MONASH University

Monash University, Ammonia Production from Renewables R&D Project

Mid-term Activity Report, July 2020

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PROJECT SUMMARY AND SCOPE

This project aims to further develop the nitrogen reduction to ammonia process being developed at Monash University in collaboration with University of Wollongong. Using renewables as the input energy the process can produce ammonia from atmospheric nitrogen at ambient conditions. The project will further optimise the process and the design of the electrolytic cells, lifting its TRL from 2 to 4. The product of this process, liquid ammonia, is increasingly seen as a viable renewable energy export vector; the handling, pipeline transfer and shipping of ammonia by bulk carrier are well recognised technologies. Also emerging is an understanding of the wide range of transportation and power generation technologies in which ammonia cans serve as a direct substitute for fossil fuels such as diesel, kerosene, LPG and natural gas.

The project origins were several discoveries in the Australian Centre for Electromaterials Science (ACES) at Monash University in 2016 and 2017. The ARENA funded project aims to develop and optimise these discoveries building from TRL 2 to TRL 4. The technology is based on the principle that high selectivity towards nitrogen reduction can be obtained in an electrolysis type cell by limiting the presence of water in the electrolyte. The project therefore involves further optimisation and development of the electrolyte chemistry as well as the electrode substrate and other components that are intrinsic to the electrochemical reaction.

At the same time, development to higher TR Levels requires new cell engineering to optimise the interaction of the gaseous reactant (nitrogen) the ultimately gaseous product (ammonia) with the liquid or gelled electrolyte and the solid phase electrode material. Aspects of this are similar to fuel cell technology and others are similar to traditional water electrolyser technology. Building on expertise developed within ACES at University of Wollongong the project therefore also focusses on electrode design and preparation.

The project is making good progress towards its goal of laying the ground work for further scale up and commercial development of the Monash process towards large scale renewable ammonia as an exportable form of renewable energy.

Key anticipated outcomes of the project:

1 move the electrolytic nitrogen reduction concept from TRL2 to TRL4 and creating a laboratory prototype that produces ammonia at the rate of at least 4 g h^{-1} m^{-2};
2 further development of expertise in the field of electrolytic ammonia production to maintain Australian research at the forefront of worldwide transportable renewable energy technology.

Mid-term milestones for the period under report:

Milestone 2.1 Optimisation of existing iron-based catalysts developed at Monash University via doping and surface decoration to enhance the activity by ≥30%.

Milestone 2.2 Cell apparatus capable of operation with a pressure maximum of 30 bar and a temperature maximum of 70°C designed and validated.

Milestone 2.3 Demonstration of the electrolytic ammonia production at the rate ≥0.5 g h^{-1} m^{-2}.

PROGRESS UPDATE

The overall progress of the project towards achieving the planned outcomes and milestones has been excellent. All key milestones for the reporting period have been successfully met through our significant advancements in the N_2 electroreduction technology based on a redox mediated approach. We have demonstrated that this process becomes particularly advantageous when combined with our previous developments in the design of aprotic electrolyte systems for the nitrogen reduction reaction (NRR). Scrutiny of the effects of the key system parameters on the selectivity and productivity of NRR carried out in a redox-mediated mode has enabled us to achieve an order of magnitude higher than planned improvement of the performance (Milestone 2.1), and demonstration of a NH_3 generation rate of more than 0.6 g h^{-1} m^{-2} on a significant timescale (achieving Milestone 2.3). In parallel, advanced electrolytic cells capable of accommodating this redox mediated process, including a scalable thin two-electrode device, have been developed and tested, as per Milestone 2.2.

COVID related laboratory closures during April and May reduced productivity somewhat, however we were able to keep activities moving forward using a skeleton staff.

KEY HIGHLIGHTS AND DIFFICULTIES EXPERIENCED

Our highlight achievement is our development of a system based on a copper working electrode, tetrahydrofuran as the main solvent, a lithium salt, and ethanol proton source which was optimised to achieve the ammonia yield rate of as high as 1 nmol s^{-1} cm^{-2} (0.6 g h^{-1} m^{-2}) at a high faradaic efficiency of 60-70 %. This level of performance was demonstrated at an optimal dinitrogen pressure of 15 bar for at least 12 h. Therefore, our Milestone 2.3 target of the electrolytic ammonia production at the rate ≥0.5 g h^{-1} m^{-2} has been successfully achieved.

The successful achievement of the milestones 2.1-2.3 naturally supports the progress of the project towards its key outcome – advancement of the ammonia electrosynthesis technology to TRL 4 and demonstration of a productivity of at least 4 g h^{-1} m^{-2} (Outcome 1). Based on the broad array of the results obtained that have significantly improved our understanding of the system, we are confident that the planned level of performance will be not only achieved, but substantially exceeded by the end of the project. Equally importantly, we have been very actively disseminating the new knowledge to create a broader awareness of the unique advantages offered by the technology being developed in this ARENA project (Outcome 2). Also as part of this we have been engaging widely with government, business and technologists in furthering an understanding of Australia's potential as a large scale renewable energy exporter.

COMMENTARY ON COMMERCIALISATION PROSPECTS

Monash University in June 2020, initiated a business development project regarding the technology arising from this project. This involved the commissioning of an external consultant to (i) develop a business plan and (ii) pursue discussions about scale up targets with a number of parties who have already expressed interest. The consultant advised the University of commercialisation options in August 2020. Based on this evaluation the University initiated the creation of a spin-out vehicle to be named Jupiter Ionics Pty/Ltd. It is expected that the company will be operational by March 2021. The initial investors include several Melbourne-based high net worth investors.

Building on the work funded by the ARENA project, the company is focused on advancing the technology's technical and commercial maturity so as to lay a strong foundation for seeking a further (Series-A) round of funding during 2022.

A detailed technoeconomic model has been constructed in collaboration with Dr Mike Mason (UK). This is under continued development to allow modelling of future scenarios in terms of energy supply intermittency and energy storage needs. Our intention is to publish this model such that it can be widely accessed.

SUMMARY OF KNOWLEDGE SHARING ACTIVITIES COMPLETED

Our initiatives towards the development of the expertise in the electrosynthesis of ammonia is very broad and involves a range of scientific and public activities. Some of these activities are closely interconnected with those undertaken within the scope of the 2018/RND008 ARENA project. Further details are summarised below:

Australian Chapter of the Ammonia Energy Association

Prof Douglas MacFarlane and Monash researchers are organisers and hosts of the Australian chapter of the Ammonia Energy Association (https://www.ammoniaenergy.org). In 2019, the Monash team has run the AEA "Ammonia = Hydrogen 2.0" Conference, which attracted a very significant attention from both government and industry. The event has featured the presentations from Representative Director at the Green Ammonia Consortium (Japan) and Executive Advisor at Tokyo Gas Mr Shigeru Muraki, and Victorian Minister for Energy, Environment and Climate Change, Minister for Solar Homes Honourable Lily D'Ambrosio. Other high-profile speakers included representatives from Siemens, Yara Pilbara Fertilisers, MAN Energy Solutions, Haldor Topsøe, ThyssenKrupp Industrial Solutions and ARENA.

A second "Ammonia = Hydrogen 2.0" conference is planned for August 2020. This will be delivered in a "virtual" mode. Lead speakers include Australian Chief Scientist Dr Alan Finkel, and Dr Rob Stevens from Yara International as well as an update from Mr Shigeru Muraki on the Green Ammonia Consortium.

Other Conference Presentations and Seminars

Professor MacFarlane, Dr Simonov and other members of the group have made presentations to a number of conferences and groups during the project as follows:

- Plenary talk on "Ionic Liquids for Ammonia Synthesis" at 8th Congress on Ionic Liquids, Beijing 12/5/19.
- Keynote talk on "Electromaterials for renewable ammonia synthesis" at Materials Chemistry 14, Birmingham, 12/7/19.
- Plenary presentation on "The Sustainable N-Cycle" at Green Chemical NZ, Auckland 4/12/19.
- Keynote conference presentation at Frontiers in Renewable Energy Storage & Harvesting Conference at Sungkyunkwan University, Korea 12/12/19.

• Webinar on "Sustainable Ammonia" presented for Victorian Government through Chief Scientist Dr Amanda Caples 24/3/20.

• Webinar on "Sustainable Ammonia" presented for Woodside Ltd, 16/4/20.

• A keynote virtual seminar delivered to 9th International Workshop on Advances in Cleaner Production: "A Roadmap to the Ammonia Economy" on 25/5/20.

• Webinar delivered to Clean Energy Council: "Roadmap to the Ammonia Economy" on 17/6/20.

Hosting of delegations from academia, industry and government

In 2019 and 2020, the groups of Prof MacFarlane and Dr Simonov at Monash have hosted three high-level delegations:

- a delegation from Germany led by the German Academy of Engineering and the German Industry Federation, the BDI focussed on Energy Futures based on hydrogen and ammonia;
- a delegation headed by Mr Hiroshi Kajiyama, Japanese Minister of Economy, Trade and Industry, along with the Australian Minister for Trade, Tourism and Investment, Senator Simon Birmingham;
- a delegation headed by the President of the National Academy of Engineering Korea Prof Oh-Kyong Kwon.

All visits included a showcase of Monash expertise in the renewable hydrogen and ammonia technologies, as well as discussions of the joint development of the renewable hydrogen and ammonia technologies between Australia and Japan, Korea and Germany.

High profile publications

Our vision on the development of the renewable ammonia and hydrogen technologies has been summarised in several recent publications, including:

1 Suryanto, B. H. R. *et al.* **Challenges and prospects in the catalysis of electroreduction of nitrogen to ammonia.** *Nature Catalysis* **2**, 290–296, doi:10.1038/s41929-019-0252-4 (2019).

2 MacFarlane, D. R. *et al.* **Liquefied Sunshine: Transforming Renewables into Fertilizers and Energy Carriers with Electromaterials.** *Adv. Mater.* 1904804, doi:10.1002/adma.201904804 (2020).

3 Jaecheol, C. *et al.* ***Matters Arising: Promoting Nitrogen Electroreduction to Ammonia with Bismuth Nanocrystals and Potassium Cations in Water.*** Nature Catalysis (2020).

4 Hodgetts, R. Y. *et al.* **Refining Universal Procedures for Ammonium Quantification via Rapid ^{1}H NMR Analysis for Dinitrogen Reduction Studies.** **5**, 736-741, doi:10.1021/acsenergylett.9b02812 (2020).

5 MacFarlane, D. R. *et al.* **A Roadmap to the Ammonia Economy.** *Joule* **4**, 1186-1205, doi:https://doi.org/10.1016/j.joule.2020.04.004 (2020).

Patent Activities

Two new provisional patent applications have been filed as outcomes of this project, the first in December 2019 and the second in July 2020. These will expand the existing IP portfolio of two patent families that have been filed since the first discoveries at Monash in 2016. These patent families will become the basis of the spin-out commercialisation vehicle that is being planned.

Outreach

We actively communicate the latest developments and achievements of the present ARENA project as well as our broader activities in the renewable fuels space to a diverse audience through meetings, seminars and workshops. These include detailed discussions of the electrosynthesis technologies with high-level representatives from Woodside Energy, SABIC Research and Technology, Viva Energy Australia (Shell Licensee), BP, Equatorial Launch Australia, Incitec Pivot, Burnaby Group, Baker's Delight, Broad Acre Farmer, Rina Consulting, Deep Science Ventures (DSV), Titania Resources, Solvay Ltd Canada, Neometals, Intecsa Industrial, European Commission and Australian Government.

Additionally, Prof MacFarlane gave a broad range of interviews on the green ammonia technologies, including interviews for BBC Radio, ABC Radio, ACES, Monash University News, Australian Science Media Centre (AusSMC), Physics Today, Chemical and Engineering News, Chemistry World, and the Australian Academy of Science.

LESSONS LEARNT AND NEXT STEPS

The key challenge of the project, as well as one of its key goals, is achieving high rates and efficiencies of nitrogen reduction to ammonia and our results have easily surpassed our Milestone 2 target. We were able to maintain limited lab access and therefore achieve good progress during the COVID related lockdowns and indeed some of our key developments took place during those periods. This validated the strong culture of teamwork that we have worked to establish within our lab group.

Our work has attracted very strong interest from potential Australian and overseas partners interested in sustainable ammonia production in general, and in particular in our developments in the field. As detailed above, the spin-out company Jupiter Ionics has been formed with an initial seed round of investment from several local shareholders. The company will play an important role both as a conduit for commercial feedback from potential end-users of the technology, as well as providing engineering resources to assist with scale up, alongside the existing ARENA-supported work. As the company moves towards a Series-A funding round, we envisage involving a consortium of strategic and professional investors who can provide additional financial, technical and engineering support to take the technology to the next level. However, we are mindful that this is a competitive space globally, with ARPA-E in the US and other government funding agencies supporting multiple international competitors. With the global market for Green Ammonia gaining increasing recognition, time will be of the essence as we seek to demonstrate the distinctive value proposition of our technology in operation at commercially-relevant scales.