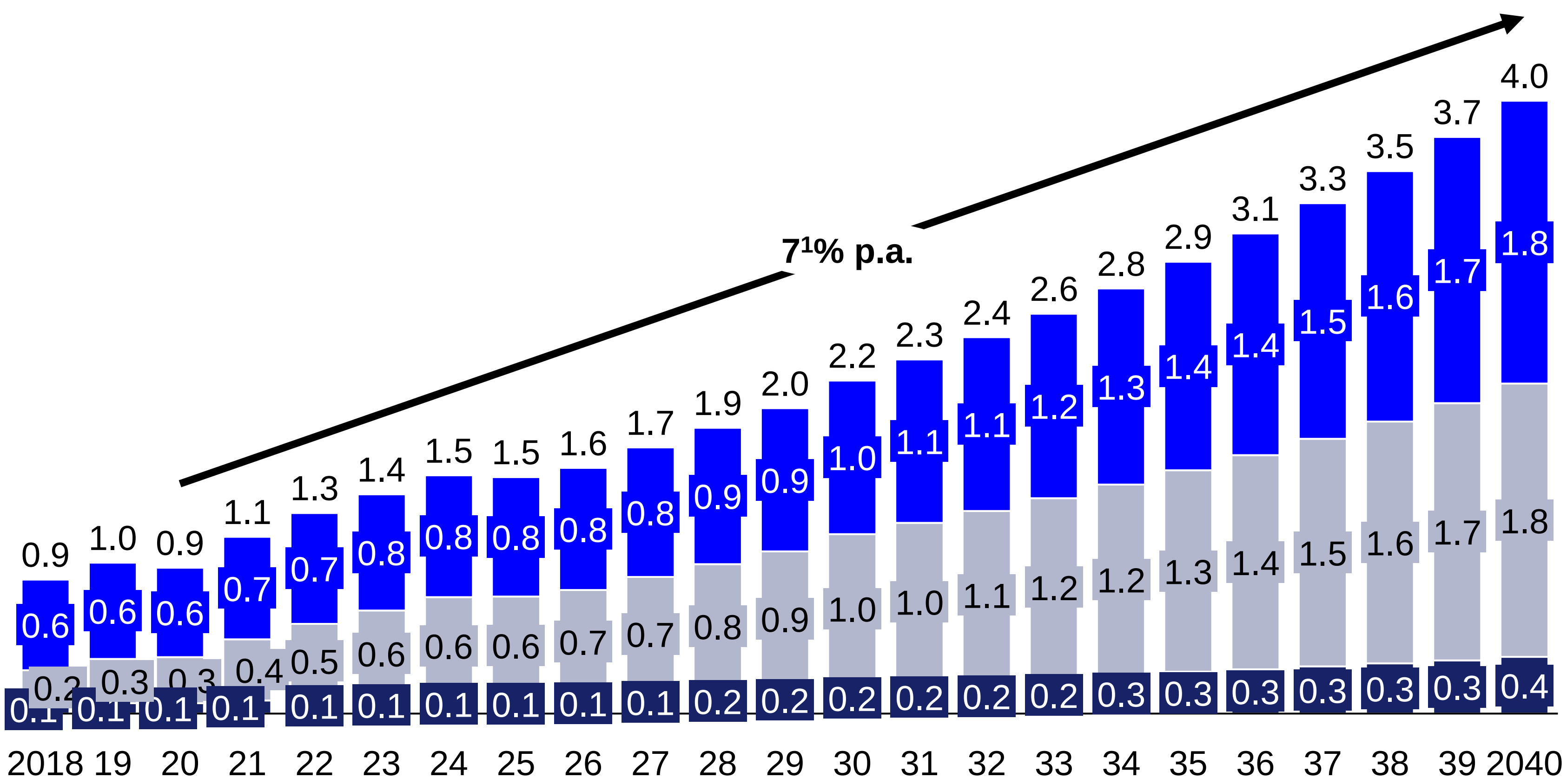
Upper bound: Assumes green hydrogen is used in:

- **Downstream processing** for same uses as in lower bound scenario
- **Upstream processing** by replacing 100% natural gas in DRI, plus an additional 1-2 DRI plants by 2040

Assumes iron ore is imported and government incentivizes local production

A. Demand for finished steel products may continue to rise as a result of the construction boom

Demand for steel in Kenya,
million MT, 2018-2040



1. 2020-2030 is based on steel intensity using GDP and population growth; 2031- 2040 is based on the past 5-year CAGR scenario

Source: McKinsey’s Basic Materials model

Kenya's annual demand for steel may grow by 7% p.a. from 2020 to 2040, from ~945,000 MT to ~4 million MT; driven by major infrastructure developments, and investments into housing

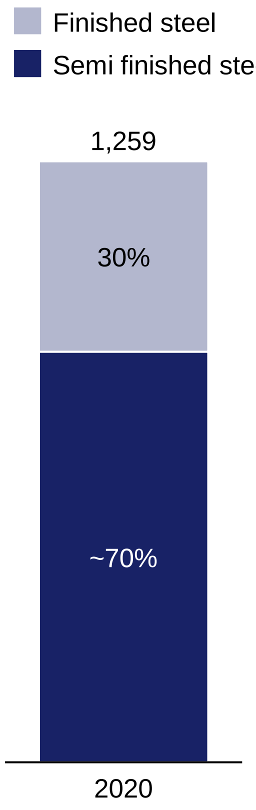
Most of the iron to make the steel is imported from South Africa, Japan, India and China

The local steel sector makes a variety of products from local and imported steel such as flat, long and tube

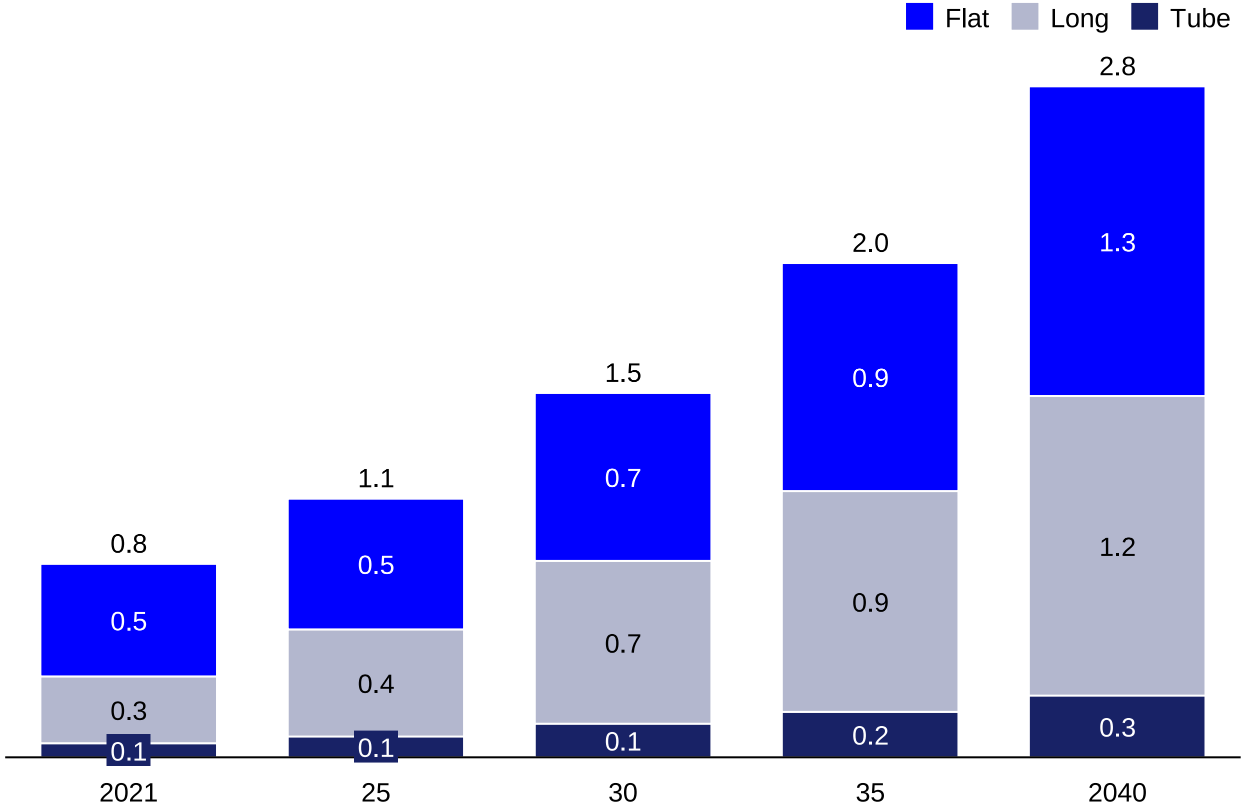
Most of the steel products produced in Kenya tend to be used in the construction industry

A. Of the total demand for finished steel products, ~70% may have undergone downstream processing in Kenya

Volume of imported steel in Kenya



Volume of finished steel products that may have undergone downstream processing in Kenya,
million MT, 2018-2040



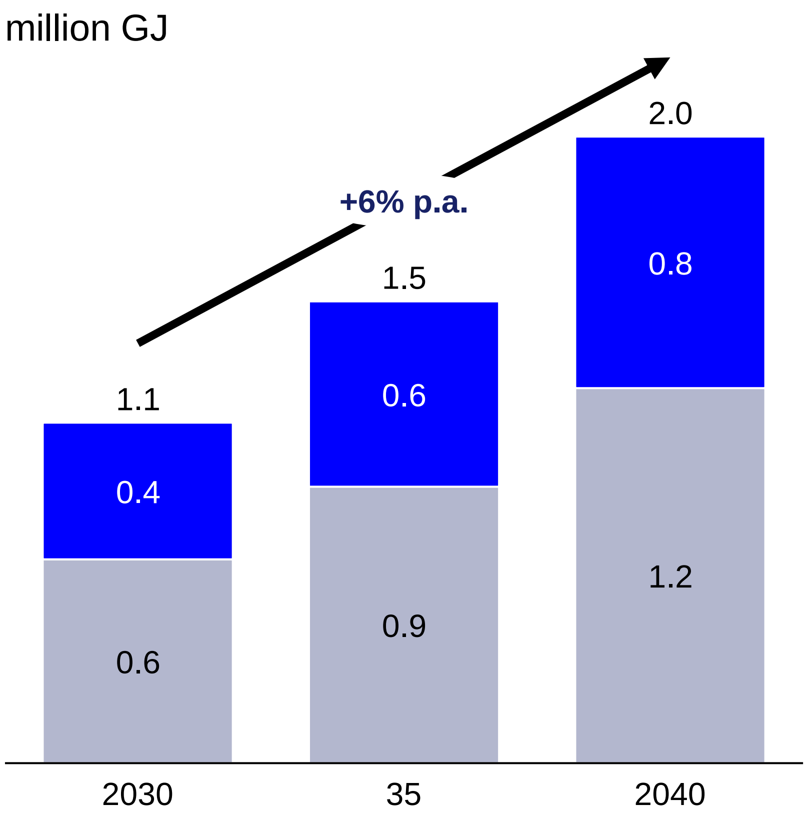
~70% of all imported steel products are semi-finished products, and therefore we assumed that ~70% of Kenya’s finished steel products demand could have undergone downstream processing in Kenya

Source: UNComtrade, McKinsey’s Basic Materials model

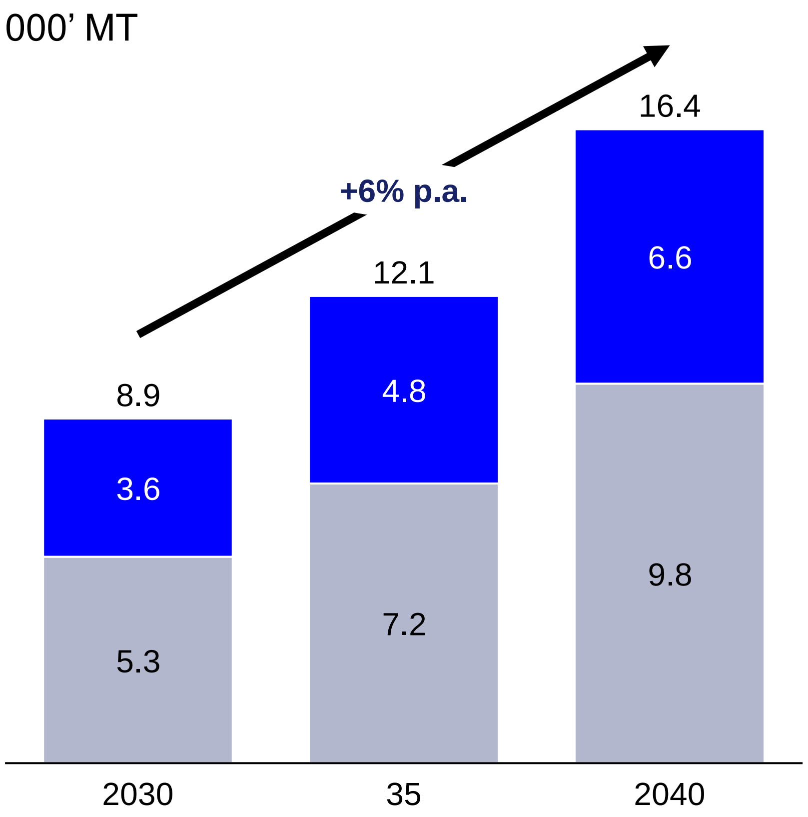
A. In 2040, there could be ~16,000 MT of green H2 demanded for downstream steel processing

🟦 Flat
▨ Long

Potential amount of heat required for reheating processes in downstream steel manufacturing in Kenya



Potential demand for green H2 for reheating processes in downstream steel manufacturing in Kenya



Source: McKinsey's Basic Materials model

The potential amount of heat used in the downstream process was projected based on:

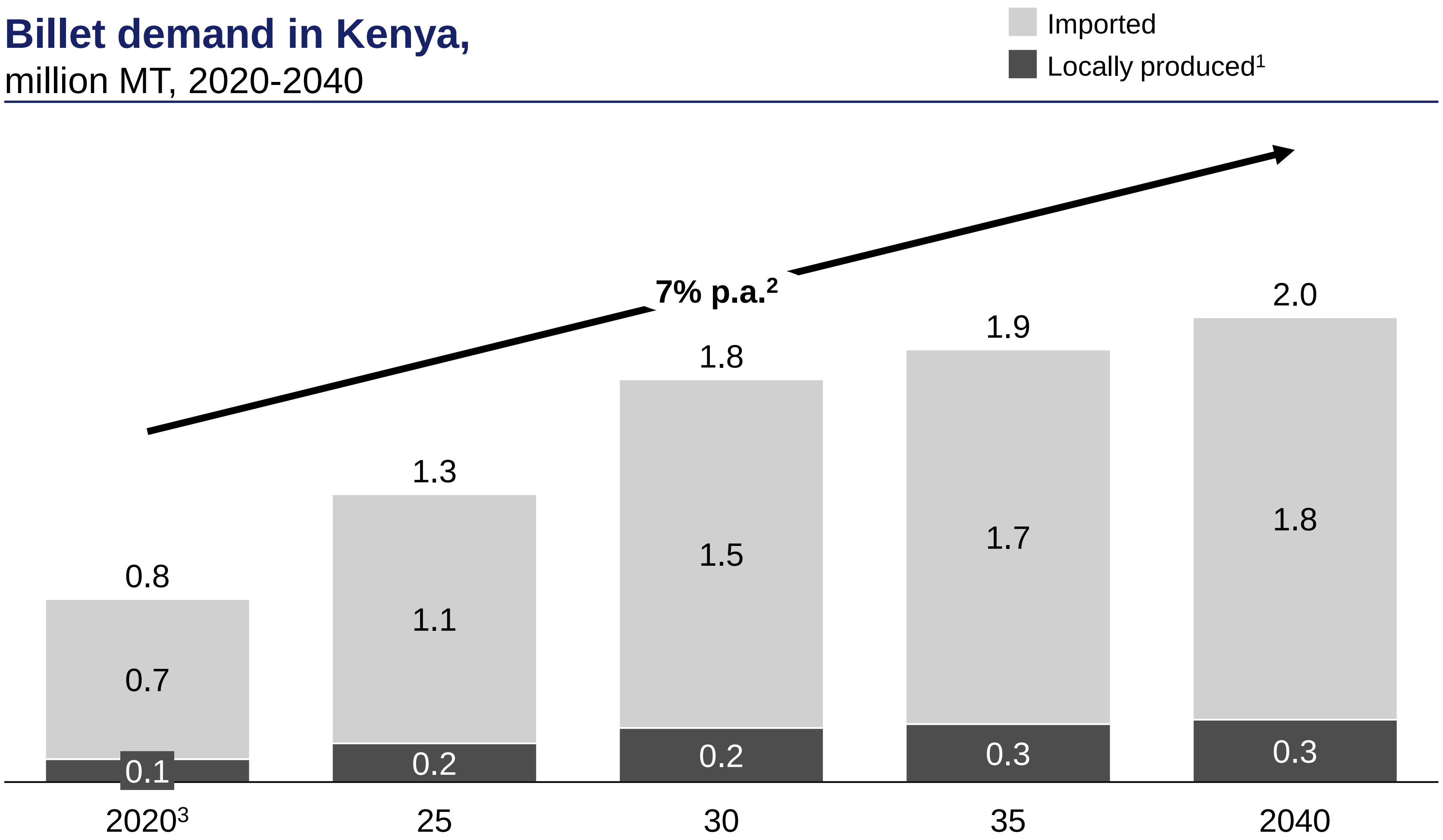
- Flat cold rolling requiring 0.8GJ/t
- Flat hot rolling requiring 1.3 GJ/t
- Long hot rolling requiring 1 GJ/t

Potential volume of green hydrogen required for reheating processes in downstream steel manufacturing calculated assuming 8.3 kg of hydrogen per GJ of natural gas (or equivalent)

B. Billet demand in Kenya may continue to grow at ~7% p.a. to ~2Mn MT in 2040

PRELIMINARY

Billet demand in Kenya,
million MT, 2020-2040



	2020[3]	25	30	35	2040
Imported	0.7	1.1	1.5	1.7	1.8
Locally produced[1]	0.1	0.2	0.2	0.3	0.3
Total	0.8	1.3	1.8	1.9	2.0

1. Assumes split between local production and imports is based on 2020 figures where 13% of billet demand was produced locally, which is assumed until 2040
2. 2020-2030 is based on steel intensity using GDP and population growth; 2035- 2040 is projected based on 2010-2020 CAGR
3. Assumed ~100,000 MT produced by AGI via DRI and melting shop (before their additional capacity at Mombasa comes online in 2022)

Source: Trademap, James F. King (JFK), World Steel Association

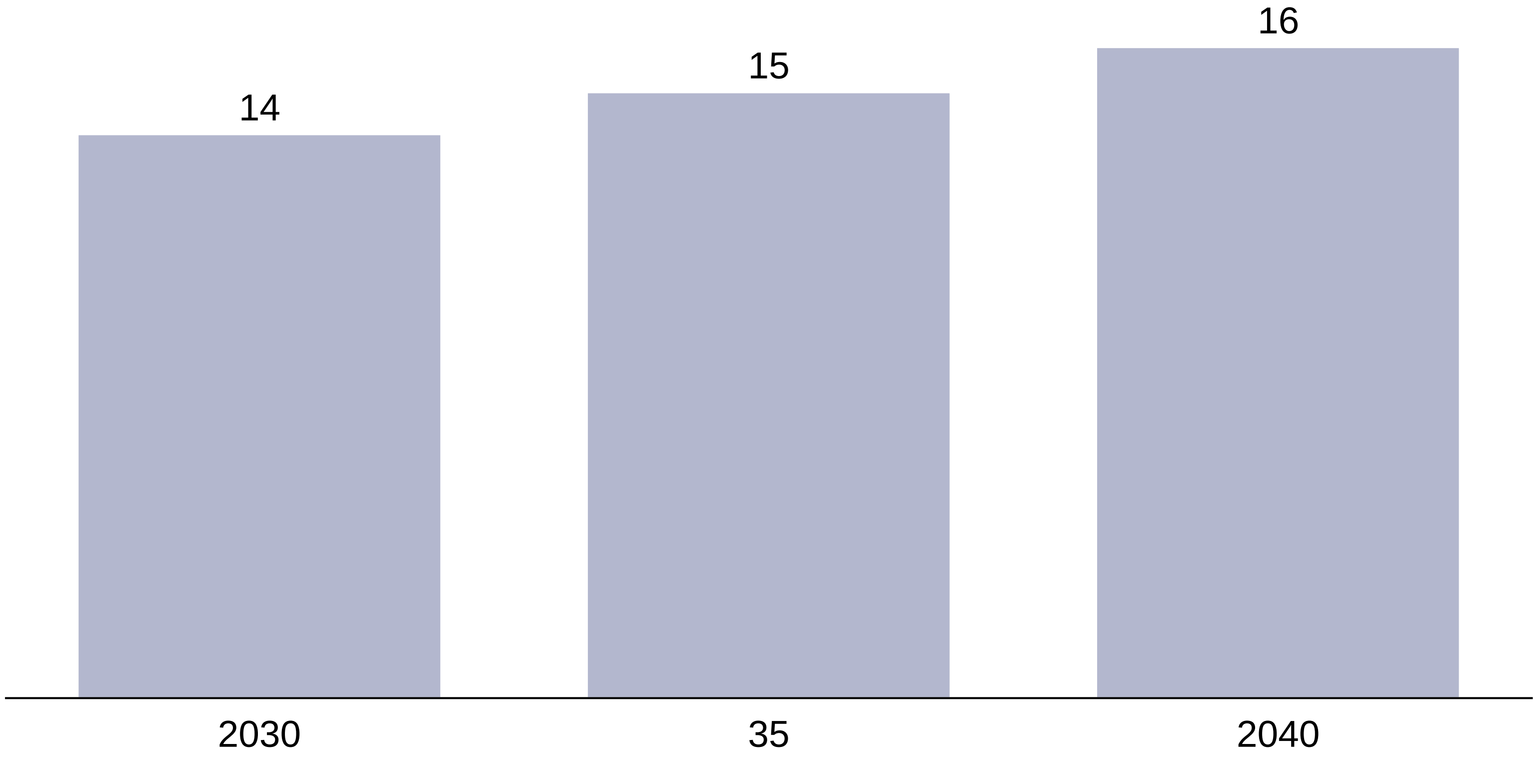
Kenya's annual demand for steel billets may grow by 7% p.a. from 2020 to 2040, based on steel intensity and historical CAGRs

This could be driven by the boom in the construction industry and the introduction of a new Induction heating plant by Devki by the end of 2022, and a potential 1-2 additional DFI or Bf-BOF plants introduced by 2040

Assumption that iron ore is imported, and government incentivizes steel production, therefore yielding to 2-3 additional DFI plants in the future

B. By 2040, Kenya could demand ~16,000 MT of green hydrogen for billet production via BF-BOF

Demand for green hydrogen for steel billets produced in Kenya, 000’ MT



1. 2020-2030 is based on steel intensity using GDP and population growth; 2035- 2040 is based on the past 11-year CAGR scenario

Source: Trademap, James F. King (JFK), World Steel Association

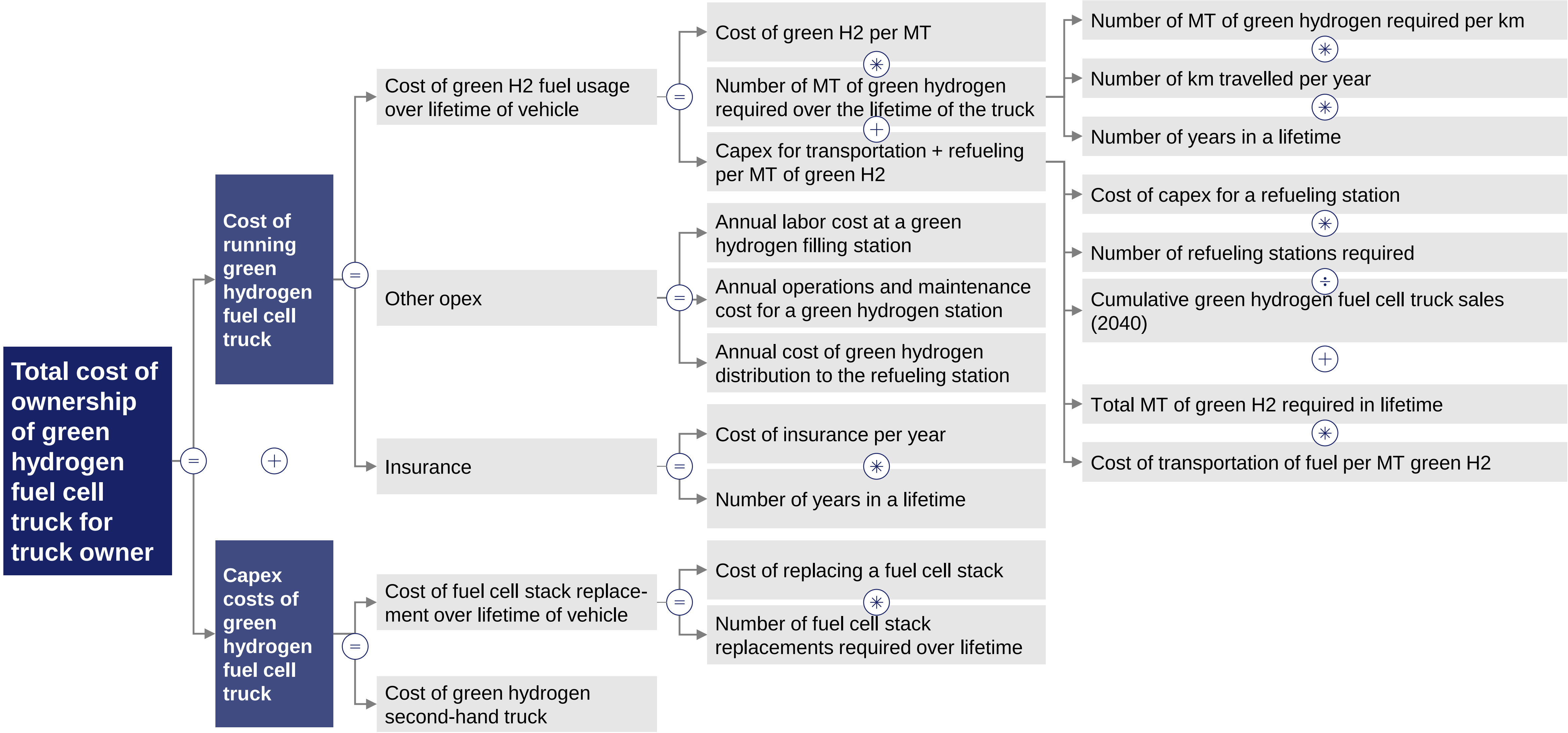
Assumes that in 2040, Kenya produces ~300,000 MT of steel (billets), or ~1/8 of the total billet demand

This assumes that the same proportion of demand that is met by local production in 2020 (i.e., ~1/8) persists for 2040, and would need to assume that iron ore is imported, and that the government incentivizes local production

Demand for green hydrogen assumes ~19.5kg of green H2 per MT of steel produced via blast furnace

Appendix

We estimate the total cost of ownership by estimating the cost of running the vehicle and the cost of the vehicle



Total cost of ownership of green hydrogen fuel cell truck for truck owner

=

Cost of running green hydrogen fuel cell truck

+

Capex costs of green hydrogen fuel cell truck

Cost of running green hydrogen fuel cell truck =

Cost of green H2 fuel usage over lifetime of vehicle

Other opex

Insurance

Cost of green H2 fuel usage over lifetime of vehicle =

Cost of green H2 per MT

*

Number of MT of green hydrogen required over the lifetime of the truck

+

Capex for transportation + refueling per MT of green H2

Number of MT of green hydrogen required over the lifetime of the truck:

Number of MT of green hydrogen required per km

*

Number of km travelled per year

*

Number of years in a lifetime

Capex for transportation + refueling per MT of green H2:

Cost of capex for a refueling station

*

Number of refueling stations required

÷

Cumulative green hydrogen fuel cell truck sales (2040)

+

Total MT of green H2 required in lifetime

*

Cost of transportation of fuel per MT green H2

Other opex =

Annual labor cost at a green hydrogen filling station

Annual operations and maintenance cost for a green hydrogen station

Annual cost of green hydrogen distribution to the refueling station

Insurance =

Cost of insurance per year

*

Number of years in a lifetime

Capex costs of green hydrogen fuel cell truck =

Cost of fuel cell stack replacement over lifetime of vehicle

Cost of green hydrogen second-hand truck

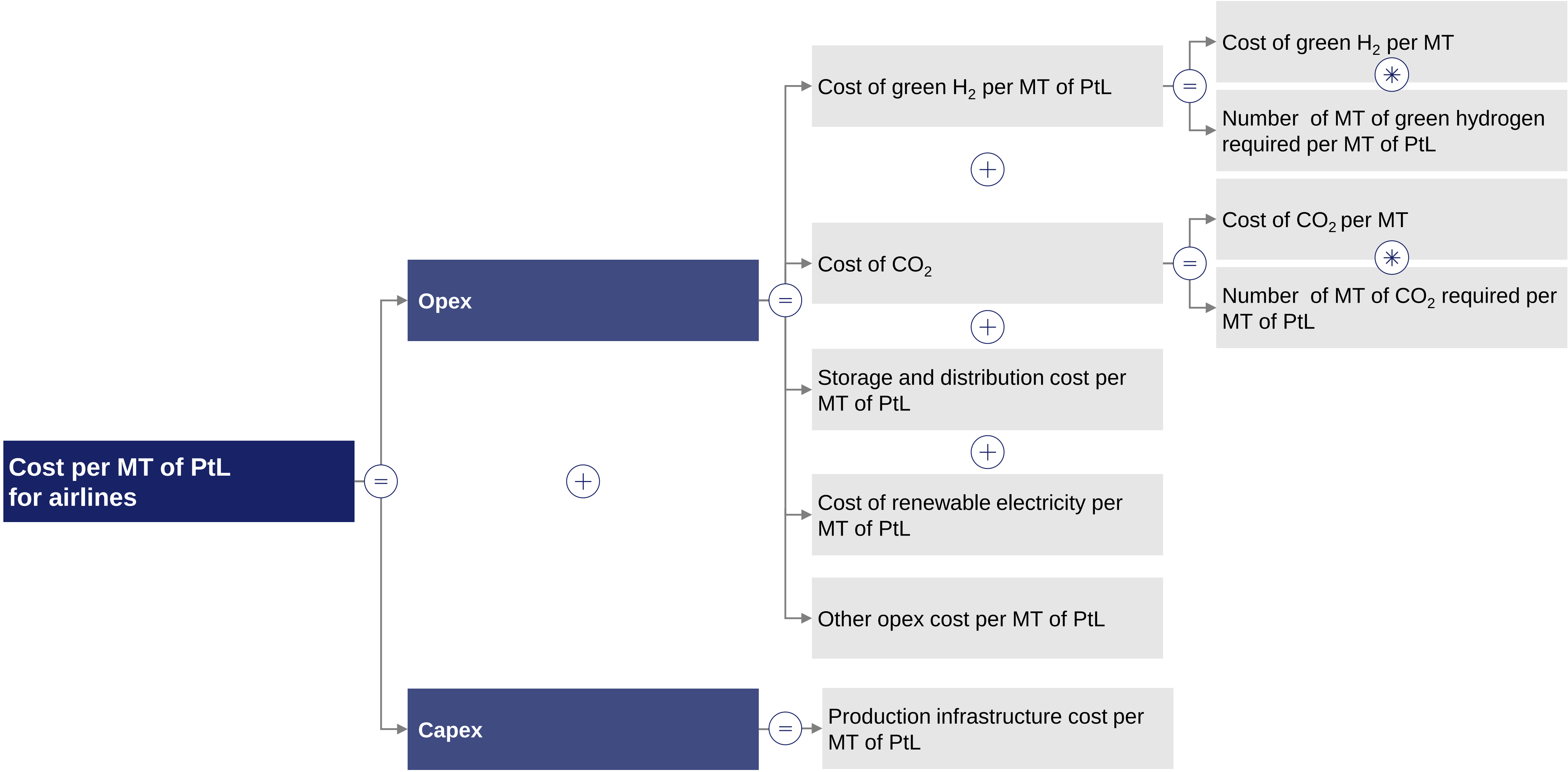
Cost of fuel cell stack replacement over lifetime of vehicle =

Cost of replacing a fuel cell stack

*

Number of fuel cell stack replacements required over lifetime

For Kenya, we estimate the costs per MT of PtL by estimating costs of green H_2, feedstock, and capex required for production



Cost per MT of PtL for airlines

Opex

Capex

Cost of green H_2 per MT of PtL

Cost of CO_2

Storage and distribution cost per MT of PtL

Cost of renewable electricity per MT of PtL

Other opex cost per MT of PtL

Production infrastructure cost per MT of PtL

Cost of green H_2 per MT

Number of MT of green hydrogen required per MT of PtL

Cost of CO_2 per MT

Number of MT of CO_2 required per MT of PtL