Your Energy Partner®
OPPD
Omaha Public Power District

OPPD BOARD OF DIRECTORS

BOARD MEETING MINUTES

May 18, 2023

The regular meeting of the Board of Directors of the Omaha Public Power District ("OPPD" or "District") was held on Thursday, May 18, 2023 at 5:00 p.m. at the Omaha Douglas Civic Center, 1819 Farnam Street, 2nd Floor Legislative Chamber, Omaha, Nebraska and via WebEx audio and video conference.

Present in person at the Civic Center were Directors A. E. Bogner, M. J. Cavanaugh, M. R. Core, S. E. Howard, J. M. Mollhoff, C. C. Moody, M. G. Spurgeon and E. H. Williams. Also present in person were L. J. Fernandez, President and Chief Executive Officer, S. M. Bruckner and T.F. Meyerson of the Fraser Stryker law firm, General Counsel for the District, E. H. Lane, Sr. Board Operations Specialist, and other members of the OPPD Board meeting logistics support staff. Chair E. H. Williams presided and E. H. Lane recorded the minutes. Members of the executive leadership team present in person included: J. M. Bishop, K. W. Brown, C. V. Fleener, S. M. Focht, T. D. McAreavey, K.S. McCormick, L. A. Olson, M. V. Purnell, B. R. Underwood, and T. R. Via.

Board Agenda Item 1: Chair Opening Statement

Chair Williams gave a brief opening statement, including reminders for using the WebEx audio and video conferencing platform.

Board Agenda Item 2: Safety Briefing

Randy Bland, Shift Security Advisor, provided physical safety reminders. President Fernandez provided psychological safety reminders, including current safety focus reminders about: (i) Situational awareness; (ii) Preventing falls; and (iii) Sprains of spring.

Board Agenda Item 3: Guidelines for Participation

Chair Williams then presented the guidelines for the conduct of the meeting and instructions on the public comment process in the room and using WebEx audio and video conferencing features.

Board Agenda Item 4: Roll Call

Ms. Lane took roll call of the Board. All members were present in person.

Board Agenda Item 5: Announcement regarding public notice of meeting

Ms. Lane read the following:

> *"Notice of the time and place of this meeting was publicized by notifying the area news media; by publicizing same in the Omaha World Herald, OPPD Outlets newsletter, oppd.com and social media; by displaying such notice on the Arcade*

Level of Energy Plaza; and by e-mailing such notice to each of the District's Directors on May 12, 2023.

A copy of the proposed agenda for this meeting has been maintained, on a current basis, and is readily available for public inspection in the office of the District's Corporate Secretary.

Additionally, a copy of the Open Meetings Act is available for inspection on oppd.com and in this meeting room."

Board Consent Action Items:

6. Approval of the April 2023 Meeting Minutes and the May 18, 2023 Agenda
7. Standing Committee Charters Revisions and District's Bylaws and Board Policies Updates – Resolution No. 6567
8. SD-3: Access to Credit Markets Monitoring Report – Resolution No. 6568
9. NO5 Air Preheater Basket & Seal Replacement -- Materials Contract Award – Resolution No. 6569
10. NC1 Air Preheater Basket & Seal Replacement -- Materials Contract Award – Resolution No. 6570
11. NO4 Air Preheater Basket & Seal Replacement -- Labor Contract Award – Resolution No. 6571
12. Acquisition of Land Rights for Energy Production Infrastructure Project associated with and in proximity to the Nebraska City Station – Resolution No. 6572

It was moved and seconded that the Board approve the consent action items.

Chair Williams noted the Board discussed the action items during the All Committees meeting held on Tuesday, May 16, 2023.

Chair Williams then asked for public comment. There was no comment from the public in attendance at the meeting or via WebEx.

Thereafter, the vote was recorded as follows: Bogner – Yes; Cavanaugh – Yes; Core – Yes; Howard – Yes; Mollhoff – Yes; Moody – Yes; Spurgeon – Yes; Williams – Yes. The motion carried (8-0).

Board Agenda Item 13: President's Report

President Fernandez next presented the following information:

- April Baseload Generation
- April Balancing Generation
- April Renewables
- NERC Alert – Cole Weather Preparations
- Near term Generation Recommendation
- Tree Line USA Utility
- Rock the Block – Fort Calhoun
- Cinco de Mayo Parade
- AMA Pinnacle Award

- In Memoriam – Argil Harshburger

Board Agenda Item 14: Opportunity for comment on other items of District Business

Chair Williams asked for comments from the public on other items of District business.

Mr. David Begley, 4611 S. 96th Street, Omaha, presented information on EPA rules and presented the Board with materials attached to these minutes.

Mr. Laverne T. (address unintelligible), presented information on hydrogen power production and presented the Board with materials attached to these minutes.

Mr. David Corbin, 1002 N. 49th Street, representing the Nebraska Sierra Club, shared his opinion on growth in the area and demand side management.

Ms. Liz Veazey, 912 N. 49th St, Omaha, requested more time for public review of the near term generation recommendation.

Mr. John Pollack, 1412 N. 35th Street, Omaha, provided comments on air quality in North Omaha and a weather update.

Mr. Ryan Wishart, 912 N. 49th St, Omaha, commented on the need to address energy burdens for low income community members.

Ms. Katherine Finnegan, 3326 S. 98th, representing Citizens Climate Lobby commented on the environmental impact study and reaching the goal of net zero carbon impact by 2050.

There were no additional comments from the public in attendance at the meeting or via WebEx.

There being no further business, the meeting adjourned at 6:12 p.m.

DocuSigned by:
S. M. Focht
B626AD4392E3483...

S. M. Focht
Vice President – Corporate Strategy and Governance and Assistant Secretary

DocuSigned by:
Erin Lane
965CE2363A0A42C...

E. H. Lane
Sr. Board Operations Specialist

Proposed OPPD resolution, May 18, 2023

RESOLUTION #65XX

WHEREAS, on May 8, 2023, the EPA issued a 681-page proposed regulation that would fundamentally change the production of electricity in the United States;

WHEREAS, the proposed regulation is open for comments at Docket ID. No. EPA-HQ-OAR-2023-0072;

WHEREAS, OPPD will eventually spend the sum of approximately $651 million to construct two new natural gas plants at Standing Bear Station and Turtle Creek Station;

WHEREAS, in September 2022 OPPD borrowed $420,000,000, *inter alia*, to pay for the two new natural gas plants;

WHEREAS, if the EPA's proposed rule is adopted in substantially in its current form, OPPD will be required to spend millions more by 2035 in order to add carbon capture technology at Standing Bear Station and Turtle Creek Station;

WHEREAS, there are 13 carbon capture systems in use around the world and none of them work as planned and some are total failures;

WHEREAS, carbon capture technology can never economically work because it violates the second law of thermodynamics, that is, it requires energy to capture carbon dioxide and capturing and storing it will require more energy than the power plant produces;

WHEREAS, the proposed EPA regulation will also require OPPD to continue its Power with Purpose plan that will require OPPD to spend at least $28 billion by 2050 to achieve net zero carbon; and

WHEREAS, it is not in the best interest of OPPD's customer-owners to spend billions of dollars to achieve net zero carbon by 2050.

NOW, THEREFORE, BE IT RESOLVED, that the Fraser Stryker law firm and management are authorized to submit comments in opposition to the proposed EPA regulation;

NOW, THEREFORE, BE IT RESOLVED, that if the proposed EPA regulation is not revoked or substantially modified after comments are submitted and considered, then the Fraser Styker law firm is authorized to file a lawsuit against the EPA raising the following two issues:

1. The EPA has exceeded its authority under the Major Questions doctrine, that is, only Congress can make such fundamental changes in the production of electricity in the United States; and
2. That *Massachusetts v. EPA*, 549 U.S. 497 (2007) was wrongly decided with its holding that carbon dioxide is a pollutant within the meaning with the Clean Air Act.

Prepared and submitted by customer-owner David D. Begley, 4611 South 96th Street, Omaha, NE mail.com

Tweet by Janey Utah on Twitter

From: [redacted]>
To: [redacted]>
Date: Apr 27, 2023 6:59:08 AM

Janey Utah
@janetherevelatr

Another friend who regularly attends OPPD meetings tells me that David Begley shows up every month to rant about the negative effects of solar power, how COVID was caused by 5G, things of that nature.
4/26/23, 9:49 PM

Sent from my iPhone

Cruel Neutrality

Duty SD-2, SD-4

Hedge

Proposed OPPD resolution, May 18, 2023

RESOLUTION #65XX

WHEREAS, on May 8, 2023, the EPA issued a 681-page proposed regulation that would fundamentally change the production of electricity in the United States;

WHEREAS, the proposed regulation is open for comments at Docket ID. No. EPA-HQ-OAR-2023-0072;

WHEREAS, OPPD will eventually spend the sum of approximately $651 million to construct two new natural gas plants at Standing Bear Station and Turtle Creek Station;

WHEREAS, in September 2022 OPPD borrowed $420,000,000, *inter alia*, to pay for the two new natural gas plants;

WHEREAS, if the EPA's proposed rule is adopted in substantially in its current form, OPPD will be required to spend millions more by 2035 in order to add carbon capture technology at Standing Bear Station and Turtle Creek Station;

WHEREAS, there are 13 carbon capture systems in use around the world and none of them work as planned and some are total failures;

WHEREAS, carbon capture technology can never economically work because it violates the second law of thermodynamics, that is, it requires energy to capture carbon dioxide and capturing and storing it will require more energy than the power plant produces;

WHEREAS, the proposed EPA regulation will also require OPPD to continue its Power with Purpose plan that will require OPPD to spend at least $28 billion by 2050 to achieve net zero carbon; and

WHEREAS, it is not in the best interest of OPPD's customer-owners to spend billions of dollars to achieve net zero carbon by 2050.

NOW, THEREFORE, BE IT RESOLVED, that the Fraser Stryker law firm and management are authorized to submit comments in opposition to the proposed EPA regulation;

NOW, THEREFORE, BE IT RESOLVED, that if the proposed EPA regulation is not revoked or substantially modified after comments are submitted and considered, then the Fraser Styker law firm is authorized to file a lawsuit against the EPA raising the following two issues:

1. The EPA has exceeded its authority under the Major Questions doctrine, that is, only Congress can make such fundamental changes in the production of electricity in the United States; and
2. That *Massachusetts v. EPA*, 549 U.S. 497 (2007) was wrongly decided with its holding that carbon dioxide is a pollutant within the meaning with the Clean Air Act.

Prepared and submitted by customer-owner David D. Begley, 4611 South 96th Street, Omaha, NE mail.com

---

Tweet by Janey Utah on Twitter

From: [redacted]
To: [redacted]
Date: Apr 27, 2023 6:59:08 AM

Janey Utah
@janetherevelatr

Another friend who regularly attends OPPD meetings tells me that David Begley shows up every month to rant about the negative effects of solar power, how COVID was caused by 5G, things of that nature.

4/26/23, 9:49 PM

Sent from my iPhone

Cruel Neutrality

Duty SD-2, SD-4

Hedge

pillsbury

Hydrogen Highlights in the Bipartisan Infrastructure Bill

By Elizabeth Vella Moeller, Sheila McCafferty Harvey, Moushami P. Joshi, Elina Teplinsky, Mona E. Dajani, Meghan Claire Hammond

TAKEAWAYS

The Senate-passed bill authorizes and appropriates $9.5 billion for clean hydrogen research, development and demonstration programs to be managed by the Secretary of Energy.

The bulk of this funding—$8 billion—is authorized to the newly created Office of Clean Energy Demonstrations for the development of four regional clean hydrogen hubs to be located in different geographic regions across the U.S. with the goal of demonstration projects and end-use diversity, which are likely to be led by companies. The biggest amount will go into carbon capture and developing hydrogen-based power systems.

For the first time, U.S. law will define "clean hydrogen"—the current definition explicitly includes hydrogen produced from renewables, fossil fuels with carbon capture, utilization and sequestration technologies, nuclear, and other eligible sources.

08.31.21

On August 10, 2021, the U.S. Senate passed the Infrastructure Investment and Jobs Act (IIJA) by a bipartisan vote of 69–30. In addition to funding for roads and bridges, the $1.2 trillion infrastructure package includes a number of provisions to spur investment in clean energy innovation technologies—in particular, it provides resources to accelerate research, development, demonstration, and deployment of clean hydrogen in the United States. This includes development of a definition for "clean hydrogen," clean hydrogen supply chains, regional clean hydrogen hubs, and a focus on commercializing the use of clean hydrogen in transportation, utility, industrial, commercial and residential sectors. This is in line with goals stated during President Biden's campaign to create "green hydrogen at the same cost as conventional hydrogen within a decade."

Defining "Clean Hydrogen"

In what would be the first definition for clean hydrogen in U.S. law, the IIJA requires the Secretary of Energy in consultation with the Environmental Protection Agency, to develop an initial standard for the carbon intensity of clean hydrogen production. It initially defines "clean hydrogen" to mean hydrogen "produced with a carbon intensity equal to or less than 2 kilograms of carbon-dioxide equivalent produced at the site of production per kilogram of hydrogen produced." However, the IIJA provides that the Secretary may adjust that standard after its consultation with the EPA. It also mandates that the clean hydrogen standard be applied to hydrogen produced from "renewable, fossil fuel with carbon capture, utilization and sequestration technologies, nuclear, and other fuel sources using any applicable production technology."

Regional Clean Hydrogen Hubs

The IIJA requires the Secretary of Energy to solicit proposals for regional clean hydrogen hubs 180 days after its passage, and select four regional hubs within one year from that date. The bill authorizes and appropriates $8 billion for fiscal years 2022-2026 to the newly created Office of Clean Energy Demonstrations under the Secretary of Energy to carry out this program. These hubs will demonstrate the production, processing, delivery, storage, and end-use of clean hydrogen.

The hubs will have to demonstrate feedstock diversity, as the bill requires at least one hub produce hydrogen from nuclear energy, one from fossil fuels, and one from renewables. Additionally, at least one of each of the hubs will be required to demonstrate hydrogen end-use in either electric power generation, industrial sector, residential heating or transportation. The four hubs are required to be located in different regions of the U.S. and, if feasible, there is preference that at least two hubs be located within natural gas producing regions.

The Secretary of Energy, on the recommendation of the Office of Clean Energy Demonstrations, will allocate grants to each regional hub to accelerate commercialization of, and demonstrate the production, processing, delivery, storage, and end-use of, clean hydrogen.

Clean Hydrogen Electrolysis Program

The IIJA also requires the Department of Energy, within 90 days after the bill's passage, to establish a program to reduce the cost of producing hydrogen through electrolyzers. The goal of the program is to reduce the cost of producing clean hydrogen to less than $2 per kilogram by 2026, and $1 billion has been authorized and appropriated to the Office of Clean Energy Demonstrations for such efforts. Grants will be awarded through the Department of Energy's Office of Energy Efficiency and Renewable Energy on a competitive basis through contracts and cooperative agreements for projects that demonstrate the production of clean hydrogen through electrolysis and the feasibility of commercial deployment of these technologies. The eligibility criteria for these grants is to be determined by the Secretary of Energy.

Clean Hydrogen Manufacturing Initiative

Also through the Office of Energy Efficiency and Renewable Energy, the government will award multiyear grants to and enter into contracts, cooperative agreements, or any other agreements with eligible entities (as determined by the Secretary of Energy) for research, development, and demonstration projects:

- to advance new clean hydrogen production, processing, delivery, storage, and use equipment manufacturing technologies and techniques; and
- to create innovative and practical approaches to increase the reuse and recycling of clean hydrogen technologies.

The IIJA authorizes and appropriates $500 million in grants between 2022-2026 at $100 million each fiscal year.

Overall, the IIJA puts a significant investment, $9.5 billion, towards clean hydrogen research, development, and demonstration. The bill is now set to be considered by the House, which may reject the bill, pass it as is, or pass it with further amendments. The IIJA is part of Senate Majority Leader Schumer's two-track strategy to pass "hard" infrastructure spending in the IIJA and other additional social and clean energy programs through a second budget reconciliation bill. Speaker Nancy Pelosi has indicated she will not bring the IIJA to a vote until House Democrats vote to pass the $3.5 trillion budget reconciliation bill, but she has agreed to take a vote on the IIJA at least by September 27, 2021. While there are no specific provisions for clean hydrogen in the budget reconciliation bill, it currently has a Clean Electricity Payment Program (CEPP) designed to promote all zero-carbon energy sources.

Companies looking to invest in clean hydrogen research and demonstrations projects in the near future should pay special attention to how the statutory amendments proposed in the infrastructure bill play out during House negotiations and may wish to lobby their representatives to shape the outcome of the legislation. Pillsbury has seasoned environmental, energy and public policy attorneys who can assist with such efforts.

Pillsbury's Hydrogen practice, one of the first launched by an AmLaw 100 firm, brings together experienced practitioners from across corporate and transactional, finance, regulatory, environmental, intellectual property, tax and dispute resolution practices. The team also created and maintains The Hydrogen Map, the first public resource tracking the development of hydrogen projects worldwide.

TAGS

Energy, Nuclear Energy, Hydrogen, American Infrastructure Investment Resource Center

MEMORANDUM OF UNDERSTANDING
Mid-Continent Clean Hydrogen Hub – MCH2

This Memorandum of Understanding ("MOU") made on this 4th day of April, 2023, by and between the States of Iowa, Missouri, and Nebraska, establishes a framework for coordinating and developing a regional clean hydrogen hub ("Hydrogen Hub") as contemplated by the 2021 Infrastructure Investment and Jobs Act, Pub. Law 117-58 ("Act"). The States of Iowa, Missouri, and Nebraska have created the Mid-Continent Clean Hydrogen Hub ("MCH2") and may be referred to collectively as "Participating States" or "Signatory States." MCH2 consists of a world class and diverse team, including Monolith Materials, Inc., Project Meadowlark, VERBIO, Ideal Energy, and Greenfield Nitrogen (collectively the "Parties").

WHEREAS, clean hydrogen has the potential to advance the interests of the Participating States in clean air, reduction of carbon emissions, jobs, rural and urban economic development, and equitable energy opportunities.

WHEREAS, the 2021 Act allocates $8 billion in funding for four or more regional hydrogen hubs.

WHEREAS, the Participating States are uniquely qualified and situated to serve as a Hydrogen Hub with a thriving hydrogen economy given the presence of high-quality wind, solar, biomass, nuclear, agricultural, and other energy resources; a sophisticated oil and natural gas industry; a robust energy transportation infrastructure; an established carbon management infrastructure and favorable geology; early-stage public and private hydrogen economy development initiatives; world-leading national laboratory facilities and academic institutions; and industrial areas that are potential early adopters of clean hydrogen technologies.

WHEREAS, addressing the shared challenges of a healthy environment and modern energy economy require regional collaboration.

WHEREAS, the agricultural assets of the Participating States are complementary, including crop, animal, fertilizer production, and end users.

WHEREAS, the energy assets of the Participating States are complementary, including electricity generation sources, pipelines, underground storage availability, and end users.

WHEREAS, the success of a Hydrogen Hub rests firmly on the collaboration, leadership, and innovation of states, researchers, and private businesses with diverse expertise and talents.

WHEREAS, a cost-effective strategy with the ability to scale the production, transportation, storage, and use of clean hydrogen benefits from interstate collaboration and coordination.

WHEREAS, the Participating States share a mutual interest in the demonstration and growth of clean hydrogen production, transportation, storage, and use to advance their individual and collective goals.

NOW, THEREFORE, the Governors of the Participating States agree as follows:

I. Commitment

The Signatory States hereby pledge their support for MCH2 for funding under the Act that advances a compelling vision for a hydrogen economy, including production and use in the central United States ("U.S"). The Signatory States are committed to an application that works with academic, research, industry, and community partners and stakeholders to ensure the application:

- Drives economic growth and development for each of the participating states and the region.
- Incorporates the latest science, research, and technology for the cost-effective production, transportation, storage, and use of clean hydrogen.
- Ensures protections for and the participation of frontline and disadvantaged communities, including safeguards around public health, safety, and labor.
- Develops a pathway for workforce development and training.

- Provides for information exchange and collaborative research, including engagement with research and educational institutions, to maximize economic opportunities, monitor emissions and MCH2 performance, and thoughtfully plan expansion of MCH2 and the use of hydrogen technology over time.
- Addresses pipeline safety, leak minimization, and pathways for new pipeline construction.
- Proactively evaluates and addresses the potential impacts of hydrogen production on water use and seeks opportunities to use water that is currently used for or generated by other industrial or power generation purposes.
- Engages key stakeholders, including end-users in the agricultural, industrial, buildings, aviation, power generation, and transportation sectors.
- Addresses the air quality impacts of hydrogen production, transportation, storage, use, and combustion, including emissions of nitrogen oxides.
- Identifies current and possible State resources, incentives, policies, and plans that can be leveraged in support of a flourishing and competitive hydrogen economy among the participating States.
- Respects the unique needs and policy approaches of each participating State.

The MCH2 will conduct its work by Participating States' collaboration in the creation of a robust and sustainable model that will include hydrogen production pathways and volumes from multiple sources, transportation and storage, market / fabrication / end user, and carbon intensity metrics. The model will be able to optimize on a state-by-state or regional perspective. The results of the model will inform the Participating States' activities, but shall not bind the Participating States to particular actions or outcomes.

II. Hub Oversight and Management Agreements

In addition to an application for funding, the Parties intend to develop and finalize a Collaboration Agreement ("Collaboration Agreement"). The Collaboration Agreement shall set forth the structure, governance, obligations, expectations, management, and oversight of the Hydrogen Hub and the roles, responsibilities, obligations, and authority of the Parties involved in the Hydrogen Hub for the entire duration of MCH2. The Collaboration Agreement will confirm the methodology for the distribution of any U.S. Department of Energy (DOE) funds through the MCH2 regional hub.

III. Timeline

The Participating States collective work will meet FOA DOE submittal team deadlines for Federal funding opportunities for regional hydrogen hubs for the final FOA and support submittal submission of an application by the due date of April 7, 2023.

IV. Disclosure of Information

Participating States and those entities performing contractual services on behalf of the MCH2 will not make public or private representations as to the purpose or intent behind each Participating State's participation, except as expressly agreed to by the respective Participating State. As governed by the laws and regulations of each Participating State, Participating States and those entities performing contractual services on behalf of the MCH2 will maintain the confidentiality of details pertaining to the Hydrogen Hub.

V. Additional Member States

Upon agreement of all Participating States, additional States may be added to this MOU to support the MCH2, subject to the provisions being developed under the Collaboration Agreement, to enhance the ability to establish a Hydrogen Hub.

VI. Voluntary Initiative

This MOU is not legally binding and does not create any legal, equitable, or financial rights, commitments, obligations or liabilities for the Participating States. Any Participating State may cease cooperation under this MOU at any time upon written notice to the other Participating States. This MOU may be amended by a written instrument signed by each Participating State. The terms of this MOU do not preclude any Participating State from participation in other efforts, including, but not limited to, other hydrogen hubs.

Administrative costs to support the MCH2 funding application to the DOE will be based on any use of consultation work to support specific funding project requests, modeling, or evaluation and in accordance with the terms of the DOE award. Funding support for any State-based projects for this application and any future requests will be governed by the respective projects' corresponding budget funding requests. This MOU does not obligate any Participating State to receive, distribute, or contribute any funds for these purposes.

VII. Duration

This MOU is at-will and may be terminated by any State upon written notice to the other States. The MOU will continue following any such termination, so long as the remaining Participating States agree.

[Signature page follows]

IN WITNESS WHEREOF, the Participating States have executed the foregoing Memorandum of Understanding effective as of the date first indicated above.

State of Iowa

By: Kim Reynolds

Title: Governor

Date: 4/5/23

State of Missouri

By: Mike Parson

Title: Governor

Date: 4/4/2023

State of Nebraska

By: Jim Pillen

Title: Governor

Date: 4/4/23

IN WITNESS WHEREOF, the Participating States have executed the foregoing Memorandum of Understanding effective as of the date first indicated above.

State of Iowa

By: Kim Reynolds

Title: Governor

Date: 4/5/23

State of Missouri

By: Mike Parson

Title: Governor

Date: 4/4/2023

State of Nebraska

By: Jim Pillen

Title: Governor

Date: 4/4/23

MEMORANDUM OF UNDERSTANDING
Mid-Continent Clean Hydrogen Hub – MCH2

This Memorandum of Understanding ("MOU") made on this 4th day of April, 2023, by and between the States of Iowa, Missouri, and Nebraska, establishes a framework for coordinating and developing a regional clean hydrogen hub ("Hydrogen Hub") as contemplated by the 2021 Infrastructure Investment and Jobs Act, Pub. Law 117-58 ("Act"). The States of Iowa, Missouri, and Nebraska have created the Mid-Continent Clean Hydrogen Hub ("MCH2") and may be referred to collectively as "Participating States" or "Signatory States." MCH2 consists of a world class and diverse team, including Monolith Materials, Inc., Project Meadowlark, VERBIO, Ideal Energy, and Greenfield Nitrogen (collectively the "Parties").

WHEREAS, clean hydrogen has the potential to advance the interests of the Participating States in clean air, reduction of carbon emissions, jobs, rural and urban economic development, and equitable energy opportunities.

WHEREAS, the 2021 Act allocates $8 billion in funding for four or more regional hydrogen hubs.

WHEREAS, the Participating States are uniquely qualified and situated to serve as a Hydrogen Hub with a thriving hydrogen economy given the presence of high-quality wind, solar, biomass, nuclear, agricultural, and other energy resources; a sophisticated oil and natural gas industry; a robust energy transportation infrastructure; an established carbon management infrastructure and favorable geology; early-stage public and private hydrogen economy development initiatives; world-leading national laboratory facilities and academic institutions; and industrial areas that are potential early adopters of clean hydrogen technologies.

WHEREAS, addressing the shared challenges of a healthy environment and modern energy economy require regional collaboration.

WHEREAS, the agricultural assets of the Participating States are complementary, including crop, animal, fertilizer production, and end users.

WHEREAS, the energy assets of the Participating States are complementary, including electricity generation sources, pipelines, underground storage availability, and end users.

WHEREAS, the success of a Hydrogen Hub rests firmly on the collaboration, leadership, and innovation of states, researchers, and private businesses with diverse expertise and talents.

WHEREAS, a cost-effective strategy with the ability to scale the production, transportation, storage, and use of clean hydrogen benefits from interstate collaboration and coordination.

WHEREAS, the Participating States share a mutual interest in the demonstration and growth of clean hydrogen production, transportation, storage, and use to advance their individual and collective goals.

NOW, THEREFORE, the Governors of the Participating States agree as follows:

I. Commitment

The Signatory States hereby pledge their support for MCH2 for funding under the Act that advances a compelling vision for a hydrogen economy, including production and use in the central United States ("U.S"). The Signatory States are committed to an application that works with academic, research, industry, and community partners and stakeholders to ensure the application:

- Drives economic growth and development for each of the participating states and the region.
- Incorporates the latest science, research, and technology for the cost-effective production, transportation, storage, and use of clean hydrogen.
- Ensures protections for and the participation of frontline and disadvantaged communities, including safeguards around public health, safety, and labor.
- Develops a pathway for workforce development and training.

- Provides for information exchange and collaborative research, including engagement with research and educational institutions, to maximize economic opportunities, monitor emissions and MCH2 performance, and thoughtfully plan expansion of MCH2 and the use of hydrogen technology over time.
- Addresses pipeline safety, leak minimization, and pathways for new pipeline construction.
- Proactively evaluates and addresses the potential impacts of hydrogen production on water use and seeks opportunities to use water that is currently used for or generated by other industrial or power generation purposes.
- Engages key stakeholders, including end-users in the agricultural, industrial, buildings, aviation, power generation, and transportation sectors.
- Addresses the air quality impacts of hydrogen production, transportation, storage, use, and combustion, including emissions of nitrogen oxides.
- Identifies current and possible State resources, incentives, policies, and plans that can be leveraged in support of a flourishing and competitive hydrogen economy among the participating States.
- Respects the unique needs and policy approaches of each participating State.

The MCH2 will conduct its work by Participating States' collaboration in the creation of a robust and sustainable model that will include hydrogen production pathways and volumes from multiple sources, transportation and storage, market / fabrication / end user, and carbon intensity metrics. The model will be able to optimize on a state-by-state or regional perspective. The results of the model will inform the Participating States' activities, but shall not bind the Participating States to particular actions or outcomes.

II. Hub Oversight and Management Agreements

In addition to an application for funding, the Parties intend to develop and finalize a Collaboration Agreement ("Collaboration Agreement"). The Collaboration Agreement shall set forth the structure, governance, obligations, expectations, management, and oversight of the Hydrogen Hub and the roles, responsibilities, obligations, and authority of the Parties involved in the Hydrogen Hub for the entire duration of MCH2. The Collaboration Agreement will confirm the methodology for the distribution of any U.S. Department of Energy (DOE) funds through the MCH2 regional hub.

III. Timeline

The Participating States collective work will meet FOA DOE submittal team deadlines for Federal funding opportunities for regional hydrogen hubs for the final FOA and support submittal submission of an application by the due date of April 7, 2023.

IV. Disclosure of Information

Participating States and those entities performing contractual services on behalf of the MCH2 will not make public or private representations as to the purpose or intent behind each Participating State's participation, except as expressly agreed to by the respective Participating State. As governed by the laws and regulations of each Participating State, Participating States and those entities performing contractual services on behalf of the MCH2 will maintain the confidentiality of details pertaining to the Hydrogen Hub.

V. Additional Member States

Upon agreement of all Participating States, additional States may be added to this MOU to support the MCH2, subject to the provisions being developed under the Collaboration Agreement, to enhance the ability to establish a Hydrogen Hub.

VI. Voluntary Initiative

This MOU is not legally binding and does not create any legal, equitable, or financial rights, commitments, obligations or liabilities for the Participating States. Any Participating State may cease cooperation under this MOU at any time upon written notice to the other Participating States. This MOU may be amended by a written instrument signed by each Participating State. The terms of this MOU do not preclude any Participating State from participation in other efforts, including, but not limited to, other hydrogen hubs.

Administrative costs to support the MCH2 funding application to the DOE will be based on any use of consultation work to support specific funding project requests, modeling, or evaluation and in accordance with the terms of the DOE award. Funding support for any State-based projects for this application and any future requests will be governed by the respective projects' corresponding budget funding requests. This MOU does not obligate any Participating State to receive, distribute, or contribute any funds for these purposes.

VII. Duration

This MOU is at-will and may be terminated by any State upon written notice to the other States. The MOU will continue following any such termination, so long as the remaining Participating States agree.

[Signature page follows]

DocuSign Envelope ID: 073F0BD6-CBA8-4BA4-BA4B-6F927DCD9E85

IN WITNESS WHEREOF, the Participating States have executed the foregoing Memorandum of Understanding effective as of the date first indicated above.

State of Iowa

Kim Reynolds

By: Kim Reynolds

Title: Governor

Date: 4/5/22

State of Missouri

Speech by Olaf Scholz, Member of the German Bundestag and Chancellor of the Federal Republic of Germany, at the World Economic Forum in Davos on January 18, 2023

Wednesday, 18 January 2023 in Davos

Professor Schwab, dear Klaus,

ladies and gentlemen,

What a difference a year makes! When I spoke to you last year around this time, our discussions revolved around the global economy's path out of the pandemic. At the start of 2022, many people were expecting a boom– or at least a substantial boost for our economies' transition toward climate neutrality.

Then came February 24.

Since then, Russia has been waging an imperialist war of aggression, here on our doorstep in Europe. With dreadful consequences, that Ukrainians are bearing more than anyone. Just today the Secretary of the Interior and 15 other victims were killed in a tragic helicopter crash. We are with their families.

But the war is also having an impact on all of us. For a while, energy prices jumped to levels higher than we had ever seen before. Around the world, production costs and consumer prices exploded.

Many people fear that coal and oil will make a lasting comeback all across the world. If that were to happen, the 1.5 degree target would become meaningless.

Our supply chains must be adapted to new geopolitical realities – realities that you called a "messy patchwork of powers" in your speech yesterday, Klaus.

And over all of this hangs a sword of Damocles: the danger of a new fragmentation of the world, of deglobalization and decoupling.

And yet, ladies and gentlemen, this is just one part of the story of last year, just one part of the reality that we are looking at here in Davos.

The other part of the story is this: Russia has already failed completely in reaching its imperialist goals. Ukraine is defending itself with great success and impressive courage. A broad international alliance – led by the G7– is providing the country with financial, economic, humanitarian, and military support.

Germany alone made available over 12 billion euro last year. And we will continue to support Ukraine – for as long as necessary.

In Berlin at the end of October, we worked with international experts to draw up a Marshall Plan for the long-term reconstruction of Ukraine. A platform of major donors is coordinating the process and – in consultation with Ukraine – ensuring that it is well implemented.

Private-sector capital will play a key role here. I know that many companies in Germany and beyond are very aware of the opportunities that a Ukrainian economic miracle could offer to them. Particularly as the country moves toward the European Union after the end of the war.

But in order for the war to end, Russia's aggression must fail.

That is why we are continuously supplying Ukraine with large quantities of arms, in close consultation with our partners. This includes air defense systems like IRIS-T or Patriot, artillery, and armored infantry fighting vehicles, marking a profound turning point in German foreign and security policy.

And there's another part to the story of last year: Within a few months, Germany made itself completely independent from Russian gas, Russian oil, and Russian coal. We concluded new partnerships– in Asia, Africa, and America– thus lessening our dependence. And so, I can say that our energy supply for this winter is secure – thanks to well-filled storage facilities, thanks to improved energy efficiency, thanks to remarkable solidarity within Europe, and thanks to the readiness of our companies and of millions of citizens to save energy.

As a result, energy prices have recently seen a huge drop.

Our measures to reduce the burden on private citizens, companies, and businesses are working. Inflation is falling slowly – thanks, incidentally, also to resolute moves by the central banks. Industrial production in Germany has remained stable over the past few months, against all the odds. Our employment rate is at record levels and has recently increased even further. Most importantly, our transformation toward a climate-neutral economy– the fundamental task of our century – is currently taking on an entirely new dynamic.

Not in spite of, but because of the Russian war and the resulting pressure on us Europeans to change.

Whether you are a business leader or a climate activist, a security policy specialist or an investor– it is now crystal-clear to each and every one of us that the future belongs solely to renewables. For cost reasons, for environmental reasons, for security reasons, and because in the long run, renewables promise the best returns!

So: Yes, the past year brought fundamental change for Germany and Europe.

But Germany itself has fundamentally changed as well!

We are resolutely pushing forward with the decarbonization of our industry.

We want to be climate-neutral by 2045. And at the same time, we will remain a country with a strong manufacturing sector. And despite all the difficulties this past year showed us: we can and we will succeed in that.

In less than seven months, we built up an entirely new import infrastructure for LNG in Wilhelmshaven. In the future it can also be used for hydrogen. Just last Saturday, I opened our second LNG terminal within just a few weeks, in Lubmin. The day after tomorrow another terminal-ship is expected to arrive at the port of Brunsbüttel. More will follow. This is not only good news for our energy security and that of our European neighbors who will be receiving gas from these terminals.

Above all, it shows: Germany can be flexible; we can be unbureaucratic; and we can be fast.

I spoke of a new Deutschland-Geschwindigkeit in this regard, a new "German speed".

We will make this German speed the benchmark – also for the transformation of the economy as a whole. Your companies can hold us to this standard. A new law mandates that the expansion of wind power, solar energy, as well as electricity and hydrogen networks now take priority. We will make available no less than two percent of our country for wind power – with a minimum of red tape.

We have streamlined our processes so that approvals for electricity grids – to name just one example – are granted on average two years faster than before. And we intend to step up the pace even more.

You can also rely on our targets. The obstacles have been swept aside.

For 2023, we have more than doubled the volume of calls for tender for onshore wind farms alone. By the year 2030, 80 percent of our electricity production will come from renewable sources – again, double what it is at present. At the same time, our electricity requirements are increasing – from 600 terawatt hours today to 750 by the end of the decade. And we are expecting them to double, yet again, in the 2030s.

This is a massive increase.

That's why the Federal Network Agency has been given a clear mandate to prepare and expand our electricity grids accordingly. We will regularly review the progress made. If it's not on schedule, the measures will be adjusted. However, electricity alone is not enough to run Germany's industry.

I am thinking, for instance, of steel production. Hydrogen will play a decisive role there. And that is not a far-off scenario. Last fall, Thyssenkrupp gave the green light to build a direct reduction plant for low-carbon premium steel. With a capacity of 2.5 million metric tons, the plant will save 3.5 million metric tons of CO_2 per year.

This is just one example of Europe's strength in innovation. Europe is the world's number one in hydrogen patents. And one in ten global applications comes from Germany. The first supply chains for green hydrogen are currently being built up in our country. For our own production, we are using offshore wind in the North Sea. In parallel, we are concluding hydrogen partnerships worldwide. For as long as quantities are small and the costs of production correspondingly high, the state will bring prices down to a level lucrative for the industry.

Our goal is nothing less than an electrolysis boom. And, as quantities increase, a hydrogen-powered industrial sector will emerge that preserves the climate and is independent of volatile prices for fossil fuels.

Because one thing is absolutely certain: Energy must remain affordable – in Germany, in Europe, and worldwide. In Germany, we decided to cap electricity and gas prices for private citizens and companies. These measures will run until 2024. Annually, we will use around 2.2 percent of our GDP for this, a total of up to 200 billion euro. That is both forceful and proportionate. It will give your companies the reliable energy prices and the planning certainty you need to invest in Germany's transformation.

In the European Union, we have agreed on joint targets for gas filling and saving. We will purchase gas jointly more often and coordinate storage better. And we will use our market power to ensure that European prices do not decouple completely from the world market. Moreover, we are also aware of our global responsibility. Let me say this expressly to our friends and partners in Asia, Africa, Latin America and the Caribbean: The fact that we Europeans purchase LNG on the world market, must not lead to scarcity elsewhere.

We will need alternatives for the roughly 120 billion cubic meters of gas from Russian pipelines missing from the world market – more renewables, of course, but also, temporarily, additional gas resources.

Otherwise there is a danger that without affordable gas, emerging economies in particular might switch back to coal. This would be even more harmful to the environment.

Of course, we must avoid new lock-ins, new path dependencies at all costs – by making new projects HO2-ready from the very outset and by expanding renewables in parallel. In the short term this may lead to higher costs. In the long term we all stand to save if the impact of climate change is less dramatic.

In Germany, too, switching to a climate-friendly economy will take efforts.

We are talking about investments around 400 billion euro for the expansion of renewables between now and 2030. Investments, by the way, which are already well underway. The most recent example is a contract worth billions for Siemens Energy to connect a new offshore wind park to the grid. And this is just one example illustrating why this turning point towards a climate-friendly industry is not the end of our industrial powerhouse. But a new start!

After all, even before the energy crisis that Russia triggered, Germany's business model was not only based on the energy-intensive mass production of aluminum, cement, or crude steel. But on highly specialized research- and technology-intensive industrial products. Products that are needed all around the world. All the more so, actually, when the world is now transitioning towards a climate neutral future.

Even before Russia's war of aggression, Germany's energy prices were not the lowest. And yet Germany was and remains competitive. This is because of thousands of small and medium-sized enterprises all across the country. Enterprises that are highly innovative and adaptable – which explains why they are so often global leaders. This is thanks to high public and private investment in research and development, which, for example, ensured that the first COVID-19 test and the first safe and effective COVID-19 vaccine were developed in Germany. Just in December, a team at the Helmholtz Center in Berlin set a new world record for the efficiency of solar cells. And now, just a few weeks later, our companies are already setting up pilot lines for the use of these tandem cells.

That, ladies and gentlemen, is and remains the German business model – particularly now as we chart our path to a climate-neutral future.

Where else is there such broad consensus between businesses, employees, and politics that the path to climate neutrality is not just ecologically necessary but also offers new opportunities in global competition? When it comes to basic and professional training for employees, for example, politics, business, and trade unions in Germany are working hand in hand. And before the year is out, our country will finally benefit from modern immigration legislation.

After all, if we want to remain competitive as a leading industrial nation, we need experienced practitioners – qualified engineers, tradesmen, and mechanics. Those who want to roll up their sleeves are welcome in Germany. That is our message!

For decades now, the forecasts have been predicting a shrinking German population. But it is up to us to decide whether this happens. So far it certainly hasn't. Today Germany has more inhabitants and employed persons than ever before. And this is precisely the trend we are going to continue.

Ladies and gentlemen,

a climate-neutral future is, needless to say, not something any single country can achieve on its own. That is why our dialogue and a forum like Davos are so crucial. What we are doing in Germany also serves the goal of making Europe the first climate-neutral continent by 2050. At a European level, we are going to lower our net greenhouse gas emissions by at least 55 per cent by 2030 compared to 1990. This decision stands.

Here, we are relying on the market, on competition, and on innovation. The EU's emissions trading system is a case in point. Even today we are using it to cut permissible emission levels in a way that is predictable for all. At the same time, this system is serving as a catalyst for innovation.

But to ensure the most ambitious are not disadvantaged, we prepare a carbon border adjustment mechanism in Europe. At the same time however, Europe remains open for international trade. I am doing my utmost to ensure that the free trade agreements we have successfully negotiated with Canada, Korea, Japan, New Zealand, and Chile will soon be followed by new ones: with MERCOSUR, India, and Indonesia. And we are also open to discuss a tariff agreement for the industrial sector with the United States.

Through these agreements we are creating a level playing field and we are preventing high-emission industries from heading off to countries with less ambitious climate targets.

This is also the aim of the international Climate Club we launched during Germany's G7 Presidency. A Secretariat has recently been set up at the OECD and the International Energy Agency. So the Club is now open to new, ambitious members.

In the United States, this ambition has a name: the Inflation Reduction Act. Some 370 billion dollars have been earmarked for energy and climate change mitigation over the next ten years. I very much welcome this investment.

Through the German Climate and Transformation Fund we have made almost 180 billion euro available ourselves for the period 2023 to 2026. But local content requirements for certain products must not result in discrimination against European businesses. Protectionism hinders competition and innovation and is detrimental to climate change mitigation. We, as EU members, are talking to our American friends about this.

And at the same time, we are looking at what we ourselves can do to further improve investment conditions here in Europe. The Chips Act, for instance, has brought about a new start for chip manufacturing in Europe. Investors are starting new production plants for billions of euros. They can build on an existing semi-conductor industry. This could become a model for other key technologies – particularly in the digital and climate sectors. And the funding is there for the taking. To date, only 20 percent of the more than 700 billion euro in the European Recovery Fund has been paid out. Its full impact will thus emerge over the coming years.

To remain competitive, we will have to make European legislation on state aid more agile and flexible – just as European Commission President Ursula von der Leyen has proposed and reaffirmed here yesterday. So that investors know in advance what support to expect – and don't have to wait until years after their investment to find out.

Ladies and gentlemen,

the past year challenged us as seldom before. Yet at the same time, we changed and moved things forward as seldom before. Germany itself is changing.

If I may make a prediction: My successor will address you at the World Economic Forum in 2045. Sure: He or she will present Germany as one of the world's first climate-neutral industrial nations. Energy supplies in Germany and Europe will then be sourced almost exclusively from green electricity, heat, and hydrogen. We will be moving emission-free on our roads and railroads. Our buildings will be energy efficient. Our businesses will be producing on a climate-neutral basis. And what is more, they are the ones who will have driven this transition, who will continue to drive it.

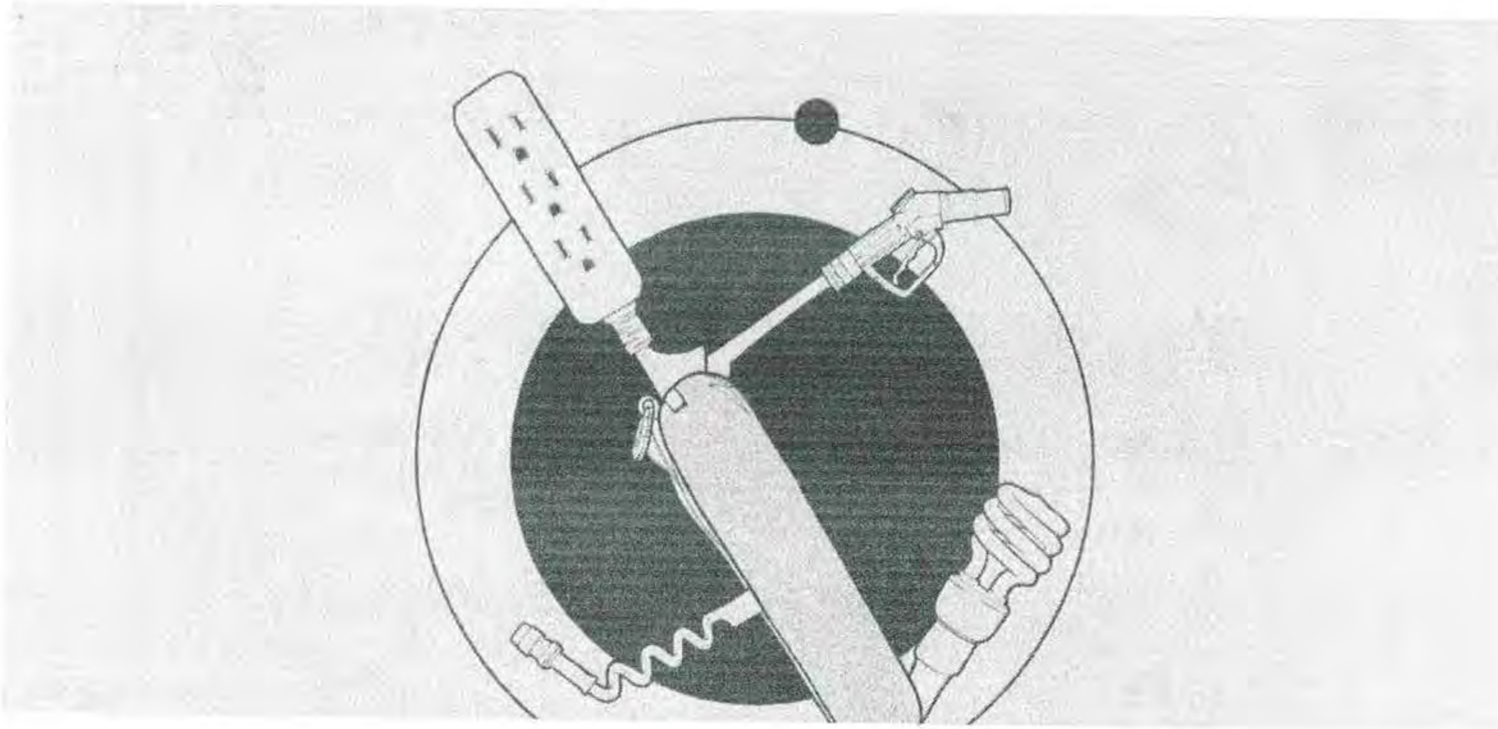
So, if you ask me today where you can invest in the future sustainably with a high return, my answer is: Don't look any further! Come to us, to Germany, and to Europe!

Thank you very much.

THE OTHER HYDRO POWER

To cut emissions, use this Swiss Army Knife

By Bill Gates | June 21, 2022 4 minute read



When most people picture greenhouse gas emissions, they think about cars and electricity. That's because they turn keys, press buttons, and flip switches every day. The good news is, we already have ways to decarbonize these types of emissions (solar, wind, and nuclear power and lithium ion batteries). The bad news is, they add up to only about one third of the total.

The other two thirds—almost 35 billion tons—are much harder for most people to see. For example, we all use products made of cement, plastic, and steel, but most of us don't manufacture them or load them onto cargo ships. To zero out emissions on these products, we need new technologies. Enter clean hydrogen. It has so many potential uses that some people refer to it as the Swiss Army Knife of decarbonization.

Bill Gates

2.9M subscribers

To cut emissions, use this Swiss Army knife

<div class="player-unavailable"><h1 class="message">An error occurred.</h1><div class="submessage">Try watching this video on www.youtube.com, or enable JavaScript if it is disabled in your browser.</div></div>

What hydrogen can do

The world already uses 70 million tons of hydrogen each year as a chemical in some manufacturing processes like making fertilizer. Today, nearly all that hydrogen is produced from fossil fuels. If we make that hydrogen clean, we eliminate the 1.6 percent of global emissions that it is responsible for now.

But that's just the beginning. Hydrogen is pure, reactive chemical energy. If we can bring the cost down far enough and make enough of it, we can also start using clean hydrogen to replace fossil fuels in all sorts of other industrial processes, including important ones like making plastic and steel, liquid fuels, and even food. (It's called the Swiss Army Knife for a reason.)

In addition, clean hydrogen opens the door to all sorts of possibilities beyond industry. For example, as more and more electricity comes from variable sources, the world will have to get better at balancing energy supply and demand so we don't go dark when the sun isn't shining or the wind isn't blowing. Electricity can be converted into hydrogen through a process called electrolysis, then stored for months at a time, and finally converted back into electricity when it's needed.

Another potential use for hydrogen lies in heavy-duty transport. Battery-electric vehicles work great for passenger transportation and trucking over shorter distances, but aviation, shipping, and long-distance trucking remain a challenge. And together they account for 8 percent of global emissions. Clean hydrogen has the potential to provide a net-zero solution for moving cargo around the world.

So in theory, clean hydrogen can do a lot of things we need to do urgently. And governments in many European countries, Australia, Japan, and the United States have ambitious plans for using it to decarbonize their economies. But how do we make hydrogen clean in practice?

How to make hydrogen clean

Innovators are working on several different technologies, some of which are more mature than others.

One option is to use solar, wind, or nuclear power to turn water into hydrogen and oxygen. This process, known as electrolysis, was invented in 1800 using the first-ever battery that had just been invented by Alessandro Volta. More than two centuries later, the same basic principle may be the key to massive clean hydrogen production. There are four different electrolyzer technologies being developed, and the price of each one needs to go down to make electrolyzed hydrogen cost-competitive.

Another option is to produce hydrogen using the current methods that burn fossil fuels and then capture the CO_2 produced in the process before it's released in the atmosphere. It may never be economical to capture 100 percent of the carbon released using incumbent technologies, but while we're waiting for thousands of industrial facilities to retrofit their infrastructure, carbon capture can help drive emissions way down.

Other clean hydrogen technologies are further away.

Methane (CH_4) is the primary fossil fuel used to produce hydrogen now. When it reacts with water (H_2O) at a high temperature, both H_2 and CO_2 are produced. However, through a different heating process that happens in the absence of oxygen, called pyrolysis, it's possible to separate the hydrogen atoms and leave just solid carbon—think of the lead in a pencil.

Finally, there are reserves of hydrogen in geologic formations around the world, and in theory geologic hydrogen has the potential to provide a vast supply of affordable, zero-emissions hydrogen. Scientists are still in the early stages of researching ways to find and extract geologic hydrogen from natural reserves.

Making clean hydrogen cheap

So the potential of clean hydrogen is tantalizing, and its necessity is becoming clearer every day. Take Russia's war in Ukraine, which has made hydrogen not just a climate change issue but also an energy security issue. The EU has already announced its intention to produce and import 20 million tons of green hydrogen by 2030, enough to reduce its dependence on Russian natural gas imports by at least a third.

But hydrogen faces the same challenge as just about every other clean technology: Can we get the price down far enough, fast enough? If people have to pay too much to be green, change will happen too slowly. But if we get the Green Premiums down near zero, there is a chance to build a prosperous net-zero economy. It's going to take a big push for collaboration between business and governments, which, together, can make innovation happen much faster than usual by being aggressive with investments and policies.

Breakthrough Energy, the climate initiative I helped start, is supporting the commercialization of clean hydrogen in many ways. The Breakthrough Energy

Fellows program funds innovators working on early stage ideas. Breakthrough Energy Ventures invests in companies working on clean hydrogen. And the Breakthrough Energy Catalyst program speeds up the time to market for clean hydrogen, among other climate technologies.

The more everyone gets excited about the many benefits of clean hydrogen, the faster businesses and governments will put in the work to make it a real alternative to fossil fuels. That's how we avoid a climate disaster.

nature COMMUNICATIONS

ARTICLE

Check for updates

https://doi.org/10.1038/s41467-022-28953-x OPEN

A high-performance capillary-fed electrolysis cell promises more cost-competitive renewable hydrogen

Aaron Hodges[1,3], Anh Linh Hoang[1,3], George Tsekouras[1], Klaudia Wagner[1,2], Chong-Yong Lee[1,2], Gerhard F. Swiegers[1,2✉] & Gordon G. Wallace[1,2]

Renewable, or *green*, hydrogen will play a critical role in the decarbonisation of hard-to-abate sectors and will therefore be important in limiting global warming. However, renewable hydrogen is not cost-competitive with fossil fuels, due to the moderate energy efficiency and high capital costs of traditional water electrolysers. Here a unique concept of water electrolysis is introduced, wherein water is supplied to hydrogen- and oxygen-evolving electrodes via capillary-induced transport along a porous inter-electrode separator, leading to inherently *bubble-free* operation at the electrodes. An alkaline *capillary-fed electrolysis* cell of this type demonstrates water electrolysis performance exceeding commercial electrolysis cells, with a cell voltage at 0.5 A cm^{-2} and 85 °C of only 1.51 V, equating to 98% energy efficiency, with an energy consumption of 40.4 kWh/kg hydrogen (vs. ~47.5 kWh/kg in commercial electrolysis cells). High energy efficiency, combined with the promise of a simplified balance-of-plant, brings cost-competitive renewable hydrogen closer to reality.

1800-642-5720

Rows 7 accross Photo

Omaha Performing Arts

[1]Intelligent Polymer Research Institute, University of Wollongong, Wollongong, NSW 2522, Australia. [2]Australian Research Council Centre of Excellence for Electromaterials Research, University of Wollongong, Wollongong, NSW 2522, Australia. [3]These authors contributed equally: Aaron Hodges, Anh Linh Hoang. ✉email: swiegers@uow.edu.au

Anthropogenic climate change, driven largely by the burning of fossil fuels, poses a global existential threat. This has motivated a growing number of nations and corporations to aim for net-zero carbon emissions by 2050 to limit global warming to 1.5 °C above pre-industrial levels[1,2].

A critical element of the future net-zero world will be renewable hydrogen, or green hydrogen, produced by water electrolysis powered by renewable electricity, such as solar and wind. The electrolysis of water requires the input of electrical energy and heat energy, resulting in the evolution, from water, of hydrogen gas at the cathode and oxygen gas at the anode according to:

$$2H_2O_{(l)} \rightleftharpoons 2H_{2(g)} + O_{2(g)} E^0 = -1.229\,V$$

Green hydrogen will be essential to the decarbonisation of hard-to-abate sectors such as steel manufacture, long-haul transport, shipping and aviation[1–3]. It may also be used for the seasonal storage of renewable electricity[1–7] and as a chemical feedstock[1–5]. However, the levelised cost of green hydrogen (LCOH) is presently not competitive with fossil fuels. This is due to the high capital expenditure (CAPEX) and high operational expenditure (OPEX) of present-day water electrolysers. The OPEX is, by far, the larger component of LCOH and it is dominated by the overall energy efficiency of the water electrolyser and the cost of the input renewable electricity to which it applies[2]. At sub-MW scale, state-of-the-art commercial water electrolysers typically require ~53 kWh of electricity to produce 1 kg of hydrogen, which contains 39.4 kWh of energy, according to its higher heating value (HHV)[2]. Of that, the electrolysis cell, which is ~83% energy efficient (HHV) at the operating current density, consumes ~47.5 kWh, with the engineering system, known as the balance-of-plant, consuming the remaining ~5.5 kWh[2]. The International Renewable Energy Agency (IRENA) has set a 2050 target[2] to decrease cell energy consumption to <42 kWh/kg. Any improvements in net energy efficiency create a proportionally equivalent decrease in the levelised cost of the produced hydrogen (Supplementary Fig. 1).

This work introduces a unique concept of water electrolysis that promises notably reduced CAPEX and OPEX compared to conventional water electrolysers, making renewable hydrogen more cost-competitive with fossil fuels.

Inspired by the historic evolution of water electrolysis cells, which recently culminated in asymmetric polymer electrolyte membrane (PEM) cells that directly produce one of the gases in a gas collection chamber rather than bubbling through the liquid electrolyte[8], we have developed a capillary-fed electrolysis (CFE) cell concept in which both gases are produced directly in gas collection chambers (Fig. 1). The aqueous electrolyte is constantly supplied to the electrodes by a spontaneous capillary action in the porous, hydrophilic, inter-electrode separator. The bottom end of the separator is dipped in a reservoir, resulting in capillary-induced, upward, in-plane, movement of electrolyte. Porous gas diffusion electrodes are held against opposite sides of the separator, above the level of the electrolyte. The electrodes draw in liquid laterally from the separator and are covered with a thin layer of the electrolyte. The application of sufficient voltage between the electrodes results in the electrolysis of water, which is continuously replenished by water moving up the separator from the reservoir. Because the generated hydrogen and oxygen gases readily migrate through the thin layer of liquid electrolyte covering their respective electrodes, the capillary-fed cell concept provides for bubble-free electrolysis in which water is converted directly to the bulk gases without forming gas bubbles[9–13].

In so doing, the cell avoids bubbles masking the electrodes and maintains access to the catalytic sites on the electrodes. This includes access to the most active crevice, cleft and defect sites that are the first to be blocked by bubble formation, sometimes permanently so[14]. It also ensures that water flow to an electrode does not counteract gas flow away from the electrode, thereby avoiding the counter multiphase flows inherent in conventional water electrolysers and their associated mass transport limitations. In diminishing the energy needed to overcome such inefficiencies, the capillary-fed cell realises significantly improved energy efficiency.

It is also important to assess whether new cell configurations increase or decrease the complexity (i.e. the energy consumption and CAPEX) of the balance-of-plant. In the case of CFE cells, notable simplifications in the balance-of-plant are apparent. The absence of gas bubbles and associated gas-liquid froth formation

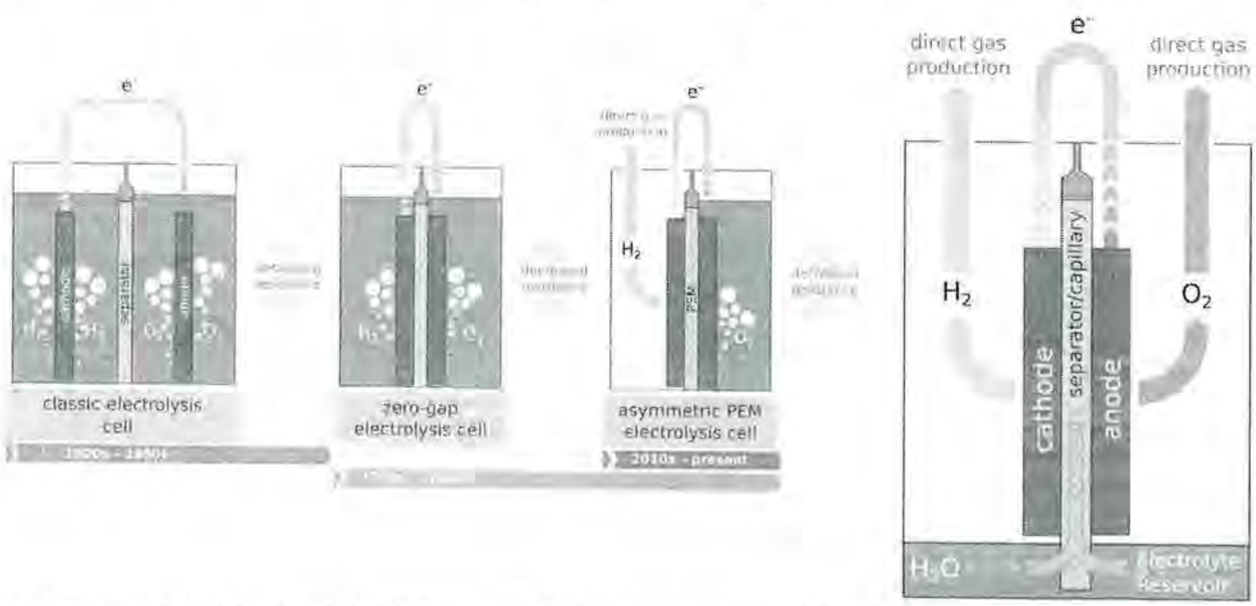


Fig. 1 Conceptualisation of the Capillary-Fed Electrolysis (CFE) cell. Inspired by the historic evolution of water electrolysis cell architectures culminating in the direct production of one of the gases, the Capillary-Fed Electrolysis cell directly produces both gases. Liquid electrolyte is continuously drawn up the separator by a capillary effect, from a reservoir at the bottom of the cell. The porous, hydrophilic separator sustains the flow rate required for water electrolysis.

in the cell stack, removes the need for liquid circulation, eliminating the gas-liquid separator tanks normally required and their piping, pumps, and fittings (Supplementary Figs. 2–3). The high energy efficiency, further, permits air-cooling, or radiative self-cooling, eliminating need for water-cooled chillers (Supplementary Tables 1–2). The small volumes of liquid electrolyte in each cell reservoir decrease the overall volume of water required (Supplementary Table 3). Unwanted and wasteful shunt currents found in conventional alkaline water electrolysers, may also be avoided. These simplifications in the balance-of-plant lead to downward pressure on electrolyser CAPEX.

The capillary-induced flow of aqueous 27 wt% KOH electrolyte up a saturated, hydrophilic, porous, polyether sulfone (PES) separator is initially measured and modelled, demonstrating its ability to indefinitely support water electrolysis at 1 A cm^{-2} and ≥80 °C for a height of up to 18 cm. This height restriction, which is created by gravity, is taken into account here, although it may in future be avoided by locating the reservoir at the top of the separator.

In this work we show that a capillary-fed cell, employing a known NiFeOOH oxygen evolution electrocatalyst on the anode and Pt/C hydrogen evolution electrocatalyst on the cathode, tested at 80–85 °C with 27 wt% KOH electrolyte, yields water electrolysis with performance that exceeds conventional, bubbled control cells, and commercial alkaline and PEM cells. Faradaic efficiencies approach 100%, with low gas crossover. Cell energy efficiencies at 85 °C of 95% (HHV) at 0.8 A cm^{-2} and 100% (HHV) at 0.3 A cm^{-2} (39.4–41.6 kWh kg^{-1} H_2) surpass the IRENA 2050 target and combine with the promise of a simplified balance-of-plant to bring cost-competitive renewable hydrogen closer to reality.

Results

Model for in-plane capillary-induced transport of a liquid through a porous material. The starting point for modelling of in-plane transport of a liquid within a porous material under a capillary action, is the Hagen–Poiseuille equation, to which a term for tortuosity (τ) was added to reflect the actual distance travelled by the liquid [Eq. 1]:

$$Q = \frac{n\pi r^4 \Delta P}{8\tau\mu L} \quad (1)$$

where Q is the flow rate, n is the number of capillaries of radius r, ΔP is the pressure drop, μ is the viscosity of the liquid, and L is the length of the porous material.

Equations for porosity, and for the tortuosity of porous membranes[15], as well as the Young–Laplace equation, are shown below:

$$\varepsilon = \frac{n\pi r^2}{A} \quad (2)$$

$$\tau = \frac{(2-\varepsilon)^2}{\varepsilon} \quad (3)$$

$$\Delta P = \frac{2\gamma cos\theta}{r} \quad (4)$$

where ε is porosity of the porous material, A is the cross-sectional area of the porous material, γ is the surface tension of the liquid, θ is the contact angle of the liquid on the material that comprises the porous material, and r is the average pore radius of the porous material.

Substituting Eqs. (2), (3), and (4) into (1) yields:

$$Q = \frac{\varepsilon^2 Ar\gamma cos\theta}{4(2-\varepsilon)^2 \mu L} \quad (5)$$

Eq. (5) permits a first-principles calculation of the capillary-induced rate of in-plane transport of a liquid (e.g. an aqueous KOH electrolyte) through a thin porous material using measurable or known quantities.

Capillary-induced, in-plane transport of aqueous KOH electrolyte within porous polyether sulfone (PES) filters. A search was undertaken to identify potential inter-electrode separators that could draw up aqueous KOH electrolyte by a capillary action. This led to a series of commercially available porous, hydrophilic polyether sulfone filtration membranes that were specified as having average pore diameters of 0.45 µm, 1.2 µm, 5 µm, and 8 µm. Each was characterised for its capacity to draw up a 27 wt% aqueous KOH solution from a reservoir by capillary action. This electrolyte closely represents, at 20–80 °C, the 6 M KOH that has historically been used in industrial alkaline electrolysers. The capillary flow rates at different heights, when the filter was full of liquid, were measured (as described in the Method section and in Supplementary Fig. 4). A linear flow regime, termed Darcy flow, is observed. A dry filter filling itself for the first time exhibits non-linear Washburn flow (Supplementary Fig. 4).

Figure 2a shows the capillary-induced, in-plane, Darcy flow rates of the polyether sulfone filters at room temperature. Modelled flow rates, using Eq. (5), showed reasonable agreement with the measured flow rates (Source Data—Figs. 2–4). The contact angle (70.3°) was measured with the captive bubble technique; literature values provided surface tension and viscosity[16,17].

The flow rates can be seen to decline with increasing height and with smaller pores. The polyether sulfone filter having 8 µm average pore diameter demonstrated the highest flow rates (Fig. 2a(i)) and was selected for further use. If employed as an inter-electrode separator, this filter has a modelled flow rate at room temperature sufficient to indefinitely support capillary-fed water electrolysis at 0.5 A cm^{-2} up to a height of at least 15 cm (lower dotted line in Fig. 2a(i)). Modelling using Eq. (5), indicated that at ≥80 °C, water electrolysis at 1 A cm^{-2} could be supported up to at least 18 cm in height (upper dotted line in Fig. 2a(i)), permitting the construction of water electrolysis cells with practical height.

Pore structure, porosity, and the ionic resistance of the polyether sulfone (PES) separator. Further investigations of the polyether sulfone separator with 8 µm average pore diameter revealed it to have a porous, open structure. Figure 2b depicts SEM micrographs of its cross-section and two sides, one of which had a gloss, and the other a matte appearance. It was found to be 80% porous (see the Methods section).

The ionic resistance of the polyether sulfone filter, when filled with 27 wt% KOH, was measured as described in Supplementary Fig. 5. Table 1 compares its ionic resistance at room temperature with those of separators typically used in commercial alkaline (Zirfon PERL UTP 500)[18] and PEM electrolysis cells (Nafion™ 115 and Nafion™ 117)[19]. All of these ionic resistances include the resistance of electrolyte incorporated within them. The polyether sulfone separator displayed 244 mΩ cm^2 lower ionic resistance than Zirfon PERL UTP 500, due to its lesser thickness and higher porosity. Its ionic resistance was also 174 mΩ cm^2 less than Nafion™ 117 and 96 mΩ cm^2 less than Nafion™ 115. The low ionic resistance of the PES separator compared to commercial separators contributes to the high energy efficiency of the capillary-fed cell described below.

Capillary-fed electrolysis cell outperforms conventional and commercial water electrolysis cells. To evaluate the CFE cell concept, a test cell was fabricated using the polyether sulfone filter with 8 µm average pore diameter, as the electrode separator.

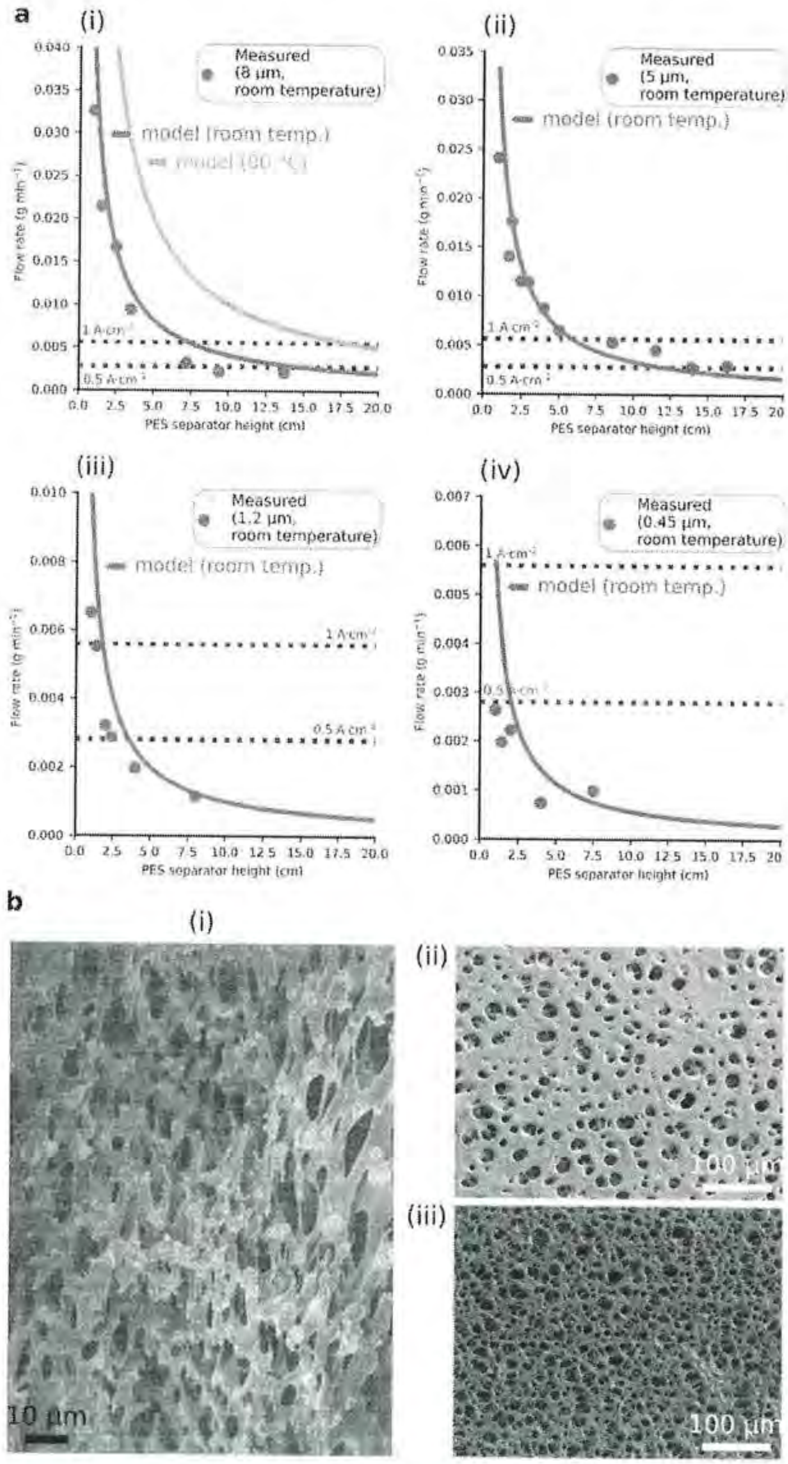


Fig. 2 Capillary-fed inter-electrode separator. a Flow rates at different heights inside a capillary-fed inter-electrode separator. Measured (data points) and modelled (blue line) flow rates (Darcy flow), at room temperature, of 27 wt% aqueous KOH within polyether sulfone (PES) separators that were specified as having average pore diameters of: (i) 8 µm, (ii) 5 µm, (iii) 1.2 µm, and (iv) 0.45 µm. The measured data was obtained as described in the Methods section and Supplementary Fig. 4. The modelled data was obtained as described in the text. The orange line in (i) depicts the modelled flow at 80 °C. The dotted lines show the rate of water consumption by a 1 cm^2 water electrolysis cell operating at 0.5 A cm^{-2} (lower dotted line) and 1 A cm^{-2} (upper dotted line). The capillary-induced flow rate within the 8 µm polyether sulfone separator is sufficient to supply water electrolysis at 0.5 A cm^{-2} at a height of 15 cm at room temperature, and at 1 A cm^{-2} at a height of 18 cm at 80 °C. **b** Pore structure of the polyether sulfone separator. Scanning electron micrographs of the polyether sulfone filter, showing: (i) its structure in cross-section, and (ii) its gloss surface and (iii) its matte surface.

Table 1 Ionic resistance of separators at room temperature.

Separator	Electrolyte	Thickness (µm)	Porosity (%)	Ionic Resistance (mΩ cm²)
PES (8 µm)	27 wt% KOH	140	80	46
Zirfon PERL UTP[18]	30 wt% KOH	500	55	290
Nafion 115[19]	Hydrated	125	0	142
Nafion 117[19]	Hydrated	183	0	220

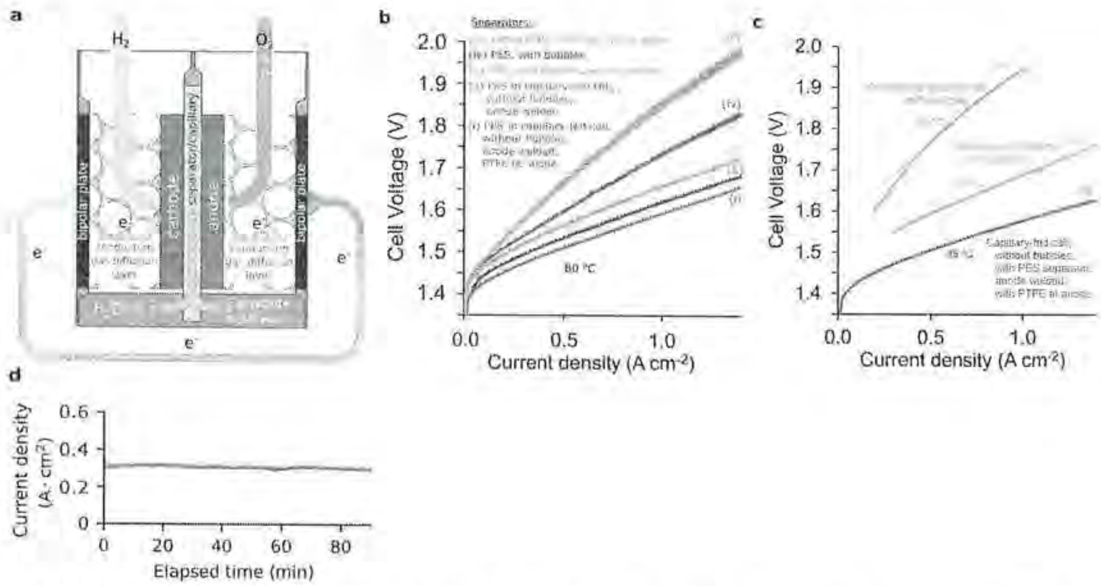


Fig. 3 Capillary-fed electrolysis cell. a Schematic depiction showing how the bipolar plate and conducting gas diffusion layer in the capillary-fed cell were combined into a single bipolar plate structure that comprised a sheet of Ni with many small holes to allow evolved gases to exit the electrode. The anode electrode was welded to its bipolar plate. The cathode was compressed against its bipolar plate and not welded. Supplementary Fig. 6 provides a picture of the cell used. **b** Polarisation curves of capillary-fed electrolysis cell and controls (80 °C). Plots of (2-electrode) cell voltage vs. current density, from bipolar plate to bipolar plate across the cell, excluding cathodic oxygen depolarisation, of cells with identical NiFeOOH anodes and Pt/C cathodes, at 80 °C, of: (i) Capillary-fed cell with PTFE at the anode, (ii) Capillary-fed cell without PTFE at the anode, (iii) control, conventional, bubbled cell with Zirfon PERL UTP 500 as inter-electrode separator, (iv) control, conventional, bubbled cell with polyether sulfone filter (8 µm average pore diameter) as inter-electrode separator, and (v) control, conventional, bubbled cell with polyether sulfone filter (8 µm average pore diameter) as inter-electrode separator, where the anode is welded to its bipolar plate. **c** Comparison of capillary-fed electrolysis cell (85 °C) with commercial alkaline and PEM electrolysis cells (90 °C) representative of the state-of -the-art. Polarisation curves of: (i) the capillary-fed electrolysis cell with PTFE at the anode at 85 °C, (ii) commercial alkaline electrolysis cell at 90 °C [24] representative of the state-of-the-art, and (iii) commercial PEM electrolysis cell at 90 °C[20] representative of the state-of-the-art. **d** Performance of capillary-fed electrolysis cell at a fixed 100% energy efficiency (HHV) (85 °C). (i) Current density at 85 °C of the capillary-fed electrolysis cell in Fig. 3c(i) when poised at a fixed cell voltage of 1.47 V, which equates to 100% energy efficiency (HHV). Supplementary Fig. 10 provides data from 1-day and 30-day tests at 80 °C and room temperature, with a large reservoir that was regularly manually replenished.

Figure 3a depicts a schematic of the cell. Polyether sulfone filters of much smaller pore diameter have been previously tested as inter-electrode separators in water electrolysis cells[21,22].

In commercial systems, bipolar plates are normally employed to carry current into and out of electrolysis cells. Within a cell, each bipolar plate connects electrically to their corresponding electrode via a conducting gas diffusion layer (also called a porous transport layer in PEM electrolysis cells) (Fig. 3a). The present work sought to replicate this arrangement to make fair comparisons with commercial cells. This was done by combining the bipolar plate and conducting gas diffusion layer into a thick sheet of Ni with many small holes to allow evolved gases to exit (Supplementary Fig. 6). This bipolar plate/flow field structure was housed within a gas chamber that could be sealed to the external environment. Leak-tight bolts through the walls of the gas chambers were used to press the bipolar plates and their attached electrodes against the polyether sulfone separator (Supplementary Fig. 6). The gas chambers were flushed with nitrogen prior to operation.

For the anode, a fine Ni mesh was electrocoated with a NiFeOOH electrocatalyst, as previously described by Benedetti and colleagues[23] and then spot-welded to its bipolar plate, without loss of catalyst, using the approach depicted in Supplementary Fig. 7. No carbon was present in the anode to avoid oxidative carbon corrosion currents, which can lead to highly misleading results.

In some cells, a 60 wt% dispersion of polytetrafluoro-ethylene (PTFE, also known as Teflon™) was included in the electrocoating solution. Catalyst coatings from the resulting solution were found to display enhanced anode performance.

For the cathode, a Pt/C electrocatalyst was deposited as previously described by Liu et al.[24], to a loading of 0.5 mg cm^{-2} Pt on a conducting, carbon paper gas diffusion layer. As the carbon paper could not be welded, the cathode was pressed tightly against its bipolar plate as described in Supplementary Fig. 6. The structure of the cathode is described in detail in Supplementary Note 3.

Table 2 Performance at 85 °C of the capillary-fed electrolysis cell with PTFE at the anode.

Current density (A cm^{-2})	Cell voltage (V)	Energy efficiency (HHV) (%)	Energy consumption	
			(kWh kg^{-1} H_2)	(kWh Nm^{-3} H_2)
0.294	1.470	100	39.4	3.55
0.500	1.506	98	40.4	3.64
0.800	1.551	95	41.6	3.75
1.000	1.575	93	42.2	3.80

Two-electrode measurements, including the polarisation curves, were recorded between the anodic and cathodic bipolar plates, across the cell, as they would be in a commercial cell. The electrolyte was 27 wt% aqueous KOH.

The current densities reported here are relative to the geometric area of the electrodes that were covered with electrocatalysts. Prior to testing, the current produced by the metal structures in the cell that were not coated with catalyst, was determined by operating the cell without catalysts, with and without the gas chambers filled with air. Currents of <0.025 A cm^{-2} were observed up to a cell voltage of 2.1 V.

With catalysts, and with the gas chambers initially filled with air, oxygen depolarisation of the cathode occurred only up to 0.030 A cm^{-2}, whereafter hydrogen production overwhelmed oxygen ingress (Supplementary Fig. 8).

The CFE cell with the above electrodes and polyether sulfone separator was then tested at 80 °C, giving the current-voltage curves in Fig. 3b(i) (with PTFE in the anode) and Fig. 3b(ii) (without PTFE in the anode) (Source Data—Figs. 2–4). As can be seen in Fig. 3b(i), with PTFE incorporated in the anode, the cell required a voltage of 1.59 V to drive water electrolysis at 1 A cm^{-2}. Without PTFE in the anode, 1.61 V was needed at 1 A cm^{-2} (Fig. 3b(ii)).

For comparative purposes, and to investigate changes in the cell resistance, identical zero-gap water electrolysis cells that were fully flooded with liquid electrolyte, causing them to produce gases in the form of bubbles, were also prepared. These control cells employed the same cathode and anode (without PTFE) as above, with 27 wt% KOH. They were tested at the same temperature of 80 °C.

With the well-known commercial alkaline separator, Zirfon PERL UTP 500, the resulting, bubbled control cell required 1.86 V to produce 1 A cm^{-2} (Fig. 3b(iii)).

When the Zirfon was replaced with the polyether sulfone separator, the cell needed 1.74 V at 1 A cm^{-2} (Fig. 3b(iv)), which was 0.12 V lower. This equates to a decrease in the cell resistance of 120 mΩ cm^2, which can be almost entirely attributed to the lower ionic resistance of the polyether sulfone separator compared to Zirfon PERL UTP 500 at 80 °C (Supplementary Fig. 5).

Following operation, a contact resistance was found to have developed between the anode and its bipolar plate. This contact resistance was due to the formation of a layer of poorly conducting Ni oxide on the contacting Ni surfaces by the oxygen produced at the anode.

To overcome this contact resistance, the control cell with the polyether sulfone separator, was modified by welding its anode to its corresponding bipolar plate. The anodes of the capillary-fed cells had been welded to their bipolar plates for the same reason. The effect was to decrease the voltage required at 1 A cm^{-2} to 1.66 V (Fig. 3b(v)), which equates to a further decline of 0.08 V and an 80 mΩ cm^2 lower cell resistance. This result is relevant insofar as some commercial water electrolysis cells still employ compression to create electrical contact[2], rather than welding, which is routinely used in other types of electrolysis cells[25].

The contact resistance between the cathode and its bipolar plate after operation was separately measured to be a much lower 3–5 mΩ cm^2. The reducing environment of the cathode avoids formation of poorly conducting surface layers.

Accordingly, the capillary-fed cell in Fig. 3b(i) significantly outperformed its conventional, bubbled, control cells employing the same electrodes and electrolyte in an identical zero-gap configuration.

The performance of the above CFE cell with PTFE at the anode, was also compared with data from commercial alkaline and PEM electrolysis cells representative of the current state-of-the-art[20,26]. As the commercial data had been collected at a higher temperature of 90 °C, the CFE cell was tested at 85 °C.

As can be seen in Fig. 3c, the CFE cell substantially outperformed the commercial cells. It improved on alkaline cells, which are typically operated commercially[2] at ~0.2–0.8 A cm^{-2}. It also improved on commercial PEM cells, which must be operated at higher current densities in the 1.5–3.0 A cm^{-2} range to be commercially viable[20].

To produce typical commercial operating current densities of 0.5 A cm^{-2} for alkaline and 1.8 A cm^{-2} for PEM, the commercial cells required ~1.77 V (Fig. 3c(ii)–(iii)), equating to a cell energy efficiency of ~83% (HHV) and an energy consumption of ~47.5 kWh kg^{-1} H_2. By contrast, the alkaline CFE cell required only 1.506 V at 0.5 A cm^{-2} (Fig. 3c(i)), which represents a cell energy efficiency of 98% (HHV) with consumption of only 40.4 kWh kg^{-1} H_2, or 3.64 kWh Nm^{-3} H_2 (Table 2). The ~7.1 kWh kg^{-1} decrease in energy consumption surpasses the IRENA 2050 target[2] of <42 kWh kg^{-1} and realises a 15% improvement in cell energy efficiency.

When held at the thermoneutral voltage for water electrolysis, 1.47 V at 85 °C, which equates to 100% energy efficiency (HHV), the capillary-fed cell produced a constant ~0.3 A cm^{-2} (Fig. 3d). As far as the authors are aware, no water electrolysis cell, either alkaline or PEM, has ever produced 0.3 A cm^{-2} at 100% energy efficiency (HHV).

The CFE cell also demonstrated sustained stable performance over extended periods from 1 working day to 30 days continuously at 80 °C and room temperature, respectively, with periodic replenishment of the consumed water to the reservoir (Supplementary Fig. 10). Water spontaneously migrated from the reservoir up the separator, possibly under an osmotic as well as a capillary impulse to counteract increases in the KOH concentration in the separator due to water consumption at the electrodes. No KOH build up or crystallisation was observed in or on the separator.

The origin of the high performance of the capillary-fed electrolysis cell. The unprecedented performance of the CFE cell in Fig. 3b(i) and Fig. 3c(i) may be explained in part by the well-known high activity of the NiFeOOH anode electrocatalyst[25,27–30] and Pt/C cathode electrocatalyst, and the low ionic resistance of the polyether sulfone separator (Table 1).

Galvanostatic electrochemical impedance spectroscopy could be used to determine the resistances in the capillary-fed cell under active water electrolysis, but not their origin. For example, at 0.35 A cm^{-2} and 80 °C, the cell demonstrated a series resistance of ~40 mΩ cm^2 that was mainly but not completely attributable to the low ionic resistance of the polyether sulfone separator (Supplementary Fig. 11).

To elucidate the major elements that contributed to the high performance of the CFE cell at 80 °C, the control, conventional, bubbled cell with Zirfon PERL UTP 500 separator (Fig. 3b(iii))

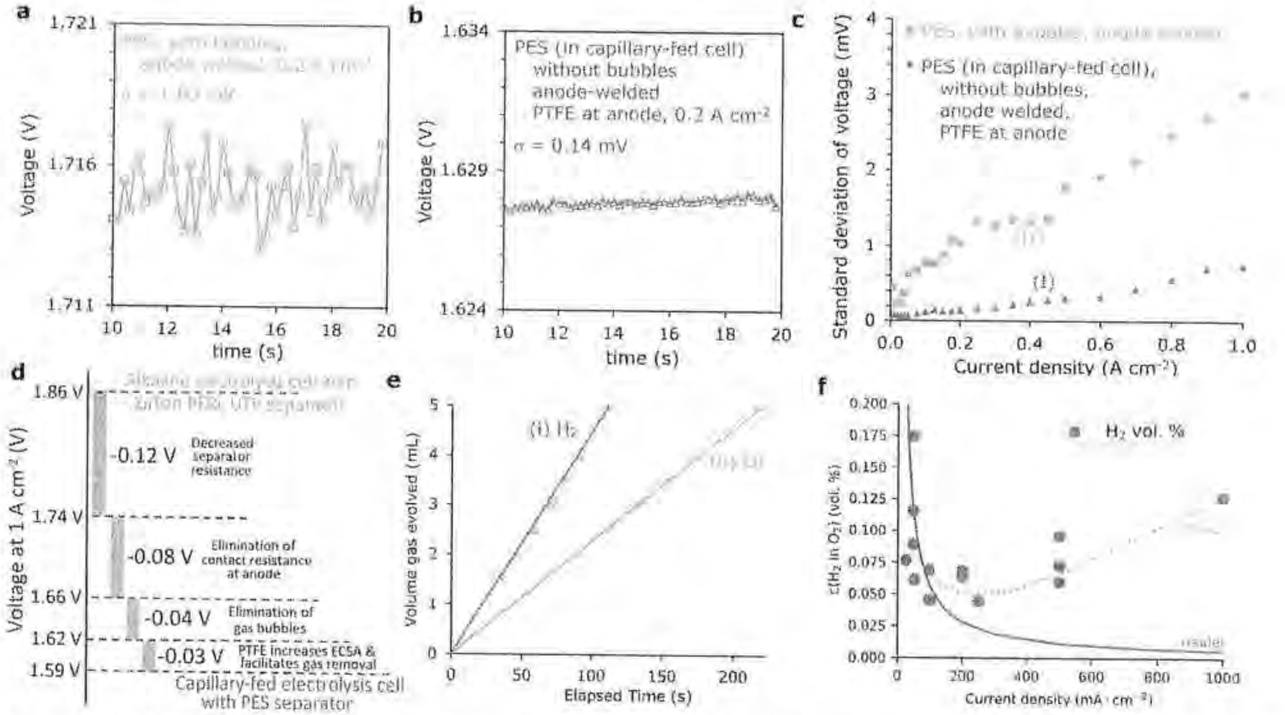


Fig. 4 Capillary-fed electrolysis cell characterisation. (At room temperature with 27 wt% KOH unless stated otherwise). **a** Voltage profile due to bubble formation. Voltage fluctuations in the bubbled, control cell in Fig. 3b(v) over the last 10 s of a 20 s step at 0.2 A cm^{-2} (σ = standard deviation). **b** Voltage profile in the capillary-fed cell. Voltage fluctuations in the cell in Fig. 3b(i) over the last 10 s of a 20 s step at a fixed 0.2 A cm^{-2}. **c** Voltage profile uniformity as a function of current density. Plot of the standard deviation in voltage for the cells in: (I) Fig. 3b(i), and (II) Fig. 3b(v), at different current densities, each held for 20 s, with the standard deviation measured over the last 10 s of the 20 s period. The bubbled control cell in Fig. 3b(v) displays much larger fluctuations in voltage due to bubble formation than the capillary-fed cell in Fig. 3b(i), which exhibits largely bubble-free operation at ≤0.2 A cm^{-2}, and substantially bubble-free operation at 0.25-1 A cm^{-2}. **d** Voltage declines and their origins. Waterfall plot showing the voltages declines observed at 1 A cm^{-2} (80 °C) and their sources. **e** Faradaic efficiency. Rates of: (i) hydrogen generation, and (ii) oxygen generation by the capillary-fed electrolysis cell in Fig. 3b(i), at a fixed 0.350 A/cm^2 at atmospheric pressure, after 30 min. The data points indicate the measured volumes. The solid lines plot the theoretical rate of gas generation at 100% Faradaic efficiency. The overall Faradaic efficiency of the cell, determined by comparing the slopes of the measured and theoretical data, including both gases, was 99.5 ± 1.3%. **f** Hydrogen crossover. The data points show the hydrogen crossover into the anodic oxygen stream of the capillary-fed electrolysis cell in Fig. 3b(i) as a function of current density, at room temperature and atmospheric pressure. Each data point was collected after operating the cell for 30 min at the relevant current density. The solid line shows the gas crossover expected from diffusion only[31, 32]. The dashed line depicts the trend in the data.

was therefore taken as a baseline. That cell needed 1.86 V to generate 1 A cm^{-2} (Fig. 3b(iii)).

When the Zirfon was replaced with the polyether sulfone separator, the voltage required at 1 A cm^{-2} was 1.74 V (Fig. 3b(iv)), which was 0.12 V less. As noted, the resulting 120 mΩ cm^2 reduction in resistance is almost all due to the lower ionic resistance of the polyether sulfone separator.

The effect of welding the anode of the bubbled cell with the polyether sulfone separator, to its bipolar plate was to further decrease the voltage needed at 1 A cm^{-2} to 1.66 V (Fig. 3b(v)). The resulting 80 mΩ cm^2 decrease in resistance arose by elimination of a contact resistance that developed between the anode and its bipolar plate during operation.

The CFE cell achieved still lower voltages. Without PTFE at the anode, it required a cell voltage of 1.62 V at 1 A cm^{-2} (Fig. 3b(ii)), which is 0.04 V lower, equating to a further 40 mΩ cm^2 decrease in resistance.

With PTFE at the anode, the capillary-fed cell required only 1.59 V at 1 A cm^{-2} (Fig. 3b(i)), which constituted a still further decrease of 0.03 V, with an additional lowering in cell resistance of 30 mΩ cm^2.

These improvements may be attributed to the combined contribution of several possible factors, including the following.

Firstly, the CFE cells were largely bubble-free during operation. This was confirmed by comparing voltage fluctuations due to bubble formation and release at a series of fixed current densities[12]. Fig. 4a and b show the results and analysis of steady-state chrono-potentiometric measurements of the bubbled control cell in Fig. 3b(v) and the capillary-fed cell in Fig. 3b(i), respectively, over the last 10 s of a 20 s period at 0.2 A cm^{-2}. The voltage of the bubbled cell (Fig. 4a) (Source Data—Figs. 2–4) was characterised by a noisy response attributable to the nucleation, growth, coalescence, and release of gas bubbles. The standard deviation (σ) of the voltage signal for the bubbled cell was 1.03 mV. By contrast, the voltage of the capillary-fed cell under the same conditions was remarkably steady (Fig. 4b), with a significantly lower σ of 0.14 mV. The steady voltage signal and low σ value of the capillary-fed cell is consistent with bubble-free operation.

Steady-state chrono-potentiometric measurements of bubbled and capillary-fed cells over a range of current densities from 0.01 to 1 A cm^{-2} and analysis of the results permitted the construction of the standard deviation vs. current density plot in Fig. 4c. The bubbled cell demonstrated a relatively steep increase in σ values commencing from the lowest current density of 0.01 A cm^{-2}. By contrast, the capillary-fed cell had much lower and flatter σ values between 0.01 and 0.2 A cm^{-2}, before the σ values increased modestly as the current density was raised to 1 A cm^{-2}. The results suggest that the capillary-fed cell was largely bubble-free up to and including 0.2 A cm^{-2}, and substantially bubble-free between 0.25 and 1 A cm^{-2}. At 1 A cm^{-2}, the capillary-fed cell displayed a σ value of 0.75 mV, which was comparable to the bubbled cell at ~0.09 A cm^{-2}, suggesting that <10% of the current went into gas production via bubble formation (Supplementary Fig. 9).

These findings are supported by the fact that the performance of the capillary-fed cell in Fig. 3c(i) mainly differed from the commercial PEM cell in Fig. 3c(iii) in having a lower onset potential; the slopes of the curves were similar. Previous studies have demonstrated that bubble-free operation decreases the onset potential[10,11,13]. The bubble-producing cells in Fig. 3b(iii)–(v) had onset potentials of ≥1.45 V, while that of the capillary-fed cell in Fig. 3b(i) was ~1.39 V.

Bubble-free gas evolution likely contributed to the voltage decline insofar as the electrodes were not masked with bubbles, leaving the catalytic sites on the electrodes more available for reaction. This probably enhanced the overall performance of, particularly, the most active catalytic sites that are the source of most bubbles and the first to be blocked by bubbles. The resulting fuller use of the available electrocatalytic sites likely improved performance.

The avoidance of bubble formation at ≤0.2 A cm^{-2}, which was likely due to the gas-liquid interface being within diffusion distance of the electrode, may also have decreased the supersaturation of the electrolyte, leading to a voltage decline[10,13]. According to the Nernst equation, elevated gas concentrations increase E^{o}[33]. At higher current densities, supersaturation may have been needed at some electrode locations to produce the few bubbles observed.

The architecture of the capillary-fed cell may also have contributed insofar as it ensured that the flow of water toward each electrode did not counter the flow of gas away from the electrode. That is, the architecture of the capillary-fed cell inherently avoided the counter multiphase flows present in conventional, bubbled water electrolysers.

At this stage it is not possible to determine the absolute contribution of each of the above factors, but cumulatively they resulted in a 40 mΩ cm^2 lower resistance in the capillary-fed cell without PTFE at the anode (Fig. 4d).

With PTFE at the anode, additional improvements were realised in the capillary-fed cell (Fig. 3b(i)). Electron micrographs indicated that the PTFE was dispersed as needle-like structures on the anode (Supplementary Fig. 12). The double layer capacitance of the anode increased by ~12-fold, from 0.46 mF cm^{-2} without PTFE to 5.50 mF cm^{-2} with PTFE (Supplementary Fig. 13). This suggests that the electrochemically/catalytically active surface area (ECSA) of the anode increased significantly. As the specific capacitance of the catalyst with PTFE is not known, the precise scale of the increase could not be determined. However, the PTFE clearly increased the porosity of the electrocatalytic layer and this increased the ECSA.

A body of previous work has also demonstrated that PTFE surfaces on an electrocatalyst may scavenge, coalesce and transport away newly formed, dissolved gases[34]. PTFE is highly aerophilic, with low surface energy. A similar mechanism may have been partly responsible for the improved, bubble-free performance of the anode when PTFE was incorporated. That is, the PTFE on the anode may have amplified the catalytic performance by facilitating migration of newly formed gas along its aerophilic surfaces, across the gas-liquid interface, to thereby avoid gas bubble formation. As described in Supplementary Note 3, it is potentially significant that the same elements of aerophilic PTFE surface pathways for gas transport across the gas-liquid interface were also present on the cathode, which exhibited similarly bubble-free performance.

Whatever the origin of the improved performance, the incorporation of PTFE in the anode contributed a decrease in voltage of 0.03 V at 1 A cm^{-2}, equating to a decline in resistance of 30 mΩ cm^2 (Fig. 4d).

In summary, the capillary-fed cell continues the evolution of water electrolysis cells by systematic decreases in cell resistance, as illustrated in Fig. 1. However, the large net decrease realised did not have a single origin. It involved many smaller contributions that, cumulatively, led to a 270 mΩ cm^2 reduction in cell resistance at 80 °C, over the standard commercial configuration of a bubbled, zero-gap cell with a Zirfon PERL UTP 500 separator (Fig. 4d).

Faradaic efficiency approaching 100%, and low hydrogen crossover. The Faradaic efficiency and gas crossover are important features of electrolysis cells. The latter is a potential safety issue as a hydrogen stream containing >4.6% oxygen, or an oxygen stream with >3.8% hydrogen, constitutes an explosive mixture (at 80 °C)[10].

The volumes of hydrogen and oxygen produced by the best performing capillary-fed cell at a fixed 0.35 A cm^{-2} were measured (Fig. 4e). There was a close agreement between the measured volumes and what would be expected if all electrons went into water electrolysis, giving an overall Faradaic efficiency, including both gases, of 99.5 ± 1.3% (Source Data—Figs. 2–4).

To measure the extent of hydrogen gas crossover, the CFE cell with PTFE at the anode was connected to a gas chromatograph and measurements were taken of the hydrogen impurity in the anodic oxygen stream. Figure 4f shows the concentration of hydrogen in the anodic oxygen stream as a function of current density. These results, which fell between 0.04 and 0.14 vol% at 0.1–1.0 A cm^{-2}, are notably lower than reported rates of hydrogen crossover with conventional separators (Supplementary Table 5).

The oxygen impurity in the cathodic hydrogen stream was similarly examined, however no crossover could be observed within the detection limit of 0.001 vol% (10 ppm).

The low crossover of the capillary-fed cell may be ascribed to a different and unique mechanism of gas crossover.

In fully flooded, bubbled alkaline electrolysis cells, gas crossover is known to occur in two ways[34,35]: (1) diffusion of dissolved gas through the liquid in the separator, and (2) advective flow of liquid electrolyte, carrying dissolved gas and bubbles with it, through the porous separators that are generally used. The latter is driven by fluctuating or perpetual pressure differentials across the separator, and is, by far, the larger contributor, producing orders of magnitude more crossover[35,36]. To decrease the advective cross flow of electrolyte, separators in alkaline electrolysis are designed to have the smallest possible pores (<0.15 μm diameter)[35]. The rate of diffusion-based crossover in alkaline cells is exceedingly low because the high levels of K^+ and OH^- ions in alkaline electrolytes salt-out dissolved gases like hydrogen and oxygen, which have very low solubilities and diffusion coefficients in alkaline electrolytes[31,32].

In PEM electrolysis cells, the proton exchange membranes are non-porous. This eliminates advective flows as a significant mechanism of gas crossover since the de-ionised water used in such cells is unable to freely pass through the membrane[36,37]. The only available mechanism of gas crossover is diffusion[3]. The combined solubility and diffusion coefficients of hydrogen and oxygen are, however, 40–120-times higher in de-ionised water than in typical alkaline electrolytes at 80 °C[31,32,36]. While advective crossover is absent in PEM cells, diffusion-based crossover, with balanced hydrogen and oxygen pressures on opposite sides of the PEM membrane, is therefore usually notably larger than in alkaline systems (Supplementary Table 5)[36–38]. The industry has overcome this issue by using very high hydrogen pressures but only atmospheric oxygen pressures on the opposite sides of the PEM membrane. This maintains the produced hydrogen free of oxygen impurity[37].

The CFE cells are in the unique position of avoiding advective crossover, whilst also having low diffusion-based crossover because of the high molarity alkaline electrolyte used.

Advective crossover is not available as a mechanism of crossover in capillary-fed cells since there are no unrestricted bodies of liquid electrolyte on both sides of the separator that are free to flow through it under the influence of a pressure differential. That is, only diffusion-based crossover is possible. However, a high molarity alkaline electrolyte is used, and this provides for only a small diffusion-based crossover.

This explanation is supported by the fact that, whereas separators in conventional, fully flooded, bubbled alkaline electrolysis cells can only minimise crossover by having very small pores (<0.15 μm), the capillary-fed cell has the largest of the available pores (8 μm) but still exhibits minor gas crossover.

It is further supported by the observation in Fig. 4b, that, at current densities of $\leq 0.2\,A\,cm^{-2}$, the measured rates of gas crossover lie within the range expected for diffusion only, which is depicted as the solid line. At current densities above $0.2\,A\,cm^{-2}$ however, hydrogen crossover diverges from the diffusion-only model and trends moderately upward (Fig. 4f, orange dotted line). This is consistent with the observed minor bubble formation above $0.2\,A\,cm^{-2}$ in Fig. 4c, which may involve supersaturation at a few locations on the hydrogen-generating cathode[36]. Such localised supersaturation would create a partial pressure gradient resulting in moderately increased hydrogen crossover.

Simplification of the balance-of-plant. Capillary-fed electrolysis (CFE) cells may be readily incorporated into a bipolar cell stack of the type used in commercial electrolysers (Supplementary Fig. 2). The engineering system required to manage such a stack, known as the balance-of-plant, may then be compared with a typical, conventional balance-of-plant[13].

Supplementary Fig. 3 depicts this comparison. As can be seen, the balance-of-plant needed for the CFE cell concept (Supplementary Fig. 3b) is notably less complex than that needed for a conventional, bubbled electrolysis cell (Supplementary Fig. 3a).

There is, firstly, no need for pumped liquid circulation, or for gas/liquid separators, as there are no liquid-enveloped gas bubbles that need to be constantly swept away from the electrodes (Supplementary Fig. 3b). The gas-liquid froths that are generated when gas bubbles are produced must normally be pumped to separator tanks for partitioning into bulk liquid and gas phases (Supplementary Fig. 3a).

The high-volume electrolyte pumps (depicted below each separator tank in Supplementary Fig. 3a) are therefore also not needed, nor are their associated piping and fittings, namely, the anolyte and catholyte forward and return lines. Pumps and piping of this type are expensive because they need to avoid corrosion by KOH (in the case of an alkaline electrolyser) or leaching of metal ions into the de-ionised water used (in the case of a PEM electrolyser) and comply with stringent hydrogen or oxygen safety standards.

In a conventional balance-of-plant, de-ionised make-up water would typically be added to each electrolyte circulation loop, via the scrubbers, from a pressurised dispensing system (as shown at the top of Supplementary Fig. 3a). In the capillary-fed balance-of-plant, a comparable pressurised dispensing system would be needed to add de-ionised water to the individual reservoirs (as shown at the bottom of Supplementary Fig. 3b). Such arrangements are already used in the chlor-alkali industry, where make-up water and brine are routinely dispensed to individual half cells[39].

Another feature of conventional balance-of-plants are the need for water-cooled chillers to remove the excess heat produced during electrolysis (Supplementary Fig. 3a). The high energy efficiency of the capillary-fed cell produces only modest Joule heating during operation however, avoiding the need for a water-cooled chiller as demonstrated in Supplementary Note 1, Supplementary Tables 1–2, and Supplementary Data 1. Instead, air-cooling or radiative self-cooling of the stack may be possible.

Because of the need for large volumes of liquid to remove and separate the gas bubbles formed, conventional commercial cell stacks and their balance-of-plants typically contain ~10,000 L of water per MW. By contrast, as shown in Supplementary Note 2 and Supplementary Table 3, a, the CFE system is likely to require only ~500 L of water per MW.

One effect of a lower water requirement is a reduced need for water purification and replacement in the balance-of-plant. This is especially relevant to PEM electrolysers, which require on-going de-ionisation of the water content, using a costly class 1 de-ioniser, to achieve a stack lifetime of ~70,000 h. In alkaline electrolysers, only the input make-up water needs deionisation, with the entire body of liquid electrolyte typically needing replacement every 5–6 years[8].

A final advantage of the capillary-fed cell system is its capacity to avoid the wasteful and corrosive high voltage shunt currents[13] that flow between cells along the catholyte and anolyte return lines in conventional alkaline electrolysers. In the capillary-fed balance-of-plant, the only potential liquid conduction path between cells is along the water dispensing line shown at the bottom of Supplementary Fig. 3b. But this contains de-ionised water that is not conductive.

These simplifications in the balance-of-plant lead to downward pressure on electrolyser CAPEX. They may also lower the power consumption of the balance-of-plant, further decreasing the energy needed per kg hydrogen.

Discussion

This work introduced the CFE cell concept. Using existing catalysts, with Faradaic efficiencies approaching 100%, and low hydrogen crossover, this architecture significantly improved the energy efficiency of the water electrolysis cell. At the operating current density used in many commercial alkaline electrolysis cells of $0.5\,A\,cm^{-2}$, a cell voltage of only 1.506 V was needed to produce hydrogen at 85 °C. This represents a cell energy efficiency of 98% (HHV), with consumption of just $40.4\,kWh\,kg^{-1}\,H_2$, or $3.64\,kWh\,Nm^{-3}\,H_2$. This result surpasses commercial electrolysis cells, which consume ~$47.5\,kWh\,kg^{-1}\,H_2$, and exceeds the 2050 IRENA target[2] of <$42\,kWh\,kg^{-1}$.

The CFE cell also allows for a notably simplified balance-of-plant, further reducing energy consumption and putting downward pressure on CAPEX.

These substantial improvements on present-day state-of-the-art electrolysis cells translate to direct declines, of similar proportion, in the levelised cost of hydrogen. Combined with the promise of a simplified system balance-of-plant, they bring cost-competitive renewable hydrogen closer to reality.

Methods

Materials. Porous polyether sulfone (PES) filters of 0.03 μm, 0.45 μm, 1.2 μm, 5 μm, and 8 μm average pore diameters (Pall Corporation and Sterlitech), Carbon black (AkzoNobel), 10% Pt on Vulcan XC-72 (Premetek), $NiCl_2.6H_2O$ and $FeCl_2.4H_2O$ (Sigma-Aldrich), PTFE (60 wt.% dispersion in alcohols/H_2O; Sigma-Aldrich, 510211), Nafion™ dispersion (5% in in alcohols/water; Sigma-Aldrich), Sigracet™ 22BB carbon paper (Fuel Cell Store), Zirfon PERL UTP 500 (Agfa), KOH 90%, flakes (Sigma-Aldrich), Ni mesh (Century Woven, Beijing).

Porosity and in-plane flow model values. Porosity was determined by comparing the weight of dry and saturated polyether sulfone. Cross-sectional area was calculated by multiplying width (1 cm, nominal) by thickness (140 µm, measured). Average pore diameter was determined using capillary flow porometry. Contact angle was measured using the captive bubble technique. Viscosity[16] and surface tension[17] were obtained from the literature.

In-plane flow rate measurements. In-plane flow rates were measured using the setup shown in Supplementary Fig. 4(a). For each experiment a 1 cm-wide polyether sulfone microfiltration strip was encased in plastic sheathing of length L to avoid electrolyte evaporation; 1.5 mm at each end of the polyether sulfone strip was left exposed. To the top of the strip was clamped a pad composed of several layers of absorbent paper. The bottom of the strip was dipped in electrolyte. The weight of the assembly was measured over time. An example weight vs. time plot is provided in Supplementary Fig. 4(b) and shows an initial curved response corresponding to initial filling of the strip (Washburn flow), followed by a linear response corresponding to continuous flow through the fully wetted strip (Darcy flow). The in-plane flow rate was taken as the slope of the linear part of the weight vs. time plot.

Ionic resistance of polyether sulfone separator. The ionic resistance of the polyether sulfone separator was determined using a method described in the literature[40] and the setup shown in Supplementary Fig. 5. The conductivity of the KOH electrolyte was measured with and without a polyether sulfone separator present using a four-point conductivity probe (Mettler Toledo Sevencompact with Inlab ISM-731 Probe) as described in Supplementary Fig. 5.

Electrode preparation. The hydrogen-evolving cathode was prepared using a literature method[24]. 100 mg 10% Pt on Vulcan XC-72, 0.8 mL 5 wt% Nafion solution, 1.5 mL deionised water, and 3 mL iso-propanol were combined and sheared at 10,000 rpm for 5 min using a homogeniser (IKA T25). The resulting dispersion was air brushed onto the microporous layer side of a 1 cm × 1 cm carbon fibre paper (Sigracet 22BB) to a loading of 0.5 mg cm^{-2} Pt.

The oxygen-evolving anode was prepared following a literature method[23]. Prior to use, Ni mesh (200 LPI, ø 50 µm wire, 75 µm aperture) was cleaned by ultrasonication in isopropyl alcohol for 10 min and dried, then pickled in 5 M HCl for 10 min, rinsed with deionised water, and dried. After taping as shown in Supplementary Fig. 7, electrodeposition was performed at room temperature in a 3-electrode cell comprising 1 cm × 1 cm Ni mesh working electrode, oversized Ni mesh counter electrode, and Ag/AgCl (3 M NaCl) reference electrode. The nickel mesh was placed in an electrocoating solution that comprised of a 3:1 mixture of $NiCl_2.6H_2O$ (0.075 M) and $FeCl_2.4H_2O$ (0.025 M) (following Fig. 8(c) and Fig. 1(a) in ref. [23]), along with 1 M KCl supporting electrolyte (following Fig. 8(b) in ref. [23]). The nickel mesh immersed in the electrocoating solution was coated with NiFe by repeated cycling using cyclic voltammetry between −1.0 V and −0.2 V (vs. Ag/AgCl) at 10 mV s^{-1} until a charge of 17 C had been deposited (following Fig. 1 in ref. [23]). A BioLogic VSP potentiostat was used. The lower voltage of −1.0 V allowed for inclusion of a PTFE dispersion, without precipitation; the upper voltage of −0.2 V was found to provide the best catalytic performance. A dispersion of PTFE could be incorporated into the anode by including the equivalent of 10 g L^{-1} PTFE in the electrocoating solution. Following electrodeposition, the working electrode was rinsed with deionised water and dried at room temperature. The electrocoating tape was then removed and the anode was welded to the bipolar plate as shown in Supplementary Fig. 7.

Capillary-fed cell. A picture of the capillary-fed cell used experimentally is provided in Supplementary Fig. 6. The polyether sulfone separator (8 µm average pore diameter) was initially soaked in deionised water and then kept in 27 wt% KOH electrolyte overnight. Ni gas diffusion bipolar plates measured 1.4 cm × 1.4 cm × 0.1 cm and included numerous 1 mm holes to allow evolved gases to exit the electrode. They performed the function of both the bipolar plate and the gas diffusion layer/porous transport layer in electrolysis cells. Bare Ni mesh was spot-welded to the Ni gas diffusion-bipolar plate on the cathode side and then pressed tightly against the rear of the Sigracet cathode substrate. The contact resistance was 3–5 mΩ cm^2. The Ni mesh anode was spot-welded to the Ni gas diffusion bipolar plate on the anode after coating with NiFe catalyst as described in Supplementary Fig. 7. The capillary-fed cell had the architecture: Ni bipolar plate/Ni mesh/Pt-C on carbon paper/ polyether sulfone separator/NiFe-coated Ni mesh/Ni bipolar plate. The anode and cathode were pressed against the polyether sulfone separator by leak-tight bolts passing through the gas chambers (Supplementary Fig. 6). Finally, the reservoir into which the bottom end of the polyether sulfone separator was dipped, was filled with 27 wt% KOH electrolyte.

Electrochemical measurements. Electrochemical measurements were performed using a BioLogic VMP3 potentiostat. Linear sweep voltammetry was performed by sweeping the cell voltage upward from 1.2–1.4 V at 10 mV s^{-1} until the current density reached 1.5 A cm^{-2}. Measurements at 80 °C or 85 °C were performed upon temperature equilibration after placing the capillary-fed cell into an oven at that temperature. Galvanostatic electrochemical impedance spectroscopy (GEIS) was performed at 0.350 A cm^{-2} DC bias, 0.050 A cm^{-2} AC perturbation, and between 100 kHz and 100 mHz.

Faradaic efficiency. Faradaic efficiency was calculated by comparing the measured volumes of hydrogen and oxygen produced at the cathode and anode, of a capillary-fed cell, respectively, at a fixed current of 0.350 A cm^{-2} at room temperature, with the expected volumes of hydrogen and oxygen if all electrons resulted in gas evolution (including the expected water vapour content of the gases and considering the gas crossover, which was measured at the same time). Gas volumes were measured by collecting the produced gas in a submerged, upturned burette. The cell was operated for 30 min at 0.350 A cm^{-2} prior to taking each set of measurements.

Hydrogen crossover. The concentration of hydrogen in the anode oxygen stream of a capillary-fed cell operated at different current densities at room temperature was determined by piping the anode gas output for analysis to a gas chromatograph (Shimadzu GC8A), operating with thermal conductivity detection and flame ionisation detector and argon as a gas carrier. The hydrogen and oxygen peaks were identified by their retention times and integrated to determine the relative quantities of gas present.

Data availability

Source data are provided with this paper.

Received: 16 October 2021; Accepted: 17 February 2022;
Published online: 15 March 2022

References

1. The Future of Hydrogen. (International Energy Agency, Paris, France, 2019).
2. Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 °C Climate Goal. (International Renewable Energy Agency, Abu Dhabi, 2020). OPEX is, by far, the major component of the LCOH for the following reason: Fig. ES1 in this reference provides an average electrolyser CAPEX (today) of USD$770 per 1 kW capacity. Over 10 years of continuous operation the electricity consumed by that 1 kW capacity, which will comprise most of the OPEX, will be: 24 × 365 × 10 = 1,752,000 kWh. At the average electricity price of USD$53/MWh, this gives a total OPEX of at least USD$91,104, which is 118-times larger than the CAPEX. The dominance of the OPEX over the CAPEX in the LCOH is projected to increase. Using the best future CAPEX of USD$130/kW and electricity price of USD$20/MWh over 10 years of continuous operation: the OPEX of USD$35,040 will be 270-times larger than the CAPEX. The IRENA 2050 cell energy consumption target is given in Table 6 (Stack electrical efficiency).
3. van Renssen, S. The hydrogen solution? *Nat. Clim. Change* **10**, 799–801 (2020).
4. Saeedmanesh, A., MacKinnon, M. A. & Brouwer, J. Hydrogen is essential for sustainability. *Curr. Opin. Electrochem.* **12**, 166–181 (2018).
5. Maric, R. & Yu, H. in *Nanostructures in Energy Generation, Transmission and Storage* (ed Yanina Fedorenko) 95–117 (IntechOpen, 2019).
6. Lund, P. D., Lindgren, J., Mikkola, J. & Salpakari, J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renew. Sustain. Energy Rev.* **45**, 785–807 (2015).
7. Bogdanov, D. & Breyer, C. North-East Asian Super Grid for 100% renewable energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options. *Energy Convers. Manag.* **112**, 176–190 (2016).
8. Godula-Jopek, A. *Hydrogen Production by Electrolysis*, Wiley-VCH, 2015, and references therein. ISBN: 978-3-527-33342-4.
9. Winther-Jensen, O., Chatjaroenporn, K., Winther-Jensen, B. & MacFarlane, D. R. Towards hydrogen production using a breathable electrode structure to directly separate gases in the water splitting reaction. *Int. J. Hydrog. Energy* **37**, 8185–8189 (2012).
10. Tiwari, P., Tsekouras, G., Wagner, K., Swiegers, G. F. & Wallace, G. G. A new class of *bubble-free* water electrolyzer that is intrinsically highly efficient. *Int. J. Hydrog. Energy* **44**, 23568–23579 (2019).
11. Li, J. et al. Breathing-Mimicking Electrocatalysis for Oxygen Evolution and Reduction. *Joule* **3**, 557–569 (2019).
12. Tsekouras, G. et al. Insights into the phenomenon of '*bubble-free*' electrocatalytic oxygen evolution from water. *Sustain. Energy Fuels* **5**, 808–819, and references therein, https://doi.org/10.1039/D0SE01633K (2021).
13. Swiegers, G. F. et al. The prospects of developing a highly energy-efficient water electrolyser by eliminating or mitigating bubble effects. *Sustain. Energy Fuels* **5**, 1280–1310 (2021). and references therein.

MENU

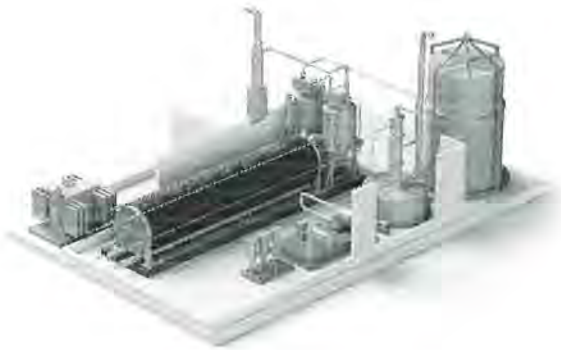
Water electrolysers / hydrogen generators

With more than 3,500 reliable, cost efficient electrolysers installed around the globe, Nel Hydrogen is the recognized industry leader of Alkaline (https://nelhydrogen.com/product/atmospheric-alkaline-electrolyser-a-series/) and Proton Exchange Membrane (https://nelhydrogen.com/product/m-series-3/) (PEM) water electrolysis.

Since our founding in 1927, sustained R&D efforts have contributed to continual improvement of electrolyser technology, setting the benchmark in the market. Our electrolysis technology is today widely respected for its robustness, reliability and energy efficiency.

Our water electrolysers make a superior choice for Industry, Transport and Power-to-X applications. Multiple, scalable, flexible, modular product ranges are set to meet any customer requirements.

MENU



(https://nelhydrogen.com/product/atmospheric-alkaline-electrolyser-a-series/)

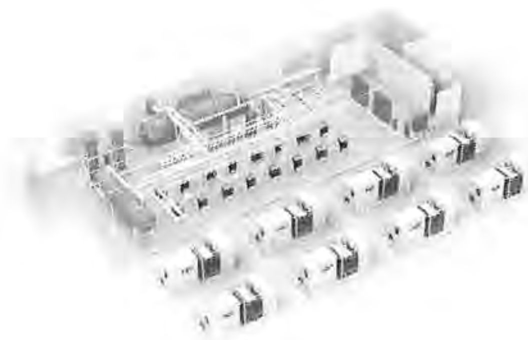
A SERIES

Atmospheric Alkaline Electrolyser (https://nelhydrogen.com/product/atmospheric-alkaline-electrolyser-a-series/)

The world's most energy efficient electrolysers, the A Series features a cell stack power consumption as low as 3.8 kWh/Nm3 of hydrogen gas produced, up to 2.2 MW per stack. A Series electrolysers can produce up to 3,880 Nm3/h of hydrogen or just over 8 ton per day.

View product (https://nelhydrogen.com/product/atmospheric-alkaline-electrolyser-a-series/)

MENU



(https://nelhydrogen.com/product/m-series-3/)

M SERIES

PEM Electrolyser (https://nelhydrogen.com/product/m-series-3/)

The M Series provides fast response times and production flexibility making it ideal for hydrogen generation utilizing renewable power sources. With minimal maintenance and siting requirements, M Series electrolysers can produce up to 4,000 Nm3/h of hydrogen gas at 99.9998% purity on-demand. Featuring a scalable modular design that can be containerized, these systems offer solutions that are well-suited for a variety of industrial, fueling and renewable energy applications energy applications.

MENU

View product (https://nelhydrogen.com/product/m-series-3/)

(https://nelhydrogen.com/product/m-series-containerized/)

M SERIES CONTAINERIZED

Containerized PEM Electrolyser (https://nelhydrogen.com/product/m-series-containerized/)

In situations where plant space is at a premium, customers may want to site their electrolysers outside. At other times customers may want to configure an electrolyser for a more turnkey operation. MC electrolysers deliver the M Series platform in a containerized form for easy outdoor installations. Typical applications include renewable energy storage, industrial process gas, and hydrogen fueling.

MENU

View product (https://nelhydrogen.com/product/m-series-containerized/)

(https://nelhydrogen.com/product/c10-c20-c30/)

C SERIES

PEM Electrolyser (https://nelhydrogen.com/product/c10-c20-c30/)

The C Series electrolysers are ideal for a variety of industrial applications. Producing up to 30 Nm³/h of hydrogen gas at 99.9998% purity, these units replace the need for hydrogen tube trailers or liquid hydrogen storage.

View product (https://nelhydrogen.com/product/c10-c20-c30/)

MENU

(https://nelhydrogen.com/product/h-series/)

H SERIES

PEM Electrolyser (https://nelhydrogen.com/product/h-series/)

H Series electrolysers offer turnkey solutions for small-

scale applications requiring up to 6 Nm^3/h of hydrogen gas at 99.9995% purity. These units make a minimal impact to facility floor space, are easy to maintain and can be installed within hours.

View product (https://nelhydrogen.com/product/h-series/)

MENU

(https://nelhydrogen.com/product/s-series/)

S SERIES

PEM Electrolyser (https://nelhydrogen.com/product/s-series/)

Producing high purity hydrogen of 99.9995% at up to 1.05 Nm^3/h, S Series electrolysers replace the need for pressurized hydrogen cylinders in a variety of industrial processes. Each unit is low maintenance, compact, quiet, and can be installed within hours virtually anywhere in a facility.

View product (https://nelhydrogen.com/product/s-series/)

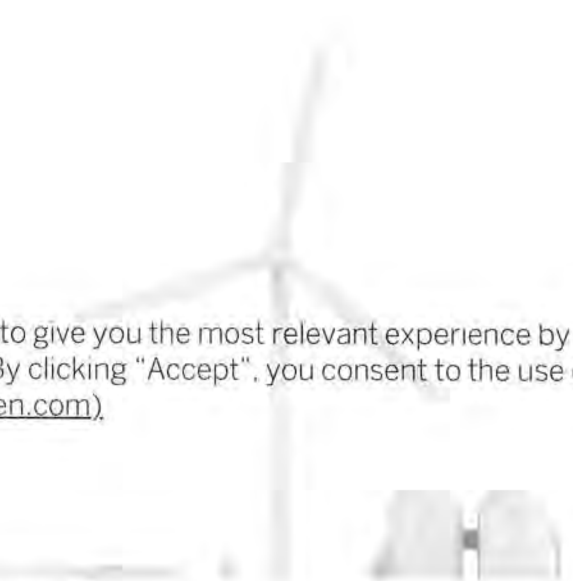
HYDROGEN SOLUTIONS

MENU

Your development partner

As the world turns to renewables, a growing number of hydrogen based applications emerge worldwide. Our extensive experience with industrial electrolysis and hydrogen fueling represents new opportunities for proven Nel technology and products.

Read more (https://nelhydrogen.com/solutions/)



MENU

Product wizard

Let us help you pair the right hydrogen generation solution with your operation.

Get started! (https://nelhydrogen.com/product-wizard)

Cookies (https://nelhydrogen.com/cookies/)

Privacy Policy (https://nelhydrogen.com/privacy-policy/)

(ht tps :// twi tte r.c om /n elh ydr og en) (ht tps :// ww w.f ac eb oo k.c om /N el hydr og) (ht tps :// ww w.li nk edi n.c om /c om pa ny /n el) (ht tps :// ww w.i nst agr am .co m/ nel hy dr og)

MENU

Vision

At Nel, our vision is all about 'Empowering generations with clean energy forever'. Our technology allows people and businesses to make everyday use of hydrogen, the most abundant element in the universe.

MENU

Mission

We unlock the potential of renewables and enable global decarbonization.

Values

We believe simplicity is key. This can be a real challenge when dealing with complex technologies, but we believe being a customer of Nel should be simple, with a complete solution that meets your requirements. We value technology that is easy to operate, has a long lifetime, low cost of ownership, and is hassle-free for the end user. Simplicity is the guiding star in our business and values:

Commitment

We put our hearts into what we do and are uncompromising when it comes to safety and product excellence.

Honesty

MENU

We do what we say and are open about what we do.

Boldness

We lead the way in our industry, accelerating the energy transition; turning what used to be impossible into reality.

Code of Conduct

Our Code of Conduct is based on principles of business ethics which are fundamental to Nel. The Code of Conduct includes mandatory requirements for everyone who works in Nel or acts on behalf of Nel.

Compliance with applicable national and international laws and regulation is mandatory for all our activities. Further, we must ensure that we conduct our business with the highest integrity, respecting the cultures, dignity, and rights of individuals in all the regions where we operate.

The Code of Conduct is our guide to ethical business practice. It reflects Nel's values and our belief that conducting business in an ethical and transparent manner is not just the right way to work, but the only way to conduct our business.

If anything is unclear or you have any questions about the Code of Conduct, you should seek guidance from your manager or other internal resources. I further strongly encourage all employees and stakeholders to ask questions if you observe any suspicious behavior and/or possible violations of the Code of Conduct.

Any report of concern can be done through one of our reporting channels.

- Jon André Løkke, CEO

(https://96e597bb58d206f85397.b-cdn.net/wp-content/uploads/2021/05/Nel-Code-of-Conduct-29.04.2021.pdf)

MENU

Download (https://96e597bb58d206f85397.b-cdn.net/wp-content/uploads/2021/05/Nel-Code-of-Conduct-29.04.2021.pdf)

Our business

Nel is a global, dedicated hydrogen company, delivering optimal solutions to produce, store and distribute hydrogen from renewable energy. We serve industries, energy and gas companies with leading hydrogen technology. Our roots date back to 1927, and since then, we have had a proud history of development and continuous improvement of hydrogen technologies. Today, our hydrogen solutions cover the entire value chain from hydrogen production technologies to hydrogen fueling stations, enabling industries to transition to green hydrogen, and providing all fuel cell electric vehicles with the same fast fueling and long range as fossil-fueled vehicles – without the emissions.

MENU

Context

Why we believe renewable hydrogen will be number 1 in the future:

- The world needs a new energy carrier to replace oil and gas
- Hydrogen is the element with the highest energy density
- Through electrolysis hydrogen can be produced from water and renewable energy
- Access to renewable energy is practically infinite
- The electric grids do not have the capacity to handle the entire future energy demand alone
- The demand for stable energy supply diverge from the fluctuating nature of renewable energy production in general

general

Large scale introduction of renewable energy is dependent on energy storage solutions

MENU

Timeline

1927

The first small electrolyser installation at Norsk Hydro, Notodden, Norway. Testing for pure hydrogen to fertilizer production.

1940

The largest installation in the world of water electrolysers at Rjukan, Norway, with a total hydrogen production capacity exceeding 30.000 Nm3/hour, from hydropower.

MENU

1953

Starts up a second large scale hydropowered electrolyser plant for supplying hydrogen to ammonia production, in Glomfjord, Norway.

1959

Complete redesign of the electrolyser unit, forming the basis for today's atmospheric electrolyser from Nel.

1974

Our renowned electrolyser technology made available for other companies and other industries.

MENU

1988

The world's first electrolyser supplier to provide non-asbestos alkali electrolysers.

2001

Our first pressurised electrolyser introduced to the market.

2003

Nel opens the world's first publicly available hydrogen fueling station in Reykjavik, Iceland.

MENU

2014

Nel becomes the first 100% dedicated hydrogen company listed on the Oslo Stock Exchange.

2015

Nel acquires H2 Logic, adding world leading hydrogen fueling technology to the product portfolio.

2017

Nel acquires Proton OnSite, adding world leading PEM electrolysis technology to product portfolio, becoming the world's largest electrolyser company.

MENU

2018

Nel completes construction of the world's largest manufacturing plant for hydrogen fueling stations, with a capacity of 300 units per year.

2019

Nel announces construction plans for the world's largest electrolyser manufacturing plant to accommodate multi-billion NOK orders.

MENU

2020

Nel opens first H2Station™ in Korea.

Nel group management

MENU

Anders Søreng (https://nelhydrogen.com/person/anders-soreng/)
CTO

MENU

Kjell Christian Bjørnsen (https://nelhydrogen.com/person/kjell-christian-bjornsen/)

CFO

MENU

Caroline Duyckaerts (https://nelhydrogen.com/person/caroline-duyckaerts/)

Chief Human Resources Officer

MENU

Hans H. Hide (https://nelhydrogen.com/person/hans-h-hide/)
SVP Projects

MENU

Filip Smeets (https://nelhydrogen.com/person/filip-smeets/)
SVP Nel Electrolyser Division

MENU

Robert Borin (https://nelhydrogen.com/person/robert-borin/)

SVP Fueling

Board members

Ole Enger (https://nelhydrogen.com/person/ole-enger/)
Chair

MENU

Hanne Blume (https://nelhydrogen.com/person/hanne-blume/)
Board member

MENU

Charlotta Falvin (https://nelhydrogen.com/person/charlotta-falvin/)
Board member

MENU

Beatriz Malo De Molina (https://nelhydrogen.com/person/beatriz-malo-de-molina/)

Board member

MENU

Tom Røtjer (https://nelhydrogen.com/person/tom-rotjer/)

Board member

Company structure

Nel ASA

Electrolyser

Fueling

We use cookies on our website to give you the most relevant experience by remembering your preferences and repeat visits. By clicking "Accept", you consent to the use of ALL the cookies. Read More (https://nelhydrogen.com)

Cookie settings ACCEPT

MENU

Resources

All Resources (https://nelhydrogen.com/resources/)
Technical Specifications (https://nelhydrogen.com/resources/?tech-specs)
Brochures (https://nelhydrogen.com/resources/?brochures)
White Papers (https://nelhydrogen.com/resources/?white-papers)
Articles (https://nelhydrogen.com/resources/?articles)
Presentations (https://nelhydrogen.com/resources/?presentations)
Video / Podcasts (https://nelhydrogen.com/resources/?video-podcasts)
FAQ (https://nelhydrogen.com/faq/)
Glossary (https://nelhydrogen.com/glossary/)

MENU

Did you know?

Hydrogen is amazing

You can drive up to 130 km with one kg of hydrogen

One kg of hydrogen replaces 10 liters of diesel/petrol

Hydrogen cars emit nothing but pure water

Cookies (https://nelhydrogen.com/cookies/)

Privacy Policy (https://nelhydrogen.com/privacy-policy/)

RENEW ECONOMY
Clean Energy News and Analysis

Stanford study demonstrates 100% renewable US grid, with no blackouts

Joshua S Hill (https://reneweconomy.com.au/author/joshua-hill/) 10 December 2021 10

Share Tweet in S 0

A study led by Stanford University professor Mark Jacobson has demonstrated that the US energy system running on wind, water and solar, coupled with storage, not only avoids blackouts but lowers energy requirements and consumer costs while creating millions of jobs, improving health, and freeing up land.

RMI

Shares

Gigawatts of drogen

A look at how we can deploy the hundreds of gigawatts of electrolyzers needed this decade

October 11, 2021 | By Tessa Weiss

Of all the technologies unleashed in the energy transition, few have

RECENT POSTS

Five Things that Rang True for Climate and Energy Experts in *Don't Look Up*

generated the level of excitement that green hydrogen has. As a potential enabler of economically viable, zero-carbon solutions for everything from steel manufacturing to marine shipping, green hydrogen is positioned as a cure-all for the "hard-to-abate" sectors. This has drawn interest from many of the world's largest companies, with steelmakers, refineries, and fertilizer producers driving the majority of current projects.

However, there remains a wide gulf between the promise of green hydrogen and the reality on the ground today. There are 0.3 GW of electrolyzers powered by renewable energy installed today with a projected 40 GW to be commissioned by 2030 according to Bloomberg New Energy Finance's (BNEF) Hydrogen Production Database. This project pipeline pales in comparison to the 850 GW of electrolyzers needed by 2030 for hydrogen to play its part in a net zero world.

We Must Start Now

We are face-to-face with a need and opportunity to rapidly scale green

Local Governments Are Stepping Up Grid Decarbonization in 2022

Financing 1.5°C: Five Trends to Watch in Climate-Aligned Finance in 2022

Reality Check: US Renewable Energy Portfolios Can Outcompete New Gas Plants

Washington State Could Lead the Nation on Building Electrification Codes

hydrogen and it is critical we start now, for several reasons. First, we risk locking ourselves into a fossil fuel-based future with a significant stranded asset risk if we do not actively pursue a zero-emissions pathway today.

Second, we could contribute to growing a mismatch between electrolyzer manufacturing capacity and the demand for electrolyzers if we do not actively develop more projects. Taking BNEF's recent survey of available manufacturing capacity and proposed project pipeline, within the next 5 years projects could only account for 25% of available manufacturing capacity. If these assessments are true, original equipment manufacturers (OEMs) will compete over supply of proposed projects to fill order books, potentially cutting the price of electrolyzers to unsustainably low levels for increased competitiveness.

As a result, OEMs will not see significant return on investments until the overcapacity of the supply market is remedied, but instead will be forced to operate on tight or negative profit margins. Demand must increase to fill order books,

CATEGORIES

Africa

Aviation

BRC: Business Renewables Center

Breakthrough Technologies

Building Electrification

Buildings

Caribbean Islands

China

Climate Aligned Industries

Climate Alignment

Climate Intelligence

Climate-Aligned Finance

Commercial Buildings

which in part will be accelerated if costs fall more rapidly than expected. But regardless of the potential cost point, off-takers must recognize the need for green hydrogen today and begin to plan a future with green hydrogen in mind to ensure there is a match between supply and demand.

Finally, we will expedite the opportunity to enable dramatic cost reductions far sooner than expected and will foster green hydrogen's widespread cost competitiveness once we start to scale, as seen in the chart below.

With a reduced electrolyzer capital cost, projects see greater flexibility in where they can be sited and how they should be designed. Locations with less abundant and more intermittent renewables will become cost-competitive producers of green hydrogen. Projects will see a different and cheaper mixture of renewables built to maximize cost savings now that cost competitive production can allow for more intermittency in electricity supply given a lifting of previous economic constraints.

Community-Scale Solar

Corporate Renewables

Disruptive Technologies

Distributed Grid Infrastructure

e-Lab: Electricity Innovation Lab

Electricity

Energy Efficiency

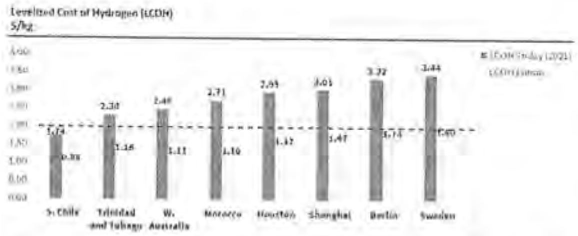
Energy Inputs

Energy Web Foundation

General Energy

Global Energy Transitions

Global South



Sub $2/kg hydrogen production, the standard for "cost competitiveness", becomes more widely achievable for locations once electrolyzer capital costs fall and system efficiency improves. Storage and compression of hydrogen to provide around-the-clock availability will add $0.4 to $1.3/kg to the LCOH for these locations. Assumptions: Electrolyzer capex $700/kW today, $200/kW in the future; System efficiency 49.5 kWh/kg today, 44 kWh/kg in the future.

Overcoming Capital Challenges

However, although these risks of delaying green hydrogen deployment and opportunities for low-cost production are clear, scaling green hydrogen is challenging. This is especially true given limited public policy support and a narrow set of

Hydrogen
India
Materials
Methane Emissions
Microgrids
Mining
Mobility
Net-Zero Energy
Residential Buildings
Shipping
Strategic Analysis and Engagement
Third Derivative
Transportation
Trucking
Uncategorized
United States
Urban Transformation
US Policy

criteria that must be met for project viability. Driven by high electrolyzer capital costs, projects today require a significant amount of upfront capital to be paid out. As a result, high and early cash flows must be prioritized, driving a need to operate the electrolyzers as many hours of the year as possible.

Viable green hydrogen projects are therefore restricted to locations with ample and steady supplies of renewable electricity to maximize the resulting hydrogen production. Additionally, electrolysis plants often must be collocated with points of demand off-take as high storage and transportation costs add to the already high cost per kilogram, sending costs above the upper bound for parity. These two criteria, quality renewables and collocation with off-take, greatly limit the breadth of feasible projects, as it is rare that locations of demand are located alongside optimal renewable availability.

Even with these constraints, there are several strategies that can create favorable economics to support getting projects off the ground today. These tactics utilize the current

Works by Amory Lovins

ARCHIVES

2022

2021

2020

2019

2018

2017

2016

2015

2014

2013

2012

2011

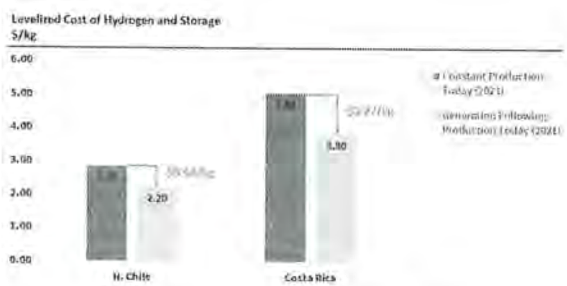
2010

technological standards of the system but modify project design, operation, or off-take strategies to enable cost reduction. Three of these methods include producing hydrogen exclusively during times when the sun is shining or the wind is blowing, integrating green hydrogen into existing grey hydrogen supply, and supplementing the system's electricity input with curtailed power to reduce costs.

Matching Hydrogen Production with Renewable Output

Conventionally, we think of supplying a constant stream of hydrogen for every hour of the year. This imposed constraint drives up the amount of storage required to smooth out any intermittencies in production due to the natural variability of renewable electricity and requires an oversizing of renewables to create a stock and flow of hydrogen.

The desire for around-the-clock hydrogen production is not without warrant: ammonia synthesis and steel manufacturing traditionally require a steady stream input to avoid ramping up and down equipment. However, where off-takers can absorb intermittent hydrogen production, namely one that follows the natural availability of renewables throughout the year, projects can immediately unlock cost savings of $0.60/kg to $1.20/kg. This is seen in the chart below.



Hydrogen production that follows the natural intermittencies of solar and wind will enable significant cost savings through a reduction in hydrogen storage required. Here, N. Chile and Costa Rica are both produce hydrogen exclusively during times of solar electricity generation. Every location will have a unique optimal pattern of following wind and solar generation to maximize cost savings.

Partial Offtake to Incentivize Green Hydrogen

Utilizing existing grey hydrogen demand as an opportunity to build up green hydrogen capacity could provide an additional pathway for market integration. Partially integrating green hydrogen into current grey hydrogen usage such as in fertilizer production eases the challenge of transition as off-takers are already positioned to use hydrogen in their processes: all that needs to be built is the electrolysis and necessary renewables capacity.

This minimal complexity of green hydrogen adoption will help foster initial project development, leading to electrolyzer capex reduction from economies of scale. Over time as electrolyzer capital costs fall, more and more green hydrogen capacity can be built out at a lower cost, naturally enabling a transition from grey hydrogen use into green while maximizing low-cost installations. As seen recently in India's mandate for green hydrogen's integration into existing refineries and fertilizer manufacturing, countries are starting to recognize partial off-take deployment as a method of creating demand and fostering decarbonization today.

Utilizing Curtailed Power to Reduce Costs

Another strategy to foster increased cost competitiveness involves rethinking the mixture of electricity supplied to the electrolyzer. As the electricity input accounts for 50 to 75 percent of the levelized cost of hydrogen today, depending on location, finding opportunities to reduce these costs are critical.

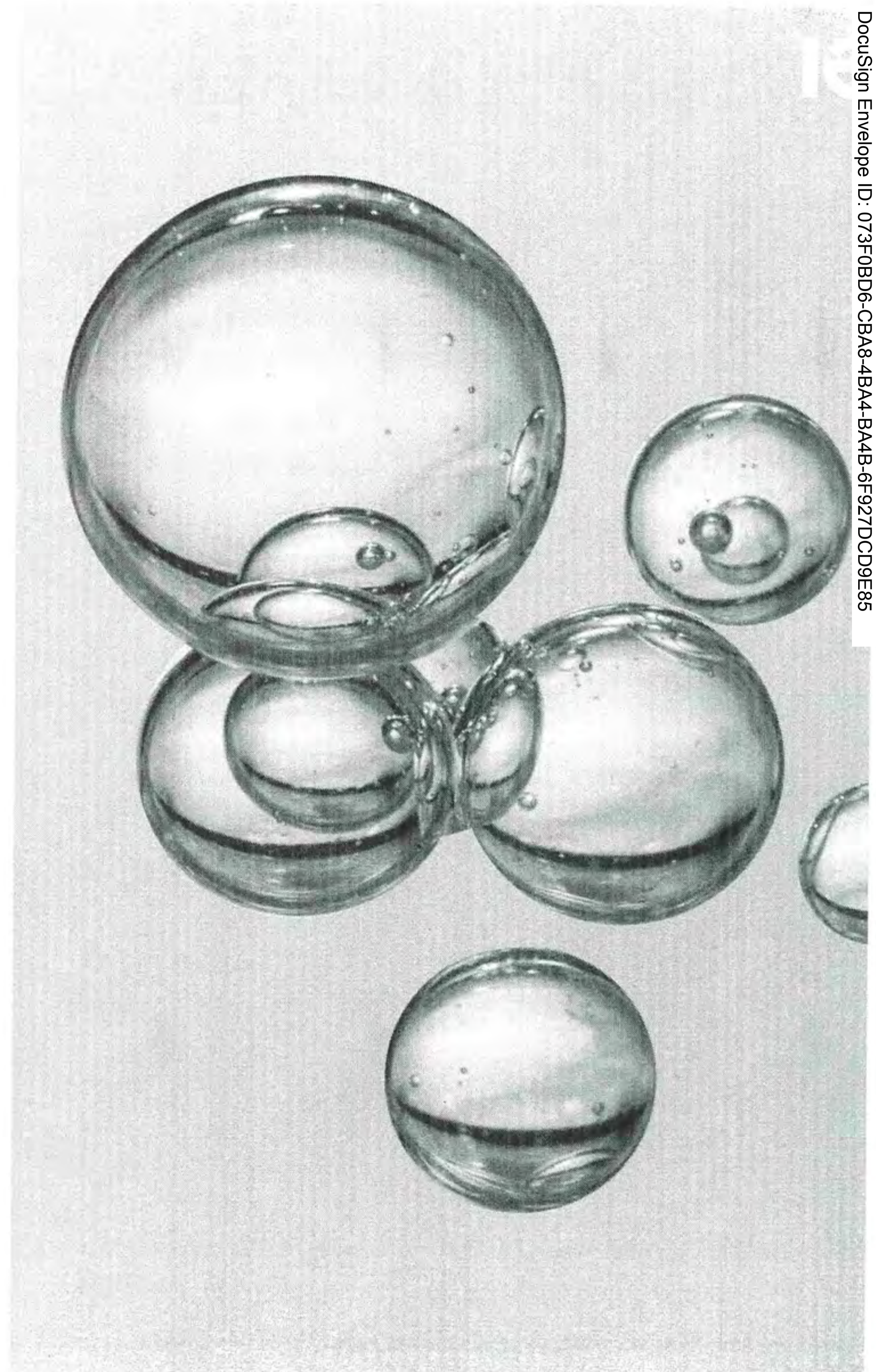
In areas with significant curtailed renewable electricity, such as California or Texas, surplus power is sold at a low or negative prices during times of peak generation. Given the need for abundant and consistent renewables to power electrolyzers today, exclusive reliance on curtailed electricity is likely insufficient to produce hydrogen in an economically viable manner. However, there is opportunity to integrate curtailed power supplemented with complementary, onsite renewable capacity to increase the stability of electricity input. Costs can be saved in reducing the magnitude of new renewables built and the grid can be stabilized through a consistent off-taker of excess electricity.

Accelerating Cost Declines

Green hydrogen is a both a necessary and economically viable pathway for many sectors with limited options for decarbonization. Investors are recognizing this opportunity, and the market is moving. Accelerating the rate at which we grow the gigawatts of green hydrogen installed will quickly foster cost declines and enable us to meet our goals for global decarbonization. The tactics described above can help reduce the costs of green hydrogen production today while capital costs remain high and public policy remains inadequate.

Debates over green hydrogen's relevance in a clean energy future are no longer meaningful; we know that it is needed. Now is the time to accelerate green hydrogen's path towards being cost-competitive, sooner than ever expected.

Global Hydrogen Review 2021



INTERNATIONAL ENERGY AGENCY

The IEA examines the full spectrum of energy issues including oil, gas and coal supply and demand, renewable energy technologies, electricity markets, energy efficiency, access to energy, demand side management and much more. Through its work, the IEA advocates policies that will enhance the reliability, affordability and sustainability of energy in its 30 member countries, 8 association countries and beyond.

Please note that this publication is subject to specific restrictions that limit its use and distribution. The terms and conditions are available online at www.iea.org/t&c/

This publication and any map included herein are without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

International Energy Agency
Website: www.iea.org

IEA member countries:
Australia
Austria
Belgium
Canada
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Ireland
Italy
Japan
Korea
Luxembourg
Mexico
Netherlands
New Zealand
Norway
Poland
Portugal
Slovak Republic
Spain
Sweden
Switzerland
Turkey
United Kingdom
United States

IEA association countries:
Brazil
China
India
Indonesia
Morocco
Singapore
South Africa
Thailand

Table of Contents

iec

Executive summary

Executive Summary

After several false starts, a new beginning around the corner

The time is ripe to tap into hydrogen's potential contribution to a sustainable energy system. In 2019, at the time of the release of the IEA's landmark report The Future of Hydrogen for the G20, only France, Japan and Korea had strategies for the use of hydrogen. Today, 17 governments have released hydrogen strategies, more than 20 governments have publicly announced they are working to develop strategies, and numerous companies are seeking to tap into hydrogen business opportunities. Such efforts are timely: hydrogen will be needed for an energy system with net zero emissions. In the IEA's Net Zero by 2050: A Roadmap for the Global Energy Sector, hydrogen use extends to several parts of the energy sector and grows sixfold from today's levels to meet 10% of total final energy consumption by 2050. This is all supplied from low-carbon sources.

Hydrogen supplies are becoming cleaner ... too slowly

Hydrogen demand stood at 90 Mt in 2020, practically all for refining and industrial applications and produced almost exclusively from fossil fuels, resulting in close to 900 Mt of CO_2 emissions. But there are encouraging signs of progress. Global capacity of electrolysers, which are needed to produce hydrogen from electricity, doubled over the last five years to reach just over 300 MW by mid-2021. Around 350 projects currently under development could bring global capacity up to 54 GW by 2030. Another 40 projects accounting for more tha 35 GW of capacity are in early stages of development. If all thos projects are realised, global hydrogen supply from electrolysers coul reach more than 8 Mt by 2030. While significant, this is still well belo the 80 Mt required by that year in the pathway to net zero CC emissions by 2050 set out in the IEA Roadmap for the Global Energ Sector.

Europe is leading electrolyser capacity deployment, with 40% c global installed capacity, and is set to remain the largest market i the near term on the back of the ambitious hydrogen strategies of th European Union and the United Kingdom. Australia's plans sugges it could catch up with Europe in a few years; Latin America and th Middle East are expected to deploy large amounts of capacity as wel in particular for export. The People's Republic of China ("China made a slow start, but its number of project announcements i growing fast, and the United States is stepping up ambitions with it recently announced Hydrogen Earthshot.

Sixteen projects for producing hydrogen from fossil fuels with carbo capture, utilisation and storage (CCUS) are operational toda producing 0.7 Mt of hydrogen annually. Another 50 projects are unde development and, if realised, could increase the annual hydroge production to more than 9 Mt by 2030. Canada and the United State lead in the production of hydrogen from fossil fuels with CCUS, wit more than 80% of global capacity production, although the Unite

iea

Kingdom and the Netherlands are pushing to become leaders in the field and account for a major part of the projects under development.

Expanding the reach of hydrogen use

Hydrogen can be used in many more applications than those common today. Although this still accounts for a small share of total hydrogen demand, recent progress to expand its reach has been strong, particularly in transport. The cost of automotive fuel cells has fallen by 70% since 2008 thanks to technological progress and growing sales of fuel cell electric vehicles (FCEVs). Thanks to the efforts by Korea, the Unites States, China and Japan, the number of FCEVs on the road grew more than sixfold from 7 000 in 2017 to over 43 000 by mid-2021. In 2017, practically all FCEVs were passenger cars. Today, one-fifth are buses and trucks, indicating a shift to the long-distance segment where hydrogen can better compete with electric vehicles. However, the total number of FCEVs is still well below the estimated 11 million electric vehicles on the road today. Several demonstration projects for the use of hydrogen-based fuels in rail, shipping and aviation are already under development and are expected to open new opportunities for creating hydrogen demand.

Hydrogen is a key pillar of decarbonisation for industry, although most of the technologies that can contribute significantly are still nascent. Major steps are being taken. The world's first pilot project for producing carbon-free steel using low-carbon hydrogen began operation this year in Sweden. In Spain, a pilot project for the use of variable renewables-based hydrogen for ammonia production will start at the end of 2021. Several projects at a scale of tens c kilotonnes of hydrogen are expected to become operational over th next two to three years. Demonstration projects for using hydrogen i industrial applications such as cement, ceramics or glas manufacturing are also under development.

Governments need to scale up ambitions and support demand creation

Countries that have adopted hydrogen strategies have committed a least USD 37 billion; the private sector has announced an additiona investment of USD 300 billion. But putting the hydrogen sector o track for net zero emissions by 2050 requires USD 1 200 billion c investment in low-carbon hydrogen supply and use through to 203C

The focus of most government policies is on producing low-carbo hydrogen. Measures to increase demand are receiving less attentior Japan, Korea, France and the Netherlands have adopted targets fc FCEV deployment. But boosting the role of low-carbon hydrogen i clean energy transitions requires a step change in demand creatior Governments are starting to announce a wide variety of polic instruments, including carbon prices, auctions, quotas, mandates an requirements in public procurement. Most of these measures hav not yet entered into force. Their quick and widespread enactmer could unlock more projects to scale up hydrogen demand.

Low-carbon hydrogen can become competitive within the next decade

A key barrier for low-carbon hydrogen is the cost gap with hydrogen from unabated fossil fuels. At present, producing hydrogen from fossil fuels is the cheapest option in most parts of the world. Depending on regional gas prices, the levelised cost of hydrogen production from natural gas ranges from USD 0.5 to USD 1.7 per kilogramme (kg). Using CCUS technologies to reduce the CO_2 emissions from hydrogen production increases the levelised cost of production to around USD 1 to USD 2 per kg. Using renewable electricity to produce hydrogen costs USD 3 to USD 8 per kg.

There is significant scope for cutting production costs through technology innovation and increased deployment. The potential is reflected in the IEA's Net Zero Emissions by 2050 Scenario (NZE Scenario) in which hydrogen from renewables falls to as low as USD 1.3 per kg by 2030 in regions with excellent renewable resources (range USD 1.3-3.5 per kg), comparable with the cost of hydrogen from natural gas with CCUS. In the longer term, hydrogen costs from renewable electricity fall as low as USD 1 per kg (range USD 1.0-3.0 per kg) in the NZE Scenario, making hydrogen from solar PV cost-competitive with hydrogen from natural gas even without CCUS in several regions.

Meeting climate pledges requires faster and more decisive action

While the adoption of hydrogen as a clean fuel is accelerating, it st falls short of what is required to help reach net zero emissions b 2050. If all the announced industrial plans are realised, by 2030:

- Total hydrogen demand could grow as high as 105 Mt – compared wi more than 200 Mt in the NZE Scenario
- Low-carbon hydrogen production could reach more than 17 Mt – on eighth of the production level required in the NZE Scenario
- Electrolysis capacity could rise to 90 GW – well below the near 850 GW in the NZE Scenario
- Up to 6 million FCEVs could be deployed – 40% of the level deployment in the NZE Scenario (15 million FCEVs)

Much faster adoption of low-carbon hydrogen is needed to put th world on track for a sustainable energy system by 2050. Developin a global hydrogen market can help countries with limited domesti supply potential while providing export opportunities for countries wit large renewable or CO_2 storage potential. There is also a need t accelerate technology innovation efforts. Several critical hydroge technologies today are in early stages of development. We estimat that USD 90 billion of public money needs to be channeled into clea energy innovation worldwide as quickly as possible – with around ha of it dedicated to hydrogen-related technologies.

Stronger international co-operation: a key leaver for success

International co-operation is critical to accelerate the adoption of hydrogen. Japan has spearheaded developments through the Hydrogen Energy Ministerial Meeting since 2018. Several bilateral and multilateral co-operation agreements and initiatives have since been announced, including the Clean Energy Ministerial Hydrogen Initiative, the Hydrogen Mission of Mission Innovation and the Global Partnership for Hydrogen of the United Nations Industrial Development Organization. These join the existing International Partnership for Hydrogen and Fuel Cells in the Economy and the IEA Hydrogen and Advanced Fuel Cells Technology Collaboration Programme. Stronger coordination among such initiatives is important to avoid duplication of efforts and ensure efficient progress.

IEA policy recommendations

Governments must take a lead in the energy transformation. In The Future of Hydrogen, the IEA identified a series of recommendations for near-term action. This report offers more detail about how policies can accelerate the adoption of hydrogen as a clean fuel:

- **Develop strategies and roadmaps on the role of hydrogen in energy systems**: National hydrogen strategies and roadmaps with concrete targets for deploying low-carbon production and, particularly, stimulating significant demand are critical to build stakeholder confidence about the potential market for low-carbon hydrogen. This is a vital first step to create momentum and trigger more investments to scale up and accelerate deployment.
- **Create incentives for using low-carbon hydrogen to displace unabated fossil fuels**: Demand creation is lagging behind what is needed to help put the world on track to reach net-zero emissions by 2030. It is critical to increase concrete measures on this front to tap into hydrogen's full potential as a clean energy vector. Currently, low-carbon hydrogen is more costly to use than unabated fossil-based hydrogen in areas where hydrogen is already being employed – and it is more costly to use than fossil fuels in areas where hydrogen could eventually replace them. Some countries are already using carbon pricing to close this cost gap but this is not enough. Wider adoption combined with other policy instruments like auctions, mandates, quotas and hydrogen requirements in public procurement can help de-risk investments and improve the economic feasibility of low-carbon hydrogen.
- **Mobilise investment in production, infrastructure and factories**: policy framework that stimulates demand can, in turn, prom investment in low-carbon production plants, infrastructure an manufacturing capacity. However, without stronger policy action, th process will not happen at the necessary pace to meet climate goal Providing tailor-made support to selected shovel-ready flagshi projects can kick-start the scaling up of low-carbon hydrogen and th development of infrastructure to connect supply sources to deman centres and manufacturing capacities from which later projects ca benefit. Adequate infrastructure planning is critical to avoid delays the creation of assets that can become stranded in the near or mediu term.
- **Provide strong innovation support to ensure critical technologie reach commercialisation soon**: Continuous innovation is essential drive down costs and increase the competitiveness of hydroge technologies. Unlocking the full potential demand for hydrogen w require strong demonstration efforts over the next decade. An increas of R&D budgets and support for demonstration projects is urgent needed to make sure key hydrogen technologies reac commercialisation as soon as possible.
- **Establish appropriate certification, standardisation and regulatio regimes**: The adoption of hydrogen will spawn new value chains. Th will require modifying current regulatory frameworks and defining ne standards and certification schemes to remove barriers preventin widespread adoption. International agreement on methodology calculate the carbon footprint of hydrogen production is particular important to ensure that hydrogen production is truly low-carbon. It w also play a fundamental role in developing a global hydrogen market

Introduction

Overview

In the run-up to the 26th Conference of the Parties to the UN Framework Convention on Climate Change (COP 26), a growing number of countries are announcing targets to achieve net zero GHG emissions over the next decades. In turn, more than 100 companies that consume large volumes of energy or produce energy-consuming goods have followed suit. As demonstrated in the IEA Net zero by 2050 roadmap, achieving these targets will require immediate action to turn the 2020s into a decade of massive clean energy expansion.

Hydrogen will need to play an important role in the transition to net zero emissions. Since the first Hydrogen Energy Ministerial (HEM) meeting in Japan in 2018, momentum has grown and an increasing number of governments and companies are establishing visions and plans for hydrogen.

At the Osaka Summit in 2019, G20 leaders emphasised hydrogen's role in enabling the clean energy transition. The IEA prepared the landmark report The Future of Hydrogen for the summit, with detailed analysis of the state of hydrogen technologies and their potential to contribute to energy system transformation, as well as challenges that need to be overcome. In addition, during the 10th Clean Energy Ministerial (CEM) meeting in Vancouver, the Hydrogen Initiative (H2I) was launched to accelerate hydrogen deployment, and during the 6th Mission Innovation Ministerial, th Clean Hydrogen Mission to reduce the cost of clean hydrogen wa announced.

This Global Hydrogen Review is an output of H2I that is intended t inform energy sector stakeholders on the current status and futur prospects of hydrogen and serve as an input to the discussions a the HEM of Japan. It comprehensively examines what is needed t address climate change and compares actual progress with state government and industry ambitions and with key actions announce in the Global Action Agenda launched in the HEM 2019. Focusin on hydrogen's usefulness in meeting climate goals, this Revie aims to help decision makers fine-tune strategies to attra investment and facilitate deployment of hydrogen technologie while also creating demand for hydrogen and hydrogen-based fuel

This Review's analysis comprises seven chapters. First, the chapte on **policy trends** describes progress made by governments i adopting hydrogen-related policies. Next, two comprehensiv chapters on **global hydrogen demand** and **supply** provide ir depth analyses of recent advances in different sectors an technologies and explore how trends could evolve in the mediur and long term.

A chapter on **infrastructure and hydrogen trade** emphasises the need to develop both these areas while ramping up demand and supply. It also details the status and opportunities for deploying hydrogen infrastructure, as well as recent trends and the outlook for hydrogen trade.

Investments and innovation are combined into one chapter to reflect how they mutually underpin trends in the development and uptake of hydrogen technologies. Meanwhile, the chapter on **insights on selected regions** recaps progress in regions and countries where governments and industry are particularly active in advancing hydrogen deployment.

The final chapter provides **policy recommendations** to accelerate the adoption of hydrogen technologies in the next decade, with a view to ensuring it becomes economically and technically viable and socially acceptable.

The Hydrogen Initiative

Developed under the CEM framework, H2I is a voluntary multi-government initiative that aims to advance policies, programmes and projects that accelerate the commercialisation and deployment of hydrogen and fuel cell technologies across all areas of the economy. Ultimately, it seeks to ensure hydrogen's place as a key enabler in the global clean energy transition.

The IEA serves as the H2I co-ordinator to support member governments as they develop activities aligned with the initiative. H2I currently comprises the following participating governments and intergovernmental entities: Australia, Austria, Brazil, Canada, Chile, the People's Republic of China (hereafter China), Costa Rica, the European Commission, Finland, Germany, India, Italy, Japan, the Netherlands, New Zealand, Norway, Portugal, the Republic of Korea (hereafter Korea), the Russian Federation (hereafter Russia), Saudi Arabia, South Africa, the United Kingdom and the United States. Canada, the European Commission, Japan, the Netherlands and the United States co-lead the initiative, while China and Italy are observers.

HYDROGEN INITIATIVE

AN INITIATIVE OF THE CLEAN ENERGY MINISTERIAL

H2I is also a platform to co-ordinate and facilitate co-operation amon governments, other international initiatives and the industry secto The Initiative has active partnerships with the Hydrogen Council, th International Partnership for Hydrogen and Fuel Cells in the Econom (IPHE), the International Renewable Energy Agency (IRENA Mission Innovation (MI), the World Economic Forum (WEF) and th IEA's Advanced Fuel Cells and Hydrogen Technology Collaboratio Programmes (TCPs), all of which are part of the H2I Advisory Grou In addition, several industrial partners actively participate in the H2 Advisory Group's bi-annual meetings, including Ballard, Enel, Engie Nel Hydrogen, the Port of Rotterdam and Thyssenkrupp.

The Global Hydrogen Review

Following IEA recommendations in The Future of Hydrogen, this Global Hydrogen Review aims to track progress in hydrogen production and demand, as well as in other areas of critical importance such as policy, regulation and infrastructure development. To do this effectively and comprehensively, the IEA has established co-operative relationships with other relevant institutions to provide sound analysis based on the best possible data, and to create synergies among other international efforts, building on their respective strengths and experiences.

The Hydrogen Council in particular shared critical information on technology costs and performance from its industry network, which enriched IEA databases, modelling assumptions and techno-economic parameters.

Meanwhile, the IPHE contributed inputs on the developmental status of standards, codes and regulations. Leveraging its government network and established process to collect data and work collaboratively on regulatory issues, it also provided valuable information on the technology deployment and policy targets of its member governments.

The IEA TCPs and their networks of researchers and stakeholders also provided valuable inputs. The Hydrogen TCP helped the IEA update its latest assessment of the technology readiness levels of specific hydrogen technologies and offered insights on emergin technologies and barriers that need to be overcome to facilitate the deployment. The Advanced Fuel Cells TCP contributed with it annual tracking of fuel cell electric vehicles and infrastructur deployment.

Types of hydrogen in the Global Hydrogen Review

Hydrogen is a very versatile fuel that can be produced using all type of energy sources (coal, oil, natural gas, biomass, renewables an nuclear) through a very wide variety of technologies (reforminç gasification, electrolysis, pyrolysis, water splitting and many others In recent years, colours have been used to refer to different hydroge production routes (e.g. green for hydrogen from renewables and blu for production from natural gas with carbon capture, utilisation an storage [CCUS]), and specialised terms currently under discussio include "safe", "sustainable", "low-carbon" and "clean". There is n international agreement on the use of these terms as yet, nor hav their meanings in this context been clearly defined.

Because of the various energy sources that can be used, th environmental impacts of each production route can var considerably; plus, the geographic region and the proces configuration applied also influence impacts. For these reasons, th

IEA does not specifically espouse any of the above terms. Recognising that the potential of hydrogen to reduce CO_2 emissions depends strongly on how it is produced, this report highlights the role low-carbon hydrogen production routes can have in the clean energy transition. Low-carbon hydrogen in this report includes hydrogen produced from renewable and nuclear electricity, biomass, and fossil fuels with CCUS.[1]

Production from fossil fuels with CCUS is included only if upstream emissions are sufficiently low, if capture – at high rates – is applied to all CO_2 streams associated with the production route, and if all CO_2 is permanently stored to prevent its release into the atmosphere. The same principle applies to low-carbon feedstocks and hydrogen-based fuels made using low-carbon hydrogen and a sustainable carbon source (of biogenic origin or directly captured from the atmosphere).

This report also highlights the importance of establishing standards and certification to properly recognise the carbon footprints of the different hydrogen production routes. Since no standards have been internationally agreed and adopted, the IEA continues to differentiate the types of hydrogen by the technology used in their production, and uses this as the basis of its current definition of low-carbon hydrogen. This may evolve as dialogue within the international hydrogen community advances and more evidence and agreement emerge.

[1] In this report, CCUS includes CO_2 captured for use (CCU) as well as for storage (CCS), including CO_2 that is both used and stored (e.g. for enhanced oil recovery [EOR] or building materials) if some or all of the CO_2 is permanently stored. When use of the CO_2 ultimately leads to it being re-emitted to the atmosphere (e.g. urea production), CCU is specified.

Scenarios used in this Global Hydrogen Review

Outlook for hydrogen production and use

This Global Hydrogen Review relies on three indicators to track progress on hydrogen production and use:

- on-the-ground progress in hydrogen technology deployment
- government ambitions to integrate hydrogen into long-term energy strategies
- gaps between on-the-ground progress, government ambitions and projected energy transition requirements.

In this report, the Projects Case reflects on-the-ground progress. It takes all projects in the pipeline[2] into account as well as announced industry stakeholder plans to deploy hydrogen technologies across the entire value chain (from production to use in different end-use sectors).

Government targets and ambitions related to deploying hydrogen technologies are presented as hydrogen pledges. To gather relevant information from governments around the world, a joint IEA–European Commission work stream was established within the framework of the CEM Hydrogen Initiative, to consult governments around the world about their hydrogen targets and ambitions.

Pledges presented in this report include official targets (i.e. clea goals of national hydrogen strategies and roadmaps) as well a ambitions (i.e. plans communicated in consultations through the H2 work stream, but for which governments have not yet made officia announcements or adopted a strategy or roadmap).

For the first time, the IEA's May 2021 report Net zero by 2050 lay out in detail what is needed from the energy sector to reach net zer CO_2 emissions by 2050, in line with the Paris Agreement's ambitiou target to limit global temperature rise to 1.5°C. Based on thes findings, this Review compares actual implemented actions wit clean energy transition needs using two IEA scenarios: the Net zer Emissions by 2050 Scenario and the Announced Pledges Scenario

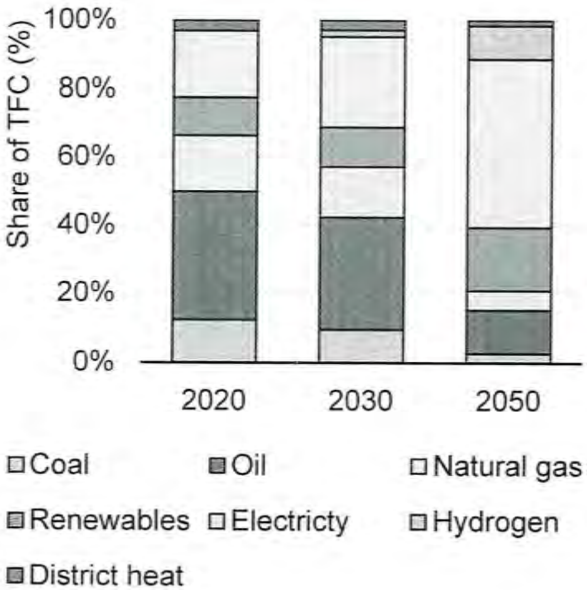
The Announced Pledges Scenario considers all national net zer emissions pledges that governments have announced to date an assumes they are realised in full and on time. This scenario thereb shows how far full implementation of national net zero emission pledges would take the world towards reaching climate goals, and highlights the potential contributions of different technologie including hydrogen.

[2] In addition to projects already operational, this includes those currently under construction, that have reached final investment decision (FID) and that are undergoing feasibility studies.

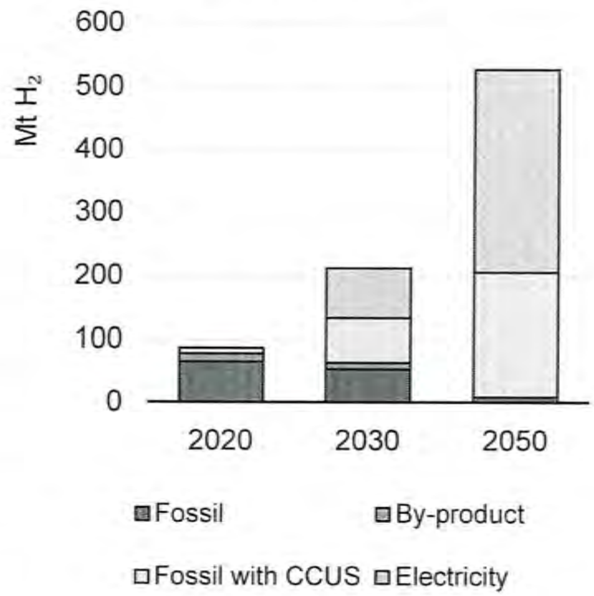
The role of hydrogen in the Net zero Emissions by 2050 Scenario

Hydrogen is an important part of the Net zero Emissions Scenario, but is only one piece of the puzzle

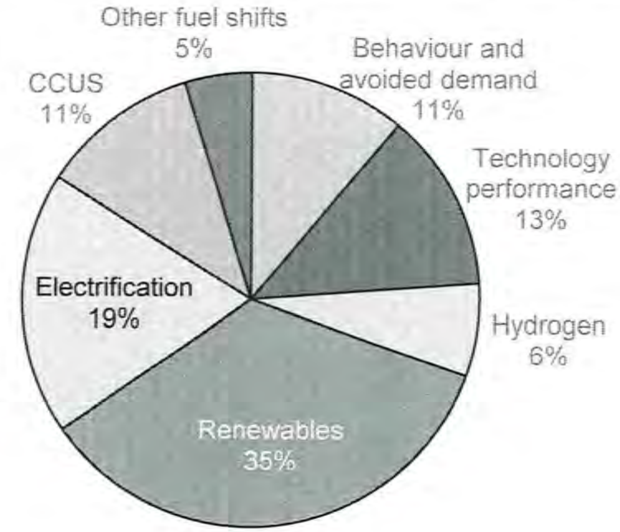
Share of total final energy consumption by fuel in the NZE, 2020-2050



Sources of hydrogen production in the NZE, 2020-2050



Cumulative emissions reduction by mitigation measure in the NZE, 2021-2050



Notes: NZE = Net zero Emissions Scenario. TFC = total final energy consumption. CCUS = carbon capture, utilisation and storage. "Behaviour" refers to energy service demand changes linked to user decisions (e.g. heating temperature changes). "Avoided demand" refers to energy service demand changes from technology developments (e.g. digitalisation). "Other fuel shifts" refers to switching from coal and oil to natural gas, nuclear, hydropower, geothermal, concentrating solar power or marine energy. "Hydrogen" includes hydrogen an hydrogen-based fuels.

Source: IEA (2021), Net zero by 2050.

Achieving net zero emissions by 2050 will require a broad range of technologies to transform the energy system. The key pillars of decarbonising the global energy system are energy efficiency, behavioural change, electrification, renewables, hydrogen and hydrogen-based fuels, and CCUS. The importance of hydrogen in the Net zero Emissions Scenario is reflected in its increasing share in total final energy consumption (TFC): in 2020, hydrogen and hydrogen-based fuels accounted for less than 0.1%,[3] but by 2030 they meet 2% of TFC and in 2050, 10%.

Nevertheless, this demand increase alone is not enough to make hydrogen a key pillar of decarbonisation. Hydrogen production must also become much cleaner than it is today. For instance, of the ~90 Mt H_2 used in 2020, around 80% was produced from fossil fuels, mostly unabated. Practically all the remainder came from residual gases produced in refineries and the petrochemical industry. This resulted in almost 900 Mt CO_2 emitted in the production of hydrogen, equivalent to the CO_2 emissions of Indonesia and the United Kingdom combined.

In the Net zero Emissions Scenario, hydrogen production undergoes an unparalleled transformation. By 2030, when total production reaches more than 200 Mt H_2, 70% is produced using low-carbo technologies (electrolysis or fossil fuels with CCUS). Hydroge production then grows to over 500 Mt H_2 by 2050, practically a based on low-carbon technologies. Reaching these goals will requir that installed electrolysis capacity increase from 0.3 GW today t close to 850 GW by 2030 and almost 3 600 GW by 2050, while CC captured in hydrogen production must rise from 135 Mt today t 680 Mt in 2030 and 1 800 Mt in 2050.

Strong hydrogen demand growth and the adoption of cleane technologies for its production thus enable hydrogen and hydroger based fuels to avoid up to 60 Gt CO_2 emissions in 2021-2050 in th Net zero Emissions Scenario, representing 6.5% of total cumulativ emissions reductions. Hydrogen fuel use is particularly critical fc reducing emissions in the hard-to-decarbonise sectors in which direc electrification is difficult to implement, i.e. heavy industry (particularl steel manufacturing and chemical production), heavy-duty roa transport, shipping and aviation. In the power sector, hydrogen ca also provide flexibility by helping to balance rising shares of variabl renewable energy generation and facilitating seasonal energ storage.

[3] This excludes industry sector on-site hydrogen production and use, which consumes around 6% of final energy consumption in industry today. Including on-site hydrogen production in industry, hydrogen and hydrogen-based fuels meet 1% of total final energy consumption today, 4% by 2030 and 13% by 2050 in the Net Zero Emissions Scenario.

Policy trends across key areas for hydrogen deployment

Progress in five key areas for hydrogen policymaking

Introduction

Integrating hydrogen as a new vector into energy systems is a complex endeavour: without government intervention, it will not be realised at the pace required to meet climate ambitions. Many governments are therefore already working with diverse stakeholders to address key challenges and identify smart policies that can facilitate this transformation. As needs differ for each country and industry, policies and actions must be based on relevant priorities and constraints, including resource availability and existing infrastructure.

In The Future of Hydrogen, the IEA identified five key areas for governments to define comprehensive policy frameworks to facilitate hydrogen adoption across the entire energy system:

1. Establish targets and/or long-term policy signals.
2. Support demand creation.
3. Mitigate investment risks.
4. Promote R&D, innovation, strategic demonstration projects and knowledge-sharing.
5. Harmonise standards and removing barriers.

The Global Hydrogen Review tracks and reports progress in thes areas with the aim of apprising governments and stakeholders of th pace of change in hydrogen policymaking. The Review highlight new policies being adopted around the world, assesses their impact and identifies potential gaps. Its dual objectives are to hel governments adopt or adapt other countries' successful experience and avoid repeating failures.

1. Establish targets and/or long-term policy signals

In their long-term energy strategies, governments should determine the most efficient way hydrogen can be used to support decarbonisation efforts. They should then set policies that send long-term signals about this role to boost stakeholder confidence in development of a marketplace for hydrogen and related technologies. Integrated actions can guide future expectations, unlock investments and facilitate co-operation among companies and countries.

When The Future of Hydrogen was released in June 2019, only Japan and Korea had published national hydrogen strategies to define the role of hydrogen in their energy systems, and France had announced a hydrogen deployment plan. Since then, 13 countries (Australia, Canada, Chile, the Czech Republic, France, Germany, Hungary, the Netherlands, Norway, Portugal, Russia, Spain and the United Kingdom) have published hydrogen strategies, along with the European Commission. Colombia announced the release of its strategy for the end of September 2021.

Two countries (Italy and Poland) have released their strategies for public consultation and more than 20 others are actively developing them. Several regional governments have also defined hydrogen strategies and roadmaps, including in Australia (Queensland, South Australia, Tasmania, Victoria and West Australia), Canada (British Columbia), China, France, Germany (Baden-Württemberg, Bavaria North Germany, North Rhine-Westphalia) and Spain (Basqu Country).

Some governments have even taken the additional step of definin hydrogen's role in other, overarching policy frameworks. Japan' Green Growth Strategy, for example, describes the country's visio for producing and using hydrogen and for developing internation supply chains.

A coherent picture of future-use cases for hydrogen

The strategies published to date show that, with slight difference almost all countries hold broadly similar views of the role hydroge should play in their energy systems. Practically all the strategies (1 of 16) highlight its vital importance in decarbonising the transpo and industry sectors.

In the case of transport, most governments emphasise medium- an heavy-duty transport, and Japan and Korea envisage an importar role for cars. Several governments highlight the potential use hydrogen and ammonia in shipping, while a smaller number ar considering producing synthetic fuels (synfuels) to decarbonis aviation (Germany recently released a power-to-liquids [Ptl roadmap) or using hydrogen in rail transport. Japan has taken th additional step of publishing an Interim Report of the Public-Private Council on Fuel Ammonia Introduction on using ammonia in electricity generation and shipping.

In the industry sector, each country's plans focus on the main industries: some target certain subsectors (chemicals in Chile and Spain; steel in Japan), while others take a more cross-sectoral approach (Canada and Germany). Canada and Chile have highlighted the role of hydrogen in decarbonising mining operations, and all countries with significant refining capacities prioritise this sector as well.

Other potential hydrogen uses that are mentioned in strategies but have received less attention are electricity generation – including energy storage and system balancing (11 of 16) – and heat in buildings (7 of 16). Finally, if international hydrogen trade develops, some countries have a clear plan to become exporters (Australia, Canada, Chile and Portugal) while others have started exploring the possibility of importing hydrogen if national production capacity cannot meet future demand (the European Union, Germany, Japan and the Netherlands).

Different views on how to produce hydrogen

Countries that have adopted hydrogen strategies present quite diverse visions on how it should be produced. Hydrogen production from electricity is common to all strategies, in some cases being the preferred route in the long term. Some prioritise renewable power (Chile, Germany, Portugal and Spain), while others are less specifi about the origin of the electricity (France's strategy mention renewable and low-carbon electricity).

While several governments (9 of 16) have set a significant role fc the production of hydrogen from fossil fuels with CCUS, other (including the European Union) consider this option for only th short and medium term to reduce emissions from existing asset while supporting the parallel uptake of renewable hydrogen. Canad has taken a different approach; instead of prioritising any specifi production pathway, it is focusing on the carbon intensity (hydrogen production, with targets to drive it to zero over time. Som countries (e.g. Canada and Korea) have flagged the potential us of by-product hydrogen (from the chlor-alkali or petrochemic industries) to meet small shares of demand.

Finally, most strategies refer to the potential for emergin technologies, such as methane pyrolysis or biomass-based route As these technologies are still at early stages of developmen prospects are considered uncertain.

Intermediate milestones to anchor long-term targets

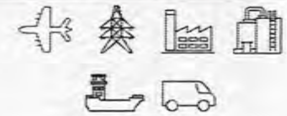
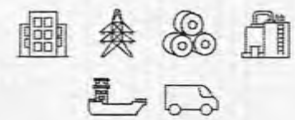
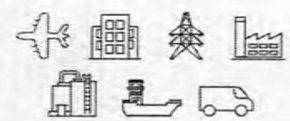
Almost all governments have adopted a phased approach t integrate hydrogen into their energy systems. How they defin phases varies, but strategies tend to recognise three stages: scalin up and laying the market foundations (early 2020s); widesprea adoption and market maturity (late 2020s to early 2030s); and full implementation of hydrogen as a clean energy vector (post-2030).

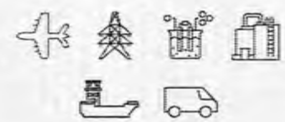
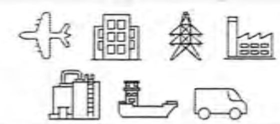
Deployment targets, while not present in all strategies, are a common feature to anchor expected progress within these phases. In some cases, targets have been proposed as a vision or an aspiration (Canada, Japan); in others, they convey a firm commitment with the intent to send strong signals to industry about the future marketplace for hydrogen. To date, practically none of these targets is legally binding.

Governments with adopted national hydrogen strategies; announced targets; priorities for hydrogen and use; and committed funding

Buildings · Electricity · Exports · Industry · Industry (chemicals) · Industry (steel) · Mining · Refining · Shipping · Transport. · Aviation

Country	Document, year	Deployment targets (2030)	Production	Uses	Public investment committed
Australia	National Hydrogen Strategy, 2019	None specified	Coal with CCUS Electrolysis (renewable) Natural gas with CCUS	Buildings, Electricity, Exports, Industry, Shipping, Transport	AUD 1.3 bln (~USD 0.9 bln)
Canada	Hydrogen Strategy for Canada, 2020	Total use: 4 Mt H_2/y 6.2% TFEC	Biomass By-product H_2 Electrolysis Natural gas with CCUS Oil with CCUS	Buildings, Electricity, Exports, Industry, Mining, Refining, Shipping, Transport	CAD 25 mln by 2026[1] (~USD 19 mln)
Chile	National Green Hydrogen Strategy, 2020	25 GW electrolysis[2]	Electrolysis (renewable)	Buildings, Exports, Industry (chemicals), Mining, Refining, Transport	USD 50 mln for 2021
Czech Republic	Hydrogen Strategy, 2021	Low-carbon demand: 97 kt H_2/yr	Electrolysis	Industry (chemicals), Transport	n.a.
European Union	EU Hydrogen Strategy, 2020	40 GW electrolysis	Electrolysis (renewable) Transitional role of natural gas with CCUS	Industry, Refining, Transport	EUR 3.77 bln by 2030 (~USD 4.3 bln)
France	Hydrogen Deployment Plan, 2018 National Strategy for Decarbonised Hydrogen Development, 2020	6.5 GW electrolysis 20-40% industrial H_2 decarbonised [3] 20 000-50 000 FC LDVs [3] 800-2 000 FC HDVs [3] 400-1 000 HRSs [3]	Electrolysis	Industry, Refining, Transport	EUR 7.2 bln by 2030 (~USD 8.2 bln)

Country	Document, year	Deployment targets (2030)	Production	Uses	Public investment committed
Germany	National Hydrogen Strategy, 2020	5 GW electrolysis	Electrolysis (renewable)		EUR 9 bln by 2030 (~USD 10.3 bln)
Hungary	National Hydrogen Strategy, 2021	Production: 20 kt/yr of low-carbon H_2 16 kt/yr of carbon-free H_2 240 MW electrolysis Use: 34 kt/yr of low-carbon H_2 4 800 FCEVs 20 HRSs	Electrolysis Fossil fuels with CCUS		n.a.
Japan	Strategic Roadmap for Hydrogen and Fuel Cells, 2019 Green Growth Strategy, 2020, 2021 (revised)	Total use: 3 Mt H_2/yr Supply: 420 kt low-carbon H_2 800 000 FCEVs 1 200 FC buses 10 000 FC forklifts 900 HRSs 3 Mt NH_3 fuel demand(4)	Electrolysis Fossil fuels with CCUS		JPY 699.6 bln by 2030 (~USD 6.5 bln)
Korea	Hydrogen Economy Roadmap, 2019	Total use: 1.94 Mt H_2/yr 2.9 million FC cars (plus 3.3 million exported)(5) 1 200 HRSs(5) 80 000 FC taxis(5) 40 000 FC buses(5) 30 000 FC trucks(5) 8 GW stationary FCs (plus 7 GW exported)(5) 2.1 GW of micro-cogeneration FCs(5)	By-product H_2 Electrolysis Natural gas with CCUS		KRW 2.6 tln in 2020 (~USD 2.2 bln)
Netherlands	National Climate Agreement, 2019 Government Strategy on Hydrogen, 2020	3-4 GW electrolysis 300 000 FC cars 3 000 FC HDVs (6)	Electrolysis (renewables) Natural gas with CCUS		EUR 70 mln/yr (~USD 80 mln/yr)
Norway	Government Hydrogen Strategy, 2020 Hydrogen Roadmap, 2021	n.a. (7)	Electrolysis (renewables) Natural gas with CCUS		NOK 200 mln for 2021 (~USD 21 mln)

Country	Document, year	Deployment targets (2030)	Production	Uses	Public investment committed
Portugal	National Hydrogen Strategy, 2020	2-2.5 GW electrolysis 1.5-2% TFEC 1-5% TFEC in road transport 2-5% TFEC in industry 10-15 vol% H_2 in gas grid 3-5% TFEC in maritime transport 50-100 HRS	Electrolysis (renewables)		EUR 900 mln by 2030 (~USD 1.0 bln)
Russia	Hydrogen roadmap 2020	Exports: 2 Mt H_2	Electrolysis Natural gas with CCUS		n.a.
Spain	National Hydrogen Roadmap, 2020	4 GW electrolysis 25% industrial H_2 decarbonised 5 000-7 500 FC LDVs-HDVs 150-200 FC buses 100-150 HRSs	Electrolysis (renewables)		EUR 1.6 bln (~USD 1.8 bln)
United Kingdom	UK Hydrogen Strategy, 2021	5 GW low-carbon production capacity	Natural gas with CCUS Electrolysis		GBP 1 bln (~USD 1.3 bln)

Note: TFEC = total final energy consumption. (1) In addition to CAD 25 mln, Canada has committed over CAD 10 bln to support clean energy technologies, including H_2. (2) This targe refers to projects that at least have funding committed, not to capacity installed by 2030. (3) Target for 2028. (4) From the interim Ammonia Roadmap. (5) Target for 2040. (6) Target for 2025 from the National Climate Agreement, 2019 (currently under revision). (7) Norway's strategy defines targets for the competitiveness of hydrogen technologies and project deployment.

2. Support demand creation

Creating demand for low-carbon hydrogen is critical for its widespread adoption. Policy support to "pull" investment across the value chain will be needed to make projects bankable and overcome deployment hurdles. For technologies that use hydrogen and are ready for commercialisation, policy support to close the price gap with incumbents can stimulate faster deployment and accelerate cost reductions that result from scaling up and learning by doing. Progress is under way, but not enough policies have been implemented to support longer-term targets and create demand for low-carbon hydrogen.

A dynamic situation in the transport sector

National hydrogen strategies place great value on using hydrogen in transport. As fuel cell electric vehicles (FCEVs) are commercially available for passenger cars, light-duty vehicles (LDVs) and buses, several countries have policies to support their deployment.

More than 20 countries offer specific purchase subsidies for FCEVs, ranging from EUR 1 500 (~USD 1 700) per vehicle in Finland to more than USD 30 000 in Korea. In fact, purchasers of fuel cell buses in Korea receive KRW 300 million (~USD 250 000). Tax benefits are in place in at least 20 countries, and at least 17 apply specific company tax benefits to support FCEV adoption in professional fleets.

China launched a new FCEV pilot cities programme in 2020 t enlarge FCEV industry supply chains. In contrast with vehicl purchase subsidies, the scheme rewards clusters of cities based o a series of parameters. To be eligible for financial rewards, cit clusters must deploy more than 1 000 FCEVs that meet certai technical standards; achieve a delivered hydrogen price at maximum of CNY 35.00/kg (~USD 5.00/kg); and provide at least 1 operational hydrogen refuelling stations (HRSs). Based on the pla and how well objectives are met, a maximum of CNY 1.5 billio (~USD 220 million) will be transferred to each selected city cluste between 2020 and 2023.

Hydrogen vehicles may also benefit from programmes to suppo zero emission vehicles (ZEVs) and implementation of CO_2 emission standards. Recent examples include California's ZEV mandate; th Dutch government's announcement that ZEVs will make up all publi transport bus sales by 2025; and the EU CO_2 emissions standard for heavy-duty vehicles (HDVs). In 2018, Switzerland adopted th LSVA road tax, which levies trucks weighing more than 3.5 tonne but waives the fee for ZEVs. This created an attractive business cas for hydrogen trucks, which are expected to reach about 200 by th end of 2021. While not specific to hydrogen vehicles, which have t compete with alternatives such as battery electric vehicles (BEVs these policies can stimulate FCEV deployment.

Other policies that can support hydrogen uptake in transport are the California Low Carbon Fuel Standard, Canada's Clean Fuel Standard and the UK Renewable Transport Fuel Obligation, which can also spur adoption of low-carbon hydrogen in biofuel production and refining. Meanwhile, in 2020 the Norwegian government announced that the country's largest ferry connection (Bodø-Værøy-Røst-Moskenes) will be fuelled by hydrogen and in March 2021 the Port of Tokyo stated that it will waive the entry fee for ships powered by LNG or hydrogen. These are the first measures implemented to support hydrogen or hydrogen-derived fuels in shipping, but as the technology has not yet reached the commercial level, it will take time to realise the impact of these policies.

Policies to support hydrogen-derived synthetic fuel use in aviation have attracted attention recently. As part of its Fit for 55 package, in July 2021 the European Commission proposed the ReFuel Aviation Initiative to mandate minimum synthetic fuel shares in aviation, rising from 0.7% in 2030 to 28% in 2050. This measure awaits European Council and European Parliament approval. Germany's strategy mentions a minimum quota of 2% synthetic fuels in aviation by 2030, which has now passed the parliamentary process and is legally binding. In addition, Germany's recently released power-to-liquids (PtL) roadmap targets 200 000 tonnes of hydrogen-based sustainable aviation fuel in 2030. The Dutch government has already expressed interest in these types of measures.

Policies for other sectors still under discussion

Little progress has been achieved on policies for low-carbo hydrogen adoption in other sectors. Despite its anticipate importance, few policies have been designed specifically to creat demand for low-carbon hydrogen in industry.

Also in its Fit for 55 package, in July 2021 the European Commissio proposed a modification of the Renewable Energy Directive t include a 50% renewable hydrogen consumption in industry by 203(Germany's strategy includes the potential implementation (obligatory quotas for selected clean products (e.g. hydrogen-base steel) and aims to explore how to implement such solutions at th national and European levels.

India has also announced mandatory quotas for using renewabl hydrogen in refining (10% of demand from 2023-24, increasing t 25% in the following five years) and fertiliser production (5% (demand from 2023-24, increasing to 20% in the following five years with potential extension to the steel industry in the near future. Thi will spur India to replace part of its current capacity for hydroge produced from natural gas (typically imported) with hydrogen fror renewables while also creating new demand for locally produce hydrogen.

Injecting hydrogen into the natural gas grid has also attracte attention as another means of creating new hydrogen demand. Whil no measures have yet been adopted, some countries are taking steps in this direction. For instance, Portugal's national strategy targets 10-15 vol% H_2 blending by 2030 and Chile is preparing a bill to mandate blending quotas.

Lack of targets and policies for demand creation can stall low-carbon supply expansion

Because most government targets and policies to date have been focused exclusively on enlarging hydrogen supplies, low-carbon hydrogen production has outpaced demand growth. Strategic action is therefore needed to avoid the value chain imbalances that can result in inefficient policy support.

If hydrogen demand is not sufficiently stimulated, producers may not be able to secure off-takers and the development of low-carbon hydrogen supply capacity may held back. This could result in low-carbon hydrogen capacity replacing only certain parts of current production in industrial applications, which would impede scale-up and discourage cost reductions, and ultimately delay adoption of hydrogen as a clean energy vector.

3. Mitigate investment risks

Many projects currently under way face risks related to uncertain demand, lack of experience and value chain complexity. Measures to address risks linked to capital and operational costs can help tip the balance in favour of private investment in these first projects.

European countries are leading the way

European policymakers have been particularly active in implementing measures to mitigate the risks of hydrogen-related project developers. In its Climate Agreement (launched June 2020), the Netherlands proposed including hydrogen in the SDE++ scheme, which offers incentives to develop CO_2 reduction technologies and renewable energy. This scheme recently triggered its intended actions and in May 2021 the Dutch government committed EUR 2 billion for the Porthos project to bridge the gap between current rates for CO_2 emissions allowances and the costs involved in capturing, transporting and storing CO_2 underground. This will facilitate development of projects to produce hydrogen from fossil fuels with CCUS.

In September 2020, the European Commission announced a call for tenders for projects to build electrolysis plants at the 100-MW scale. All proposals have been evaluated and some awarded projects have been announced. Perhaps more importantly, the Commission included hydrogen in the Important Projects of Common European Interest (IPCEI) scheme, which allows projects validated by bot member states and the Commission to receive public support beyon the usual boundaries of state aid rules. This is expected to unloc significant project investment across the entire hydrogen value chair stimulating scale-up in the next decade.

Countries beyond Europe are also taking action. In June 202 Canada announced a new Clean Fuels Fund to help private investor overcome the barrier of high upfront capital costs to construct ne clean fuel production capacity, and will provide support to a minimur of ten hydrogen projects.

Public financial institutions are getting involved

Financial institutions can be critical in mitigating the investment risk of first movers. While the European Investment Bank (EIB) provide significant investments for R&D in hydrogen projects in the las decade, it has now shifted its focus to offer financial support an technical assistance for the development of large-scale projects. Th EIB signed related collaboration agreements with France Hydrogèn (2020) and the Portuguese government (2021).

In May 2020, the Australian government, through the Clean Energ Finance Corporation, made AUD 300 million available through th Advancing Hydrogen Fund, thereby taking the first steps to facilitat investments in hydrogen projects to scale up production and end uses. In 2021, the government of Chile launched (through CORFO) a USD 50-million call for funding to develop electrolysis projects.

New policy instruments are coming into play

Governments are developing new and innovative policy instruments to support investment in hydrogen projects. In June 2021, the German government announced the H2 Global programme, with the aim of ramping up the international market for hydrogen produced from renewable electricity. The scheme will tender ten-year purchase agreements on hydrogen-based products, providing certainty to investors on project bankability. With a total budget of EUR 900 million, the scheme expects to leverage more than EUR 1.5 billion in private investments.

In its national hydrogen strategy, Germany's federal government also announced that it will launch a new Carbon Contracts for Difference (CCfD) pilot programme to support the use of hydrogen from renewable energy sources in the steel and chemical industries. This programme will pay the difference between the CO_2 abatement costs of the project and the CO_2 price in the EU Emissions Trading Scheme (EU ETS). If the EU ETS price rises above the project's CO_2 abatement costs, companies will have to repay the difference to the government. If the pilot is completed successfully, the scheme may be expanded to other industry subsectors.

The European Commission announced that it is also considering th carbon contracts for difference (CCfD) concept. Recent pric increases in the EU ETS – which nearly doubled in 2021 to more tha EUR 60/t CO_2 – are expected to limit the public spending needed t bridge the cost gap in these schemes.

Auctions are also a powerful policy instrument, and they have bee critical in ramping up other clean energy technologies, such as sola PV and wind energy. They are now about to be applied to hydroger with India's New and Renewable Energy Minister announcing (i June 2021) auctions for the production of hydrogen from renewables The Netherlands' national strategy also mentions the potential use c combined auctions for offshore wind and hydrogen production.

In Chile, the government is holding regular public and open tender to develop large-scale projects for producing hydrogen fror renewable energy sources on public land. As these projects requir large land areas, facilitating access to public land with goo renewable resources can reduce investment risks and accelerat deployment.

Along with its Hydrogen Strategy, the United Kingdom launched public consultation on a business model for low-carbon hydrogen wit the aim of defining specific policy instruments to help proje developers overcome costs barriers.

4. Promote R&D, innovation, strategic demonstration projects and knowledge-sharing

The future success of hydrogen will hinge on innovation. Today, low-carbon hydrogen is more costly than unabated fossil fuel-based hydrogen, which undermines its uptake. Multiple end-use technologies at early stages of development cannot compete in open markets, in part because they have not yet realised the economies of scale that come with maturity. Governments play a key role in setting the research agenda and adopting policy tools that can incentivise the private sector to innovate and bring technologies to the market.

Selected active hydrogen R&D programmes

Country	Programme	Funding and duration
Australia	ARENA's R&D Programme CSIRO Hydrogen Mission	AUD 22 mln (~USD 15 mln) – 5 yr AUD 68 mln (~USD 47 mln) – 5 yr
European Union	Clean Hydrogen for Europe	EUR 1 bln (~USD 1. bln) – 10 yr
France	PEPR Hydrogène	EUR 80 mln (~USD 91 mln) – 8 yr
Germany	National Innovation Programme for Hydrogen and Fuel Cell Technology	EUR >250 mln (~USD 285 mln) – 10 yr
	Wasserstoff-Leitprojekte	EUR 700 mln (~USD 800 mln) – n.a.
Japan	NEDO innovation programmes	JPY 699 bln (~USD 6.5 bln) – 10 yr
Spain	Misiones CDTI	EUR 105 mln (~USD 120 mln) – 3 yr
United Kingdom	Low Carbon Hydrogen Supply	GBP 93 mln (~USD 119 mln) – n.a.
United States	H2@Scale M²FCT – H2New Consortia DOE Hydrogen Program	USD 104 mln – 2 yr USD 100 mln – 5 yr USD 285 m/yr

Hydrogen innovation requires a boost

Programmes to foster hydrogen innovation are not yet flourishing although some positive signals are emerging and severa governments have launched hydrogen-specific programmes to fun R&D in technologies across the entire hydrogen value chair However, current public R&D spending on hydrogen is below level dedicated in the early 2000s during the last wave of support fc hydrogen technologies (see Chapter Investments and Innovation Further, integrated efforts will be required to avoid bottlenecks alon the value chain.

Government and industry co-operation is critical to ensure th implementation of robust innovation programmes. With more tha EUR 1 billion in funding provided since 2008, the Fuel Cells an Hydrogen Joint Undertaking (FCH JU) is a prime example of a public private partnership to support R&D and technology demonstratior Building on its success, the European Commission will launch th Clean Hydrogen for Europe Joint Undertaking at the end of 2021, wit matching budgets of EUR 1 billion from public funding and privat investment until 2027.

The European Commission also initiated the European Clea Hydrogen Alliance in July 2021 to bring together industry, nationa and local public authorities, civil society and other stakeholders t establish an investment agenda for hydrogen. Similarly, the Chilean Energy Sustainability Agency introduced a Green Hydrogen Incubator in 2021 to co-ordinate stakeholders and provide consulting services to facilitate the development of technology demonstration projects. In Morocco, stakeholders from the private sector, academia and the government established the Green Hydrogen Cluster to support the emerging renewable hydrogen sector. In the United States, the Department of Energy (DOE) launched the First Energy Earthshot dedicated to hydrogen, bringing together stakeholders with the target of slashing the cost of clean hydrogen by 80% (to USD 1.00/kg H_2) by 2030.

International co-operation is growing rapidly

Multilateral initiatives and projects can promote knowledge-sharing and the development of best practices to connect a wider group of stakeholders. For instance, Mission Innovation (MI), which works to catalyse R&D action and investment, has engaged with the FCH JU through the Hydrogen Valley Platform to facilitate collaboration and knowledge-sharing within more than 30 hydrogen valleys across the globe. With the launch of the Clean Hydrogen Mission in June 2021, MI took another step to boost R&D in hydrogen technologies, with th goal of reducing end-to-end clean hydrogen costs to USD 2.00/kg b 2030. MI also aims to establish at least 100 hydrogen valleys, to b featured on the Hydrogen Valley Platform.

In addition to the several bilateral agreements signed betwee governments in recent years, international co-operation agreement have been established between governments and the private sectc (the MOUs between the Port of Rotterdam and the governments c Chile and South Australia is one example). All have the short- t medium-term objective of co-operating to share knowledge, bes practices and technology development to reduce costs. They als share the long-term aim of laying the foundations for futur international hydrogen supply chains to ensure the development c trade in hydrogen and hydrogen-derived fuels.

In June 2020, the energy ministers of the Pentalateral Forur (Austria, Belgium, France, Germany, Luxembourg, the Netherland and Switzerland) signed a joint political declaration affirming the commitment to strengthen co-operation on hydrogen.

Selected bilateral agreements between governments to co-operate on hydrogen development, 2019-2021

Countries	Objective
Germany - Australia	Formulate new initiatives to accelerate development of a hydrogen industry, including a hydrogen supply chain between the two countries. Focus on technology research and identification of barriers.
Germany - Canada	Form a partnership to integrate renewable energy sources, technological innovation and co-operation, with a focus on hydrogen.
Germany - Chile	Strengthen co-operation in renewable hydrogen and identify viable projects.
Germany - Morocco	Develop clean hydrogen production, research projects and investments across the entire supply chain (two projects have already been announced by the Moroccan agencies MASEN and IRESEN).
Germany - Saudi Arabia	Co-operate on the production, processing and transport of hydrogen from renewable energy sources.
Morocco - Portugal	Examine opportunities and actions needed to develop hydrogen from renewable energy sources.
Netherlands - Chile	Establish a structured dialogue on the development of import-export corridors for green hydrogen, aligning investment agendas and facilitating collaboration among private parties.
Netherlands - Portugal	Co-operate to advance the strategic value chain for producing and transporting renewables-based hydrogen, connecting the hydrogen plans of the two countries.
Japan – United Arab Emirates	Co-operate on technology development, regulatory frameworks and standards to create an international hydrogen supply chain.
Japan - Argentina	Strengthen collaboration on the use of clean fuels and promote investments to deploy large-scale hydrogen production from renewable energy sources.
Japan - Australia	Issue a joint statement highlighting the commitment already in place between the two countries and recognising the importance o co-operation on an international hydrogen supply chain.
Singapore - New Zealand	Boost collaboration on establishing supply chains for low-carbon hydrogen and its derivatives, and strengthen joint R&D, network and partnerships.
Singapore - Chile	Foster co-operation on projects and initiatives to advance hydrogen deployment through information exchange and the establishment of supply chains and partnerships.
Australia - Korea	Develop joint hydrogen co-operation projects with specific action plans.

5. Harmonise standards and removing barriers

Two broad issues have emerged regarding regulations, codes and standards for hydrogen deployment. The first is the need to review national regulations that define the roles of utilities and grid operators. At present, certain aspects of market structure warrant regulatory frameworks that keep these entities separate. If hydrogen deployment is successful, however, it can concurrently become an integral part of the gas network and support electricity grid resilience and reliability of the electricity grid. Hydrogen will thereby facilitate sector coupling between electricity and gas utilities, creating a new role requiring specific regulation.

The second issue is the need to ensure that a standardisation framework based on national or international norms is in place and is appropriately applicable to the use of hydrogen and its carriers. This ongoing process involves numerous international organisations.

Regulations need to be adapted to remove barriers in the near term

The IPHE's Regulations, Codes, Standards and Safety Working Group conducted a Regulatory Gaps Compendium survey among its participating countries to determine regulatory needs in critical areas for hydrogen and fuel cell deployment. Participants provided input on focal areas within two topics: hydrogen infrastructure and hydrogen for mobility/transportation.

Survey results indicated broad regulatory needs, particularly a industry activity increases and expands beyond road transportatio Critical within the infrastructure area is the establishment of a leg framework for injecting hydrogen into natural gas systems (at bot the distribution and transmission levels) and requirements for th scale-up and public use of liquid hydrogen in refuelling infrastructur

Concerning transportation/mobility, the most critical priority is t enable the use of hydrogen in non-road transport modes – i.e. ra shipping and aviation. The survey also determined that safet (including maintenance requirements, approvals and inspections) i a priority and improvements should be incorporated into efforts t address the other needs identified.

To remove barriers to hydrogen adoption, some countries have take the first steps to adapt their regulations. For instance, in 2020 th Chinese National Energy Administration released a draft of the ne Energy Law in which hydrogen is classified, for the first time, as a energy carrier. This means hydrogen will now be a freely tradabl energy asset and its transportation will be subject to less stringe requirements than for hazardous substances (its previou classification).

Other countries, including Chile, Colombia, Korea and France, hav modified their energy legislation to facilitate the adoption of hydroge as an energy carrier. As tax regulations can also create significant barriers to hydrogen technology endorsement, several countries are exploring options to reduce this impact. The European Commission recently proposed revision of the Energy Taxation Directive to avoid double taxation of energy products, including hydrogen, and Germany announced that hydrogen produced from renewable electricity will not be subject to the levy used to fund support for clean power.

A low-carbon hydrogen market requires carbon accounting standards

International hydrogen trade could become a cornerstone of the clean energy transition, enabling the export of low-carbon hydrogen from regions with abundant access to renewable energy or low-cost production of hydrogen from fossil fuels with CCUS. To facilitate trade, however, relevant standardisation bodies will need to develop international standards – based on a common definition of low-carbon hydrogen – to remove and/or reduce regulatory barriers.

During the 32nd IPHE Steering Committee, countries recognised that developing internationally agreed accounting standards for different sources of hydrogen along the supply chain will be vital to create a market for low-carbon hydrogen. To this end, a Hydrogen Production Analysis Task Force was established to review and reach consensus on a methodology and analytical framework for determining GHG emissions related to one unit of produced hydrogen.

Such a mutually recognised, international framework will avoi mislabelling or double-counting environmental impacts and shoul provide consensus on an approach to "certificates of origin". Th methodology is based on principles of inclusiveness (methodologie should not exclude any potential primary energy), flexibilit (approaches must allow for unique circumstances and henc flexibility), transparency (methodologies must be transparent i approach and assumptions to build confidence), comparability (th approach should be comparable with those used for other energ vectors), and practicality (methodologies must be practica facilitating uptake by industry and use in the market).

The methodology also describes the requirements and evaluatio methods applied from "well to gate" for the most-used hydroge production pathways: electrolysis, steam methane reforming wit CCUS, by-product and coal gasification with CCUS. Over time, th Task Force intends to develop other methods and to potentially appl the approach to different physical states of hydrogen, diverse energ carriers and emissions arising during transport to the end user. I addition to IPHE activities, some countries (e.g. Australia, France an the United Kingdom) have started to develop certification scheme for hydrogen's carbon footprint.

Research to develop evidence-based safety standards

During its recent bi-annual Workshop on Research Priorities for Hydrogen Safety, the International Association for Hydrogen Safety (HySafe) mapped state-of-the-art and recent progress in pre-normative research to support standards development, including identifying and ranking pending research needs. Ultimately, research needs were identified for five key safety areas: liquid hydrogen use; the compatibility of certain materials (metals and plastics) with hydrogen; hydrogen leak detection; hydrogen phenomena modelling; and electrolysis safety for unsteady-state operations. Despite recent progress, a significant lack of understanding regarding the accidental behaviour of liquid hydrogen was identified as an outstanding challenge. At the engineering level, major research gaps exist for the non-road transport subsectors.

Hydrogen demand

Overview and outlook

Hydrogen demand has grown strongly since 2000, particularly in refining and industry

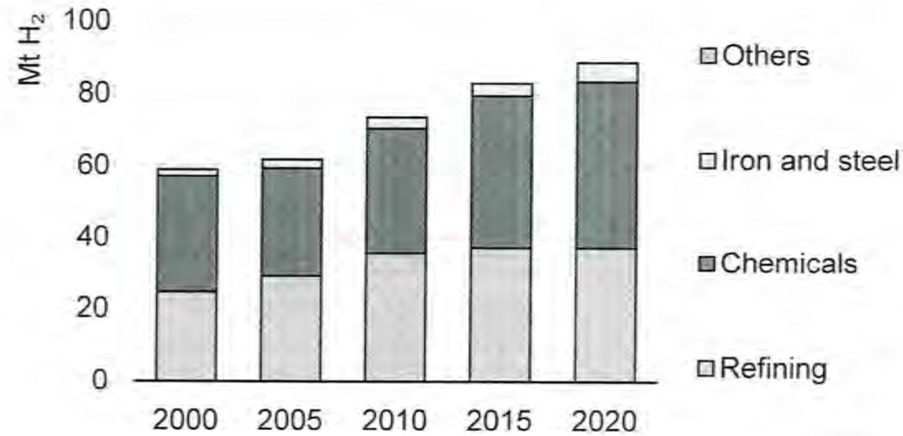
Global hydrogen demand was around 90 Mt H_2[4] in 2020, having grown 50% since the turn of the millennium. Almost all this demand comes from refining and industrial uses. Annually, refineries consume close to 40 Mt H_2 as feedstock and reagents or as a source of energy.

Demand is somewhat higher (more than 50 Mt H_2) in the industry sector, mainly for feedstock. Chemical production accounts for around 45 Mt H_2 of demand, with roughly three-quarters directed to ammonia production and one-quarter to methanol. The remaining 5 Mt H_2 is consumed in the direct reduced iron (DRI) process for steelmaking. This distribution has remained almost unchanged since 2000, apart from a slight increase in demand for DRI production.

The adoption of hydrogen for new applications has been slow, with uptake limited to the last decade, when fuel cell electric vehicle (FCEV) deployment started and pilot projects began to inject hydrogen into gas grids and use it for electricity generation. Positive results from these experiences prompted the development of some hydrogen technologies to the point of commercialisation.

In parallel, concerns about climate change have increased and governments and industry are making strong commitments to reduce emissions. Although this has accelerated the adoption of hydroge for new applications, demand in this area remains minuscule. I transport, for example, annual hydrogen demand is less than 20 kt H – just 0.02% of total hydrogen demand. As shown in the IEA' Net zero by 2050 roadmap, achieving government decarbonisatio goals will require a step change in the pace of rolling out hydroge technologies across many parts of the energy sector.

Hydrogen demand by sector, 2000-2020

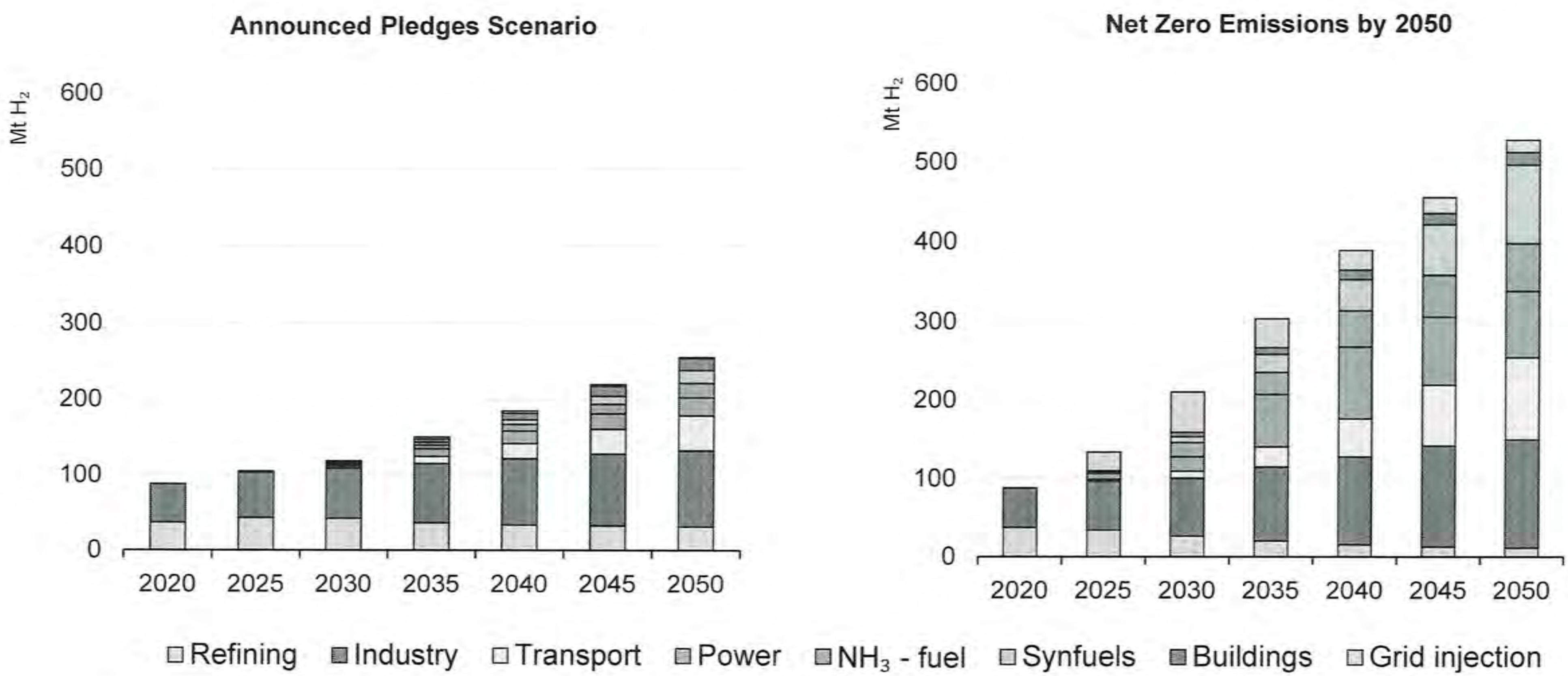


Note: "Others" refers to small volumes of demand in industrial applications, transport, grid injection and electricity generation.

[4] This includes more than 70 Mt H_2 used as pure hydrogen and less than 20 Mt H_2 mixed with carbon-containing gases in methanol production and steel manufacturing. It excludes around 30 Mt H_2 present in residual gases from industrial processes used for heat and electricity generation as this use is linked to the inherent presence of hydrogen in these residual streams rather than to any hydrogen requirement – these gases are not considered here as a hydroge demand.

Government pledges suggest greater hydrogen use, but not nearly enough to the level needed to achieve net zero energy system emissions by 2050

Hydrogen demand by sector in the Announced Pledges and Net zero Emissions scenarios, 2020-2050



Notes: "NH_3 - fuel" refers to the use of hydrogen to produce ammonia for its use as a fuel. The use of hydrogen to produce ammonia as a feedstock in the chemical subsector is included within industry demand.

Hydrogen-based fuel use must expand to meet ambitious climate and energy goals

The pathway to net zero emissions by 2050 requires substantially wider hydrogen use in existing applications (e.g. the chemical industry) and a significant uptake of hydrogen and hydrogen-based fuels for new uses in heavy industry, heavy-duty road transport, shipping and aviation.

In the Net zero Emissions Scenario, hydrogen demand multiplies almost sixfold to reach 530 Mt H_2 by 2050, with half of this demand in industry and transport. In fact, industry demand nearly triples from around 50 Mt H_2 in 2020 to around 140 Mt H_2 in 2050. Transport demand soars from less than 20 kt H_2 to more than 100 Mt H_2 in 2050, owing to the volumes that small shares of hydrogen can achieve in certain segments.

Power sector penetration also increases significantly as hydrogen's use in gas-fired power plants and stationary fuel cells helps to balance increasing generation from variable renewables; integrate larger shares of solar PV and wind; and provide seasonal energy storage. Hydrogen use in buildings also increases, although its penetration is very limited to certain situations in which other clean and more efficient technologies cannot be adopted and/or it is needed to increase electricity grid flexibility.

By 2050, around one-third of hydrogen demand in the Net zero Emissions Scenario is used to produce hydrogen-based fuels such as ammonia, synthetic kerosene and synthetic methane. Ammoni use expands beyond existing applications (primarily nitroge fertilisers) to be adopted for use as a fuel.

As ammonia has advantages over the direct use of hydrogen fc long-distance shipping, in the Net zero Emissions Scenario it meet around 45% of global shipping fuel demand. To reduce CC emissions in power generation, ammonia is also increasingly cc fired in existing coal plants, with some former coal-fired units bein fully retrofitted to use 100% ammonia to provide low-carbo dispatchable power.

Synthetic fuels (synfuels) manufactured from hydrogen and CC captured from biomass applications (bioenergy-fired power c biofuel production) or from the atmosphere (direct air capture [DAC are also used in energy applications in the Net zero Emission Scenario. Synthetic kerosene in particular meets around one-thir of global aviation fuel demand while synthetic methane meet around 10% of demand for grid gas use in buildings, industry an transport.

Overall, hydrogen and hydrogen-based fuels meet 10% of global final energy demand in 2050[5].

Refining is the only application for which hydrogen demand decreases in the Net zero Emissions Scenario – from close to 40 Mt H_2 in 2020 to 10 Mt H_2 in 2050: the reason is simply that the need to refine oil drops sharply as clean fuels and technologies replace oil-derived products.

Although recent government net zero commitments create momentum for adopting hydrogen-based fuels across the energy system, volumes are insufficient to achieve net zero emissions by 2050. While in the Announced Pledges Scenario hydrogen demand nearly triples to over 250 Mt H_2 by 2050, this is less than half the amount modelled in the Net zero Emissions Scenario.

Demand in the Announced Pledges Scenario is lower in almost all sectors, with refining being the exception as the rate of replacing oil-based fuels is lower. This strongly impacts hydrogen and hydrogen-based fuel uptake in transport applications, with hydrogen use in transport 55% lower in the Announced Pledges than in the Net zero Emissions Scenario. The difference in demand for hydrogen to produce hydrogen-based fuels is the largest, at 80% less for synfuels in the Announced Pledges than in the Net zero Emission Scenario, and close to 70% less for ammonia production.

Furthermore, a slower rate of renewables deployment mean electricity systems require less balancing of generation an seasonal storage in the Announced Pledges than in the Net zer Emissions Scenario; as a result, hydrogen demand for electricit generation in the Announced Pledges Scenario is about one-quarte that of the Net zero Emissions.

In the case of industry, as the largest single use of hydrogen is fc feedstock, demand growth is robust in both scenarios, although it i 30% less in the Announced Pledges than in the Net zero Emission:

[5] This excludes onsite hydrogen production and use in the industry sector. Including on-site hydrogen production in industry, hydrogen and hydrogen-based fuels meet 13% of global final energy demand by 2050 in the NZE.

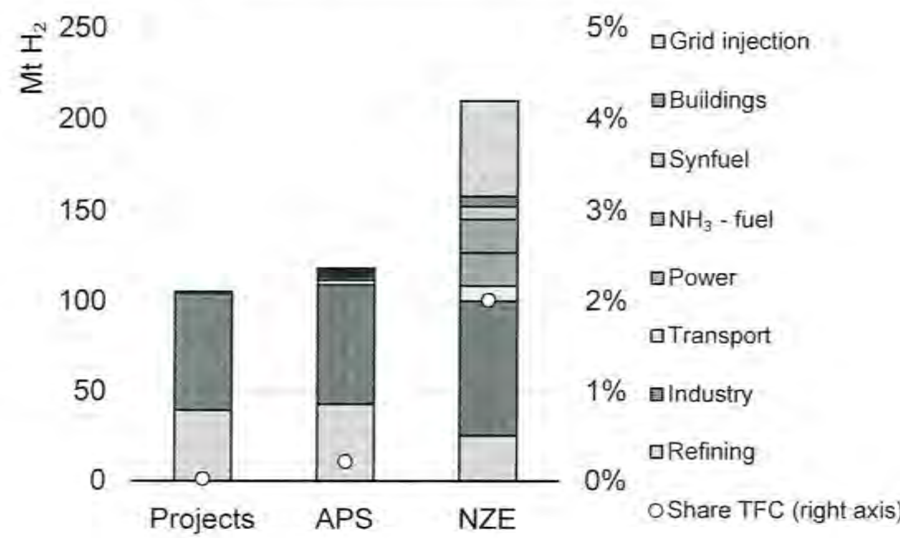
The next decade will be decisive in for laying the foundation for hydrogen's role in the clean energy transition

Increasing the use of hydrogen as a new energy vector is a long-term endeavour, as it can take decades for a new fuel to significantly penetrate the energy mix. Immediate action is therefore required to facilitate the scaling-up process and create the conditions needed by 2030 to ensure that hydrogen technologies can be widely diffused to secure their long-term usefulness in the clean energy transition.

Despite recent strong momentum, projects currently under development indicate that anticipated hydrogen technology deployment in demand sectors does not yet align with the Net zero Emissions Scenario's ambitions. Present government focus on decarbonising hydrogen production is stronger than on stimulating demand for new applications. Apart from notable exceptions for deploying different vehicle types of FCEVs in China, Korea, Japan and some EU countries, few government targets seek to accelerate the adoption of hydrogen-based fuels in end-use sectors.

Moreover, current country ambitions to stimulate hydrogen use for new applications is not sufficient to meet their net zero pledges. Using target-setting on its own as a long-term signal is not effective enough to create the market dynamics needed to unlock private sector investments and stimulate deployment of hydrogen technologies. Targets need to be accompanied by concrete policies to support implementation, including strong demand-side measure that create clearly identifiable markets.

Hydrogen demand in the Projects case, Announced Pledges an Net zero Emissions scenarios, 2030



Notes: APS = Announced Pledges Scenario. NZE = Net zero Emissions Scenario. TF = total final energy consumption. "Share TFC" excludes on-site hydrogen production and use in the industry sector. Including it, hydrogen and hydrogen-based fuels meet less than 2% of total final energy consumption today, 2% in the APS and 4% in the NZE by 2030. "NH_3 fuel" refers to the use of hydrogen to produce ammonia for its use as a fuel.

Governments need to act quickly and decisively from now until 2030 to trigger this transformation. Implementing quotas or mandates to inject hydrogen into the gas grid can create dependable hydrogen demand in this early deployment phase, which can help building up new low-carbon hydrogen production capacity while governments decide, plan and develop hydrogen-specific infrastructure. Once new infrastructure is ready, low-carbon hydrogen production capacity developed in the early deployment phase can migrate from the natural gas grid to supply hydrogen directly to end users in new applications, several of which should be demonstrated and scaled up in upcoming years.

Adopting hydrogen in transport will require support to deploy FCEVs and fuelling infrastructure. In particular, early demonstration and scaled-up hydrogen use in heavy-duty trucks, for operations in which hydrogen may have advantages over battery electric powertrains (e.g. for certain long-haul operations[6]), and the installation of high-throughput, high-pressure refuelling stations along key road freight corridors are important foundations for hydrogen use in road transport.

While BEVs are expected to dominate the transition to net zero emissions in light-duty road transport owing to their higher efficiency and lower total cost of ownership (TCO), support for near-term adoption of hydrogen fuel cells for light-duty vehicles (LDVs) an buses could boost hydrogen and fuel cell demand as well a infrastructure expansion, ultimately reducing the cost of fuel ce trucks and encouraging their adoption.

Similarly, demonstrating hydrogen and ammonia as fuels fc shipping, setting quotas for synfuels in aviation, and deploying th corresponding refuelling infrastructure at ports and airports woul support hydrogen and hydrogen-based fuel uptake in these sector in which emissions are hard to abate.

Demonstration of specific end-use technologies, such as hydroger based DRI in steelmaking or high-temperature heating application: will be critical to unleash significant demand growth in industry. I buildings, all sales of natural gas equipment (when it is preferre over electric heat pumps) should be compatible with hydrogen t allow eventual switching. Demonstration and pilot projects for fue cells and other hydrogen equipment for domestic applications ar needed to raise consumer confidence in hydrogen technologie: operational safety and reduce financial risk.

In the power sector, gas turbine manufacturers are confident the can provide gas turbines that run on pure hydrogen by 2030. T incentivise the use of low-carbon hydrogen to reduce emission from existing gas-fired plants and provide electricity syster

[6] For a comparison of distance-based total cost of ownership (TCO) see Figure 5.7 of Energy Technology Perspectives 2020

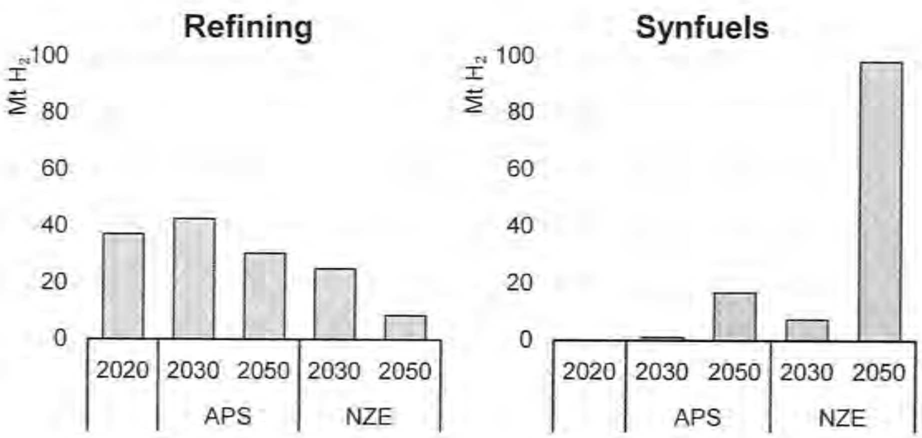
iea

flexibility, strong government support and measures will be needed to close the cost gap between natural gas and low-carbon hydrogen. Co-firing of ammonia in coal-fired power plants has been successfully demonstrated at low co-firing shares, but more RD&D is needed in using pure ammonia directly as fuel in steam or gas turbines.

Refining

Hydrogen demand in refining declines as climate ambitions increase, but synfuels offer new opportunities

Hydrogen demand in refining and synthetic fuels production in the Announced Pledges and Net zero Emissions scenarios, 2020-2050



Notes: APS = Announced Pledges Scenario. NZE = Net zero Emissions Scenario.

Oil refining was the single largest consumer of hydrogen in 2020 (close to 40 Mt H_2). Refineries use hydrogen to remove impurities (especially sulphur) and to upgrade heavy oil fractions into lighter products. China is the largest consumer of hydrogen for refining (close to 9 Mt H_2/yr), followed by the United States (more than 7 Mt H_2/yr) and the Middle East (close to 4 Mt H_2/yr). Together, these three regions account for more than half of global demand.

Around-half of refining demand is met with by-product hydrogen fror other processes in the refinery (e.g. catalytic naphtha reforming) c from other petrochemical processes integrated into certain refinerie (e.g. steam crackers). The remainder is met by dedicated on-sit production or merchant hydrogen sourced externally. The majority c on-site production is based on natural gas reforming, with som exceptions such as the use of coal gasification, which makes u almost 20% of dedicated hydrogen production at refineries in China

In 2020, hydrogen production to meet refining demand wa responsible for close to 200 Mt CO_2 emissions. However, som ongoing efforts to reduce these emissions are already operative: si plants with facilities retrofitted with CO_2 capture and two others usin electrolysers to produce hydrogen. At least another 30 projects ar under development to retrofit current fossil-based hydroge production with CCUS; develop new capacities based on advance reforming technologies coupled with CCUS; or deploy electrolysi capacities. In the short term, refineries can offer anchor demand fc the development of low-carbon hydrogen supplies.

Oil refining is the only sector that shows declining hydrogen deman in the Announced Pledges and Net zero Emissions scenarios. A climate ambitions increase, oil refining activity declines more sharpl as oil demand declines, especially after 2030. In the Announced Pledges Scenario, hydrogen demand increases to more than 40 Mt H_2 to then drop to around 30 Mt H_2 in 2050. In the Net zero Emissions shows 25 Mt H_2 in 2030 and 10 Mt H_2 in 2050. Dropping oil demand will create a dilemma for refinery operators, as investing in decarbonising current hydrogen production can be difficult to justify if falling demand entails the risk of stranded assets.

However, the emergence of new sources of hydrogen demand could bolster the business case for such investments by offering the opportunity to supply developing hydrogen markets and meet demand in new sectors (e.g. transport, other industry applications and electricity generation), such as those covered in the Announced Pledges and the Net zero Emissions scenarios. Using low-carbon hydrogen could be an option to decarbonise high-temperature-heat operations in refineries, helping meet the net zero targets of oil and gas companies. Producing low-carbon synthetic hydrocarbon fuels (synfuels) is another significant opportunity. Synfuels are "drop-in" fuels, meaning they can directly replace fuels that are currently oil-derived and make use of existing distribution infrastructure and end-use technologies without modifications.

Demand for such fuels grows in both the Announced Pledges and Net zero Emissions scenarios as they replace incumbent fossil fuels in applications for which direct electrification is challengin Refineries can also use established supply chains to deliver synfuel to end users, serving today's users of oil-derived fuels. Convertin hydrogen into synfuels is very costly, however, which could be primary impediment to their widespread use (see Chapter Hydroge supply). The expertise and skills of refinery operators will be critic to develop innovative, efficient and cost-effective solutions.

By 2030 in the Announced Pledges Scenario, hydrogen demand fc synfuels reaches 1 Mt H_2. By 2050, it climbs to over 15 Mt H_2, mor than making up for the more than 5 Mt H_2 drop in refining demand. I the Net zero Emissions Scenario, hydrogen demand for synfuel climbs to more than 7 Mt H_2 by 2030, compensating for nearly twc thirds of the more than 10-Mt H_2 drop in refining demand. By 2050, reaches close to 100 Mt H_2, not only replacing the 26 Mt H_2 drop i refining demand but more than doubling current demand – an representing a significant investment opportunity.

If all projects currently in the pipeline materialise (including thos already operational; under construction; having reached fin investment decision; and undergoing feasibility studies), aroun 0.25 Mt H_2[7] could be used in synfuel production by 2030, meetin one-fifth of Announced Pledges Scenario requirements but just 3° of the Net zero Emissions Scenario's.

[7] This could increase to 0.5 Mt H_2 if projects at very early stages of development are included (a co-operation agreement among stakeholders has just been announced).

Selected projects operative and under development to decarbonise hydrogen production in refining

Project	Location	Status	Start-up date	Technology	Size
Horizon Oil Sands	Canada	Operational	2009	Oil + CCUS	438 kt CO_2/yr
Port Arthur *	US		2013	Natural gas + CCUS	900 kt CO_2/yr – 118 kt H_2/yr
Port Jerome *	France		2015	Natural gas + CCUS	100 kt CO_2/yr – 39 kt H_2/yr
Quest	Canada		2015	Natural gas + CCUS	1 000 kt CO_2/yr – 300 kt H_2/yr
H&R Ölwerke Hamburg-Neuhof	Germany		2018	Electrolysis (PEM)	5 MW
North West Sturgeon refinery	Canada		2020	Bitumen gasification + CCUS	1 200 kt CO_2/yr
Pernis refinery (gasification)	Netherlands	CCU project – Operational CCUS project – Feasibility studies	2005 2024	Heavy residue gasification with CCU (CCUS from 2024)	400 kt CO_2/yr – 1 000 kt H_2/yr 1 000 kt CO_2/yr – 1 000 kt H_2/yr
Refhyne (2 phases)	Germany	Phase 1 – Operational Phase 2 – Feasibility studies	2021 2025	Electrolysis (PEM)	10 MW 100 MW
HySynergy (3 phases)	Denmark	Phase 1 – Under construction Phases 2/3 – Feasibility studies	2022 2025-30	Electrolysis (PEM)	20 MW 300 MW / 1 000 MW
Multiphly	Netherlands	Under construction	2022	Electrolysis (SOEC)	2.6 MW
Prince George refinery	Canada	FID	2023	Electrolysis (Unknown)	n.a.
OMV Schwechat Refinery	Austria		2023	Electrolysis (PEM)	10 MW
Westkuste 100 (2 phases)	Germany	Phase 1 – FID Phase 2 – Feasibility studies	2023-28	Electrolysis (Alkaline)	30 MW / 300 MW
H24All	Spain	Feasibility studies	2025	Electrolysis (Alkaline)	100 MW
Gela biorefinery	Italy		2023	Electrolysis (PEM)	20 MW
Taranto Sustainable refinery	Italy		2023	Electrolysis (PEM)	10 MW
Castellon refinery	Spain		2023	Electrolysis (Unknown)	20 MW
Pernis refinery (electrolysis)	Netherlands		2023	Electrolysis (Unknown)	200 MW
Saras Sardinia refinery	Italy		2024	Electrolysis (Unknown)	20 MW
Stanlow refinery	United Kingdom		2025	Natural gas + CCUS	90 kt H_2/yr
H2.50	Netherlands		2025	Electrolysis (Unknown)	250 MW
Preem CCS	Sweden		2025	Natural gas + CCUS	500 kt CO_2/yr
Grupa Lotos refinery	Poland		2025	Electrolysis (Unknown)	100 MW
Zeeland refinery	Netherlands		2026	Electrolysis (Unknown)	150 MW
Lingen refinery (2 phases)	Germany	Phase 1 – Feasibility studies Phase 2 – Early stages	2024 n.a.	Electrolysis (Unknown)	50 MW 500 MW
Deltaurus 1 (2 phases)	Netherlands		2024 n.a.	Electrolysis (Unknown)	150 MW 1 000 MW

* These plants produce merchant hydrogen to supply refineries.

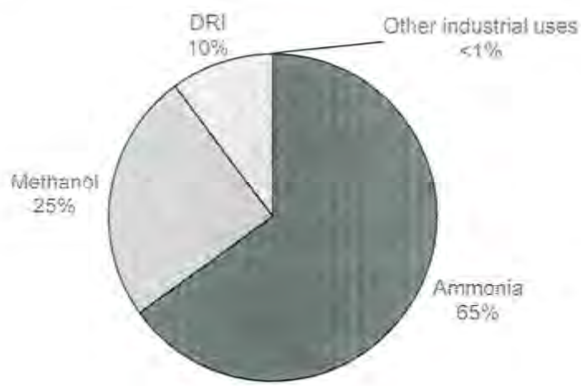
Notes: Size expressed in captured CO_2 for projects using CCUS and in electrolysis installed capacity for projects using electrolysis.

Industry

Hydrogen technologies are key to industry decarbonisation

Accounting for 38% of total final energy demand, industry is the largest end-use sector and accounts for 26% of global energy system CO_2 emissions. Across industry, 6% of total energy demand is used to produce hydrogen, which serves primarily as a feedstock for chemical production and a reducing agent in iron and steel manufacturing. Industry demand for hydrogen is 51 Mt annually.

Hydrogen demand in industry, 2020



Note: DRI = direct reduced iron.

Economic development and population growth will require greater output from the key industry sectors that currently use hydrogen, however it is produced. The pursuit of net zero goals for energ systems will drive changes in supply for current uses and initiate ne uses, impacting existing assets. Industrial hydrogen demand in th Announced Pledges Scenario therefore rises to 65 Mt by 2030, 30% increase over current figures, with new uses accounting for 5% By 2050, demand doubles from today, with the share of new use rising to 26%.

In the context of clean energy transitions, a major shift to low-carbo hydrogen – produced via electrolysis or through the continued use c fossil fuel technologies equipped with CCUS – displaces currer reliance on fossil fuels in hydrogen production. In 2020, industr produced 0.3 Mt of low-carbon hydrogen, mostly through a handful c large-scale CCUS projects, small electrolysis projects in the chemic subsector, and one CCUS project in the iron and steel subsector. B 2030 in the Announced Pledges Scenario, low-carbon hydroge consumption in industry reaches 7 Mt H_2, growing by a factor c almost 25 to make up 10% of total industry hydrogen demand.

However, analysis of the current pipeline of low-carbon hydroge projects suggests that around 55% of global demand projected in th Announced Pledges Scenario in 2030 will be met.[8] CCUS-equippe

[8] This could increase to almost 70% if projects at very early stages of development are included (a co-operation agreement among stakeholders has just been announced).

projects producing low-carbon hydrogen are close to projected deployment: with the current CCUS pipeline expected to produce 1.0 Mt of low-carbon hydrogen, they fall just 7% short of the Announced Pledges Scenario's demand of 1.1 Mt H_2. In sharp contrast, electrolytic hydrogen – a key source of low-carbon hydrogen needed to reach climate goals in industry – lags far behind. Announced electrolytic projects expected to be operational by 2030 account for only one-third of required demand in the Announced Pledges Scenario (close to 6 Mt H_2).

Reaching net zero emissions by 2050 requires even higher hydrogen deployment. Relative to the Announced Pledges Scenario, Net zero Emissions shows total hydrogen demand from industry 11% higher in 2030 and 32% higher in 2050 – almost three times greater than current demand. Low-carbon hydrogen plays an even larger role, amounting to 21 Mt H_2 by 2030 (more than three times higher than in the Announced Pledges Scenario). As early as 2030, electrolytic hydrogen consumption is almost triple that of the Announced Pledges Scenario while CCUS-equipped production is more than five times higher.

Chemicals

With demand of 46 Mt H_2 in 2020, ammonia and methanol productio – together with other smaller-scale chemical processes – account fc the vast majority of industrial use of hydrogen.

Ammonia, predominantly used to produce nitrogen fertiliser accounts for 2% of global final energy demand and around 1% c energy-related and process CO_2 emissions from the energy secto Aside from fertiliser[9] applications (70% of total demand), ammonia i used for industrial applications in explosives, synthetic fibres an other specialty materials. As producing 1 tonne of ammonia require 180 kg of hydrogen, total production of 185 Mt in 2020 require 33 Mt H_2 as feedstock, i.e. 65% of total industry hydrogen demand.

Methanol production is the second-largest consumer of hydrogen i industry, requiring 130 kg H_2/t produced commercially from foss fuels. Its largest-volume derivative is formaldehyde, but several fu applications, either directly or after conversion, are also importar (e.g. methyl-tert-butyl ether). The 100 Mt of methanol produce globally accounts for 28% of hydrogen demand in the chemic subsector and one-quarter of total industry hydrogen demand. I China, methanol serves as an intermediate in the production c olefins (key chemical precursors for making plastics) from coal, a

[9] Specific decarbonisation opportunities for this subsector are explored in the IEA's forthcoming Nitrogen Fertiliser Technology Roadmap.

iea

alternative to conventional oil-based routes. Producing methanol generates, on average, 2.2 t CO_2 per tonne of end product.

Demand for hydrogen in the chemical subsector is expected to grow, particularly because of rising demand for ammonia and methanol. In the Announced Pledges Scenario, it increases nearly 25% by 2030 and close to 50% by 2050. As current methods to produce both chemicals require hydrogen (irrespective of how it is generated), by 2050 total hydrogen demand from chemicals is roughly the same in the Net zero Emissions Scenario.

New demand comes mostly from new applications in which hydrogen displaces fossil fuels for generating the high-temperature heat required for producing chemicals. Thus, converting to low-carbon hydrogen, rather than expanding the use of hydrogen, is the main challenge for the chemical subsector. Opportunities to obtain low-cost, low-carbon hydrogen may spark chemical production in new regions that have access to low-cost renewable electricity but not fossil fuels.

CO_2 capture is already a mature process technology in specific chemical industry applications. During ammonia production, core process equipment separates CO_2 from hydrogen, and the CO_2 is then used for industrial-scale urea production (note: this leaves a significant portion of generated emissions unabated).

In the United States, the practice of using CO_2 captured from ammonia production for enhanced oil recovery (EOR) is well established; similar projects are also operational in Canada an China. Based on the size of the capture installation and assumption on capture rate and the energy intensity of the process, in aggregat these projects produce around 0.2 Mt of low-carbon hydroge annually for ammonia production.

Using electrolytic hydrogen for ammonia production, particularly wit variable renewable electricity, is at an early stage of developmen Nevertheless, several demonstration projects (1-4 kt H_2/yr) ar advancing quickly, including a project by Fertiberia and Iberdrol (Spain) to blend hydrogen produced by solar PV-powere electrolysis, expected to become operational at the end of 2021; CF Industries electrolyser project (United States); the Wester Jutland Green ammonia project (Denmark); and green fertilise projects with Yara (in the Netherlands, Norway and Australia). I addition, some recently announced projects – extensions of th Fertiberia and Iberdrola partnership, Australian projects in Dyn Nobel's Moranbah plant, and the Origin Energy development i Tasmania's Bell Bay – are aiming to scale up this project t 30-140 kt H_2/yr.

For methanol production, most projects currently sourcing low-carbo hydrogen are related to electrolytic hydrogen. Volumes are very sma to date, with pilot plants operating at 1 MW in Germany and 0.25 MV in Denmark, for example. Together with pre-commercial plants i Iceland and China, electrolytic hydrogen amounts to about 2 kt/yr (low-carbon hydrogen. Several projects aiming to demonstrate th use of electrolytic hydrogen for methanol production at scales in the range of 1-10 kt H_2/yr include e-Thor and Djewels (the Netherlands), North-C-Methanol (Belgium), and LiquidWind (Sweden).

Although only small projects capturing CO_2 emissions from methanol production are operating, projects currently under development are about to grow in size. Two demonstration projects capturing CO_2 for EOR are under way in China, another is to start in the United States in 2025, and one is under consideration for Canada by 2025. Together, they can add more than 0.3 Mt/yr of low-carbon hydrogen.

New applications in chemicals include the use of hydrogen for producing high-value chemicals (via either methanol or synfuel used in steam crackers) or for providing high-temperature process heat in downstream chemical production. By 2030, such uses trigger additional low-carbon hydrogen demand of 1.0 Mt in the Announced Pledges Scenario and 2.1 Mt in the Net zero Emissions.

While hydrogen demand per tonne of ammonia and methanol is expected to remain stable, rising demand for chemical products, along with the possibility of sourcing hydrogen from renewable electricity and of using additional hydrogen for heat to produce other chemicals in addition to ammonia and methanol, could revolutionise the sector.

Producing chemical products without carbon fuels could also creat opportunities to find new sources of carbon, including CCUS an DAC. Overall, the chemical subsector's project pipeline represent only 2.3 Mt of low-carbon hydrogen through 2030,[10] short of targel of 4 Mt in the Announced Pledges Scenario and 7 Mt in Net zer Emissions. Clearly, a redoubling of efforts is required over the ne: ten years.

Iron and steel

The iron and steel subsector accounts for 10% of industry hydroge demand, stemming specifically from use in the DRI-EAF steelmakin process route, which accounts for 7% of total crude steel productio globally. In the DRI process, hydrogen is produced as a componer of a synthesis gas, which together with carbon monoxide reduces iro ore to sponge iron. The synthetic gas is a mixture of carbon monoxid and hydrogen, depending on the energy source used in DF production. On average, around 40 kg H_2 is needed per tonne c sponge iron. The traditional DRI mixture can contain 0-70% hydrogen.

The most common steel production route today (the integrated route a sequence of blast and basic oxygen furnaces) does not requir hydrogen as an input, as it uses carbon monoxide-rich gases fc

[10] 3.1 Mt H_2 if projects at very early stages of development are included.

iron ore reduction. However, a small amount of hydrogen is still generated within the blast furnace as an intermediate and as a by-product in the process off-gases.

As a result of announced policies and projects as well as increased steel production through the DRI-EAF process, hydrogen demand from iron and steel almost doubles by 2030 in the Announced Pledges Scenario and increases more than fivefold by 2050. In sharp contrast to small differences in scenario projections in the chemical subsector, Net zero Emissions shows hydrogen demand from iron and steel 85% higher than in the Announced Pledges Scenario by 2030 and 70% higher by 2050. New uses for hydrogen form a key decarbonisation strategy for the iron and steel subsector; in turn, high decarbonisation ambition will spur required levels of deployment.

Multiple new applications present novel opportunities for the future of hydrogen in iron and steel production, with potential volumes of demand in a hydrogen-based DRI-EAF route being the most important. While commercial-scale production for 100% hydrogen-based DRI is not expected until the early 2030s, this route opens an avenue for extensive hydrogen use in the sector. Blending pure hydrogen in DRI and blast furnaces to substitute for a portion of coal and gas, as is currently being trialled, is an incremental step towards the near zero emissions production of crude steel.

Hydrogen can also be used to generate heat for ancillary unit including rolling and other finishing processes, despite being les attractive than induction technology. By 2030, these new use amount to 2 Mt H_2 or 17% of hydrogen use in iron and steel in th Announced Pledges Scenario and 9 Mt H_2 in Net zero Emission Most of these uses of hydrogen are still at pilot or demonstratio scale; to meet deployment levels outlined in the Announced Pledge and Net zero Emissions scenarios, rapid action is needed in the ne five years for their full commercialisation.

Projects in the pipeline amount to 0.5 Mt[11] of low-carbon hydroge use. These include the longest-standing low-carbon hydrogen proje – a DRI plant equipped with CCUS in United Arab Emirates, whic captures CO_2 for use in nearby EOR. In Germany, the Carbon2Che project uses CO_2 captured from blast furnace gas for methan production; using some of the carbon entering the blast furnace twic lowers emissions overall relative to a counterfactual in whic methanol is produced from fossil fuels (by far, the most widesprea practice today). Opportunities to convert gases arising from iron an steelmaking into other chemicals are also under development.

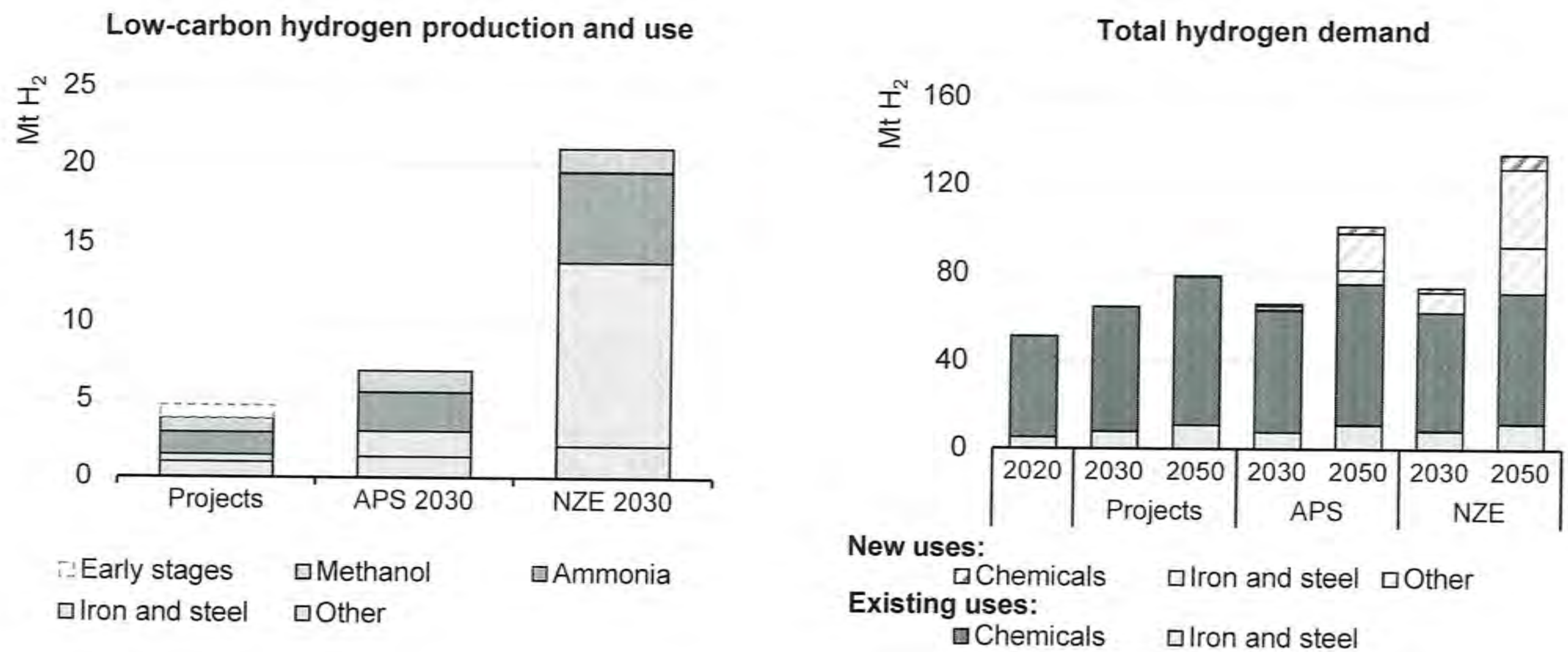
Multiple EU projects are also trialling hydrogen injection into DRI an blast furnaces. The SALCOS (Germany) and H2FUTURE (Austri projects are operating trials that substitute electrolytic hydrogen t reduce natural gas consumption, amounting together to ove

[11] 0.6 Mt H_2 if projects at very early stages of development are included.

1 kt H_2/yr. Thyssenkrupp has successfully trialled the substitution of coal by hydrogen in one tuyere of one of its blast furnaces in Germany and is currently testing higher blending rates. ArcelorMittal (Spain) has also committed to build a DRI unit using hydrogen produced directly from renewable sources.

Aside from blending hydrogen in existing DRI and blast furnaces, high blending shares (up to 100%) in hydrogen-based DRI facilities offer an opportunity to produce steel with very limited use of fossil fuels. As early as the 1990s, a 0.5 Mt full hydrogen-based plant was already operational in Trinidad and Tobago (it is no longer active). The HYBRIT project, developed by SSAB, LKAB and Vattenfall – which will produce sponge iron using 100% hydrogen in combination with biomass – is working towards transitioning from a pilot to large-scale (~1 Mt of DRI) operation by 2025 in Sweden. In June 2021, Volvo Cars signed a collaboration agreement with SSAB to be an off-taker of the fossil-free steel produced in this project.

Low-carbon hydrogen use, 2030, and total hydrogen demand in industry in the Projects case, Announced Pledges and Net zero Emissions scenarios, 2020-2030



Notes: APS = Announced Pledges Scenario. NZE = Net zero Emissions Scenario. Other applications include hydrogen use for ceramics production, nickel refining and industrial heating.

Source: IEA (2021), Hydrogen Projects Database.

Selected projects that can increase the use of low-carbon hydrogen in industry

Project	Location	Status	Start-up date	Technology	Size
			Ammonia		
Coffeyville fertiliser	United States		2013	CO_2 capture from oil-based ammonia production; used for EOR	1 Mt CO_2/yr
PCS Nitrogen	United States	Operational	2013	CO_2 capture from gas-based ammonia production; used for EOR	0.7 Mt CO_2/yr
Nutrien fertiliser	Canada		2020	CO_2 capture from gas-based ammonia production; used for EOR	0.3 Mt CO_2/yr
Olive Creek	United States	Under construction	2021	Ammonia production via methane pyrolysis	n.a.
Fertiberia/Iberdrola	Spain	Phase 1 – Under construction Phases 2-4 – Feasibility studies	Phase 1 – 2021 Phases 2-4 – 2027	Hydrogen production from solar PV for ammonia production	Phase 1 – 20 MW Phases 2-4 – 810 MW
Western Jutland Green ammonia	Denmark		2023	Electrolytic ammonia production from renewables	10 MW
CF industries	United States	FID	2023	Electrolytic ammonia production using electricity from the grid	20 MW
Green fertiliser project Porsgrunn	Norway		2023	Electrolytic ammonia production using electricity from the grid	Up to 25 MW
Engie - Yara Pilbara	Australia		2023	Electrolytic ammonia production from renewables	10 MW
HyEx	Chile		2024	Electrolytic ammonia production form solar PV	50 MW
Yara Sluiskil	Netherlands		2025	Electrolytic ammonia production from renewables	100 MW
Barents blue ammonia	Norway	Feasibility studies	2025	CO_2 capture and stored from gas-based ammonia production	1 Mt NH3/yr
Esbjerg green ammonia	Denmark		2027	Electrolytic ammonia production from offshore wind	1 GW
CF Fertilisers Ince	United Kingdom		n.a.	CO_2 capture and stored from gas-based ammonia production	0.3 Mt CO_2/yr
			Methanol		
Commercial Plant Svartsengi	Iceland		2011	Electrolytic methanol production from dedicated renewables	6 MW
Karamay Dunhua Oil Technology CCUS EOR	China		2015	CO_2 capture and stored from methanol production; used for EOR	0.1 Mt CO_2/yr
MEFCO2	Germany	Operational	2019	Electrolytic methanol production	1 MW
Power2Met	Denmark		2020	Electrolytic methanol production	0.25 MW
Fine Chemical Industry Park of Lanzhou	China		2020	Electrolytic methanol production from dedicated renewables	4.5 MW
Green lab skive	Denmark	Under construction	2022	Electrolytic methanol production from dedicated renewables	12 MW
DJEWELS Chemiepark	Netherlands		2022	Electrolytic methanol production from dedicated renewables	20 MW
Lake Charles Methanol	United States	Feasibility studies	2025	Production of hydrogen and methanol from petcoke gasification with CCUS	4.2 Mt CO_2/yr

Project	Location	Status	Start-up date	Technology	Size
North-C-Methanol	Belgium	Phase 1 – Feasibility studies Phase 2 – Early stages	2024 2028	Electrolytic methanol production from dedicated renewables	Phase 1 – 63 MW Phase 2 – 300 MW
Power-to-Methanol	Belgium		2023 n.a.	Electrolytic methanol production from dedicated renewables	10 MW 100MW
			Iron and steel		
Al Reyadah CCUS	United Arab Emirates		2016	CCUS plant applied on DRI; captured CO_2 used for EOR	0.8 Mt CO_2/yr
Carbon2Chem	Germany		2018	Use of blast furnace gases for methanol production	2 MW
H2FUTURE	Austria	Operational	2019	Feeding hydrogen via the coke gas pipeline into resource-optimised blast furnaces	6 MW
GrInHy2.0	Germany		2020	Use of waste heat from integrated steelworks for H_2 production	0.72 MW
SALCOS	Germany		2021	Blending of hydrogen into natural gas-based DRI	2.5 MW
HYBRIT	Sweden	Phase 1 – Operational Phase 2 – Under construction	Phase 1 – 2021 Phase 2 – 2025	100% hydrogen-based steelmaking currently operating at pilot scale; plan to move to demonstration plant by 2025	Phase 1 – 4.5 MW Phase 2 – n.a.
Thyssenkrupp steel plant	Germany		2022 2025	Hydrogen injection into blast furnaces	100 MW 400 MW
ArcelorMittal	Spain	Early stages	2025	Use of hydrogen produced from solar PV electrolysis in DRI	n.a.
H2 Green Steel	Sweden		2030	100% hydrogen-based steelmaking using dedicated renewables	1.5 GW
HBIS	China		n.a.	Using high levels of hydrogen together with coke oven gas in DRI	n.a.
			Other applications		
Sun Metals Zinc Refinery	Australia	FID	2022	Replacement of natural gas in zinc refinery process	1 MW
BHP Nickel West Green Hydrogen	Australia		2023	Use of electrolytic hydrogen for nickel refining	10 MW
ORANGE.BAT Castellon	Spain		2024	Use of green hydrogen for ceramic production	100 MW
Grange Resources Renewable Hydrogen	Australia	Early stages	n.a.	Use of hydrogen to replace natural gas for industrial heating in pelletising facilities	100 MW
GREENH2KER	Spain		n.a.	Use of green hydrogen for ceramic production	n.a.

Source: IEA (2021). Hydrogen Projects Database.