EXECUTIVE SUMMARY

This report assesses **progress in the development of large-scale clean hydrogen supply chains** and looks at industry efforts to produce clean hydrogen. It focuses on the two main clean hydrogen production pathways: steam methane reforming (SMR) of natural gas combined with carbon capture and storage (CCS) (blue hydrogen) and water electrolysis of renewable electricity (green hydrogen). The main findings are summarized hereunder.

Hydrogen is a highly flexible and versatile clean energy carrier, as it can be produced from almost all energy sources, be used in a wide variety of applications and, when it is combusted, it emits no CO_2 but only water vapor as a by-product. A clean energy vector, hydrogen can be transported, stored and blended to some extent with current fuels. It is a key lever for achieving deep decarbonisation in an affordable and competitive way compared to full electrification solutions. Hydrogen can help to tackle various critical energy challenges, including facilitating the large-scale integration of intermittent renewables, enabling grid balancing and seasonal storage, as well as decarbonising a range of sectors – including hard-to abate sectors. It can also help to improve air quality and strengthen energy security.

Falling renewable energy and electrolysers production costs, coupled with continued development of CCS technologies, have improved the commercial prospects for large-scale production of clean hydrogen, enabling new uses of hydrogen as an energy carrier, clean fuel and feedstock. In recognition of this reality, there is **unprecedented political and business momentum for clean hydrogen**. Key governments and leading companies around the world are proactively investing in research, development, and demonstration (RD&D), as well as deployments of clean hydrogen and related technologies. They expect to gain environmental benefits and leadership in these new technologies/hydrogen products and create new export markets. The growing number of deployments, strategies, alliances, and technology developments in wider geographies and sectors demonstrates the rapidly growing interest in clean hydrogen. The focus is on reducing production costs, extending hydrogen use to new applications and demonstrating international supply chains.

Nonetheless, clean hydrogen is an **emerging market**. Its development requires suitable financial, infrastructural and **policy support** to de-risk investment during the early years of its deployment. **Strong collaboration** between stakeholders is required to scale up hydrogen production and bring cost down, enabling a substantial expansion of supply with its climate benefits. In addition, adequate **policy frameworks for market uptake** are required to enable and accelerate investment in the different value chains.

Over just the past two years, the industry, with support from national governments and regional financial institutions, has advanced technologies to produce clean hydrogen and has scaled up hydrogen projects' size, which will allow for substantial cost savings.

Several projects for bulk production of blue hydrogen have been announced. Today, there are five large-scale hydrogen production facilities with CCS operating globally, three under construction and another three in advanced development. Over the past two years, an additional ten CCS projects involving blue hydrogen have been proposed by major companies. Most projects are in Europe where hydrogen is seen as a key part of the decarbonisation policy. There are also new CCS projects involving hydrogen in the US, Australia, China and Canada. Projects are **very large scale**, producing bulk hydrogen and saving millions of tons of CO_2 emissions. They are expected to come online in the middle of the 2020s and demonstrate at scale the economic and technical feasibility of decarbonising large industrial clusters and injecting hydrogen into gas networks. Most recent blue hydrogen projects have adopted a hub and cluster approach, integrating the production of blue hydrogen and its supply to various customers in a shared hydrogen network infrastructure. SMR with CCS is a mature technology, which can produce blue hydrogen at scale and at lower cost than green hydrogen. But its deployment is contingent on the establishment of CCS infrastructure. There is an

urgent need to **accelerate CO_2 transport and permanent storage infrastructure**. Without it, the development of a clean hydrogen market at scale will be difficult to achieve. **Strong collaboration** among policy makers, investors, regulators and developers is key to developing blue hydrogen value chains.

Current green hydrogen production is tiny, with only 252 MW of capacity deployed at the end of 2019, though the **pipeline of new projects is growing fast** (more than 3 GW), driven by deployments in Europe, Asia and North America, and increased interest from major international stakeholders. The unit size of electrolysers is expanding rapidly. Green hydrogen is now moving to the **industrial scale** with several 100-MW projects to be completed by 2025. They will demonstrate the feasibility of green hydrogen production at industrial scale and its use in multiple sectors. These projects involve the production of tens of thousands of tons of green hydrogen and savings of hundreds of thousands of tons of CO_2 emissions. Larger-scale initiatives (GW) have been launched in regions with access to low-cost renewables (e.g. offshore wind in the North Sea, solar and wind in Australia). Green hydrogen could become a game changer, but its widespread adoption faces challenges. Today green hydrogen remains expensive due to the prices of grid renewable electricity and the cost of electrolysers. The current absence of a policy and regulatory framework for electrolysis is inhibiting market development. **Further R&D, mass production and learning-by-doing** is needed to achieve significant cost reductions.

Europe is a frontrunner in both clean hydrogen production routes. Northwest Europe, with its long-standing experience in hydrocarbon production and its vast geological CO_2 storage capacity, leads blue hydrogen projects. Germany is a front-runner in the electrolysis market, but green hydrogen projects have now spread to other European countries as well as to Australia, China, Japan, Canada and the US, among others.

The production cost of clean hydrogen is expected to fall drastically by 2030. This can be attributed to the falling costs of renewable electricity generation, scaling up and automation of electrolyser manufacturing, larger unit size of electrolysers, economies of scale in auto-thermal reforming (ATR) with carbon capture and development of lower-cost carbon storage facilities. Green hydrogen is expected to have a steeper learning curve than blue hydrogen, although blue hydrogen is expected to remain the least cost option at least until 2030.

The two technology routes are complementary solutions; both can support the development of a large-scale market for hydrogen. There are synergies and complementarities between green and blue hydrogen deployment. The hydrogen demand from urban areas is more likely to require large-scale hydrogen production infrastructure such as SMR with CCS. Electrolysis could provide the sector coupling mechanism required for the integration of renewables. **The best pathway towards a clean hydrogen economy is therefore a mix of both routes.** Due to its maturity, cost and scale advantages, blue hydrogen can kick-start the energy transition by enabling infrastructure build-out and creating a path to integrate rising green hydrogen production. It can help reaching deep decarbonisation in shorter timescales.

For both technology routes, **the cost of hydrogen varies significantly across regions/countries**, as it depends heavily on the prices and availability of energy inputs. It is expected that many countries with large-scale demand for clean hydrogen will call on regional imports to reduce cost procurements, enhance security of supply and achieve their deep decarbonisation targets. This could lead to the creation of a global clean hydrogen market, creating opportunities for countries with low-cost renewable energy sources/gas resources to create a new export market.

Similar to the international gas market, a global hydrogen supply chain will likely consist of **long-distance pipelines as well as maritime shipping routes**. There are three main **energy carriers** for shipping hydrogen in liquid form internationally: liquefied hydrogen (LH_2), methylcyclohexane (MCH), and ammonia (NH_3). Japan's strategy to import clean hydrogen and similar initiatives in Europe (e.g.

the HYPER project) offer a taste of how the international market could potentially evolve. All projects are demonstration pilots or feasibility studies that aim to solve technical issues to ensure cost-efficient and safe shipping of hydrogen. Cost estimates vary considerably depending on the distance transported, methods of transport used and end-user requirements. For short distances, transporting large volumes of hydrogen as a gas by pipeline is the cheapest method and its economics can be improved by using existing gas pipelines. For longer distances, maritime shipping of LH_2 or NH_3 (depending on the end use) is likely to be more cost-effective but is a costly option today. Innovations in both production, transportation and reconversion (when needed) will be required to increase the efficiency of the energy carriers and bring significant cost reductions. **The end use and mastering of new technologies in importing countries** will be a key determining factor for international hydrogen trade, as it creates assured demand.

The scale and shape of the future global hydrogen market remains uncertain today. Although potential exporting countries are well identified, future international supply chains are complex with multiple alternatives. They still encounter several technical and economic issues. To establish a global clean hydrogen market, several actions have to be taken by policy makers and other stakeholders, such as clear import signals, extended cooperation/partnerships, investment risk mitigation, international standards and certification.

While it is early stage in terms of global deployments, clean hydrogen has shifted from technology development to **market activation and industrial deployment**. More and more oil and gas majors and national oil companies are including hydrogen as one of the tools to decarbonise their oil and gas activities, together with efficiency, reduction in methane emissions, CCS and biofuels. For major exporting countries, hydrogen provides a hedge against possible future restrictions on high-carbon fuels. Similarly, in regions with well-established gas networks (e.g. Europe), gas infrastructure companies are preparing their grid for the transport, storage and distribution of clean hydrogen, together with other types of renewable and decarbonised gases. The task will be complex as numerous questions remain open today: how and where clean hydrogen will be produced? Will clean hydrogen be imported and under which form? While substantial uncertainty remains on the future scale of the hydrogen economy, the industry is taking steps to be at the forefront of developing what could be a disruptive technology in the future.