ANNEX A

LIST OF LCER PHASE 1 PROJECTS AND LCER PHASE 2 DIRECTED HYDROGEN PROGRAMME TOPICS

List of LCER Phase 1 Projects

SN	Research Theme	Proposal Title, Lead PI, and Organisations	Proposal Description
1	H_2	**Proposal Title**: Ammonia Cracking: New Catalyst Development, Reaction Engineering and System Design **Lead PI:** Assoc Prof Yan Ning, NUS **Organisations:** NUS; NTU; Surbana Jurong Infrastructure Pte Ltd	**Project Aim:** To develop more efficient processes to release H_2 from ammonia, by examining the development of robust and efficient ammonia cracking technologies suitable for use in Singapore. **Potential Benefits:** H_2 is difficult to transport in its native state, which requires high pressures and extremely cold temperatures to compress. One way to make it easier to transport is to convert the H_2 into a carrier such as ammonia. However, releasing H_2 from ammonia is an energy intensive process. An improved and more efficient process will reduce the energy penalty of transporting H_2 in the form of ammonia and reduce the cost of H_2 adoption in Singapore.
2	H_2	**Proposal Title**: Miniature H_2 leakage and purity sensors for downstream H_2 use **Lead PI**: Dr Doris Ng Keh Ting, A*STAR **Organisations**: A*STAR; Hydrogen and Fuel Cell Association of Singapore (TAC)	**Project Aim**: To develop two types of H_2 sensors, a H_2 purity sensor and a H_2 leakage sensor, with small form factor, high selectivity minimal interferences and immunity to poisoning for downstream use. Standards will also be created for H_2 sensors evaluation and quality.

			Potential Benefits: Improve the safety of H_2 use, allow deployment of sensors economically to enable trading and safety and increase confidence towards adoption of H_2 for downstream uses
3	H_2	**Proposal Title**: Methane Pyrolysis for H_2 and Carbon Nanotube Production via Novel Catalytic Membrane Reactor System **Lead PI**: Assoc Prof Sibudjing Kawi, NUS **Organisations**: NUS; A*STAR; University of California@Davis; Curtin University; Université de Toulouse-Centre RAPSODEE-CNRS; Dyna Mac Engineering Services; Sembcorp Industries Ltd	**Project Aim**: To develop an improved process for methane pyrolysis, i.e. catalytic cracking and separating natural gas/methane into H_2 gas and solid carbon. It examines development of a novel bi-functional catalytic membrane reactor (CMR) process, where ultra-pure H_2 and highly-ordered carbon nanotubes (CNTs) are co-produced via methane (natural gas) pyrolysis process with zero carbon dioxide (CO_2) emission. **Potential Benefits**: Methane pyrolysis is a potential pathway to producing low-carbon H_2 in Singapore. The process is currently costly and energy intensive. If successful, this can reduce the cost of H_2 production in Singapore whilst producing valuable carbon products at the same time.
4	H_2	**Proposal Title**: Liquid Organic Hydrogen Carriers (LOHCs) Technology for Singapore **Lead PI**: Prof Xu Rong, NTU **Organisations**: NTU; NUS; Chiyoda Corporation; PSA Corporation Limited; Sembcorp Industries Ltd; City Gas Pte Ltd; Jurong Port Pte Ltd; Singapore LNG Corporation; Mitsubishi Corporation	**Project Aim**: To develop new catalysts and systems to reduce the costs of extracting H_2 from methylcyclohexane (MCH) as an LOHC technology and to design a minimum-cost H_2 supply chain network for Singapore. **Potential Benefits**: MCH can be transported in liquid state at ambient conditions using the existing petroleum infrastructures, but the process to extract H_2 from the MCH molecule requires high-performance and cost-effective catalyst and is energy intensive. This proposal could improve the performance and reduce the cost of existing SPERA catalyst from Chiyoda and design new reactors

			of better heat transfer, therefore reducing the cost of importing H_2 using this carrier. A comprehensive financial model to access the cost of the H_2 supply chain in Singapore will also be developed by collaborating with our industrial partners.
5	CCUS	**Proposal Title**: Alternative Sand from Carbon Dioxide and Waste Materials **Lead PI**: Dr. Bu Jie, A*STAR **Organisations**: A*STAR; NUS; NTU; Samwoh Innovation Centre Pte Ltd; EnGro Corporation Ltd	**Project Aim**: To examine the processes for the capture and mineralisation of CO_2 into alternative sand that can be used for building and construction purposes. **Potential Benefits**: Captured CO_2 can be used to make useful products such as construction material in this case.
6	CCUS	**Proposal Title**: Capturing waste with waste: Continuous carbon capture using highly efficient sorbents derived from incineration ashes **Lead PI**: Asst Prof Liu Wen Paul, NTU **Organisations**: NTU; A*STAR; Surbana Jurong Infrastructure Pte Ltd; Mursun Pte Ltd; Tsinghua University; Kunming University of Science and Technology	**Project Aim**: To develop a carbon capture process (calcium looping) by using novel sorbents derived from calcium-rich incineration ashes, collected from Singapore's waste-to-energy facilities. **Potential Benefits**: This will enable the use of incineration ash, which is a waste material, for CO_2 capture. Both waste streams: incineration ashes and CO_2, can be subsequently turned to sustainable construction materials after carbon capture.
7	CCUS	**Proposal Title**: Towards Energy Efficient Electrochemical CO_2 Reduction to Synthetic Chemicals: A Paradigm Shift in Sustainable Chemical Production	**Project Aim**: To examine the development of a sustainable technology to produce important commodity chemicals for Singapore (e.g., ethylene and propanol), using only CO_2 and water

		Lead PI: Prof Chen Wei, NUS **Organisations**: NUS; NTU; A*STAR; Stanford University; Tsinghua University and ExxonMobil	as feedstock. Thus, reduce the energy intensity of producing chemicals from CO_2. **Potential Benefits**: Converting CO_2 to fuels/chemicals is a potential utilisation pathway for captured CO_2. Reducing the energy requirement for such processes will improve the economic viability of such CO_2 utilisation pathways.
8	CCUS	**Proposal Title**: Development and module scale validation of novel hollow fiber membranes for CO_2 capture **Lead PI**: Asst Prof Zhang Sui, NUS **Organisations**: NUS; NTUitive Pte Ltd; Chevron Singapore Pte Ltd; Surbana Jurong Infrastructure Pte Ltd	**Project Aim**: To develop more efficient ways to capture CO_2 from exhaust streams. It aims to develop and validate hollow fiber membranes for efficient carbon capture via novel chemistry and machine learning. The performance of the developed and scaled membranes will be validated through in-house pilot testing under simulated conditions as well as field-testing on larger pilot under real-world conditions. **Potential Benefits**: To improve the capture efficiency of CO_2 from existing exhaust/flue gas which is the first step in CCUS.
9	CCUS	**Proposal Title**: Stable and long term carbon dioxide hydrate based storage (CO_2-HyStore) in deep ocean sediments **Lead PI**: Prof. Praveen Linga, NUS **Organisations**:NUS; Purdue University and Lawrence Berkeley National Laboratory; ExxonMobil	**Project Aim**: To demonstrate a proof-of-concept requiring design, build and validation of potential of CO_2 storage in deep-ocean sediments as gas hydrates. It will help to validate the possibility of storing CO_2 in deep ocean sediments (as opposed to conventional sites which require specific geological formations) **Potential Benefits**: This may open possibilities for long term storage of captured CO_2.

10	CCUS	**Proposal Title**: Process Systems Engineering for Guiding R&D on Low-Carbon Technologies **Lead PI**: Prof Iftekhar A Karimi. NUS **Organisations**: NUS; ExxonMobil	**Project Aim**: This project proposes a new paradigm in which materials research is conducted under the continuous of Process Systems Engineering (PSE) in order to keep focus on the KPIs right from the start of research. **Potential Benefits**: It develops digital toolkits that predict the system-level performances of several CCUS and H_2 projects, helping to guide them to faster and successful scale-up.
11	CCUS	**Proposal Title**: Adsorptive Carbon Capture Using Framework Materials **Lead PI**: Assoc Prof Zhao Dan, NUS **Organisations**: NUS; and Northwestern University; ExxonMobil	**Project Aim**: To develop more efficient ways to capture CO_2 from exhaust streams. This project enhances CO_2 capture by using state-of-the-art framework sorbents engineered for high CO_2 selectivity, high intrinsic stability, and facile regenerability from moisture. **Potential Benefits**: Improve the capture rate of CO_2 from existing exhaust/flue gas which is the first step in CCUS.
12	CCUS	**Proposal Title**: Nanostructured Catalysts for Direct CO_2 Hydrogenation to Higher Alcohols and Fuels **Lead PI**: Asst Prof Sergey Kozlov, NUS **Organisations**: NUS; NuStar Technologies Pte Ltd	**Project Aim**: To reduce the energy intensity of producing higher alcohols and fuels from CO_2. It examines development of nanostructured catalysts and computational capability in catalyst design and reaction modelling, including process optimisation. **Potential Benefits**: CO_2 to fuels/chemicals is a potential utilisation pathway for captured CO_2. Reducing the energy requirement for such processes will improve the economic viability of such CO_2 utilisation pathways.

LCER Phase 2 Directed Hydrogen Programme Topics

Type	Topic
Ammonia Cracking	Ammonia Cracking: Efficient synthesis of large amounts of ultra-stable next-generation catalysts (from milligram lab scale to multi-kilogram scale)
	Scale-up the ammonia cracking plant from 10 kg/day to 10 tonnes/day (tpd), with techno-economic analysis up to 1000 tpd (current scale is 40 tpd)
	System integration of ammonia cracking into centralized/decentralized use cases, focusing on the thermal efficiency and handling (such as decentralized cracking as part of blended H_2 combined cycle gas turbine operations, using waste heat or zero-carbon fuel combustion to power the ammonia cracker)
Ammonia Utilisation	Improve the understanding of the combustion characteristics of NH_3 and related blends/mixes
	Investigate solutions that allow the ammonia turbine to meet Singapore's unique requirements (fuel changeover capabilities)
	Address technical limitations, such as low flame speed, issues with ramping capacity up and down and high NO_X emissions and ammonia slippage (which must be treated with a selective catalytic reduction system)
	Develop improved mid to high temperature ammonia fuel cells
H_2 Transport and Distribution	Improve storage design and materials to withstand the necessary temperature and pressure to scale up the capacity and distance of liquid H_2 shipped
	For H_2 transport and distribution, optimise system level efficiency in energy recovery for liquid H_2 utilisation
	Improve the accuracy of metering and tracking the transfer of liquid H_2 and carriers via calibration and communication for H_2 transport and distribution

	Improve the H_2 tolerant properties of structural materials and coatings for pipelines to reduce H_2 embrittlement and leakage for cost-effective, large-scale distribution of H_2
	Develop methods to repurpose or retrofit existing liquid natural gas tanks for H_2 or H_2 carrier storage for H_2 distribution
Safety and Regulatory Standards	Modelling and simulation research and development projects would help regulators better understand the technical assumptions and limitations of existing standards
	Design improved hazard mitigation systems and new H_2 infrastructure with smaller health and safety buffers to fit Singapore's context
	Develop suitable preventive, corrective mitigative, and/or 'inherently safe' measures for the potential use-cases for H_2 energy
	Safety and regulatory standards for Singapore H_2 energy
	Design improved hazard mitigation systems and new H_2 infrastructure with smaller health and safety buffers to fit Singapore's context