Australian Government
Department of Climate Change, Energy, the Environment and Water

AHRN
THE AUSTRALIAN HYDROGEN RESEARCH NETWORK

CSIRO

Australia's National Science Agency

Australian hydrogen research delegation to Singapore

19–23 June 2023

Final Report

Contents

1 Executive summary

This report summarises the primary activities of the Australian delegation to Singapore in June 2023. In the four-day visit, extensive engagement was conducted with academics and researchers of Singaporean leading universities (National University of Singapore and Nanyang Technological University), research organisation A*STAR, and the Maritime & Port Authority of Singapore. The delegates met with basic and applied research and policy makers along the green hydrogen value chain – from upstream hydrogen production, to middle stream hydrogen transformation and transport, and to downstream hydrogen distribution for end users.

Consultants KBR were contracted by CSIRO to provide the primary services required to plan for and manage the delegation logistics, and a defined portion of reporting for the delegation for the International Hydrogen Research Collaboration Program.

Singapore has signalled their intent to develop a hydrogen economy that could contribute to longer-term decarbonisation targets under its Long-Term Low Emissions Development Strategy, supported by its strong innovation landscape, and potential role as a hydrogen hub signalled in its Hydrogen Strategy. Singapore has established bilateral and multilateral relations with other countries to enable future hydrogen offtakes, and collaborates on the development of technical codes, regulations, and standards with respect to hydrogen production, transport, and supply-chain operations.

A wealth of research opportunities in renewable energy production, storage, and utilisation have been identified, including (photo-)electrochemical CO_2 conversion, CO_2 hydrogenation, biomass upcycling, ammonia and hydrogen handling, hydrogen and ammonia fuel cells, and battery recycling. Some of the key factors that will influence Singapore's hydrogen strategy include resource limitations, enhanced air quality and lower carbon emissions, and the creation of new industries and jobs. Singapore's hydrogen strategy and industry priorities are underpinned by its overarching Green Plan 2030 which has highlighted the intent to import green energy sources globally, particularly within the ASEAN region. This will facilitate Singapore's *Long-Term Low-Emissions Development Strategy* which is founded on the three pillars of transforming industry, economy, and society; harnessing emerging technologies as they mature; and pursuing international collaborations.

Singapore's plans for hydrogen deployment could include domestic hydrogen production via steam methane reforming (SMR), gasification, and methane pyrolysis with carbon capture, utilisation and storage (CCUS), exporting hydrogen knowledge and technologies such as solid oxide electrolysis (SOE), international supply chains (for hydrogen import), and industrial manufacturing including oil refining, chemicals, auto producers and hydrogen merchants.

Through in-depth bilateral discussion and syndication, it is clear that there are opportunities for Singapore-Australia funding of applied RD&D coming up, and the relevant industry stakeholders have shown interest in collaborative projects that will "shift the dial" when it comes to supporting and enabling decarbonisation. The importance of funding support including those to lift some of the context up to a wider industry activity is well recognised to continue and strengthen future collaboration.

2 Australian delegation

Prof Rose Amal, delegation lead, UNSW

Dr Tom Hughes, Monash University

Dr Fengwang Li, University of Sydney

Dr Daniel Roberts, CSIRO

Assoc Prof Jonathan Love, Queensland University of Technology

Prof Bahman Shabani, RMIT

Assoc Prof Siva Karuturi, ANU

Assoc Professor Simon Smart, University of Queensland

Dr Saif Al Ghafri, University of Western Australia

Prof Klaus Regenauer-Lieb, Curtin University

Dr David Harris, CSIRO

Mr Graeme Moya, CSIRO

3 Country organisations

KBR together with the management team identified the following key stakeholders to ensure there was appropriate traction at the key levels of government, regulatory agencies, and potential industry participants. The figure below outlines the overall ecosystem and levels engaged:

Figure 1: Singapore ecosystem and stakeholder level map

(Diagram courtesy of KBR)

Key organisations

The delegation met with the following organisations in Singapore.

National University of Singapore (NUS) is a national public collegiate and research university in Singapore. Founded in 1905, NUS is the oldest autonomous university in Singapore. It offers degree programs in disciplines at both the undergraduate and postgraduate levels.

NUS is highly ranked globally: #8 in the QS World University Rankings 2024, #19 in the Times Higher Education (THE) World University Rankings 2024, #26 in the USNWR 2022-2023 Best Global Universities Rankings, and #71 in the Academic Ranking of World Universities (ARWU) 2023. NUS exhibited strong global standing in subjects of particular relevance to this delegation. For example, the Chemical Engineering, Chemistry, Materials Sciences, and Environmental Sciences were ranked #6, #8, #12, and #10, respectively, in the QS World University Rankings by Subject 2023.

Nanyang Technological University (NTU) is another of Singapore's most prestigious universities. Founded in 1981, it is the second-oldest autonomous university in the country. NTU is organised across numerous colleges and schools, including the College of Engineering, College of Science, Nanyang Business School, Lee Kong Chian School of Medicine, College of Humanities, Arts and Social Sciences, Graduate College, National Institute of Education, and S. Rajaratnam School of International Studies.

NTU is frequently ranked within the world's top 30 universities according to most major international rankings. Globally, NTU was ranked #26 in QS World University Rankings 2024, #36 in the THE World University Rankings 2023, #30 in USNWR 2022-2023 Best Global Universities Rankings, and #93 in ARWU 2023. NTU also exhibited strong global standing in subjects of Chemical Engineering, Chemistry, Materials Sciences, and Environmental Sciences (#10, #11, #6, and #15, respectively) in the QS World University Rankings by Subject 2023.

Agency for Science, Technology and Research (A*STAR) is a statutory board under the Ministry of Trade and Industry of Singapore. It supports RD&D that is aligned to areas of competitive advantage and national needs for Singapore. These span the four technology domains of Manufacturing, Trade and Connectivity, Human Health and Potential, Urban Solutions and Sustainability, and Smart Nation and Digital Economy set out under the nation's five-year RD&D plan (RIE2025).

As a science and technology organisation, A*STAR bridges the gap between academia and industry in terms of research and development, integrates the relevant capabilities of its research institutes, and collaborates with the wider research community as well as other public sector agencies towards meaningful and impactful outcomes. Together with the other public sector agencies, A*STAR develops industry sectors by integrating our capabilities to create impact with multinational corporations and globally competitive companies; partnering local enterprises for productivity and gearing them for growth; and nurturing RD&D-driven startups by seeding for surprises and shaping for success.

Maritime & Port Authority of Singapore (MPA) is a statutory board under the Ministry of Transport of the Government of Singapore. As port authority, MPA regulates and manages port and marine services, facilities and activities within the Singapore waters. This includes vessel traffic and navigational safety and security, through regulation on operational efficiency and on the environment. As developer and promoter, MPA works with other government agencies and maritime industry partners to make Singapore a leading global hub port and a top international maritime centre. Its aims include attracting a core group of ship owners and operators to set up operations in Singapore, broadening the breadth and depth of maritime ancillary services offered there, and improving on the business environment for the maritime industry. As the national sea transport representative, the MPA safeguards Singapore's maritime/port interests in the international arena. This extends to being the government's advisor on matters relating to sea transport, and maritime/port services and facilities.

Key contacts

NUS

- Associate Professor Sibudjing Kawi, NUS Chemical and Biomolecular Engineering, Email: chekawis@nus.edu.sg.
- Dean's Chair Associate Professor Qing Wang, Department of Materials Science and Engineering, Email: msewq@nus.edu.sg.
- Presidential Young Professorship - Assistant Professor Yanwei Lum, NUS Chemical and Biomolecular Engineering, Email: lumyw@nus.edu.sg.
- Doctor Juan Alfredo Guevara Carrio, Senior Research Fellow at the Centre for Advanced 2D Materials in NUS. The centre is directed by Professor Antonio H. Castro Neto (Email: c2dhead@nus.edu.sg).
- Professor Bin Liu, Deputy President (Research and Technology) of NUS. Email: liubin@nus.edu.sg. While Prof Liu did not directly participate in the delegation visit, she has been instrumental in the development of vibrant innovation clusters across the NUS's colleges, faculties, and schools, including the NUS Sustainability Cluster.

NTU

- Professor Siew Hwa Chan, Co-Director of Energy Research Institute @ NTU (ERI@N), Fellow of Academy of Engineering, Singapore and President's Chair in Energy. Email: mshchan@ntu.edu.sg.
- Associate Professor Hong Li, School of Mechanical & Aerospace Engineering/School of Electrical and Electronic Engineering, Email: ehongli@ntu.edu.sg.
- Associate Professor Lydia Helena Wong, School of Materials Science & Engineering, Cluster Director at ERI@N, Email: lydiawong@ntu.edu.sg.
- Professor Alessandro Romagnoli, School of Mechanical and Aerospace Engineering, Cluster Director at ERI@N. Email: a.romagnoli@ntu.edu.sg.
- Doctor Kamal Elouarzaki, Program Director at Centre of Advanced Catalysis Science and Technology (CAT) in NTU, Email: eqkamal@ntu.edu.sg.

A*STAR

- Doctor Yong-Wei Zhang, Distinguished Principal Scientist and Distinguished Institute Fellow at A*STAR's Institute of High-Performance Computing (IHPC), Email: zhangyw@ihpc.a-star.edu.sg. Research interests: multiscale modelling and simulation methods to understand material properties and provide guidance for material design, synthesis, and fabrication.

Talking to hydrogen mobility researchers at NTU

4 Key insights

The Australian delegation to Singapore has gained extensive understanding of research strength and interest in Singapore and Australia through diverse activities in the four-day workshops and site visits. These include:

- Day 1 – workshop and industry panel discussion on "Constellation of hydrogen RD&D", prospects for the hydrogen economy and need for innovation, and industry perspectives across the supply chain.
- Day 2– workshops on RD&D focus topics in Singaporean universities and research organisations and the delegation.
- Day 3 – workshops on RD&D clusters and syndications and laboratory and facility visits in NUS and NTU.
- Day 4 – site visits to Semakau Island which hosts many renewables and integrated hydrogen test bedding projects, including those by NTU (ERI@N), ENGIE and other companies, and site visit and roundtable discussion at the Maritime Port Authority (MPA) Head Office.

In Day 1 workshop and industry panel discussion, industry representatives of Chevron, Keppel, KBR, MPA, and Temasek provided the perspectives of green hydrogen development from the point of view of Singapore government and industries, summarised as below.

- Considering the Singapore 2050 zero emission target, they anticipate hydrogen to play a significant role by supplying almost 50% of the country's energy demand by that time. Singapore has published its own National Hydrogen Strategy.
- The industries showed particular interest in utilising ammonia to store and transport hydrogen indicating readiness to invest in research and development in this field.
- They displayed interest in low-risk high TRL and CRL projects with quick return on investment while demonstrating less appetite for investing in low TRL projects at fundamental levels.
- Battery technologies, especially innovations to reduce their mass and volume while ensuring compatibility with Singapore climate condition was another line of their interest.
- Decarbonising the Singapore maritime industry is a priority of the Singapore Government, as stated in their National Hydrogen Strategy as well as by the industry representatives. Hence, many industries who are getting involved in hydrogen are setting themselves up to play roles and be part of this plan, to meet some ambitious emission reduction targets of this sector by 2030.

Days 2 and 3 involved workshops for the initial understanding of research activities and strengths in three critical research organisations, namely, NUS, NTU, and A*STAR, as well as organisations of Australian delegations. The engagement was further deepened by on-site visits to NUS and NTU, and research cluster syndication discussions on these two campuses. The workshop consisted of research presentations from 13 Singaporean delegates and 12 Australian delegates.

A wealth of research topics with Australia-Singapore synergy have been identified, spanning electrochemical CO_2 conversion, CO_2 hydrogenation, biomass upcycling, ammonia and hydrogen

handling, solid oxide fuel cells, and battery recycling. Below summarises the key observations in these workshops.

- The Singapore researchers came from diverse backgrounds, covering most of the hydrogen value chain from production to end users.
- Most Singapore researchers are primarily focused on the chemical engineering aspects of hydrogen solutions. Significant research on stack design and components are also conducted, such as those on thin sheet bipolar plates and coating, control strategy development, PEMFC system integration and heat recovery and thermal management.
- NUS and NTU collaborate with A*STAR to access scale and industrial connections.

On Day 4 the delegates visited the Renewable Energy Integration Demonstrator - Singapore (REIDS) on Semakau Island in the morning. Some key insights are summarised as below.

- This is a facility designed to support scale up and demonstration activities that are unable to be undertaken on the Singapore mainland, due to size/land availability or regulations. It is a piece of core infrastructure providing power systems and some renewable energies. It acts as a hub, allowing NTU researchers and collaborating organisations to operate test-bed operations off-the-grid.
- NTU offer a fairly well-organised 'research collaboration agreement' pathway to engagement and are experienced at establishing client projects on REIDS relatively quickly.
- NTU had several highly invested industry collaborative MW scale projects implemented in the REIDS. This is an autonomous microgrid facility running on PVs and a 50-kW backup diesel generator with a 200-kWh battery energy storage unit.
- The REIDS' plans to bring hydrogen into the picture are pursued for Semakau Island. The island's hot climate imposes challenges for the performance of batteries; hence, hydrogen is explored as an alternative or complementary solution. Furthermore, the introduction of hydrogen would facilitate the trial of introducing fuel cell (FC) vehicles on the island.
- No real load was connected to the system in Semakau Island and electronic loads are in place to mimic the expected load to be handled by their renewable microgrid.

In the afternoon of Day 4, delegates visited the MPA and held a roundtable discussion with the Chief Sustainability Officer / Chief Engineer, THAM Wai Wah, and his engineering team, who are facilitating a number of hydrogen and ammonia related pilots designed to help decarbonise the maritime sector in Singapore. The key insights are summarised as follows:

- Their strategy focusses on terminals, fuels, harbour craft, and aspects of carbon management and accounting and data science to support operations and efficiency gains. They have done the work and are clear that ammonia is going to be a significant feature of their operations as they and the international maritime fleet decarbonises; however, they have not discounted methanol and other alternative fuels and are considering the need for ports such as theirs to be able to support multi-fuel fleets.
- Their own operations will be decarbonised by a mixture of biofuels, electrification, and probably ammonia – these include harbour craft and power systems. These are the aspects of the transition that they have under their control, although – especially with ammonia – there

remain considerable uncertainties regarding safety and environment, due to the lack of relevant standards.

- Bunkering of ammonia remains a challenge. While ship loading and unloading of ammonia is established around the world, the bunkering aspect is not. There are no standards for ammonia bunkering and the safety/environment angle is considerable here.
- The role of RD&D in addressing these challenges is discussed. There is considerable scope for research to support the development of a greater understanding of plume dispersion and ammonia behaviour in the context of a spill – especially under tropical conditions. Practical aspects of refuelling ships with ammonia are considerable and can be addressed with new engineering science and technology.
- Much of their insights and input into this area is via A*STAR, and there is a significant opportunity for Australian researchers to bring complementary capabilities to solving these challenges.
- Workforce issues also remain unresolved. There was considerable interest in learning from some of the education programs being developed and delivered in Australia.

Learning about new technology research at REIDS on Semakau Island

5 Opportunities for collaboration

Singapore's RD&D landscape and priorities

Singapore has been dubbed Asia Pacific's most innovative economy for the last decade by the Global Innovation Index, thanks to its strong institutions, sound regulatory environment, business friendliness, and its technologically skilled workforce.[1] RD&D implementation is carried out by research institutes, universities, large multinational company labs, small and medium enterprises (SMEs), and defence science labs, with the Agency for Science, Technology and Research (A*STAR) being the lead RD&D agency in Singapore.

Singapore has a critical role in how technologies related to the different hydrogen energy carriers will progress to scale, because of the importance of its maritime port and liquid fuel bunkering links to the high economic trade across the region. MPA are developing a roadmap with several liquid renewable fuels (ammonia, e-methanol/bio-methanol, e-diesel/biodiesel, liquid hydrogen) to build at scale and pace preparing for the world's maritime fleets transition to low emission fuels. Significant questions remain, such as what standards will be required for large scale storage of ammonia in locations near high population densities. Australia is well placed to be a producer of these liquid renewable fuels.

International collaboration is central to Singapore's strategy for incorporating hydrogen into its economy. This is because Singapore is reliant on energy imports to meet its energy needs and is also an international trading hub with opportunities for re-export. This means that hydrogen supply chains will need to be built with key trading partners. Greater RD&D collaboration with Singapore will provide greater certainty in technology and supply at scale, requiring coordinated timing and effort between countries to satisfy the many maritime energy transition stakeholders in the region.

In the area of hydrogen, the key bodies responsible for strategy and policy are the NRF, the NCCS, the EDB (Economic Development Board) and the EMA. A*STAR is the key institution involved in the implementation of the RD&D tied to Singapore's hydrogen strategy and hosts the Coordination Office for the Low Carbon Energy Research Funding Initiative. Singapore also has several prominent universities, SMEs and large multi-national corporations making a significant contribution to hydrogen research globally

Singapore also has a number of consortia of industry, public sector and research sector players; including advocacy groups like the Hydrogen and Fuel Association of Singapore (HFCAS) and research consortia like the Singapore Energy Centre (SgEC). Private hydrogen funding is provided through the SgEC consortium, founded by Nanyang Technological University (NTU), the National University of Singapore (NUS), and ExxonMobil, and now also includes A*STAR. Private hydrogen funding is also provided by Temasek to the Centre for Hydrogen Innovations (CHI) at NUS. The Global Centre for Maritime Decarbonisation and the Singapore Maritime Institute have also funded studies and RD&D in hydrogen related technologies as part of their efforts on decarbonisation of the maritime sector. There are also a number of MoUs that have been signed between companies collaborating in the development of the hydrogen value chain.

[1] WIPO (2020) Global Innovation Index 2023: Singapore https://www.wipo.int/edocs/pubdocs/en/wipo-pub-2000-2023/sg.pdf

Singapore's NRF has also established the Campus for Research Excellence and Technological Enterprise (CREATE) – an international program for the purpose of RD&D collaboration. This program enables the creation of dedicated research centres with international partners, in various technology areas including sustainable energy and carbon emissions reduction. This program could support sustained research collaborations in the future. The NRF also issues International Grant Calls, often resulting from MoUs between Singapore and partner countries, as another avenue for future RD&D collaboration.

Singapore's strategy centres around its unique position as an international trading hub and its high-tech skills base. As such, trade of hydrogen and its derivatives, utilisation across maritime, industrial, and heavy vehicle applications, and hydrogen technology export, have been cited as promising areas for development in Singapore. To prepare for this, Singapore has established international partnerships with countries such as Australia to secure off-take agreements, facilitate the development of hydrogen supply chains, and to collaborate on regulations and standards.

The hydrogen and renewable power microgrid on Semakau Island: Renewable Energy Integration Demonstrator - Singapore (REIDS) is an impressive facility with industry-university collaboration demonstrating higher TRL distributed renewable energy products on a dual microgrid capable of testing significant research and industry questions. Collaborative studies in developing low-cost pathways for Australian based production, transport and Singapore based bunkering for the range of liquid renewable fuels that Singapore is considering is a significant opportunity to work on. There are very few test-beds with higher TRL distributed renewable energy products around the world and accelerated learnings are possible from collaboration and mutual learnings across test-beds in Singapore at REIDS and in Australia such as QUTs H2Xport test-bed and KETH, and perhaps others in future. Several more niche topics are also evident such as hybrid electrolysis and biomass/plastic upgrading at NTU.

Direction can be sought from formal agreements in place such as the 2020 Australia and Singapore MoU to work together on low-emissions technologies and solutions driving hydrogen-specific focus areas including supply-chain studies, standards, and RD&D across the value chain. There is also the Australia-Singapore Low Emission Technology (ASLET) Initiative designed to accelerate Australia and Singapore's maritime and port sectors move towards a low-carbon future, while delivering mutual economic benefit.

More specific opportunities identified during the delegation for future collaboration are tabulated below.

Researchers from Australian and Singapore on Day 2.

Research topic	Singaporean researchers	Australian researchers
Decoupled electrolysis, flow batteries, battery recycling	Qing Wang	Siva Karuturi Fengwang Li
Electrocatalysis for downstream carbon-based chemicals production, ammonia cracking, and green H2	Yanwei Lum Kamal Elouarzaki Yong-wei Zhang Poh Chee Kok	Rose Amal Fengwang Li Jonathan Love Siva Karuturi Tom Hughes Klaus Regenauer-Lieb Daniel Roberts Simon Smart David Harris
2D materials for separation and H2 storage	Juan Carrio	Rose Amal
Catalytic hollow fibre membranes for biomass gasification, methane activation, and CO2 hydrogenation	Sibudjing Kawi	Daniel Roberts Rose Amal Simon Smart Tom Hughes Jonathan Love Fengwang Li
PV+photochemical reactions	Lydia Wong	Rose Amal Siva Karuturi Fengwang Li
Hybrid electrolysis for H2 production and biomass/plastic upgrading	Hong Li Wong Roong Jien David Tan	Klaus Renenauer-Lieb Rose Amal Fengwang Li Jonathan Love Daniel Roberts Siva Karuturi
H2 and ammonia fuel cells	Siew Hwa Chan	Bahman Shabani Saif Al Ghafri Jonathan Love David Harris Fengwang Li Simon Smart Siva Karuturi Daniel Roberts
Sustainable CO2 capture, cryogenic liquid storage, energy system modelling	Alessandro Romagnoli	Kaus Regenauer-Lieb Saif Al Ghafri Tom Hughes Bahman Shabani David Harris

Table1: Aligning research themes between researchers

6 Risks and barriers

It is clear that there are opportunities for Singapore-Australia funding of applied RD&D coming up, and the relevant industry stakeholders want to see us come together to undertake projects that will "shift the dial" when it comes to supporting and enabling decarbonisation. The will is clear, and resourcing isn't a problem – we just need to propose good concepts.

Some considerable interest arises in the discussion around an A*STAR test bed/prototyping/demo facility and there seems a good way forward to provide some infrastructure and capability to address the commonly discussed challenge of bridging the lab-industry gap.

In the discussion on NUS campus with NUS academics, it appears they collaborate with A*STAR to access scale and industrial connections. In Assoc Prof Kawi's research, his operating model is strongly aligned with grant funding and PhD student projects. This has the potential to make it difficult to initiate collaborative activities without clear project funding. There don't seem to be 'shelf concepts' or ongoing areas of work in which collaborations could be seeded in a pre-project arrangement.

NUS academics have accessed NRF funding to support Australian visits to access beamlines and see NRF as an opportunity to support Australia collaborative activities.

In the discussion of potential emerging funding opportunities for Australia-Singapore activities, it is important to lift some of the context up to a wider industry activity, within which student- and grant-like activities could occur.

The importance of some funding to support collaborations were also recognised in the discussions with NTU academics. Examples include a recent AU-SIN Co-Green Co-innovation program and the developing ASLET initiative. It was agreed that demo projects such as CSIRO's ammonia engine concept would be well-suited to REIDS, for example, especially in the context of pre-work to provide outcomes that cannot be undertaken on the mainland.

It will be important to keep well acquainted across decisions occurring on Singapore's bunkering portfolio, and how quickly Australia's building production capability and export of liquid renewable fuels pathways can feed into the opportunities.

7 Capturing relevant existing projects

Key research initiatives, centres, and/or institutes in NUS and NTU, relevant to hydrogen RD&D

Project / Program	Organisations involved	Brief description
Centre for Advanced 2D Materials	NUS	Established in 2010 within the NUS, the Graphene Research Centre (GRC) was created for the conception, characterisation, theoretical modelling, and development of transformative technologies based on two-dimensional crystals, such as graphene. In 2014, the National Research Foundation (NRF) of Singapore has awarded NUS with a S$ 50 M grant over the next 10 years in order to support the operational costs of CA2DM's labs and micro and nano-fabrication facility and the exploration, synthesis, and development of new devices based on two-dimensional (2D) materials of which graphene is the most famous, creating a new Centre for Advanced 2D Materials, directed by Prof. Antonio H. Castro Neto.
Energy Research Institute @ NTU (ERI@N)	NTU	Established in 2010, the Energy Research Institute @ NTU (ERI@N) distinguishes itself through research excellence directed towards outcomes of industry relevance, with focus on systems-level research for tropical megacities. The Institute integrates research across NTU in the context of the energy challenge, and then helps translate outcomes into industry and practice. The Institute's research focuses on a host of Interdisciplinary Research Programmes, Flagship Programmes, Consortium Platform and an Accelerator Programme that covers the energy value chain from generation to innovative end-use solutions, motivated by industrialisation and deployment. The Institute is directed by Professor Siew Hwa Chan.
Renewable Energy Integration Demonstrator – Singapore (REIDS)	NTU	The Renewable Energy Integration Demonstrator - Singapore (REIDS) is part of the ERI@N. It is a Research, Development and Demonstration (RD&D) platform dedicated to designing, demonstrating, and testing sustainable and cost-effective energy solutions for Southeast Asia. Paving the way towards sustainable multi-activity off-grid communities, REIDS fosters systemic research and development in the broad energy arena in support of Singapore corporate and public stakeholders, thereby strengthening their position on the rapidly growing renewable energy and microgrids markets. REIDS Low Voltage Microgrid Cluster (LVMGC) testbed on Semakau Landfill is a living lab for industries, researchers, and government agencies to explore next-generation distribution grid solutions and to solve engineering,

		economic, environmental and societal energy transition challenges for off-grid and urban communities. Bolstering flexible reconfiguration capabilities, REIDS platform offers grid of grids test scenarios such as dynamic system optimization, smart grid clusters network management, energy trading, interoperability & cybersecurity which are instrumental to explore pre-competitive RD&D opportunities in energy sector.
Centre of Advanced Catalysis Science and Technology (CAT)	NTU	The centre focuses on catalysis-related RD&D and technique translation and the program manager is Dr Kamal Elouarzaki. The CAT provides an interdisciplinary research platform for collaboration internally between NTU research groups and externally with industrial partners. The centre aims at exploring novel approaches to catalysis and catalytic reaction engineering, which will benefit the issues ranging from local industrial manufacturing to global warming threat. The research focuses on several key areas, including material science, catalysis, reactor, and process engineering, which will potentially feed into future "lab-to-industry" applications. The centre develops roadmaps of economy-critical chemicals, including areas such as future fuels, healthcare, specialty and bulk chemicals, mining, and water treatment, which require urgent replacement to achieve carbon-neutral industry in the timeframe needed to address 2050 climate objectives.
Institute of Sustainability for Chemicals, Energy and Environment (ISCE^2, pronounced "I-S-C-E-squared")	A*STAR	ISCE^2 was established by A*STAR in 2022 to support Singapore's sustainability goals, including the Singapore Green Plan and Zero Waste Masterplan, through strong partnerships with academia, public agencies, and industry. ISCE^2 aims to help industries transition to renewable carbon and green chemistry, accelerated by digitalization and automation in three focus areas: Decarbonisation, which focuses on reducing carbon dioxide emissions through conversion to fuels, chemicals, construction materials, etc.; Green materials, including the development of environmentally friendly products which are biodegradable and circular materials which can be recycled and upcycled; Green processes, that reduce carbon footprint and solvent waste, and improve energy efficiency, for example in sustainable pharmaceutical manufacturing. With its core competences in organic and biomolecular chemistry, sustainable polymers, formulation technologies, catalysis, and process RD&D, the institute will advance RD&D in areas such as low-carbon technologies, carbon life cycle assessment, sustainable materials, and green manufacturing processes. ISCE^2 is a re-organisation of A*STAR's former Institute of Chemical and Engineering Sciences.

8 Recommendations and way forward

One of the overarching goals of the delegation and International Program is to foster RD&D mobility and tangible, sustained collaboration across Australian and Singaporean universities and research institutes.

There are a number of priority research themes that the researchers formed clusters of interest around, including, but not limited to:

- advanced catalyst design and developments (with strong interest in A*STAR-led RD&D)
- novel electrochemical/electrocatalytic processes to produce H_2 and other derivatives
- RD&D into graphene and other materials for membranes in H_2 processing (at NUS)
- production of H_2 via biomass / methane decomposition (NTU-led RD&D)
- innovative heat recovery, cold energy, cryogenic-related CO2 capture methods (NUS).

It is recommended that RD&D collaboration clusters are further defined in time and the researchers and their respective institutions:

1. agree on and action steps around collaborative, targeted RD&D work outcomes
2. identify most plausible commercial/industrial applications and likely benefits from the development(s)
3. specify RD&D needs and resources and the respective capabilities available in each country to complete the associated RD&D work.

In parallel to these collaborative clusters, respective leaders should identify potential commercial/industrial hosts where opportunities exist for their RD&D outputs to attract industry support and involvement in both countries. There are clear benefits for the Australian Hydrogen Research Network to identify priority RD&D collaborations and partner research institutions to fashion more targeted visits and exchanges going forward. The International Program can continue to build a systematic, coherent framework of clustered RD&D topics globally, along the lines of a hydrogen industry supply chain – an approach that was successfully tested during the Singapore delegation. This thematic approach will also help when engaging and attracting industry participants to be part of the program in the future.