Australia's National
Science Agency

Methane Fuel Carrier Project

Knowledge sharing report

ARENA R&D Program Renewable Hydrogen for Export

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Cooling tower for absorption of CO_2 from the air

Gas/liquid contactor for characterisation of fill materials

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Acknowledgement

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Contents

1 Project summary and scope

The project has assessed the production of methane as a readily exportable, renewable fuel derived from atmospheric carbon dioxide and hydrogen produced from renewable sources. The process (Figure 1) entails the capture of CO_2 from air using a dedicated amine[1]-solution based process which is integrated with the exothermic methanation process for optimum energy conversion efficiency.

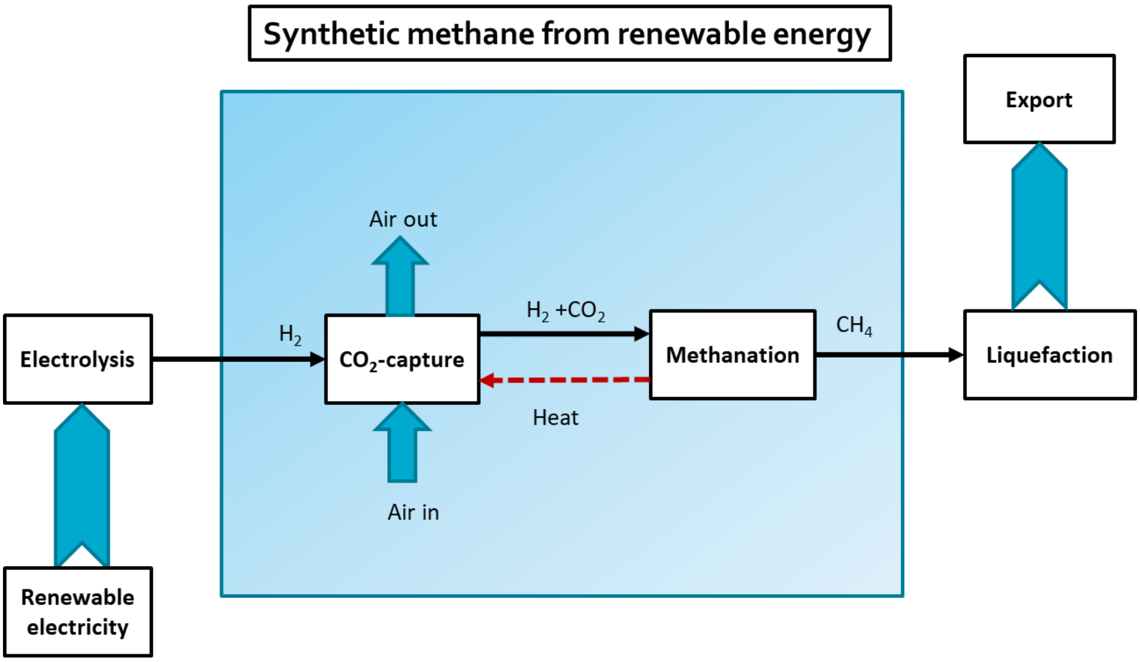

Figure 1 Overview of process for production of synthetic methane from renewable energy

Given the distributed nature of the methane production process the concept has the potential to incrementally replace the production of coal seam gas by renewable gas, using the existing gas collection and transportation infrastructure.

The project addressed the following aspects which are considered critical for further development:

1. Development of a cost-effective process for energy efficient recovery of carbon dioxide from ambient air with a focus on process and equipment design supported by laboratory-based experiments.

2. Optimisation of the integration of the carbon dioxide recovery process with the methanation process and the electrolytic hydrogen production process supported by process modelling.

The anticipated project outcome is a conceptual design of a modular unit that can produce synthetic methane for export from entirely renewable sources.

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[1] Amines are chemicals, derivatives from ammonia, that are commonly used for CO_2-capture.

2 Key findings

2.1 Overall project outcomes

The project has developed an amino-acid salt solution-based process that can effectively capture atmospheric CO_2 using commercially available cooling tower equipment. The capture process can be effectively integrated with the methanation process resulting in zero thermal energy requirement for regeneration of the absorption liquids. The costs to produce synthetic liquefied methane, excluding hydrogen production, were below AU$10/GJ.

The key findings of the project are:

1. Direct air capture using amino-acid salt solutions is feasible.
2. Direct air capture using liquid absorbents in cooling towers is advantageous.
3. Methanation processes provide significant heat input to the liquid absorbent regeneration process.
4. Direct air capture cost can be decreased to costs below AU$100/tonne CO_2 at a capacity of 1 Mta[2] CO_2.
5. The cost analysis for the production process of 364 kta liquefied synthetic methane resulted in an overall cost of AU$37.4/GJ at the chosen economic input parameters[3].
6. Electricity cost are the dominant cost contribution in the production of liquefied synthetic methane.

2.2 CO_2-capture from ambient air – cost reduction pathway

The project work has focused on the CO_2-capture process because of the inherent challenge of the low CO_2-concentrations in ambient air for recovery of CO_2. It was anticipated this would dominate the overall process cost. For the purpose of guidance and prioritisation of our research and development activities, a baseline techno-economic framework using a standard 5 M monoethanolamine (MEA) solution as the CO_2-capture agent was defined. This used a modified absorber/desorber process design targeting the production of 0.291 tonne CO_2/hour. This CO_2-production was combined with the hydrogen produced by a 2.7 MW electrolyser to feed into a methanation process that produced 148 m^3/hour of synthetic methane. The economic assessment used a standard set of parameters[4], that resulted in a capture cost of AU$1859/tonne CO_2.

The project followed a systematic, staged improvement process, aiming for cost reductions. This process incorporated the following steps:

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[2] 1 Mta = 1,000,000 tonnes per year

[3] Interest rate (8%), project life (20 years), electricity cost (60 AU$/MWh)

[4] The economic parameters used are interest rate (8%), project life (20 years), electricity cost (60 AU$/MWh) and heat cost (13 AU$/GJ)

- Adaptation of post-combustion CO_2 capture technology to air capture conditions

The operation at ambient temperatures enabled the use of cooling tower technology which reduced costs for the gas/liquid contactors. The use of amino-acid salt solutions for CO_2-capture simplified the absorption process as a water wash to recover amine vapours was not needed. Both adaptations reduced cost by 62% to AU$705/tonne CO_2. The laboratory work identified two amino-acid salts that demonstrated adequate mass transfer performance and robustness in service.

- Technology optimisation and integration with methanation process

Electricity costs for pumps and blowers could be reduced through a combination of lowering the liquid/gas ratio in the CO_2-absorber and pressure drop reduction in cooling tower geometries as determined by a comprehensive technical assessment of different packing materials. The thermal energy requirement for the regeneration process could be reduced to zero by integration with the exothermic methanation process at a small input of electricity for the vapour compression process that recovered latent heat from the CO_2-desorber. The technology optimisation and integration of the capture process with the methanation process resulted in a 77% cost reduction bringing down the capture cost to AU$436/tonne CO_2.

- Scale-up to full scale (1 Mta CO_2)

The impact of scale-up of the technology from the capacity of an individual module to a full-scale plant, a 436 times scale-up, was assessed using a scale-up factor of 0.7. This resulted in the cost for capture reduced to AU$87/tonne CO_2 which represented a reduction of more than 95% compared to the baseline capture unit. Table 1 below summarises the improvement steps and resulting costs. The capital cost remains the dominant cost contribution due to the large gas/liquid contactors needed for the absorption of CO_2 into the absorption liquid.

Table 1 Overview of cost reductions in the direct air capture process

Improvement step **Costs (AU$/tonne CO_2)**	**MEA-based standard**	**Amino-acid salt based + cheap contactors**	**Amino-acid salt based + cheap contactors + energy optimisation/ integration with methanation**	**Amino-acid salt based + cheap contactors + energy optimisation/ integration + scale-up**
Capital	1175	362	299	48
O&M	458	142	117	19
Electricity	87	62	20	20
Heat	139	139	0	0
Total	1859	705	436	87
Cost reduction	-	62%	77%	95%

2.3 Costs for production of liquefied synthetic methane

The techno-economic assessment of the overall production of synthetic liquefied methane using renewable electricity built on the costs for the direct air capture process, adding the cost for hydrogen production using electrolysis, methanation and methane liquefaction. The costs for the latter processes were sourced from the literature. The process scale was 364 kta[5] methane, produced from 182 kta hydrogen and 1 Mta carbon dioxide. For comparison the costs for the production of the same amount of hydrogen and its liquefaction were also estimated.

Using the same economic parameters, the production cost for liquefied synthetic methane were determined to be AU$37.4/GJ with the hydrogen production cost contributing 75% to this. This represented a hydrogen production cost of AU$3.14/kg H_2. If one assumes that the methane liquefaction is already in place, the production cost could come to AU$35.1/GJ. The cost contribution from the direct air capture process, methanation process and methane liquefaction totalled AU$9.4/GJ and was below the target cost of AU$10/GJ.

The production costs for liquefied hydrogen using renewable electricity was slightly higher at AU$39.4/GJ, with hydrogen production contributing 55% to these costs and the remainder contributed by the liquefaction process. The production of liquefied hydrogen is slightly more efficient than the production of liquefied methane as shown by the electricity consumption Table 2.

Table 2 Overview of costs for production of synthetic fuels

Synthetic fuel	Methane	Hydrogen
Hydrogen production (AU$/GJ)	28.0	22.2
Direct air capture (AU$/GJ)	4.3	-
Methanation (AU$/GJ)	1.6	-
Liquefaction (AU$/GJ)	3.5	17.1
Total (AU$/GJ)	37.4	39.3
Electricity consumption (kWh/GJ)	479	457

The electricity price was quite dominant in the production cost for both liquefied synthetic methane (77%) and liquefied hydrogen (70%). Overall, the production cost for both fuels exceeded current and projected cost for natural gas (low gas price: AU$5.8/GJ; high gas price: AU$11.8/GJ). The impact of the electricity price and a carbon price was also evaluated with results shown in the Figure 2. At a projected electricity price of AU$40/MWh a carbon price in the range AU$300-400/tonne CO_2 would be required to achieve parity with natural gas prices including the carbon price premium.

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[5] 1 kta= 1,000 tonnes per year

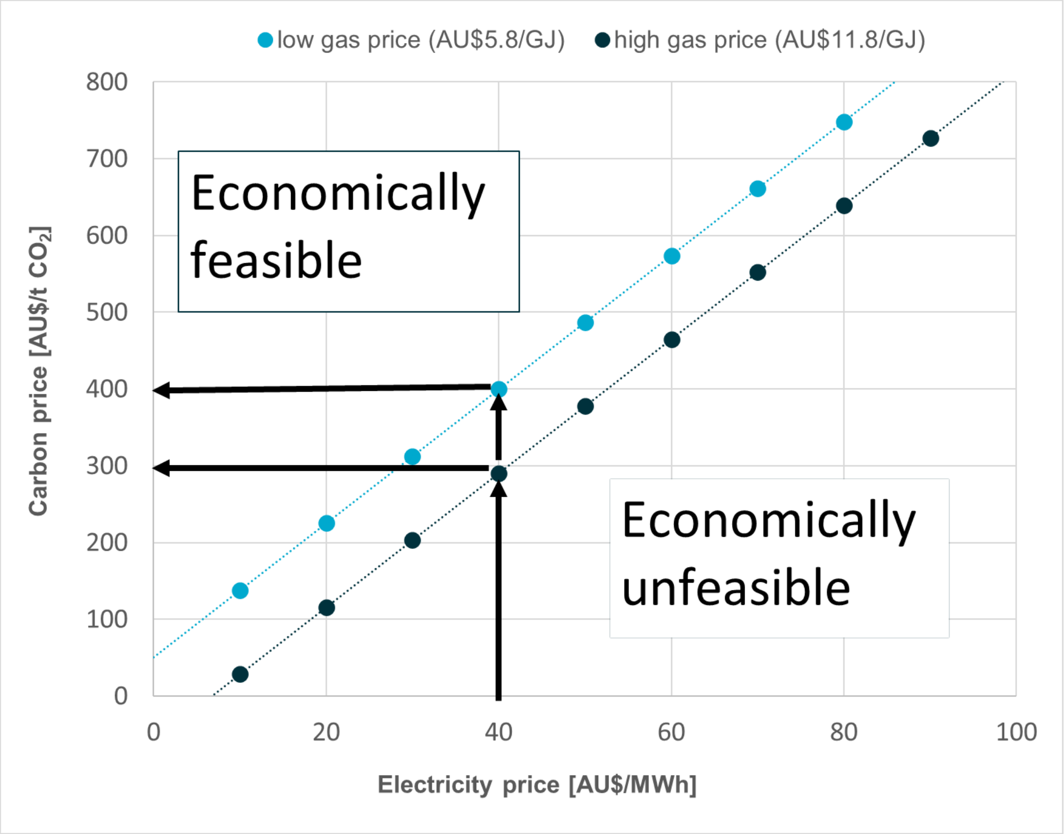

Figure 2 Economic feasibility map to produce liquefied synthetic methane for low-high natural gas price (Interest rate = 8%, project life = 20 years)

2.4 Outcomes of direct air capture technology development

The direct air capture technology involved experimental research to evaluate process performance and process modelling to assess and optimise different concepts. The experimental program has focused on the use of 6 types of amino-acid salt solutions for CO_2-capture from air through performance assessment of CO_2-absorption rates (investment cost absorber), oxidative stability (operation in air) and thermal stability (liquid regeneration at high temperature). This resulted in the following observations:

- CO_2-absorption rates for amino-acid salt solutions are similar to that for a standard MEA-solution,
- Two amino-acid salt solutions showed better oxidative stability than MEA,
- MEA exhibited best thermal stability with one of the chosen amino-acid salt solutions having similar thermal stability.

A representative 2 M amino-acid salt solution was selected for larger scale CO_2-absorption experiments conducted in two gas/liquid contactors, a commercial cooling tower and a cylindrical packed column. A total of 166 experiments were conducted using different packing materials and ambient air. The volumetric mass transfer for the cooling tower was 2-3 times lower than calculated for the 5 M MEA in the baseline techno-economic assessment. The cooling tower was, however, able to operate at low liquid flow rate and exhibit 10 times lower pressure drop which resulted in a lowering of the energy consumption of the capture process.

Further process modelling was carried out aimed at the reduction of the energy requirement for liquid absorbent regeneration in the CO_2-capture process, to facilitate thermal integration with the methanation process. This resulted in a process design using vapour compression of the desorber overhead with subsequent latent heat recovery that reduced the heat requirement to a level that it could be supplied by the methanation process. At this point the heat requirement was reduced to zero and the “transactional energy” requirements resulting from the movement of large volumes of air and absorption liquids, have become the largest energy requirement of the process. Overall, this represented a 77% reduction in the electricity requirement for the direct air capture process.

2.5 Methanation process assessment

Progress in methanation process development was assessed via a literature review that addressed different reactor geometries, process designs, catalysts and media suitable to extract useful heat from the exothermic process. A commercially available methanation process design based on a series of adiabatic fixed bed reactors was simulated to determine the production of thermal energy as determined by the methanation pressure. At a pressure of 10 bar the thermal energy was sufficient for the regeneration of the absorption liquids. It was recognised that the methanation process design was quite complex and therefore costly at the small-scale studied. New isothermal designs are likely to be simpler and be of lower cost.

2.6 Recommendations

The project has provided significant technical information and economic data on the overall process for the production of renewable methane from atmospheric carbon dioxide and hydrogen that points towards several recommended areas for further progress:

- Development of the business case for application

Process commercialisation will require formation of a consortium of one or more end-users and suppliers of the separate technologies (CO_2-capture, methanation) and a technology integrator. The consortium will develop the detailed pathway towards commercialisation, in particular the scale-up steps needed to achieve the production of renewable methane at lowest cost. This involves the definition of the elementary process module for scale-up as determined by the process architecture.

- Technology demonstration of direct air capture process

The information gathered in this project will enable the basic design of a direct air capture technology demonstrator that can be used to evaluate and validate process performances, such as capture rate and energy consumption. This will encompass the validation of the vapour compression process for absorption liquid regeneration that enables the residual heat requirement to be met by the methanation process. Furthermore, the demonstrator can also be used to assess the water balance under a range of operating conditions, as well as the losses through drift, i.e. carry-over of absorption liquid via small droplets.

- Selection of preferred methanation technology

Several options for the methanation technology have been identified through literature study. While methanation technology is commercially available further work is needed to select the best configuration for integration with the direct air capture process at smaller scale than the currently available methanation technologies.

3 Commercialisation prospects

3.1 Development of the business case for liquefied synthetic methane production

The anticipated market approach will entail the formation of a consortium of one or more end-users and suppliers of the separate technologies (CO_2-capture, methanation) and a technology integrator. Specifically, it will require the involvement of the following stakeholders:

- Operators of coal seam gas facilities and LNG (liquefied natural gas) plants interested in exploring this option for production and export of renewable gas,
- Engineering companies and manufacturers for the design and fabrication of suitable gas/liquid contactors and supply of the overall process and equipment,
- Suppliers and/or developers of low cost methanation processes and equipment that could be integrated with the CO_2-capture process,
- Suppliers of hydrogen systems and renewable energy providers.

The consortium will develop the detailed pathway towards commercialisation, in particular the scale-up steps needed to achieve the production of renewable methane at lowest costs. This involves the definition of the elementary process module for scale-up as determined by the process architecture.

The business case to produce liquefied synthetic methane and use the existing coal seam gas infrastructure will require strong involvement from its operators, who will be a key stakeholder in the development of the business case and ensuing developments.

The availability of synthetic methane produced with renewable energy might catalyse other applications:

- Use in industrial processes replacing fossil fuels, thereby reducing the carbon footprint of these processes
- Injection into the gas grid to increase penetration of green gas beyond the level at which hydrogen can be injected.
- Use as back-up fuel or meeting peak demand using gas turbines to support penetration of renewable energy sources into the electricity grid with near-zero emission electricity generation.

3.2 Direct air capture applications

The amine-solution based concept for CO_2 capture from air developed in this project, which we have named the Ambient CO_2 Harvester (ACOHA), will also have relevance for a range of CO_2 utilisation options and geological storage of CO_2.

Geological storage of CO_2 is essential for the achievement of Net Zero Emissions by the middle of the century. Capturing CO_2 from the air near a suitable CO_2-storage location will avoid the transportation of CO_2 via pipelines from the emission sources such as power plants. This will reduce the investment costs for pipeline infrastructure and there is potential for the creation of significant carbon off-sets through air capture with subsequent geological storage of CO_2.

Apart from the realisation of negative emissions it is also possible to create carbon neutral or carbon negative products if the product CO_2 is used to replace merchant CO_2 or for production of aviation fuels and chemicals or embodied into mineral products.

The first step towards commercialisation of the concept will entail the establishment of a pilot plant that demonstrates the CO_2-capture from air process, continuously producing a stream of CO_2. This is required to verify the process performances and its robustness.

4 Knowledge sharing activities

Publications

- Techno-Economic Assessment for CO_2 Capture from Air Using a Conventional Liquid-Based Absorption Process, Ali Kiani, Kaiqi Jiang and Paul Feron, Front. Energy Res. 8:92, doi: 10.3389/fenrg.2020.00092
- Liquefied synthetic methane from ambient CO_2 and renewable H_2 - a techno-economic study, Ali Kiani, Michael Lejeune, Chaoen Li, Jim Patel, Paul Feron, Journal of Natural Gas Science and Engineering, 2021, 104079 (https://doi.org/10.1016/j.jngse.2021.104079)

Conference presentations

- Direct Capture of CO_2 from Ambient Air, Ali Kiani, Kaiqi Jiang, Paul Feron, presented at PCCC5, Kyoto Japan, September 2019
- A Techno Economic Analysis of Synthetic Methane Production from Ambient CO_2 and Renewable H_2, Ali Kiani, Michael Lejeune, Chaoen Li, Jim Patel, Paul Feron, presented at GHGT15, 15-18 March 2021

Others

- A short video is available on the Ambient CO_2 Harvester:

  https://www.csiro.au/en/Research/EF/Areas/Renewable-and-low-emission-tech/Carbon-capture-storage/Ambient
- The project was also presented at the Falling Walls Lab Australia event on 2 September 2019 in Canberra.
- The project was presented at ARENA Hydrogen R&D Roundtable in February 2021, with this link to the presentations: https://arena.gov.au/knowledge-bank/arena-funded-hydrogen-rd-project-presentations/

5 Conclusions and next steps

5.1 Conclusions

The project results have provided strong evidence for the following conclusions across the domains of technology and economic assessment.

Technology assessment

1. Direct air capture using amino-acid salt solutions is feasible.

   Two amino-acid salt solutions have demonstrated robustness, adequate mass transfer and thermal regenerability that makes them suitable for direct air capture.

2. Direct air capture using liquid absorbents in cooling towers is advantageous.

   Cooling towers, although having a lower mass transfer performance, can be operated at low liquid/gas ratio that result in low energy requirement for the transport of gases and liquids

3. Methanation processes provide significant heat input to the liquid absorbent regeneration process.

   The process assessment of a leading methanation process integrated with the direct air capture process indicated that the additional heat requirement could be reduced to zero through the inclusion of a vapour recompression process in the liquid absorbent regeneration.

Overall, it was concluded that the technology elements for production of methane using CO_2 from the ambient air and hydrogen produced from renewable energy i.e. the direct air capture process and methanation process were feasible.

Economic assessment

4. Direct air capture cost can be decreased to costs below AU$100/tonne$CO_2$ at a capacity of 1 Mta CO_2.

   The project has followed a systematic and staged approach in cost reduction involving adaptation of post-combustion CO_2-capture technology to air capture, technology optimisation and integration with methanation and technology scale-up that resulted in a 95% cost reduction compared to the standard amine solution.

5. The cost analysis for the production process of 364 kta liquefied synthetic methane resulted in an overall cost of AU$37.4/GJ at the chosen economic input parameters[2].

   The cost for liquefied synthetic methane was slightly lower than the equivalent liquefied hydrogen production process (= AU$39.3/GJ).

6. Electricity cost were the dominant cost contribution in the production of liquefied synthetic methane.

   Electricity contributed 77% to the overall cost, mostly for the hydrogen production process, indicating the significance of the availability of low-cost electricity. At an interest rate of 4% and an electricity price of AU$30/MWh the overall production cost for liquefied synthetic methane will come down to AU$19.9/GJ.

Overall, the export of renewable energy as liquefied synthetic methane appears as attractive as export of liquefied hydrogen with the crucial advantage of avoiding large investments in infrastructure for hydrogen transport and utilisation. As such this renewable export pathway will experience much lower physical, logistical, and cost barriers towards introduction because the fuel product remains largely unchanged along the supply chain. Therefore, it could help smoothen the energy transition towards the use of carbon neutral fuels by providing an alternative route for the export of renewable hydrogen.

5.2 Next steps

Further work will need to be conducted in several areas, both in terms of development of the business case for application and further development of the technology.

Development of the business cases for application

Our next steps will focus on the establishment of a direct air capture technology demonstrator. Technology development and commercialisation will be pursued based on the intellectual property generated in this project in partnership with stakeholders having complementary interests and capabilities. Apart from the production of renewable methane, the options of CO_2-storage and liquid fuels production will also be pursued. The general approach to commercialisation of the direct air capture technology and its applications is schematically shown in Figure 3.

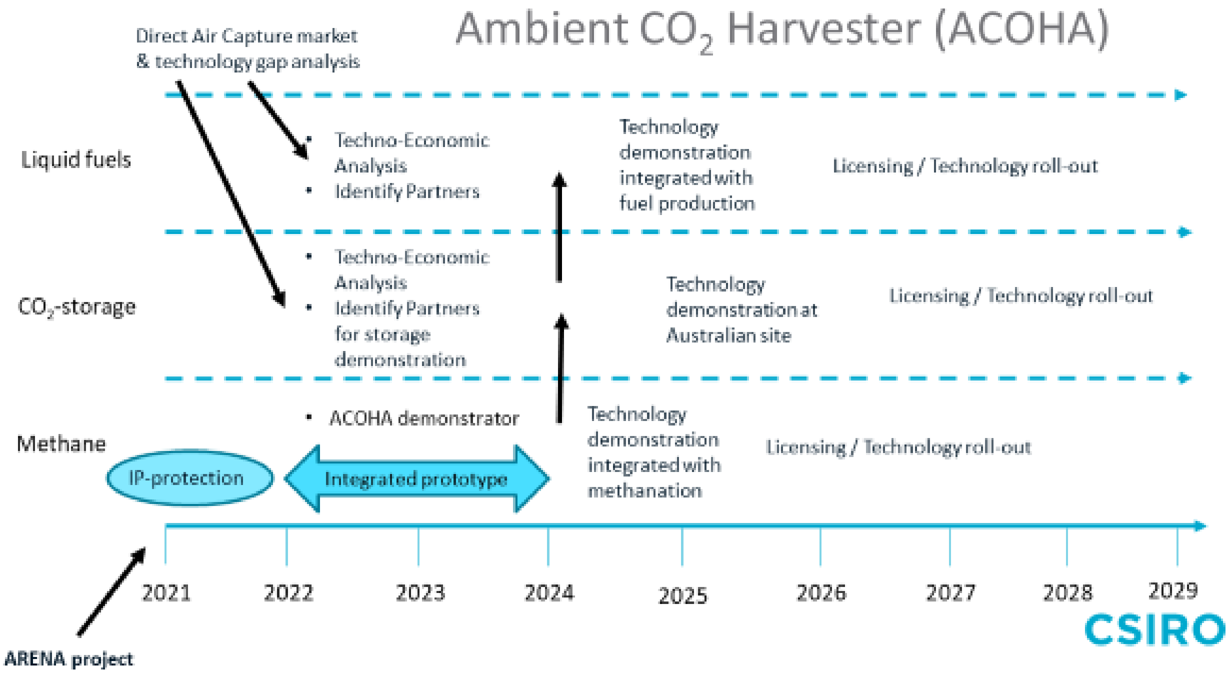

Figure 3 Pathway towards commercialisation of direct air capture technology ACOHA

Based on our discussions with industry and investors to date, we have concluded that the crucial next step is to realise the ACOHA technology demonstrator, which is an integrated prototype of the technology to enable achievement of TRL-6. The successful operation of the technology demonstrator at a scale of 100 – 250 kta CO_2 will significantly increase investor confidence for the next development step. This phase will also determine the design of an elementary ACOHA technology module (~2500 kta CO_2) that can be mass produced and is the basis for commercial roll-out. Based on our experience in commercialisation of post-combustion CO_2-capture technology over the last decade, we anticipate that the technology demonstrator will require mostly public funding. In the ensuing phase larger scale demonstrators will be integrated with the specific applications in industry. This phase is considered to be largely funded by industry and/or investors.

In parallel the market opportunity for different applications and their integration with the ACOHA technology will be further detailed. Such applications are currently explored through CSIRO's CO_2-commodisation roadmap initiative (https://ecos.csiro.au/turning-carbon-from-a-waste-into-a-resource/) with the final report due to be released in July 2021.

The business case for synthetic methane production will require strong engagement from industry to optimise the integration of the process with the existing infrastructure. CSIRO will use its business development and commercialisation function and its Missions program to obtain further support from industry, in addition to the usual methods of communication of research results, such as publications and conference presentations. The development of a full life cycle analysis for the production of synthetic methane, including a comparison with other options for export and use of renewable fuels, will significantly enhance the strength of the business case.

Development of technology components

- Technology demonstration of direct air capture process

The information gathered in this project will enable the basic design of a direct air capture technology demonstrator that can be used to evaluate and validate process performances, such as capture rate and energy consumption. This will encompass the validation of the vapour compression process for absorption liquid regeneration that enable the residual heat requirement to be met by the methanation process. Furthermore, the demonstrator can also be used to assess the water balance under a range of operating conditions, as well as the losses through drift. The technology demonstrator will a valuable tool in all direct air capture technology applications including mineralisation, geological storage and production of liquid fuels.

- Selection of preferred methanation technology

Several options for the methanation technology have been identified through literature study. While methanation technology is commercially available further work is needed to select the best configuration for integration with the direct air capture process at smaller scale than the currently available methanation technologies.

- Overall process lay-out and technology module design

The project has used the average size of a coal seam gas well and the largest electrolyser (at the start of the project) as the basis for design and the techno-economic analysis. The process lay-out should be further updated and detailed using the technical information for existing coal seam gas operations and current electrolyser sizes to enable further optimisation work that will the basis for the design of the individual technology modules for air capture and methanation.

For further information

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