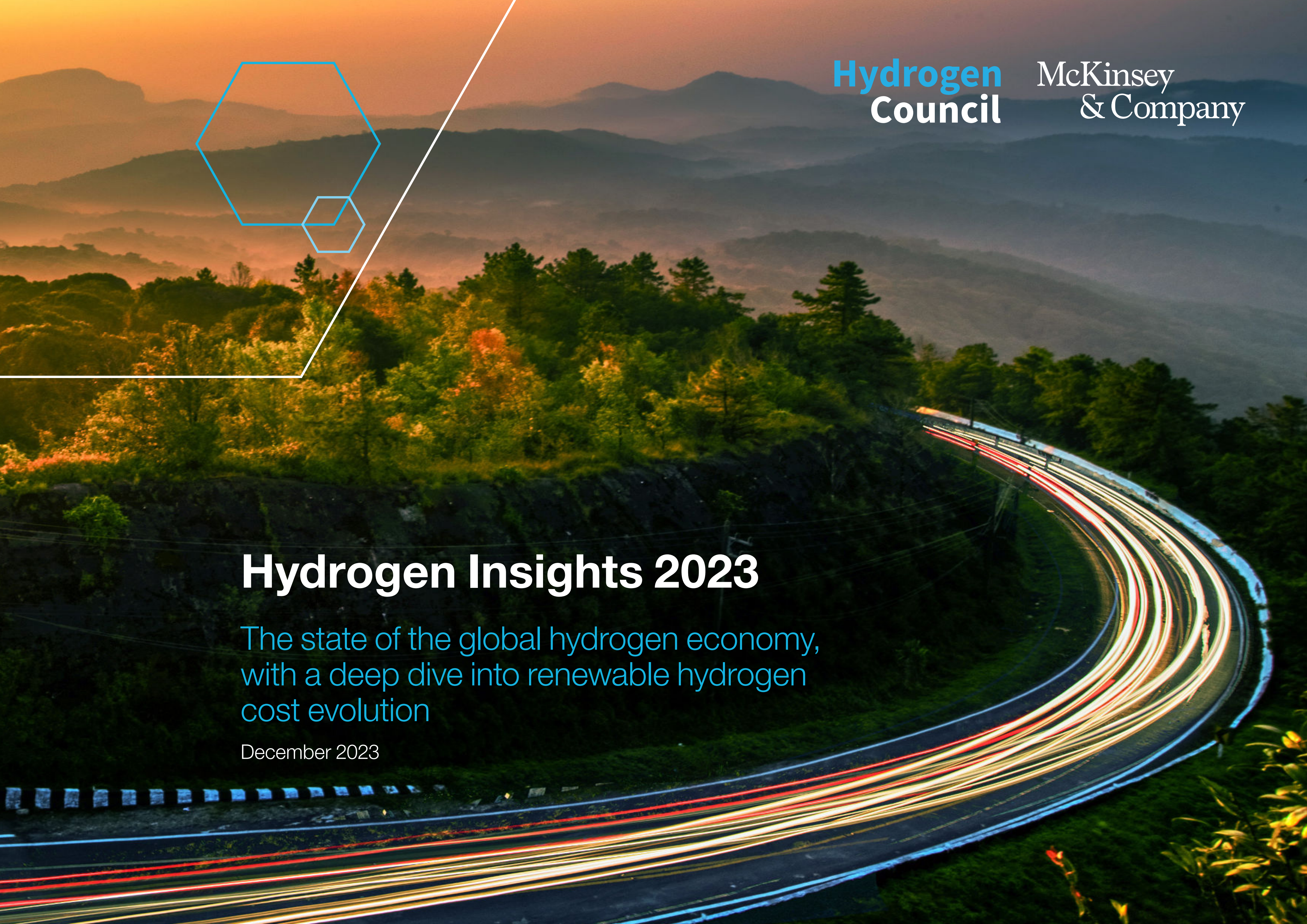

Hydrogen Council
McKinsey & Company

Hydrogen Insights 2023

The state of the global hydrogen economy, with a deep dive into renewable hydrogen cost evolution

December 2023

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1. There are no recommendations and / or any measures and / or trajectories within the report that could be interpreted as standards or as any other form of (suggested) coordination between the participants of the study referred to within the report that would infringe the EU competition law; and

2. It is not their intention that any such form of coordination will be adopted.

Whilst the contents of the report and its abstract implications for the industry generally can be discussed once they have been prepared, individual strategies remain proprietary, confidential, and the responsibility of each participant. Participants are reminded that, as part of the invariable practice of the Hydrogen Council and the EU competition law obligations to which membership activities are subject, such strategic and confidential information must not be shared or coordinated – including as part of this report.

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with a united vision and long-term ambition for hydrogen to foster the clean energy transition

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Hydrogen Insights is the Hydrogen Council's perspective on the hydrogen industry's evolution. It summarizes the current state of the global hydrogen sector and actual hydrogen deployment. The Hydrogen Council and McKinsey & Company co-author this publication. It represents a collaborative effort to share an objective, holistic, and quantitative perspective on the status of the global hydrogen ecosystem.[1]

1. Detailed methodology explained in Hydrogen Insights 2021

Executive summary

1 Hydrogen will play a crucial role in decarbonizing hard-to-abate sectors, enable the at-scale transport of energy to resource-constrained regions, and enable a clean and resilient energy system. Its deployment is at an inflection point – on one hand there are tailwinds such as a growing and gradually maturing pipeline of projects and supportive decarbonization regulation. On the other hand, there are headwinds: cost increases, project delays, continued regulatory uncertainty, and higher financing costs.

2 The project pipeline is growing, with over 1,400 projects announced across all regions (up from about 1,040 in the previous publication), equaling USD 570 billion investments (previously USD 435 billion[2]) and 45 million tons per annum (Mt p.a.) of clean hydrogen[3] supply announced through 2030 (previously 38 Mt p.a.). Europe shows the largest number of projects (540), followed by North America (248). A quarter of projects with known commissioning date has progressed past final investment decision (FID), representing 7% of the total announced investments. Investments are maturing, with USD 110 billion in front-end engineering and design (FEED) and beyond (up from USD 75 billion), with 60% growth in investments undergoing FEED. Electrolysis deployment globally has shown similar growth, passing the 1 gigawatt (GW) mark (up from 0.7 GW previously), with about 12 GW capacity having passed FID.

3 The regulatory landscape overall is evolving. For instance, support is materializing via production tax credits (PTC) and financial support for hydrogen hubs in the US, renewable hydrogen mandates in the Renewable Energy Directive (RED III) in Europe, or contracts for difference (CfD) in Japan. However, regulatory uncertainties remain, such as the definition of requirements to receive the US Inflation Reduction Act (IRA) PTC and the implementation of RED III in EU member states, implying these policies have not yet fully impacted the market.

4 The clean hydrogen industry is facing headwinds. Costs and cost expectations have risen substantially, particularly for renewable hydrogen. The estimated levelized cost of producing renewable hydrogen (LCOH) is about 4.5 to 6.5 USD per kilogram (USD/kg) if built today,[4] up by 30% to 65%. Multiple factors have caused this increase - higher labor and material costs, higher cost for building the balance of electrolyzer plants, 3 to 5 percentage points higher cost of capital, and an increase of renewable power cost by more than 30%. However, the cost of producing renewable hydrogen is expected to decline to 2.5 to 4.0 USD/kg towards 2030, driven by advancements in electrolyzer technology, manufacturing economies of scale, design improvements, and reduction in renewable power cost.

5 The headwinds have caused a slower development of the global hydrogen industry than had been previously expected. Such hurdles are reflected in, for instance, a 10% drop in announced clean hydrogen supply through 2025. Concerted action of industries and governments will likely be needed to further global clean hydrogen growth, facilitating additional decarbonization.

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2. An increase in total direct investment reflects refined estimates of capital expenditures required (primarily for renewable hydrogen supply) resulting in the previously estimated USD 320 billion increasing to USD 435 billion.
3. See clean hydrogen definition in 'Hydrogen for Net-Zero' report on page 52.
4. Example from the US Gulf Coast.

01

Hydrogen momentum continues to accelerate, but investment decisions are lagging

1,418
hydrogen projects announced globally,
1,011 of which plan full or partial deployment by 2030

USD 570 billion
direct investments in hydrogen projects announced through 2030 (+30%) – USD 39 billion (+26%) have passed FID

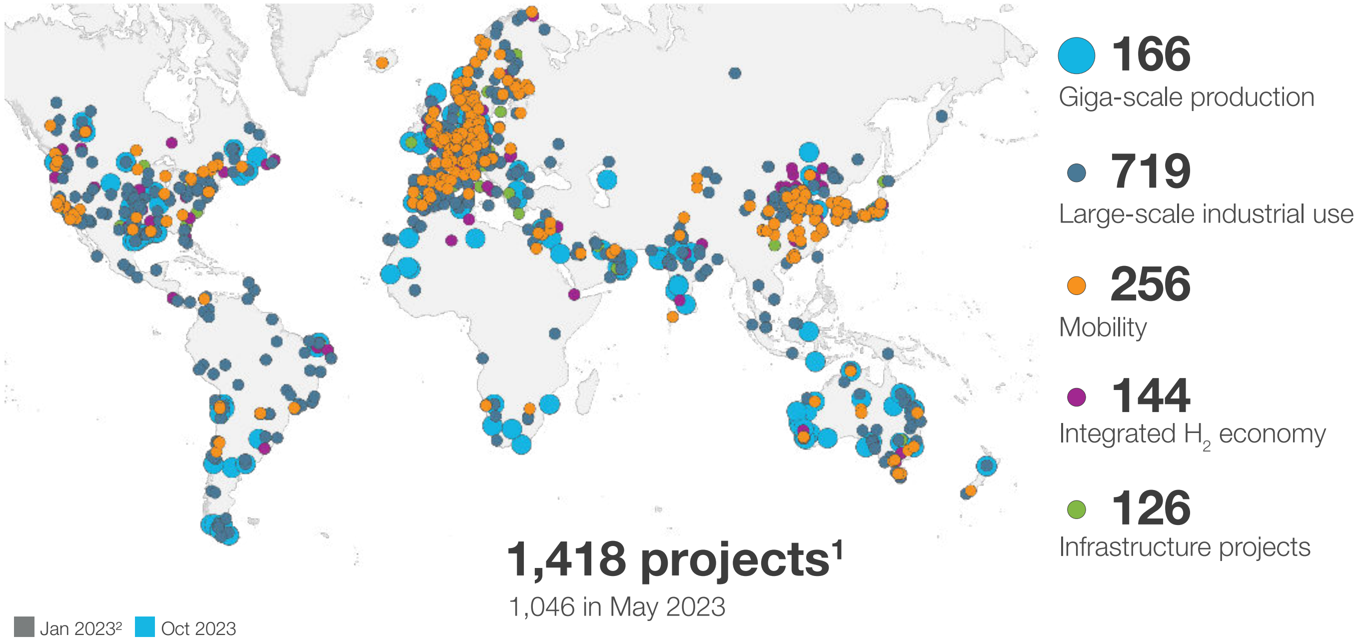
45 Mt p.a.
of clean hydrogen supply announced by 2030,
of which 70% is renewable and 30% is low-carbon

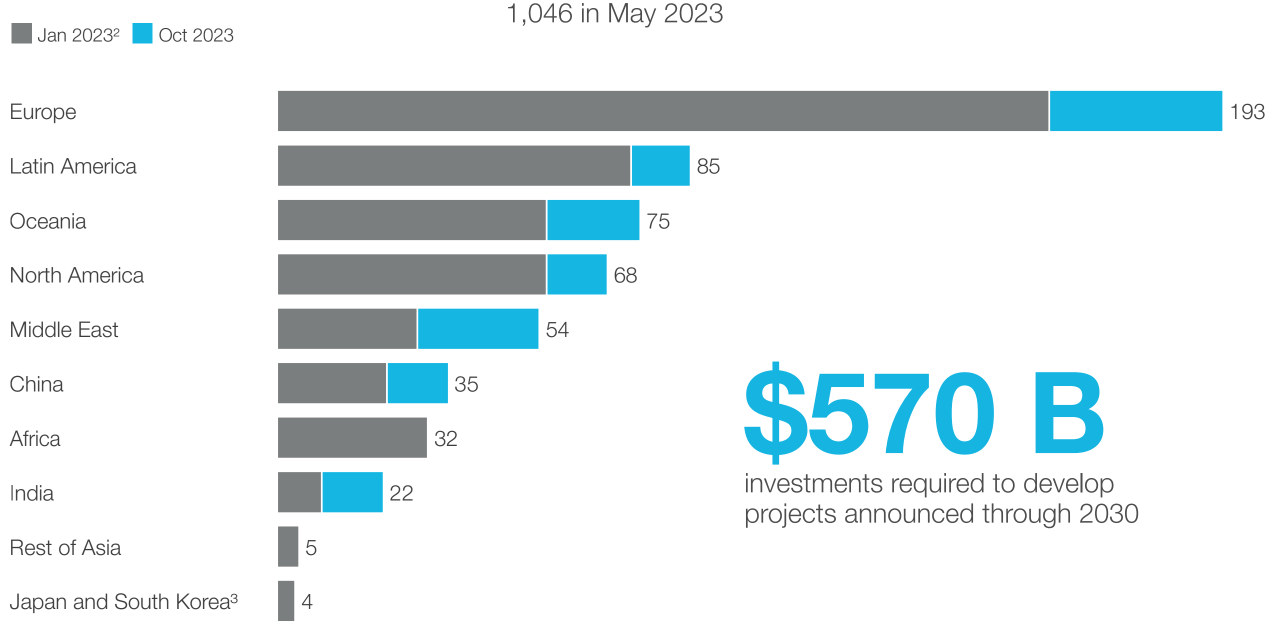
Exhibit 1

Hydrogen momentum is strong: 1,418 projects have been announced globally – USD 570 billion investments announced

Globally, the industry has announced 1,418 clean hydrogen projects as of October 2023. Since the previous publication,[5] 372 new projects have been announced. of the total, more than 1,000 aim to be fully or partially commissioned through 2030, representing investments of about USD 570 billion in hydrogen value chains (up from USD 435 billion). Giga-scale projects (over 1 GW of electrolysis for renewable hydrogen supply or more than 200,000 Mt p.a. of low-carbon hydrogen) account for over USD 330 billion.

Growth is apparent across most regions in terms of both investments and the number of projects. Europe continues to have the largest number of projects (540), followed by North America (248). Europe also has the highest total investments announced (USD 193 billion) as well as the highest absolute investment growth (USD 32 billion). Latin America has the second largest volume of investments announced (USD 85 billion), even though it has announced fewer than half the number of projects of North America (120), due to larger project sizes and a higher share of giga-scale renewable hydrogen projects. Growth in announcements in North America was USD 12 billion, an increase of about 20%, indicating continued momentum following the announcement of the IRA. India shows the highest relative growth in investments of about 140%, corresponding to about 40 projects. The Middle East and China follow with about 80% and 50% growth in investments, respectively.





1. Project announcements below 1 MW excluded; includes 7 projects without specified type
2. Jan 2023 values have been updated to most recent capex estimations to keep values comparable
3. Restatement of Jan 2023 data for Japan and South Korea prevents comparison to Oct 2023 data

Source: Project & Investment tracker, as of Oct 2023

5. Hydrogen Insights 2023, published in May 2023; comparisons in this report are relative to this publication unless stated otherwise.

Exhibit 2

The project funnel is growing across project stages, with most growth occurring in the advanced planning stage

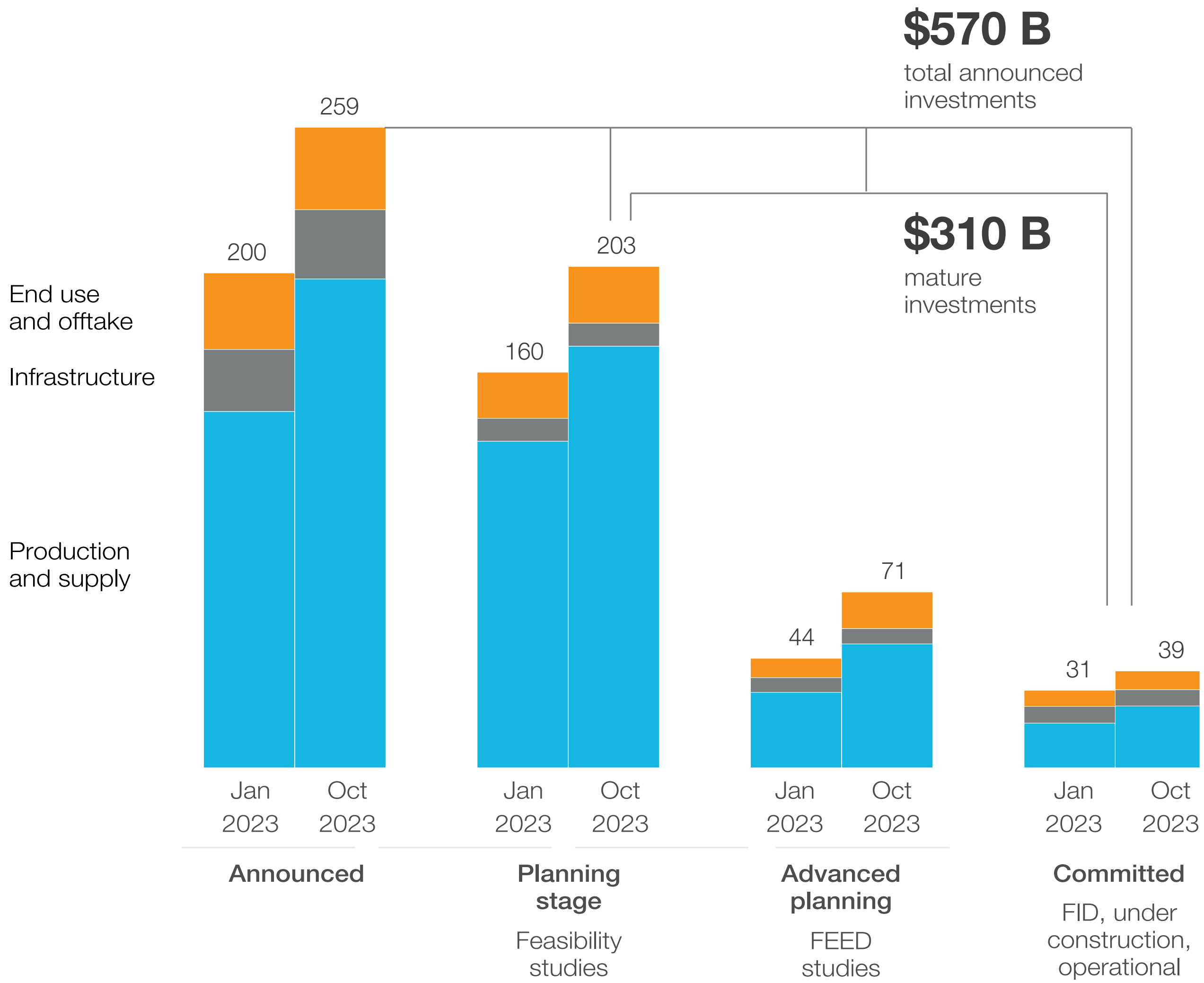
The total announced investments through 2030 have increased by 30% in the past nine months – from about USD 435 billion to more than USD 570 billion. The increase is unevenly distributed across project maturity stages with the strongest growth in advanced planning (FEED) of about 60%, followed by announced (about 30%), planning (about 25%), and committed (about 25%). The growth in investments at the advanced planning stage was strongest in North America (about USD 11 billion), followed by Europe (about USD 9 billion) and Oceania (about USD 5 billion). The pipeline is maturing but remains tilted toward announced and planning stage (about 75%), with only 7% of the announced investments into clean hydrogen having passed FID.

Of the committed investment volumes, China leads with about USD 12.5 billion (adding about USD 6 billion) due to several large projects located in central and northern China that account for the largest share of investment. North America reached about USD 10 billion in committed investments (adding about USD 0.5 billion), followed by Europe at about USD 7.5 billion (adding about USD 1 billion). This implies that only 4% of announced investments in Europe have passed FID, even though the region has the most total investment volumes. In contrast, the share of investments past FID stands at 35% and 15% in China and North America, respectively. The lowest project pipeline maturity is found in Latin America and Oceania where less than 1% of investments have passed FID.

The investment pipeline continues to lean toward clean hydrogen supply (about 75%), whereas investments in infrastructure and end use account only for about 10% and 15%, respectively. Looking only at mature investments, regions differ significantly in the sectoral composition. Africa shows the strongest concentration with about 95% of mature investments focused on supply, followed by China (about 80%) and Latin America (about 80%). Reflecting their strong focus on imported clean hydrogen, Japan and South Korea show a share of only 3% of supply-focused investments.

When looking at end use investments, China has the highest share of investments past FID, followed by North America and Europe. The focus varies across regions – ammonia and industrial usage lead in China and North America, whilst Europe is more prominent in mobility and refining.

Direct hydrogen investments until 2030, $B



+30%
investment growth in 9 months[1]

75%
of investments focus on supply

1. Jan 2023 values have been updated to most recent capex estimations to keep values comparable

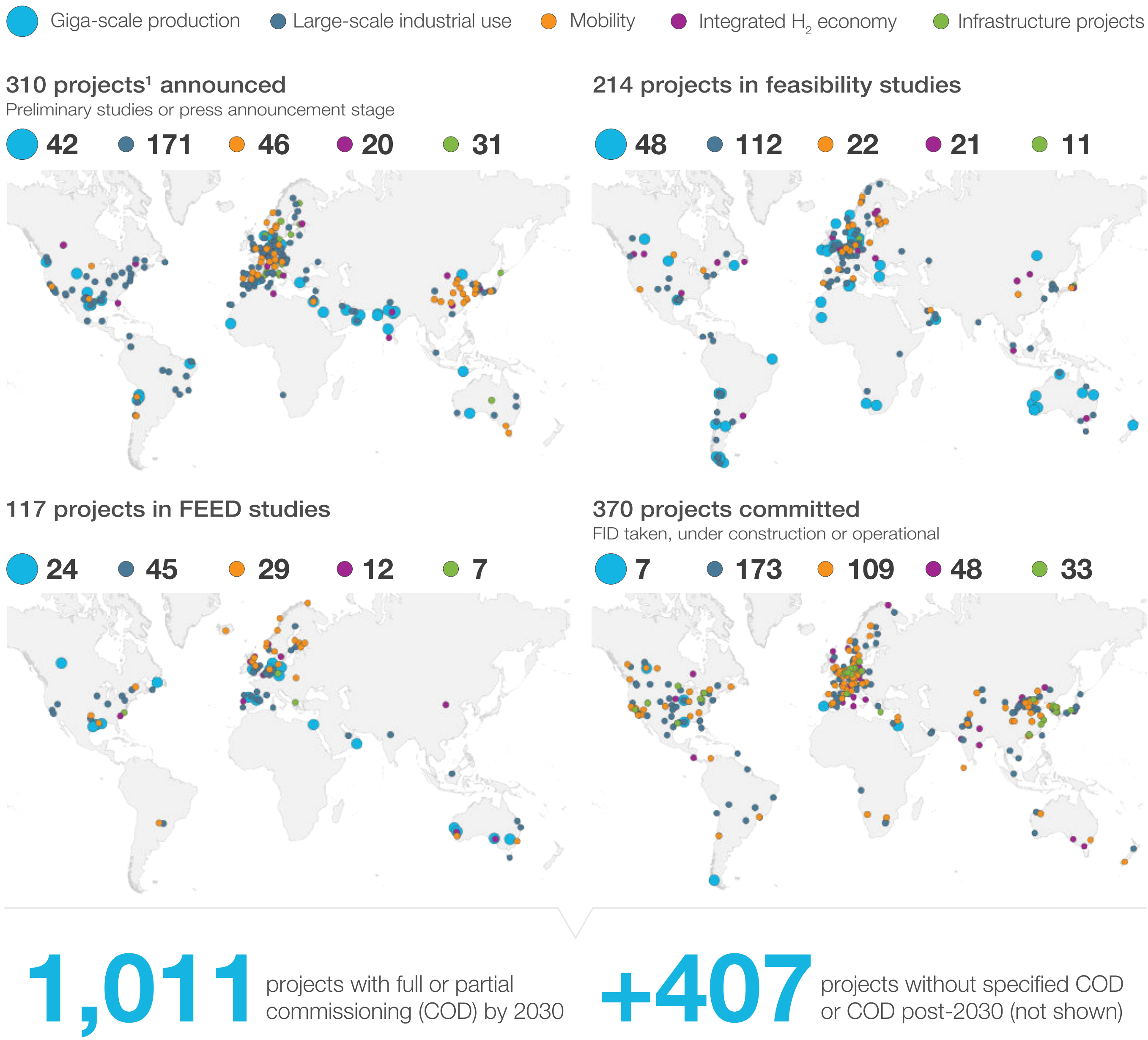
Source: Project & Investment tracker, as of Oct 2023

Exhibit 3

Europe, North America and China have the largest number of projects with committed capital

Considering projects with partial or full commissioning by 2030, more projects (by number of projects) have passed FID stage (about 35%) than the announced stage (about 30%). However, about 45% of the projects past FID are not yet operational. The projects that have passed FID are centered in Europe, Asia, and North America. This implies markets with an earlier focus on clean hydrogen as a decarbonization vector have already built early experience in deploying clean hydrogen projects.

Generally, clean hydrogen projects in earlier stages of development tend to be larger. 166 giga-scale projects have been announced, 121 of these with commissioning date through 2030. However, these are mostly still in early stages of development. Only 71 projects surpassing USD 100 million announced investments have passed FID, 7 of these with announced investment of more than USD 1 billion. Projects that have passed FID have an average investment size of about USD 160 million. However, as pilot projects continue to represent a large share of projects past FID, the median investment volume for such projects is considerably lower at USD 20 million. Projects in the earlier stages of development (announced to FEED) have a significantly larger average investment size of about USD 890 million (median about USD 280 million), which reflects over 110 projects with announced investments exceeding USD 1 billion.



1. For multiphase projects, phase 1 decides the project maturity

Source: Project & Investment tracker, as of Oct 2023

Exhibit 4

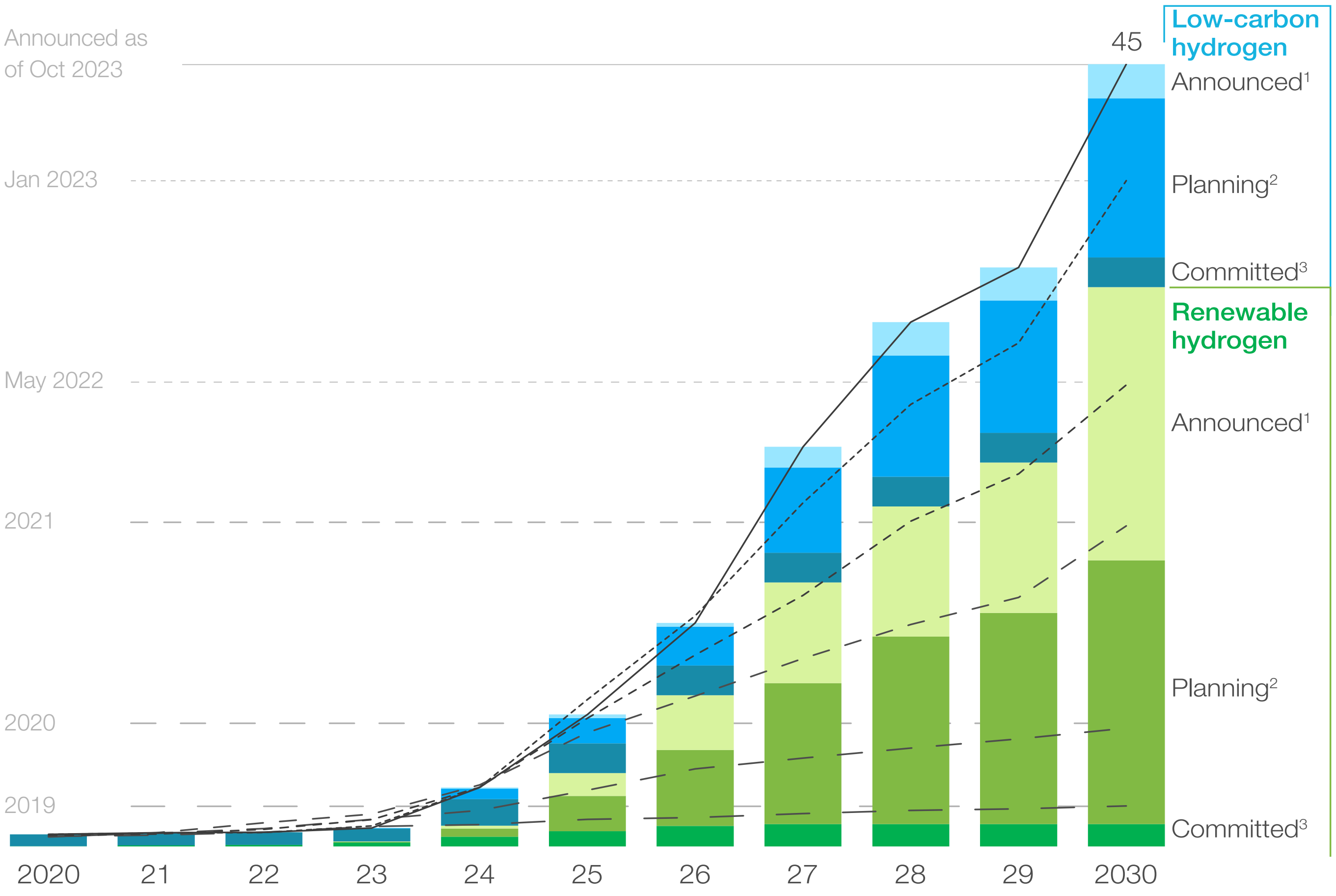
Announced production volumes increased to 45 Mt p.a.

Companies have announced 45 Mt p.a. of clean hydrogen production capacity globally through 2030 across low-carbon and renewable hydrogen (previously 38 Mt p.a.), of which about 50% of volume is in the planning stage and 7% is committed. More than 70% of the 45 Mt p.a. is renewable hydrogen capacity (about 32 Mt p.a.), the remainder being low-carbon (about 13 Mt p.a.). Of the 7 Mt p.a. capacity announced in the past nine months, more than 90% is for renewable hydrogen driven by the high growth in announcements coming from renewables-rich regions in the global south.

However, deployment is not moving as fast as previously expected by developers. Although announcements in 2021 indicated 6 GW of the electrolysis would be operational by the end of 2022, operational deployment as of October 2023 stands at 1.1 GW, or about 20% of that number. Scaling up is a considerable challenge: about 860 kt p.a. of capacity is operational with about 3 Mt p.a. past FID (slight growth compared with previous publication). About 60% of committed capacity is located in North America, followed by China (about 20%), and Europe as well as the Middle East (about 8% each).

Considering the share of low-carbon and renewable hydrogen, low-carbon hydrogen accounts for more than 75% of today's operational clean hydrogen volume, potentially due to its lower cost. Announced investments suggest the balance may start to shift towards a higher share of renewable hydrogen before 2025 - if announced volumes are deployed according to the planned timeline. Changes in composition of clean hydrogen over time will likely reflect a wide range of factors such as regulatory developments and input cost.

Cumulative production capacity announced, Mt p.a.



70%
share of capacity in top 3 markets (Europe, North America, Latin America)

+15 Mt
additional capacity (low-carbon and renewable) announced for post-2030

1. Preliminary studies or at press announcement stage
2. Feasibility studies or at front-end engineering and design stage
3. Final investment decision has been made, under construction, commissioned or operational

Source: Project & Investment tracker, as of Oct 2023

Exhibit 5

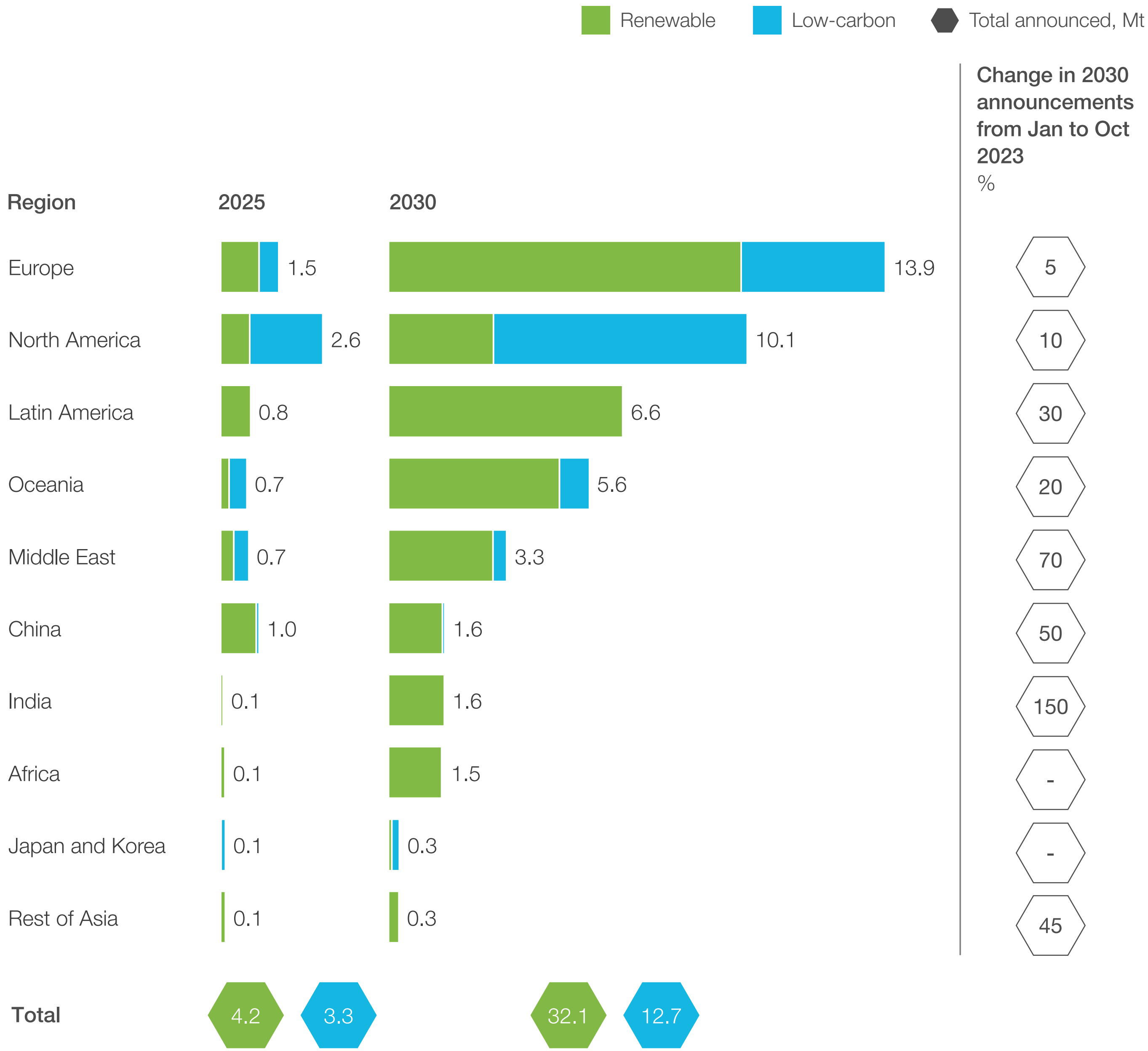
Europe is the largest region in terms of announced supply, followed by the Americas and Oceania

Globally announced clean hydrogen capacity by 2030 continues to grow across most regions, with Europe, the Americas and Oceania together accounting for over 80% of the total of about 45 Mt p.a. of announced volumes. China, India and the Middle East show the highest relative growth in announced clean hydrogen production by 2030, with growth between 50% (in China) and 150% (in India) in the past nine months. The highest absolute growth in announced clean hydrogen production is in Latin America and the Middle East (about 1.4 Mt p.a. each). Notably, relative growth in Europe and North America, the two largest regions, is about 5% and 10% respectively – lower than their growth in investment volumes (about 20% each). This could indicate companies are focusing more on maturing existing announced projects or on developing other parts of the hydrogen value chain.

Announced capacity by 2025 has declined from 8.4 Mt p.a. by 10% overall, indicating delays in project deployment. China is a notable exception with about 40% growth in 2025 volumes. The greatest reduction is seen in the Middle East and Europe (about a 30% reduction), pointing to project delays which may be due to delayed funding or challenges in securing offtake agreements. Further project progress in all regions will likely be impacted by the development of the corresponding regulatory and economic environments.

Global growth in renewable hydrogen announcements by 2030 (more than 6.5 Mt p.a.) substantially outpaced low-carbon hydrogen announcements (about 0.4 Mt p.a.). The stronger growth in renewable hydrogen announcements could be linked to, for instance, a stronger regulatory focus on renewable hydrogen or the larger number of regions with attractive resources for renewable hydrogen production.

Clean hydrogen volumes announced, Mt p.a.



Source: Project & Investment tracker, as of Oct 2023

Exhibit 6

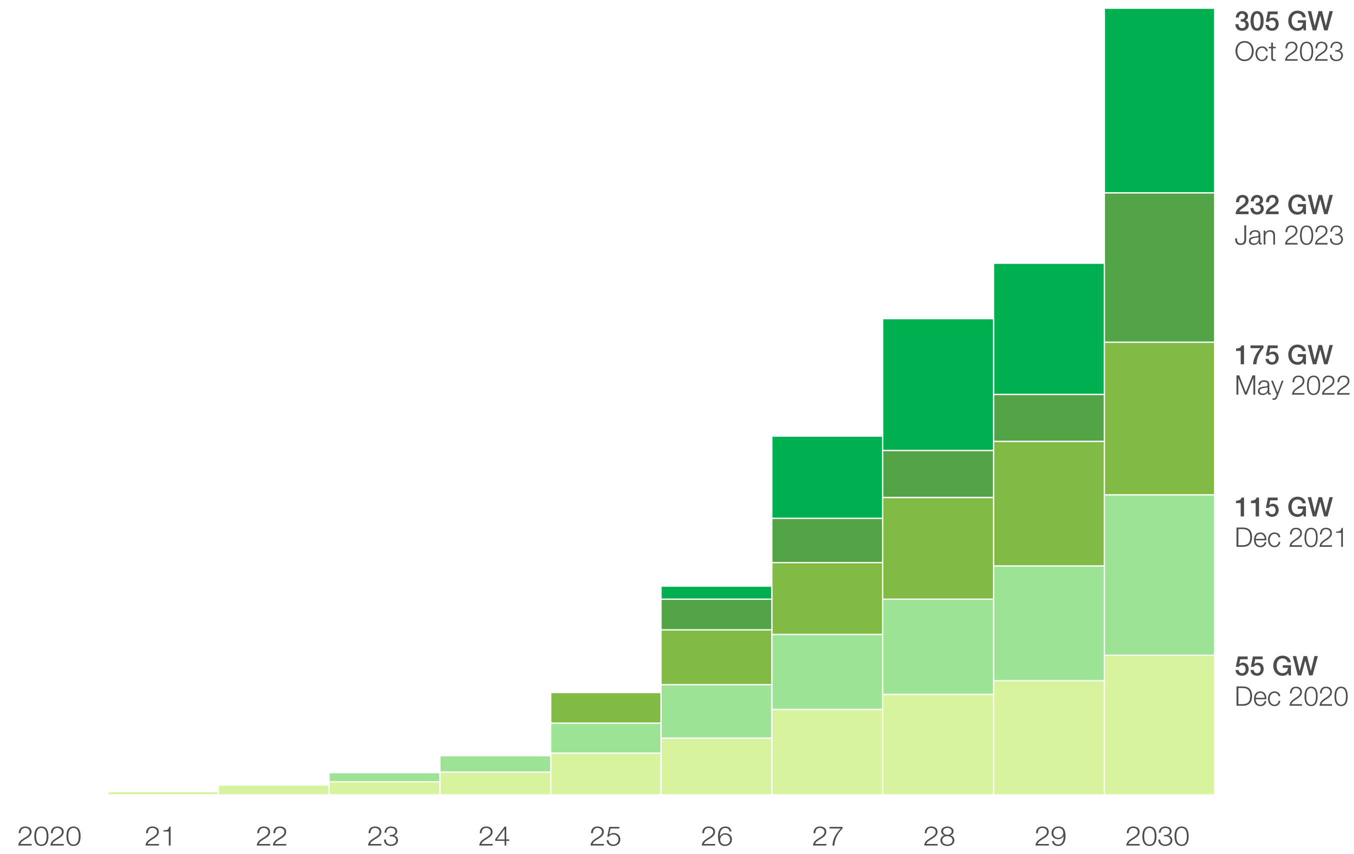
Over 300 GW of electrolysis capacity has been announced through 2030, up from 232 GW previously

305 GW of electrolysis deployment has been announced through 2030,[6] 73 GW more than previously announced. Half this capacity (about 150 GW) is past the 'announced only' stage. Nearly 140 GW are undergoing feasibility or FEED studies, and another 12 GW have passed FID. The volumes of electrolysis capacity past FID increased from 9 GW to 12 GW, with most of the capacity in China (about 55% of the 12 GW) followed by the Middle East (about 15%), Europe (about 15%), and North America (about 5%). Previously, China accounted for about 40% of committed electrolyzer volumes, implying that deployment in China is outpacing the rest of the world.

Of the European renewable hydrogen investment pipeline, 40 GW (about 45%) has entered at least the planning stage. Despite support schemes through the IRA, the North American renewable hydrogen pipeline stands at about 20 GW through 2030. Latin America is home to 20% of all announced volumes through 2030.

Despite the large volume, less than 5% of renewable hydrogen supply investments are committed. To realize the pipeline of 305 GW, significant acceleration in the coming seven years is needed to grow today's 1.1 GW installed electrolysis capacity by a factor of more than 250. For announced projects to deploy, those planned to become operational in the coming three to five years would need to reach financial close in the next one to two years. This implies not only that project developers across regions and sectors need to mature projects, but also that original equipment manufacturers (OEMs) need to scale up supply chains and manufacturing capacity.

Cumulative electrolysis capacity (announced),[1] GW



+73 GW
increase in announced electrolysis capacity by 2030 in the past 9 months

>60%
capacity announcements found in 3 regions, i.e., Europe, Latin America, and Oceania

>90 GW
announced electrolysis capacity by 2030 in Europe

6. Note that announced electrolyzer capacity cannot be directly translated to renewable hydrogen volumes. Hydrogen output depends on the capacity factor of a given electrolyzer, determined by individual technical setup.

1. For projects without known deployment timeline, capacity additions were interpolated between known milestones

Source: Project & Investment tracker, as of Oct 2023

Exhibit 7

An investment gap of USD 430 billion remains to be in line with the 2030 ambition

Announced investments through 2030 surpassed USD 570 billion (previously about USD 435 billion). However, more projects need to emerge across the clean hydrogen value chain to be in line with a net-zero scenario.[7] The remaining total investment gap of about USD 430 billion through 2030 stands at about 45% of the total need. The gap narrowed by about 10% of the total need compared with the previous publication.

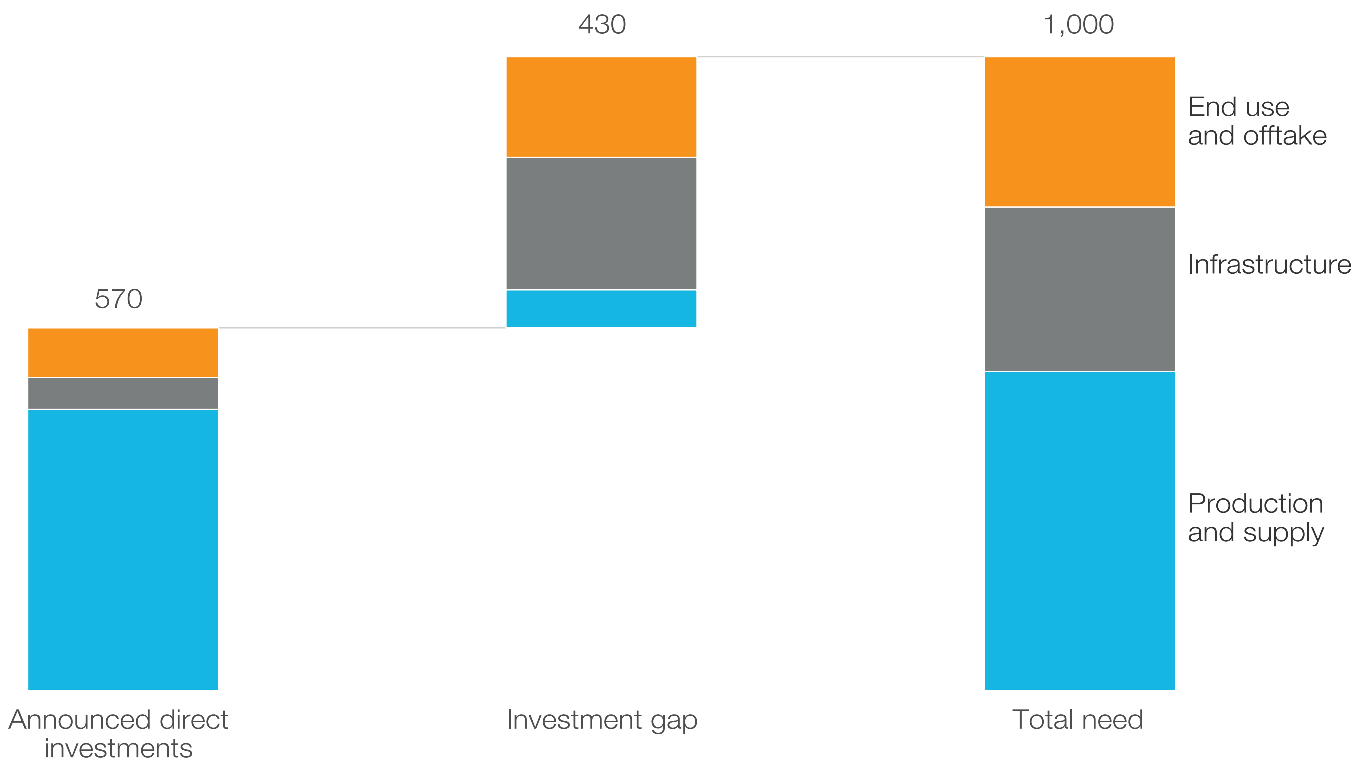
The largest absolute gap remains within hydrogen infrastructure (about USD 210 billion) where only about 20% of required investments have been announced. It is followed by gaps in end use and offtake (about USD 160 billion), and production and supply (about 60 billion), representing gaps of about 65% and about 10%, respectively. The slower rate of announced investments into hydrogen infrastructure could stem from uncertainty as to the timeline of hydrogen supply and end use deployment in some regions. At the same time, large-scale infrastructure initiatives such as the European Hydrogen Backbone are focusing on deploying a comprehensive hydrogen infrastructure.

Growth in announced hydrogen supply projects continues to outpace end use and infrastructure investments, accounting for about 75% of total announced investments, and growing by about USD 120 billion in the past nine months. Announced investments in hydrogen infrastructure grew only by USD 3 billion (about 5% relative to the previous publication) reaching USD 50 billion, whereas announcements of end use investments grew by about USD 15 billion (approximately 25% relative to the previous publication), reaching about USD 80 billion.

Although over half the needed investments have been announced, more are needed. The current announced projects need to be matured and deployed to close the gap from USD 39 billion past FID today to more than USD 1 trillion deployed through 2030. More projects are likely needed beyond the USD 1 trillion mark, as not all currently announced projects are likely to be realized. As the industry is focusing on maturing the existing project pipeline, it should also continue developing new projects.

7. For a detailed explanation of the applied net-zero scenario see 'Hydrogen for Net-Zero'

Announced and required direct investments into hydrogen until 2030, $B



$160 B investment gap in end use applications

$210 B investment gap in infrastructure

$60 B investment gap in production and supply

Source: Project & Investment tracker, as of Oct 2023

02

Clean hydrogen deployment steadily continues

>1.1 GW
of electrolysis capacity deployed globally by October 2023 (additional 400 MW), with about 12 GW having passed FID globally (additional 3 GW)

860 kt p.a.
operational clean hydrogen supply capacity deployed today – about 1% of the grey hydrogen market today

>1,100
hydrogen refueling stations deployed globally, with more than 60% growth over the last two years

Exhibit 8

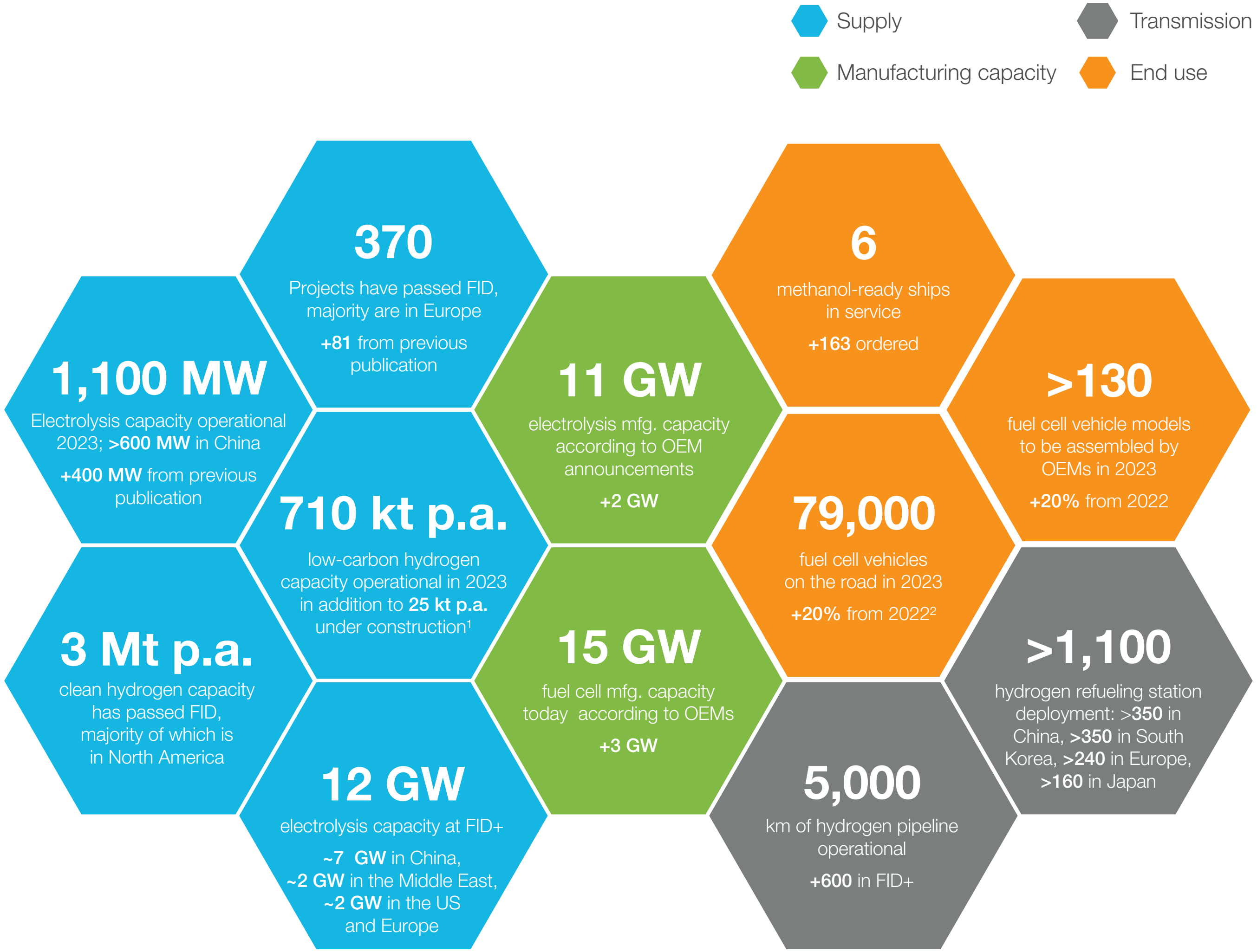
Deployment is steadily growing across the value chain

Supply: About 860 kt p.a. of clean hydrogen supply is operational globally, up from 800 kt p.a. previously. About 710 kt p.a. is low-carbon hydrogen (primarily in North America), and the remainder is renewable hydrogen. About 3 Mt p.a. have passed FID, of which 55% is low-carbon hydrogen.[8]

Infrastructure: The deployment of hydrogen infrastructure is slowly progressing towards ensuring that low-cost and clean hydrogen supply meets demand. Committed investments in hydrogen infrastructure have grown to about USD 6.5 billion, of which 45% are in Middle East. This has not yet translated into a substantial increase in, for instance, hydrogen pipeline capacity. Today, there are about 5,000 km[9] of hydrogen pipelines, primarily in existing grey hydrogen hubs and industrial areas. The deployment of infrastructure for hydrogen-fueled mobility is gradually growing, with more than 1,100 hydrogen refueling stations deployed globally, concentrated in China, South Korea, and Japan.

Manufacturing capacity: Electrolyzers and fuel cell manufacturers are preparing to scale up. Electrolyzer manufacturing capacity has reached nearly 11 GW (up from 9 GW previously) according to OEM statements. For fuel cell manufacturing, the total global capacity stands at 15 GW (up from 12 GW), with South Korea, China, and Japan as the largest supply markets.

Hydrogen end use: Committed investments in hydrogen end uses have reached more than USD 7.5 billion, with the largest investment amount in Europe (total committed investments of USD 4.5 billion). By sector, mobility has the highest committed investments (USD 4.5 billion) followed by the power sector (USD 1.2 billion). Within mobility, cumulative fuel cell electric vehicle (FCEV) sales as of June 2023 stood at about 79,000 vehicles,[10] up 10% from end-of-year 2022. Vehicle OEMs have announced over 130 FCEV models expected to be assembled in 2023, of which the majority consist of commercial vehicles (trucks and buses) in China.



1. Low-carbon hydrogen capacity was adjusted downwards compared to the May 2023 report due to a restatement of the underlying data
2. FC electric bus sales in China were adjusted downwards compared to the May 2023 report due to an error in the underlying data

Source: Hydrogen Council; McKinsey

8. Due to restatements of underlying data, net growth appears smaller compared to previous reports
9. IEA, Global Hydrogen Review, 2023
10. Cumulative fuel cell electric bus sales in China were adjusted downward compared to the previous report due to an error in the underlying data.

Exhibit 9

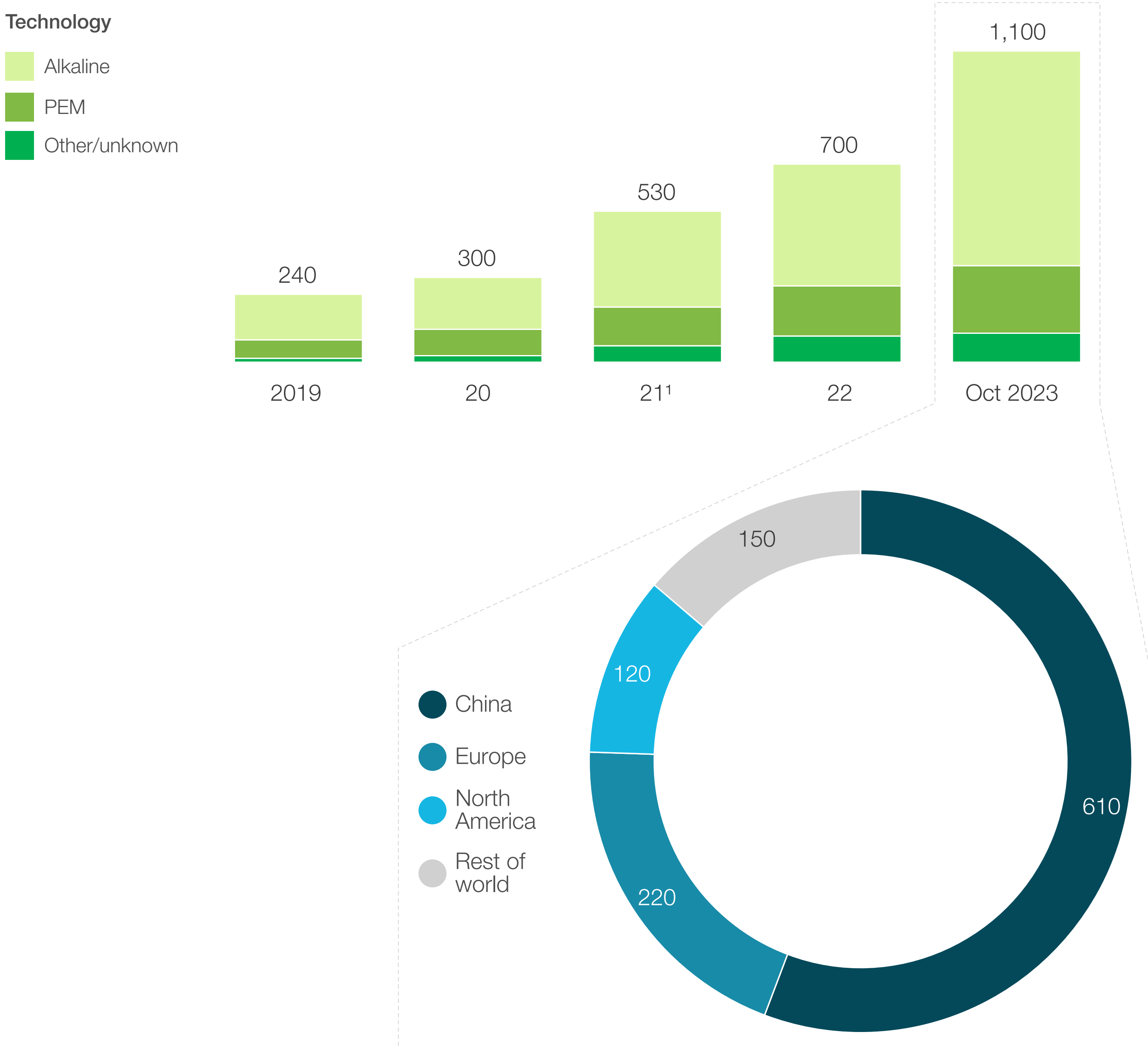
400 MW electrolysis has been deployed since January, bringing the total to 1.1 GW, with most capacity added in China

The deployment of electrolysis capacity grew by around 60% in 2023 versus 2022, reaching 1.1 GW, up from 700 MW. The installed capacity equals about 150 kt p.a. of renewable hydrogen supply, meaning renewable hydrogen accounts for about 15% of installed clean hydrogen production capacity globally. Growth rate has almost doubled over the last two years. Much of the growth in the past year has been driven by a single large project of 260 MW in China, which accounted for 65% of the growth.

Today, the largest deployed electrolyzer capacity is in China (610 MW), where the world's two largest operational projects with capacities of 260 MW and 150 MW are located. China is followed by the United States and Germany (60 MW each), as well as Spain, Taiwan, Sweden, and Canada (each with about 25 MW). In the past year, the largest volumes added outside China were in the United States and Sweden (about 50 MW and 20 MW, respectively).

Of the 12 GW of electrolyzer volumes that passed FID globally, about 40% have a stated technology - around 80% is alkaline and 20% proton-exchange membrane (PEM); implying that the share of PEM remains stable. Within China, 90% of the deployed electrolysis capacity is based on alkaline technology, whereas PEM technology is more prevalent in Europe and North America, accounting for 80% of the total installed capacity.

Global cumulative installed electrolysis capacity, MW



1. Growth from 2020 to 2021 driven by 150 MW Ningxia Project

Source: IEA Global Hydrogen Review 2021 and 2022; Project & Investment tracker, as of Oct 2023

Exhibit 10

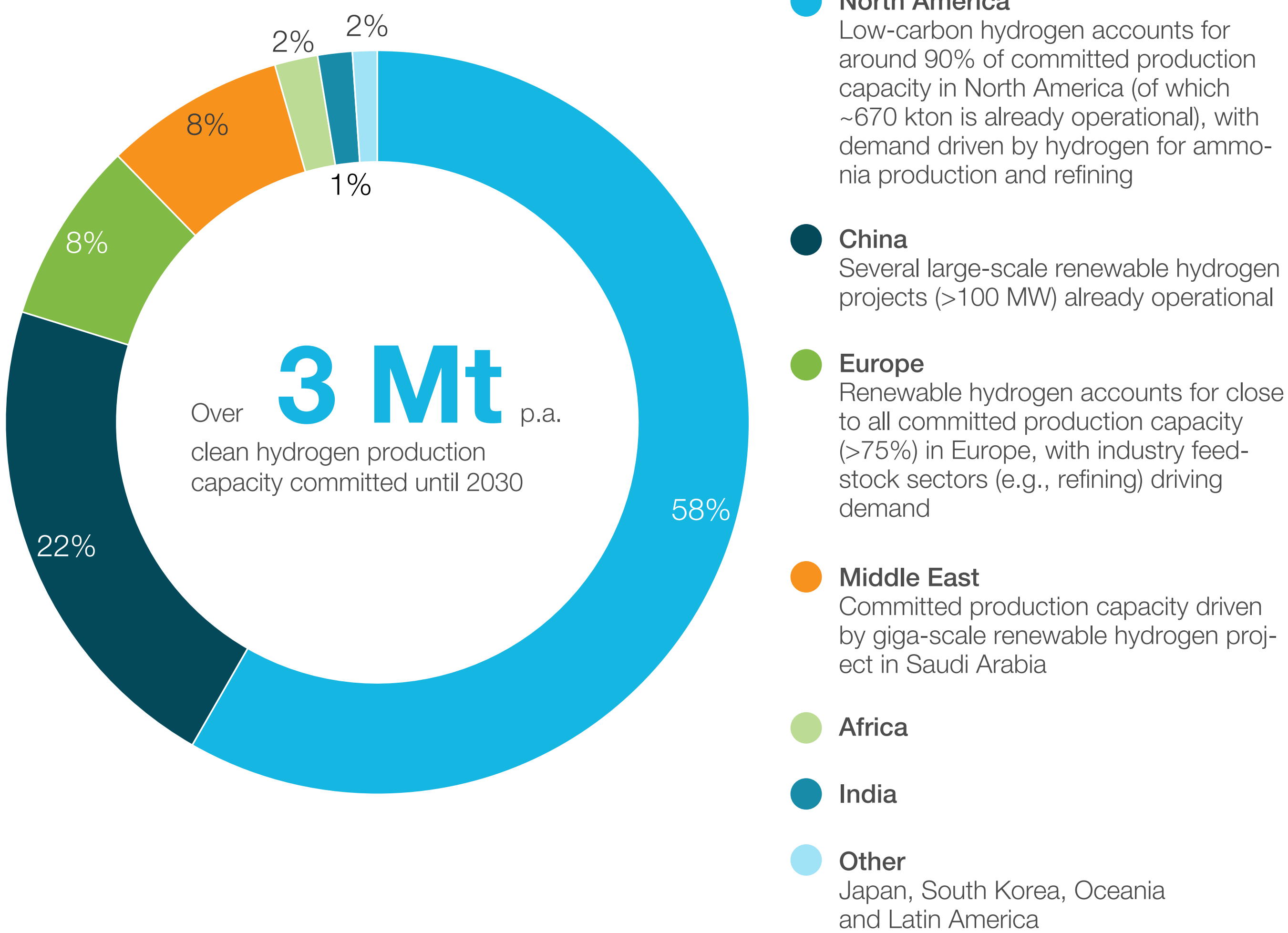
Currently, over 3 Mt p.a. of clean hydrogen capacity has passed FID, with North America and China leading

In addition to the 860 kt p.a. of operational capacity, about 2.2 Mt p.a. of clean hydrogen has passed FID. Most committed and operational capacity is low-carbon hydrogen (1.7 Mt p.a.), and the rest is renewable. Net committed capacity has grown by about 0.1 Mt p.a. since the previous publication driven by an increase in committed renewable hydrogen capacity, but held back by a reduction in capacity due to delayed projects.

North America is the largest market in terms of committed clean hydrogen capacity with volumes of about 1.8 Mt p.a. About two-thirds of this capacity is in the United States, and one-third in Canada. Around 90% of these volumes are low-carbon hydrogen, potentially due to higher maturity and driven by the early deployment of carbon capture and storage (CCS) technology in grey hydrogen production. Of the North American low-carbon hydrogen volumes past FID, about 65% have stated technology. About 40% of this is autothermal reforming (ATR), and about 30% each of steam methane reforming (SMR) and coal gasification coupled with CCS. Renewable hydrogen capacity (about 1.3 Mt p.a.) is concentrated in China (about 0.6 Mt p.a.), followed by the Middle East (0.25 Mt p.a., of which a large majority comes from a single giga-scale project).

By region, China has the largest share of committed clean hydrogen volumes at about 40% of its announced hydrogen supply. North America follows, with about 20% of its announced 10 Mt p.a. having passed FID. The Middle East has committed 7% of its announced supply volumes of 3.3 Mt p.a., followed by Africa (4%) and Europe (2%). Less than 1% of the announced capacities in Latin America and Oceania have passed FID.

Committed[1] production capacity until 2030, %



1. Final investment decision has been made, under construction, or operational

Source: Project & Investment tracker, as of Oct 2023

Exhibit 11

Hydrogen refueling infrastructure deployment continues to accelerate in China and South Korea with slower growth in Europe and North America

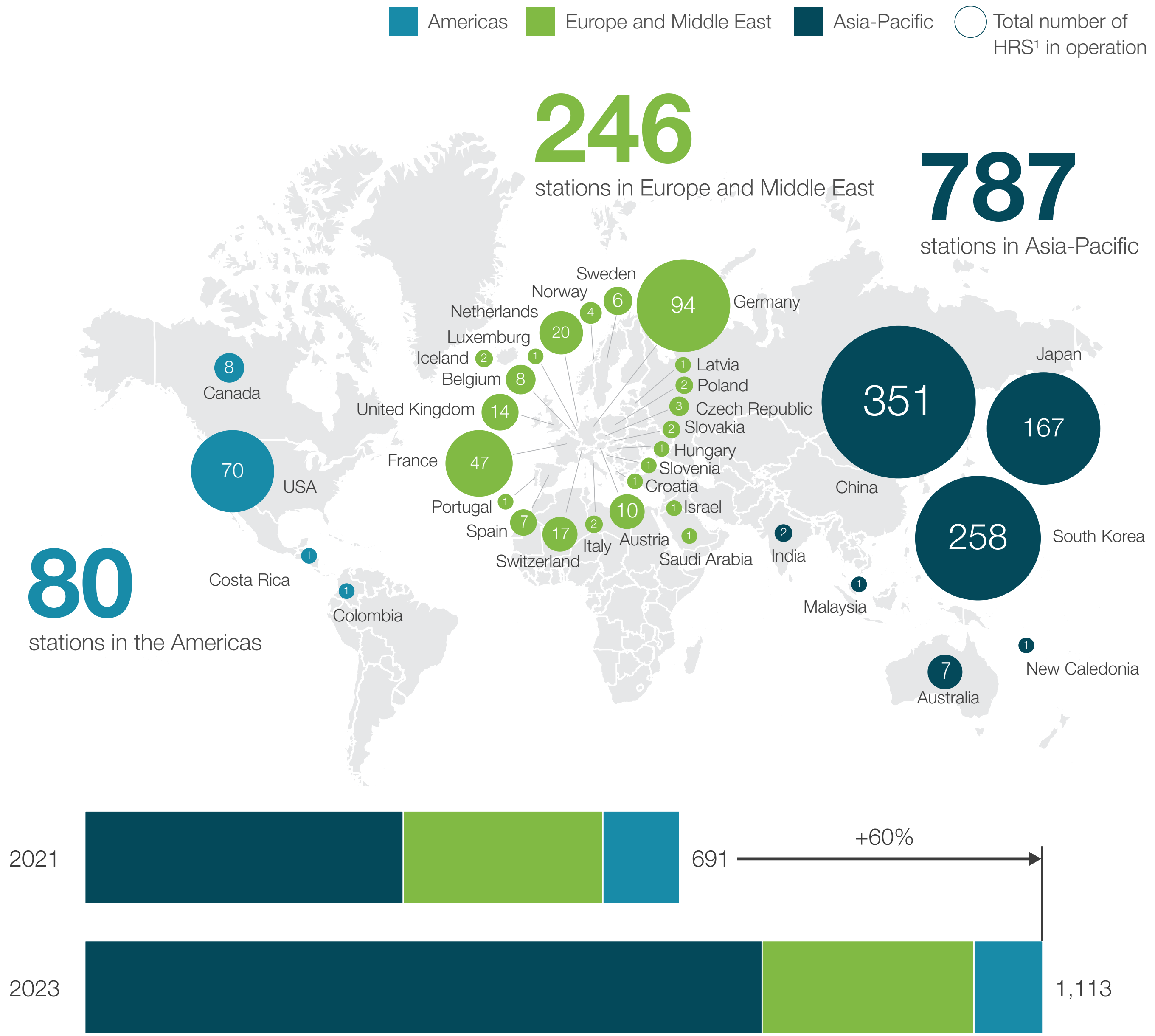
More than 1,100 hydrogen refueling stations are now operational globally, with deployment growing by 60% from 2021 to October 2023. Most of these stations are in Asia. China, Japan, and South Korea are the largest markets with nearly 800 stations in total, followed by Europe with around 250 stations.

The number of hydrogen refueling stations could grow significantly if ambitious government targets are realized. South Korea and Japan plan to expand their networks to more than 600 stations each by 2030, which could double the number of stations in Asia. In the EU, the recently adopted Alternative Fuels Infrastructure Regulation (AFIR) will require the deployment of a hydrogen refueling station every 200 km along the Trans-European Transport Network (TEN-T). In addition, over the last six months, more than 10 countries (mostly in Europe) have installed or have announced plans to install their first hydrogen refueling stations.

Sales of hydrogen-powered vehicles correlate geographically with the roll-out of hydrogen refueling infrastructure. South Korea continues to lead in light hydrogen-fueled vehicles (about 50% of current light vehicle fleet), and China in the global hydrogen truck and bus market (about 80% and 90% of each respective market). Heavy hydrogen-fueled vehicles, especially trucks, are gaining momentum. This is reflected in the number of hydrogen-fueled bus and truck models exceeding one hundred. As the hydrogen-fueled vehicle park could potentially transition toward heavier vehicles, requiring higher refueling station capacities, existing stations might require expansion and adaptation. Additional hydrogen refueling infrastructure might be needed for off-road mobility such as rail and inland shipping.

While most hydrogen-fueled vehicles continue to be FCEVs, some developers are also working on hydrogen combustion powertrains for new and existing vehicle models.

Hydrogen refueling stations



1. 350 and 700 bar HRS included as well as public and non-open HRS

Source: h2stations.org

03

Clean hydrogen production costs have increased

30–65%

increase in LCOH driven by capital expenditure, financing, and cost of renewable power

2.5–4.0 USD/kg

cost estimate for LCOH by 2030, down from current costs of about 4.5–6.5 USD/kg

30–45%

capital expenditure decrease by 2030 compared with current levels

Exhibit 12

Near-term levelized costs for renewable hydrogen have increased by 30% to 65%

Renewable levelized costs of hydrogen are facing global headwinds that are driving up near-term renewable LCOH estimates by 30% to 65%, to 4.5 to 6.5 USD/kg. As renewable hydrogen production technology and the supporting renewable power supply is highly capital intensive, renewable LCOH is sensitive to the global hike in interest rates which have significantly increased the cost of capital. Other factors driving up costs include a global supply constrained by renewable power and pain points such as rare earth metals as well as (in some jurisdictions) skilled labor shortages and interrupted supply chains. The hydrogen sector is not unique in this, with cost increases seen in other sectors.

While these cost drivers may increase LCOH up in the near-term, unsubsidized renewable LCOH could still decline to 2.5-4.0 USD/kg[11] by the end of the decade, depending on the region,[12] declining further to 1 to 2 USD/kg by 2050. Near-term decline in renewable LCOH would require the normalization of renewable power capital expenditure (capex), lowered financing costs, and the rapid scale-up of global electrolyzer manufacturing capacity.

Despite the recent hike in costs, electrolyzer costs could fall as much as 45% by 2030 and 70% by 2050 compared with today. While hyper-scaling global electrolyzer production could result in a steeper system cost decline before 2030, continued learning could drive further cost declines through 2050.

The LCOH of low-carbon hydrogen produced via SMR or ATR technology coupled with CCS could be lower than renewable hydrogen near-term, and could be competitive with grey hydrogen in jurisdictions with adequate carbon prices. Low-carbon hydrogen costs will likely lie below renewable hydrogen costs through 2030, except in a few select regions with very attractive renewable power resources.

11. Displaying as nominal USD of 2023
12. Actual LCOH for renewable hydrogen will depend on individual geographies' specific physical, economic and regulatory conditions.

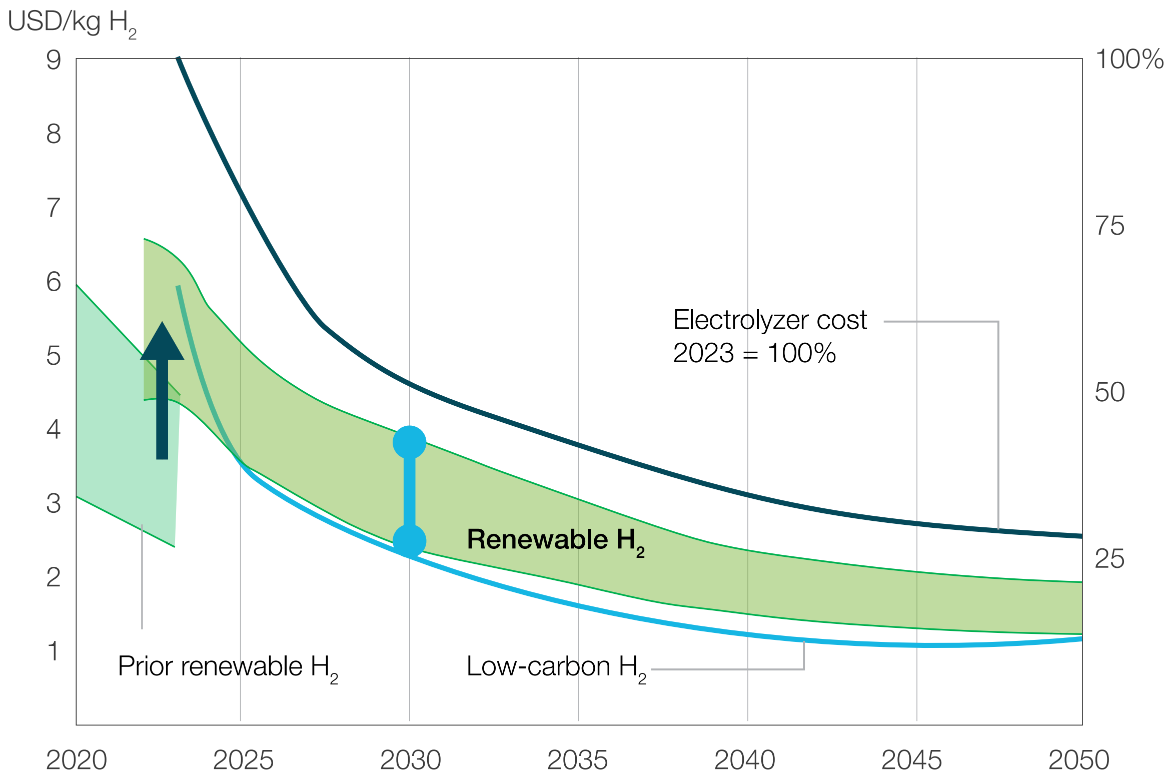
Development of levelized cost of hydrogen

+30–65%

increase[1] in LCOH driven by capex, financing and renewables costs

$2.5–4.0

cost target by 2030



1. Midpoint to midpoint increase

Low-carbon hydrogen production costs prior to 2023 have been excluded due to strong natural gas price volatilities impeding meaningful comparison.
Natural gas prices continue to drive up costs of low-carbon hydrogen
Core assumptions: Yearly production of 1 Mt of hydrogen; Dedicated solar PV and wind capacity "behind the meter" feeding into the electrolyzer

Source: McKinsey Capital Analytics; Survey of Hydrogen Council Member FEED studies

Exhibit 13

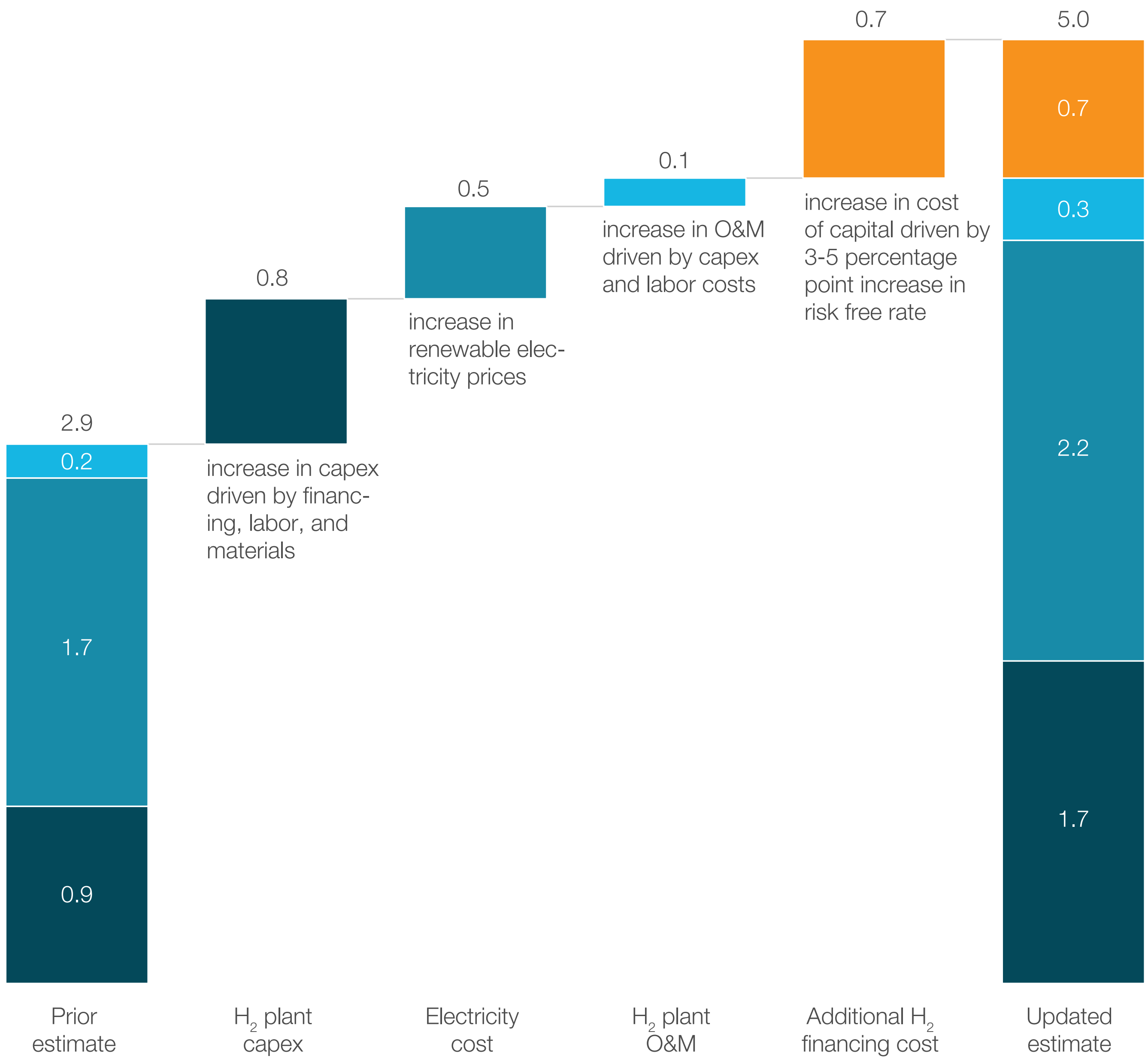
Higher plant, financing and electricity costs are driving increased renewable LCOH

The impact of recent cost increases is illustrated with an example from the US Gulf Coast, where renewable LCOH today increased by about 2 USD/kg versus previous cost estimates. Increased near-term capital expenditures had the largest absolute impact on the rise in the renewable LCOH (about 40%), followed by higher financing costs (about 30%) and the cost of renewable electricity (about 25%). Higher operation and maintenance costs have only a minor impact on the renewable LCOH (about 5%). Absolute cost increases and the impact of the contributing factors may vary significantly across regions as e.g., financing cost and supply chain constraints dynamics differ. Renewable power costs remain the largest contributor to overall renewable LCOH across regions.

As risk-free rates have increased by up to 5 percentage points, the cost of financing has grown in kind. While the cost of capital has risen globally, rates vary significantly across regions with country risk premiums ranging from none to about 25%. Differences in the maturity of regulatory frameworks as well as country-specific political and macroeconomic conditions drive variations in cost of capital for renewable hydrogen projects between different countries.

Cost increases apply largely independently from the quality of available renewable power resources. In 'behind-the-meter' setups where net new renewable capacity is purpose-built as part of an integrated project, renewable power capex carries the same cost of capital as the overall renewable hydrogen project. 'Behind-the-meter' renewable power capex is therefore often higher than what independent power producers might be able to attain for grid-connected renewable power assets.

Levelized cost of hydrogen (US Gulf Coast example), 2023, USD/kg



Core assumptions: Yearly production of 1 Mt of hydrogen; Dedicated solar PV and wind capacity "behind the meter" feeding into the electrolyzer

Source: McKinsey

Exhibit 14

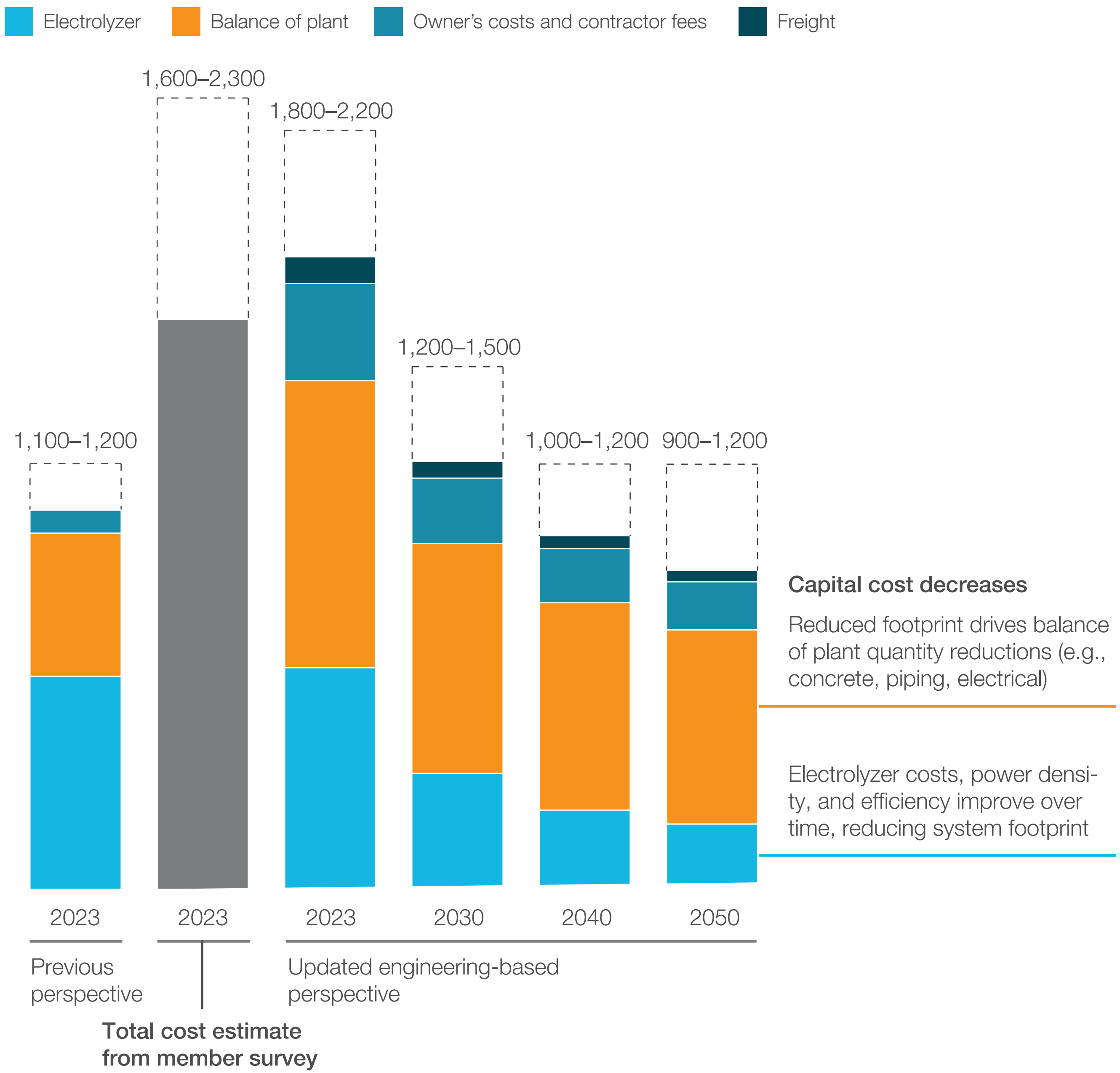
Electrolyzer plant capital expenditure costs could decline by about 45% through 2030

Near-term renewable hydrogen capex is higher than prior public consensus estimates have suggested. In depth analysis breaking down the electrolyzer, material components, and installation costs suggests that costs could still fall by as much as 35% to 45% through 2030. Multiple factors have increased near-term capex estimates: inflation rates on materials, equipment, and labor, together with a more sophisticated understanding of the developer costs. Balance of plant and indirect costs (e.g., contractor fees, owner's costs) account for the largest differential versus prior estimates.

Lower electrolyzer system costs are likely the primary drivers for cost-down efforts through 2030. Achieving this projected system cost-down would be contingent on successfully ramping up electrolyzer manufacturing capacity to meet giga-scale mid to late-decade demand. Electrolyzer cost reductions could also result from designing-to-cost, including minimizing precious metal content in core components and streamlining system designs. In parallel, increases in electrolyzer power density and efficiency could serve both to reduce overall system footprint and decrease the nominal electrolyzer capacity needed to achieve similar hydrogen output.

Technological advancements in electrolyzer systems could have knock-on effects that reduce both the balance of plant and indirect costs. More efficient and streamlined plant design with smaller footprint require less materials (e.g., concrete, steel, piping, electrical conduits) and fewer construction labor hours, as well as marginally lower unit shipping costs. Indirect costs like overhead, contractor fees, and owner's costs that are calculated as a factor of direct costs decrease commensurately with total direct capex.

Renewable H_2 capex (US Gulf Coast 1 GW alkaline facility example), USD/kW, for fully installed system



Source: McKinsey Capital Analytics; Survey of Hydrogen Council Member FEED studies

Exhibit 15

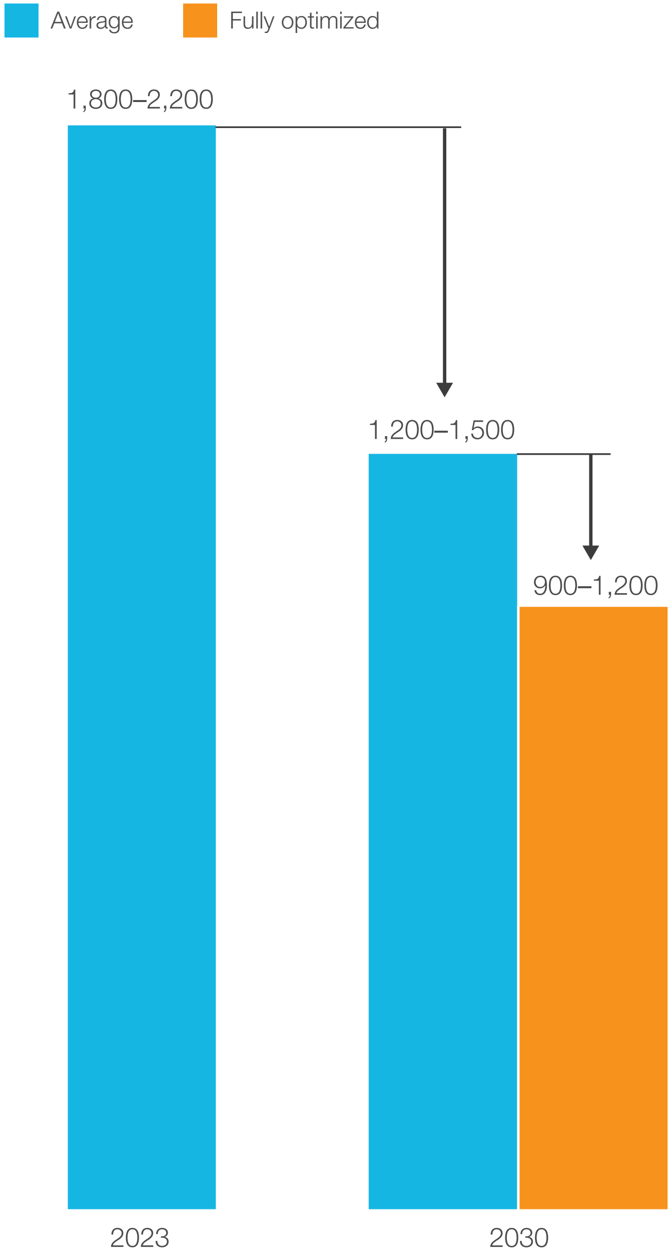
Fully optimized systems could reduce capital expenditure by as much as 25%

Advances in electrolyzer technology and manufacturing, improvements in the balance of plant, and knock-on effects will likely drive down electrolyzer plant capex for most projects. Additional actions could further accelerate the cost-down trajectory, if project delivery is substantially redesigned. Three such measures to fully optimize and accelerate the cost-down trajectory of projects include:

- Building successive projects to maximize learning rates
- Procuring at scale across multiple projects to achieve volume discounts
- Implementing rigorous design simplification and standardization

Implementing all these measures to reduce electrolyzer plant capex could further reduce renewable LCOH by an additional 0.2 - 0.4 USD/kg by 2030. However – only the best-in-class developers who will radically challenge base assumptions in design, installation, and scale-up will be able to attain these fully optimized costs.

Renewable H_2 capex (US Gulf Coast 1 GW alkaline facility example), USD/kW, for fully installed system



-30–45%

Potential cost reduction drivers through 2030

- Electrolyzer technology and manufacturing advancements
- Balance of plant improvements
- Knock-on effects to indirect costs

-10–25%

Additional actions that could be taken to fully optimize projects to reduce costs further

- Build successive projects to maximize learning rates
- Procure at scale across projects to achieve volume discounts
- Implement design standardization and simplification

Source: McKinsey Capital Analytics; Survey of Hydrogen Council Member FEED studies