Prospective FEnEx CRC R&D Projects for Program 2: Hydrogen Export & Value Chains.

R&D Project	Category	Description
Optimum method to transport renewable hydrogen	Efficient Hydrogen Storage and Transport	A number of potential options present themselves for the export of renewable hydrogen such as liquefaction, using a liquid carrier (ammonia, methyl cyclohexane *etc.*) and in the form of a solid state hydrogen storage material. The research will focus on identifying the most suitable method for the various potential global hydrogen markets and uses.
Materials Compatibility and Longevity with Hydrogen Under Extreme Conditions	Materials Testing for Export Applications	Multiple extensive studies of the compatibility & degradation of key materials under extreme operating conditions (high pressure H_2 gas, cryogenic liquid H_2 temperatures, high-process temperatures associated with conversion) including the effects of hydrogen embrittlement on containment materials. The materials will be verified for use under transient design duty cycles through understanding of degradation mechanisms and normal and transient failure modes.
Hydrogen Production from Novel Pyrolysis-Reforming Technologies	Large-scale Blue Hydrogen Production	Pyrolysis allows for the efficient production of hydrogen from biomass or even coal at large scale with the benefit of carbon sequestration through the return of biochar into the soil to deliver carbon-negative hydrogen. Tests will also investigate the ability of mobile pyrolysers to reform bio-oil to produce hydrogen: mobile technology solves issues & costs associated with distributed biomass stocks. A techno-economic analysis of key parameters and trade-offs will be completed.
Low-Cost Renewable Hydrogen through Advanced Electrolysis & Process Sensing	Large-scale Green Hydrogen Production & Storage	Using the specialised pilot-scale facilities available through the CRC partners, new green hydrogen production technologies will be tested and benchmarked using large-scale infrastructure able to deliver flexible renewable energy, particularly concentrated solar PV and Si-PV. Advanced electrolysis technologies capable of splitting alkaline and/or sea-water will be tested e.g. using novel catalysts that can perform both sides of the water splitting process, i.e. H_2 evolution and O_2 evolution: these are more suitable for intermittent energy sources. Also proton exchange membrane (PEM) electrolysers will be tested and optimized further. In particular the electrical characteristics of the rapid response PEM components will be studied in terms of their ability to contribute to electricity grid stability via demand response and/or frequency control services to the National Electricity Market (NEM).

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Solid-state hydrogen storage for concentrated solar-thermal generation	Large-scale Green Hydrogen Production & Storage	Hydrogen can be stored within solid metal hydrides and be used as a 'battery' to store energy generated from concentrated solar-thermal power. The stored energy is readily released to power generators or heat engines, particularly at night, mitigating the variable nature of renewable energy. Additionally such storage technologies could displace current spinning reserves in power systems and/or other ancillary services. This project will also explore the use of high-temperature hydrides unsuited to other applications.
Efficient Syngas Conversion to Methanol through Process Intensification	Efficient Hydrogen Transport & Storage	Develop a miniaturised process technology for synthesising renewable MeOH from biomass pyrolysis syngas. Catalysts will be developed for small-scale MeOH synthesis & micro-reactor configurations evaluated. Production of MeOH from electrolytic hydrogen and biogenic or industrial CO_2 sources will also be investigated.
Renewable LNG as a Hydrogen Vector[8]	Efficient Hydrogen Transport & Storage	Production of methane from renewable hydrogen and either biogenic or industrial sources of CO_2 will be investigated to deliver renewable LNG as the hydrogen vector. The use of hydrogen in hydrogen-fired turbines to drive the methane liquefaction process and nearly eliminate the carbon foot-print of the export product will be explored. Commercial-scale demonstration of methane pyrolysis at the point of end-use would be included in the value chain analysis.
Advanced Sensors and Integrated Refrigeration Cycles for Improved Hydrogen Liquefaction	Efficient Hydrogen Transport & Storage	Hydrogen exists in two different spin states, the ratio of which changes as temperature is lowered. An inefficient transition between these states increases the amount of energy lost during the liquefaction process. Novel sensors can be used to monitor and thus improve control of this transition, improving the efficiency of hydrogen liquefaction, which is much more challenging than those used in the LNG industry. Further reductions in both capital and operational cost can be achieved by integrating current LNG liquefaction processes with the refrigeration cycles used to produce liquid hydrogen. Finally, sensors that help avoid blockages due to freeze-out in the specialised cryogenic heat exchangers developed for the LNG program could be adapted for use at the lower temperatures required for hydrogen.

[8] This project would also fit within the *Efficient LNG Value Chains* program.

R&D Project	Category	Description
Efficient Integration of CCS into Steam Methane Reforming	Large-scale Blue Hydrogen Production	Large-scale and cost-efficient hydrogen production by steam methane reforming is well established and the most viable means to supply export scale quantities of hydrogen through the conversion of natural gas. Integration of SMR with carbon capture and storage processes to render blue hydrogen is significantly less mature and far from optimised. The use of kW-scale solid oxide fuel cells to produce H_2 from natural gas or LPGs together with CCS will also be considered. This project will investigate and optimise the process integration required with a techno-economic analysis to minimise emissions and cost.

Extended descriptions of certain and/or additional Program 2 projects, including a basis of value estimate, are given below

Extended descriptions of select Program 2 projects, including a basis of value estimate

R&D Project	Category	Description
Hydrogen Production from Novel Natural Gas Pyrolysis Technologies with Chemical Looping	Large-scale Blue Hydrogen Production	Pyrolysis of natural gas allows for the efficient production hydrogen with a 90% reduction in CO_2 emissions, which are only generated from the heat needed to drive the pyrolysis reaction. Pyrolysis generates a range of high value carbonaceous products with the hydrogen ($CH_4 \rightarrow C+2H_2$), spanning carbon nano-materials, carbon fibres and carbon black to agricultural char that can be used to replace some fertilisers. The project will develop a patent-pending chemical looping reactor under development at the University of Adelaide from TRL-3 to TRL-5 with strong potential to offer efficient conversion of LNG to hydrogen and carbon, together with potential to extract high value carbon products. Value basis This approach has potential to allow LNG to be converted to hydrogen at the point of import while consuming only ~10% of the fuel, thereby offering potential to increase the value and life of existing LNG infrastructure. Techno-economic assessments have estimated future production costs at <$15/GJ and, if sufficient value can be obtained from the carbon, at cost parity with natural gas.
Hydrogen Production from Novel Solar Thermal Pyrolysis-Reforming Technologies	Large-scale Blue Hydrogen Production	The project will develop to TRL-5 a technology suitable for large-scale conversion of natural gas to carbon-neutral hydrogen and solid carbon (also avoiding any CO_2 production) through solar-driven pyrolysis. The project will develop a patent-pending solar thermal reactor/receiver under development at the University of Adelaide from TRL-3 to TRL-5 to support this pathway. Value basis This technology achieves CO_2-free hydrogen from pyrolysis because the endothermic pyrolysis reactions are driven with concentrating solar thermal energy and the other products being carbonaceous with potential value, as described above or, as a worst case, lower cost of disposal than does CO_2.

R&D Project	Category	Description
Low cost solar thermal CO_2 air capture for carbon offsetting	Large-scale Blue Hydrogen Production	The project will develop to TRL-5 a technology suitable for large-scale, cost-effective, solar-driven technology for direct air capture of CO_2 (DAC), which has potential to offset any net CO_2 emissions arising from blue hydrogen production. Solar-driven DAC offers potential to position the technology at locations with coincidence in excellent solar resource and site suitable for enhanced gas recovery, CO_2 sequestration or further conversion into a fuel. The project will develop an approach to replace with concentrated solar thermal energy the natural gas used to drive a commercial DAC technology being supplied by Carbon Engineering. The patent-pending solar technology under development at the University of Adelaide is already at TRL-3 and will be developed to TRL-5. Value basis This approach offers an important option for achieving carbon neutral hydrogen from blue hydrogen that does not fully achieve net zero CO_2 emissions.
Hydrogen production and nano-catalytic photo-thermal steam reforming of hydrocarbons in micro-reactors	Large-scale Blue Hydrogen Production	The project will develop to TRL-3 a novel micro-reactor technology that offers potential to lower the cost of natural gas reforming (both steam and mixed) by harnessing heat and/or light from concentrated solar radiation. Relative to current solar thermal reforming, this offers potential to lower the reaction temperature, thereby lowering radiation losses and increasing the cost-effectiveness of thermal energy storage. The technology is presently at TRL-2 and will be developed to TRL-4. Value basis Relative to commercial steam-methane reforming, this offers the potential to avoid any consumption of the fuel, thereby reducing net CO_2 emissions by 20-40% (depending on the feedstock).

R&D Project	Category	Description
Scaling up Hydrogen Production from Photocatalytic Water-Splitting	Large-scale Green Hydrogen Production & Storage	Photocatalysis is an emerging technology that can generate fuels directly from solar energy, particularly water-splitting to produce hydrogen from water. A major recent advance in is the development of photocatalyst sheets. Combined with specially developed reactors, photocatalysis is now being advanced towards commercialisation with upscaling. The project will develop to TRL-5 and beyond, a highly innovative photo-catalysis reactor. Value basis Photocatalysis has inherent features that give it a huge advantage compared to other renewable energy technologies. Its sheer simplicity means that low capital expenditure is required and operational costs are also small. Techno-economic assessments of photocatalytic water-splitting have estimated future production costs at <$2/kg.
Photocatalytic CO_2 Reduction	Large scale CO_2 capture and utilisation	Solar-induced, photocatalytic conversion of carbon dioxide and water into methane or methanol using novel catalysts incorporated into an abundant photo-active substrate. The process combines the ideal virtues of carbon neutral solar energy harvesting and storage as fuels, as well as the reduction of CO_2 streams. Value basis: The photocatalytic reduction of CO_2 to re-generate versatile, liquid hydrocarbon fuels using solar radiation not only provides an energy efficient and renewable energy source but, when coupled with other processes that generate CO_2, is able to effectively reduce the carbon footprint of the whole system and turn a waste product into profit.
Low-cost hydrogen production by chemical looping with concentrated solar energy	Large-scale Green Hydrogen Production & Storage	The project will partner with DLR (German Aerospace) to support a large-scale demonstration and evaluation of a novel technology for thermo-chemical production of hydrogen that is already at TRL-5 and scheduled to be demonstrated at TRL-6 by 2021. This technology uses a sulphur dioxide to hydrochloric acid cycle to produce hydrogen and oxygen with less energy than via electrolysis and is also expected to offer lower cost production. The project will undertake techno-economic analysis to support the demonstration and detailed measurements of heat transfer to de-risk further upscaling of the technology.

R&D Project	Category	Description
Lowering the cost of commercial hydrogen and ammonia production from green electricity	Large-scale Green Hydrogen Production & Storage	The project will undertake detailed process analysis and optimisation of state-of-the-art plant for commercial production hydrogen, using electrolysis technology, its conversion to green ammonia and/or its re-use to generate high value electricity from stored hydrogen and/or ammonia. Value basis It will generate both the understanding and process models needed to enable improved profitability from the large-scale production of green hydrogen and ammonia for export, combined with high value electricity generation into the local market during periods of high demand, to increase the penetration of commercial green hydrogen technology.
De-risking the conversion of green ammonia to electricity via combustion in a gas turbine	Large-scale Green Hydrogen Production & Storage	The project will undertake technology development in collaboration with international partners to increase the performance of the utilisation of ammonia, as a form of stored green hydrogen, in gas turbines. The project will utilise the University of Adelaide's existing world-leading laser diagnostics facilities and facilities operable at either pressurised or atmospheric pressure conditions. Value basis This will open the door to increased profitability of local exporters, by being able to benefit from high prices of electricity in the local market, while also increasing the value of ammonia as an export fuel by enabling increased penetration of ammonia as a fuel for gas turbines.
Training the next generation of skilled workers for the green hydrogen industry	Large-scale Green Hydrogen Production & Storage	The project will establish a state-of-the-art training program for graduate engineers and technologists in the production and conversion of green hydrogen by an integrated program that provides hands-on access to a state-of-the-art production facility as part of their graduate degree programs. Students will be trained in the design, operation and optimisation of hydrogen and ammonia production technologies, together with hydrogen power generation, by access to the H2U hydrogen facility at Port Lincoln as an integrated part of degrees spanning B.Tech, B.Eng and M.Eng.Sc at UA and other partner universities.

R&D Project	Category	Description
Developing safe procedures and processes to underpin the establishment of a green hydrogen export market	Large-scale Green Hydrogen Production & Storage	The project will investigate Australia's safety processes, Regulations and Standards to ensure that we have adequate measures in place to handle bulk transport of hazardous substances. The veracity and validity of control measures will be assessed. Whilst we have outstanding track record of safe operation, historically this is through self-regulation by the relevant industries. With an increase in production, and increased interface with international partners, additional emphasis on safety will become important. Moreover, there is a need for independent research to determine whether current approaches are best-practice for safe handling of flammable goods and what improvements could be made. Through systematic research, the project will also investigate whether aspects of the safety requirements could potentially be relaxed and thus lead to economic savings. Value basis The project will reduce the cost of ensuring safe operation and identify barriers to safe processes that have potential to cause lengthy delays.
Catalysts for Hydrogen-Free Ammonia Production by Electrochemical Method	Large-scale Green Hydrogen Production & Storage	This project aims to realise the next generation of ammonia production under ambient conditions without hydrogen feedstock. Through a combination of theoretical molecular-level understanding and experimental materials engineering, a range of catalysts will be developed under a well-planned materials discovery scheme for electrochemical nitrogen reduction to ammonia. These new catalysts, featuring high activity, efficiency, selectivity, and stability, will facilitate an alternative artificial nitrogen fixation technology powered by renewable energies. This technology will enable the production of green fertilisers and provide a hydrogen export vector, which are key environmental and energy challenges that Australia and world currently face.

R&D Project	Category	Description
Electrocatalysts for Hydrogen-Free CO2 Reduction to Multi-Carbon Products	Large-scale Green Hydrogen Production & Storage	This project aims at efficient and sustainable production of fuels and chemicals using abundant sources like water, carbon dioxide and sunlight by an intergraded reaction system. Through understanding molecular design principles and material engineering, a range of novel electrocatalysts will be developed featuring high activity, efficiency, selectivity and stability for carbon dioxide reduction and hydrogen evolution reactions. New catalysts will facilitate a hybrid reaction cell as artificial leaf mimics by associating photocatalysis and electrocatalysis processes. This is of great importance for solar fuel generation and carbon dioxide utilization, which are the key energy and environmental challenges facing today's Australia and world.
Distributed green ammonia production using novel plasma technology	Vectors for Efficient Hydrogen Transport & Storage	The project will develop to TRL-4 both the reactor technology and business models for distributed production of ammonia from green hydrogen and nitrogen using innovative plasma technology. Value basis The use of plasma technology enables the reaction to be undertaken at small scale, without high temperatures or pressures, opening the door to distributed production. This, in turn, will offer new business models which cannot be operated with traditional technology. Those businesses themselves will be economic, create new jobs through new fertiliser-, green energy- and chemical-trades within Australia, displacing current imports at high costs. In addition, it offers environmental benefits by reducing carbon footprint and enhancing soil conservation. The project will build on novel plasma technology already under development at The University of Adelaide for application as fertilizer in the agricultural sector.