CSIRO

Australia's National
Science Agency

External communique of 2022 hydrogen research delegations

Led by CSIRO, Funded by the Australian Government

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Contents

Program background

Australia's National Hydrogen Strategy[1] *and* CSIRO's 2019 *Hydrogen Research, Development and Demonstration*[2] report identified Australia's need to stimulate international research connectivity and knowledge sharing, build hydrogen RD&D capability and support industry development. The strategy called for more international research collaboration – and to not only develop technology, but also in cross-cutting areas such as community acceptance, health, international standards, and certification.

This was the catalyst behind the *International Hydrogen Research Collaboration Program*, a collaboration between CSIRO's Hydrogen Industry Mission and the Department of Climate Change, Energy, the Environment and Water (DCCEEW). A key platform of the program is the international research delegations, aimed at establishing two-way fellowships between countries, looking to collectively share resources and research talent globally. Countries were selected based on strategic alignment to Australia's values and opportunities emerging in hydrogen, joint learning approaches to integrate hydrogen into our economies, and capacity for research to meet challenging clean energy transformation goals.

During September to December 2022, CSIRO led research delegations involving 37 delegates across 14 Australian universities to Germany, France, Japan, UK, and the USA. Other delegations are occurring in 2023 to Singapore, Republic of Korea, and India. Delegation members were drawn from the national R&D sector (the Australian Hydrogen Research Network, AHRN) and included researchers across all hydrogen research fields. The delegations to France, Germany, Japan and the United Kingdom were five intensive days of visits, while the United States delegation was eight days, visiting with government departments, research institutes and industry sites. The objectives of the delegations are to:

- understand the depth and significance of commitment to the use of clean hydrogen as a fuel across countries leading this innovation
- learn the state of technological readiness across the supply chain and end uses
- showcase Australia as a strategic partner and establish a two-way exchange program between countries
- identify two-way research opportunities between our countries.

By the end of these activities, Australia, with our international research partners, will have stronger connections, collaborative pathways, and knowledge sharing leading to stronger relations between our countries.

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[1] COAG Energy Council (2019) Australia's National Hydrogen Strategy

[2] Srinivasan et al. (2019) National Hydrogen Research, Development and Demonstration: Priorities and Opportunities for Australia. CSIRO.

In addition to these delegations, is the 'Research Fellowship Program' where up to 40 Australian researchers will receive funding to visit selected research institutions and labs, identified by the delegations, to undertake between 3 and 12-month overseas placement activities. An expression of interest (EOI) is now open to the Australian research community to fill these positions (see, Australian Hydrogen Researcher Network (ahrn.org.au)). Australia also welcomes overseas researchers to come to Australia to share knowledge, build our researcher connections and to research in matched placements.

Main takeaways from the five delegations

The five countries visited in 2022 have well-defined strategies for hydrogen to play a significant role in the global energy transition, highlighting they cannot do it alone. Research is considered a primary driver for the international cooperation needed to achieve the transition. Now more than ever, many countries note the critical need for international collaboration to maximise the global effort to address many shared transition challenges; increase the impact that energy research makes in our communities; and provide international research career opportunities for researchers.

Each country visited presented its own drivers, opportunities, and challenges related to research, and many of these are also shared themes. The following describes the main insights gleaned from our visits, and country-specific findings recorded by the Australian delegates are in the next section. It should be noted that these outcomes are not intended to present a formal prioritisation of research areas but can be used to guide future dialogue on RD&D collaboration opportunities.

Overall insights

- A two-way research exchange program was highly supported during our visits, and several ideas were put forward on how to carry them out (6 to 12-month visits being generally preferred and shorter timeframes possible for cross-cutting and other innovative ideas).
- There is a distinct urgency to develop secure, clean energy options in all countries. Germany and Japan will need to import energy; and all countries require a great deal of analysis and planning to integrate clean technologies into their systems and optimal use options along their supply chains.
- Conversely, research can be time consuming and challenged to meet such urgent, system wide needs.
- For this reason, research to accelerate the development of the hydrogen economy is required to enable governments to fast-track investment more rapidly than would otherwise have occurred if left purely to the private sector. This requires productive network and collaboration techniques between government, industry, and research bodies.
- The goals and strategies being set by governments are challenging and require great effort and focus to be able to meet the timescales needed.

- Further creation and use of international collaboration techniques and tools would be helpful – to plan and implement research and share knowledge along the way. There was a universal perspective that no one country can do this alone – we need to share our expertise and skills more; and there is a genuine concern to meet policy and energy development targets and community expectations across the globe.
- Technology research costs are large (particularly for pilot projects) and hydrogen research budgets and associated government funding of early demonstration initiatives overseas is prodigious. For example, the estimated total public energy research, development, and demonstration (RD&D) budget for IEA member countries reached USD 23 billion in 2021. The increase in public RD&D budgets among IEA countries has mainly been driven by energy efficiency but the most rapid increase has been for hydrogen and fuel cells technologies[3].
- Hydrogen research activity is focused along the full industry supply chain exploring clean production; energy carriers and distribution processes; cost-effective applications; integrated systems; and 'enabling' or cross-cutting research focusing on safety and labour skills, policy development, economics, and community acceptance. Efforts are aimed at lowering production costs and scaling technologies.
- National labs with international reach are being established to coordinate and focus research efforts. For example,
    - the Translational Energy Research Centre is a new national-scale research facility, part-funded by the UK government and the European Regional Development Fund
    - the many institutes and research units coordinated by Fraunhofer Hydrogen Network in Germany
    - the Energy Hydrogen Program, led by the Hydrogen and Fuel Cell Technologies Office (HFTO) within the Office of Energy Efficiency and Renewable Energy (EERE), at the Department of Energy (DoE) in the USA
    - the coordination of the National Research Program on low-carbon hydrogen, and the Research Federation on Hydrogen at CNRS in France, and
    - the Japanese government's R&D coordination efforts with corporations led by National Institute of Advanced Industrial Science and Technology (AIST) to jointly develop demonstration projects with industry partners.
- There is value in further coordinating these efforts under international frameworks such as the Clean Hydrogen Mission – Mission Innovation (mission-innovation.net) and the International Partnership for Hydrogen and Fuel Cells in the Economy (iphe.net).

[3] https://www.iea.org/data-and-statistics/data-product/energy-technology-rd-and-d-budget-database-2, visited 31 January 2023

- Domestic networks such as the AHRN and programs like Hydrogen technologies | GlobH2E | Australia and HyResearch: Australian Hydrogen R&D Portal (csiro.au) in Australia will also assist coordinating efforts and foster international relationships.
- Many participants see value in using these frameworks and tools to build the bilateral and multilateral partnerships required, and further definition and efforts are needed to capture and optimise opportunities. It will also be necessary to look for private sector finance to help build capacity and skills across the supply chain of work required.
- There is a great deal of parallel research activity occurring (particularly in electrolysis and fuel cells). Ongoing coordination, and governance of the research at the multilateral level, under technology-based groups, or under aspiration goals such as exporting hydrogen, could assist research efficiencies.
- The nations we visited continue to explore and establish research partnerships in hydrogen and its role in the energy transition.

Summary research opportunities

During their visit, the delegates and their counterparts discussed the potential value of building a two-way knowledge and research exchange, and complementary capabilities to accelerate hydrogen industry development in Australia and abroad across the following priority areas. Further work is now needed to refine these topics and the R&D opportunities to jointly work on.

Research opportunities include:

- electrolysis pathways
- hydrogen conversion and power generation
- industrial scale integrated system demonstrations
- exporting hydrogen and its carrier derivatives
- assessing green steel manufacturing as well as export/import outcomes based on mutual economic gains – especially for hot briquetted iron (HBI)
- large scale hydrogen production using blue hydrogen, biomass, and plastic waste (to fast track an infrastructure gateway for green hydrogen and regional transitioning)
- Sustainable Aviation Fuel (SAF)
- maritime fuels
- heavy vehicles
- large scale storage identifying sizes required, locations, materials and performance standards
- materials science – compatibility, embrittlement, catalysts etc.
- transitioning fossil fuel based regions and industrial areas towards net zero emissions

- demand creation, hydrogen finance and investment decisions (being able to raise capital quickly and what's required for development and demonstration projects and commercialisation of technologies) to address the 'chicken and egg' demand creation/supply investment conundrum
- establishing frameworks, standards, certification systems and regulatory research to fast-track hydrogen trading
- labour, skills, and planning
- national and international energy sector transition modelling
- cross-cutting areas (policy, safety, socio-economic-techno analysis, and others) so that we move from *know-how* to effectively build and transfer knowledge towards *how-do* focusing efforts on integrating infrastructure at scale
- open data sharing and developing online tools to show 'how to build' and consider a systems approach for analysis and design e.g. solid oxide electrolysers, fuel cells, e-fuels, mobility, micro-grids, seasonal storage; noting the advanced state of prototyping, LCA and safety research and associated equipment/ infrastructure in several labs.

There is strong interest from potential partners to conduct joint research projects in the above areas with each country presenting its own specialities and aspirations. This presents many specific opportunities in each country and also raises questions around technology choice and whether to adopt certain technologies or develop them to fill gaps in hydrogen supply chains.

Potential risks or issues

- There is a risk that Australia will be overtaken as a hydrogen/hydrogen derivative supplier by other countries (Middle East, South America). Australia is a long comparative distance from Europe.
- There is a somewhat lesser risk that Australia might also be in competition for green hot briquetted iron (HBI) supply from countries such as Brazil.
- There is a risk that countries with strong trade unions may not be willing to give up employment opportunities in fossil fuel areas (energy production, steel, metals, chemicals, cement) unless there was some additional employment benefit which would grow their green or low-emissions production value-add by making it more cost competitive.
- These risks can be mitigated by collaboration on policy development on trade based on robust socio-techno-economic assessments, and by establishing investment incentives using certification support.
- There are a range of challenges with research mobility across IP and partnering agreements, funding mechanisms, capability matching, logistics, and capacity of individual researchers to relocate for long periods.

Country findings

France

Overarching insights

The delegation discussed technology developing along sovereign lines with global opportunities – that is, securing a ‘French pathway’ and an ‘Australian pathway’ where shared industry-research collaboration and commercialisation can accelerate industrial and economic transformation, sustainable value creation, high-value job creation and economic diversification. France aims to be self-sufficient with hydrogen and with many of its energy technologies and to be a net exporter of energy and its associated technologies. French industry involvement in other countries' energy transitions is already strongly supported.

In general, significant investment, related strategies, targets and subsidies combined with a different culture influenced by EU requirements makes the situation quite different to Australia’s in terms of ability to deliver low-cost hydrogen production. It is evident that economic factors are considered in parallel with whole of life sustainability in technology solutions and is also an integral part of research design, outputs and impact.

France was one of the first countries to deploy a national hydrogen program, publishing a national strategy in 2020 for the development of decarbonised and renewable hydrogen in France. The €7bn national strategy has three priorities:

1. decarbonising industry by developing a French electrolysis sector
2. developing the use of decarbonised hydrogen for heavy-duty mobility
3. supporting research, innovation and skills development to promote the uses of tomorrow.

The strategy cites a goal for France to stay at the best global level by bringing researchers together, facilitating industrial cooperation and pooling funds; “to make the France of tomorrow the champion of decarbonised hydrogen”.

Other highpoints are: 6.5GW electrolysis production capacity by 2030; industry and mobility focused; 9 billion Euros investment plan for industry up to 2030; 680,000 tons of hydrogen p.a. (1,090,000 tonnes more ambitious); create 50,000 – 150,000 jobs; in collaboration with European partners (IPCEI); and many R&D support programs such as the Priority Research Program and Equipment (PEPR) – TRL 1-4 (80 million Euro). 'H2' PEPR explores new directions likely to lead to breakthrough innovations of interest as regards the strategy but also as support tools for industry. The PEPR focuses on issues involving the production, storage and transport of carbon-free hydrogen and also its usage for heavy mobility. Work will also be carried out to support rolling out hydrogen systems through life cycle analyses and studies of technical and socio-economic issues and safety aspects.

PEPRs are backed up by the national strategy aimed at helping remove scientific barriers or obstacles linked to the strategy. There is a €2 billion overall budget allotted to PEPRs.

France also has several *National acceleration strategies* to accelerate transformations at the national level in a comprehensive and coordinated way in terms of standards, finance, taxation and so forth. Investments are intended to cover an innovation's entire life cycle - from the emergence of the original idea in a research laboratory or university to its commercialisation. This includes the university training required by tomorrow's scientists and entrepreneurs and all the essential collaboration projects between laboratories and companies.

The main government bodies leading hydrogen strategy, policy and funding in France are the Ministry of Economy, Finance and Recovery (MEFR), and the Ministry for the Ecological Transition (METS). The French National Research Agency (ANR) operates under the Ministry for Higher Education, Research and Innovation (MESRI) to fund RD&D projects led by public institutions. The Agency for Ecological Transition (ADEME) also provides public funding for hydrogen RD&D. Public investment banks at the national level (such as Bpi France and Banque des Territories) and the EU level (such as the European Investment Bank) are financing hydrogen activities including demonstration projects.

Lhyfe's hydrogen production site in Nantes, with renewable electricity from wind turbines

The three main public bodies undertaking hydrogen RD&D are the National Centre for Scientific Research (CNRS), and the Alternative Energies and Atomic Energy Commission (CEA), who lead the Federation of Hydrogen Research (FRH2) encompassing 29 laboratories across France. And France has several highly active consortia and industry associations involved in hydrogen.

There are a total of 20 *National acceleration strategies* with policy integrated into each strategy. There is a selection of energy-related ones, such as nuclear sector; advanced energy system technologies (PV, offshore wind, distributed RE integration); decarbonisation of industries (efficiency, heat/energy mix, processes, CCUS); and batteries.

There is substantial investment in research in all stages of TRL, substantial investment in multi-faceted aspects of decarbonisation, energy, batteries, etc. (see, for example, amounts quoted in the national acceleration strategies and the breadth of strategies).

Some of the significant challenges being addressed in the vision laid out above and discussed during the delegation include:

Cost reduction. Costs need to be reduced as green infrastructure is scaled up and new markets built. The technology is present and emerging but is expensive. One way forward is to concentrate usage of technology on territories through fewer larger projects (e.g. 10MW) rather than many small projects. Create H2 routes/corridors such as transport of fruit and vegetables through south of France from Spain.

To promote technological neutrality. Bring a focus to all needed low-emissions technologies versus single pursuits on renewable electricity. Nuclear, Steam Methane Reforming (SMR) with Carbon Capture and Storage, pyrogasification, bio pyrolysis, methane plasmalysis (plasma torch/microwave), and native hydrogen are also available to produce low-emissions hydrogen. There are likely to be constraints of renewable energy which could hamper hydrogen development.

To contribute to decarbonisation and reindustrialisation. Rapid decarbonisation with committed milestones for energy, transport, mining, and heavy industry is needed to steer our countries to net zero by 2050 and obtain Paris Agreement climate targets. We need to develop competencies and training across professions.

Access to enough clean electricity. Energy efficiency and energy justice.

Research opportunities

- Connect with French companies wanting to expand into the Australian market. Research institutes on both sides could support research on technology modifications, tests required to adapt product for Australian conditions, and work together to find demonstration sites.
- Generally, there appears to be strong use or application opportunities in Australia and the French have advanced technologies ready to be applied. That is, outcomes from facilities in French labs could be tested and applied in the Australian environment. Australia also has more access to more physical space, more sun, more wind, to test demonstrators.
- Review other existing research programs and funding mechanisms for international collaboration that involve research exchanges (cf. Brazil and Japan). Seek what could or needs to be driven at the government department or ministry levels. Note an existing research collaboration, IRN-FACES, is a French-Australian International Research Network focussing on conversion and energy storage with eight CNRS laboratories, supporting universities and four Australian universities.
- Institutes and national R&D funding programs aligned and defined by target TRL (technology readiness level). Example: CNRS (institutes) and ANR / PEPR (funding) facilitate more fundamental R&D at TRL 1-4; while CEA (institute) and ADEME (funding) supports TRL 4-6 – research and demonstrators. Equivalent seen for FEMTO S-T and FCLABS (Belfort institutes) – good connections between the labs targeting different TRLs.
- There is substantial commonality observed in research areas of interest while noting France's ability to combine with larger energy systems and consider systems approach for analysis and design e.g. solid oxide electrolysers, fuel cells, e-fuels, mobility, micro-grids, seasonal storage. Note advanced state of LCA (life cycle assessment) and safety research and associated equipment/ infrastructure in labs.
- Different institutes had different thoughts on establishing collaborative research arrangements, e.g. some see a difference between PhD students and postdocs, others thought these could all

be handled in the same way. Some questioned whether a research exchange of less than 6 months is worthwhile, many prefer annual exercises with metrics or agreements showing a "win-win" situation. CNRS safety group will consider 3 months and are willing to find opportunities to work together. Some CNRS Nantes groups have existing and Australian collaborations, thus, precedents for how an arrangement could work (IRN-FACES mentioned above) or be added to.

- There is alignment in research focus areas in general, e.g. PEM and SOE electrolysers, energy systems integration, critical minerals, materials, and storage (compressed, hydrides, liquid organic hydrogen carriers).
- Grenoble CEA has a strong focus on recycling as integrated part of most research. Possible option for collaboration with Australian researchers with slightly more advanced materials research.
- The lab visit in Belfort yielded observations of potential areas for collaboration: offering test beds to better understand what needs to be done to scale up; platform capability; researchers making novel materials to product evaluation and testing; socioeconomics; and systems modelling.
- Hydrogen safety and combustion research is very advanced and mature. CNRS-ICARE are open to sharing knowledge, models, utilisation of facilities for flame, turbulence, combustion experiments. They have advanced research in hydrogen combustion and safety and modelling and research into energy system integration on a large scale. Established programs for research-industry collaboration to advance R&D efforts to practical outcomes, commercialisation, discover faster what works, what requires re-design, and so forth.
- There are clear value propositions for organisations to develop partnerships to utilise and share advanced lab equipment and test labs, leveraging what has already been learnt/is not successful.

Australian delegates to France

NAME	ROLE	ORGANISATION	LOCATION
Professor Francois Aguey-Zinsou	Head of the MERL in research lab at the School of Chemistry **Delegation Lead**	University of Sydney	Sydney, NSW
Dr Vicky Au	Deputy Lead Hydrogen Industry Mission **Delegation Co-ordinator**	CSIRO	Clayton, VIC
Professor Ken Baldwin	Australian Hydrogen Research Network (AHRN) Steering Committee Chair of the first Australian Hydrogen Research Conference (2023)	Australian National University	Canberra, ACT
Professor Stefan Iglauer	Professor and Director Centre of Sustainable Energy and Resources	Edith Cowan University	Perth, WA

Professor Emilie Sauret	Faculty of Engineering, School of Mechanical, Medical and Process Engineering	Queensland University of Technology	Brisbane, QLD
Associate Professor Mahnaz Shafiei	Lead, Hydrogen Sensing Research School of Science, Computing and Engineering Technologies	Swinburne University of Technology	Melbourne, VIC
Professor Bradley Williams	Associate Dean External and International Engagement Faculty of Science	University of Technology Sydney	Sydney, NSW

Organisations visited

Association of industries, France H2
Australian Embassy
CEA
CNRS
FEMTO-ST and FCLAB
France Hydrogen Association
IC2PM (Poitiers)
ICARE (Orléans)
ICMCB
ICMPE (Thiais)
IRCP (Paris)
IRN-FACES
LAGEPP (Lyon)
LEPMI
Lhyfe
Liten
National Research Agency
NEEL (Grenoble)
Research & Education Ministry

Australian Ambassador's residence at the Australian Embassy in Paris, hosted by Austrade General Manager Europe and Senior Trade and Investment Commissioner Jennifer Mackinlay

Germany

Overarching insights

Germany historically has high energy demands which are forecast to grow against energy supply that is suffering from constraints from security issues arising from the Russian Ukraine war and domestic expectations on climate change and cleaner fuel sources. Germany has extensive manufacturing capabilities, and technology leadership, and a strong reputation as a global leader in hydrogen.

The key area of interest between our two countries is international trade in energy (moving hydrogen and its derivative options) and iron. Germany's ambitious climate goals, current dependence on imported fossil fuels and recently highlighted vulnerabilities to the changing geopolitics of international energy trade have all strengthened the country's plans to accelerate the development of a clean energy industry. Discussions with Germany to collaborate with Australia on clean energy occurred in the areas of:

- technology development and pilot demonstrations to enable green hydrogen derivative imports from Australia, as well as renewable energy/hydrogen embedded products such as green iron
- technology export from Germany to Australia across the supply chains producing these hydrogen products
- energy imports from Australia in form of renewable hydrogen and its carriers such as ammonia.

Other key areas of mutual alignment with Australia are hydrogen production from renewables and potentially fossil fuels with carbon capture and storage (CCS), yet there is political history for Germany to navigate options across blue hydrogen and with nuclear energy.

There is a risk that Australia will be overtaken as a hydrogen/hydrogen derivative supplier by other countries (Middle East, South America). Australia is a long comparative distance from Europe. There is a somewhat lesser risk that Australia might also be in competition for green HBI supply from countries such as Brazil. Iron making as such would require thinking and probable associated socio-economic policy development on trade and investment incentives, shared value and certification, across relevant industries and resources.

There is interest to explore hydrogen use in industrial applications (particularly in hard-to-abate industries, including steel manufacturing and chemical production) and for fuelling heavy vehicles.

There is likely to be crossover to engagement with other EU countries engaged in hydrogen research, although with different drivers. France, for example, sees itself as becoming self-sufficient in hydrogen production (potentially with some small export), and regards itself mainly as a technology contributor, so will have similar desire to collaborate with Australian technology researchers.

Many companies and research institutes visited are interested in developing a reciprocal exchange program for German researchers to go to Australia.

Germany's *National Hydrogen Strategy* focuses on investing in the production of electrolysers to produce hydrogen from renewables (wind with exploration in solar), importing hydrogen to meet its energy demand, developing a hydrogen gas pipeline network using new and old infrastructure, and using hydrogen across chemical, petrochemical and steel industries, as well as transportation modes that are difficult to electrify (heavy vehicles, trains, planes, and ships). See recent announcements regarding LNG ports.

Germany has signalled in its strategy the intent to collaborate on integrating hydrogen into existing energy trade partnerships and establishing new energy partnerships, technological collaboration, demonstrations, and pilot projects in partner countries across the entire supply chain. Later engagement between German institutes and our delegates confirmed this, including conversations with BMBF, and need to be followed up. Germany has several formalised relationships with other countries at the national level and has engaged in major supply chain demonstration projects with international partners.

Germany's targets for 2030 are to grow its hydrogen consumption across the economy to 90-110TWh, and to produce 14TWh of hydrogen from renewable based electricity. By 2050, the targets for hydrogen consumption increase to roughly 380TWh of consumption (of which more than 80TWh will be needed for green steel, and roughly 22TWh needed to switch refinery and ammonia production to hydrogen). Germany plans to add an additional 5TWh of hydrogen production capacity before 2040. Based on Germany's National Energy and Climate Plans (NECP), the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) has published a range of hydrogen deployment scenarios for Germany in 2030, where hydrogen features across all end-uses, totalling a demand of 8,900-41,300 GWh/a.

The main government bodies in Germany involved in the development of a hydrogen economy are the Ministry of Economic Affairs and Climate Action (BMWK, previously BMWi), and the Ministry for Transport and Digital Infrastructure (BMDV). The BMWK published Germany's *National Hydrogen Strategy*, and both ministries are the primary funders of hydrogen and fuel cell RD&D programs across Germany, such as the National Hydrogen and Fuel Cell Technology Innovation Programme (NIP and NIP2), and a number of mobility related programs.

Funding also comes from Germany's Green Climate Fund, which supports basic research on hydrogen production from renewables, hydrogen energy technology research, and regulatory sandboxes for the energy transition. Additionally, the European Union funds hydrogen RD&D activity in Germany through its Horizon Europe program and other EU mechanisms.

Germany has many highly active consortia and industry associations, namely the National Organisation for Hydrogen and Fuel Cell Technology (NOW GmbH), the German Hydrogen and Fuel Cell Association (DWV)and HySteel. German industry, academia and government stakeholders are also highly active in European level consortia.

Industry and academia are collaborating to bring about hydrogen clusters (also known as hydrogen valleys, hubs or ecosystems). These clusters are hydrogen value chain demonstrations and pilot projects that cut across sector applications. There are five major clusters of integrated hydrogen value chain activity in Germany.

Research opportunities

The following four strategic hydrogen subject areas were identified as specific opportunities of mutual interest between Germany and Australia that if progressed, could offer rapid industry scale-up and trade of hydrogen (or its derivatives) demonstrations and value between the two countries.

Hydrogen distribution and storage for export and use in remote applications

- Compared with NH_3 and liquid H_2, what are the Australian use cases for the liquid organic hydrogen carrier (LOHC) technology, which may include:
    i. LOHCs for short to mid-range energy export from Australia (<10,000 kms in the Asia-Pacific)
    ii. LOHCs for large mobile platforms, potentially in remote locations (e.g. mining, or agricultural vehicles, boats/barges/ships)
    iii. LOHC for remote/off-grid power supply (e.g. back-up generators, construction sites) (HIERN)
    iv. LOHC analysis for Australian domestic and export applications, potentially followed by demonstration in Australian conditions (Erlangen).
- Australia-Germany tank testbed - with DLR/ARENA2036/Fraunhofer Institutes (materials, sensing, manufacturing) - focus on the development and testing of storage and transport vessels for all forms of hydrogen and hydrogen carriers. Creating a joint opportunity for manufacturing all components of these systems cost effectively, modelling and prediction of efficiencies of storage/loss and delivery integration across global needs (high- and low-tech countries and all transport forms). Chance also to connect German and Australian Industry.
- Metal hydride storage for marine export and remote location applications (Fraunhofer Dresden).

Hydrogen conversion and power generation

- Techno-economic study of application of bipolar reversible electrolyser/fuel cell plants (somewhat less efficient than the two components optimised separately) to remote power applications, compared to the same renewable resources combined with batteries / pumped hydro storage / diesel gensets (HIERN).
- Power-to-X technology for value creation from hydrogen in Australia, using classical manufacturing on scale and/or decentralised manufacturing technologies (e.g. in rural areas): manufacture of synthetic fuels (e.g. aviation fuels) and renewable platform chemicals (e.g. methanol) (Fraunhofer Dresden & Stuttgart, KIT).
- SOEC demonstration with renewable power (e.g. QUT H2Xport) and FT to produce clean fuels from co electrolysis (Fraunhofer Dresden).

- Comparative study (technical and techno-economic) of remote area power supply applications for Powerpaste device under Australian conditions (>60°C, dry and dusty) (FI AM Dresden).

Industrial scale integrated system demonstrations:

- Industrial scale demonstration facility infrastructure for de-risking new technologies across the integrated value chain to facilitate rapid industry adoption (Fraunhofer, Stuttgart).
- Energy system integration with chemical (H2) production (flexibility) (Ruhr University Bochum).

Expanding green steel trade outcomes based on shared value between countries

Example: Direct reduction iron (DRI) with H2 (Thyssenkrupp Steel) for commodity export scale-up

- Techno-economic study of the case for replacing DRI production in German steel manufacturing with Australian hot briquetted iron (HBI), c.f. iron ore, c.f. HBI from Brazil and other potential suppliers. This opportunity provides an important example of how techno-economic assessments are required to find optimal pathways (noting benefits and costs for both countries across hydrogen v DRI options) and the need for multi-criteria analysis of the range of factors that get weighed in the decision-making process including existing assets (collaborator – TK).
- Regulatory, policy and political economy study of the prospects for foreign investment in Australian onsite production of green HBI - focused on investment models, incentives, and de-risking strategies.
- Process optimisation of electricity buffering with hydrogen storage in steel applications (and potentially other industries) – Thyssenkrupp do H2 buffering studies.

Helmholtz Centre Erlangen Nürnberg for Renewable Energy (HIERN) as the hosting organisation, which is located at the University of Erlangen in Germany

Australian delegates to Germany

Name	Role	Organisation	Location
Dr Dietmar Tourbier	Deputy Director and Science Director, Energy Business Unit **Co-Lead of the Delegation**	CSIRO	Melbourne, Victoria
Professor Ken Baldwin	Founding Director, ANU Grand Challenge: Zero-Carbon Energy for the Asia-Pacific **Co-Lead of the Delegation**	Australian National University	Canberra, ACT
Professor Peta Ashworth OAM	Chair, Sustainable Energy Futures Director, Andrew N Liveris Academy for Innovation and Leadership Chair, Hydrogen Taskforce Queensland	University of Queensland	Brisbane, Queensland
Professor Dr Leonie Barner	Principal Research Fellow School of Chemistry and Physics, Faculty of Science	Queensland University of Technology	Brisbane, Queensland
Professor Rachel A. Caruso	Director of the Enabling Capability Platform for Advanced Materials	RMIT University	Melbourne, Victoria
Dr Christian Hornung	Group Leader, Chemistry & Polymers	CSIRO	Melbourne, Victoria
Professor Iain MacGill	Joint Director of the UNSW Collaboration on Energy and Environmental Markets (CEEM) Lead for the *Value Chain and Business Models* Theme in the ARC Training Centre for the Global Hydrogen Economy	UNSW	Sydney, NSW
Professor Eric F. May	CEO, Future Energy Exports Cooperative Research Centre (CRC) Chair in Gas Process Engineering	The University of Western Australia	Crawley, Western Australia
Professor Sally McArthur	Director, Institute for Frontier Materials Deakin, Adjunct Professor for Manufacturing and MedTech Swinburne	Deakin University, Swinburne University	Melbourne, Victoria
Professor Paul Medwell	ARC Future Fellow	The University of Adelaide	Adelaide, South Australia
Dan O'Sullivan	Program Manager International Hydrogen Research Collaboration	CSIRO	Brisbane, Queensland
Professor Gerhard (Gerry) F. Swiegers	Intelligent Polymer Research Institute and CTO, Hysata Pty Ltd	University of Wollongong	Wollongong, NSW

Organisations visited

ARENA 2036
Australian Embassy
Bosch
CellCentric
Chemnitz University of Technology
Daimler
DLR
Fraunhofer Gesellschaft (Corporate)
Fraunhofer IEG
Fraunhofer Institute for Ceramic Technologies and Systems (IKTS)
Fraunhofer Institute for Manufacturing Engineering and Automation (IPA)
Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM)
Fraunhofer Institute for Material and Beam Technology (IWS)
Fraunhofer Institute for Microstructure of Materials and Systems (IMWS)

Fraunhofer Institute for Silicate Research (ISC)
Fraunhofer UMSICHT, Oberhausen (Institute for Environmental, Safety and Energy Technology)
Friedrich-Alexander University Erlangen-Nürnberg (FAU)
German HySupply Project Team
Helmholtz Institute Erlangen-Nürnberg of Renewable Energy (HIERN)
Hydrogenious LOHC Technologies, Erlangen
LAVO Europe
Linde AG
Schaeffler AG
Technical University Brandenburg (BTU)
Thyssenkrupp Steel Europe AG, Duisburg (Carbon2Chem)
University of Erlangen (Chemical & Bioengineering)

Delegates outside Fraunhofer Institute for Ceramic Technologies and Systems

Japan

Overarching insights

The Australian hydrogen research delegation to Japan was undertaken 4-9 December 2022. The delegation was based in Tokyo, with visits to research institutions undertaken by bus, train, and Shinkansen (bullet train) each day.

Building on extensive and long-term resource trade partnerships, Japan has been a long time hydrogen industry collaborator with Australia through joint initiatives such as the Hydrogen Energy Supply Chain (HESC) demonstration project, which successfully concluded with the export of a shipment of liquid hydrogen from Australia (Victoria) to Japan (Kobe) in January 2022. An announcement of the $2.5bn second phase of this project was made in March 2023 by Japan's Ministry of Trade, Economy and Industry (METI) through their 'Green Innovation Fund'. Japanese companies such as Sumitomo Corp, Chiyoda, ENEOS and Mitsui are also actively developing domestic use focussed hydrogen projects in Australia (REF HyResource).

In October 2020, Japan announced its goal of carbon neutrality by 2050. Energy policy supporting this goal is driven by METI's 'Strategic Energy Plans', the sixth of which was released in October 2021, and highlights the '3E+S energy trilemma' – energy security, environmental sustainability, economic affordability, and safety (REF Japan Scan). The strategy is underpinned by detailed analysis and target setting, and indicates a holistic approach to the energy transition including energy efficiency on the demand side, whilst on the supply side:

"We will address maximum introduction of renewable energy as major power sources on the top priority; societal implementation of hydrogen and CCUS will be promoted; and necessary amount of nuclear power will be continuously utilized on the major premise of ensuring safety and public trust."

It would clearly have been desirable for the delegation to meet with METI to discuss the research priorities behind these goals, however competing METI priorities meant that this was not possible.

A further caveat regarding the hydrogen research delegation to Japan is that it was unable to encompass industry research laboratories, which are responsible for a great deal of hydrogen research in Japan in particular. This limited the delegation's ability to identify/assess additional applied research collaboration opportunities which doubtless exist.

Following a set of presentations and a networking session at the Australian Embassy in Tokyo which was well attended by industry groups both in person (limited numbers due to COVID restrictions) and virtually on 5 December, the delegation visited a range of academic and national laboratories with specific interests in hydrogen science and technology.

As is common in other countries including Australia, the research in the national laboratories and agencies is more closely aligned with the strategic priorities identified above, with each organisation (re)orienting its differentiated research strengths to bear on enabling the production, distribution and utilisation of hydrogen in the Japanese and ultimately global context. The academic institutions meanwhile appeared to pursue more 'bottom up' priority settings based on the skills and track record of their research leaders.

Research opportunities

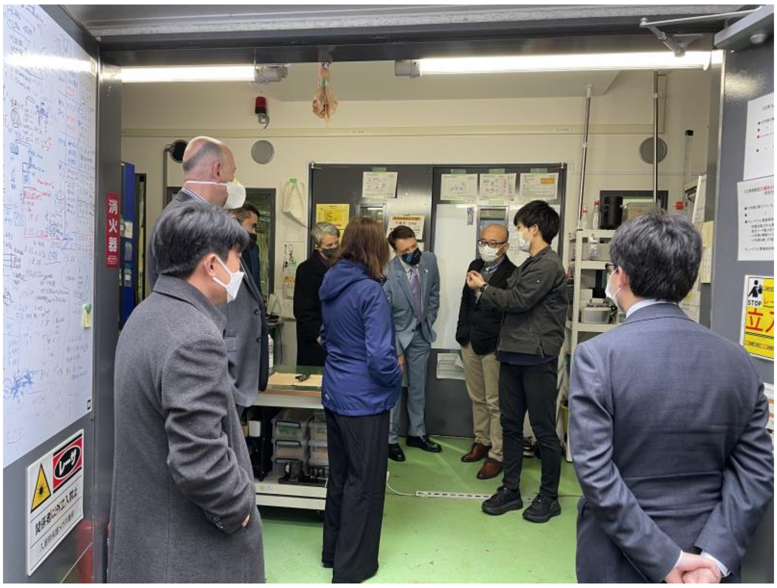
The research which was discussed during the delegation is best summarised on an institutional basis as follows:

Central Research Institute of Electric Power Industry (CRIEPI, Tokyo)

CRIEPI is a Japanese research organisation, with a focus on applied R&D supporting the electricity sector. Hydrogen is key to CRIEPI's strategic goals, supporting their impact in areas of electrification, system resilience, and zero emissions power and transport. While undertaking considerable R&D at laboratory scale, they have the facilities and expertise (in particular at their Yokosuka site south of Tokyo) to operate at pilot- and demonstration-scale, which makes them well suited to larger scale energy technology demonstration collaboration with Australia. Key areas of hydrogen research which might form the basis for collaboration with Australian groups are: electrolysis (including balance of plant), thermochemical hydrogen production (including biomass and waste gasification), ammonia co-firing, technoeconomic modelling (including import/export values chains) and life cycle analysis.

Tokyo City University

Tokyo City University has a long history of hydrogen car and truck R&D dating back to the 1970s, including the development of a series of hydrogen race cars and trucks based on hydrogen combustion engines. The group has designed innovative hydrogen fuel injector configurations. Various vehicle manufacturers have supported their hydrogen car development, including Nissan, Toyota and Hino Motors. Current research also focuses on heat transfer measurements and friction monitoring. Several research groups and SMEs in Australia are working in the hydrogen combustion engine development space which might benefit from collaboration with the Tokyo City University team and their industrial partners.



Hearing from experts at Tokyo City University

AIST Fukushima Renewable Energy Institute (FREA)

The Fukushima Renewable Energy Institute, (FREA) was established in 2014 as a resource to support the development and scale up of renewable energy technologies following the 2011

Fukushima earthquake and subsequent shutdown of Japan's nuclear power plants. The institute sits within the National Institute of Advanced Industrial Science and Technology (AIST, see below)

A particular focus for FREA is industry partnerships (eg with Shimizu) which support pilot demonstrations of Japanese renewable energy (including geothermal), and hydrogen technologies, but there may be opportunities to explore joint Australian – Japanese pilots should suitable funding and IP arrangements be put in place.

Hydrogen storage/carrier research and demonstration is a particular strength at FREA, which includes research and demonstration of ammonia, liquid organic carriers and metal hydride systems and complements areas of research at other AIST sites on formic acid and compressed / liquid hydrogen (see below). System Integration of these technologies is also a focus.

AIST GZR (Tsukuba)

The National Institute of Advanced Industrial Science and Technology (AIST) is a national applied research and development institute which focusses on industrial science and technology. With 2901 employees and annual funding of 111 billion yen (A$1.2bn), it comprises several research units across Japan, the largest being AIST Tsukuba. AIST is administered via Japan's Ministry of Trade, Economy and Industry (METI), hence the hydrogen research underway within its Global Zero Emissions Research Centre (GZR) is closely aligned with Japan's hydrogen strategy which is also formulated by METI.

The hydrogen research portfolio at AIST is broad and covers the entire hydrogen value chain (production-storage-utilisation). It also includes the cross-cutting theme of 'assessment' which includes areas such as safety, energy systems analysis and life cycle analysis. Hydrogen production research includes electrolysis technologies (Alkaline, PEM, Anion-EM), and 'fossil fuel reforming' via methane decomposition (pyrolysis). Storage research covers chemical carriers and metal hydrides (see FREA above) and physical storage (compression / liquefaction). Utilisation research topics include (electro)chemical compression and fuel cell development (PEM, SOFC). AIST has similarities to Australia's CSIRO which might be leveraged to support Australia-Japan research collaboration.

National Institute for Materials Science (NIMS, Tsukuba)

The National Institute for Materials Science (NIMS) serves as Japan's sole public institution specialised in the field of materials research with applications in public infrastructure, medicine, and energy and environment. It is the top materials science institute in Japan based on publication citations, and is sixth in overall (general) science. NIMS was born in 2001 from a merger between the National Research Institute for Metals (NRIM) and the National Institute in Inorganic Materials (NIRIM). NIMS had an annual budget of 30.8 billion JPY (A$341m) in financial year 2021, with 49% of their budget provided by direct government subsidy, 27% from competitive funds, 17% supplementary and 4% from private sectors. The institute has a workforce of 1546 of which 745 are researchers and 403 are engineers. The institute strongly values diversity with 35% of researchers being foreign nationals and 30% female. NIMS has three sites, all in Tsukuba, including headquarters at the Sengen site. The delegation visited both Sakura and Sengen sites in Tsukuba.

Unsurprisingly, hydrogen R&D at NIMS is focussed on materials science issues, both from the materials development and materials characterisation/testing viewpoints. A particular strength is in cryogenic hydrogen materials development and characterisation, including a liquid hydrogen mechanical testing facility which is under construction. A highlight was the visit to an experimental hydrogen liquefaction facility which is assessing the use of Active Magnetic Refrigeration (AMR) to achieve liquefaction efficiency improvements of up to twice the current industry standard gas refrigeration systems.

University of Tokyo, Research Centre for Advanced Science & Technology (RCAST)

The University of Tokyo was established in 1877. It ranks 39th amongst world universities according to the Times Higher Educational Supplement (2022). For reference, Australia's highest ranking universities are Melbourne and Monash Universities at 34 and 44 for respectively. The delegation was hosted by Professor Masakazu Sugiyama, Director of RCAST whom we thank both for the visit to the university, as well as for providing administrative support without which the delegation would not have been possible. The delegates were warmly received and University of Tokyo colleagues noted they had enjoyed previous interactions with Prof. Evan Gray (Griffith University). Several RCAST staff had connections to Australia through visits to UNSW (Prof. Kono and Prof. Takanabe) or collaboration with QUT (Prof. Ohara). The group have diverse research interests. Prof. Kono focuses on nickel-metal hydride batteries for vehicles. Prof. Minegeshi conducts research addressing artificial photosynthesis systems to convert water into hydrogen using solar energy. Prof. Ohara collaborates with Ian O'Hara (QUT) on bio-based chemical engineering – for example achieving a carbon negative sugar project.

University of Yamanashi

Nestled in the foothills of Mount Fuji about 2 hours west of Tokyo, the University of Yamanashi has been supported by the Japanese Ministry of Education (MEXT) to undertake research and educational activities relating to fuel cells, and more recently water electrolysis for nearly 45 years. The Hydrogen and Fuel Cell Nanomaterials Centre (HFCNC) was established in 2008 and is focussed on fundamental and applied research and

Hearing from experts at Yamanashi University development of catalysts and electrolyte materials for polymer-electrolyte (low-temperature) fuel cells and electrolysers. Research is guided by Japan's national Fuel Cell / Hydrogen Technology Development Roadmap which was developed by the New Energy and Industrial Technology Development Organization (NEDO) which sits under METI.

Key HFCNC capabilities of potential interest to Australia are in catalyst/membrane testing and characterisation with an impressive array (>20) of fully equipped test stations. A noteworthy suite of high-end physical characterisation facilities are available on site. The University indicated that it is potentially open to visits of Australian researchers to undertake collaborative work on industry-relevant testing of new materials and devices. The use of cell prototypes operated under close-to-real industrial conditions using facilities like these which are not available within Australia are critical to support the translation of Australian research and development in hydrogen fuel cell and water electrolyser technologies into commercial outcomes.

Potential collaboration on materials development might be also possible, especially considering the direct connections of HFCNC to significant industry partners who might take up Australian patented developments in areas such as materials design and synthesis for scaled-up production. The University of Yamanashi delivers a popular industry training course funded by the prefecture.

Iwatani Tokyo Tower Hydrogen Refuelling Station & Toyota Mirai Showroom

On its final day, the delegation visited the Hydrogen Refuelling Station (HRS) near Tokyo tower which is operated by Iwatani Corp (a key HRS installer in Japan), and accompanying Toyota Mirai hydrogen vehicle showroom. We observed commercial hydrogen refuelling operations, with a number of vehicles passing through the facility during the visit. The delegation was also shown the 'back room' liquid hydrogen storage (approximately 3 tonnes / 42000 l) and ionic compression facility which provided a glimpse of the infrastructure required to support mass uptake of hydrogen vehicles in an urban environment.

JST (Tokyo Headquarters)

The final visit of the delegation was to the headquarters of the Japan Science & Technology Agency (JST) in Tokyo, to undertake discussions relating to international research collaboration programs that the agency runs and which might yield opportunities for Australian institutions.

JST is an agency of Japan's Ministry of Education, Culture, Sports, Science and Technology (MEXT).

With a 2022 budget of Y170 billion (approximately A$2bn), JST supports a plethora of strategic basic research programs aligned with MEXT priority themes in Japanese universities/companies/ research institutes, industry-academia collaboration, and international collaboration activities. These encompass student, project, and university infrastructure support.

International collaborative programs are typically co-sponsored by partner countries in bilateral or multilateral arrangements with JST.

A specific goal of JST is to promote Science Technology and Innovation (STI) aligned with the UN's Sustainable Development Goals, and a specific international collaboration program highlighted was 'Adopting Sustainable Partnerships for Innovative Research Ecosystem' (ASPIRE). The latter was tentative, with a budget request of $25m currently under consideration.

ASPIRE follows a similar bilateral/multilateral blueprint to JST's other international collaboration activities, and has focus areas of biotech, AI, materials, energy semiconductors, quantum and telecommunications.

JST has been in discussion with Australia's ARC regarding international collaboration partnerships, but is unsure whether this is the most appropriate agency. The potential for CSIRO to act as Australian partner was raised during the meeting, but noting that CSIRO is not a research funding agency per se, this would require government(s) support.

Australian delegates to Japan

Name	Role	Organisation	Location
Dr **Patrick Hartley**	Leader, CSIRO Hydrogen Industry Mission **Delegation Co-Lead**	CSIRO	Melbourne, Victoria
Professor **Ali Abbas**	Professor of Chemical Engineering at the University of Sydney in the School of Chemical and Biomolecular Engineering Acting Head of School Founding Director of the Waste Transformation Research Hub	University of Sydney	Sydney, New South Wales
Professor **Rosalind Archer**	Professor / Head of School Engineering and Built Environment Griffith University, Queensland **Delegation Co-Lead**	Griffith University	Gold Coast + Brisbane, Queensland
Associate Professor **Elham Doroodchi**	Associate Professor of Chemical Engineering and a leading authority in multiphase flows and particle technology	University of Newcastle	Newcastle, New South Wales
Professor **Zhenguo Huang**	Professor leading the Hydrogen Energy Program at the University of Technology Sydney	University of Technology Sydney	Sydney, New South Wales
Professor **Shanghoon (Shawn) Kook**	UNSW Engineering Professor Direct the UNSW Engine Research Laboratory	University of NSW	Sydney, New South Wales
Dr **Daniel Roberts**	Research Program Director CSIRO	CSIRO	Brisbane, Queensland
Dr **Alexandr (Sasha) Simonov**	ARC Future Fellow, physical chemist specialising in (photo)electrochemistry and (photo)electrocatalysis	Monash University	Clayton, Victoria

Ms **Rebecca Thomson**	Manager, Hydrogen Strategy Team Climate Adaptation and New Industries Division | Clean Technology Branch	Department of Climate Change, Energy, the Environment and Water	Canberra, Australian Capital Territory
Ms **Yuko Wakamatsu**	Business Development and Global CSIRO **Delegation Co-ordinator**	CSIRO	Sydney, New South Wales

Organisations visited

AIST Fukushima Renewable Energy Institute
AIST Global Zero Emission Research Center
AIST Tsukuba
Central Research Institute of the Electric Power Industry (CRIEPI)
Electric Power Development Co., Ltd. (JPower)
Hitachi
IERE Central Office
JGC Group
Kanazawa University
Kawasaki Heavy Industries
Kyoto University
Kyushu University
Okayama University
Sumitomo Corp
Tokyo City University
Tokyo Institute of Technology
Toyota
University of Tokyo
University of Tokyo, Institute of Industrial Science
Yamanashi University

AIST Fukushima Renewable Energy Institute

United Kingdom

Overarching insights

The UK government is encouraging industry to develop and use hydrogen to achieve its transition to net-zero emissions and participate in research to bring this about. See *Hydrogen RD&D Collaboration Opportunities: United Kingdom report* that aims to enhance country-to-country engagement by providing stakeholders with an overview of the UK's hydrogen priorities and hydrogen ecosystem. There is also a strong sentiment in the UK to plan and model optimal development pathways.

The UK will leave Horizon Europe and are exploring ways to fill the gap. There will be regional differences going forward too, with Scotland potentially exporting energy and the UK importing. Hydrogen activity at UK institutions is advancing rapidly across the value chain and is also progressing up the TRL levels. Academic research in hydrogen is occurring at all of the major universities complementing an aggressive implementation aspect around hydrogen hubs throughout the UK being led by government and industry. There is a great willingness and scope to collaborate with Australian partners across research and deployment components.

The UK govt aims to encourage industry to develop and use hydrogen to achieve its transition to net-zero emissions.

The government and many others during our visits acknowledged the importance of private sector investment in research, development and innovation. See the *Hydrogen Business Model*, the *Hydrogen Research and Innovation (R&I) Roadmap*, the U*K Innovation Strategy*, and collaborative engagements with the Hydrogen Advisory Council.

The UK endeavours to increase its hydrogen production capacity by expanding facilities that produce hydrogen via renewable electrolysis and steam methane reforming (SMR) with carbon capture, utilisation and storage (CCUS); and by exploring other production technologies. By 2028, the UK aims to utilise hydrogen in limited small-scale industry applications and demonstrations – such as transport and natural gas blending. By 2035, hydrogen is expected to be utilised to support industry-wide decarbonisation across the UK. The UK aims to set a target for ore-based steelmaking to close to zero. By 2040, the UK aims to establish the world's first net-zero industrial cluster.

Discussing the green transformation of UK industrial heartlands – NW cluster – with Joe Howe, University of Chester

The Hydrogen Advisory Council (HAC), which sits within BEIS, supports the implementation of the UK's hydrogen strategy by identifying actions necessary to enable hydrogen scale-up, with a particular focus on increasing low-carbon hydrogen production capacity. The HAC is comprised of various agencies including funding institutions (Innovate UK & the Engineering and Physical Sciences Research Council (EPSRC)) and government bodies (BEIS & HM Treasury).

Several private funding mechanisms also exist for those within the UK. International researchers and organisations may access UK funding mechanisms via the Fund for International Collaboration (FIC) and through the UK Research Council.

Industry, academia, and government are collaborating to bring about hydrogen clusters (also known as hydrogen valleys or ecosystems). These are hydrogen value chain demonstrations and pilot projects that cut across sector applications.

The UK drives hydrogen innovation through multilateral partnerships and engagement with international forums and multilateral organisations and committees. Examples include the International Partnership for Hydrogen and Fuel Cells in the Economy, and the Mission innovation Clean Hydrogen Mission, which is co-led by the UK, US, Chile, European Commission, and Australia.

The UK has also established funds for international RD&D collaboration, such as the Fund for International Collaboration (FIC). Bilaterally, BEIS established the UK Science and Innovation Network (SIN), based in 31 countries.

Research opportunities

The delegation identified the following research areas of mutual interest between the UK and Australia, amongst many others:

1. Large scale production using blue hydrogen, biomass, and plastic waste (as a gateway for green hydrogen and regional transitioning).
2. Transitioning a fossil fuel based regional industrial area towards net zero integrating hydrogen into the grid and local industries. Optimal scenarios need to be found modelling socio-technical-economic factors that identify the large-scale actions and associated interventions required (examining for example Contracts for Difference and other tools). The idea is to establish 'implementation hubs' and mirror two or more regions between the UK and Australia (for example, Northwest England and Newcastle Australia). Likely institutes to be involved include University of Chester and University of Sheffield. Australia side: Jessica Allen (University of Newcastle and UNSW).
3. Large scale storage identifying sizes required, locations, materials, and performance standards.
4. Materials science – compatibility and embrittlement, Henry Royce and Imperial College
5. Sustainable Aviation Fuel (SAF); and maritime fuels. The UK are making their SAF via e.g. the Fischer Tropsch route from CO_2 or biomass (e.g. sewage sludge, pulp & paper etc.), e.g. at Birmingham or TERC.

6. National and international energy sector transition modelling, building on the excellent work of energy systems modellers in the UK, particularly at Imperial College who are developing and applying a variety of open-source tools to explore national level transition pathways and the role of hydrogen and hydrogen derivatives (IFM).

Other topical areas to consider include:

- Open data sharing - developing online tools to show 'how to build'. BIIS and the University of Sheffield would like to discuss the online international collaboration tool further.
- Electrolysis pathways. It’s clear electrolysis research and development is saturated globally, and Australia is at a challenging standpoint on choosing technology development pathways. Limitations exist, for example proceeding now with large scale might eventually constrain iridium oxide. We need to use materials that are cheap and readily available. Questions: a) can we progress alkaline electrolysis for now using uranium nickel for the electrodes? b) can we manufacture here? There seems to be an appetite to do this in Australia noting global uncertainties, and fossil fuel transition pathways for regional Australia are needed.

Translational Energy Research Centre and University of Sheffield

Australian delegates to the UK

Name	Role	Organisation	Location
Professor Paul Webley	Professor and Director Woodside Monash Energy Partnership **Lead of the Delegation**	Monash University	Melbourne, Victoria
Dr Jessica Allen	Senior Lecturer	University of Newcastle	Newcastle, New South Wales
Associate Professor Jonathan Love	School of Chemistry and Physics Centre for Clean Energy Technology and Practices, Faculty of Science	Queensland University of Technology	Brisbane, Queensland
Professor Bernard Rolfe	Associate Dean Research Faculty of Science, Engineering, and Built Environment (Also affiliated with the Institute for Frontier Materials)	Deakin University	Melbourne, Victoria
Professor Iain MacGill	Joint Director of the UNSW Collaboration on Energy and Environmental Markets (CEEM)	UNSW	Sydney, New South Wales
Mr Dan O'Sullivan	Program Manager International Hydrogen Research Collaboration	CSIRO	Brisbane, Queensland
Professor Gerhard (Gerry) F. Swiegers	Intelligent Polymer Research Institute and CTO, Hysata Pty Ltd	University of Wollongong	Wollongong, New South Wales
Dr Christian Hornung	Group Leader, Chemistry & Polymers	CSIRO	Melbourne, VIC

Organisations visited

Austrade
Australian High Commission
BEIS - Department of Business, Energy & Industrial Strategy
Henry Royce Institute
Imperial College
Johnson Matthey
National Grid
National Physical Laboratory (NPL)
Rolls Royce
Translational Energy Research Centre (TERC)
University of Birmingham
University of Chester
University of Liverpool
University of Oxford
University of Sheffield

United States

Overarching insights

The Australian hydrogen research delegation to the US was undertaken 10 -19 October 2022. This was a particularly significant time for hydrogen industry development in the US, with the recent release of the Biden administration's 'bipartisan infrastructure law' which amongst many other clean energy and hydrogen support measures totalling $9.5bn, includes specific support for the Department of Energy and "authorizes DOE appropriations of $1.5 billion over five years ($300 million per year for Fiscal Years 2022 to 2026) to support clean hydrogen manufacturing, recycling, and electrolysis". Specifically, Section 40314 amends Title VIII of the Energy Policy Act of 2005 to include a new "Section 815—Clean Hydrogen Manufacturing and Recycling" ($500 million) and a new "Section 816—Clean Hydrogen Electrolysis Program" ($1 billion). DOE intends to issue the "Bipartisan Infrastructure Law (BIL): Clean Hydrogen Electrolysis, Manufacturing, and Recycling FOA" to address these provisions of the BIL and to support the Hydrogen Energy Earthshot, a DOE initiative to reduce the cost of clean hydrogen by 80 percent to US$1 per 1 kilogram in 1 decade ("1 1 1")." [4]

Perhaps even more significantly, the Inflation Reduction Act (IRA) was passed into law in August 2022, providing up to $3 per kg tax subsidy for clean hydrogen production. Many argue that this measure alone unlocks hydrogen production economics and will stimulate the re-emergence of the USA as the global leader in hydrogen technology development, and hydrogen production and utilisation.

Important pillars for these investments are the 'made in America' opportunity and ensuring a 'energy justice' for disadvantaged communities in the net-zero energy transformation, including empowering workers and communities and enabling workforce transition from fossil fuel industries.

At the start of the delegation, we heard first-hand the focus and ambition of these programs at the 'Hydrogen Americas Summit' in Washington DC, which included an in-person appearance from Energy Secretary Jennifer Grandholm who perhaps epitomised the industry and government sentiment by stating "It's go time for hydrogen".

Following the conference and a function at the Australian Embassy in Washington, the delegation embarked on a tour of selected US Department of Energy national laboratories across the United States to hear how the ambitious hydrogen policy agenda was translating into research and development focus, with a view to identifying opportunities for research collaboration between our countries in areas of mutual strategic importance.

[4] Federal Register : Notice of Intent Regarding Bipartisan Infrastructure Law (BIL) Support for Clean Hydrogen Electrolysis, Manufacturing, and Recycling

Research opportunities

Key opportunities for R&D collaboration emerged through the national laboratory visits are summarised below.

Techno-economics (TEA) and lifecycle (LCA) analysis

These areas have emerged as critical research capabilities in underpinning the hydrogen technology business case development both in the US and Australia. The groups at the National Renewable Energy Research Lab (NREL) in Colorado and Argonne National Laboratory (near Chicago) in particular have great depth in these areas, and possess a wide range of highly developed tools and methodologies which US DoE adopts in technology target and policy setting. There is great potential for Australian researchers to leverage these capabilities and adapt them to the Australian context in order to support industry and government investment decision making.

Critical metals supply chains

Whilst a resources research area much broader than hydrogen, the availability of certain critical metals may provide a major impediment to hydrogen technology scaleup. Critical metals such as platinum and iridium are crucial catalyst materials for fuel cell and electrolysis technologies. The delegation saw no research in this area whilst visiting national labs, but senior US DoE staff pointed to this area as a potential area for collaboration with Australia in meetings during the 'Hydrogen Americas Summit' in Washington DC.

Hydrogen mobility

US DoE has both a historical and current focus on hydrogen mobility, dating back notably to the DoE "FreedomCAR and Vehicle Technologies (FCVT)" program which was developed by the Bush administration in the early 2000s. The current DoE focus in this area is on heavy transportation, an area where hydrogen is seen to be most competitive relative to battery electric transport. Key targets relate to durability and lifetime of fuel cell technologies through programs such as the 'million mile fuel cell' initiative, which includes efforts to reduce fuel cell component degradation. Cost reductions through replacing precious metals in catalyst systems are also a priority. New technologies/approaches to thermal management were also cited. Considerable investment is going into advanced materials development research to address these needs, and the opportunity to collaborate with the US in this area is discussed below.

Heavy industry decarbonisation

In line with Australia's current hydrogen strategic priorities, heavy industry decarbonisation, including the use of hydrogen in these processes is now a DoE priority. Steelmaking and 'electrons to molecules' research, which includes synthetic fuels ('e-fuels') and ammonia production are areas of interest, particularly at LBNL and NREL. The intersection between Direct Air Capture and hydrogen research was a recurring theme.

Advanced materials characterisation and analysis (including fuel cell and electrolyser materials)

Many of the national labs visited had an abundance of research related to the development of advanced materials, with a particular emphasis on fuel cell and electrolyser technologies. Specific areas such as fuel cell component durability/lifetime and precious metal replacement catalysts were well represented.

These efforts leveraged excellent access to advanced materials characterisation techniques such as synchrotron light sources which are housed within the national laboratory network.

Given the numerous projects and institutions active in this area, the DoE has established 'coopetition' coordination through consortia such as the DoE funded 'Hydrogen Materials Advanced Research Consortium (HyMARC). Whilst Australia has a strong materials science research community, collaboration in this area will need to be focussed to avoid duplication, given this substantial US research investment. Pursuing Australian involvement in consortia such as HyMARC may however provide a mechanism for Australian researchers to remain aware of the latest technology developments and target their research priorities accordingly.

We particularly acknowledge with thanks the support of the US DoE in facilitating the visits, and for the time of the many research leaders in the national labs who presented to us during our visits.

Figure 1 Delegates at the Material Engineering Research Facility at Argonne National Lab

Australian Delegates to the US

Name	Role	Organisation	Location
Professor Peta Ashworth OAM	Chair, Sustainable Energy Futures	University of Queensland	Brisbane QLD
Professor Craig Buckley	John Curtin Distinguished Professor Hydrogen Storage Research Group (HSRG)	Curtin University	Perth WA Australia
Megan Crocker	Director of Strategic Partnerships	CSIRO US	San Francisco, USA
Dr Patrick Hartley	CSIRO Hydrogen Industry Mission	CSIRO	Melbourne, VIC
Dr Siva Karuturi	Senior Lecturer, Head of ACT-H2 Research Program	Australian National University	Canberra, ACT
Dharmini Robertson	USA and Canada Counsellor CSIRO	CSIRO	Washington, USA
Professor Bahman Shabani	Lead Sustainable Hydrogen Energy Laboratory (SHEL) research group	RMIT University	Melbourne, VIC
Dr Fiona Simon	CEO	Australian Hydrogen Council	Melbourne VIC
Associate Professor Simon Smart	School of Chemical Engineering, UQ Dow Centre for Sustainable Engineering Innovation	University of Queensland	Brisbane QLD
Professor Hongqi Sun	Professor of Chemical Engineering	Edith Cowan University	Perth WA Australia

Organisations visited

Argonne Leadership Computing Facility (ALCF)
Argonne National Lab (ANL)
Department of Energy (DoE)
Embassy of Australia
Hydrogen Americas Summit
Lawrence Berkeley National Laboratory (LBNL)
National Renewable Energy Lab (NREL)
NREL's Energy Systems Integration Facility (ESIF)
SLAC National Accelerator Laboratory
Stanford Hydrogen Research Faculty
Stanford Synchrotron Radiation Lightsource (SSRL)
Stanford University SLAC (Stanford Linear Accelerator)
Sustainable Energy Council
US Embassy

Going forward

A considerable amount of RD&D globally is underway to scale up the hydrogen economy applying a diverse range of technology applications, and to reduce production and use costs. As hydrogen economies gather momentum, the rapid pace of change and concurrent country activities also create risks, uncertainty and duplication of effort across supply chains. Overcoming these challenges requires focused and collaborative global research, development, and demonstration activities.

Australia continues to drive international collaboration in energy and has recently established eight Low Emissions Technology Energy agreements with Germany, India, Japan, the Republic of Korea, Singapore, the United Kingdom, the United States, and the Netherlands. Australian researchers and partners can be a part of these initiatives as well as contribute to programs such as the Mission Innovation launched alongside the Paris Agreement to mobilise and connect global research, development, and demonstration efforts.

When reviewing the main findings of the countries visited by the hydrogen delegations discussed above, a number of critical objectives and linkages are clear between the RD&D that is required and an international hydrogen economy for Australia. These are:

- exporting renewable hydrogen into the EU and Asia from Australia
- assessing when renewable hydrogen can be transported via ship in liquid form and what will be the most competitive supply source options in the meantime
- developing mutual beneficial cross-border hydrogen technology exchange networks to help accelerate the industry and reduce costs.

Australia is blessed with abundant energy and natural resources: solar, wind, minerals, land, and methane and has a vast opportunity to integrate technologies and energy uses to capitalise on these objectives. This is bringing opportunites for hydrogen, and its derivatives in varying capacities over time, such as ammonia, LOHC, and methanol. Other export opportunities are possible such as direct reduced iron (DRI) and other manufactured products. Other fields surround this industry including AI and information, biotechnology, materials, semiconductors and telecommunications.

High level summaries of the the global picture can be made from the delegations completed in 2022 and associated reading. But these are only a snapshot. More learning and knowledge sharing between countries is critical. For example, Australia, France, the USA and UK possess strong agriculture industries with a large portion of biological waste. We are all interested in developing engineering solutions for producing hydrogen from these biological waste products. Another example is the UK, USA and Australia are building sovereign capability to construct, maintain and operate hydrogen assets in regions transitioning from methane to renewables to produce hydrogen over coming decades. Many other examples can be drawn from the above summaries to pursue and the next decade will see countries greatly extend their hydrogen specialities and exchange technology and resources. Research programs like this one funded by the Australian government can assist fast tracking this goal and help foster greater research efficiencies.

Collaboration requires careful planning and ongoing management. Along with future research we need to increase collaboration between multiple industries, governments and the research community to realise clean hydrogen industry solutions, which can be attractive to domestic and global clean hydrogen industry opportunities.

As part of this program, a number of early to mid career researchers are now researching in these countries as visiting Research Fellows, with more to depart during 2023 and 2024. For an update on the fellowship and inquiries please visit the AHRN website.

The many ideas and actions raised in this report will require ongoing attention from the Australian research community with its old and new partners and participants found in these delegations across the many institutions and geographies. Several ideas are worth pursuing, including:

- Estabish metrics across research capacity; technology exchange opportunities and delivery; and industry development impacts to monitor alignment between national strategies, industry needs and research.
- Maintain a database on new and completed research ensuring innovation opportunities are 'fit for purpose' for industry uptake through exposure to both hydrogen technologies and industry directions under development with our lead partnering countries .
- The value of such knowledge and databases is maximised when relevant modelling and assessments occur with outcomes shared globally to understand hydrogen supply chains and markets, gaps and challenges, leading to the accelerated development being sought.
- Continue to raise the profile and communicate hydrogen research and industry capabilities. Accelerated industry development and innovation occurs when the various stakeholders involved are communicating and research findings are being translated. This has the added dividend of strengthened international awareness deepening our relationships with existing trading partners and fostering new relationships.

For now, CSIRO will continue to work with government departments, universities, and industry to grow its Hydrogen Knowledge Centre uploading valuable online resources, and the AHRN will host the next Australian Hydrogen Research Conference to be held in Perth in September 2024, and promote the fellowship program.

Throughout all these activities we will continue to discuss two critical questions with our international partners:

What are the strengths and weaknesses along the hydrogen supply chain?

What is the most efficient and effective way to research them together?

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