Centre for Clean Energy Technologies and Practices

"QUT Hydrogen Process R&D project"

(Team Project Name: "H2Xport Project")

Mid-Term Activity Report

This Activity received funding from ARENA as part of ARENA's Research and Development Program – Renewable Hydrogen for Export.

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Project Summary and Scope

This project aims to develop a generic, scalable and systematic process to evaluate the operational viability of decentralised and/or regional-scale renewable energy (RE) hybrid systems to generate (green) hydrogen (H_2) for export. The project strategy is to build a benchmarking capacity using existing, readily available RE components to provide validated data for enterprise-scale economic modelling of performance as well as to provide a platform to test, at small pilot scale, the performance of new technologies developed through this project. The project will develop technologies in hydrogen production via electrolysis, in energy storage and in gas sensing. These technologies, when developed, will be integrated with the test-platform to benchmark against existing commercial standards. The project is tracking reasonably well given the conditions brought about by the Covid-19 pandemic and the nature of the vendor market over the past three years.

The primary focus of attention in the period since commencement has been design, construction, procurement, tendering and delivery of a ~50kW hybrid renewable energy pilot plant that has integral energy storage, hydrogen production and hydrogen use *via* an appropriate micro-grid/control system. The intent has been to utilise predominantly "off-the-shelf" equipment to enable benchmarking of component and system performance using this pilot plant. A schematic of the planned pilot plant identifying specific components is shown in Figure 1.

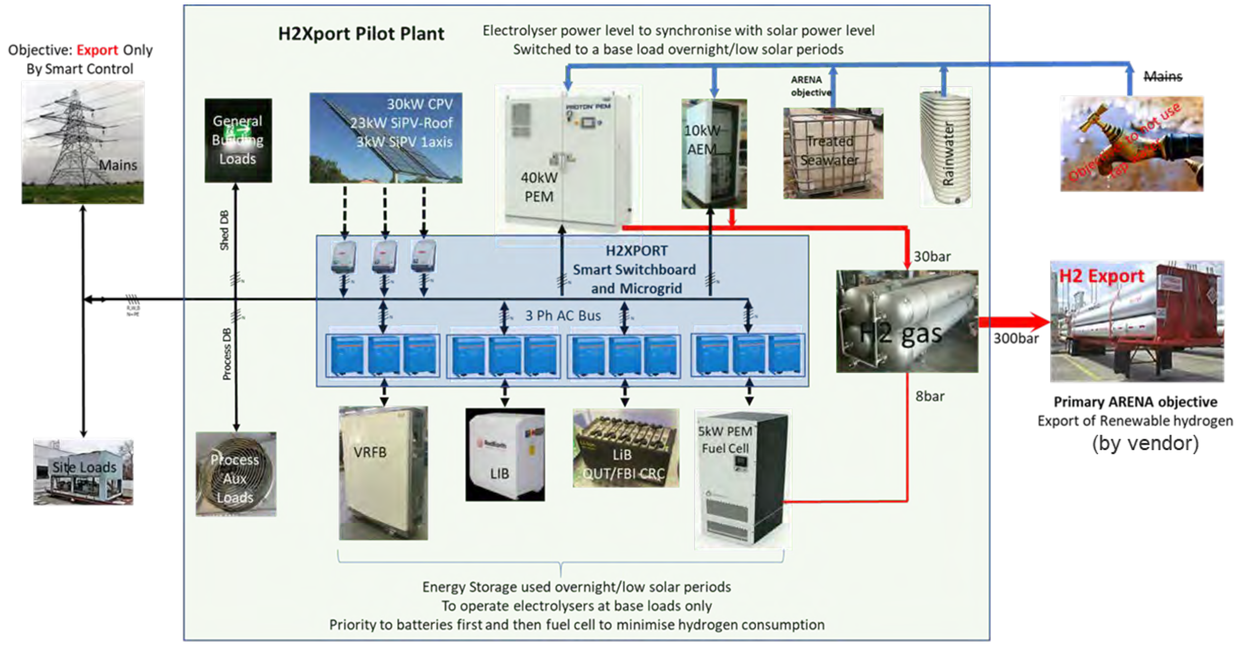


Figure 1: Schematic diagram showing the specific components for the "H2Xport" pilot plant.

Individual components and the control system are expected to be ready for commissioning in the second half of 2021. One outstanding element for final contracting is the gas network to join the electrolyser/fuel cell container to gas storage and to a second electrolyser in the system. This contract will trigger a final hazops analysis and commissioning of the pilot plant.

Laboratory-scale activities have also been impacted by Covid-19 restrictions albeit progress has been possible. Modelling and design have been key elements of desk-top work not only for the proposed pilot plant but also to translate attributes and lessons from pilot plant discussions to a broader generic approach to integration of components into viable system solutions.

Laboratory work has focused on improved understanding of battery components and battery performance (predominantly Li-based batteries) and development of novel electrodes for improved alkaline electrolysis performance. Li-based battery cathode activities have utilised our benchmark lithium-iron-phosphate (LFP) materials to assess optimum compositions (and source materials) for nickel-manganese-cobalt (NMC) formats with good success. Other key compositions for potassium-based battery formats have also been defined and corrected in the literature.

In addition, gap analysis and bench-scale work has focussed on identifying optimal performance of sensors for low temperature sensing of hydrogen gas in the presence of other gaseous components. This analysis has led to new experimental approaches to synthesise hybrid 2D materials to improve sensitivity and selectivity.

KEY HIGHLIGHTS

The following presents a brief summary of RD&D activities to date. In some cases, full details are in the public domain as listed under "*Knowledge Sharing Summary*"; journal papers in this list are referenced as [n].

Laboratory Activities

(i) Electrolysis: For the transition away from fossil fuels, it is critical to develop enabling technologies – such as electrolysis – that are unaffected by direct connection to variable production of renewable energy. Currently, alkaline electrolysers suffer from significant degradation in performance if they are rapidly powered down under reduced sunlight conditions when directly coupled with a solar cell due to reverse current flow. This work addresses this issue by creating a truly bifunctional electrode material that is switchable between the hydrogen evolution reaction (HER) and the oxygen evolution reaction (OER). Synthesis of suitable electrodes is simple and electrochemically activated. Results to date show that this electrocatalyst is switchable between both reactions without loss of activity under an accelerated stress test over a 24 hour period [3]. Cyclic voltammograms for operation over 1,000 cycles in 1M KOH solution that demonstrate stability are shown in Figure 2 below. These enhanced electrodes have also shown improved performance over a benchmark Pt electrode for ethanol and ammonia oxidation [3].

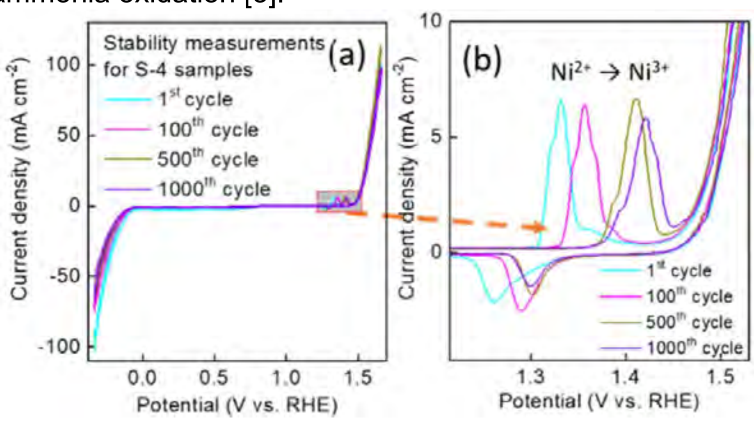


Figure 2: a) Cyclic voltammograms recorded in 1M KOH for 1,000 cycles at 100 mVs^{-1} for sample S-4, b) enlarged region showing the Ni oxidation process [3].

(ii) Gas Sensing: A comprehensive review of two-dimensional (2D) materials suggests high promise for improved performance of future gas sensors. 2D materials - nanoscale and layer structured with a high surface to volume ratio - are rapidly transforming the field of gas sensing [1, 2]. Gas sensors that are operational at room temperature offer low power demand and thermal safety during analysis. Hybrid forms of 2D materials offer great potential for improved sensing performance, i.e., high selectivity, sensitivity and stability, rapid response as well as operation at room temperature. The interaction between gas molecules and hybridised materials introduces new physical and electrical properties, which leads to improved gas sensing performance at room temperature.

Surface engineering, for example by decoration of 2D materials with quantum dots (QDs), can enhance gas sensing performance due to the unique characteristics of QDs attributed to the quantum size effect, their large extinction coefficient and shape-dependent electronic properties [1, 2]. Although some studies show high sensitivity and rapid response by 2D hybrid sensors, the fundamental mechanisms to develop applicable devices for real industrial and environmental conditions are still undetermined. Furthermore, the effect of water vapour on adsorption and/or desorption of gas molecules in a humid environment should be investigated as this may be a key enabler of commercial scale sensor development.

As part of this project, a novel microwave-assisted 2D hybrid material based on nanostructured reduced graphene oxide (rGO) doped with Pd nanoparticles (Pd/rGO) has been synthesised to investigate its hydrogen sensing performance at different operational conditions [5]. Sensing performance at various operating temperatures (room temperature up to 120°C), hydrogen concentrations (up to 1%), and relative humidity (up to ~44%) have been evaluated. The hybrid Pd/rGO shows homogeneous distribution of Pd NPs (<35 nm) on a multi-layered porous structure of rGO nanosheets. This work offers an environmentally friendly and energy-saving synthesis approach for hydrogen sensing with excellent control over experimental parameters which can lead to fabrication of a highly selective and sensitive hydrogen sensor.

(iii) <u>Modelling:</u> Many modelling activities have been undertaken including development of algorithms and code to deliver key inputs to planning for pilot plant construction as well as for larger-scale community or enterprise level integration of hydrogen-based energy production and use. This modelling includes electrical engineering constructs for micro-grid design as well as validation and use of real-time historical and present-day datasets for Si-PV and CPV installations in the Brisbane area. These models have all been implemented with an ultimate view to provide a digital twin that enjoins campus-based monitoring and control with on-site pilot plant activities. The latter longer-term digital twin objective is not a required element of this ARENA project, but it is a logical next step functionality we are pursuing in parallel.

Overall plant design and sizing can assist implementation of a solar powered hydrogen facility, but other key factors are critical to effective functional operation. To this end, a flexible virtualised replica of a renewable hydrogen plant, that not only models "plug-and-play" compatibility of components, but also identifies key elements that provide effective optimisation of system operations has been developed. Two operational factors for this virtual plant performance are: (i) electrolyser power settings to determine whether to produce hydrogen over twilight periods and/or overnight and (ii) a user-defined minimum threshold for battery state of charge to prevent charge depletion overnight if the electrolyser load is higher than its capacity. This approach to modelling targets maximum hydrogen yield while minimizing both low power supply probability (LPSP) and microgrid excess power. A "plug-and-play" capability enables significant research flexibility but also relates to hydrogen plants that need to expand, to be modified, and/or retrofitted with a mixture of the latest competitive technologies that achieve the lowest cost of capital equipment and operational costs. This approach offers not only potential longevity of a hydrogen production facility as changes in technology occur, but also anticipated cost advantages over facilities that require a rigidly defined selection of plant equipment.

Our understanding of hybrid renewable energy hydrogen production systems has also led to a community-level model that provides grid balancing services and eV station fuelling services using renewable energy located in urban centres. This model, called an adaptive response renewable energy plant (AREP) contains primary renewable energy sources and adapts operation in the short term to changing levels of excess or deficient energy on low voltage (LV) and medium voltage (MV) electricity grids. The AREP adaptively responds by (i) storing excess energy in batteries and in hydrogen tanks; (ii) returning power to the grid; (iii) providing electricity for fast charging eVs and hydrogen for FCeVs; and (iv) exporting excess stored energy as hydrogen to domestic markets. The AREP also adapts over the long term by predictive planning of charging capacity such that the type and capacity of renewable energy equipment is optimised for future operations. A key advantage of this AREP configuration is a flexible, "plug and play" capability with modular extension of energy assets that may ultimately maximise grid balancing *via* virtual power plant (VPP) configurations.

Pilot Plant Activities

(i) Housing Design and Construction: Two sets of consultant reports were utilised to provide the host institution with confidence that suitable housing could be located nearby the existing CPV and Si-PV arrays at Redlands. A final design and tender process resulted in substantial reductions to expected cost to construct. A tender was awarded in February 2020. The final outcome is shown in Figure 3 below.

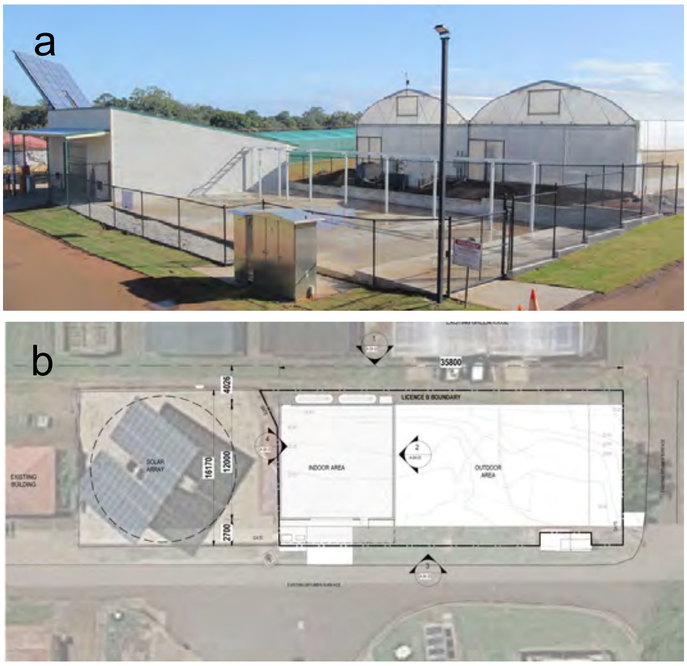


Figure 3: (a) Photo of completed housing for the H2Xport pilot plant at Redlands. (b) Overall schematic drawing showing relationship to other facilities at Redlands.

(ii) Pilot Plant Design and Procurement: Substantial re-design of the micro-grid to control and operate each of the components has been required over this period. The schematic in Figure 1 provides details of components and their respective high-level integration. Basic attributes of the components are provided in Figure 4a below. A novel aspect of interaction with vendors has been the opportunity to integrate specific components into a single container suited to shipping. The vendor ENGV – as agent in Australia for both NEL and Powercell – proposed an integration of both components prior to shipping to Brisbane in order to minimise commissioning delays on-site and to maximise use of available hard-stand. A rendering of the container which houses integrated NEL 40kW PEM electrolyser with a Powercell 5kW fuel cell is shown in Figure 4b. This container is expected to be delivered to QUT by mid-2021.

Lessons Learnt

The relevance of RD&D projects – particularly in rapidly evolving fields – is the capacity for a project team to learn many lessons about the state of the industry. These lessons not only arise from deep understanding of the scientific literature, but also from the demands imposed by translation of those research findings to practical, or pilot plant, activities. This translation process also requires strong and empathetic understanding of industry drivers as well as industry capabilities. These drivers and capabilities are influenced greatly by perception, commercial realities and many external factors (*e.g.,* Covid-19 is an exemplar). We list below a few high-level lessons learnt since commencement of the project regarding the state of the renewable energy sector as applied to hydrogen production and use.

(i) Power Engineering and Micro-grids: The state of market maturity with regard to microgrids forces the commercial provision of AC components across many sectors. In general, it would be reasonable to state that the power industry accepts efficiency losses (by using AC systems) even when power generation systems provide energy in a DC format. The perception of higher capital cost for DC components – above particular power ratings – appears to be untested. Thus, AC conversion losses will be “built-in” to hybrid renewable energy (including hydrogen) plants until supply volume and cost of DC components are reduced. It is also incumbent on the power engineering R&D community to demonstrate how improved DC components can increase the efficiency of hybrid facilities and at a lowered cost.

a

Solar: 25kW CPV + 25kW SiPV
Storage: 30kWh redox flow + LIB batteries
Water: City water/rainwater via on-board RO/treated seawater
Electrolysis: 40kW PEM, 10kW AEM
Fuel Cell: 5kW PEM
Micro-grid: REH2-FEMS microgrid flexible control
Grid bus: 380-400V AC
Storage: ~$2.5m^3$ @ 30bar (6Kg H_2 /day)
Production Rate: 8 Nm^3/hr H_2 (max)

b

Figure 4: (a) basic configuration and operational parameters of equipment for the H2Xport pilot plant. (b) vendor rendering of container housing a NEL electrolyser and Powercell fuel cell.

(ii) Electrolyser and Storage Technologies: The above principles also apply to the provision of electrolysers and batteries into the market. For example, there are few vendors offering components that receive DC power directly. Since start of this project, we have identified one vendor now offering such capability on low-end components and only one other considering the option. In a related development, the rapid growth in demand for green H_2 or green systems has reduced product choice at pilot plant scale. Many original equipment manufacturers (OEM’s) are focusing on provision to large scale markets. In some cases, this does involve manufacturing of modular components and is a welcome continuation of practice. Provision of intermediate scale (*i.e.,* suited to pilot plants) can minimise commercial risk of new systems configurations that may prove to be more efficient as well as maximises skills development for lower commercial risk.

(iii) Externalities: As the industry develops, it will be critical to minimise long lead times for equipment/component provision and for OEM engineers to install and commission. This requirement for Australia has become self-evident since the global Covid-19 outbreak where traditional supply chains have become substantially disrupted. It will be imperative for Australia to not only enhance supply chains (*e.g.,* by developing local assembly/manufacturing capacity) but also to develop the skills base to operate and maintain components for hybrid renewable energy systems.

Commercialisation Prospects

Opportunities and potential for commercialisation arising from this project are reasonable and under continuous review by collaborating partners. The format and extent of commercialisation is yet to be tested and will depend, ultimately, on the strategic and commercial intent of collaborating partners. We have evaluated potential patenting options for specific electrolysis developments, but to date, these have not progressed to full disclosure.

Knowledge Sharing Summary

A wide range of knowledge sharing activities have occurred since commencement of this project. These activities include sharing of knowledge within the teams in Australia and Japan as well as with ARENA participants and groups outside the immediate sphere of R&D activity and the general public. Highlights of these activities are provided below.

Eight journal papers have been published acknowledging full or partial support from ARENA for the work.

1. H. Hashtroudi, P. Atkin, I.D.R. Mackinnon and M. Shafiei, “Low-operating temperature resistive nanostructured hydrogen sensors,” *International Journal of Hydrogen Energy*, 44 (2019) 26646-26664.
2. H. Hashtroudi, I.D.R. Mackinnon and M. Shafiei, “Emerging 2D hybrid nanomaterials: Towards enhanced sensitive and selective conductometric gas sensors at room temperature,” *Journal of Materials Chemistry C*, 8 (2020) 13108-13112.
3. Md Abu Sayeed, J. Heron, J. Love and A.P. O’Mullane, “Activating iron based materials for overall electrochemical water splitting *via* the incorporation of noble metals” *Chemistry-an Asian Journal*, 15 (2020) 4339–4346.
4. Md Abu Sayeed, C. Woods, J. Love and A.P. O’Mullane, “Electrochemical synthesis of a multipurpose Pt-Ni catalyst for renewable energy-related electrocatalytic reactions” *ChemElectroChem*, 7 (2020) 4369–4377.
5. H. Hashtroudi, R. Kumar, R. Sava, S. Moshkalev, G. Kawamura, A. Matsuda and M. Shafiei, "Hydrogen gas sensing properties of microwave-assisted 2D hybrid Pd/rGO: Effect of temperature, humidity and UV illumination," *International Journal of Hydrogen Energy*, 46 (2021) 7653-7665.
6. T. Jenkins, J.A. Alarco and I.D.R Mackinnon, “Synthesis and characterization of a novel hydrated layered vanadium (III) phosphate phase $K_3V_3(PO_4)_4 \cdot H_2O$: A functional cathode material for potassium-ion batteries”, *ACS Omega,* 6 (2021) 1917-1929.
7. Y. Zhang, J.A. Alarco, M. Khosravi and I.D.R. Mackinnon, “Nanoscale differentiation of surfaces and cores for olivine phosphate particles – a key characteristic of practical battery materials”, *J. Phys. Energy: Topical Review*, 3 (2021) 032004, 1-11.
8. S. Ali, M. A. Jameel, A. Gupta, S. Langford, M. Shafiei “Capacitive humidity sensing performance of naphthalene diimide derivatives at ambient temperature,” *Synthetic Metals*, 275 (2021) 116739.

Three conference papers have also been published or submitted:

1. H. Hashtroudi, R. Savub, R. Kumar, S. Moskalev and M. Shafiei, “Hybrid two-dimensional nanostructured hydrogen gas sensors,” *Proc. SPIE Micro+ Nano Materials, Devices, and Applications*, Melbourne, Australia, December (2019), 11201, 112010X.
2. P. Atkin, H. Hashtroudi, I.D.R. Mackinnon and M. Shafiei, “Nanotechnology enabled hydrogen gas sensing,” *Proc. Int. Conf. on Hydrogen Safety*, Adelaide, Australia, September (2019) 1-10.
3. S.A. Gorji, H.G.Sahebi and M.H. Holakooie, “Fourth-order minimum-phase boost converters using reverse-coupled inductors”, *IEEE Trans. Power Electronics*, 2020.

In all cases above, the first author is either a PhD student or a post-doctoral research fellow.

<u>Workshops and Webinars</u>:

Internal team workshops among participant organisations as well as contractors and advisors have been conducted throughout the project timeline.

External workshops and fora noting H_2 R&D in Australia including the ARENA project:

- Australia-Japan: Science & Technology Diplomacy & Public Policy – ANU/UTokyo, November 2018.

- 6th Workshop on Global Network of Renewable Fuel – February, 2019.
- Queensland Hydrogen Forum – Brisbane, March, 2019.
- Japanese Hydrogen Delegation to Australia, RCAST industry leaders – September, 2019.
- Queensland Hydrogen Forum – Townsville, November, 2019.
- Tokyo Leading Academy, RCAS, UTokyo and IFE, QUT, November, 2019.
- Central Queensland Hydrogen Forum – Gladstone, February 2020.
- ARENA R&D Hydrogen Roundtable workshop - 17th-18th February, 2021.

External Webinars/Conferences/Platforms noting H_2 R&D in Australia including the ARENA project:

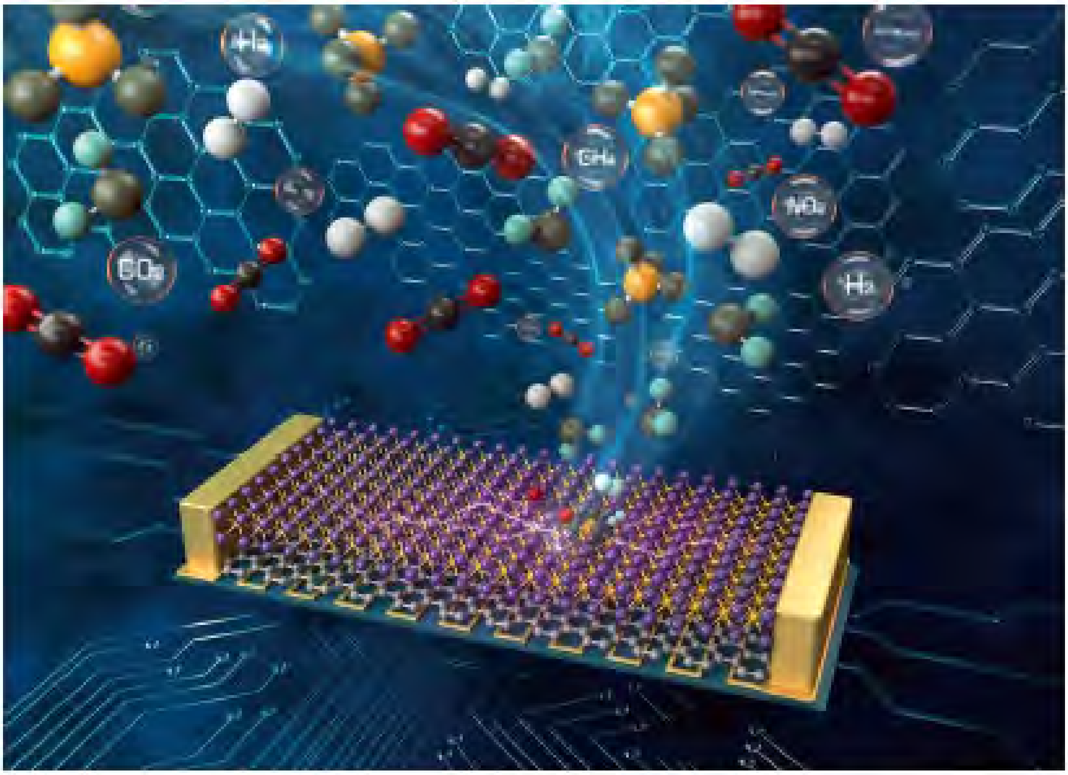
- Australian-Latin America Business Council – August 22nd, 2019.
- Queensland Association for Fire Investigators (QAFI) – October 24th, 2019.
- Engineers Australia – March 26th, 2020.
- Belgium Hydrogen Consortium – April 1st, 2020.
- UK Hydrogen and Fuel Cell Association – June 25th 2020.
- Engineers Australia: Energy Storage Seminar – July 2nd, 2020.
- University for the Third Age (Redlands Group) – July 28th, 2020.
- Local Government Assoc. QLD – Future Economy: Hydrogen – September 15th, 2020.
- National Cleantech Conference & Exhibition: Unpacking Hydrogen – September 17th, 2020.
- German Hydrogen and Fuels Cell Association – September 23rd, 2020.
- FME and ABIE Netherlands – October 7th, 2020.
- Environmental Institute Australia and New Zealand – October 8th, 2020
- Engineers Australia: Transition to Green Hydrogen – October 7th, 2020
- Institute of Chemical Engineers: Special Interest Group (Clean Energy) – October 27th, 2020.
- Australian Hydrogen Conference – November 16th, 2020.
- ALTA 2020 – Trends in Battery Technology Forum, Panel, Q&A – November 26th, 2020.
- Power, energy, clean technologies seminar – March 5th, 2021.
- Queensland Futures Institute, Brisbane – March 25th, 2021.
- International Association of Advanced Materials Medal Lecture – March 25th, 2021.
- World Science Festival, Brisbane – March 26th, 2021.

Media Releases:

Media releases directly identifying this project and team members include:

- QUT media: "*QUT leads new hydrogen pilot plant*" - October 5th, 2018.
- Manufacturer's Monthly: "*Queensland celebrates first shipment of green hydrogen to Japan*" – March 29th, 2019.
- QLD Govt Ministerial: "*Queensland's first Hydrogen Envoy announced in Japan*" – June 3rd, 2019.
- QLD Govt Ministerial: "*Boost for renewable hydrogen research in the Redlands*" – December 19th, 2019.
- Redland City Bulletin: "*Redlands plays hydrogen research role*" – January 4th, 2020.
- Channel 7 News: "*Qld academic wants hydrogen to power north*" – February 5th, 2020.
- The Australian: "*Queensland offers hydrogen as solution to Europe's energy crisis*" – November 19th, 2020.

Note: Many of the above media releases were subsequently promulgated to/with other outlets. The media list above is not exhaustive but indicative.

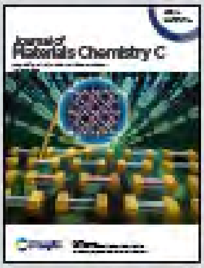


Australian Renewable Energy Agency (ARENA) Hydrogen Project, collaborative research between Swinburne University of Technology (SUT) and Queensland University of Technology (QUT), Australia

Emerging 2D hybrid nanomaterials: towards enhanced sensitive and selective conductometric gas sensors at room temperature

Hybridising different classes of 2D nanomaterials enhances the sensing performance, which is due to synergistic effects of hybrid nanomaterials.

As featured in:



See Mahnaz Shafiei *et al.*, *J. Mater. Chem. C*, 2020, 8, 13108.

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