BCG BOSTON CONSULTING GROUP

Unleashing Brazil's Low-Carbon Hydrogen potential

Brazil Climate Report 2023

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About this report

Objective	This report is a BCG vision for Brazilian leaders, decision-makers and citizens to catalyze efforts, tackle challenges & maximize value from opportunities intrinsic to BR during the transition of World's economy to Net-Zero (2020-50).
Audience	This report was built for all those willing to drive actions against Climate Change (e.g., investors, board members, executives, entrepreneurs, academia, etc.), with the focus of leveraging Brazil's green agenda and potential
Data	This document is a compilation of public information and BCG expertise, carefully selected, to bring numbers and facts to Climate discussions and decision-making. Its analysis are subject to rapidly evolving technologies and business models and should be revisited and updated accordingly.
Special thanks	BCG is thankful to the support received by the entire organizing team of Brazil Climate Summit, especially to all Brazilian students at Columbia University who contributed to accelerating the path to Net-Zero (www.brazilclimatesummit.com)

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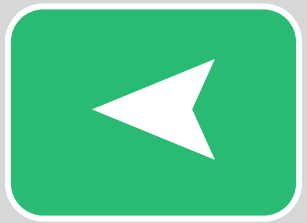

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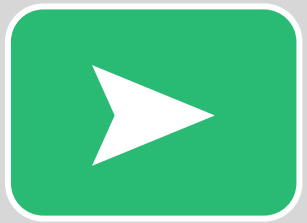

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Click to deep-dive on more detailed content on topic

Why the hype around Low Carbon Hydrogen (LC H_2)?

LC H_2 is a breakthrough alternative to decarbonize hard to abate sectors

Industry

Transport

Building and Power

Hard-to-abate sectors mostly impacted by LC H_2

Note: Low Carbon refers preferably to production of H_2 with renewable sources but also includes other alternatives with lower emissions when compared with current technology

Hard-to-abate sectors Net Zero pathways will rely on Low Carbon H_2

Avoid

Circularity

Reduce use of material and feedstock

Material & process efficiency

Improve energy efficiency using state-of-the-art technologies

Replace

Electrification

Process electrification

Power to X

Low Carbon H_2

Biobased solution

Feedstock switch

Energy

Ethanol to H_2

Biomethane to H_2

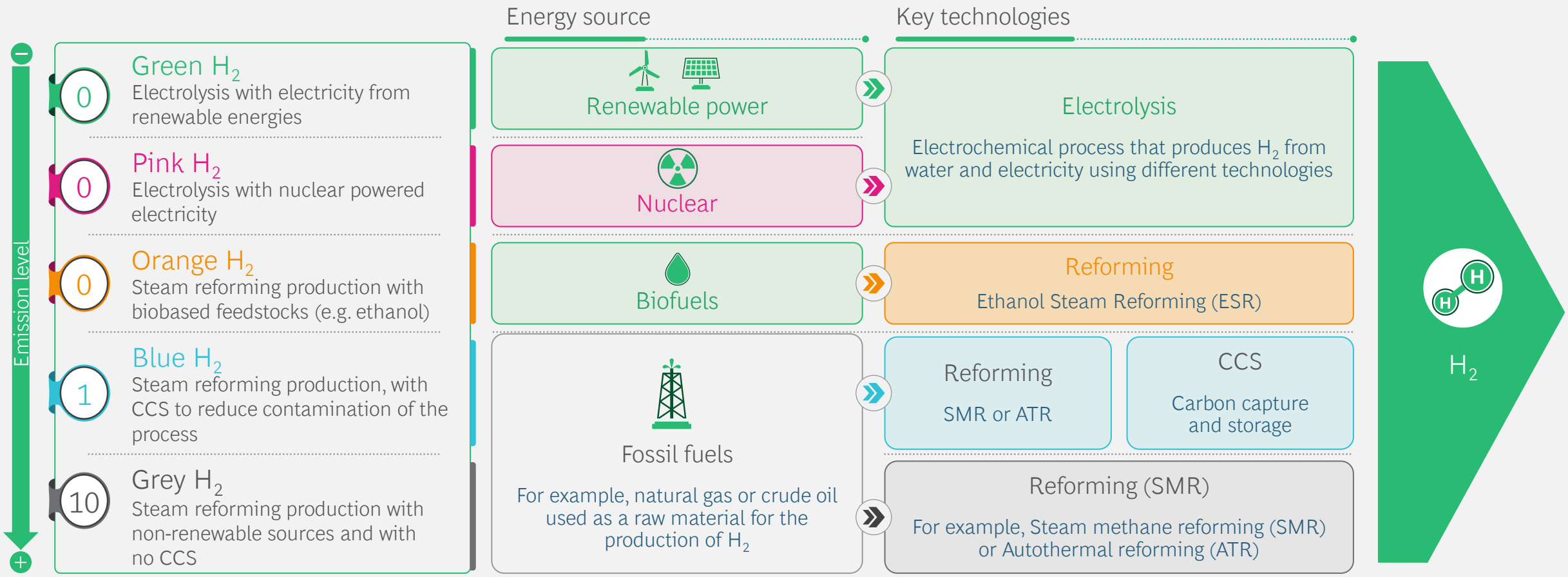
Capture

Carbon Capture, Usage and Storage

Capture process-related carbon byproduct and store or use them to prevent emissions

Focus of this report

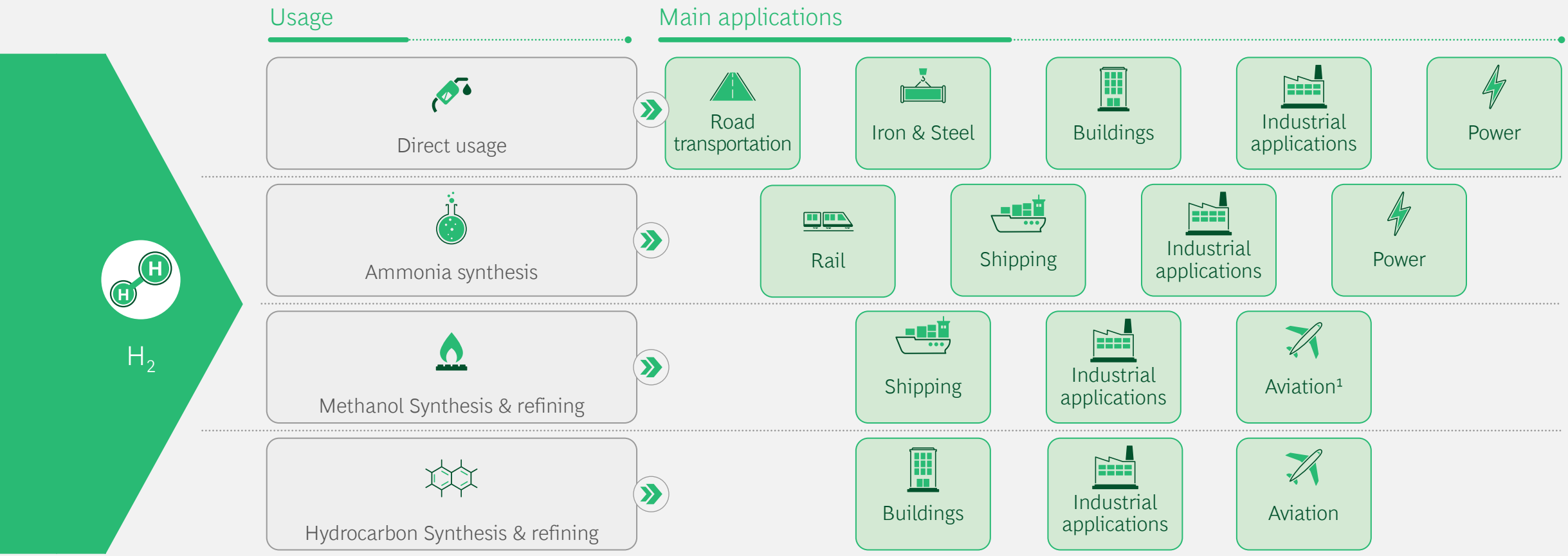
LC H_2 Production | Low carbon pathways allow lower emissions for H_2 production



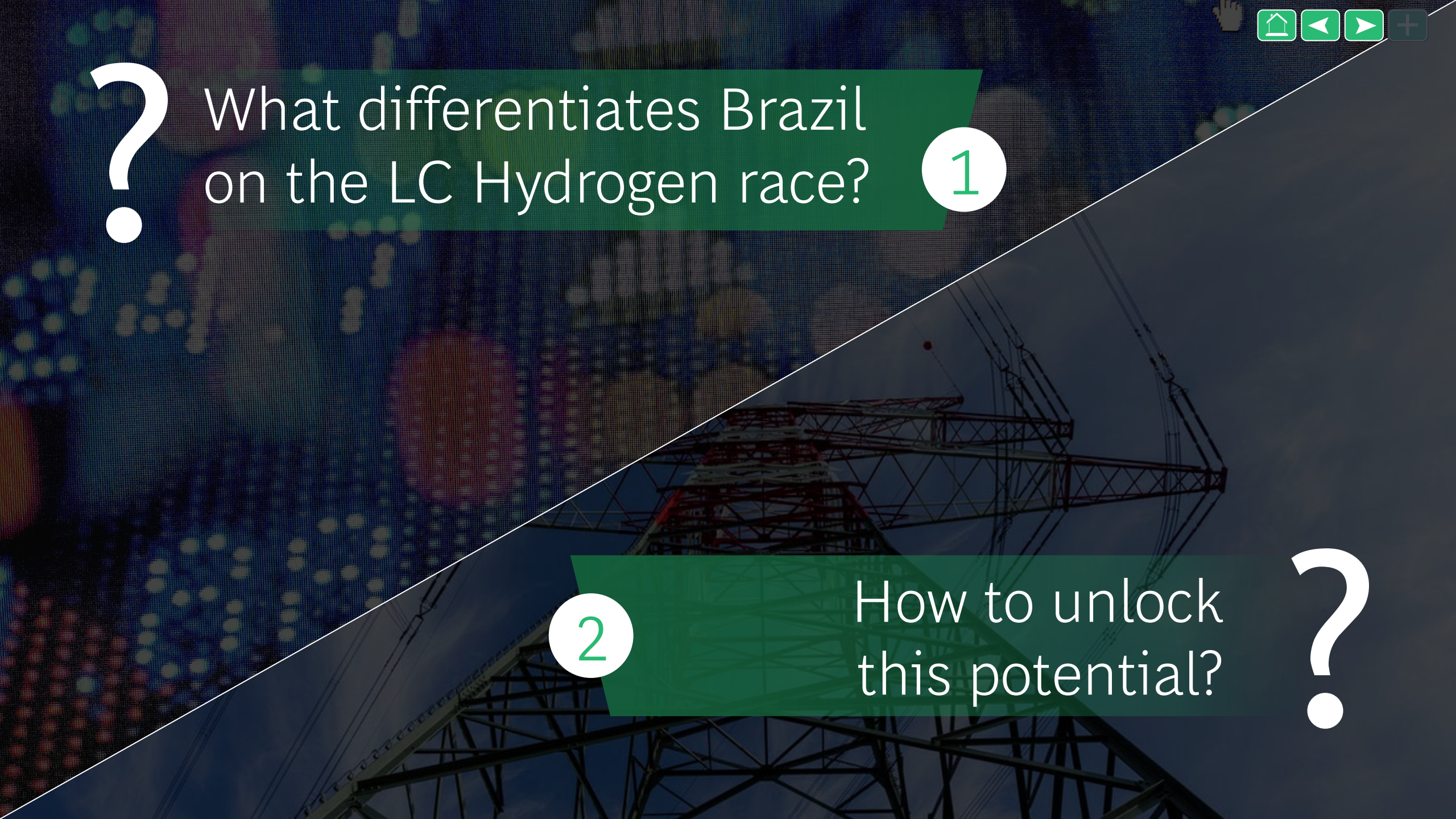
(X) CO_2 emission from the process (Kg CO_2 eq/kg H_2)

Note: CCS: Carbon capture and storage; SMR: Steam methane reforming; ATR: Autothermal reforming
Source: BCG analysis

LC H_2 Usages | Many hard to abate sector could be impacted by hydrogen and its derivatives



1. Methanol as a path to produce E-Kerosene
Source: BCG analysis


What differentiates Brazil on the LC Hydrogen race?
1
2
How to unlock this potential?

What differentiates Brazil on the LC Hydrogen race?

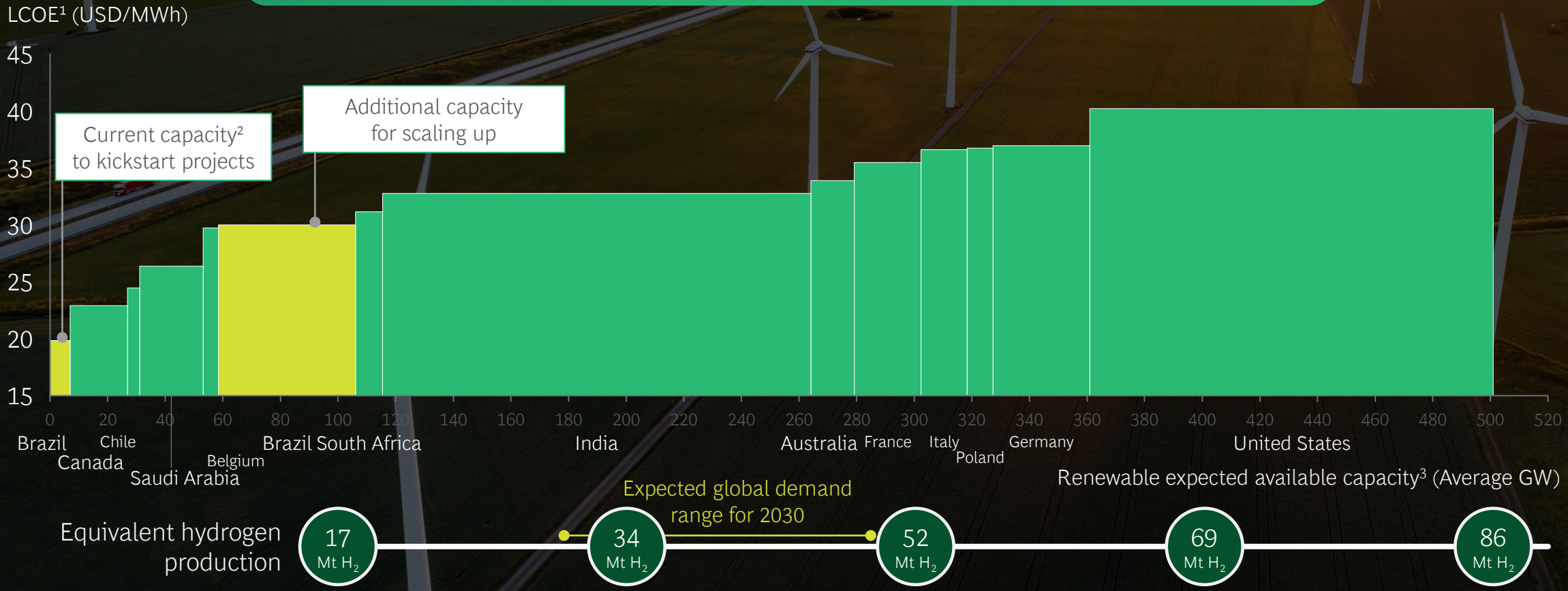
1

Extremely favorable starting point to lead low Carbon Hydrogen supply

Competitive energy costs	Low-cost and available clean energy with scale-up potential
Renewable power grid	Interconnected grid allowing higher utilization in compliance with EU rules
Local demand to boost export journey	Hard to abate industries kick-starting large export-led journey

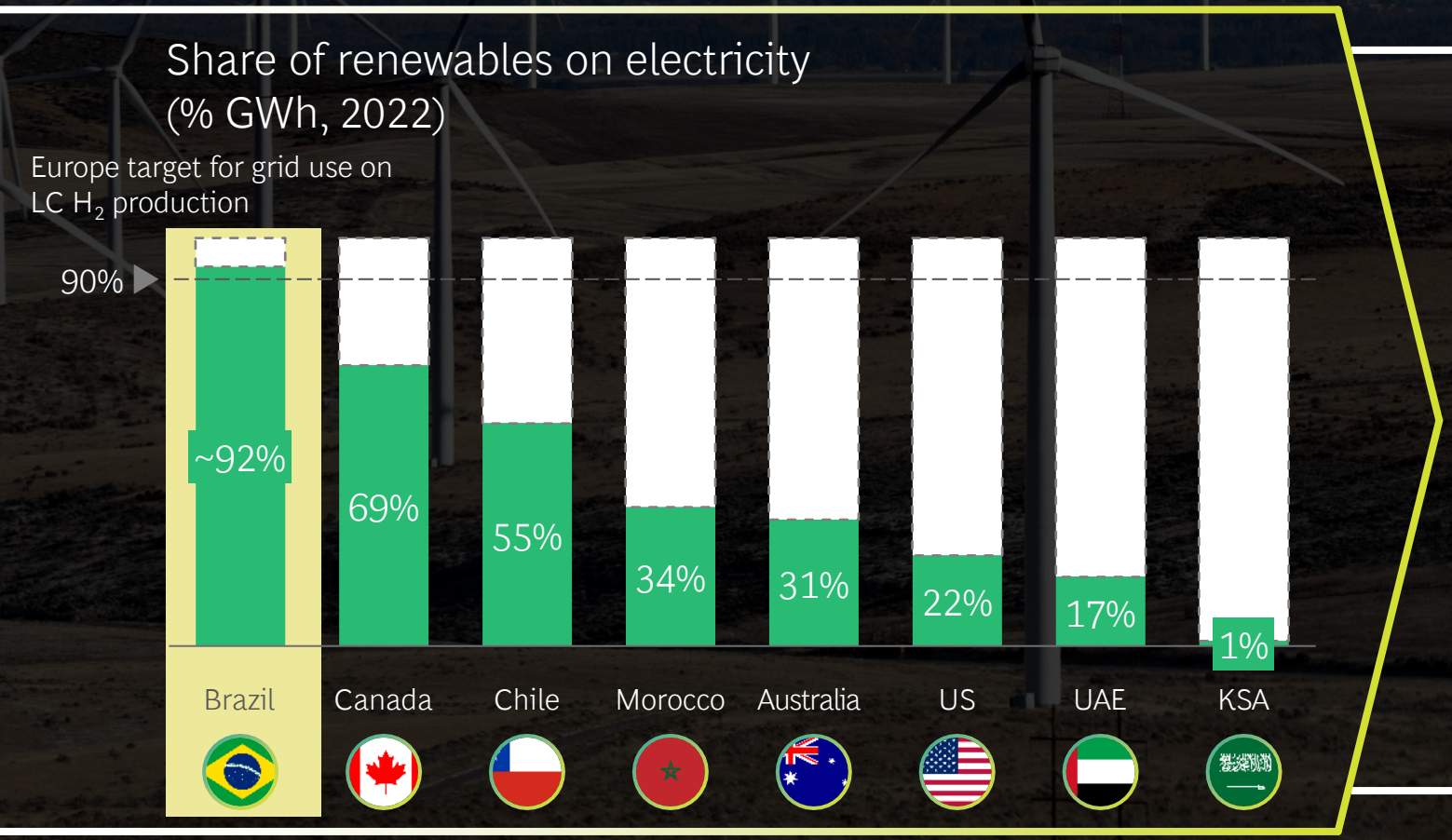
Competitive power | Low-cost and available clean energy with scale-up potential

Countries comparison considering renewable scalability and LCOE (2030)



1. Levelized Cost of Energy 2. Considering 24/7 supply, all other LCOE figures considering power availability when produced 3. Projected added renewable generation capacity until 2030
Note: LCOE doesn't consider any taxes, charges and tariffs. | Source: EnerData; BCG analysis

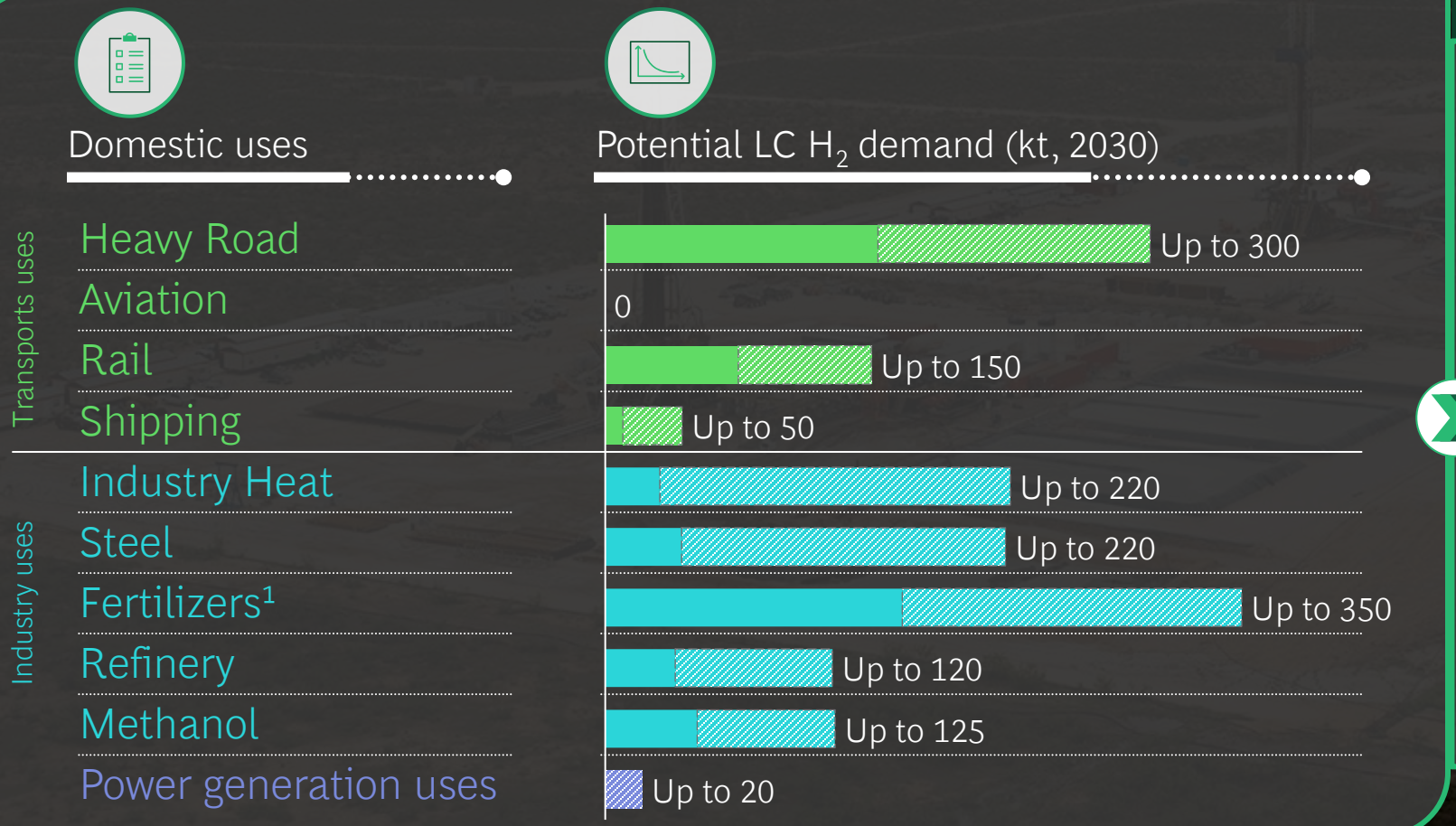
Renewable power matrix | Interconnected grid allowing higher utilization in compliance with EU rules



- ✓ Interconnected grid with 90%+ renewable supply allowing 24x7 operations
- ✓ +10pp in electrolyzer utilization reduces ~3-6% LC H_2 total production costs

Note: Countries shown were prioritized as key potential low carbon H_2 hubs for having lowest production costs
Source: EnerData, Irena; IEA World Energy Outlook 2022, BCG analysis

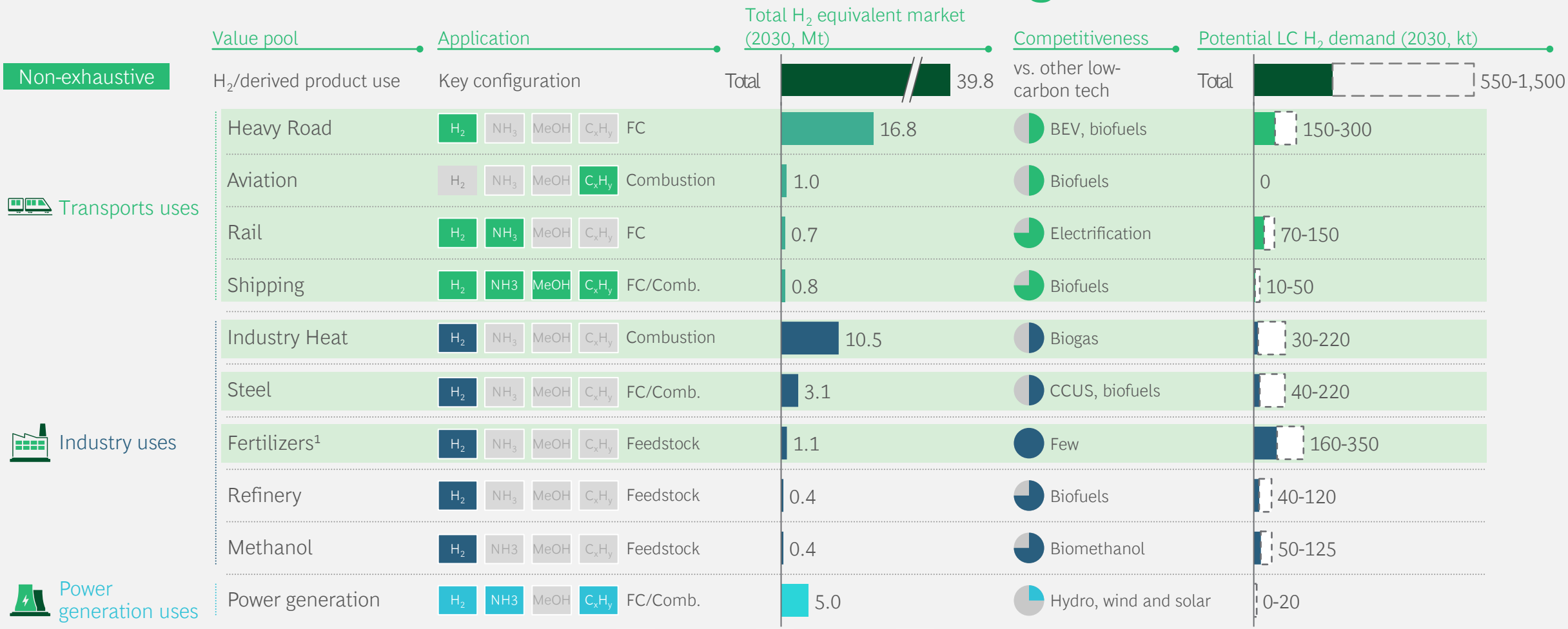
Local demand to boost exports | Hard to abate industries kick-starting the journey…



- Expected local demand of 0.5-1.5 Mt in 2030
- Ammonia and methanol use for long haul transport
- Green fertilizer production of low carbon ammonia driving industry uses
- LC H_2 boosting green steel alternatives throughout the value chain (e.g. DRI)

1. Include Ammonia for industrial use
Source: EPE, IEA, CRU Group, BCG analysis

Local Demand for H_2 in Brazil could represent 0.5-1.5 Mt in 2030 and be a base load for kickstarting



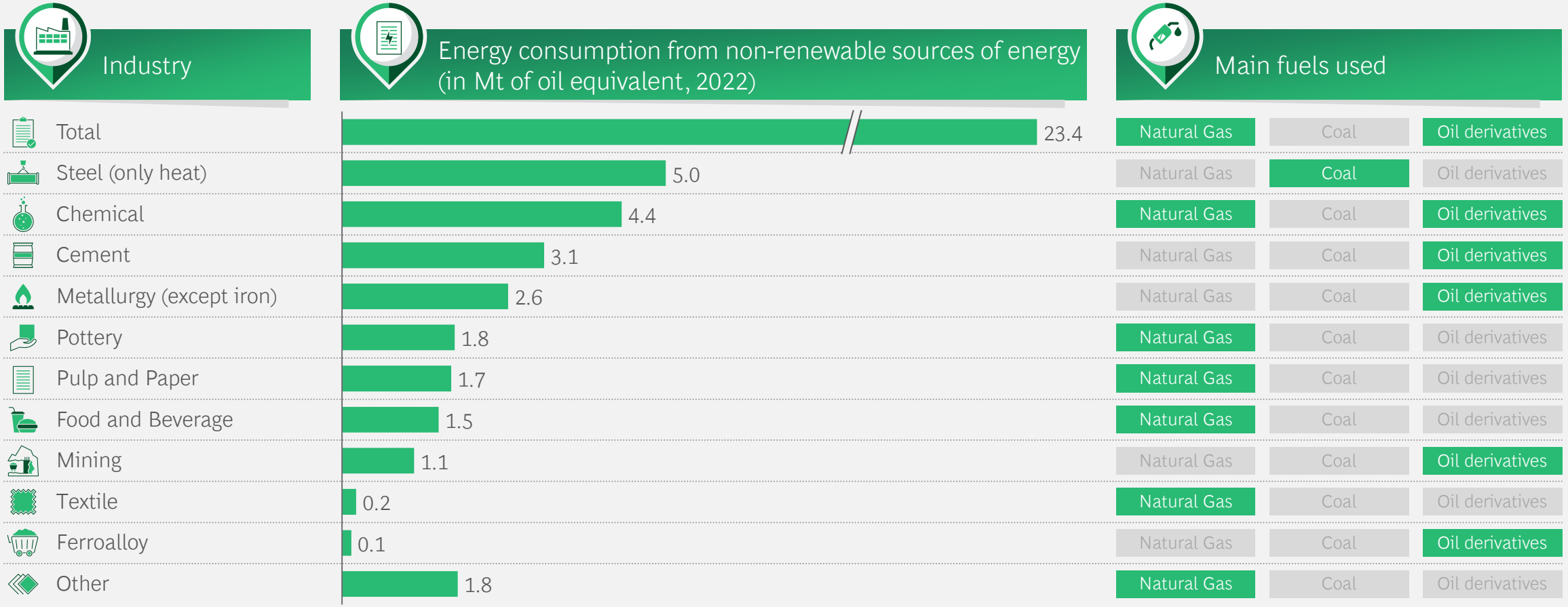
1. Include Ammonia for industrial use; FC: Fuel Cell
Source: EPE, IEA, CRU Group, BCG analysis

Transports | Sustainable fuels are a key lever for net zero – rail and shipping with most favorable perspective

Transport segment	Maturity	Application	Main challenges
Heavy Road		Fuel cell vehicle with green hydrogen as energy carrier (zero direct emissions, allows long range applications and less refuel time)	• Tough competition with other more mature green alternatives (e.g. biofuels and electric vehicles) • EVs more efficient for short distances and (emissions related to grid) • Uncertainty on economic viability vis-à-vis current solutions
Aviation		E-Kerosene (combination of green hydrogen and carbon dioxide captured from atmosphere)	• E-Kerosene production technically feasible but yet immature • Major security concerns • Power density of fuel cells to be increased to reduce weight
Rail		H_2 and Ammonia (higher energy density than electric batteries, allowing long range applications)	• Significant space requirements for H_2 storage and Hydrogen Refueling Station (HRS) needed in train stations • Safety concerns (H_2 transport) • Ammonia as emerging competitive alternative
Shipping		E-Methanol (similarity to gasoline in handling) E-Ammonia (fully carbon-free and no harmful emissions)	• Matured and cost proven technology • Vessel design adjustments (e.g., storage spaces) • Conversion of engines • High safety standards

Source: IEA, Sustainable Aviation Jet Fuel Report 2020, BCG analysis

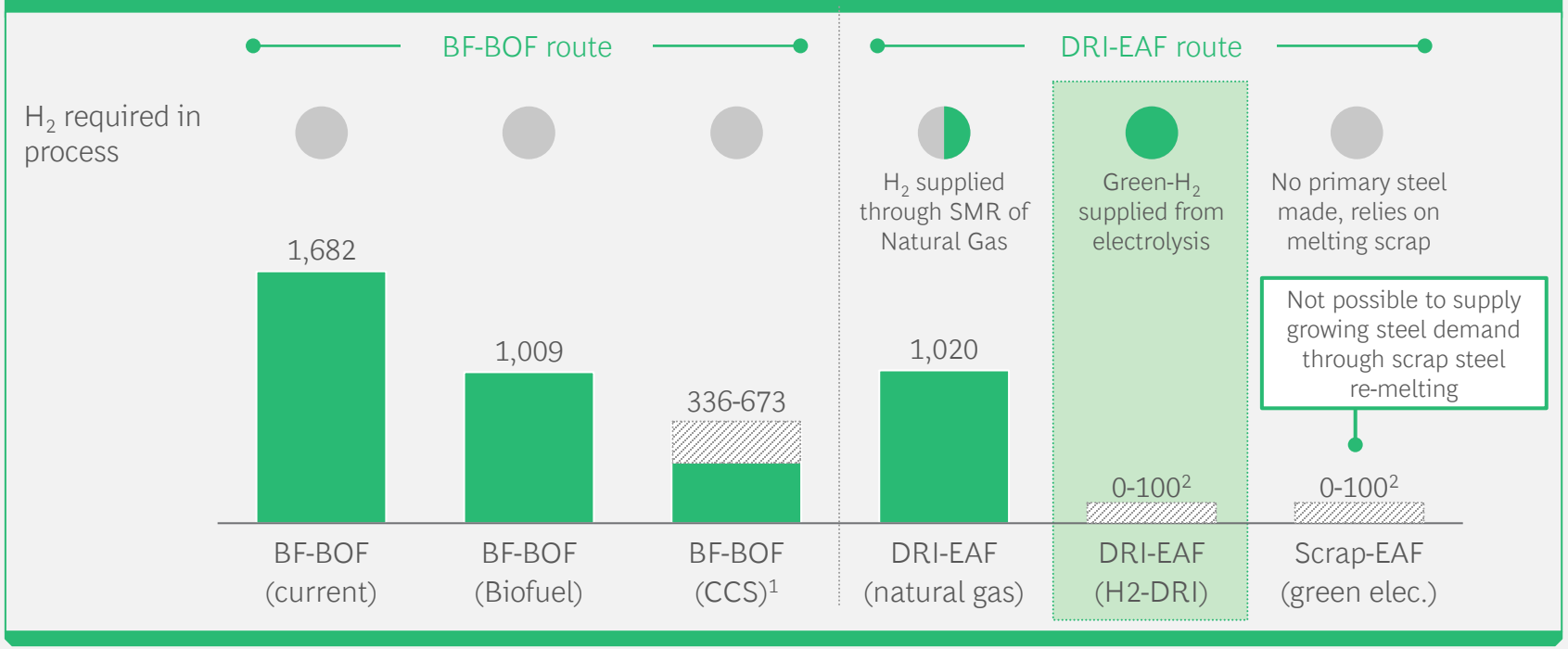
Industry Heat | Steel, Chemical and Cement industries represent ~50% of heat from non-renewable sources



Source: EPE, PDE, BEN, BCG analysis

Steel | Decarbonization will require significant green H_2 as input

Emissions intensity of crude steel production routes
kg CO2e/tonne crude steel



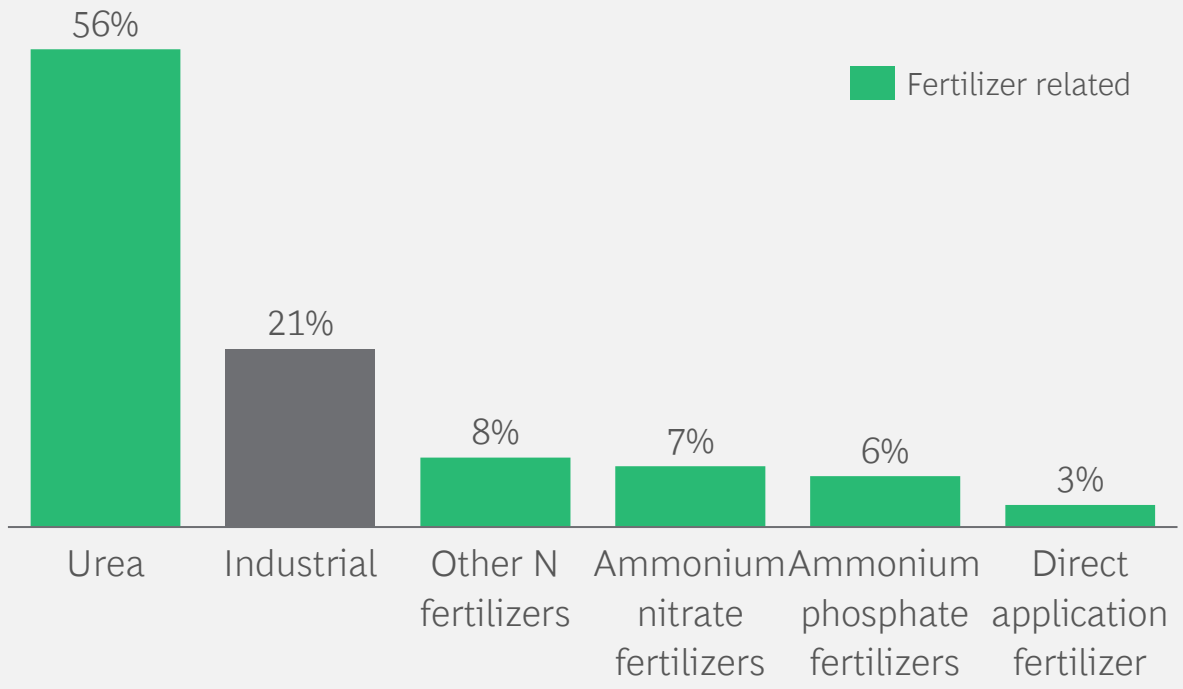
1. Estimates suggest that it is possible to capture 60-80% of the CO2 emissions produced during BF-BOF steelmaking 2. Emissions may be non-zero due to the CO2 emissions of upstream processes such as iron ore mining, as well as CO2 emissions from carbon & lime use, as well as graphite consumption in electrodes
Source: IEA, Eurofer, Vogl & Åhman "Towards a strategic decision tool for decarbonising EU steel"

- H_2-DRI the most promising de-carbonisation option for steel production
- Significant green H_2 will be required to meet long-term demand
- Green hydrogen could replace coal on the process to reduce the iron pellets into metallic iron

Fertilizers | Low carbon ammonia as pathway to reduce footprint of growing fertilizer demand

~75-80% of ammonia demand is related to fertilizers…

Ammonia applications 2019 (% of total global demand)



…and increasing fertilizer demand call for decarbonization of ammonia production

Growing global population coupled with limited land growth will drive fertilizer demand as key for sustainable production of food

- Enable 50% of global food production
- Enhance agricultural productivity, avoiding GHG from land use change
- Stimulate CO_2 uptake by crop

Green ammonia is currently the most feasible green alternative to substitute fossil fuels

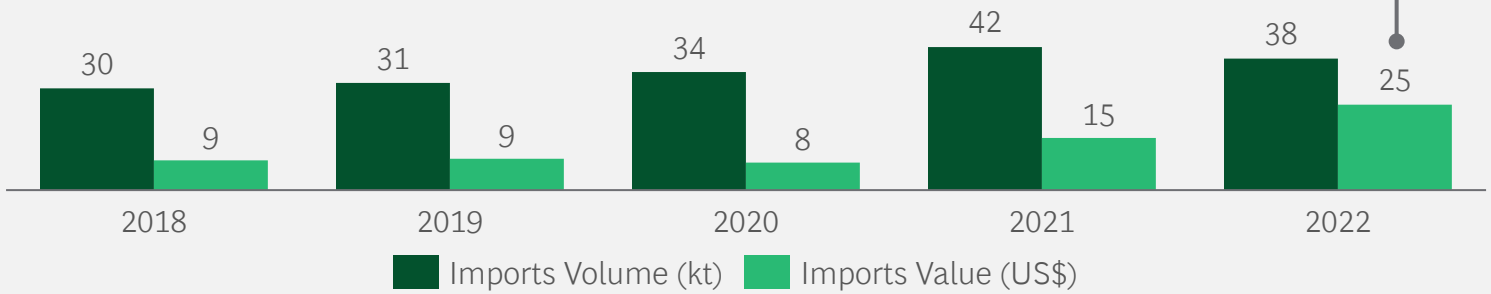
- Primarily H_2 derived from natural gas and coal is used for the ammonia synthesis, emitting 1.5-2.5 tonnes of CO_2/t of ammonia produced
- Green ammonia can substitute fossil fuels in H_2 production without CO_2 emissions

Source: Nexant, IEA, BCG analysis

Fertilizers | Brazil is a major importer of fertilizers – LC H_2 could contribute to revert the trend

~85% of total fertilizers used in Brazil are imported from other countries - prices are on peak in 2022…

Russia-Ukraine war drove strong price growth between 2021-2022 (~2x more expensive) as Russia accounts for ~25% of total imports volume



…Green ammonia may have a significant role on developing competitive local fertilizer industry

Currently, Brazil not a leading fertilizer producer

- ICMS taxes results in low competitiveness vs. imports
- Limited natural resources in Brazil to produce key fertilizers (NPK fertilizers) which require natural gas, sulphur and other mineral raw materials

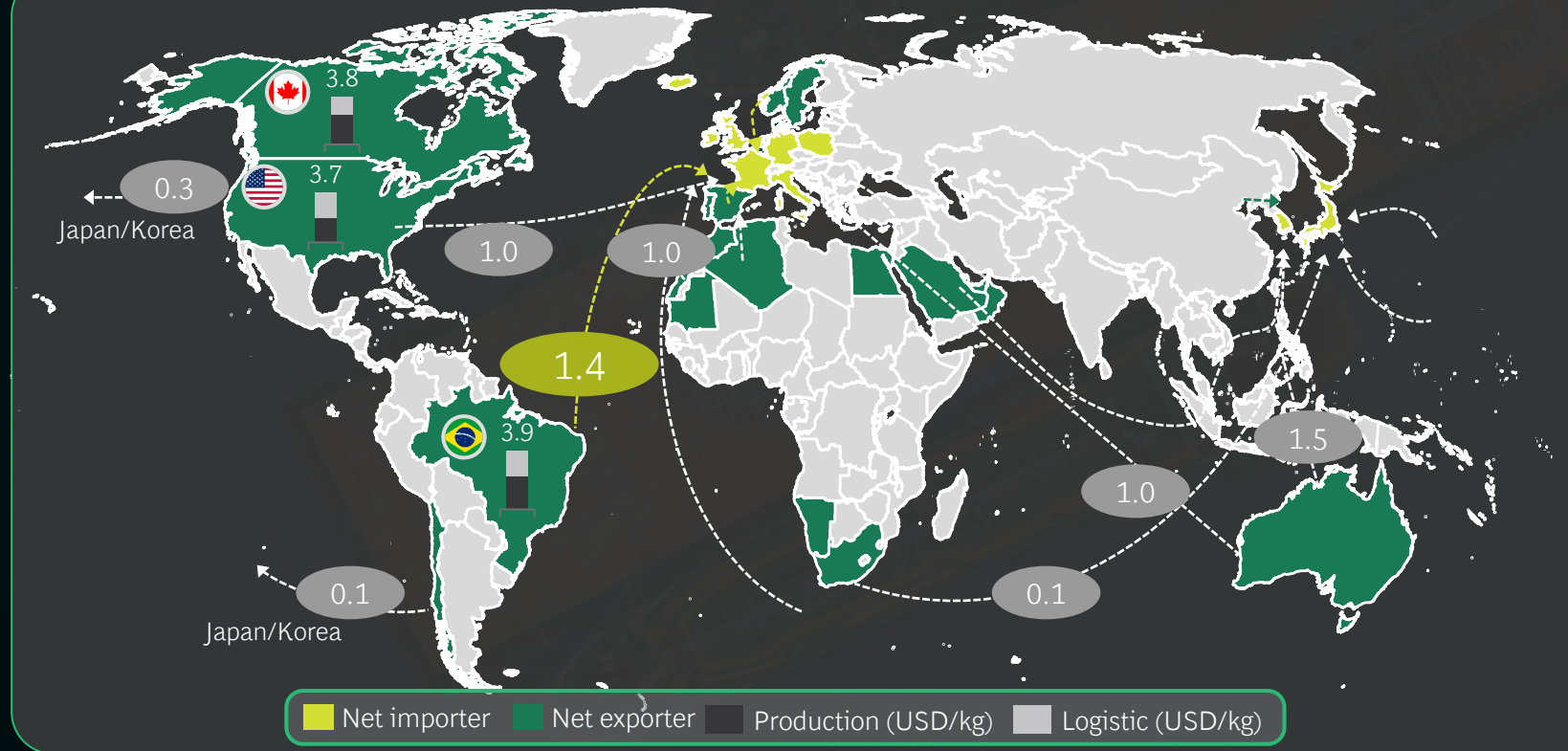
Although not self sufficient, Brazil plans to strengthen local fertilizer industry by 2050

- Brazil's National Plan for Fertilizers expect investment incentives to support a 35% growth for local production by 2050 to reduce imports dependency, but still not enough given agribusiness market size and expected growth in Brazil
- Green ammonia production through renewable energy as alternative to traditional natural gas pathway better leveraging Brazilian natural resources and competitiveness

Source: Ministry of Development, Industry and Foreign Trade, Anda, ComexStat, BCG analysis

…while Brazil's advantages could address ~15% of LC H_2 global trade flows, mostly to Europe

Expected global trade flows of LC H2 in 2030 (Mt, 2°C path scenario)



Brazil's export trajectory

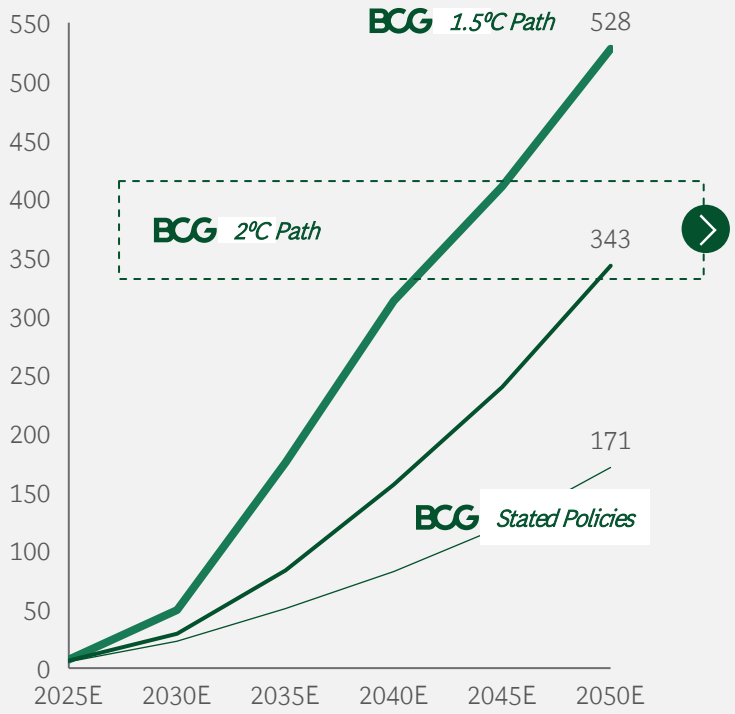
- First wave focused on exporting H_2 derivatives to Europe for chemical industries, fertilizers and ocean shipping
- Post 2030, new technology allowing, could tackle direct H_2 transport

Note: High uncertainty on potential for China, Russia and Argentina also becoming net exporters by 2030. Other countries are neutral/unclear
Source: BCG analysis

Different scenarios indicate ~340-530 Mt low-carbon hydrogen market by 2050

Low-carbon H_2 demand by scenario

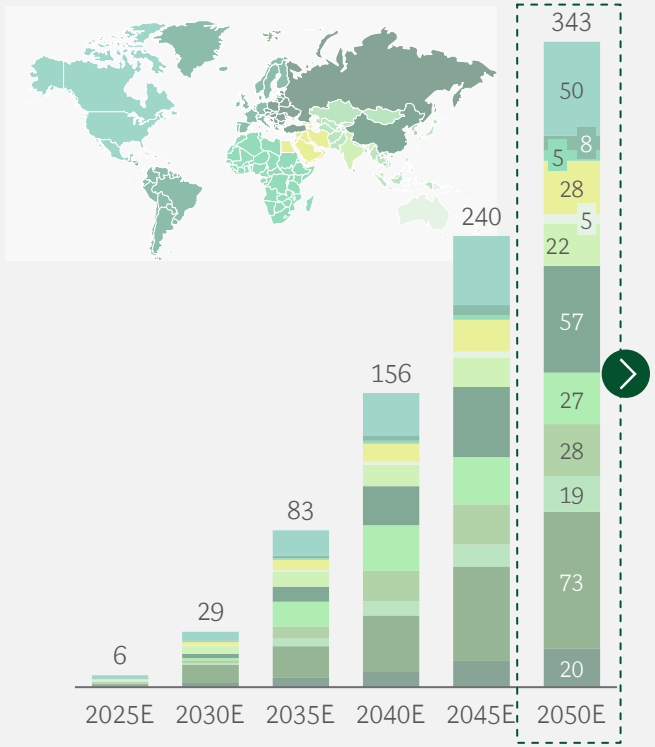
2025-2050 total global demand (Mt[1])



BCG 2ºC Path

Low-carbon H_2 demand by region

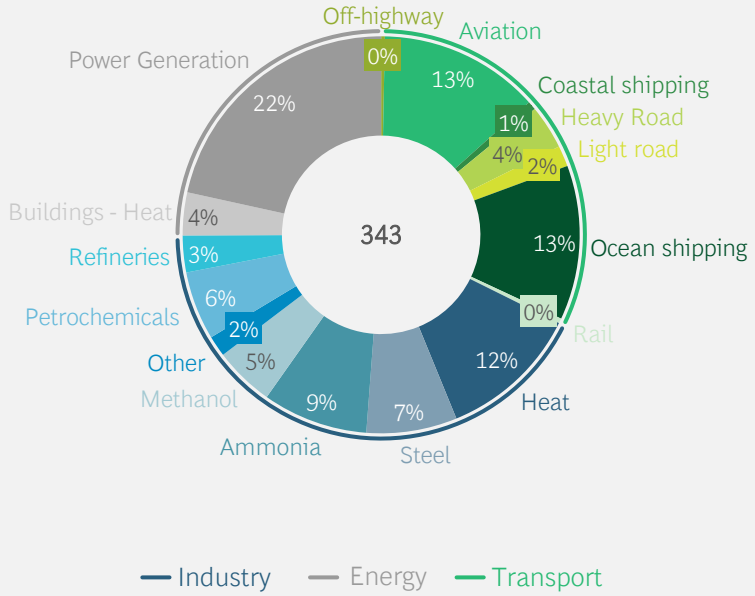
2025-2050 total global demand (Mt[1])



BCG 2ºC Path

Low-carbon H_2 demand by application

2050 total global demand share (Mt[1], %)

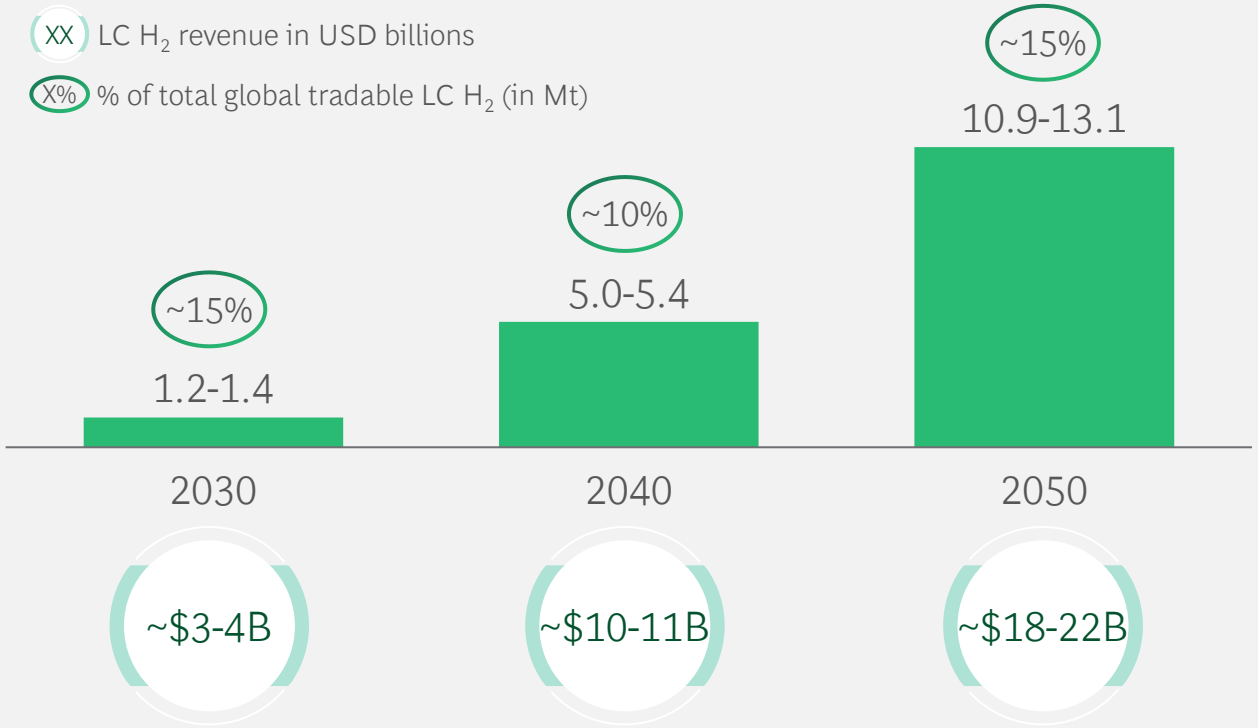


1. H_2 derivatives are normalized to H_2 input required

Source: IEA World Energy Balances, IEA WEO 2021, GlobalData, Nexant, BCG analysis

Brazil could capture ~10-15% of global exports; +10Mt by 2050

Expected Brazil's international demand for low carbon hydrogen
(Mt, USD)



Notes: Considering 2.6$/Kg H_2 in 2030, 2.0$/Kg H_2 in 2040 and 1.7$/Kg H_2 in 2050; Demands ranging from scenarios for climate change: 2º path and 1.5º path
Source: BCG analysis

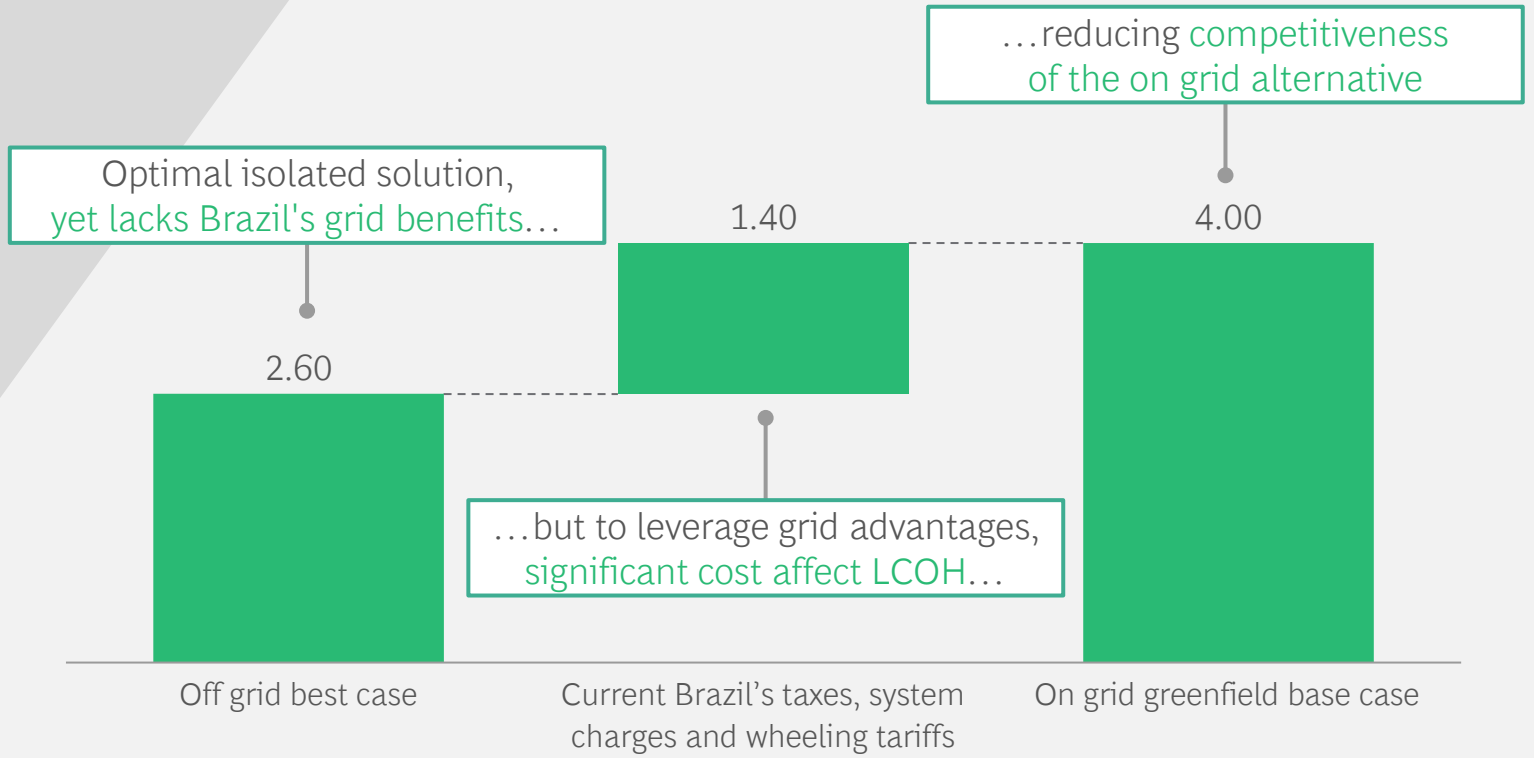
- Exports demand is the most relevant market for Brazil (~107 Mt and ~$180B global tradable hydrogen market by 2050)
- Brazil potentially well positioned to supply Europe (~60% of global imports by 2050) with low production cost, low shipping distance and high capacity
- Additionally to capturing share in Europe, Brazil could also seek to approach Japan and Korea as alternative
- Tough competition with other regions with more mature incentives (e.g. Middle East, US, North Africa, Australia)

How to unlock this potential?

2

The advantages do not translate into cost competitiveness…

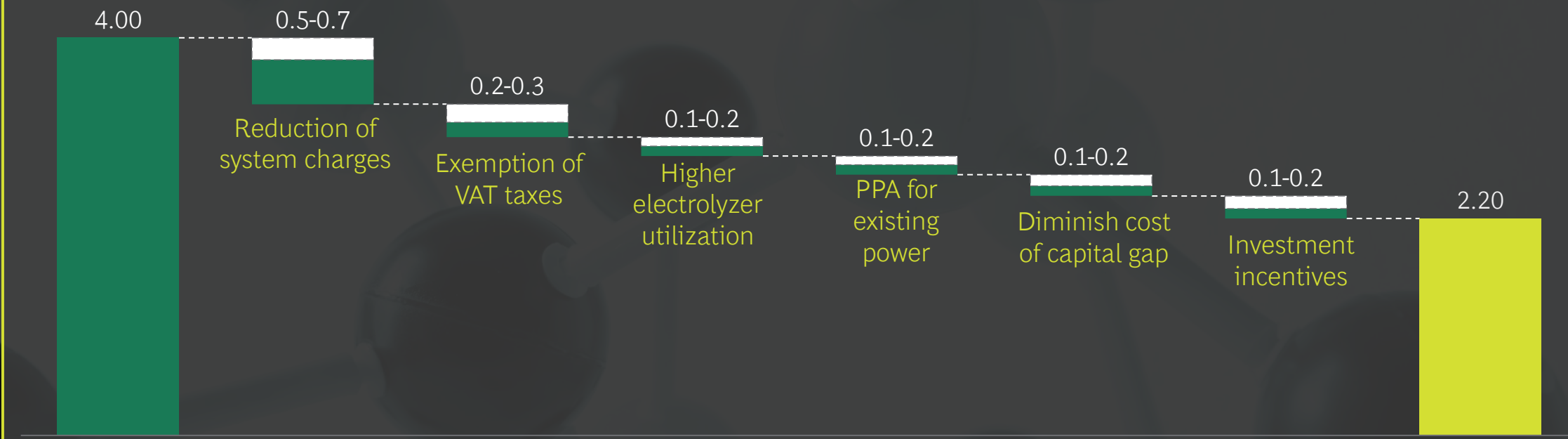
On grid breakdown of production cost of LC H_2 in Brazil (2030, USD/kg)



Source: BCG analysis

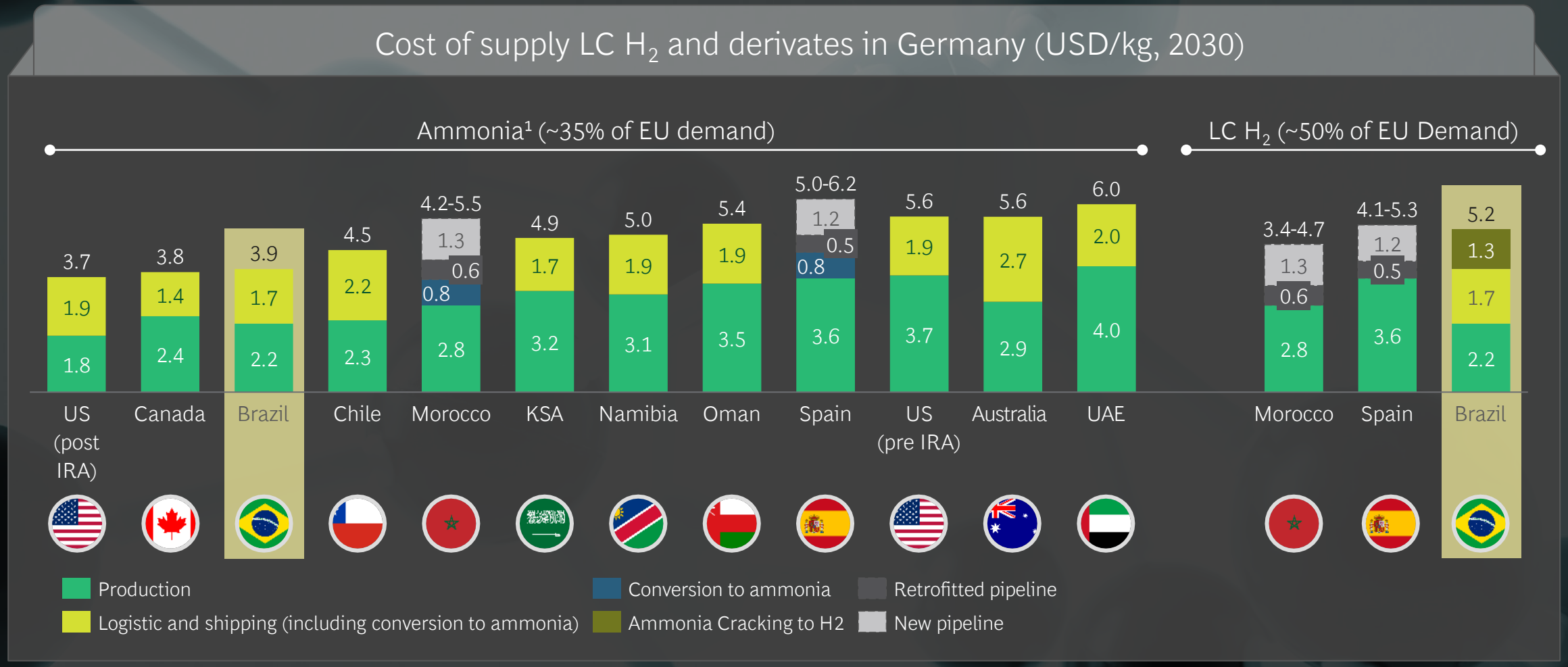
…requiring six levers to enhance attractiveness of Brazilian Low Carbon H_2

Levers to enhance competitiveness of LC H_2 in Brazil (2030, USD/kg)



Source: BCG analysis

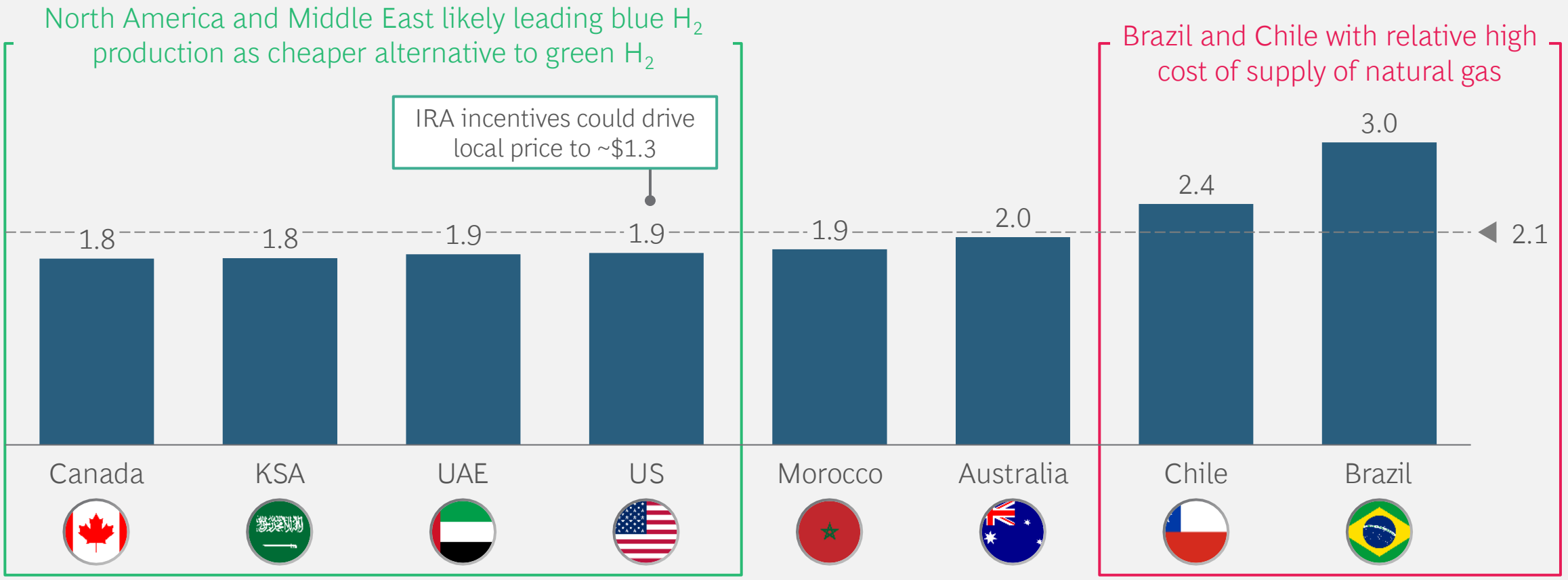
Although neighboring countries cheaper on direct H_2 supply, Brazil has cost effective ammonia delivered to Europe



Note: 1. Includes H_2 derivatives (e.g. ammonia and methanol)). Blue H_2 as ~15% of total LC H_2 demand in Western Europe (2030)
Source: BCG analysis

Natural gas cost of supply affects Brazil competitiveness for blue hydrogen production

Production cost of blue hydrogen by country (2030, USD/kg)

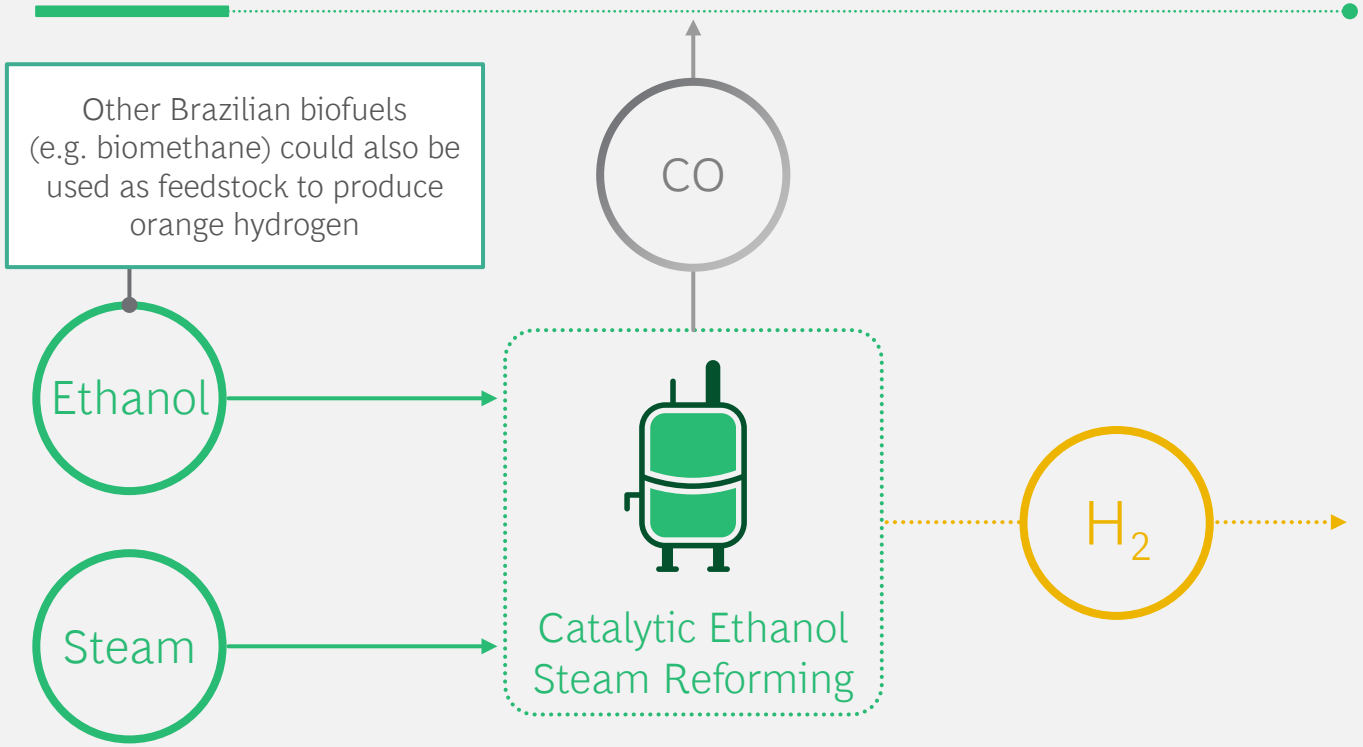


Note: Countries shown were prioritized as key potential low carbon H_2 hubs for having lowest production costs; Considering region with lowest local production cost on each country
Source: BCG analysis

Orange H_2 can be produced from biomass such as Ethanol

Illustrative

Schematic process flow diagram of the Ethanol Steam Reforming process to produce green hydrogen



Source: CGTI, WWF-Brasil, BCG analysis

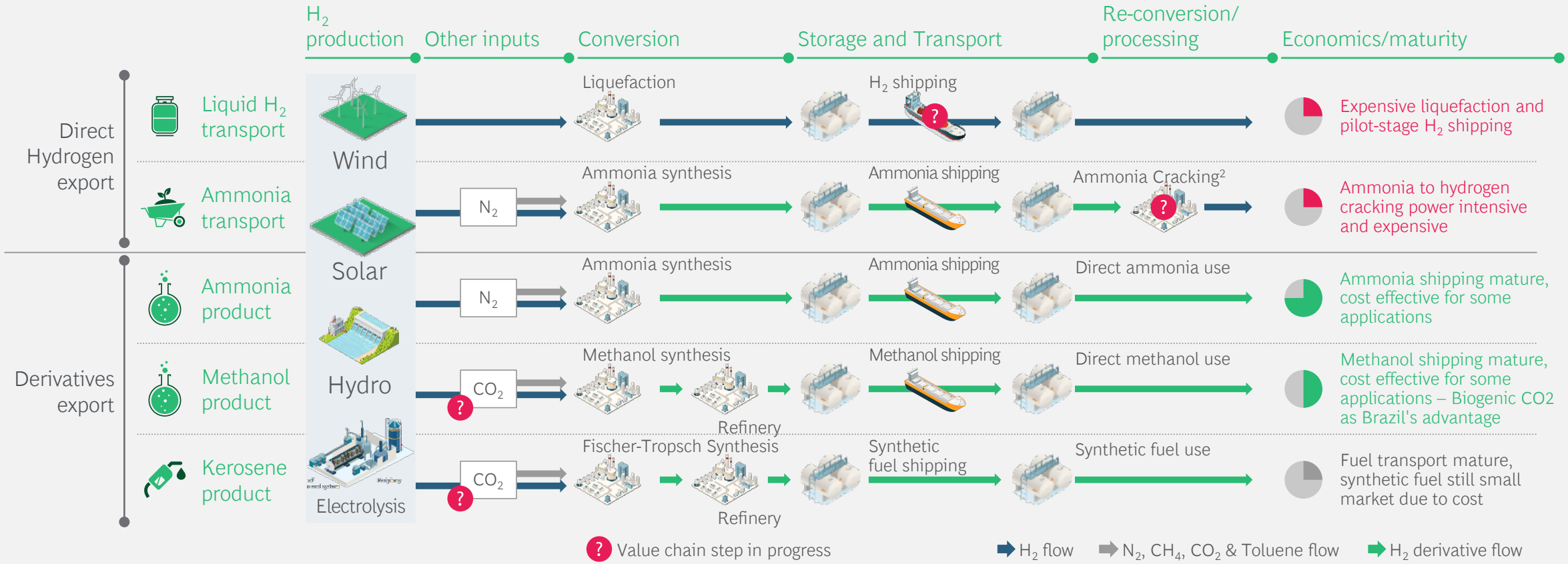
Ethanol is a biomass with high hydrogen content and the synthesis process has an efficiency of 80%…

…and hydrogen produced from ethanol is competitive both in cost and carbon footprint vs. electrolysis via solar energy (-28% production costs and -43% carbon footprint)…

…but production technology and infrastructure are still immature and in development phase with partnerships between bioenergy companies and universities

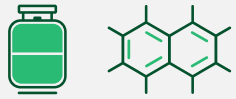
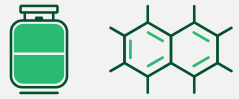
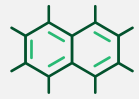
Direct H_2 export likely in the long term, but green ammonia and methanol already mature alternatives

Simplified overview[1]



1. Focus on long distance transportation paths. 2. Other methods exist, but also challenged by energy consumption
Source: BCG analysis

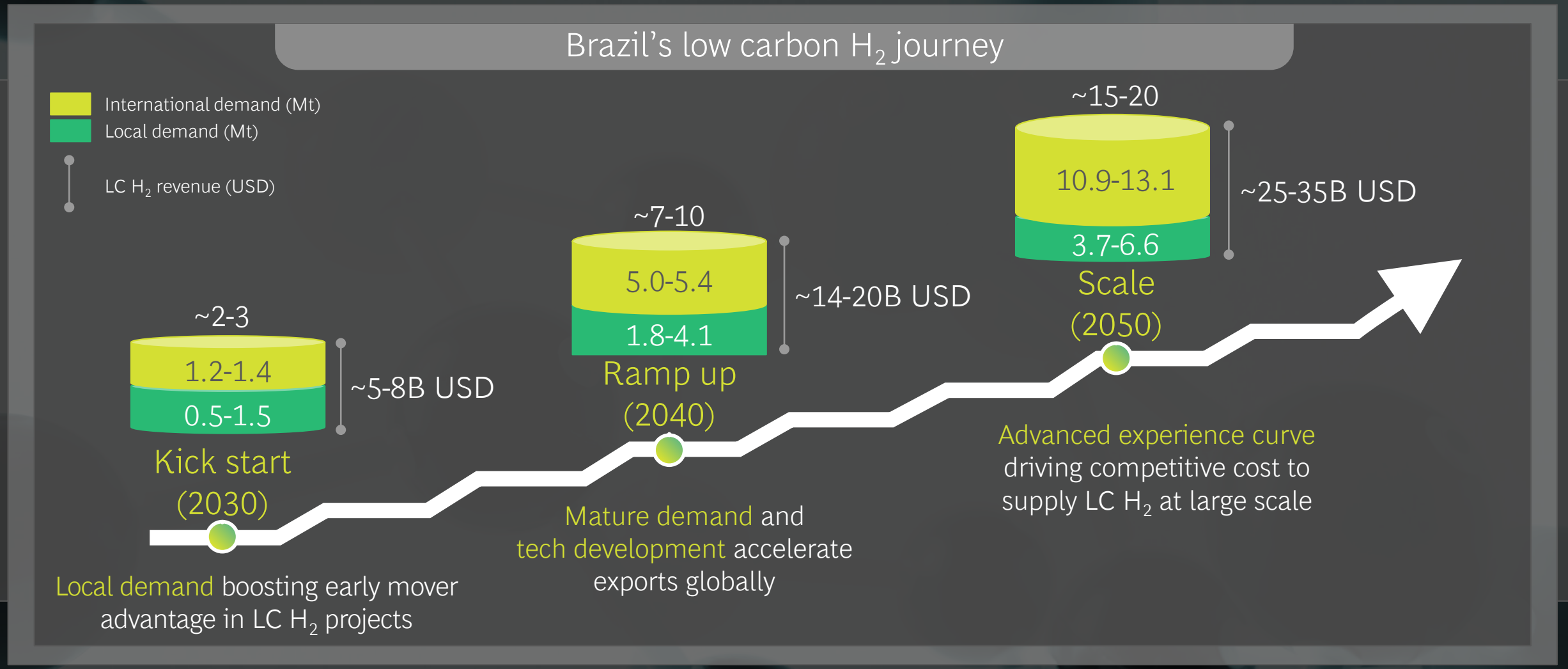
H_2 choice of carrier dependent on end-user feasibility and costs

	Compressed H_2 tank	Liquefied H_2 tank	Pipeline[1] network (gas or hydrogen)	H_2 Shipping
Overall	On-road delivery of compressed H_2 in gaseous form, limited to small capacity and distances	On-road delivery of liquid H_2, but high costs to continuously cool below -253°C	Bulk delivery similar to transporting any other gas, but dedicated network to H_2 required	Delivery as ammonia-bound H_2 in semi-refrigerated ships better suited for international distribution
Usage types	Space, electronics, backup supply, fuel stations	Labs, chemicals, electronics, backup supply, fuel stations	Industrial manufacturers, chemicals & fuel stations	H_2 trade export to selected countries
Capacity (t H_2)	Small (~1 ton)	Medium (~4 tons)	Large scale (0.3–9 tons/h)[2]	Large (1-10 tons)
Distance[3] (km)	Less than 100-200 km	More than 100-200 km	Regional network (~100 km)	International long-haul
Distribution				

High capacity / distance Low capacity / distance Gaseous H_2 Liquefied H_2 Ammonia NH_3

1. Considering a network of pipelines of a diameter of <16 inches; 2. Common flow rates of created hydrogen pipelines starting in ~ year 1995; 3. current typical usage patterns
Source: Shell - Energy of the future (2017), Linde's website (2019), IEA- The Future of Hydrogen (2018), Hydrogen Europe; NREL (2014), Gardiner (2009), IEA (2019), BCG analysis

Growth aspiration to position Brazil in the leading league of global LC H_2 market



Source: BCG analysis

Unlocking LC H_2 opportunity requires urgent and assertive government action to assure global competitiveness

Carbon market
Nudge companies' Net Zero pathways by establishing compliance targets for critical sectors

Cost of capital
Reduce spreads and risks mechanisms for investments in new "greener" technologies

Taxes and charges
Exempt taxes on LC H_2 projects and guarantee affordable power system charges

Investments and incentives
Explore alternatives to match global incentives on large scale investments (e.g. tax credits) as well as to overcome supply chain bottlenecks

Logistics and infrastructure
Ensure adequate access to infrastructure to flow LC H_2 to its main destinations

Machinery renewal
Promote machinery adaptation to boost demand for LC H_2

Global trade
Lead trade agreements to guarantee LC H_2 demand and avoid competitive pitfalls

Business environment
Design reliable and comprehensive LC H_2 regulatory framework (e.g. exploring advantages such as Biogenic CO2)

Demand side
Supply side

Brazil's position on the topic

Source: BCG analysis

Governments action with significant impact on low carbon hydrogen business framework in the coming years

United States

Strong recent incentives to accelerate low carbon hydrogen deployment

- Infrastructure Investment & Jobs Act (IIJA) and Inflation Reduction Act (IRA) include ~$17.5B in funding and tax credit dedicated to low carbon hydrogen
- US market is more favorable for blue H_2 in near-term, but production tax credit (up to USD 3/kg H_2) may improve green cost competitiveness until 2030

European Union

Leading region on policy making maturity related to H_2

- Ambitious goals to reach hydrogen development both in electrolysis capacity (8GW in 2024) and demand (20Mt in 2030)
- Mature policy making in entire value chain (production, imports, midstream and demand) with incentives already agreed on and some national regulations

Rest of world

Still immature incentives established worldwide

- Likely importers (Japan and South Korea) with demand-side policies still under discussion
- China and India already have some mandates but high uncertainty regarding wider incentives and ramp up
- Australia has trade agreements already signed with importers (Japan, South Korea and Germany), but needs to ensure exports competitiveness

Source: Press releases, BCG analysis

National H_2 Program was created in 2022 with initial guidelines…

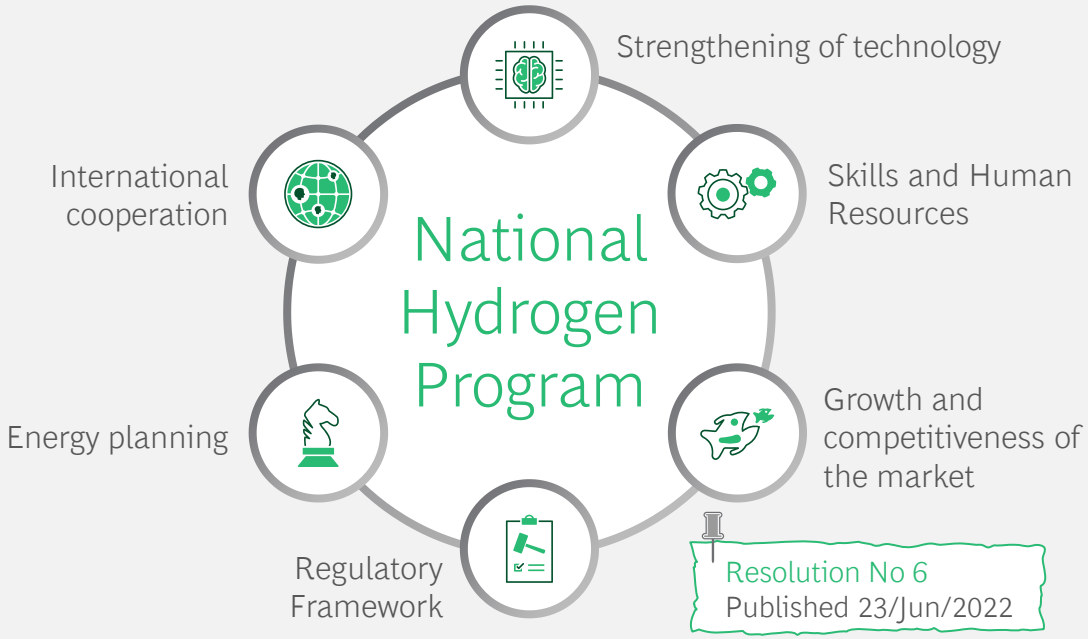
Brazil government began to establish guidelines for H_2 industry…

Market development understanding sources of production, technologies required and both internal and external demand potential

Inclusion of H_2 as a priority theme for investments in research and development & innovation

Leadership of Brazil in diplomacy on "energy transition" at UN

…6 key topics are the basis for the action plan under discussion for the National Hydrogen Program



Source: Press releases, Ministry of Mines and Energy, BCG analysis

…while a three stage workplan set ambitions for Brazil's role in the LC H_2

MME[1] - 2023-2025 Three year workplan – PN H_2

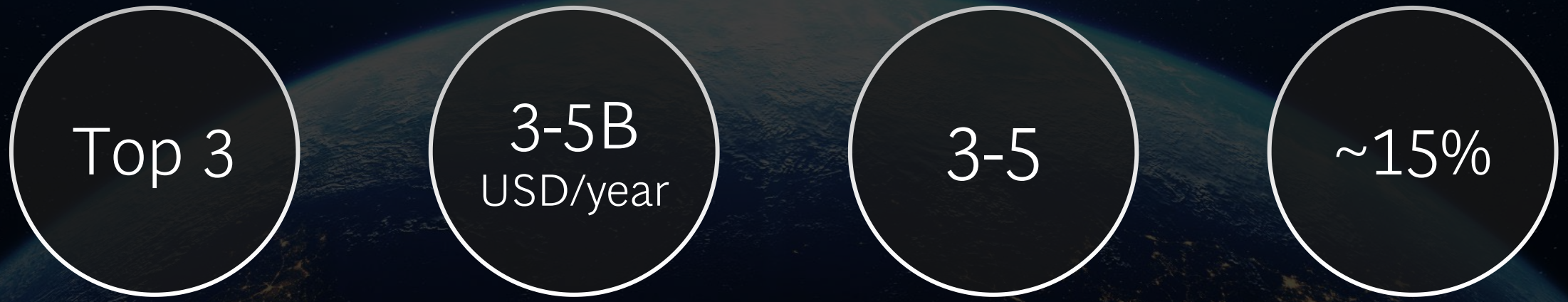
Implement pilot plants throughout all regions of the country

Consolidate Brazil as the most competitive low carbon player

Consolidate LC H_2 hubs in Brazil

1. Ministry of Mining and Energy

Brazil's Low Carbon H_2 potential: The 2030 pay-off



Low cost of supply

Brazil highly competitive on shipping LC H_2 derivatives to Europe

Revenue pool

Both local and export potential totaling 2-3Mt per year

LC H_2 industrial hubs

Industrial clusters to explore economies of scale and scope

Share of LC H_2 global trade

Brazil as a leading LC H_2 derivatives exporter

Brazil has several industrial hubs candidates for LC H_2 production - early movers potential for 3-5 until 2030

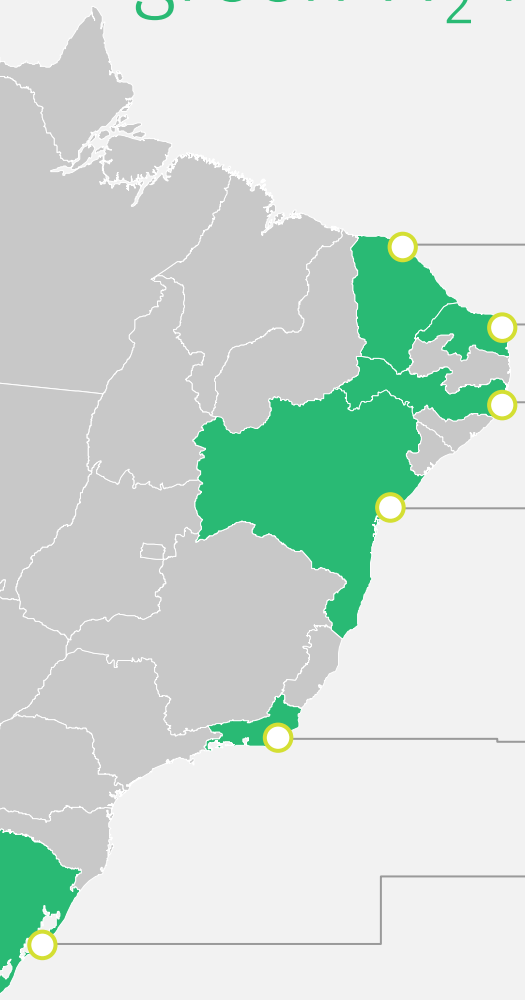
Main drivers for LC H_2 hubs in Brazil

- H_2 and Derivatives Export: Privileged position to access shipping route for exports market
- Maritime Transport Fuel: Easy access to the Brazilian coast and shipping industry
- Railway Transport Fuel: Proximity to the Brazilian railway network
- Industrial Ammonia & Fertilizers: Well connected to agribusiness and chemical industry
- Agro-industrial H_2: Potential to extract benefits for biomass, waste and capture of biogenic CO2

Source: BCG analysis

Key players in early-stage projects development of green H_2 in Brazil

Non-exhaustive



Porto de Pecém, CE	Fortescue Future Industries, TransHydrogen Alliance, edp, enegix, Qair, eneva, aes, Neoenergia, ENGIE
Rio Grande do Norte	Enterprize Energy, iEnergy, Neoenergia
Porto de Suape, PE	Qair, Neoenergia
Camaçari, BA	Unigel, thyssenkrupp
TBC[1]	Vale, H2 green steel
Porto do Açu, RJ	Fortescue Future Industries, Shell, Neoenergia
Porto de Rio Grande, RS	Neoenergia

Energy source: Solar; Wind Onshore; Wind Offshore

End product: H_2; Ammonia

1. The number of industrial hubs that will be built, their location and production capacity will be defined following feasibility studies to be developed jointly by Vale and H_2 Green Steel

Source: Press releases; BCG analysis

Low Carbon Hydrogen could drive a new green industrial cycle in Brazil

Increased scale and dash for innovation in Brazil's energy solutions

Attractive and renewable power and energy

Export and attraction of FDI and local investment for capacity expansion of green industrial products

Competitive LC H_2/PtX

Competitive boost to low cost/low emissions related industries

Sustainable decarbonization pathways of industrial and transport sectors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