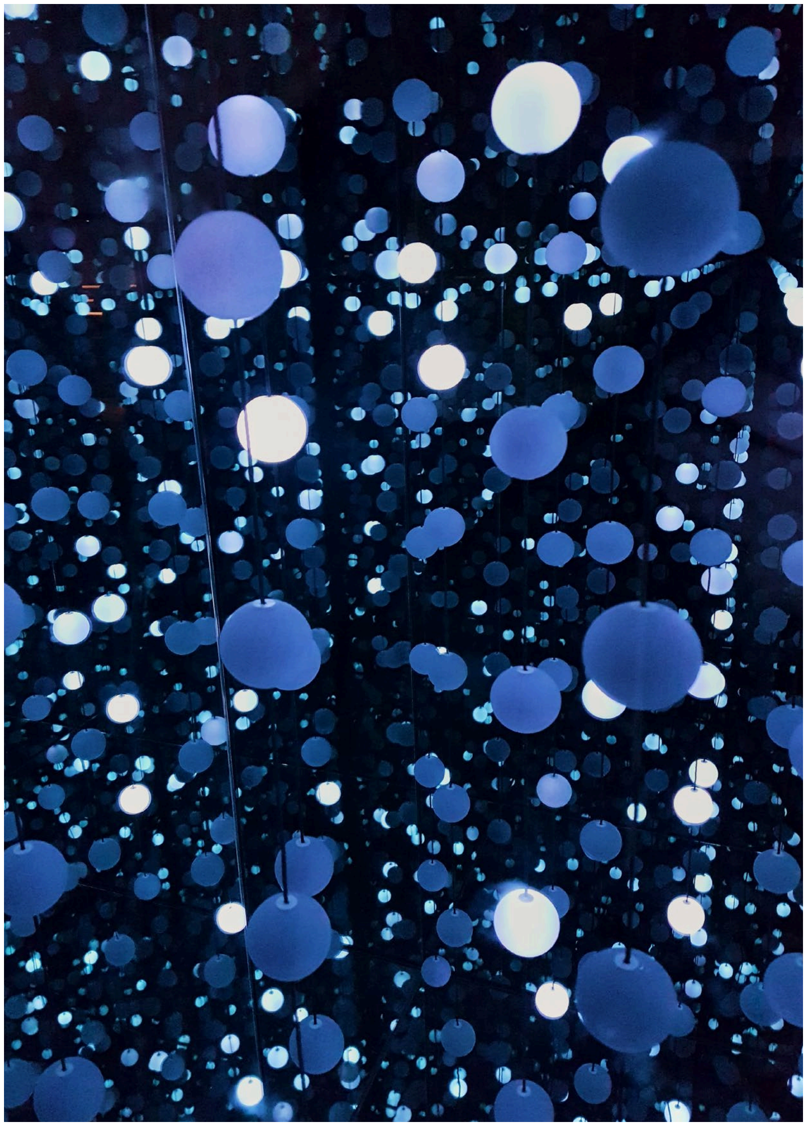
Photo by Zoe Hazelton
Kearney, London



Hydrogen applications and business models

Going blue and green?

July 2020

KEARNEY | Energy Transition Institute

Hydrogen – H2 FactBook summary

Ecosystems and societies globally face dramatic and negative consequences as accelerated anthropogenic CO_2 emissions continue to place us well above the IPCC 2 C warming scenario target.

Hydrogen's unique properties, such as high gravimetric energy density and ability to be transformed, stored, and transported under multiple forms (for example, in gaseous or liquid form or converted to other molecules), make it a powerful enabler for the decarbonization and energy transition, with benefits for both the energy system and end-use applications.

This FactBook seeks to provide an overview of hydrogen-related technologies, emerging applications, and new business models, covering the entire value chain and analyzing the environmental benefits and economics of this space along with key insights.

Hydrogen could help reduce GHG emissions in multiple sectors, representing about half of global GHG emissions

The deployment of blue hydrogen could help develop large-scale infrastructures, providing time for green hydrogen to mature and scale up

Hydrogen is broadly used in industries but remains immature in the broader set of applications, for which cost reduction and innovative business models are required

Most hydrogen business models require policy support, with heavy-duty transportation being the most promising one in the current context

The content of this summary is based on the hydrogen applications and business models FactBook.

For the complete FactBook, please visit:
https://www.energy-transition-institute.com/insights/hydrogen

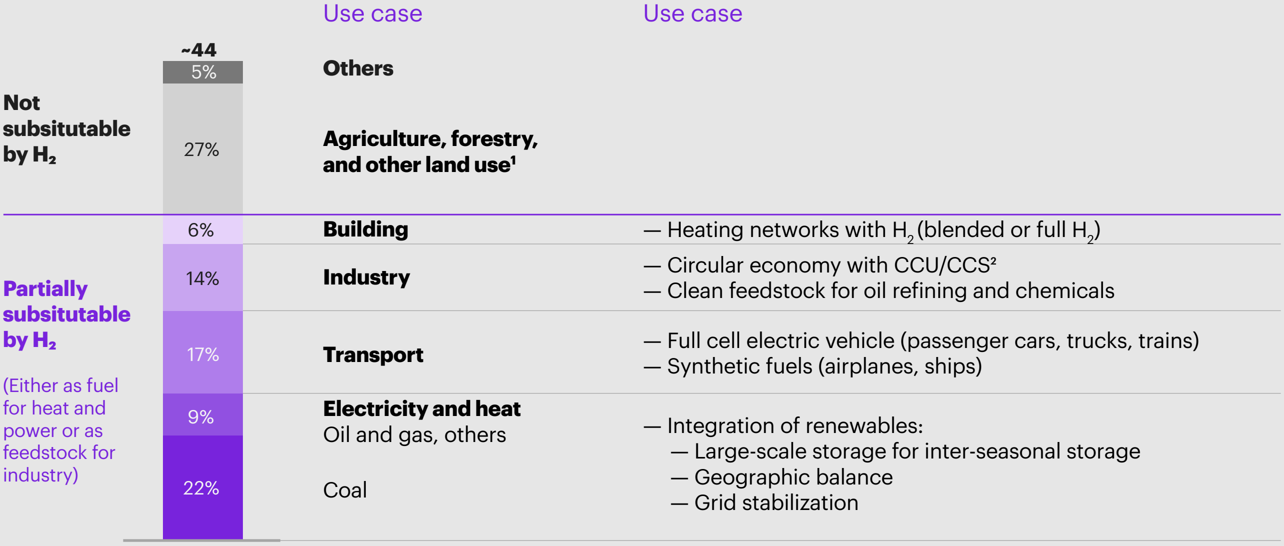
Hydrogen could partially address GHG emissions as a fuel substitute in sectors responsible for more than 65% of global emissions

Hydrogen has unique chemical properties such as high gravimetric energy density (MJ/kg) and can be stored under multiple forms (for example, gaseous, liquid, or converted to other molecules).

Hydrogen can be a viable option to decarbonize "hard-to-abate" end-use applications and sectors such as industrial processing and transport.

Most of the anthropogenic greenhouse gas (GHG) emissions (excluding AFOLU) comes from the production and transport of energy (including electricity and heat production), industry, buildings, and transport. Hydrogen provides multiple pathways to reducing GHG emissions in these sectors and could address about half of their GHG emissions if produced, stored, and carried cleanly.

Current GHG emissions by segment
(GT CO_2 eq/y)



[1] Includes land use, emissions from cattle, and so on
[2] Carbon capture utilization/carbon capture storage
Sources: IEA; FAO; Kearney Energy Transition Institute analysis

Hydrogen value chain along with respective technologies

Hydrogen relies on different production technologies: blue hydrogen is the combination of brown hydrogen sources (in other words, produced from hydrocarbon which emits 830 MtCO2/year by itself) with CCS value chain (capture, transportation, storage, or usage of CO2) for which multiple technologies are available.

Green hydrogen mostly relies on electrolysis technologies, involving an electrochemical reaction where electrical energy (derived from decarbonized sources such as renewables and nuclear) allows a water split between hydrogen and dioxygen.

Less than 0.7% of current hydrogen production is from renewables or from fossil fuel plants equipped with CCUS.

Upstream

Production technology

Thermochemical
— Steam methane reforming (SMR)
— Gasification
— Autothermal reforming (ATR)
— Pressurized combustion reforming
— Chemical looping
— Concentration solar fuels (CSF)
— Heat exchange reforming (HER) and gas heated reforming (GHR)
— Pyrolysis
— Other technologies (such as microwave)

Electrolysis
— Alkaline electrolysis (AE)
— Proton exchange membrane (PEM)
— Solid oxide electrolyzer cell (SOEC)
— Other technologies (such as chlor-alkali)

Other
— Dark fermentation
— Microbial electrolysis
— Photoelectrochemical

Brown H_2 Blue H_2 Green H_2

Main brown/grey production sources are steam methane reforming (SMR), gasification, and autothermal reforming (ATR).

Key electrolysis technologies are alkaline electrolysis, proton exchange electrolysis, and solid oxide electrolyzer cell, all based on the same electrochemical reaction but with differences in the materials used and the operating point.

Midstream and downstream

Conversion, storage, transport, and distribution

Conversion
— Hydrogen gas
— Liquid hydrogen
— NH_3
— Liquefied organic hydrogen carrier (LOHC)

Transport
— Trucks
— Trains
— Pipeline
— Tankers

Storage
— Geological storage
— Storage tanks
— Chemical reconversion
— Liquefaction and regasification

Hydrogen allows a broad range of conditioning options (for example, physical transformation or chemical reaction) to increase volumetric energy density or improve handling.

Depending on conditioning, hydrogen can be stored and transported in different ways.

Consumption

End-use applications

Industrial applications
— Oil refining
— Chemicals production
— Iron and steel production
— High-temperature heat
— Food industry

Mobility
— Light-duty vehicles
— Heavy-duty vehicles
— Maritime
— Rail
— Aviation

Power generation
— Co-firing NH_3 in coal power plants
— Flexible power generation
— Back-up and off-grid power supply
— Long-term, large-scale storage

Gas energy
— Blended H_2
— Methanation
— Pure H_2

Hydrogen can either be used as an energy carrier or as a feedstock for various industrial and chemical processes.

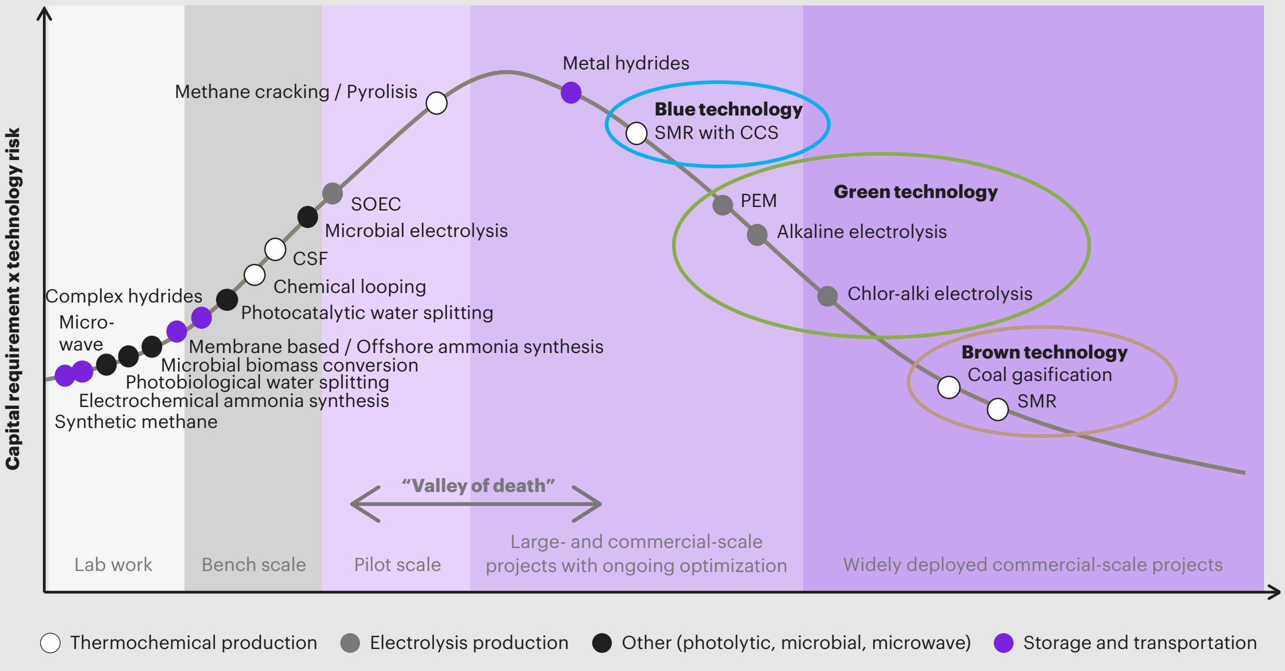
It can be burnt to release heat or converted into electricity using fuel cells.

Multiple new hydrogen production technologies are being developed, with brown technologies being the most mature

RD&D efforts required tolower LCOH for electrolyzers are primarily focused on lowering capital costs and increasing the lifetime of the system including cell and stack subcomponents.

Key innovation themes for proton exchange membrane are lower loading of platinum group metal catalysts, thinner and stable membranes, reduction of titanium use, and optimized operation set points with new low-cost designs.

Hydrogen technology maturity curve



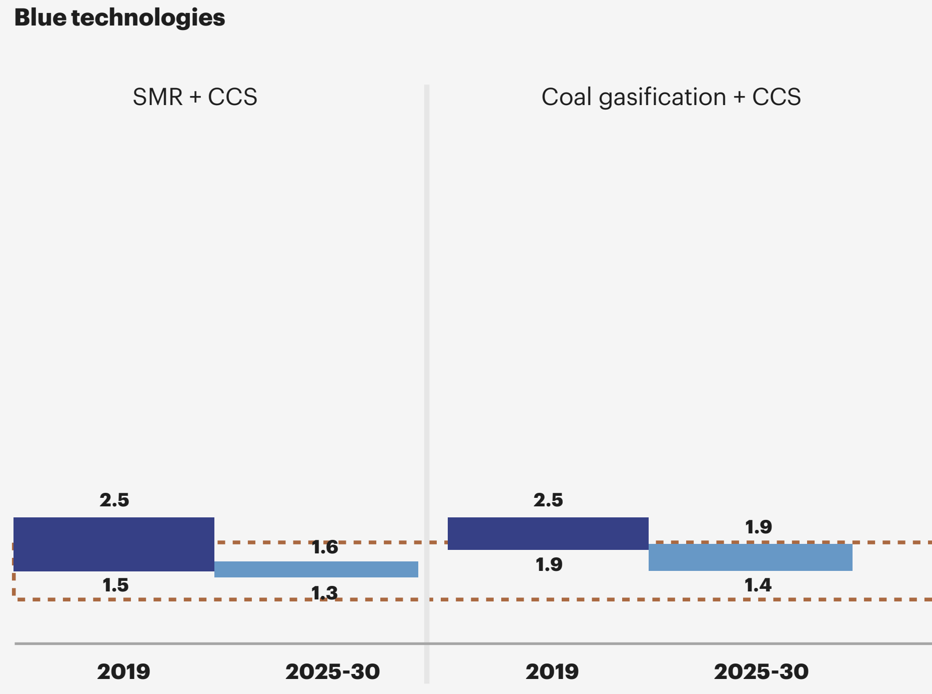
Sources: IEA – The Future of Hydrogen (2019), Csiro – National Hydrogen Roadmap (2018), IRENA – Hydrogen from Renewable Power (2015); Kearney Energy Transition Institute "Hydrogen Applications and Business Models" (2020)

Currently, hydrogen produced from brown sources is less expensive than from green or blue sources but the gap is expected to close by 2030

LCOH for thermochemical production sources is driven by fuel costs and capex, accounting for about 96% of total LCOH.

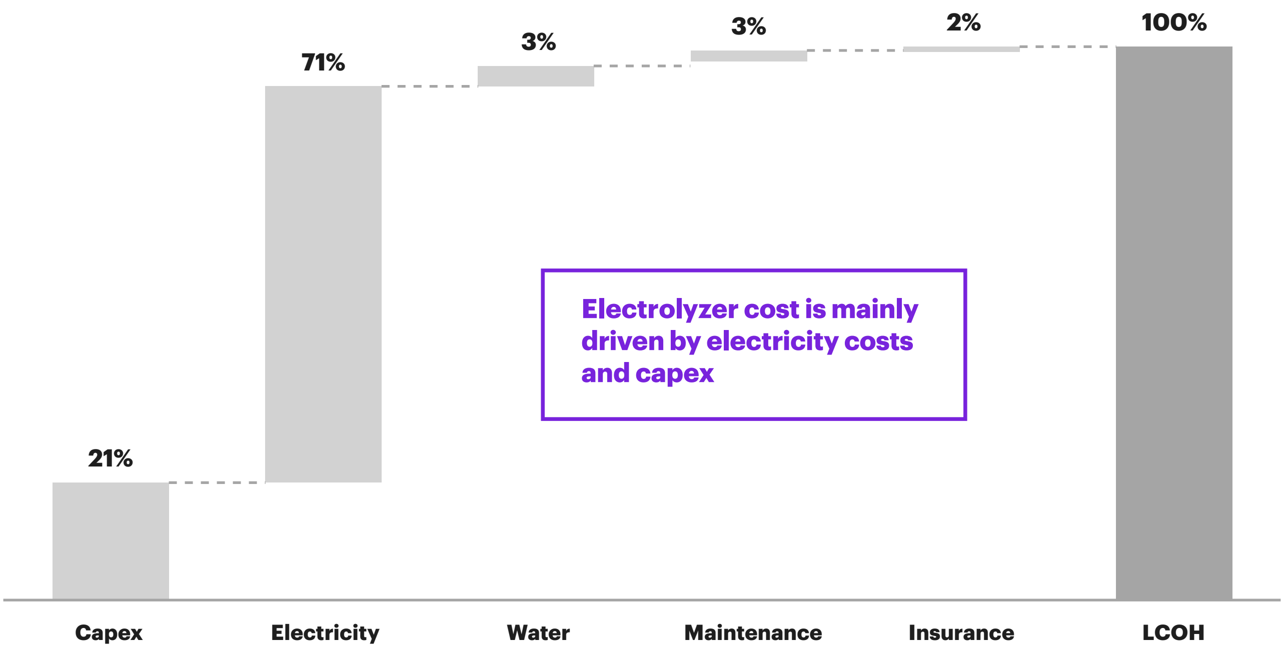
Brown hydrogen sources can be coupled with CCS to reduce emissions, but LCOH could jump by 64¢ per kg.

Hydrogen produced from brown sources (90¢ to $2.10 per kg) is two to 10 times less expensive than from green ($2.50 to $9.50 per kg) or blue ($1.50 and $2.50 per kg) sources.

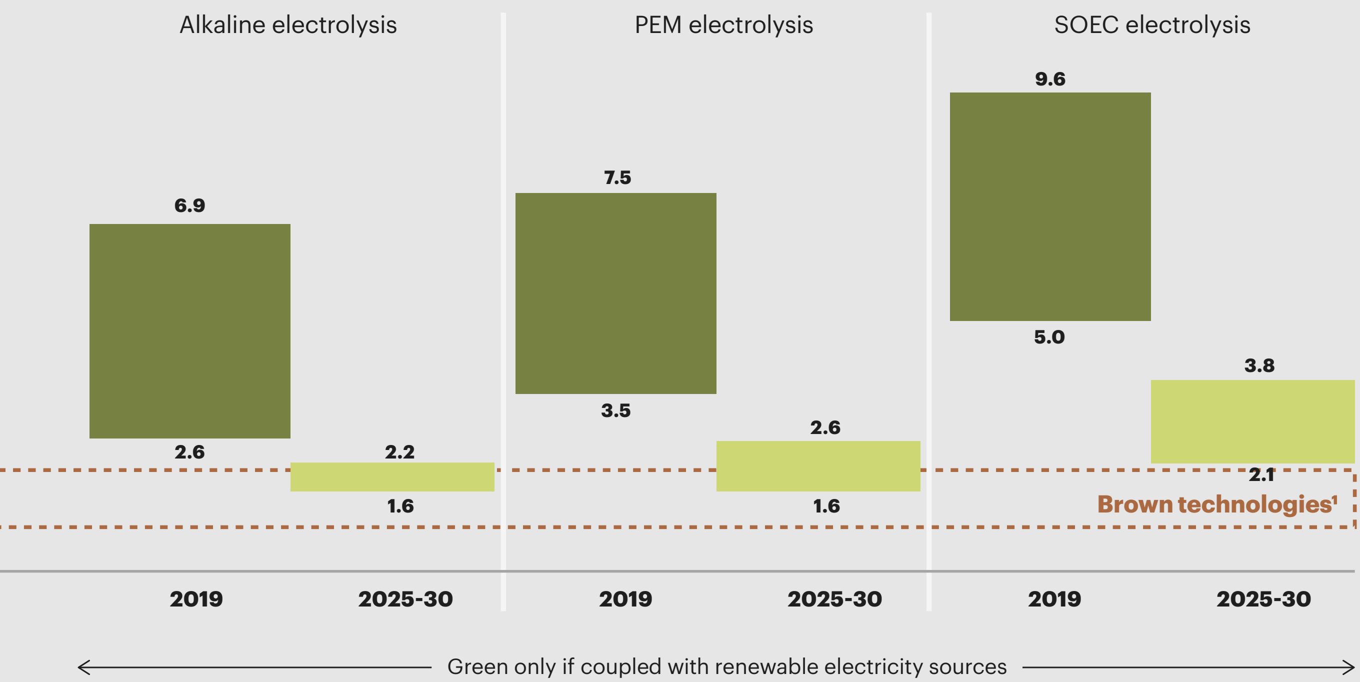


[1] AUD = 70¢
[1] Thermochemical sources LCOH range
Note: All hypotheses are detailed in the appendix. Ranges are indicative ranges. LCOH highly depends on fossil fuel prices, electricity prices, and asset utilization.
Sources: "The Future of Hydrogen," International Energy Agency, June 2019; International Energy Agency Greenhouse Gas R&D Programme; Commonwealth Scientific and Industrial Research Organisation; McPhy; Areva; Foster Wheeler; Department of Energy; International Renewable Energy Agency; Rabobank; TOTAL; CEA; Kearney Energy Transition Institute analysis

LCOH breakdown – PEM example
($ per kg)



Green technologies



Hydrogen LCOH is highly impacted by conditioning and transportation steps, which can double its LCOH cost

Compression and tank storage is the cheapest option at 20¢ to 40¢ per kg LCOH. Liquefaction LCOH is $1.80 to $2.20 per kg, Ammonia conversion LCOH is $1.00 to $1.20 per kg, and reconversion LCOH is 80¢ to $1.00 per kg and LCOH for LOHC is 40¢ per kg while reconversion can vary from $1.00 to $2.10 per kg.

Decentralized production sources or on-site consumption allow skipping the midstream value chain.

H_2 transformation, transport, and storage

Transformation method	Long-distance transportation		Short-distance distribution			Storage			
	Pipeline	Tankers	Pipeline	Trucks	Trains	Tank	Pipeline	Can	Cavern
Physical transformation									
Compression	✓	✓	✓	✓	✓	✓	✓		✓
Liquefaction		✓		✓	✓	✓			
Chemical combination									
Ammonia	✓	✓	✓	✓	✓	✓	✓		
LOHC[1]		✓		✓	✓	✓			
Hydrides		✓		✓	✓			✓	
Scale	~2,000 km	>3,000 km	<500 km	<500 km	<1,000 km	Small to mid-scale	Small to mid-scale	Small-scale	Large-scale

For a 3,000-km journey, transporting gaseous hydrogen through a pipeline is about $2.00 per kg compared to about $1.50 per kg transported by ship.

For a 500-km journey, transporting compressed gaseous hydrogen by trucks costs about $2.00 per km versus about 40¢ to 80¢ for pipelines.

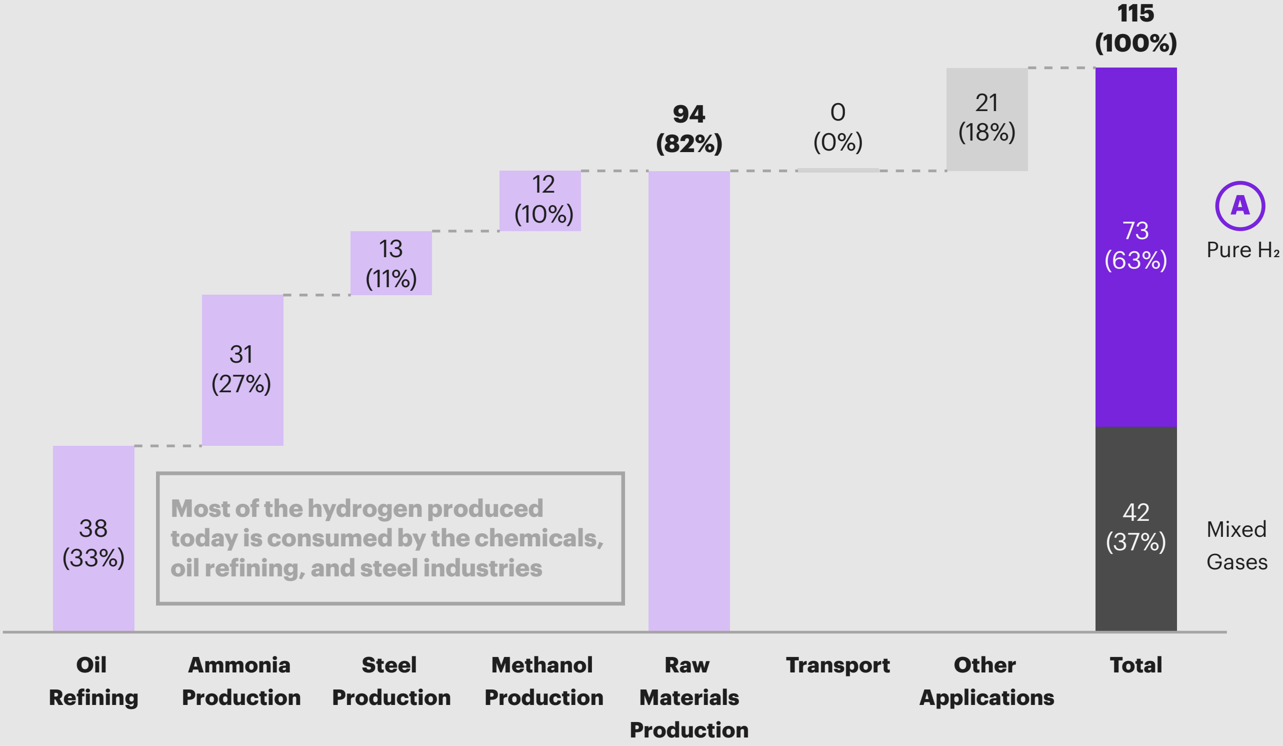
Note: LOHC is liquefied organic hydrogen carrier.
Sources: "The Future of Hydrogen," International Energy Agency, June 2019; Kearney Energy Transition Institute analysis

Driven by growth in transport and industrial applications, hydrogen consumption could reach 540 Mt per year by 2050

Current global demand for pure hydrogen (in other words, with only small levels of additives or contaminants) is around 70 Mt. The main applications for this hydrogen are oil refining and ammonia production, mainly for fertilizers (referred as A).

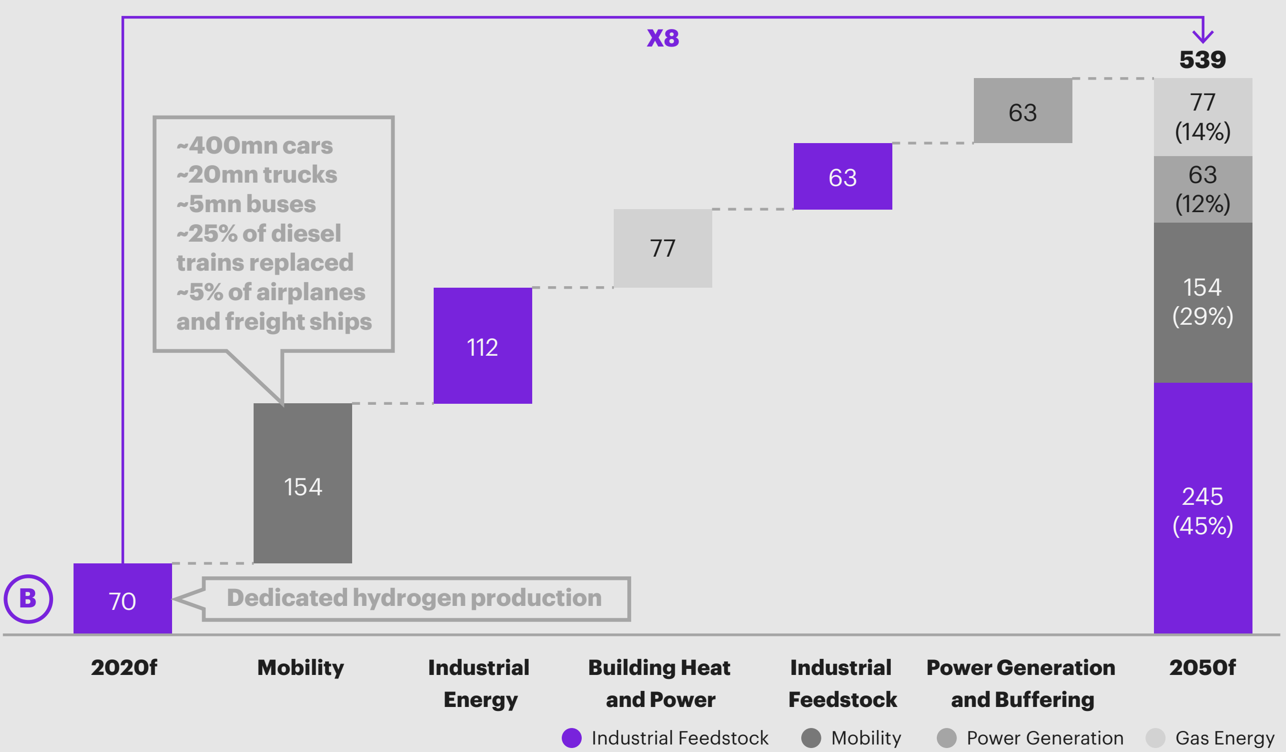
60% of the total hydrogen produced today is produced in dedicated hydrogen production plants (fossil fuel-based) which comes to around 70 Mt (referred as B).

Hydrogen consumption by category
(2018, MtH_2 per year)



Sources: Hydrogen Council; Kearney Energy Transition Institute analysis

Possible hydrogen consumption by 2050
(pure hydrogen, MTH_2)

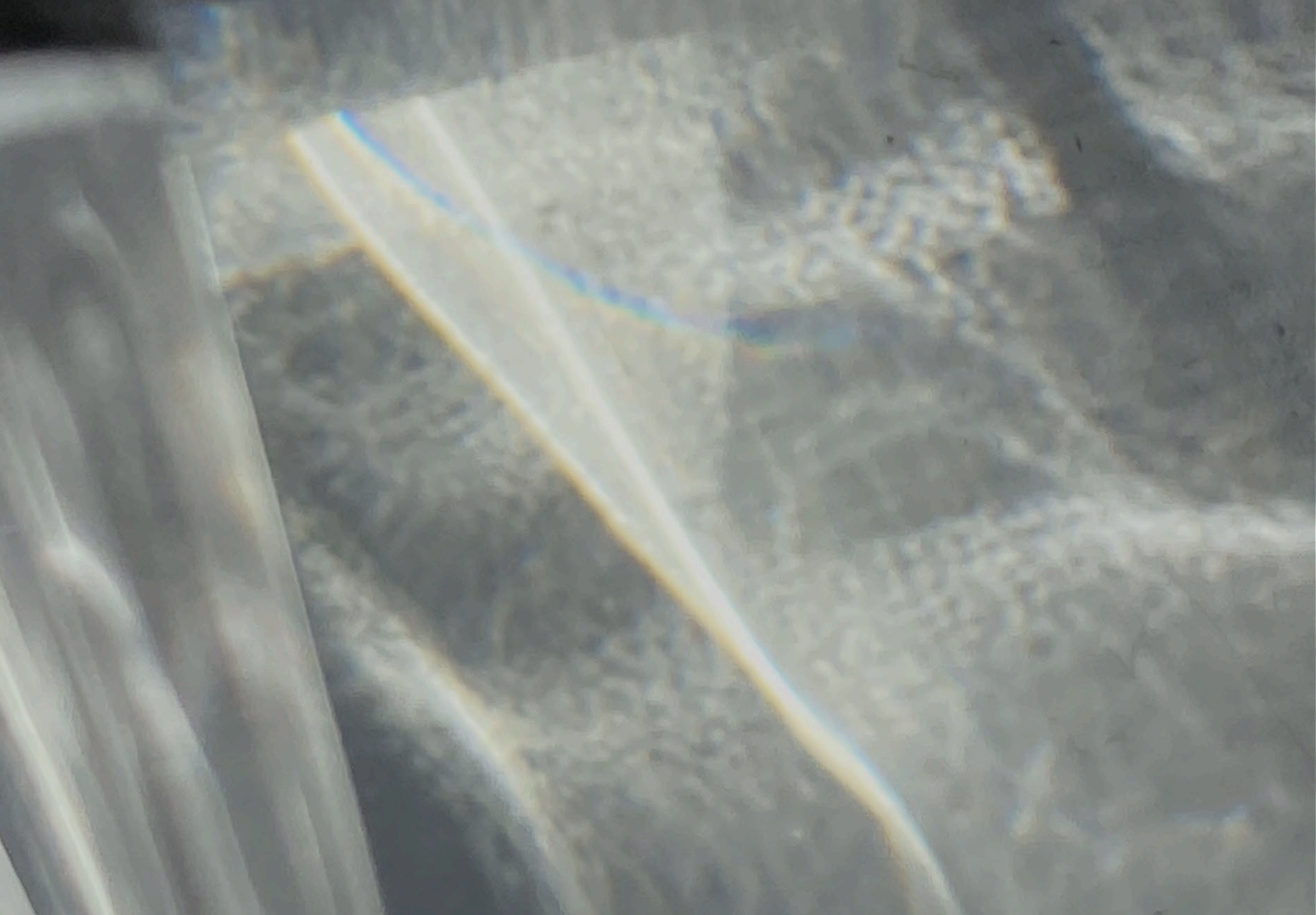


Hydrogen's versatility allows for multiple applications as a feedstock, as a gas, or for electricity generation (fuel cells)

Key future applications include chemicals and steel manufacturing, gas energy, power generation, and mobility.

Different applications will mature at different rates, with some of them already at advanced stage, including forklifts, buses, and heavy trucks.

New business models are being developed for both blue and green hydrogen-based solutions to take advantage of decarbonization potential.



Main H_2 applications

H_2 use	Application areas		End-use application
Feedstock	Industrial applications	**Oil refining**	Sulphur removal, heavy crude upgrade
Feedstock	Industrial applications	**Chemicals production**	Feedstock for ammonia and methanol
Feedstock	Industrial applications	**Iron and steel production**	Direct reduction of iron (DRI)
Feedstock	Industrial applications	**Food industry**	Hydrogenation
Energy	Industrial applications	**High temperature heat**	Fuel gas
Energy	Mobility	**Light-duty vehicles**	Fuel cells
Energy	Mobility	**Heavy-duty vehicles**	Fuel cells
Energy	Mobility	**Maritime**	Synthetic fuels / fuel cells
Energy	Mobility	**Rail**	Fuel cells
Energy	Mobility	**Aviation**	Synthetic fuels / fuel cells
Energy	Power generation	**Co firing NH3 in coal power plants**	Additional fuel for coal power plant
Energy	Power generation	**Flexible power generation**	Combustion turbines / fuel cells
Energy	Power generation	**Back-up / off-grid power supply**	Fuel for fuel cells
Energy	Power generation	**Long-term / large-scale energy storage**	Energy storage in caverns, tanks,...
Energy	Gas energy	**Blended H2**	5-20% H2 mixed with CH4
Energy	Gas energy	**Methanation**	Transformation into CH4
Energy	Gas energy	**Pure H2**	100% H2 injected on network

Sources: "The Future of Hydrogen," International Energy Agency, June 2019; Kearney Energy Transition Institute analysis

Most hydrogen-based solutions are not yet competitive with traditional solutions

Business cases (2030)

A	**Centralized production from ATR**	Convert fossil fuels into hydrogen, and capture carbon at production point.
B1	**Power-to-gas**	Convert electricity into hydrogen for heat generation.
B2	**Power-to-power**	Convert electricity into hydrogen for electricity peak management.
B3	**Power-to-molecule**	Convert electricity into hydrogen for further industrial applications.
B4	**Hydrogen cars**	Create clean fuel to power cars.
B5	**Hydrogen buses (Pau example)**	Create clean fuel to power buses.
B6	**Hydrogen trains (Cuxhaven example)**	Create clean fuel to power buses.

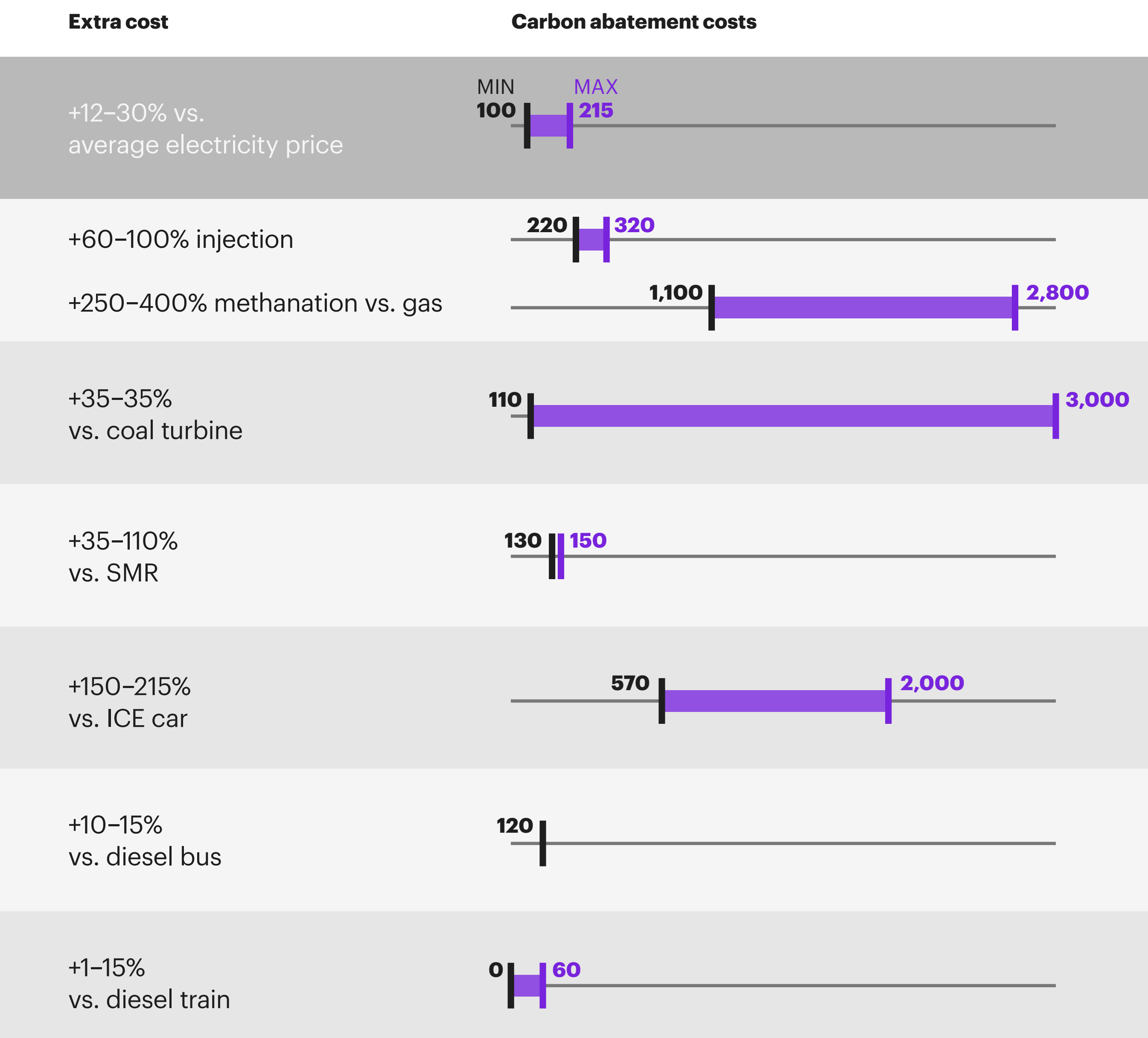
Note: The carbon abatement cost is equal to (LCOX(H2) – LCOX(Ref))/(Avoided CO2), with the LCOX(H2) being the LCOX of the H2 solution, LCOX(Ref) being the LCOX of the reference solution, both in $ per unit, and the (avoided CO2) being the CO2 avoided between the H2 solution and Ref solution, in ton per unit.
Source: Kearney Energy Transition Institute analysis

Large-scale hydrogen production that can serve multiple applications to maximize load factor is vital for competitiveness.

Carbon abatement costs vary widely depending on the business case.

Increasingly, the companies specialized in the hydrogen value chain are partnering with a broad range of other industrials to capture value which augurs well for innovation.

However, at their current stage of development, hydrogen-based business models and use cases will require policy support.



At their current stage of development, hydrogen business models require policy support

Multiple countries have formulated regulations and launched supportive initiatives to accelerate hydrogen deployment, mainly in transportation.

Countries are focused on specific strategic use cases based on their capabilities and economic situations.

Indirect value creation, such as local job creation and grid stabilization, should be considered for hydrogen potential valuation.

Source: Kearney Energy Transition Institute analysis

1

European Union

In partnership with the European Commission, Hydrogen Europe launched HyLaw to identify the legal barriers to hydrogen deployment

Strategic focus on hydrogen deployment across applications such as power generation, mobility, industrial applications, and heating. Supporting pilots and projects at country and city level to develop business cases.

2

United States

The United States has launched incentive programs to accelerate hydrogen deployment.

At the federal and state level, 280 incentive programs promote development, demonstration, and commercialization of hydrogen and fuel-cell technologies in partnership with industries and the private sector.

3

Japan

Japan was the first country to adopt a "Basic Hydrogen Strategy" and plans to become a “hydrogen society,” targeting commercial scale capability to procure 300,000 tons of hydrogen annually.

The Japanese government has dedicated $1.5 billion over the past six years to promote research, development, demonstration, and commercialization of hydrogen technologies and subsidies.

4

Australia

Australia adopted a National Hydrogen Strategy in late 2019 to open up opportunities in domestic use as well as the export market.

Since 2015, the Australian government has committed more than $146 million to hydrogen projects along the supply chain

Hydrogen will likely trail other strategies such as electrification, and its use will target specific applications such as heavy-duty transportation which show promise for the near-term impact.

Hydrogen is competing with other low-carbon solutions that tackle similar applications

Hydrogen substitution matrix

		Potential application of other decarbonization technologies (2030+ time horizon)				Potential role of hydrogen	
Sector (consuming fossil fuels)	**Total oil consumption usage (Mtoe[3], 2018)**	**Biomass (biofuels and biogas)**	**Electrification (renewables + storage)**	**Carbon capture storage[1]**	**Overall score for decarbonization solutions (other than hydrogen)**	**Hydrogen applicability**	**Opportunity for hydrogen**
Aviation and shipping	600	◑	◔	○	++	◔	▼
Rail[2]	29	◑	◔	○	++	◕	▲
Trucks	2,110	●	◑	○	+++	◕	▲
Road		●	●	○	+++	◕	▶
Industry and petrochem	915	○	○	◑	++	◑	▶
Heat and power	615	●	◕	◑	+++	◑	▼

Maturity of technologies: ● Commercial stage ◑ Pilot stage ◔ Research stage ○ Not an option

Maturity of decarbonization options: **+++** At least one commercial option **++** At least one pilot project **+** Ongoing R&D investment

— Hydrogen not mature for commercial aviation application, more applicable to shipping (small boats)
— Hydrogen application for rail is relevant to replace diesel engine in non-electrified rails
— Hydrogen relevant for heavy-duty vehicles (trucks and buses, for which battery weight is a major issue)
— Hydrogen is required for petrochemicals, and is generally produced by reforming of methane (brown)
— Relevant for heat and power but expensive and already addressed by renewables

[1] Use of CO2 from CCS is not considered in the range of possible solutions.
[2] Based on 2017 figures.
[3] Million tonnes oil equivalent
Sources: IEA WEO 2019; Kearney Energy Transition Institute

Conclusion

Hydrogen offers a possibility to decarbonize applications, end uses, and sectors which have been traditionally difficult to tackle with other clean energy solutions. Hence, it is useful to view hydrogen's contribution to the clean energy transition on a case-by-case basis, as complementary to other solutions in mitigating climate change. However, massive clean hydrogen deployment will have to achieve several milestones, notably CCS development, continuous supply of green power, and cost improvement.

In the long term, green hydrogen technologies should close the gab with brown and blue technologies and become more competitive economically. Blue hydrogen, made from natural gas with the carbon emissions buried under ground, can be a bridge for establishing an initial stage of a hydrogen-based ecosystem.

Accelerated deployment of hydrogen, through innovative business models and aggressive cost reduction, requires supportive policies and framework from governments and a coordinated deep collaboration within the private sector.

Other available FactBooks

General topics

— Climate Change – A scientific basis

— Energy Poverty – From challenges to opportunities

— Introduction to the Water and Energy Challenge – The interconnected water-energy equation

Renewable and Power Technologies

— Wind Power – Growth onshore, hope offshore
— Solar PV – Sunny Days
— Electricity Storage – Gaining momentum
— Introduction to Smart Grids – Beyond smart meters
— Hydrogen Applications and Business Models – Going blue and green?
— Hydrogen-based Energy Conversion – More than storage: System Flexibility

Natural Gas Technologies

— Introduction to Natural Gas – Gas takes off

— Gas Hydrates – Taking the heat out of the burning-ice debate

Carbon Emissions Management Technologies

— Negative Emissions Technologies – Towards a carbon-free world

— Carbon Capture and Storage – At a crossroads

Compiled by the Kearney Energy Transition Institute

Hydrogen applications and business models

About the Kearney Energy Transition Institute

The Kearney Energy Transition Institute is a nonprofit organization that provides leading insights on global trends in energy transition, technologies, and strategic implications for private-sector businesses and public-sector institutions. The Institute is dedicated to combining objective technological insights with economical perspectives to define the consequences in a rapidly changing energy landscape, exploring how businesses may both capture the opportunities that arise and address the challenges that face them in this complex and often uncertain shift. The Institute has developed deep insights in areas such as solar PV, hydrogen, negative emissions technologies, gas hydrates, carbon capture and storage, wind, smart grids, energy storage and continues to address the most pressing emerging topics such as the impact of digitalization.

The Kearney Energy Transition Institute is governed by an eight-member board and has access to a world-class scientific network comprising highly experienced individuals and academics. The Institute's independence fosters unbiased primary insights and the ability to co-create new ideas and insights with sponsors and relevant stakeholders.

Acknowledgements

The Kearney Energy Transition Institute wishes to acknowledge the following people for their review of this FactBook: Dr. Brian Efird, program director at the King Abdullah Petroleum Studies and Research Center, as well as Dr. Adnan Shihab-Eldin, Claude Mandil, Antoine Rostand, and Richard Forrest, members of the board for the Kearney Energy Transition Institute. The Institute acknowledges Lucas Bertrand, Business Development Director for ITM Power in France-Benelux-Iberia & Italy, for his important contribution, guidance and insights provided for the elaboration of this document

Their review does not imply that they endorse this FactBook or agree with any specific statements herein.

The Energy Transition Institute wishes to thank the authors for their contribution: Thibault L'Huby, Prashant Gahlot, and Romain Debarre.

energy-transition-institute.com

KEARNEY | Energy Transition Institute