Project ENCORE

Direct Air Capture

Final Report

Rolls-Royce & CSIRO

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Project ENCORE

Project ENCORE (ENvironmental CO_2 REmoval) is an exciting step in our ambition for widespread, low-cost carbon dioxide removal from the atmosphere and aligns with Rolls-Royce Group's position as leading the transition to Net Zero. ENCORE is a BEIS-funded technology demonstrator which will prove key aspects of a Direct Air Capture (DAC) system technology developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and contribute to a final engineered product developed by Rolls-Royce, which if progressed, could be available this decade. The system uses a low regeneration temperature, highly durable and non-toxic absorption liquid technology, coupled with engineering design expertise to provide a highly efficient and flexible product with a low-cost of CO_2 capture.

The partnership between Rolls-Royce, a leading UK-based global industrial technology company, and CSIRO, Australia's national science agency, brings together the innovation and engineering excellence needed to develop and productionise a competitive DAC system.

This document is a summary of our initial work to develop and design a technology demonstrator, which will be built and tested over the next two-to-three years; and our strategy to progress the DAC business after the demonstrator is complete.

Underpinning Science and Engineering

TRL4 Start Point

The starting point of the ENCORE project was the direct air capture solution produced by CSIRO, currently operating at lab scale in Australia. This rig has been used to test optimum absorption liquid formulations based on amino acid salts for CO_2 capture from ambient air. The set-up consists of absorber and desorber units which capture the CO_2 using this absorption liquid technology.

The CSIRO technology has been developed based on already commercialised absorption liquid technology for CO_2 capture from flue gases. Using this experience, and with Rolls-Royce as an industrial partner, we will now develop and scale the solution for air capture applications.

The CSIRO absorption liquid technology has the following key features and benefits which make it highly competitive with other DAC solutions:

- Low regeneration temperatures, allowing the system to operate in benign conditions, and enabling additional energy saving through opportunities to integrate with sources of waste heat. This also puts the operation within reach of established heat pump technology.
- Non-toxic, enabling safe operating and low risk of environmental impact.
- Comparable kinetics in the reaction with CO_2 to alkali metal hydroxide systems, meaning that absorber sizes and therefore the absorber capex will be similar to existing liquid systems, and the system overall cost will likely be lower, due to a single-stage regeneration step.
- Liquid-based absorbent, enabling continuous operation.
- The absorbing agent has much lower degradation rates than conventional amines, meaning the sorbent cost contributes very little to the overall levelised capture cost and embedded CO_2.

- Lower water loss than conventional liquid-based systems, significantly reducing the resource impact.

Taking this start point, the aim is to mature this technology into a full DAC product, which can be used to capture CO_2 from the air at costs of less than £100 / tonne CO_2.

Figure 1: CSIRO TRL4 DAC system development showing comparison of absorption liquid degradation against conventional MEA (top) and different types of absorbers tested (bottom)

Absorbent

Increasing absorbent life is a key area of work for this DAC system development, and will be a critical validation item in the Phase 2 demonstrator. Another important work stream is the investigation of steps that can be taken in the plant to remove the degraded absorbent while the plant is operational; and finally reviewing processes to recycle as much of the used absorbent as is economically practical. There is a precedent for the safe disposal of analogous materials at scale in other areas of chemical engineering. Maintenance activities will be performed to prevent unnecessary waste, and then to prioritize cleaning, refurbishment, and re-use. More generally, the intention is to design for high levels of recyclability and for components to be sourced from recycled materials wherever possible.

Environmental Impacts

Absorbent Emissions

The absorbent material has been selected to not only enable plant operation at benign, low temperatures and close to ambient pressure conditions, but is also itself a low toxicity chemical which will pose minimal risk to both operators of the plant and the surrounding environment. Existing DEFRA standards are being used to judge the plant emissions, and no concerns have been identified.

Water

Water is considered a key future resource. A key part of the technology development is to target a zero water loss liquid DAC system, thereby overcoming a key difficulty with other liquid DAC systems, which would be expected to lose between 3-6 m^3 water per tonne of CO_2.

Post Phase 2 Programme and Business Plan

The Product

In order to develop a demonstrator which can be used in the most cost-effective way to de-risk critical elements of the final product, it was important to first develop a product concept.

At the start of the project, a concept generation exercise was undertaken, including a functional means assessment and subsequent down-selection of concepts. In down-selecting a solution, using high level requirements as criteria, we found the preference to be to use proven, low cost technologies, which enable a cheap, longer life system.

We are targeting a modular system design, as previous experience within the Rolls-Royce Small Modular Reactor programme leads us to conclude this will have the lowest construction costs, and realise high reliability construction timescales, as well as having the benefit of cost reduction through mass manufacture. All of these factors are critical to competitive levelised CO_2 capture costs.

Figure 2: Preferred concept for production DAC system

Significant design thinking was also carried out to ensure that the product would be acceptable to the general public, and to understand how we can integrate future technologies. These are important factors to the product and would be developed fully as part of a product development programme, separate to the BEIS work. This exercise significantly influenced our concept design work, and also prompted investigation into other secondary benefits of the system such as air pollutant removal.

The approach taken to understand the size and cost profiles was to use data from existing similar systems and read across an estimate of optimum system sizing, in order to establish an optimum product size, and then determine a suitable demonstrator size. At a later stage in the product lifecycle, the models created and validated through Phase 1 and 2 of this project will be refined to model the production system, and more detailed analysis of optimum sizing will be performed.

The BEIS target demonstrator size was $100tCO_2$/year, and we are confident that we are able to meet or exceed this target within the specified time and budget.

Product Development

Development Plan

The plan commences with the current activity under **Phase 1** of the BEIS GGR competition in which the TRL4 technology concept from CSIRO has been studied and a pilot plant demonstrator has been designed. If the funding bid is successful, **Phase 2** of the BEIS Greenhouse Gas Removal competition will be launched in 2022, and will facilitate the procurement, assembly and operation that demonstrator, verifying the science and economic viability behind the concept. Data from this activity will validate the modelling exercise performed in Phase 1 and form the basis of a product development activity.

Following Phase 2, there will be a gated review to assess the commercial viability of the TRL6 technology. If this gate is passed, the project will proceed to Phase 3. Each subsequent phase will also be subject to a gated approval process.

In **Phase 3** a detailed product engineering design activity will be launched. Verification data is received and design iterations are performed for optimisation of system efficiency, cost, manufacturability and supply chain development. The quality of this work is reliant on verifying the underpinning technology to TRL6, and the technical learning from the demonstrator.

A first-generation prototype will be functionally representative of the expected final product but it will use low volume production techniques and non-cost optimised sub-systems.

In **Phase 4**, we will subject our first standard prototype to verification and validation tests alongside a sub-system rig-based test programme of accelerated life testing. Knowledge from the Phase 2 demonstrator of scaling up any lab-based experiments to larger scale will be critical to inform this work and enable rapid development.

Following lab testing and field trials we expect to generate significant performance data, operating experience and insight into durability and in-service support which will be fed back to the design stream to inform a major design iteration.

In **Phase 5**, following a successful test programme to confirm performance and durability we would expect to enter low rate production.

Further learning from accelerated lab testing, operation of deployed demonstrator plants and manufacturing and assembly experience will continue to inform the design work stream, with the opportunity to further optimise the DAC plant design in a major design iteration prior to full industrialisation in **Phase 6**.

Cost Reduction

Our approach to cost reduction is driven by efficiency improvements through bespoke product design of critical components, high levels of physical and thermal systems integration, and manufacturing scale. An attempt has been made to estimate the levelised cost of CO_2 capture of the demonstrator in a way that makes it comparable to the modelling or estimation of a production system, the method of which is outlined in this section.

Our demonstrator cost estimation was initially calculated as a scaled down version of prototype system. The actual demonstrator cost calculated includes all of the hardware for the core system, including the control system hardware, but only factoring in some of the instrumentation cost, because most of the instrumentation has a predominantly verification function rather than a system performance function.

Route to Commercialisation

We have developed a conceptual business case to guide expectations and to inform considerations around product performance, pricing, and other considerations. This is based on a series of assumptions which will clearly evolve over the life of the project.

Given the expected need to operate at scale, with production rates in the tens of thousands per year, capex is likely to be significant and unit cost critical. However, with low initial technology investment, the ability to phase capex in in increments and an opportunity for volume, the returns on the initial investment have the potential to be attractive.

Our current model assumes a phased investment in technology and product development, with an initial circa £3m technology demonstrator step funded by BEIS. If the results of this demonstrator are successful, it would be followed by an aggressive product development and industrialisation phase, which plays to the strengths of Rolls-Royce.

Key Dependencies

1. We assume there will be a market and enabling policy framework for carbon capture
2. We expect DAC will be an "AND", deployed in parallel with other carbon mitigation methods: our view of the market is based on DAC co-existing with afforestation, BECCS and point source carbon capture.
3. A carbon price of circa £100/tonne CO_2 will be implemented (either for use or storage) to make the technology economically viable
4. We do not expect carbon storage to be a constraint on the development of DAC. Based on 3rd party work, we believe that there will be sufficient capacity to store and/or use captured carbon at an acceptable cost.
5. The development of the industry will be paced by the availability of low carbon energy. We have selected a low temperature system to maximise efficiency and an architecture that allows for all-electric application to maximise potential site flexibility.
6. We expect to be able to find partners to fill capability gaps. A number of areas where we are likely to need partners to help us fill out the value chain have been identified.

Phase 2 Planning

Test Site

The demonstrator will be built and tested on the Rolls-Royce Derby site. This enables easy access to the plant for the majority of the (U.K.-based) team, does not require the same consents as would be required if using public land, and will not require licences, because the activities are covered by an encompassing site licence. It has the additional benefit of having many of the facilities required to host a complex and large scale rig, such as water, access to lifting equipment, drainage systems, and medical facilities.

The Rolls-Royce test facilities team have been engaged in order to assist with demonstrator site requirements capture, and assessment of potential test beds. A detailed set of requirements for the test location has been generated and reviewed by this team. It is considered highly feasible to plan for the demonstrator to be established within the Rolls-Royce Derby footprint, in one of the test beds, shown in Figure 3.

Figure 3: Rolls-Royce Test Bed 52, the demonstrator test location

Demonstrator Delivery & Test Plan

The plan at high level will consist of one year of site preparation and build, and one year of test work.

Key Risks

A risk register has been used throughout the duration of Phase 1 to tackle project, business, and customer-related risks. These must be managed within either near-term project activities or planned for the longer term; or for informing items of technical work, either in near-term studies or as part of the structured verification plan, to ensure a minimised level of technical risk is carried forward as the project progresses. Regular risk reviews are carried out to update the register with new or closed risks, and assess the progress of mitigation actions. This register will be carried forward to Phase 2 and maintained throughout the duration through regular risk reviews.

The technical risks will be predominantly managed as part of the verification and validation strategy, captured through a combination of the risk register and the functional failure mode and effect analysis (FFMEA). Other risks will be managed as the project progresses, and the document is kept live and reviewed regularly to ensure actions are closed out when possible.

Social Value and Impact

There are clear long-term global and national benefits of commercialising a direct air capture system, most obvious being the significant impact on climate change and the ability to limit global temperature rise. Additional to this is the potential to create widespread economic value, with significant regional job creation, as well as the ability to take advantage of a large export market.

With that in mind, there should also be a clear focus on environmental sustainability and social impact throughout the whole lifecycle of the product. Although this impact will be much smaller in the early stages of the DAC system development, Project ENCORE still has the opportunity to have a significant footprint with regards to social value.

A key part of this will be engagement with the Rolls-Royce outreach team to develop materials on direct air capture. This team have previously delivered successful outreach activities around programmes such as ACCEL, an all-electric flight demonstrator. We are keen to work with BEIS on a coordinated public education strategy in the negative emissions technology space, this being an enabler to the development of the sector. Our team is experienced in community outreach, particularly with engaging local schools in both the Bristol and Derby area in STEM activities.

Environmentally positive projects also often attract more diversity than other areas of engineering. We have already recruited engineers into the Central Technology and Strategy department, which leads the direct air capture work, to work on this project, and we see further planned recruitment as an opportunity to grow diversity in engineering and technology. The work also acts as an opportunity to repurpose engineering skills within the company for work on more environmentally sustainable technologies.

As well as skills, use of existing test bed infrastructure which today has low utilisation on the Rolls-Royce Derby site is an opportunity to continue to repurpose this infrastructure to develop new technology in the Midlands area, and continuing to develop and grow this capability is consistent with the U.K. Government's levelling up agenda.

Finally, we have engaged with U.K. suppliers where possible through the duration of the Phase 1 supply chain activity, and it has been possible to source the majority of components within the U.K. supply chain, ensuring that Government funding received for the project goes to support the local economy.

Detailed Design of the Demonstrator

Systems Engineering Approach to Development

Rolls-Royce has employed a systems engineering approach (illustrated in Figure 4) to this development, starting with a set of key requirements for the production system, which were captured using our existing knowledge of applications (and therefore potential customers), environmental regulations, and using expertise from CSIRO.

A functional flow diagram and boundary diagram were developed to ensure that the scope and key functions of the system were understood. This helped to confirm the team had a good technical insight into the whole system, and enabled a functional approach to the production version of the DAC concept, as well as the demonstrator design. This functional view enabled both a Functional-Means Assessment, which aided concept generation and subsequent down-selection of preferred concepts, and an FFMEA, which acts as a key source of requirements for the verification strategy.

A structured verification approach was then taken in order to establish a robust set of requirements for the demonstrator, which will most efficiently target key verification items and enable the optimum roadmap to move rapidly from demonstrator to product. The verification activities fall under standard categories of: Analysis; Lab/rig test; Pilot plant test; Inspection; Prototype.

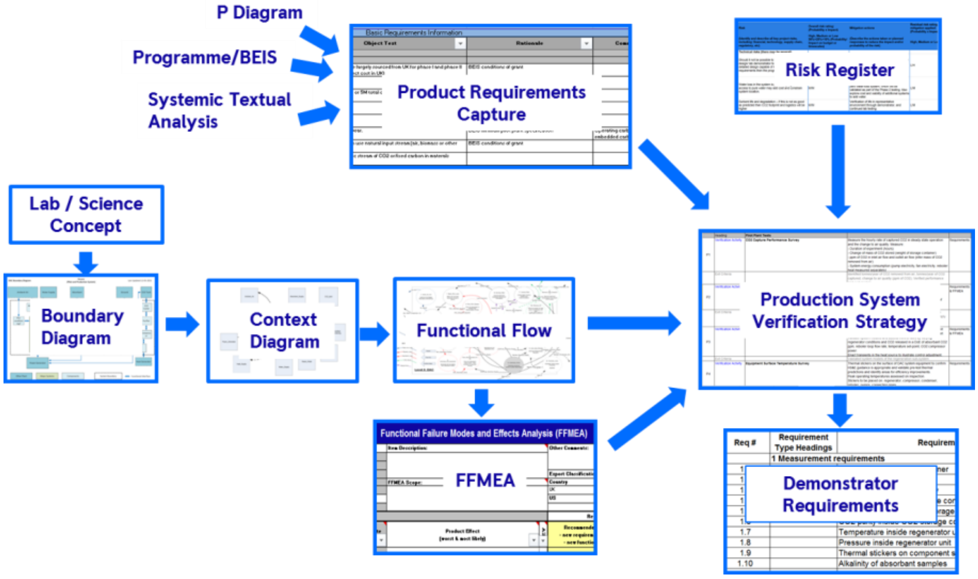

Figure 4: Overview of Systems Engineering Approach

Table 1: Examples of pilot plant requirements derived from verification activity

VI Code	Activity Title	Source	Pilot Requirements
P1	CO_2 Capture Performance	Requirements: BEIS min spec of 100tCO_2e/yr	Measurement of inlet/outlet air CO_2 ppm, CO_2 production flowrate, energy use
P5	Absorbent Sampling	Risk Register: Sorbent degradation product management	Absorbent sampling and chemical analysis capability
P10	Air Quality	Technical Sessions: Opportunities for human health pollutant removal	Inlet/outlet air sampling and analysis
P14	Safety Shutdowns	FFMEA: Over-pressure of regenerator	Measure regenerator pressure, automatic shutdown sequence triggered by input
P16	Water Loss	Risk Register: Water loss cost increase	Ambient humidity measure, hygroscopic solution concentrations, vessel level indicators, separation tank water sampling

The requirements for the demonstrator are then made up of all of the activities which are required to be verified through a pilot system, and cannot be verified e.g. through analysis or lab testing.

Table 1 illustrates some examples of pilot plant requirements which have been derived from verification activities included in the down-selected list for demonstration.

This work also forms the technical basis of the test plan, which is included and discussed further as part of the Phase 2 project plan.

System Model

Informing Design Work

A system model was then created using the functional flow diagram to provide the basic architecture. The purpose of the model is firstly to inform the demonstrator design in terms of component specifications, and secondly to calculate the expected performance of the system. Calculations in the model enable us to predict the ultimate carbon intensity of the system, and therefore the levelised cost of carbon dioxide. During the demonstrator programme, the model will be validated and evolved to become the basis for future product system models.

Two subsystem models are used within the overall system model: the absorber and desorber subsystems, which contain understanding and some parametric data from CSIRO TRL4 lab rigs, including categorisation of the absorbent behaviour. Additionally, the model requires access to cost and carbon data for individual components or materials used within the system.

Energy and CO_2 Performance

The system model also provides calculations of anticipated system performance with regards to energy and net CO_2 capture. For a final product, through design optimisation and integration, we believe we can develop a system which requires less than 1MWh/tonne CO_2.

The overall carbon removal efficiency of a minimum viable product system is estimated to be a net removal per gross plant capture capacity of ~0.8 tCO_2e/tCO_2e. This means that, for every tonne of carbon dioxide captured from the air, the atmospheric greenhouse gas concentration reduces by ~800kg after considering all emissions throughout the supply chain. This takes into account the lifecycle impact of the system. When fully optimised, the intensity could be higher than ~0.9 tCO_2e/tCO_2e removal. The assessment of lifecycle CO_2 removal has been made in line with UK Government Emissions Reporting Guidelines. Methodology for monitoring of emissions reduction will initially aim to conform to Intergovernmental Panel on Climate Change guidelines, however may need to evolve if the UK establishes specific monitoring, reporting and verification guidelines for DAC.

The overall lifecycle greenhouse gas removal of the system, and other lifecycle materials impacts, as well as the CO_2 capture costs, will continue to be monitored throughout the duration of the programme as our product system concept and design evolves. Individual end uses will have specific monitoring, reporting and verification (MRV) requirements, and these will be explored with specific partners and customers at a later stage in the programme.

Demonstrator Plant Design

Bill of Materials

The approach for sourcing hardware has been to use commercial-off-the-shelf (COTS) components where possible, as this is the lowest cost and fastest way to achieve the demonstrator verification objectives. Subsequent product designs would then be driven by this systems understanding, and consider how to reduce cost and optimise performance in key system components which are shown to drive this by the validated system model. For the production system, bespoke design and manufacture of key components is envisaged.

A back-up option to using COTS components is the Rolls-Royce fast-make facilities, which are able to rapidly replicate the majority of components required for the system, and this therefore provides a risk mitigation if any of the components cannot be supplied on time, and no back-up supplier can be established quickly. Our manufacturing services team who carry out the installation will also be able to make modifications to piping, or manufacture bespoke piping sections, which will ensure smooth demonstrator component integration.

For most COTS components within the system, we have received quotes from three separate suppliers to ensure a representative cost estimate. The chosen supplier is primarily selected by shortest lead time, although component cost is also considered. All suppliers for components are U.K. based with the exception of the absorber supplier, due to the lack of suitable suppliers who are based in the U.K.

Instrumentation and Control

Additional to the plant hardware, significant instrumentation and control hardware is required in order to fulfil the demonstrator requirements, and for safe and efficient operation of the plant. The DAC instrumentation and control concept design is based on the pilot plant requirements for measurement and control. The proposed solution has been further refined from: a deeper dive into the proposed functional flow and anticipated operation; analogy with the TRL4 DAC and post-combustion capture applications; and an understanding of evolving subsystem and component selection. The instrumentation and control solution has been developed to facilitate automated yet safe continuous operation while generating the measurement evidence to assess and understand the effectiveness of plant performance. The solution has meanwhile been developed to permit flexibility required for operation at pilot-scale readiness, while exploiting competitive commercially available equipment.

A line-by-line review of the DAC functional flows was performed to identify the high-level (non-implementation specific) remit of control across the proposed plant. In addition to considering equipment control for reaching and maintaining steady-state operation, start-up and shut-down sequences were defined.

The verification requirements determine the list of items which are required to be measured in the demonstrator system. A functional-means assessment was used to determine a suitable set of instrumentation to fulfil these measurement requirements.

Plant Layout Design

Finally, data from suppliers was used in combination with the process flow and high level piping and instrumentation diagram to produce a layout diagram. An iterative approach was then employed to take this design forward, based largely on the constraints of the test cells supplied, equipment sizes and other factors. Component size changed over the design iterations as final dimensions were refined and the process flow evolved.

The following considerations were then made to further improve the design:

1) Height of equipment relative to each other to enable gravity flow and minimise energy loss with preference of equipment being at ground level.
2) Ease of operation when accessing different valves or equipment and moving between areas of the plant.
3) Ease of maintenance by making sure each component has adequate access and ensuring enough space to move equipment in and out if necessary.
4) Future modification of the plant, such as adding additional components or functionality.
5) Emergency situations where people must rapidly leave the test bed.
6) Environmental protection to ensure leakage of any material is adequately contained.

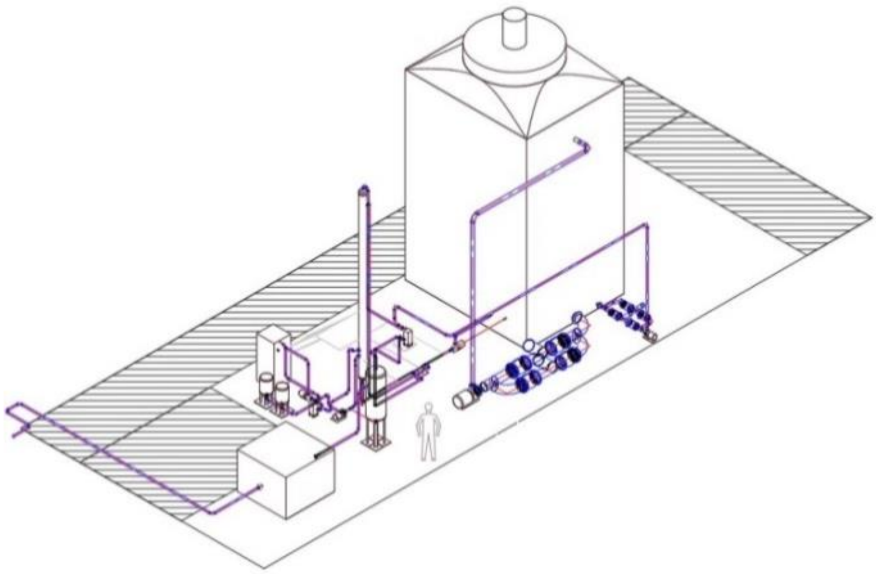

Figure 5: Plant layout design

Cost Savings and Additional Value

Funding the Rolls-Royce / CSIRO demonstrator system allows access to a range of skills and expertise in demonstrator design and build through the Rolls-Royce network, which includes access to the test bed itself, for which we do not have to pay rent, and for which we can access on-site support and expertise in preparation and test set-up. Additionally, we are able to access to software and tools, such as the computational fluid dynamics software used to model airflow through the test bed, and tooling which will be used for installation. CSIRO has significant experience in commercialising flue gas carbon capture plants as well as global regulatory expertise around direct air capture, and this knowledge can be leveraged for the purposes of commercialisation.

Finally, this work can contribute to the broader UK-Australia Clean Growth partnership as part of the Letter of Intent signed by respective ministers.

Phase 1: Project Management and Delivery

Cost and Plan

Phase 1 of the BEIS-funded ENCORE project has been highly successful in its delivery, meeting all milestones on time, and submitting final deliverables on time, with spend to budget. This highlights one of the benefits to having projects led by large engineering companies with experience of delivering complex technical programmes on time and to budget.

Experience Gained and Lessons Learned

This project has been an excellent opportunity for the team to learn more about developing a viable Direct Air Capture system. Key lessons include firstly the need for the final product to be flexible to a range of geographical locations as well as end-use applications, and therefore the need for detailed customer requirements in the product design phase. Secondly, that lifecycle CO_2 can have a significant impact in both the system effectiveness and levelised cost. Finally, although the team has worked very effectively remotely, and have made use of the time difference to work on deliverables over a 24-hour period, we have learned that in-person meetings can often be invaluable for communicating understanding and sharing ideas.

Conclusions

Project ENCORE is a first and exciting step to developing part of the solution to climate change, and Rolls-Royce and CSIRO are proud to be working together to be part of that journey. Our system shows significant promise to be able to capture CO_2 from the air in a low-cost, highly efficient, and flexible way, and we believe under the right conditions it is highly achievable to develop the technology into a viable product this decade.