Hydrogen Council

McKinsey & Company

Global Hydrogen Flows:

Hydrogen trade as a key enabler for efficient decarbonization

International hydrogen trade can reduce the cost of the energy transition by $6 trillion. This report shows how hydrogen trade could develop and the steps needed to make it happen.

October 2022

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www.hydrogencouncil.com

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Key messages

Hydrogen is a versatile energy carrier critical to decarbonization

— Hydrogen can be transported, stored, combusted, or used as feedstock, similar to hydrocarbons today

— Hydrogen will be needed across several sectors to achieve carbon neutrality, with an expected demand exceeding 660 million tons (MT) by 2050

Global hydrogen trade can accelerate the transition to a hydrogen economy

— Some of the major future demand regions, including Europe, Japan, and South Korea, will not be able to meet all of their demand at competitive costs and will need to resort to importing low-cost hydrogen and derivatives

Different trade flow patterns of hydrogen could emerge

— Pure hydrogen is a "neighborhood" business, meaning hydrogen can be predominantly sourced domestically or piped from nearby regions and only shipped if these options are not available

— Hydrogen derivatives can be shipped around the world; transportation costs are low, and production costs are primarily driven by availability of resources such as CO_2 and iron ore

Trade can unlock significant reductions in required overall investments and system costs

— Investments in long-distance transport and trade comprise less than 20 percent of overall investments but are key to unlocking substantial savings, including $5 trillion in total system costs across the supply chain

65 MT
Hydrogen already transported long distances by 2030 (out of total of 140 MT)

10
Trade routes of more than 1 million tons per annum (MTPA) of piped trade and shipped derivatives will materialize by 2030

400 MT
Hydrogen transported over long distances by 2050 (out of 660 MT of demand required for net zero)

2.5X
Cost difference between lowest- and highest-cost production locations

80 GT
Cumulative CO_2 abatement by 2050

50%
Share of pure hydrogen transported over long distances by 2050 (230 MT)

75%
Share of hydrogen derivatives transported over long distances by 2050 (170 MT)

$1.5 TN
Infrastructure and transportation investments required by 2050

$460 BN
Annual savings by 2050 from trading

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00 Context and objectives of this report

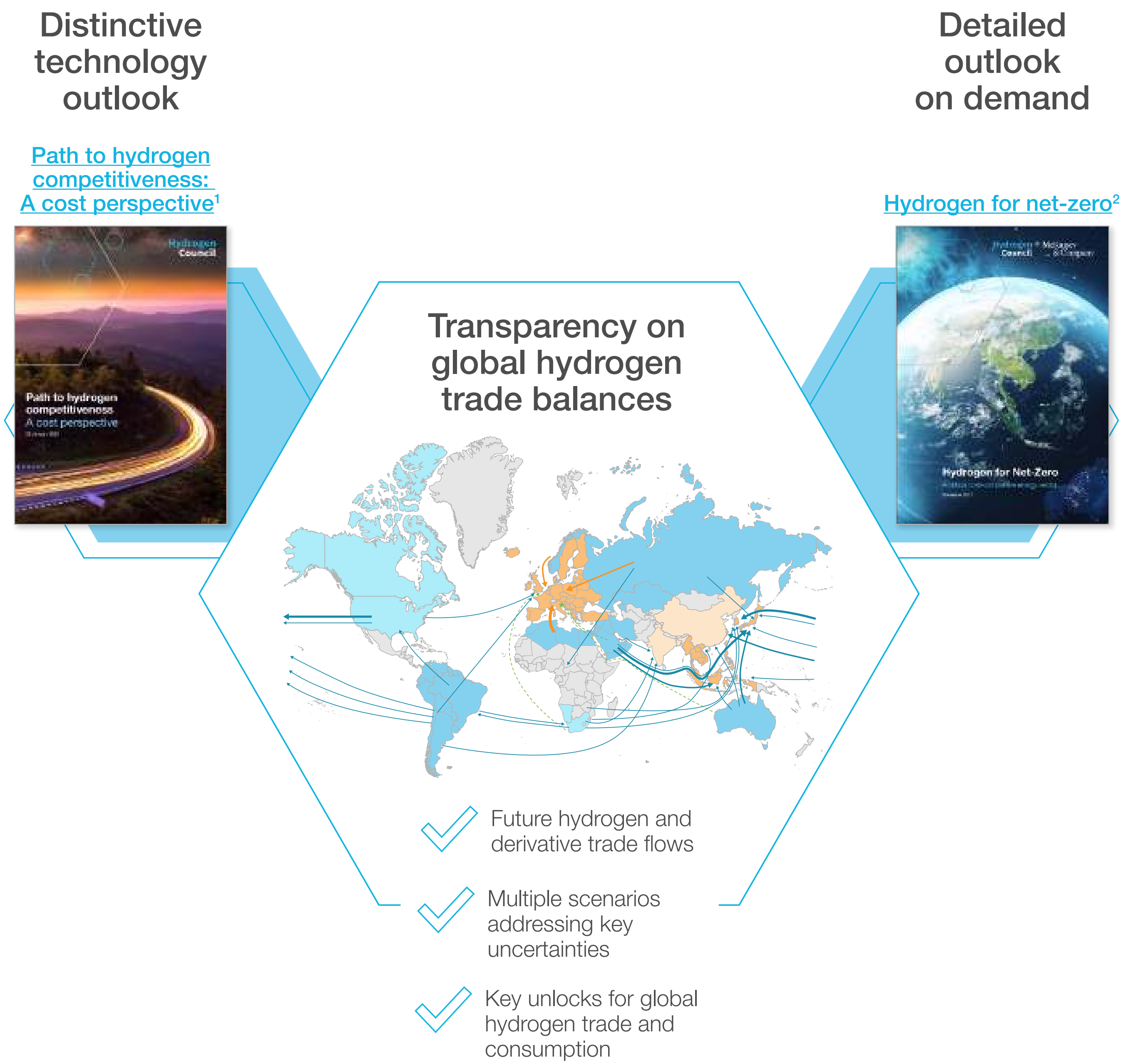
Exhibit 1

The Global Hydrogen Flows Perspective aims to inform readers on how the supply and demand views from our previous reports come together

Hydrogen and its derivatives can play a central role in helping the world reach net-zero greenhouse gas (GHG) emissions by 2050. As a complement to other technologies, including renewable power and biofuels, hydrogen and its derivatives have the potential to decarbonize certain high-emitting industries, such as steel, heavy-duty transport, and building heating, as well as support flexible power generation, among other applications. By 2050, hydrogen could contribute to more than 20 percent of annual global emissions reductions needed for the world to reach net-zero emissions.

Hydrogen's potential role in the broader energy transition is explored in a series of industry reports coauthored by the Hydrogen Council and McKinsey, including the 2020 *Path to Hydrogen Competitiveness* report, which explores the costs and economic benefits of hydrogen as a decarbonization vector, and the *Hydrogen for Net Zero* report, which stipulates overall demand growth in line with 2050 net-zero objectives.

The Global Hydrogen Flows Perspective addresses the midstream challenge of aligning and optimizing global supply and demand. It finds that trade can reduce overall system costs. In doing so, it provides a perspective on how the global trade of hydrogen and derivatives, including hydrogen carriers, ammonia, methanol, synthetic kerosene, and green steel (which uses hydrogen in its production), can develop as well as the investments needed to unlock the full potential of global hydrogen and derivatives trade (see sidebar, "About the analysis"). Our hope is that this report offers stakeholders—suppliers, buyers, original equipment manufacturers (OEMs), investors, and governments—a thorough and quantitative perspective that will help them make the decisions required to accelerate the uptake of hydrogen.



1. *Path to hydrogen competitiveness: A cost perspective*, Hydrogen Council, January 20, 2020.
2. *Hydrogen for net-zero*, Hydrogen Council, November 3, 2021.

About the analysis

The Global Hydrogen Flows Perspective is coauthored by the Hydrogen Council and McKinsey. To support our analysis, we developed a bespoke advanced-analytics optimization model that balances supply and demand across all regions and multiple carriers and end products. In total, the Global Hydrogen Trade Model optimizes across 1.5 million potential trade routes. The demand view is aligned with a net-zero pathway developed by both organizations, with projections in line with global climate targets modeled for 2025, 2030, 2040, and 2050.

The reference-case scenario we have developed is one of economically efficient decarbonization with minimized overall system costs. The scenario purposefully does not consider current geopolitical trade limitations to be a factor in the long run, although the optimization model allows us to flexibly model trade-route blockages and observe their impact.

Furthermore, in an effort to better understand the energy transition and the role of hydrogen trade, we developed three scenarios to test the reference-case scenario. These alternative scenarios evaluate the development of hydrogen trade if the decarbonization transition is delayed, if countries prioritize local supply chains and production, and if the world prioritizes renewable over low-carbon pathways. We also assess the impact of a no-trade scenario to understand the full benefits of trade on overall investments and costs.

This report uses industry data from the Hydrogen Council. The projections of future trade flows are subject to many uncertainties, so in chapter four, results have been tested relative to variations in input assumptions to find different analytical outcomes based on least-cost considerations. These results serve to inform stakeholders, rather than to predict the future. In reality, (geo-)political considerations, existing assets, capabilities and capital, business decisions (for example, first movers, lock-in effects, and so on), and other factors will influence which trade routes will emerge, where hydrogen-production costs will fall fastest, and where uptake will keep pace with projections or fall behind.

Generally, the model does not take into account regulatory incentives such as EU Important Projects of Common European Interest (IPCEI) funding. Additionally, this analysis was done prior to the introduction of the Inflation Reduction Act (IRA) in the United States. The IRA's full extent and application is uncertain given that regulations are still being implemented and that incentives may not apply for exports at all or at scale once regulations have been finalized. As such, the ultimate impact on trade flows is uncertain. If it were considered, the likely effect would be to make a portion of US production more competitive in the first decade—from 2022 to 2032—with unknown long-term impact on trade balances.

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01

Regional mismatch between hydrogen demand and supply

65%

of global hydrogen demand concentrated in North America, Europe, and East Asia

5X

difference between lowest- and highest-cost production locations

Exhibit 2

Hydrogen has a central role in helping the world reach net-zero emissions by 2050

Hydrogen can store energy, provide resilience, and transport high volumes of energy over long distances via pipelines and ships. As a result, it plays a critical role in enabling a decarbonized energy system.

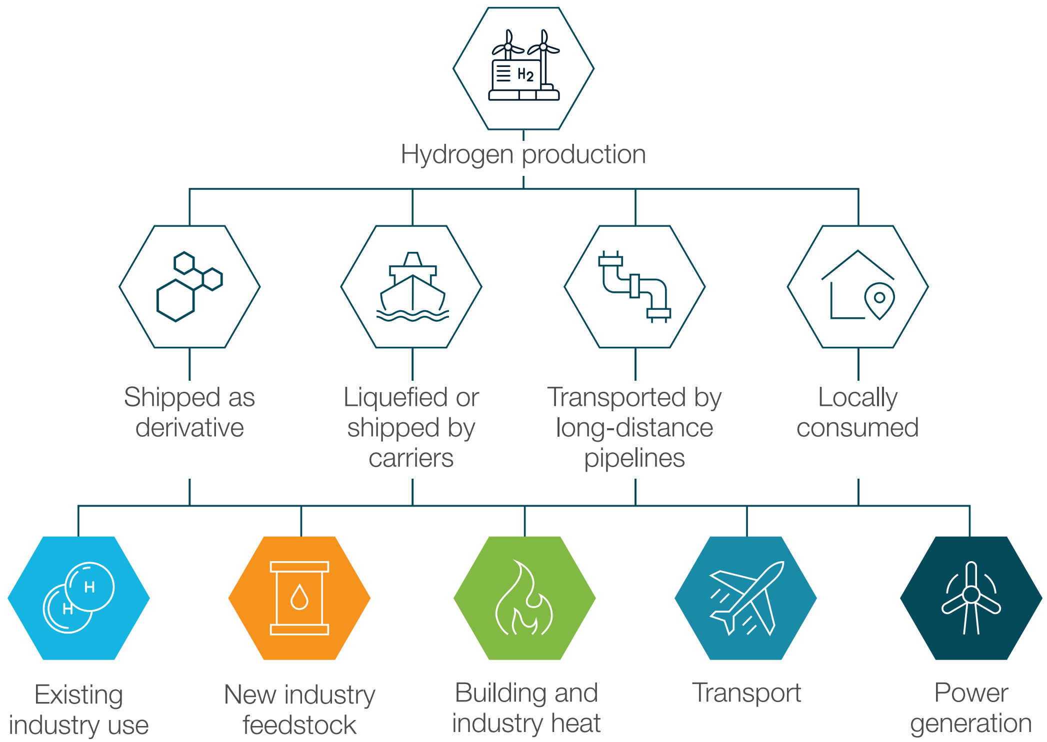
Hydrogen allows energy companies to tap extremely competitive, but otherwise "stranded," renewable energy in remote locations, enabling increased renewable-energy capacity and thereby accelerating the energy transition.

The production of hydrogen can fundamentally reshape power, gas, chemical, and fuel markets because hydrogen can be produced from electricity and used as—or converted into—fuels, chemicals, and power.

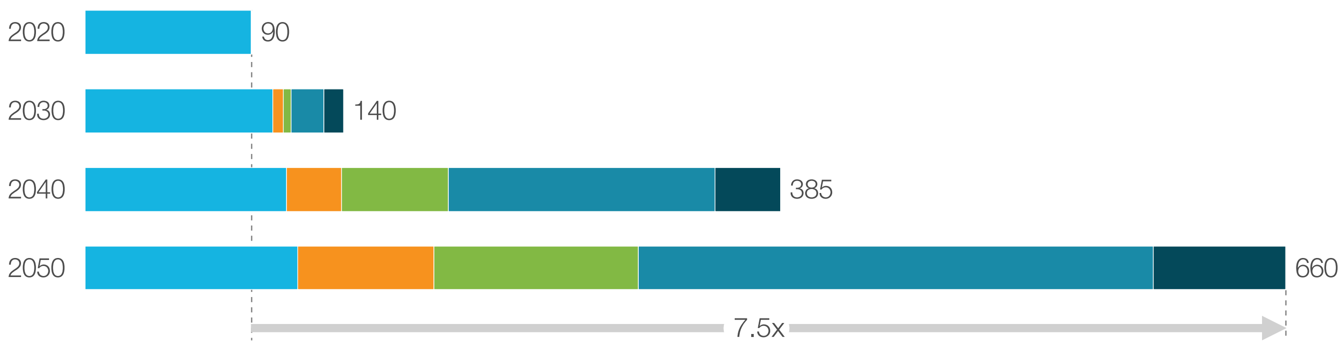
In terms of end uses, hydrogen is critical for decarbonizing industry (for example, as feedstock for steel and fertilizers), long-range ground transport (as fuel in heavy-duty trucks, coaches, long-range passenger vehicles, and trains), international travel (as LH_2 or by conversion to synthetic fuels for maritime vessels and aviation), heating applications (as high-grade industrial heat), and power generation (as dispatchable power and backup power supply).

To reach net-zero emissions, the world needs more than 660 million tons (MT) of hydrogen. Additionally, the gap between where hydrogen is in high demand but in low supply, such as Japan, and where it is in low demand but in high supply, such as Namibia or Chile, needs to be closed.

Hydrogen supply chains



Hydrogen demand, million tons



Source: *Hydrogen for net-zero,* Hydrogen Council, November 3, 2021

Exhibit 3

Clean hydrogen can abate 80 gigatons of CO_2 by 2050

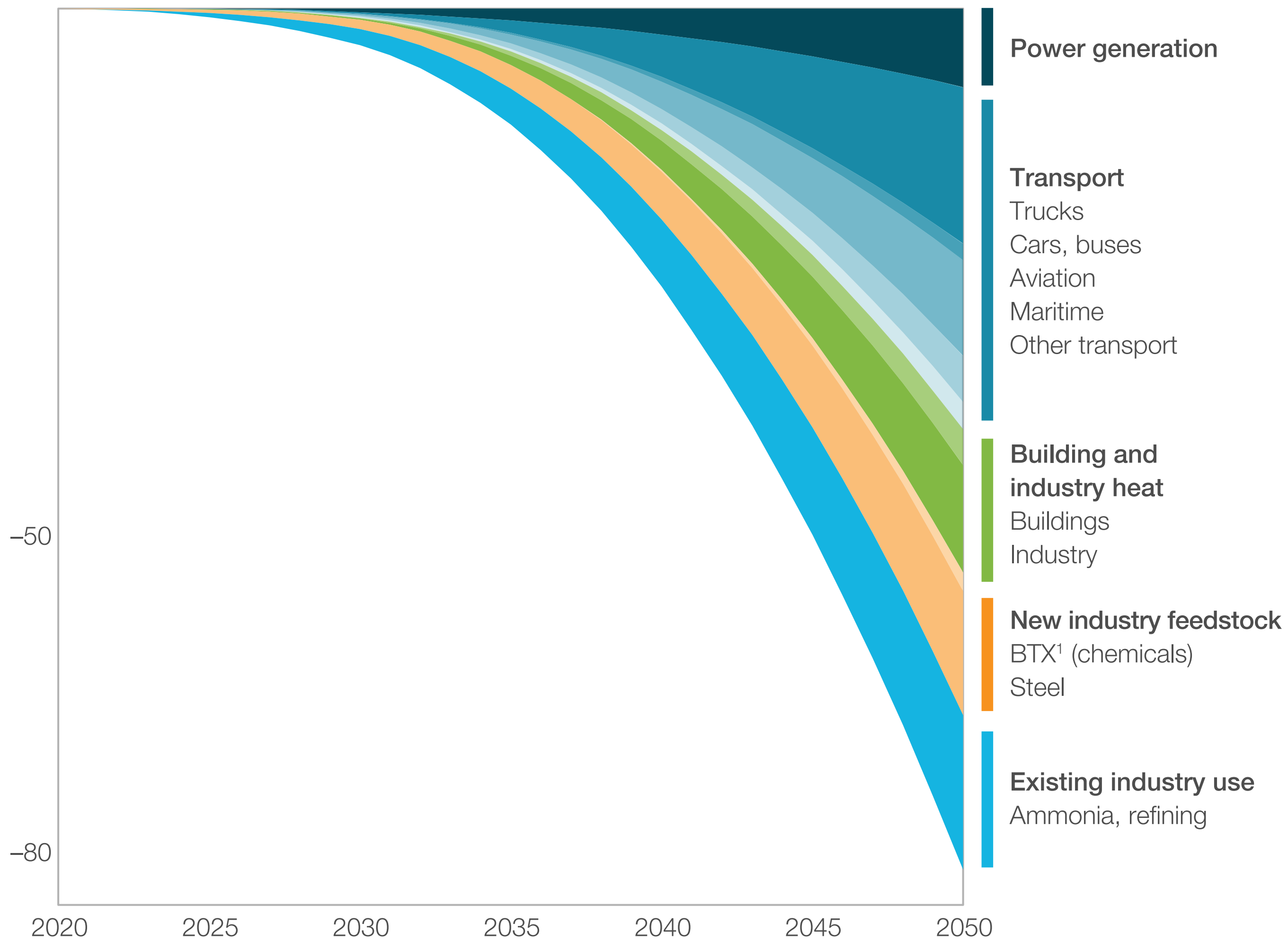
Hydrogen can provide 80 gigatons (GT) of cumulative abatement by 2050. This means that, on an annual basis, 20 percent of the emissions reductions needed to reach net zero by 2050 can be achieved by the introduction of renewable and low-carbon hydrogen.

Clean hydrogen has significant abatement potential through 2050. In fact, hydrogen could prevent 80 GT of cumulative CO_2 emissions. This is as much as eight times what China emitted in 2019, before the COVID-19 pandemic. It is also equivalent to about 11 percent of the cumulative abatement required to remain within the carbon budget that would limit global warming to 1.5 to 1.8 degrees Celsius.

The annual carbon abated from the use of clean hydrogen by 2050 could be around seven GT, or about 20 percent of annual anthropogenic emissions if the world remains on its current trajectory. Abating seven GT of CO_2 emissions would be equivalent to removing all passenger vehicles, trucks, and buses from the road and eliminating the aviation industry, or abating net emissions from the United States, Japan, and Germany in 2019.

Industry and transport can account for most of this potential by abating more than six GT of CO_2 by 2050, with cumulative abatement of 70 GT of CO_2. For aviation and maritime sectors, hydrogen-based fuels are the only viable at-scale decarbonization option, with significant potential for abating 13 GT of CO_2 by 2050 by using hydrogen. Chemicals and steel can provide another third of total potential hydrogen abatement through 2050, decarbonizing 20 percent and 35 percent, respectively, of emitted CO_2 in the current trajectory.

CO_2 abated from hydrogen end use, gigaton (GT) CO_2 cumulative by 2050, net-zero scenario



80 GT
cumulative abatement by 2050

20%
of annual emissions avoided due to H_2 by 2050 (current trajectory is around 35 GT CO_2 emitted per annum by 2050)

1. Benzene, toluene, and xylene isomers.
Source: Hydrogen Council Net Zero report

Exhibit 4

China, India, Japan, South Korea, Europe, and North America will account for 75 percent of global hydrogen demand, with China emerging as the largest consumer in the years to come

By 2050, hydrogen will be a major part of energy markets across geographies, enabling some countries to leverage their natural resources and reduce their reliance on imported oil and gas, while providing others with a new avenue for importing energy.

As the world's largest consumer of primary energy, China is likely to be the largest single market for clean hydrogen by 2050 with a demand for 200 million tons (MT) of clean hydrogen, followed by Europe and North America, each generating a demand for 100 MT of clean hydrogen; India with 55 MT; and Japan and South Korea with 35 MT.

The rest of the world, including Latin America, the Middle East, Oceania, and Southeast Asia, will account for about 175 MT of combined hydrogen demand by 2050.

Hydrogen and derivatives demand by region, million tons per annum

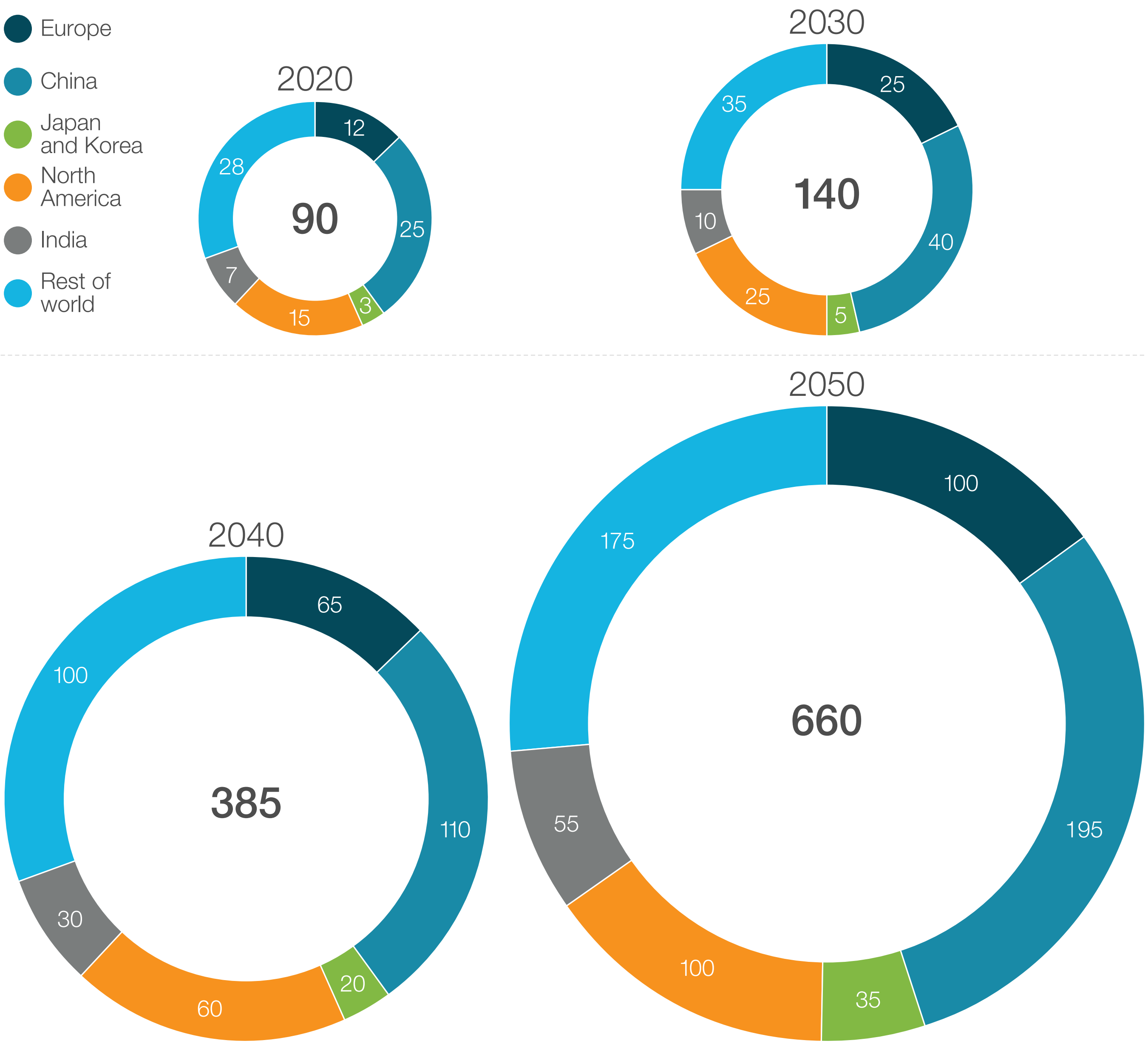


Exhibit 5

There is a mismatch between the best locations for hydrogen production and demand centers

Hydrogen can be produced in almost every global region, but competitiveness across regions varies. Japan and South Korea will have very limited competitive production resources and will need to resort to imports, while Central and Western Europe will not be able to locally produce the volumes they need because of capacity limitations.

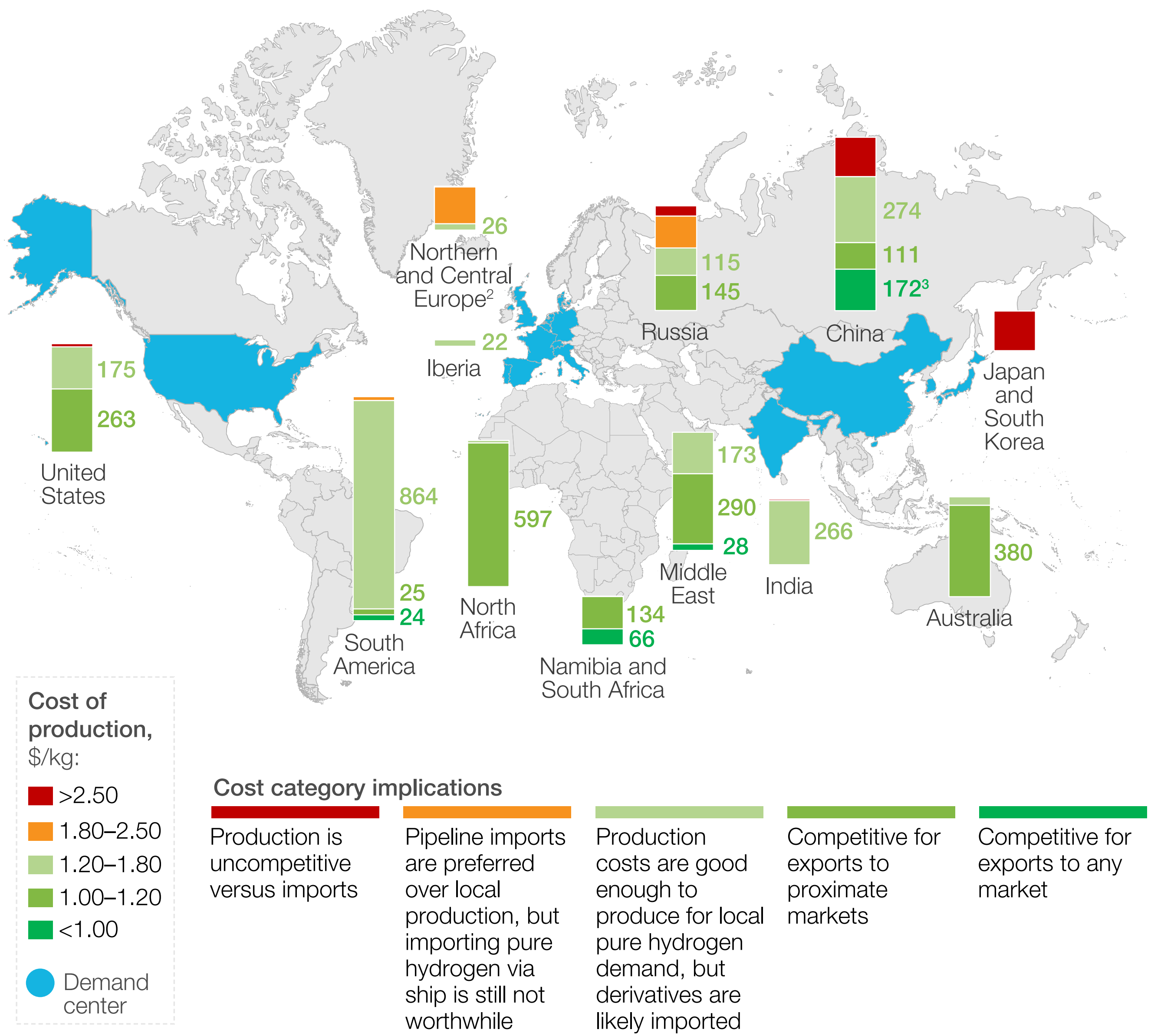
The production costs and commercial potential for each region vary widely and are driven by three main factors:

1. The levelized cost of hydrogen production, which is driven by local renewable resources and electrolyzer utilization or the local cost of methane and carbon capture and storage (CCS).

2. The availability and costs to access other critical feedstocks—for example, biogenic CO_2 for synthetic fuels or high-quality iron ore for direct reduced iron (DRI) used in green steel.

3. Country-specific factors, including the region's investment attractiveness (market efficiency, workforce availability, or country risk factor) and local public acceptance of building new infrastructure.

Hydrogen production potential,[1] 2050, million tons per annum



1. Potential for renewables and low-carbon hydrogen, constrained by a maximum of 0–3% land availability.
2. Only includes third-tier production potential, assuming that the higher-tier locations use renewable power.
3. Low-cost production in western China that requires long-distance transport to eastern China.

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Based on the discrepancy between demand for hydrogen and optimal locations for hydrogen production, there are three general categories of hydrogen-producing regions and consumers:

1. Countries with high hydrogen-export potential. These will have substantial amounts of competitive hydrogen at under $1.15 per kilogram (kg) but will lack demand. Examples include the Middle East, South America, and Southern Africa (Namibia and South Africa).

2. Countries with both cheap supply and large demand. These include China and North America, which will meet most of their demand through competitive domestic production, much of which may be transported over long distances within country borders. In the case of China, this will include hydrogen that is less than $1.00 per kg, while in the United States, most hydrogen will be produced at less than $1.15 per kg.

3. Demand locations where cheap supply is limited or not available. These include the densely populated regions of Europe, Japan, and South Korea. Here, domestically produced hydrogen will be significantly more expensive, typically at least $1.80 per kg or sometimes even more than $2.50 per kg. One reason for these high costs is the fact that domestic hydrogen production will be constrained because of land availability and resulting difficulties in developing the additional onshore wind and solar power needed to be competitive globally. Consequently, decarbonization of existing power is likely to be prioritized over new renewable-hydrogen production, except where hydrogen is used as a balancing tool.

Exhibit 6

Local hydrogen production is typically favored, but adding conversion costs favors production of derivatives and trade from the cheapest locations

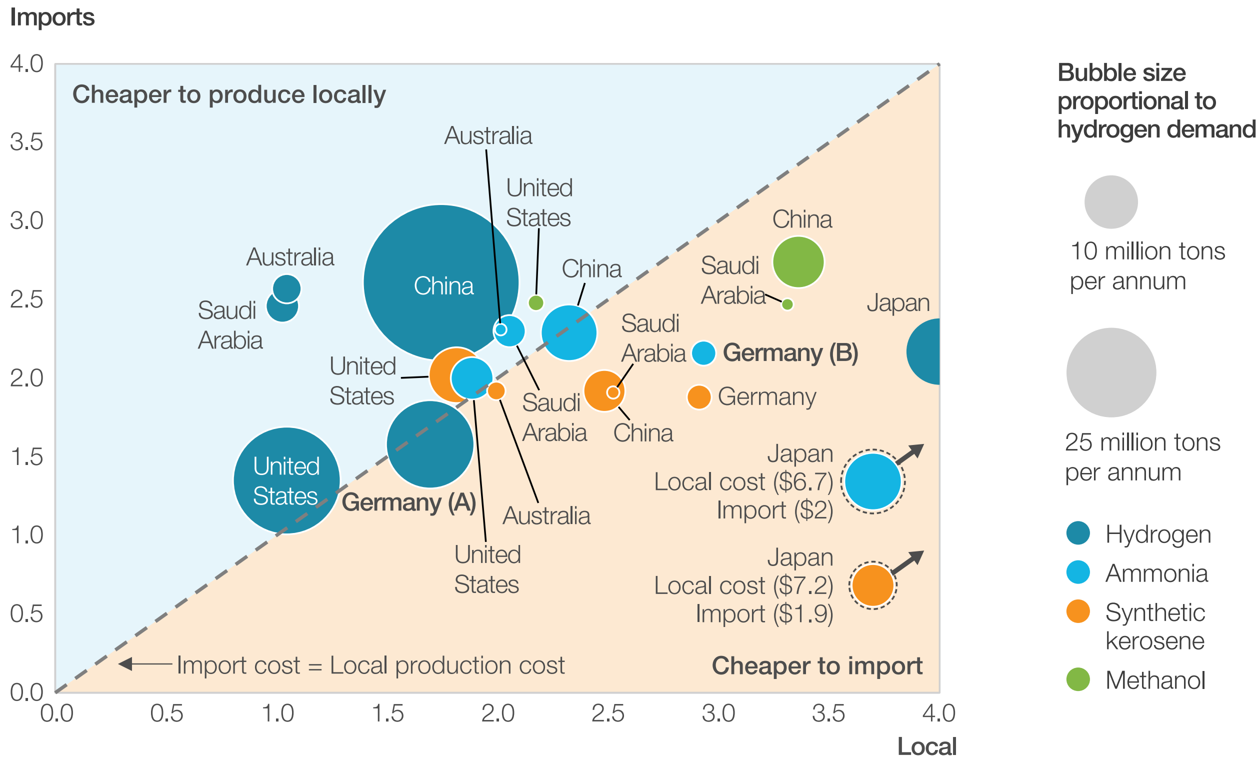
More countries will rely on production and consumption of their own hydrogen than on production of their own derivatives such as ammonia, green steel, methanol, and synthetic kerosene, which are less costly to ship around the globe.

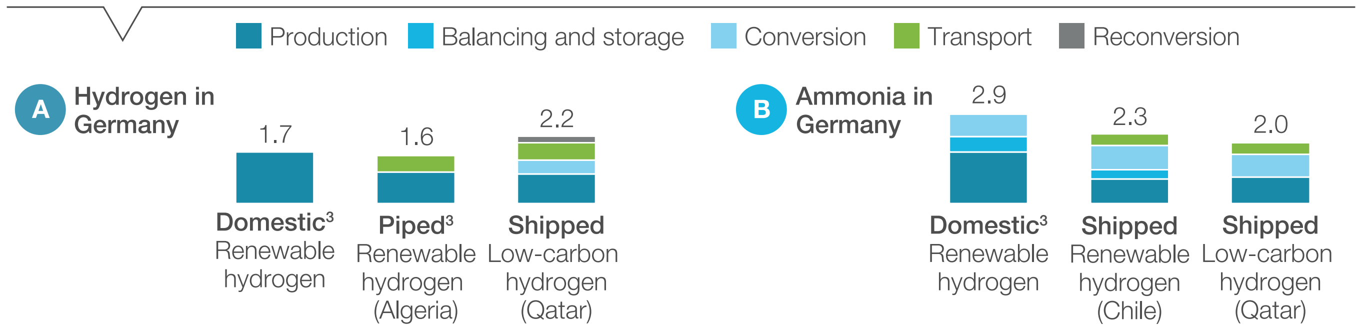
Hydrogen produced locally does not require conversion (apart from pipeline compression) or reconversion, which can add significantly to the overall cost. Consequently, only countries that are constrained in competitive domestic production typically import pure hydrogen.

By contrast, the advantage of producing derivatives locally is much smaller because the hydrogen needs to be converted regardless of location. Transportation is also a relatively small cost component compared with the overall cost as a result of higher volumetric density. The competitiveness of hydrogen-production costs therefore more than makes up for additional transportation costs.

The interaction of different starting points, as well as evolving production costs, conversion, transportation, and reconversion rates, mean that trade arbitrages will emerge and change over time. Consequently, trade requirements and routes will be dynamic.

Cost of imports versus local production[1] in 2050, $/kg hydrogen[2]





1. Includes hydrogen produced, but not derivatives.
2. This perspective is based on a detailed cost analysis across production, conversion, transportation, and reconversion. We assume a flat weighted average cost of capital (WACC) capital-expenditures compensation for all value-chain components across time and differentiated by geography for country risk. In reality, in the early stage of market developments, we expect investors to require a higher margin for an internal rate of return (IRR) that is both attractive and covers early market-entry development and commercial risk. As the market matures in the 2030s, we expect pricing to increasingly be set by the marginal production cost—just as in mature commodity markets—which would see required IRRs and margins progressively come down.
3. Only if domestic production or piped imports are available. If there are no other sources, there is a chance that the only available option is to ship imports.

Source: Hydrogen Council

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02

Efficient decarbonization trade implications

400 MT

of clean global long-distance hydrogen and derivative transport expected by 2050

250 MT

of hydrogen and derivatives supplied domestically in North America and China by 2050

Exhibit 7

In some regions, hydrogen-production costs can be several times higher than in others

Some regions, such as Chile and the Middle East, will have a cost-competitive advantage over others—and 33 percent of produced hydrogen will be at less than $1.00 per kg.

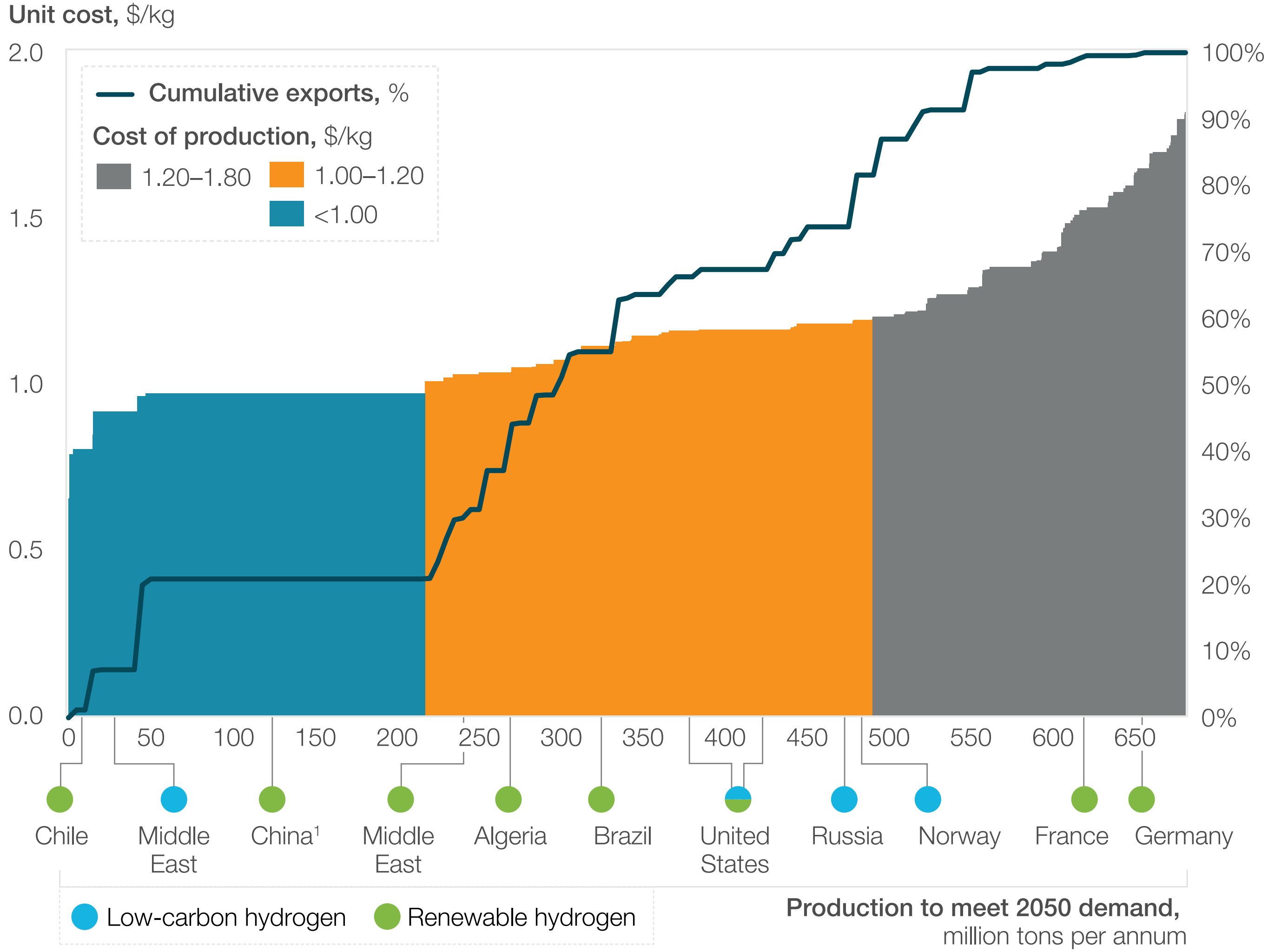
There are three tiers of producing regions:

1. The cheapest and best hydrogen producers, such as Chile and the Middle East, will have costs of less than $1.00 per kg by 2050. These are regions with the lowest-cost gas and exceptional solar radiation supported by wind. They tend to be excellent export locations.

2. The next tier of players is advantaged and typically has good but not world-beating resources, with costs between $1.00 and $1.20 per kg. This includes China, North Africa, and the United States. They tend to be able to supply their own domestic needs while also competing in markets in their periphery.

3. This third tier has high costs that typically range from $1.20 to $1.80 per kg; costs are driven by technologies such as onshore wind, solar, and competitive fixed-offshore wind. Examples of countries in this tier are France and Germany. There are other regions such as Japan and South Korea that are typically even more constrained and have even higher-cost production sources, but these will not be economically viable and therefore will not be used.

Global hydrogen-production cost curve, 2050



33%
Of hydrogen produced at <$1.00/kg

10%
Of hydrogen produced at >$1.50/kg

>2.5x
Factor between markets with the lowest and highest hydrogen-production costs[1]

1. More expensive locations, such as Japan and South Korea ($4/kg, which is five times the cheapest cost), are not expected to be used since importing becomes a cheaper alternative.

Exhibit 8

Global trade of clean hydrogen will deepen, evolve, and expand from now to 2050

Derivatives will initially comprise a greater share of long-distance transportation. End-use hydrogen will scale as pipelines develop and hydrogen carriers become more cost competitive.

There will likely be four distinct phases of hydrogen trade:

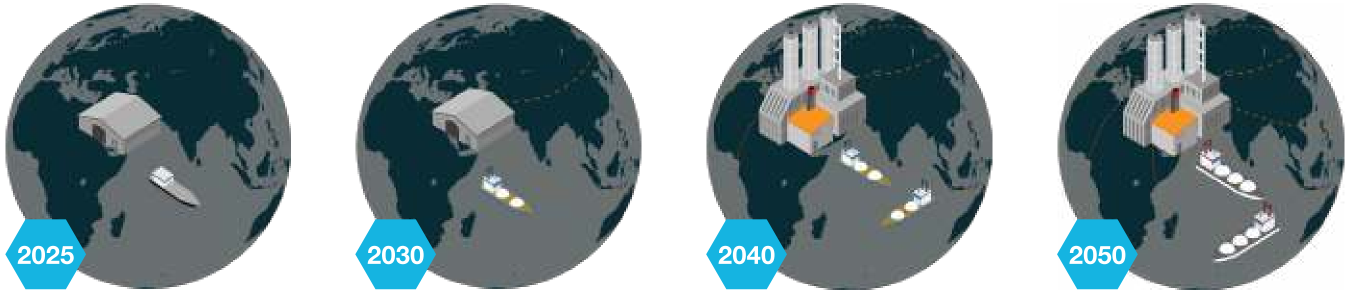
1. *First derivatives (by 2025):* Some of the existing trade of gray ammonia and methanol is replaced by some clean trade to Europe and Asia from North America, the Middle East, and Norway.

2. *Pipelines unlocked (by 2030):* The first long-distance pipelines facilitate large-scale transportation of hydrogen within North America and Europe. Derivative trade begins to scale up, particularly for ammonia and methanol, as well as first flows of green steel and synthetic kerosene.

3. *Market growth allowing increased liquidity (by 2040):* Pipeline transport accelerates, exceeding 60 million tons per annum (MTPA). Derivative trade expansion is driven by ammonia and synthetic kerosene. Hydrogen-carrier shipping reaches scale.

4. *Fully mature traded market (by 2050):* Pipeline transport continues to scale, reaching 140 MTPA. The trade of most hydrogen products increases 50 percent in ten years, including ammonia, synthetic kerosene, and green steel. Shipped hydrogen for end use grows more than 2.5 times over from nine to 22 MTPA.

Traded volumes, million tons



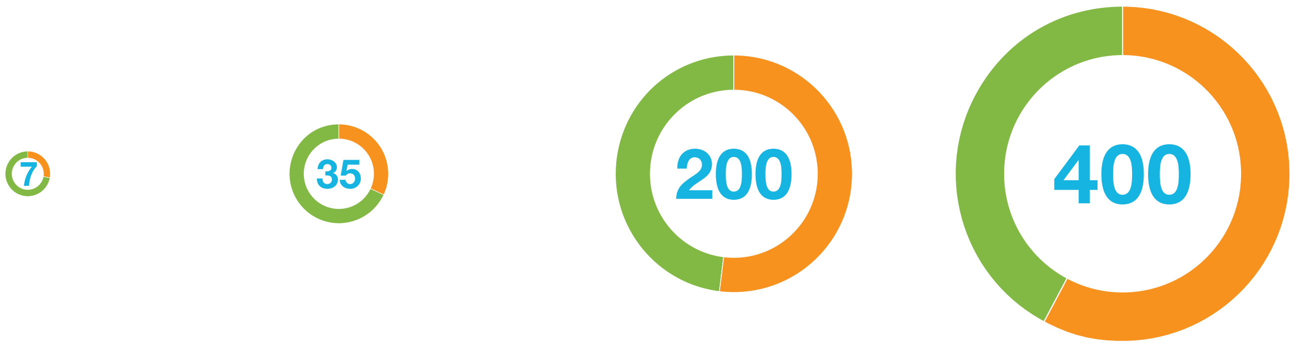
First derivatives: Clean derivative long-distance transport commences

Pipelines unlocked: Derivative and piped long-distance hydrogen transport expands fivefold

Market growth allowing increased liquidity: Global long-distance hydrogen transport scales up fivefold in ten years

Fully mature traded market: Long-distance transport doubles with established trade links

Clean long-distance transport[1] for renewable and low-carbon hydrogen, million tons hydrogen per annum



As % of demand[2]

	2025	2030	2040	2050
H_2 derivative	9	32	64	75
H_2 end-use and derivative	7	25	50	60
H_2 for end use	4	17	45	53

1. Renewable and low-carbon hydrogen.
2. Renewable, low-carbon, and gray hydrogen.

Exhibit 9

By 2030, early trade routes will have been established

Around ten trade routes will comprise volumes of more than one MTPA of piped trade and shipped derivatives, while a variety of other smaller trade routes will begin to emerge.

By 2030, the first piped imports into Europe will occur as domestic hydrogen supply is constrained and available renewable capacity is built up to decarbonize power. This facilitates competitive low-carbon supplies from markets such as Norway.

Markets such as Japan, South Korea, and Singapore will also be supply constrained and will start to import hydrogen via carriers in order to meet growing demand.

Global clean ammonia demand, in addition to clean methanol demand in Asia, will drive shipped exports from Australia, the Middle East, and North America.

Flows to Asia and Europe from competitive production locations such as Latin America, including Brazil and Chile; North Africa; and Southern Africa will also start to emerge, initially at small volumes.

Long-distance trade, such as from Australia to Europe, could also materialize if more promixate suppliers can't meet demand.

Major flows of hydrogen and derivatives, million tons hydrogen equivalent in 2030

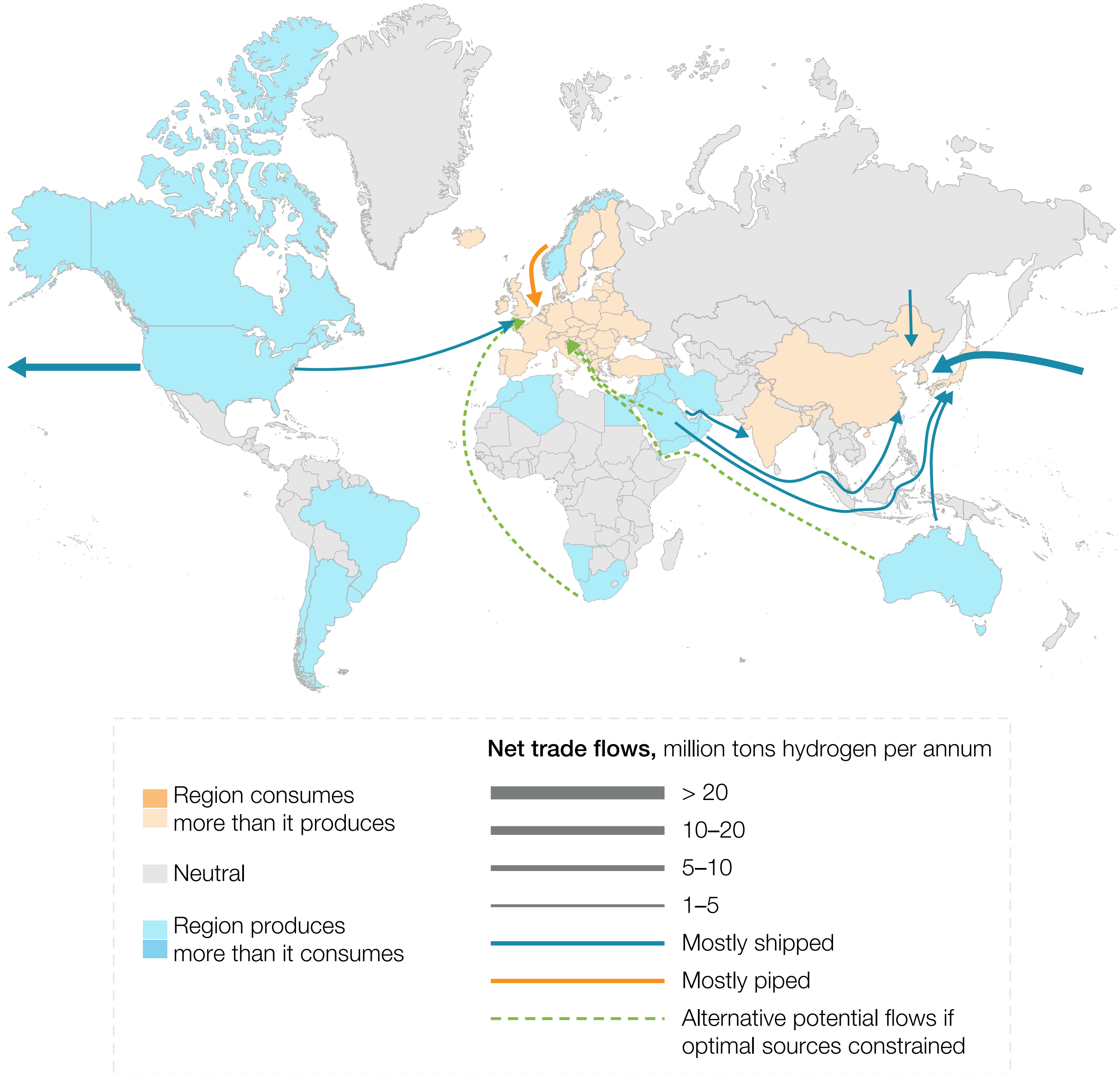


Exhibit 10

By 2050, extensive and deep trade links could connect the globe

There will likely be more than 40 different trade routes with capacity of more than one MTPA, with the largest reaching more than 20 MTPA. Europe will be primarily supplied by pipelines, while Asia will be supplied by ships.

By 2050, the market is expected to be mature with significant liquidity. Several clear priority trade routes will have emerged:

— Europe will require more hydrogen imports, opening up significant piped imports, particularly of North African renewable hydrogen.

— The Middle East will emerge as a hydrogen export powerhouse, particularly with extensive and large trade flows to Asia that primarily comprise shipped hydrogen, as well as ammonia and synthetic kerosene.

— Growing demand for green steel and synthetic kerosene in Asia and Europe allows South American exports to scale.

— Australian exports diversify as the country increasingly becomes a mainstay exporter of ammonia to the rest of Asia, with North America also a significant ammonia exporter.

— North American methanol exports to China will be facilitated by low-cost production and ample CO_2 in North America.

Major flows of hydrogen and derivatives, million tons hydrogen equivalent in 2050

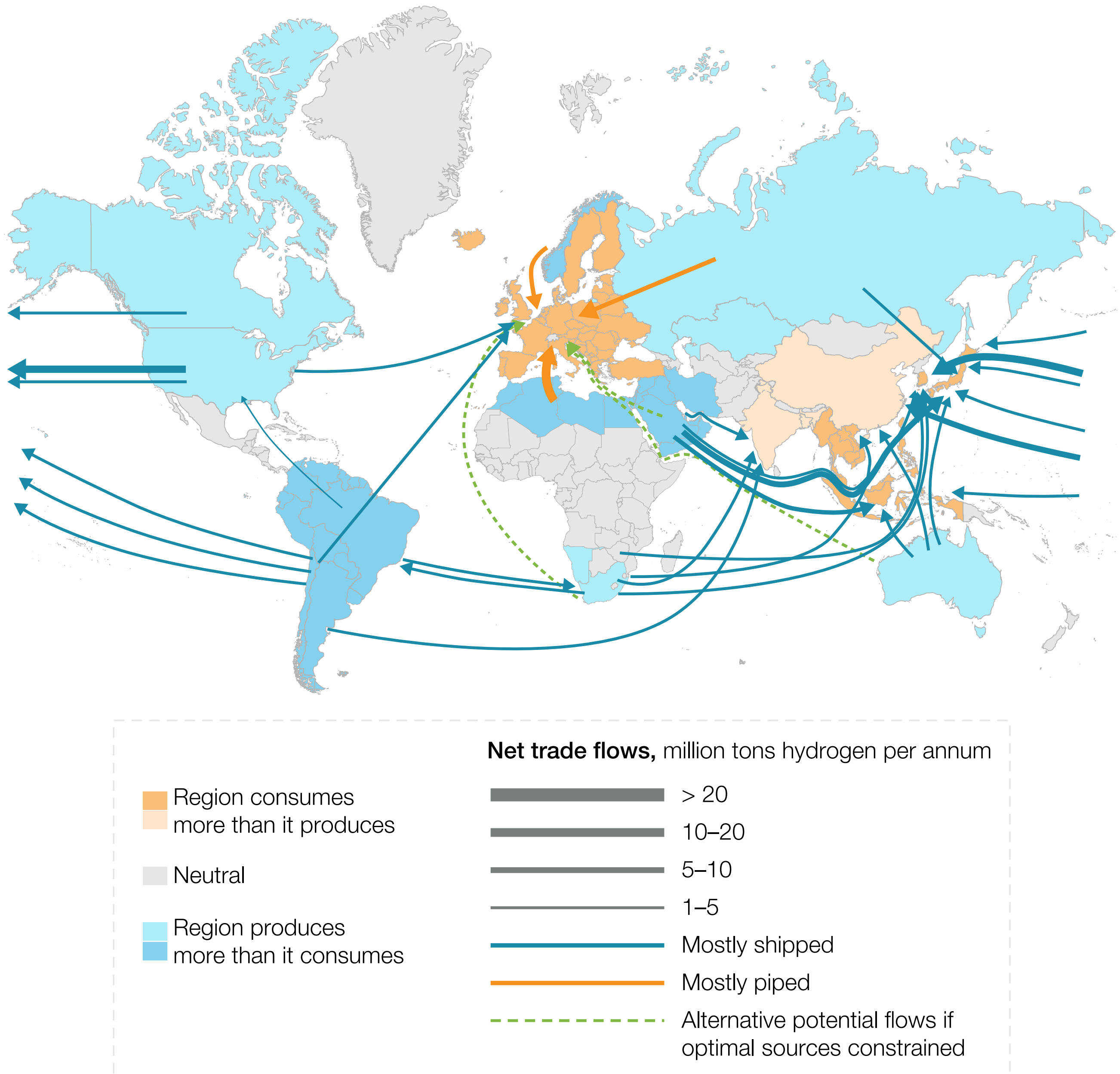


Exhibit 11

2050 will likely see an increased amount of specialization in production regions as well as reorientation of trade and transport routes related to competitiveness

Pipeline transportation will be the largest long-distance carrier, with major flows within China and North America as well as to Europe. Production regions will specialize in exporting those derivatives to where the regions have relative trade competitiveness because of local resources and shipping costs.

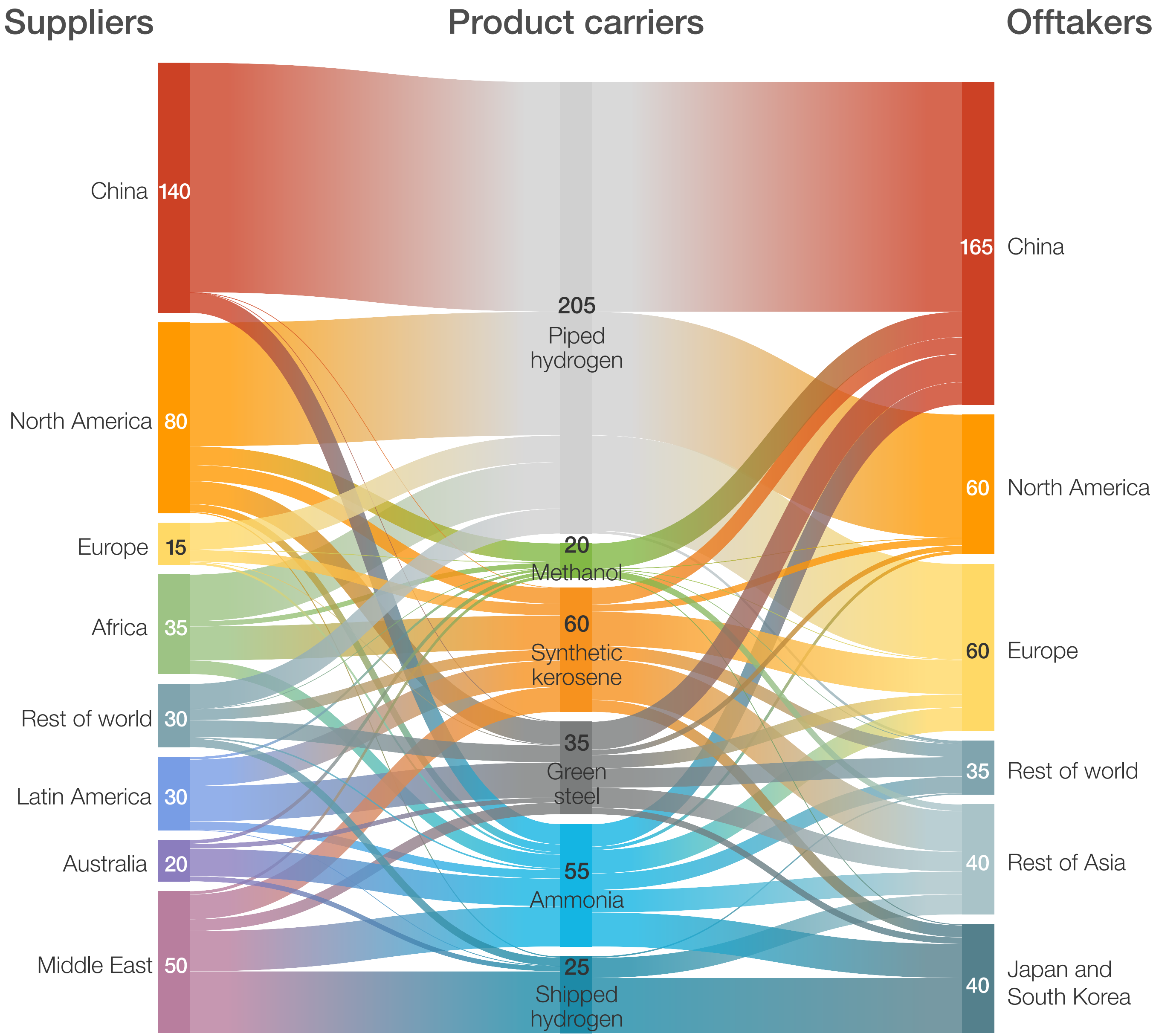
The largest-volume long-distance transfers will be domestic pipelines from western to eastern China and within the United States. Europe will also import major volumes of piped hydrogen from its periphery, including from Norway and North Africa.

After piped hydrogen, ammonia and synthetic kerosene will be the most highly traded products, with exporters and importers generally spread throughout global regions. Ammonia will have large Australian, Middle Eastern, North American, and North African exports. Synthetic kerosene's largest exporters will be Chile, the Middle East, and Southern Africa. And green steel will be dominated by Brazil and Canada, with exports to China.

Meanwhile, methanol trade from North America to China will be a key route, and shipped hydrogen will predominantly be traded from the Middle East to Japan and South Korea.

In an optimized global trade system, certain flows that may exist early on, such as Australia, the Middle East, and Southern Africa to Europe, may be reoriented to Asia to optimize overall trade flows around the world.

Global hydrogen and derivative interregional long-distance supply,[1] million tons per annum



1. Excludes local production and distribution.

Exhibit 12

70 percent of all hydrogen is expected to come from renewable sources by 2050

By 2050, hydrogen derived from natural gas without carbon capture will be phased out. If system costs are minimized, the ratio of renewable to low-carbon hydrogen will be 70:30. However, this ratio will differ by geography.

Unabated hydrogen derived from natural gas will be reduced significantly by 2040 and fully phased out by 2050. In 2030, nascent low-carbon and renewable-hydrogen production will have a similar share of overall global production and of key markets such as Europe, the Middle East, and North America.

By 2040, the growing supply from Australia, Africa, China, and Latin America will be mostly due to renewable hydrogen, and there will also be strong low-carbon hydrogen growth in the Middle East and North America.

By 2050, renewable hydrogen will account for 70 percent of overall supply as a result of China's continued expansion and growing trade with other renewable regions.

Annual hydrogen production, optimized reference-case scenario, million tons per annum

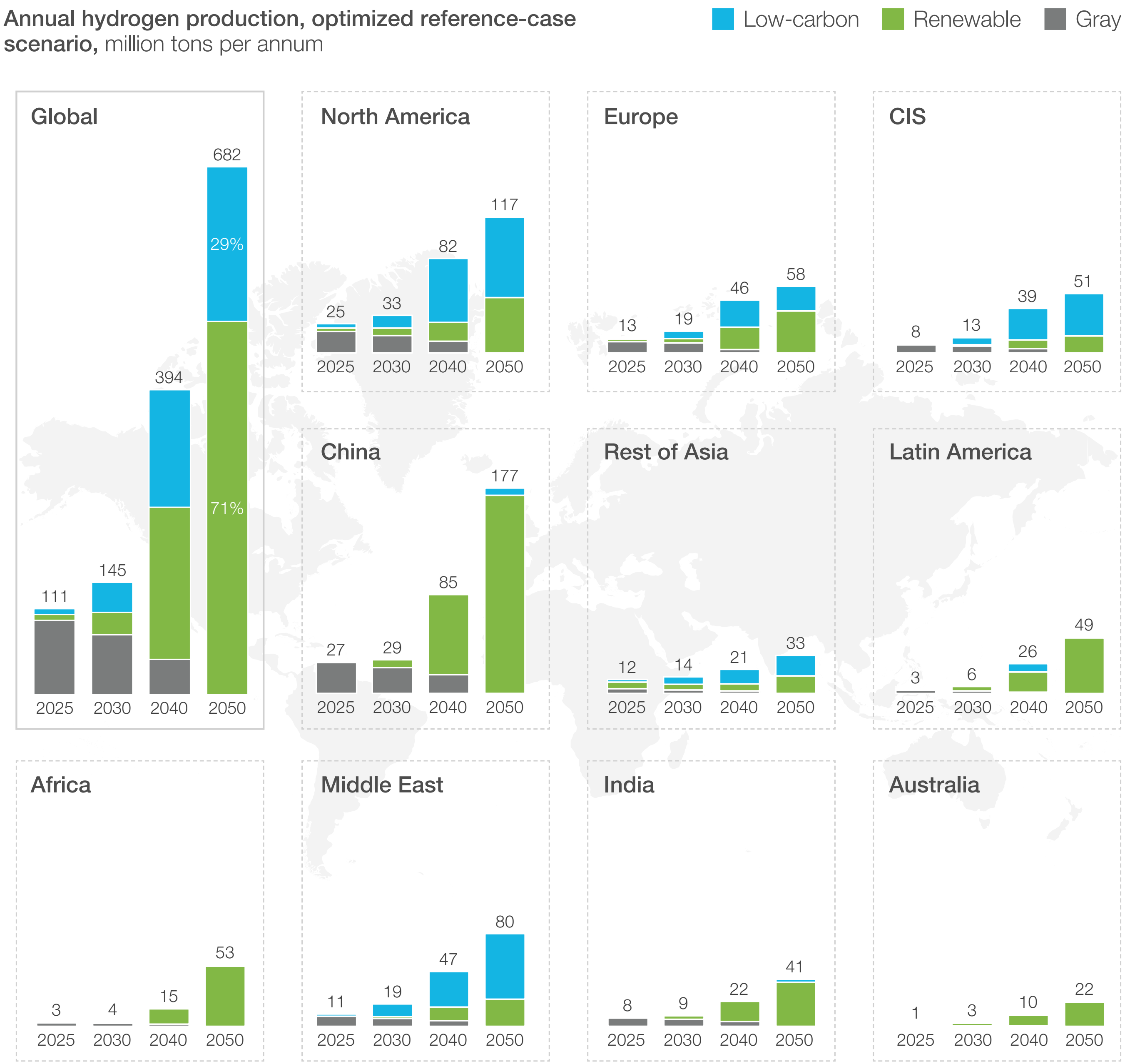


Exhibit 13

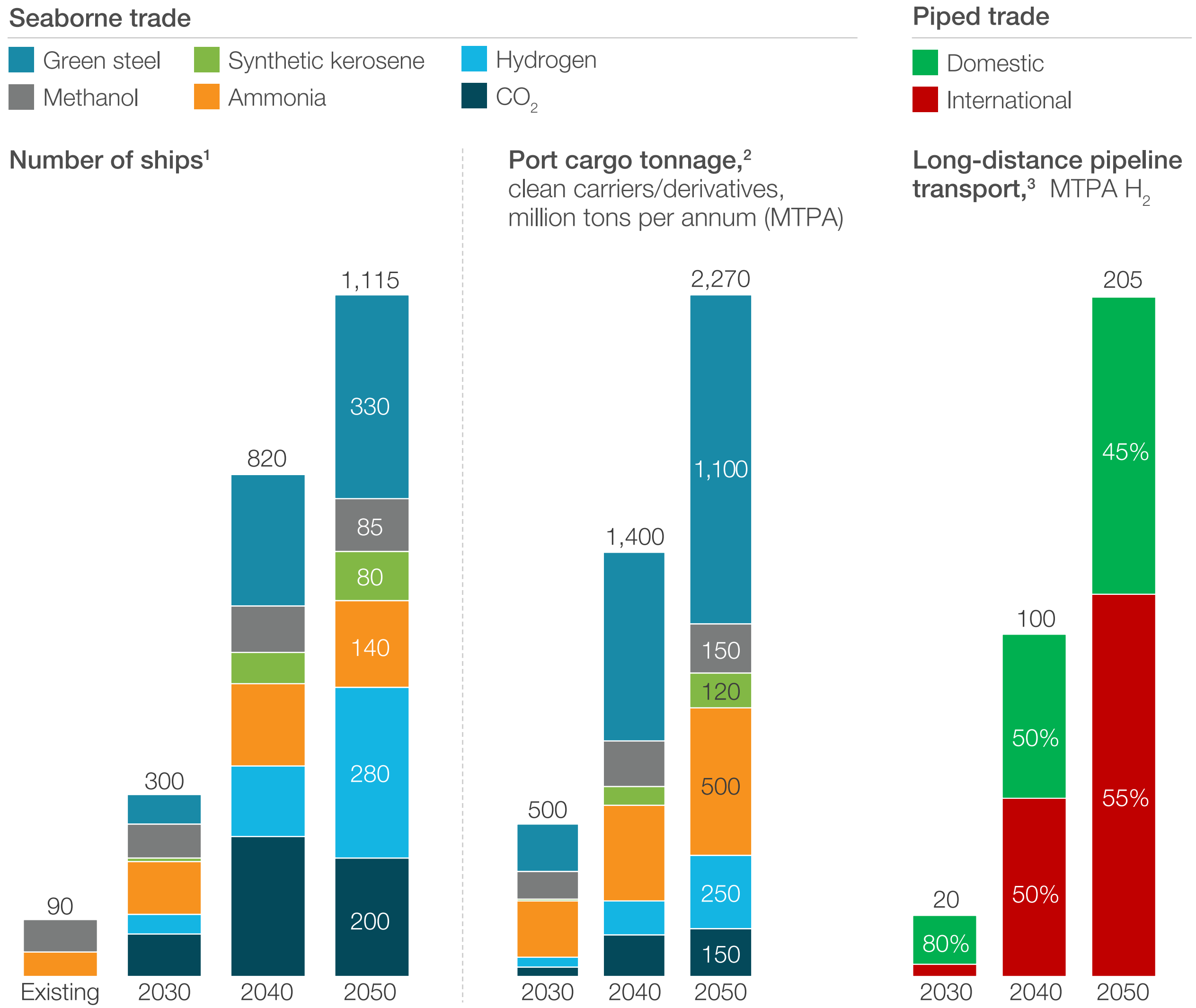
More than 1,000 ships and 200 million tons per annum (MTPA) of pipe-hydrogen capacity will be required by 2050

The transportation of hydrogen, its derivatives, and key feedstocks such as CO_2 will require substantial shipping capacity, while piped hydrogen will require natural-gas pipelines to be repurposed.

Over 1,100 ships will be required by 2050 to facilitate maritime trade of hydrogen and its derivatives. This is approximately 75 percent of today's global fleet of 1,500 liquefied-natural-gas (LNG) carriers. Existing ammonia and methanol ships could initially be reused, and synthetic kerosene and green-steel pellets could be shipped using existing product tankers and bulk carriers. Over time, these existing ships would need to be replaced with new-build ships. The main challenge is the scale-up of hydrogen and CO_2 carriers by 2030, which, if not realized, poses a risk to international trade. The potential for larger ship sizes for some hydrogen and CO_2 carriers means that significantly fewer ships than the number estimated will be required if these technologies scale.

To facilitate shipped exports and imports of hydrogen and its derivatives, global port tonnage for hydrogen carriers must be increased to more than 2,000 million metric tons. This is approximately three to four times the capacity of the ports of Rotterdam or Singapore. In major existing ports, much of the import infrastructure could be reused for green steel and most liquids, although expanded capacity for methanol and ammonia would likely be required. Greenfield supply areas in remote locations will need new port capacity.

For pipelines, half of hydrogen for end-use (around 440 million tons per annum in 2050) is transported through pipe over long distances. By 2030, almost all long-distance (greater than 1,000 kilometers) piped transport will be domestic and found in markets such as China and North America, with some international trade in Europe. As such, large pipeline transporters such as the United States, China, and Europe need to enable piped hydrogen by 2030, requiring investment decisions before 2025. By 2050, the share will be roughly equally divided between international trade and long-distance domestic transportation.



1. Assume the following sizes: green steel: 120,000 deadweight tons (dwt) (7 million tons hydrogen [MTH_2]); methanol (new): 60,000 dwt (11 KTH_2); methanol (existing): 45,000 dwt (8 MTH_2); synthetic kerosene 50,000 dwt (37 MTH_2); ammonia (new): 60,000 dwt (11 MTH_2); ammonia (existing): 19,000 dwt (3 MTH_2); hydrogen: 6,000 dwt (6 MTH_2); CO_2: 19,000 dwt. Larger ammonia tanks would require technology advancements. Bigger liquid-hydrogen vessels are also being developed.
2. Annual volumes of hydrogen carriers, hydrogen derivatives, and biogenic CO_2 for synthetic kerosene transiting through export and import shipping terminals.
3. Does not include domestic pipelines that link production centers with either ports for exports or short-distance domestic transmission system operator (TSO) pipeline connections for hydrogen distribution.

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03 Investments

$10 TN

cumulative hydrogen and derivative investments required by 2050

$140 BN

spending per year on transportation saves more than $450 billion on total annual system costs by 2050

Exhibit 14

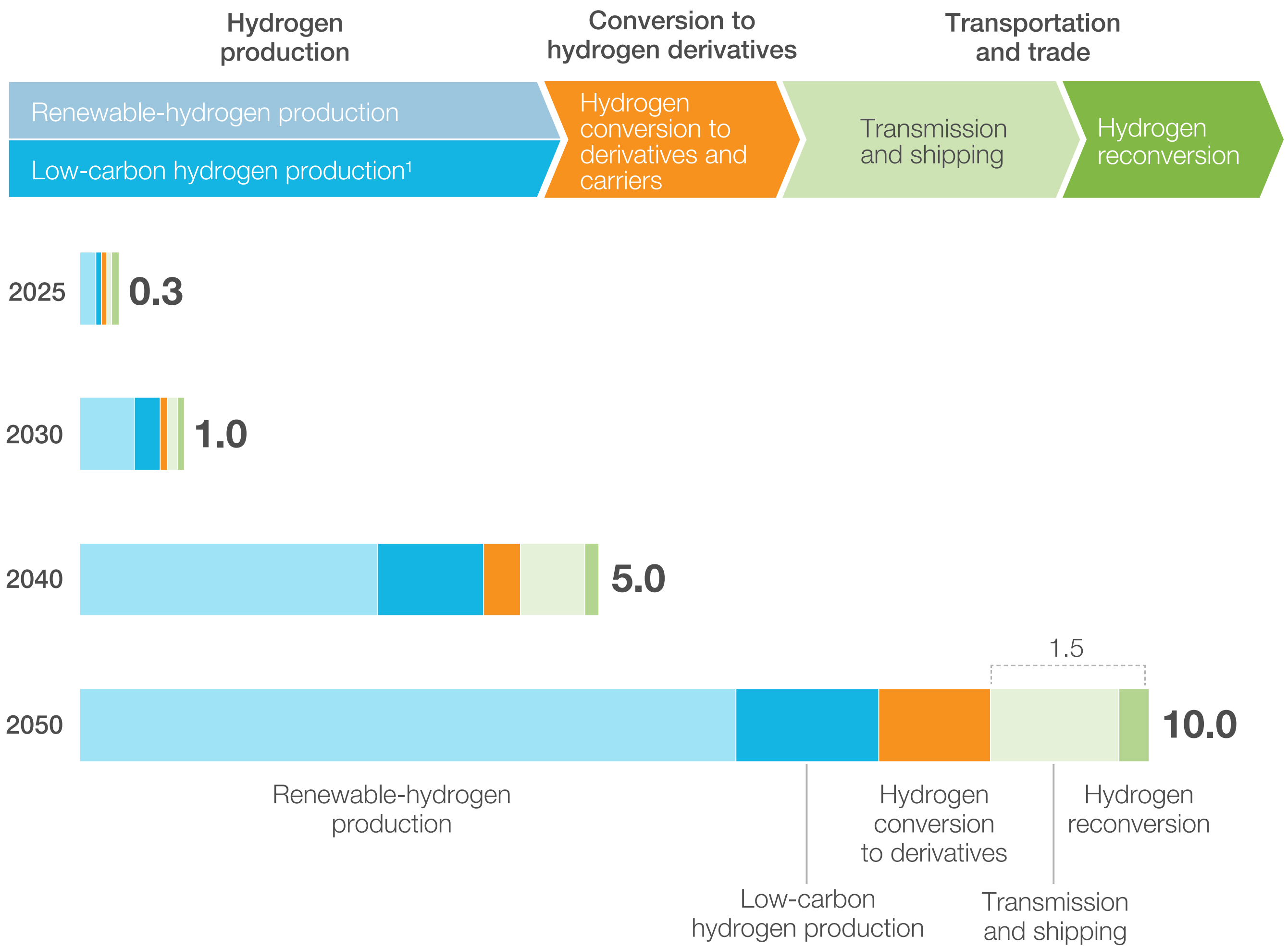
After 2030, investments will likely accelerate—and out of the $10 trillion in investments required by 2050, investments in trade-related infrastructure will account for $1.5 trillion

Cumulative hydrogen investments will grow five times over from 2030 to 2040, then double again by 2050. The bulk of investments will be for renewable-hydrogen production, while trade-related investments make up 15 percent of total investments.

Investments in renewable-hydrogen production account for 55 to 60 percent of the total investments from 2030 onwards. More than three-quarters of such investments will be in renewable power generation, including solar, onshore wind, and offshore wind.

Investments in pipelines, reconversion facilities for carriers, and shipping will only pick up after 2030 because countries with large hydrogen and derivatives demand will increasingly turn to global trade to complement domestic production.

Hydrogen and hydrogen derivatives investments, $ trillions



10X
Investment scale up required from 2030 to 2050

$1.5 TN
Investment in transportation required by 2050

1. Excludes gas upstream costs.

Exhibit 15

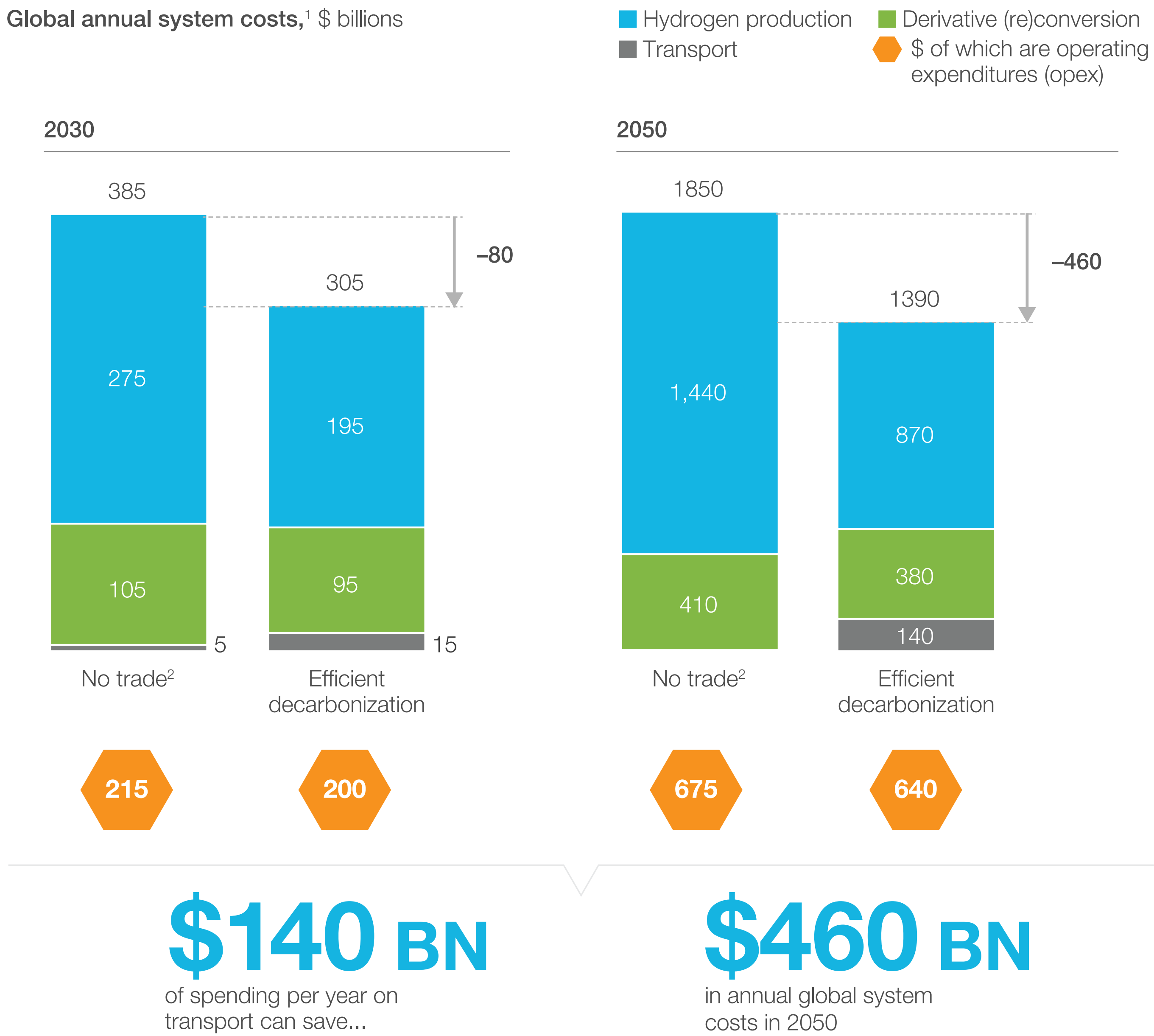
Enabling trade of hydrogen and its derivatives reduces total capital expenditures and operational expenses by 25 percent, saving $460 billion by 2050

System cost is the combination of capital expenditures and operating expenditures across the value chain. Investing in transport and reconversion can unlock substantial benefits. This effect primarily comes from reducing production costs.

To facilitate long-distance transportation, $140 billion in transport investments a year by 2050 would be required. This would cover the cost of more than 1,100 ships and carriers to transport hydrogen derivatives as well as the pipelines required to move over 200 MTPA of hydrogen.

In turn, these transportation investments, as well as $30 billion less in reconversion costs, enable hydrogen-production costs to be reduced by some $570 billion by 2050 as cheaper production areas expand production and exports.

In total, long-distance transport and trade could save over $5 trillion in aggregate system costs (capital expenditures and operating expenditures) by 2050 compared to a system that lacks trade entirely.



1. Sum of opex and annualized capital expenditures.
2. Scenario where international trade is prohibited (except for HBI Steel). Any region that would not be able to meet their demand due to production constraints has been given the option to build extra offshore wind at a cost equivalent to that of South Korea, among the higher unit costs.

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04

Scenario analysis

13% to 15%

higher investment costs in scenarios of less trade or restricted low-carbon hydrogen, increasing the cost of the energy transition

Exhibit 16

Our reference-case scenario ensures economically efficient decarbonization, while three alternative scenarios assess alternative trade evolution trajectories

We developed three alternative scenarios for the energy transition to explore critical uncertainties and the role of hydrogen trade. These scenarios focus on a delayed transition because of a failure to reach net-zero emissions, a system based on self-reliance and local supply chains, and a preference for renewable hydrogen.

Delayed transition

The world misses net-zero by 2050

- High inflation, slower economic growth, and stalled hydrogen investments result in lower hydrogen demand[1]
- Energy policy swings more strongly to energy security and development of domestic production
- More countries stick with gas for longer
- Biogenic CO_2 is not traded due to limited incentives

Self-reliance

Development of local industries and supply chains

- Prioritization of local job creation, industrial know-how, and energy security resulting in local production minimums (vs local demand) for all regions:
  - hydrogen (80%)
  - ammonia (80%)
  - synthetic kerosene (50%)
- Some regions require more expensive offshore wind capacity to fulfill this requirement

Renewable world

Concerted social push for a renewables-based energy system

- Limited investments in new autothermal-reforming (ATR) technology, with low-carbon hydrogen coming only from existing small modular reactor (SMR) facilities
- Announced low-carbon hydrogen projects do not materialize
- Accelerated renewable scale-up, resulting in a 10% cost reduction of electrolyzers

1. McKinsey's Global Energy Perspective - Current Trajectory scenario.

Exhibit 17

Encouraging the production of both low-carbon and renewable hydrogen and long-distance trade is key to achieving net-zero emissions with minimal costs

In a delayed energy transition with lower investment in decarbonization and 40 percent less hydrogen demand, over 50 percent of hydrogen would still be traded. Meanwhile, a more self-sufficient scenario would see the share of long-distance transport decrease by 15 percent while overall investments grow 15 percent. This would make hydrogen more expensive, therefore slowing the uptake of hydrogen, making the energy transition more difficult. Finally, a scenario that does not allow for low-carbon hydrogen would increase total investment costs by 13 percent with no change in trade.

To stress-test the resilience of this outlook, we developed three scenarios, each with different outcomes on global trade:

Delayed transition

Outcome: With 40 percent less demand, this scenario has a higher percentage decrease in trade (around 50 percent) because demand markets can produce more locally. Overall investments fall by 30 percent. Low-carbon producers are disfavored because gas pipelines are still in use, limiting the ability to retrofit and resulting in a higher unit cost of supply.

Self-reliance

Outcome: With reduced willingness to trade, total system capital expenditures and unit costs rise by 15 percent ($1.5 trillion) and 8 percent, respectively. Certain countries are forced to utilize expensive production sources, such as offshore wind in East Asia, instead of importing from cheaper sources.

[ ] Share of renewable hydrogen

	Net-zero 2050 achievable	2050 hydrogen production, million tons (MT)[1]	2050 share of hydrogen demand traded long-distance, MT	Cumulative investments by 2050, $ trillions	Average unit cost of supply, $/kg	Key takeaways[2] – Reference case vs test case
Reference-case scenario						
Efficient decarbonization Optimal allocation of supply across global regions (reference)	✓	680 [70%]	60%	10	2.1	Cost optimal cumulative emissions reductions of 80 gigatons (GT) by 2050
Test cases						
Delayed transition The world misses net-zero 2050 by 10 years	✗	415 [90%]	↓ –5%	↓ –3.0	↑ +0.1	Delayed transition does not meet net-zero 2050 targets, with hydrogen contributing 56 GT emissions reduction
Self-reliance Preference for local industries and supply chains	✓	680 [75%]	↓ –15%	↑ +1.5 +5.7 (High range for no-trade case)	↑ +0.2 +0.5 (High range for no-trade case)	Reducing long-distance trade increases capital-expenditures requirement and hydrogen costs. Impact increases with level of self-reliance
Renewable world Concerted social push for a renewables-based energy system	✓	680 [95%]	≈ 0%	↑ +1.3	≈	Restricting low-carbon hydrogen production increases capital-expenditures requirements

1. Includes hydrogen and hydrogen-based derivatives before losses.
2. Global takeaways conceal regional variations.


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Renewable world

Outcome: Investments increase by some $1.5 trillion as low-carbon hydrogen is removed from the playing field. However, the unit cost of supply by 2050 is nearly identical as a result of lower operating expenses compared to low-carbon hydrogen. Although global trade volumes stay comparable, specific trade routes vary widely, with renewable exporters displacing those who produce low-carbon hydrogen. For example, low-carbon pipeline supplies to Europe decline, replaced with more domestic and proximate renewable-hydrogen imports such as from North Africa and Eastern Europe.

Exhibit 18

Under different scenarios, some key trade routes are more robust than others

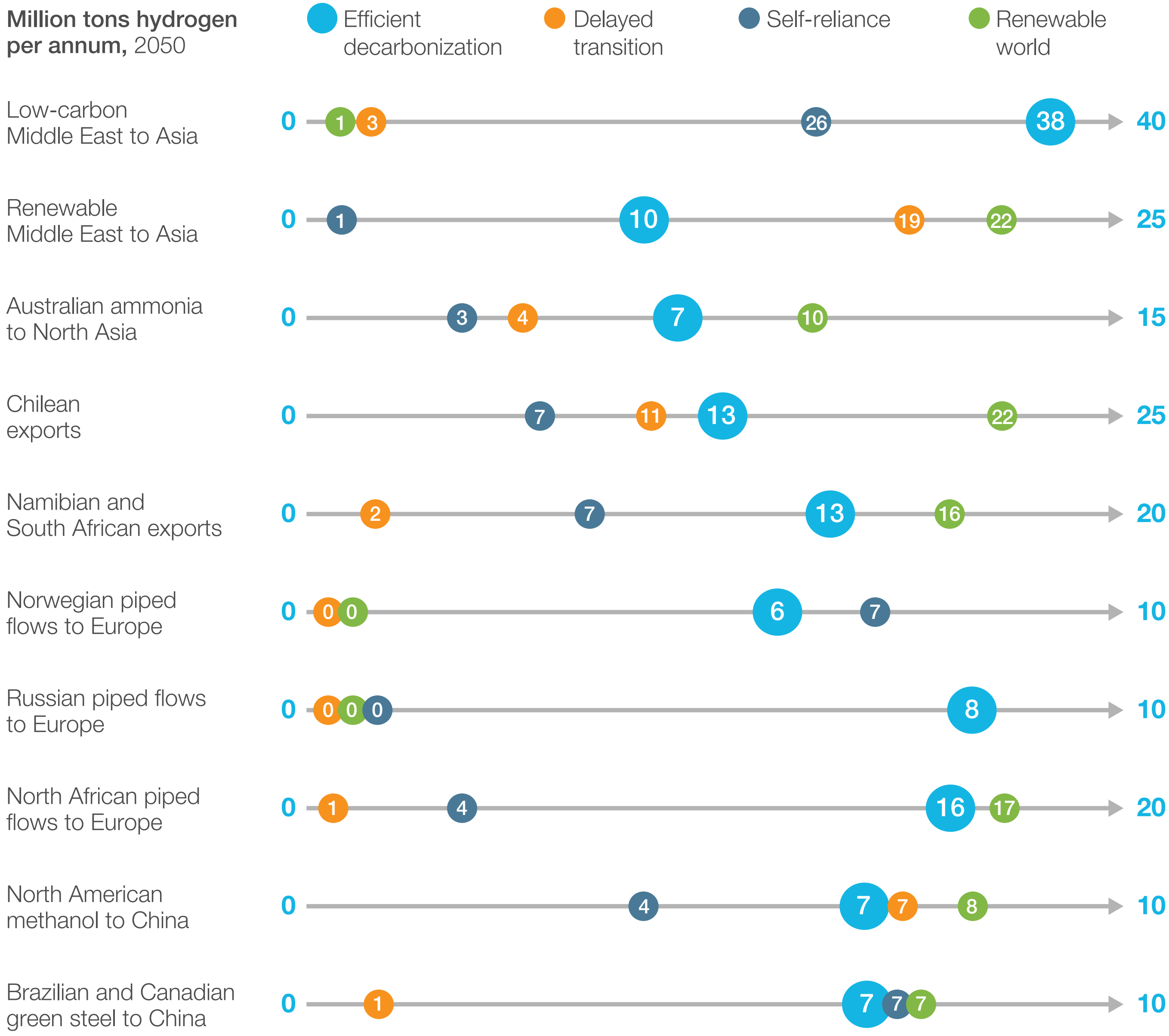
Green steel and methanol trade routes prove the most robust across scenarios.

Compared with the efficient-decarbonization scenario, in which strong, deep trade links develop between producers and offtakers, the alternative scenarios have a number of different implications for global hydrogen trade:

— *Delayed transition:* Peripheral suppliers of hydrogen will have difficulties due to lower demand and pipelines that are still used for gas, which North Africa needs to access the European market. Low-carbon-hydrogen suppliers, such as Norway and the Middle East, will continue to prioritize natural gas, given consistent demand and sustained positive netbacks. However, Europe will continue to import shipped derivatives. The Middle Eastern and Australian supply of hydrogen to Asian markets is reasonably robust because Japan and Korea will continue to import it. At the same time, the scope of ammonia demand is highly uncertain. Potential exporters of synthetic kerosene in Southern Africa and South America are at risk if they do not work on creating a consistent supply of CO_2.

— *Self-reliance:* With a push for local supply chains, Tier 2 countries will need to work hard to compete with natural low-cost suppliers. Renewable-hydrogen suppliers from the Middle East and East Asia are at risk, and the United States may lose its next-best status for ammonia and synthetic

Volumes of key trade routes in different scenarios



kerosene. Europe could become reluctant to import large quantities of hydrogen. As a result, Norway will most likely to continue to supply the region because it has the lowest cost, while North Africa could lose out. Finally, China will reduce its methanol import requirement.

— *Renewable world:* Large low-carbon exporters, such as the Middle East and the United States, risk missing out on European and Asian markets. However, additional Middle Eastern renewable hydrogen will largely replace low-carbon hydrogen from the same region. This trade opportunity extends to second-highest-cost renewable-hydrogen suppliers. North Africa could enter the derivative market too, in addition to piping pure hydrogen to Europe.

Taken together, the scenarios offer several notable takeaways. Overall, the most resilient trade routes are Canadian and Brazilian green steel, as well as US methanol to China. These routes vary only slightly across all scenarios, with some upside in a renewable world. Only green steel to China in the delayed-transition scenario is at risk because these routes are uniquely positioned in terms of access to critical resources (CO_2 and iron ore).

The largest upside is generally found in regions with competitive but stranded renewable energy sources, such as the Middle East to Asia, and renewable hydrogen and Chilean exports. These trade routes could nearly double in a renewable world.

Low-carbon pipeline exporters to Europe, such as Norway, face the greatest uncertainty. These exporters are reliant on a single primary market and have policies that favor low-carbon hydrogen. Any move toward a delayed transition, self-sufficiency, or renewables fundamentally reduces or even removes these trade routes.

In addition, in the event of a renewable world, low-carbon hydrogen from the Middle East faces displacement by renewable hydrogen from the same region, while a delayed transition would mean higher gas prices, disincentivizing hydrogen production in the region.

Exhibit 19

East Asia is most exposed to higher supply costs under other scenarios

The global marginal costs for hydrogen in major markets will range from $1.25 to $2.85 per kg in the efficient decarbonization scenario. Under other scenarios, the range widens to $1.15 to $3.70/kg.

Delayed transition

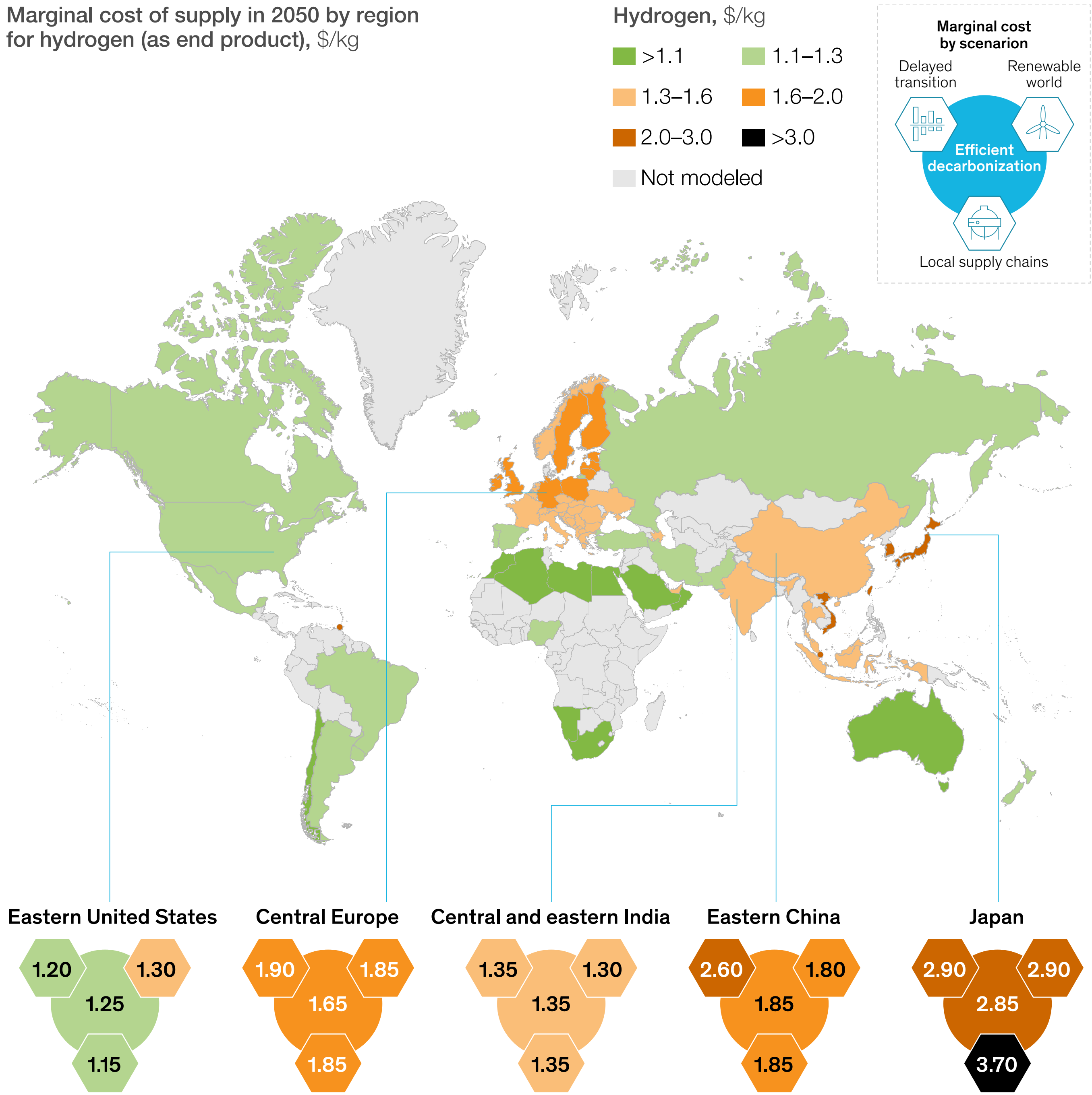
The cost range is $1.20 to $2.90. Eastern China sees the biggest change, since sustained gas demand means that natural gas pipelines can not be retrofitted for hydrogen. Instead, new build long-distance pipelines from western China need to be built, increasing costs.

Self-reliance

The cost range is $1.15 to $3.70. Restricted imports result in a greater share of domestic production in the supply mix for importing markets. The biggest consequence of this is seen in Japan, where domestic production has very high costs.

Renewable world

The cost range is $1.30 to $2.90. Overall costs do not move significantly as the lower operational costs for renewable hydrogen mitigate the additional capital expenditure required.



05

Enablers and implications

10

largest trade corridors can unlock 75% of global trade

Exhibit 20

Global regions have clear and unique leadership roles in building the traded hydrogen market

All global regions have a key role to play in developing a global traded hydrogen economy. By doing so, they can unlock benefits for themselves and ensure efficient decarbonization.

The traded market will become increasingly specialized. Regions should consider what to specialize in and invest with the goal of unlocking their relative trade advantage. The most competitive producers should produce, but others can compensate if they possess advantageous locations or feedstocks such as iron ore and carbon dioxide. Examples include Chile, which can drive aviation, and Brazil, which can drive steel decarbonization. To realize this potential, regions will need to develop and scale up these technologies.

Unlocking trade can reduce the landed cost of hydrogen for some offtakers by approximately 40 percent in the most expensive regions. For example, Japan and South Korea can develop supply chains to accelerate hydrogen-carrier technologies that will facilitate shipped imports.

In all, the top ten global trade corridors will account for more than 75 percent of global trade, so infrastructure investments along these corridors should be prioritized. Players can also identify which technologies are critical, as well as when and where to deploy them.

Namibia and South Africa

The region has the potential to be one of the main synthetic-kerosene suppliers if access to biogenic CO_2 can be secured.

North America

Cost-competitive renewable and low-carbon hydrogen can be unlocked through continental pipelines, CCS capacity east of the Rocky Mountains, and renewable hydrogen in the west and south. Conversion investments can boost clean methanol to Asia and ammonia and green steel to Europe and Asia.

Latin America

Latin America can lead global steel and aviation decarbonization by combining good solar conditions, intraregional carbon dioxide trade, and iron ore capacity.

Europe

Europe can unlock hydrogen production in Norway, Iberia, CIS, and North Africa by retrofitting existing gas infrastructure for hydrogen imports. Derivatives can be imported from overseas using existing ports.

Iberia, Ukraine, and North Africa

Europe will be the big offtaker, and trade could be successful if gas lines are replaced with hydrogen lines in a timely manner and if the region gains the ability to export derivatives via ship.

Middle East

The Middle East can meet large-scale hydrogen demand in Asia and possibly Europe through carbon capture and storage (CCS) and carrier scale-up combined with renewable technology.

China

Scaling of globally competitive renewable hydrogen in western China can be unlocked by retrofitting gas pipelines to the east. Derivatives can be imported from overseas using existing ports.

CIS

If political relations are restored, infrastructure to supply Europe in the west and Asia in the east has large potential. The key is to abate methane leakages and achieve a stable political environment.

India

Self-sufficiency can be achieved through decentralized hydrogen production aided by hydrogen-derivative imports from the Gulf region.

Australia

Australia can supply hydrogen and ammonia to North Asia via scale-up of ammonia and carriers, a process that can involve both low-carbon and renewables.

Japan and South Korea

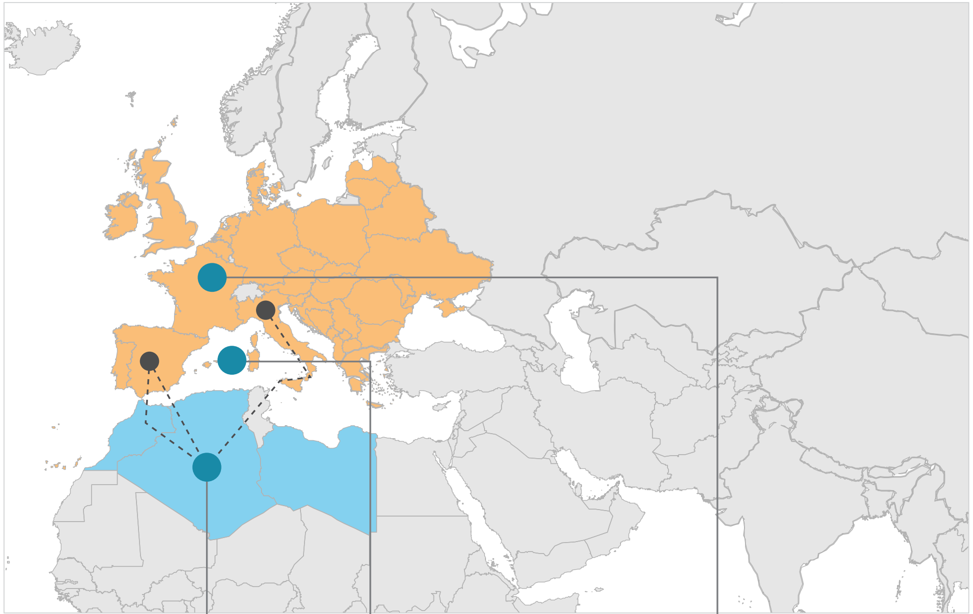
It is critical that Japan and South Korea accelerate hydrogen carrier technology to facilitate shipped imports.

Exhibit 21

Key enablers will differ per priority corridor

Illustrative

Pipeline corridor: North Africa to Europe (example)



Exporter

Encourage RES[1] and H_2 production projects through regulatory and legal stability

Earmark land for RES and projects close to existing Europe-bound gas pipelines

Exporter + importer

Coordinate retrofitting of existing gas pipelines

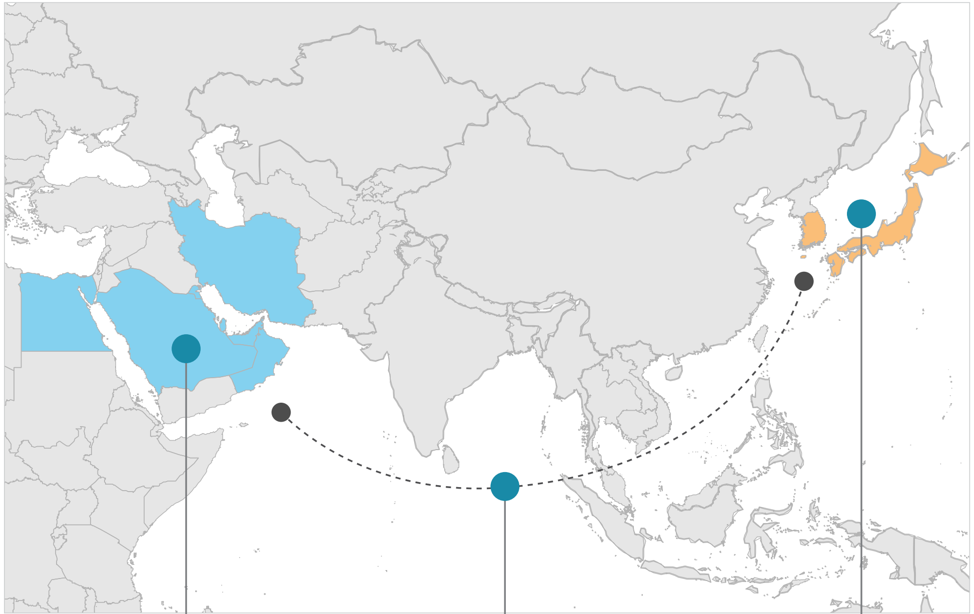
Work with financial institutions on transparent investment criteria

Importer

Establish offtake contracts with exporting countries in North Africa

De-bottleneck key axes to enable distribution of imported piped H_2 throughout Europe (eg, Spain–France, Italy–France, Italy–Switzerland)

Shipping corridor: Middle East to East Asia (example)



Exporter

Simultaneously develop production of RES and low-carbon H_2, including associated carbon capture and storage

Lead investments in large-scale conversion facilities (LH_2, LOHC, ammonia)[2]

Exporter + importer

Develop key infrastructure and shipping capacity for West–East corridor, including rerouting of current shipping capacity

Coordinate free or preferential trade flows

Importer

Derisk investments across value chain by providing demand certainty

Accelerate H_2 carrier technology uptake

Support development of reconversion and storage facilities at ports

1. Renewable energy sources.
2. Liquid hydrogen; liquid organic hydrogen carriers.

Exhibit 22

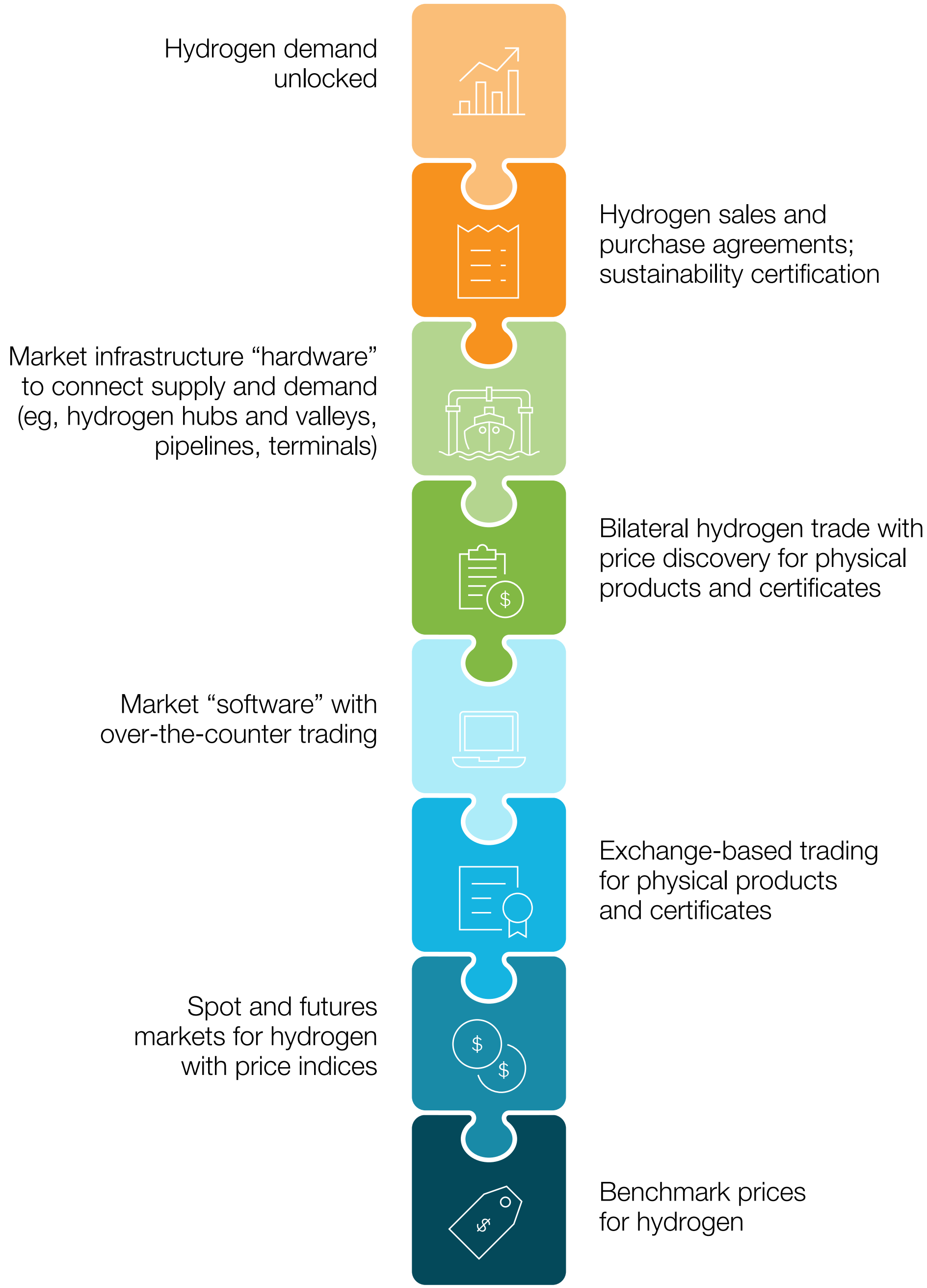
Toward a cross-border, global hydrogen commodity market

For the hydrogen traded market to develop, key market mechanisms and structures will be required. These may evolve in line with other commodities, but with key differences.

In parallel with the development and expansion of the "hardware" of the global hydrogen market infrastructure (ships, terminals, pipelines, and refueling stations), market "software" will also need to evolve. Specifically, this category includes market design, pricing methodologies, price indices, regional benchmark prices, contractual structures, and trading hubs for hydrogen and its derivatives.

Hydrogen has a long journey to becoming a mature commodity. In the short-to-medium term, cross-border trade in hydrogen is likely to start with bilateral long-term contracts and cost-plus pricing models. Standard contracts for hydrogen are expected to be a helpful tool to support cross-border trade in hydrogen and to help kick-start over-the-counter trading. The development of price discovery will in turn enable exchange-based trading and the emergence of regional spot markets for hydrogen and its derivatives. In the longer term, standardized exchange-based products such as hydrogen futures could be used by market participants for hedging purposes, similarly to the way futures are used today in mature gas markets. Furthermore, standardized products may also include certification to bring transparency into the carbon footprint of hydrogen. There are already several mechanisms and exchanges emerging that could ultimately evolve to play these roles either locally, regionally, or globally.

The evolution of the global gas and liquefied-natural-gas market may have parallels with the prospective global market for hydrogen. However, the key differentiator is that the value of hydrogen is contained in both the value of the physical product and in the value of the environmental attribute—in other words, the certification. As such, hydrogen certification will play a crucial role in building customer trust and enabling customer choice. Consequently, if this certification is realized, it will stimulate demand and enable a market-based approach to hydrogen sourcing. In turn, this will facilitate global, cross-border trade in hydrogen, enabling supply and demand to meet in an efficient manner across geographies.



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Methodology, assumptions, and detailed data appendix

Exhibit A1

The Global Hydrogen Trade Model takes more than 1.5 million trade options into account to determine optimal trade routes and supply options

Forecasting the development of future global trade is complex. Flows modeled in this report include pure hydrogen, hydrogen carriers (ammonia, liquid hydrogen, and liquid organic hydrogen carriers), and hydrogen derivatives (ammonia, methanol, synthetic kerosene, and green steel). The model optimizes future hydrogen flows, aiming to minimize overall system costs, an objective that should be pursued by the market participants of the future.

Description of the Global Hydrogen Trade Model

Inputs

- Demand forecasts
- Production costs
- Transport costs
- Production limits
- Diversification and security of supply constraints

Optimization of production and trade flows

5 end products

57 market regions

8 largest countries with a sub-country split

4 full optimization years: 2025, 2030, 2040, and 2050

8 production source categories

4 hydrogen carriers *and*

1 green-steel carrier

92 pipeline directions

Outputs

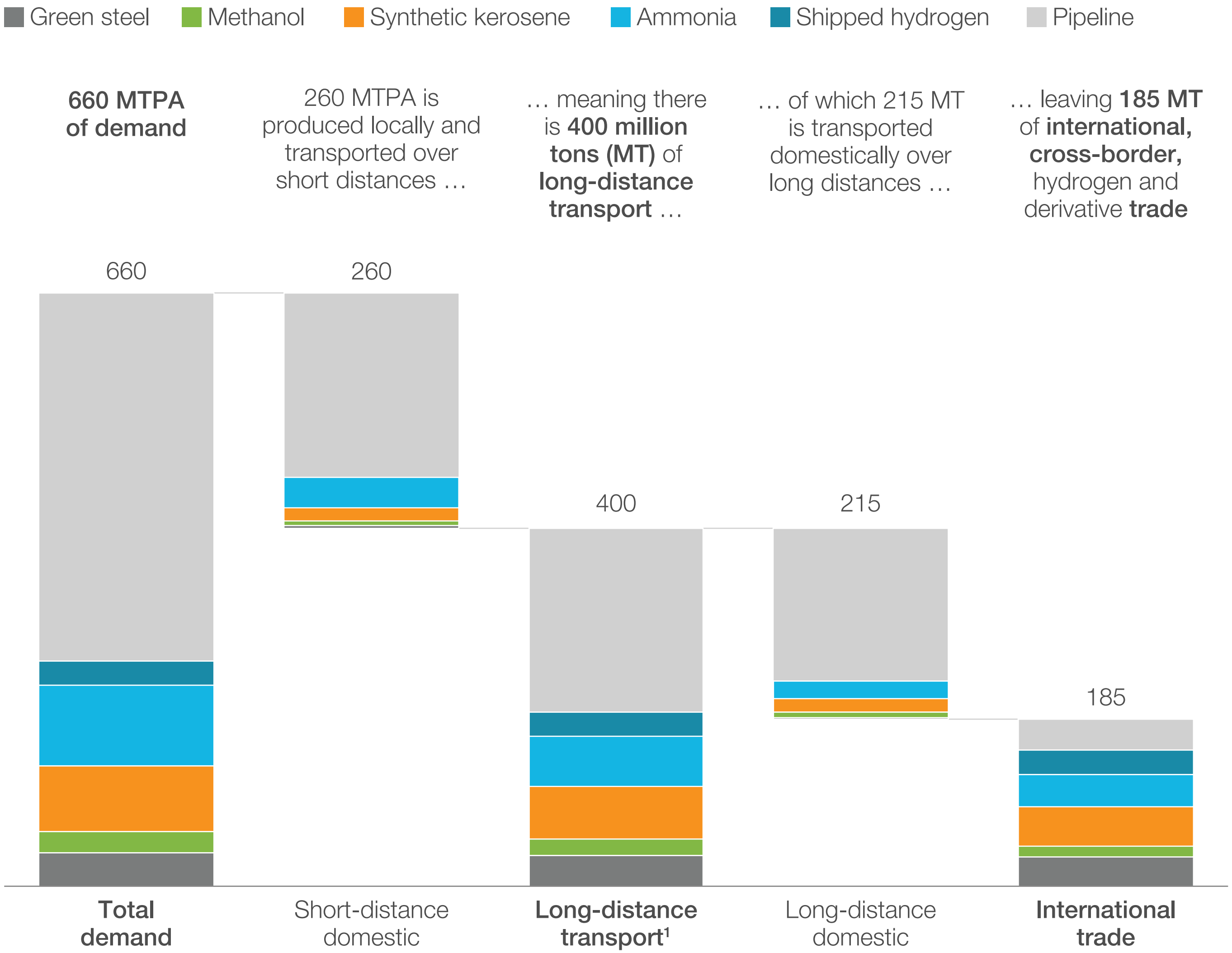
- Country production forecasts
- Flow volumes by carrier
- Destination cost curves
- Capital-expenditures forecasts
- Marginal-cost forecast
- Scenario analysis

Source: McKinsey European H_2CH_4 balancing & optimization tool

Exhibit A2

We distinguish between production, demand, long-distance transport, and international trade

Hydrogen and derivative supply, 2050, million tons per annum (MTPA)



1. Long-distance trade is defined as trade across distances of more than 1,000 km. It is estimated as a sum of 1) all international trade, 2) trade between split countries, most notably between eastern and western China, and 3) 65% of domestic production of Russia, Canada, the United States, western China, Brazil, and Australia.

Source: Efficient decarbonization scenario, McKinsey Global Hydrogen Trade Model