SMART-DAC [CO2202035]
GGR Innovation Programme

Public Facing Report Phase 1

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Executive Summary

The novel SMART-DAC process aims to capture CO_2 directly from air using a two-step process: 1) absorption of CO_2 from air by membrane gas absorption (MGA) using a potassium hydroxide (KOH) solution absorbent and 2) regeneration of the absorbent by electrodialysis bi-polar membranes (EDBP).

MGA uses a membrane to keep gas and liquid phases separated while allowing mass transfer between gas and liquid phases. The KOH absorbs the CO_2 from the air as it passes through the membrane and on contact with CO_2 converts into potassium carbonate/bicarbonate (K_2CO_3/$KHCO_3$). In the regeneration step the potassium (bi)carbonate is converted back into KOH for reuse as an absorbent and the CO_2 is concentrated and separated out.

Wind circulation will be used, as opposed to turbines used in current DAC systems, for contacting and the flow of air through the membranes. Power, in the form of electricity, will only be required for the electrochemical regeneration process of the used absorption material. Average energy consumption for the regeneration unit has been estimated to be approximately 37 kWh.

To achieve a minimum of 100 tonnes CO_2eq per annum the capacity of the pilot plant has been designed to capture 0.314 tonnes CO_2 per day. This is based on 350 operational days, including a 10% overdesign margin, giving a 110 tonnes per annum CO_2 capture capacity.

Funding through the BEIS GGR Innovation Programme has been critical in accelerating design focus and decisions to support development of the SMART-DAC technology from the formulation of technical concept and feasibility to component validation in laboratory and simulated environments, enabling a complete Front End Engineering Design (FEED) for a pilot plant.

Phase 1 funding has advanced technology readiness levels (TRL) in two key areas of SMART-DAC, membrane gas absorption from TRL 4 to TRL 5 and the regeneration process from TRL 4 close to TRL 6.

Recommendations for the next stage of development is a detailed design study to further the maturity of the proposed design parameters sufficiently to allow procurement and construction of the pilot plant.

Although tested and ready for application in the pilot plant, continued testing and optimisation of the MGA and EDBP modules will continue in parallel to the operation of the pilot plant. Improving the mass transfer rate within the MGA process will be one area of focus.

Finally, an ideal test site and partner to operate and develop SMART-DAC has been secured. B9 will host the pilot plant at their offices in Larne, Northern Ireland. Analysis shows that the area is a very favourable location for SMART-DAC.

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1. Introduction

Meeting the UK's target of Net Zero emissions by 2050 represents a significant challenge. The widespread adoption of carbon capture, utilisation and storage (CCUS) technologies, including direct air capture, will have a significant role in achieving our emissions goals. The UK Industrial Strategy has identified Clean Growth as one of the four key areas where Britain can lead the global technological revolution, predicting the UK's clean economy could grow at four times the rate of GDP. The transition to a climate-neutral economy has the potential to rapidly deliver jobs, growth of new industries, and to contribute to building more resilient societies. The Net Zero Technology Centre summary report [1] estimates that the total domestic economic impact of CCUS to the UK is in the region of £0.2tr with 15,000 jobs from direct, indirect, and induced employment by 2050.

The report also identified key technology gaps and areas of innovation that need to be addressed to reduce the current cost of carbon capture and utilisation. These centre around the capture materials (sorbents, membranes) for high-capacity CO_2 capture with minimum energy requirements for regeneration, low toxicity and long lifetime, and high CO_2 conversion efficiency for low-cost pathways to CO_2 utilisation. Significantly reducing the cost of carbon capture technology will drive growth and scale within the industry, allowing feasible business models, creating new low-carbon products from using the captured CO_2 as feedstock, and generating jobs to support the new industries. With a gap in the market the UK could position itself as a centre of excellence and innovation promoting itself at the forefront of GGR technologies.

With an estimated 10 gigatonnes of CO_2 per year needed to be removed by 2050 to reach our global warming targets, technologies like DAC for large scale deployment of CO_2 removal, will be required

This report gives a detailed description of the work undertaken by the SMART-DAC consortium (CO2CirculAir (lead), PDC, Optimus, Heriot Watt and Net Zero Technology Centre) as part of the BEIS funded GGR Innovation Programme.

The objective of the project is to redesign membrane gas absorption (MGA) modules for efficient CO_2 capture from air. This will form a basis for a complete process-design, front-end engineering and costing of a pilot unit for DAC with a capacity of at least 100 tonnes CO_2/year. The design phase will extensively research and incorporate the use of low-cost sustainable materials, the efficient use of wind (instead of turbines) as a flow mechanism through the DAC system, and the use of renewable energy for the regeneration process.

Delivery of the project has been built around three milestones, which were structured to progressively build knowledge and understanding in the functionality and optimisation of the pilot plant design from Pre-Process Design, through Process Design and finally FEED of the Pilot Plan Design.

2. SMART-DAC Concept and Basis of Design

The novel SMART-DAC process is based on two steps: 1) absorption of CO_2 from air by membrane gas absorption (MGA) using a potassium hydroxide (KOH) solution absorbent and 2) regeneration of the absorbent by membrane electrolysis/electrodialysis (ME/ED).

MGA uses a membrane to keep gas and liquid phases separated while allowing mass transfer between gas and liquid phases. The KOH absorbs the CO_2 from the air as it passes through the membrane and on contact with CO_2 converts into potassium bicarbonate ($KHCO_3$). In the regeneration step the $KHCO_3$ is converted back into KOH for reuse as an absorbent and the CO_2 is separated out.

Wind circulation will be used, as opposed to turbines used in current DAC systems, for contacting and the flow of air through the membranes. Power, in the form of electricity, will only be required for the electrochemical regeneration process of the used absorption material.

A 'smart' tanker storage system has been built into the design to manage operational down time and periods of low passage of air through the system to enable continuous and efficient operations. This will also offer the flexibility in the system to run in periods of low-cost surplus electricity or by direct use of green electricity from solar or wind powered sources.
To achieve a minimum of 100 tonnes CO_2eq per annum the capacity of the pilot plant has been designed to capture 0.314 tonnes CO_2 per day. This is based on 350 operational days, including a 10% overdesign margin, giving a 110 tonnes per annum CO_2 capture capacity.
A simplified Process Flow Diagram (PFD) for the SMART-DAC pilot plant is illustrated below in **Figure 1**.

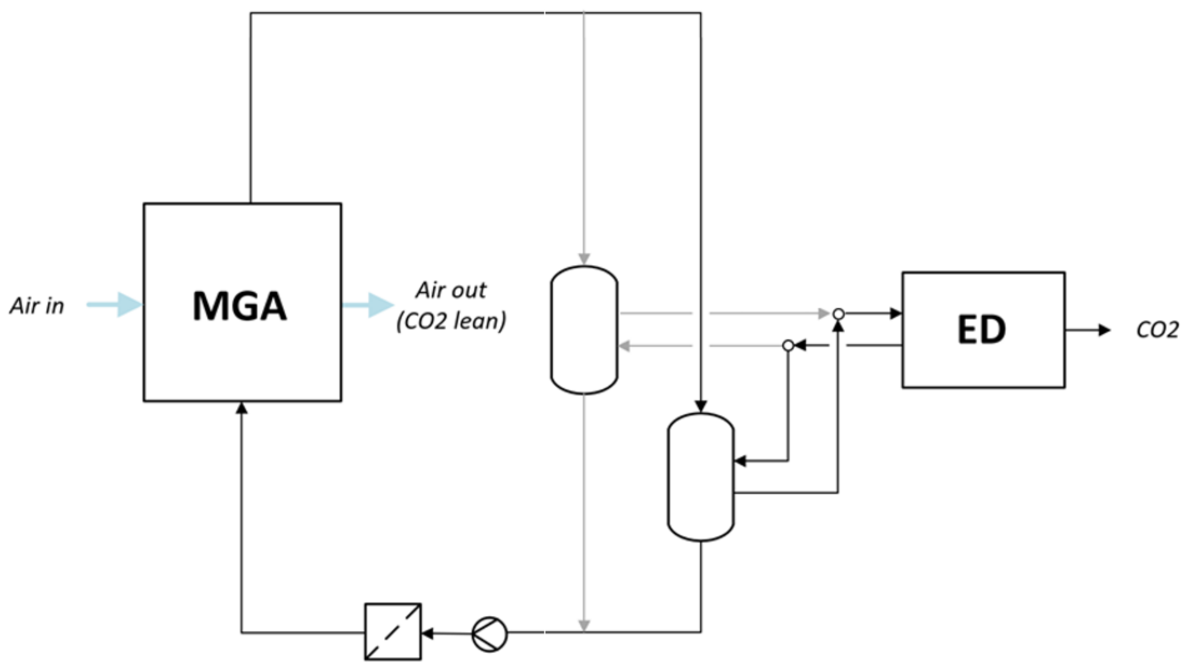


Figure 1: PFD schematic of SMART-DAC Pilot Plant

2.1 Membrane Gas absorption (MGA)

Membrane Gas Absorption (MGA) uses a membrane to keep gas and liquid phases separated while allowing mass transfer between the phases. The membrane creates the required surface area for mass transfer between the gas and liquid phases (**Figure 2**).

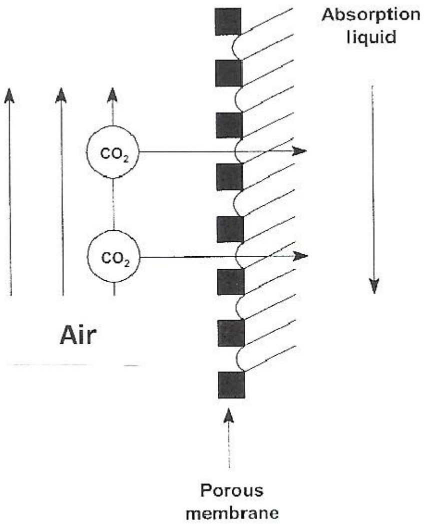


Figure 2: Principle of membrane gas absorption

MGA is a proven technology and has extensively been studied, tested, and used in gas separation processes including the absorption of CO_2 from flue gasses. Application for Direct Air Capture (DAC) requires a specialised design of the absorption modules to account for the low concentration of CO_2 in the air and in the case of SMART-DAC to allow the natural flow of air through the module.

The use of common amino-based absorbents cause leakage through the membranes. SMART-DAC overcomes this through the application of an absorbent which uses a fully inorganic absorbent (KOH) which is chemically stable, non-volatile, and regenerable without loses.

The absorption of CO_2 using a solution (4% w.) of KOH in water takes place in two steps. The first step in the absorption (half saturation) is the formation of K_2CO_3 (fast absorption/reaction); the second step (full saturation) is the formation of $KHCO_3$ from the K_2CO_3 (slow absorption/reaction).

The two-step absorption process offers flexibility in operation. At times of less wind, the regeneration can take place at half saturation and at times when low-cost energy is available the absorption process can be elongated and only generate at full absorption. The balance between CAPEX and OPEX of each process will be investigated in the pilot plant and will be dependent on the absorption velocities obtained in the models in each step. Present expectation is that the first step can be as much as ten times faster than the second.

The pilot plant has been designed to run in both batch and continuous modes. In batch mode the absorbent flows through all the parallel or serial modules in a recirculation stage before being returned to the first membrane via a recirculation vessel. The flow of the absorbent during continuous mode is controlled by pH and/or conductivity.

2.1.1 Estimation of mass transfer coefficient for CO_2 in MGA module

Estimation of the overall mass transfer coefficient, k, is based on conservative values for mass transport base on literature research. For the second part of the absorption process (carbonate to bicarbonate) no chemical acceleration is considered: k = 0,001 m/s. For the first step in the absorption process (lye to carbonate) a chemical acceleration by a factor of 5 is considered. Through testing and development, it is expected to be able to improve the performance of the membranes considerably by using thinner membranes with high porosity, increasing the overall mass transfer coefficient, and subsequently decreasing the membrane surface area needed and therefore the total number of modules required to capture the same volume of CO_2.

2.1.2 Weather Impact analysis

Design of the MGA module needed to consider the impact of wind velocity and direction. The wind velocity is important as it determines the amount of air that is transported through the module. The amount of CO_2 to be absorbed by the module depends amongst other factors on the concentration difference of CO_2 in the air and in the absorption liquid. At (very) low wind velocity the air may be depleted of CO_2 before it leaves the module, with no further transport of CO_2 into the absorption liquid. This means loss of absorption capacity. Too high a wind velocity (stormy weather) may damage the absorption modules and will require measures to protect the modules.

Other weather conditions like average temperatures and rainfall have little effect on module design. Average yearly temperatures of 8 to 10^{o}C, and rainfall between 800 to 3000 mm per year will have minimal influence on the performance of the process. Very low temperatures, a prolonged cold period, could potentially prevent operation through the freezing of the absorption liquid. However, due to a high concentration of salts in the absorption liquid the freezing point would be low enough to prevent this from happening for all but the very coldest of weather. At very severe low temperatures, the content of the absorption unit can be “drained” into storage tanks to prevent damage to the absorption unit. High temperatures do not pose an issue as any evaporation of water from the absorption module, can be supplemented by addition of extra water to the system.

The preliminary conclusion from the weather impact assessment is that CO2CirculAir considers a predominant wind direction with a narrow azimuth with an average wind velocity of Beaufort 4 (6-8ms^{-1}) to be a good basis for design of the absorption modules.

A wind profile study, by Heriot Watt, of mostly coastal locations around the UK indicated that all locations had the required average wind speed, but some locations were more suitable due a more dominant wind direction. The wind and weather profile analysis of the chosen site location for the pilot plant will be discussed later.

2.2 Regeneration Cells and Stack Design

The Electro-Dialysis with Bi-Polar membranes (EDBP) unit recovers the KOH from the K_2CO_3/$KHCO_3$ formed during the absorption process and releases the captured CO_2. A simplified schematic of the EDBP process is illustrated in **Figure**

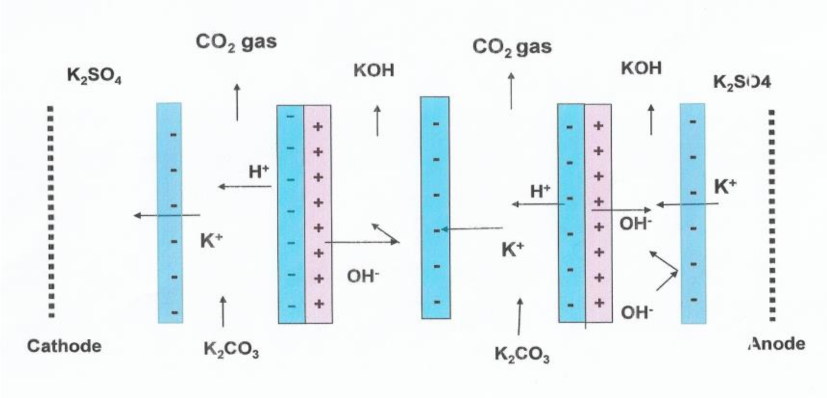


Figure 3: Simplified schematic of the EDBP process

The K_2CO_3 rich solvent is pumped into the EDBP unit. In membrane electrodialysis of K_2CO_3, potassium ions (K+) migrate through a cation permeable membrane, while H+ and OH- migrate through a bipolar membrane.

By using an aqueous electrolyte at the anode and cathode compartments of the electrodialysis unit, the formation of gaseous O_2 and H_2 is circumvented and only CO_2 is released as a gas from the regeneration unit (from the compartments that are fed with K_2CO_3 solution).

2.2.1 EDBP batch operation and design setting

The EDBP operation is required to be in batch mode. A regeneration batch cycle has completed when the content of the acid compartments recirculation vessel has changed from a K_2CO_3 solution into water and the content of the base compartments recirculation vessel has changed from water to a 4% wt KOH solution. On completion of a regeneration batch cycle the base compartment recirculation vessel will be emptied, and its contents sent to the MGA unit to be used in the absorption cycle and the vessel to be used for the next regeneration. It is not necessary to empty the acid compartment recirculation vessel, now containing water, as it is used as starting fluid for the base compartment recirculation vessel in the next regeneration batch.

2.3 Measurement and control strategy

2.3.1 MGA unit

pH changes

Lean KOH solution has a pH value ranging between 12 and 14. When KOH is converted to K_2CO_3, the pH range lowers to a range of 10 to 12, whereas $KHCO_3$ is the main component has pH values around 8 (**Figure**). By measuring pH, one can monitor and control the process with respect to the desired main component K_2CO_3 or $KHCO_3$. The final MGA product composition (ratio K_2CO_3:$KHCO_3$) depends on the residence time given for CO_2 absorption; in MGA batch-mode this means a dependency on the amount of recirculation.

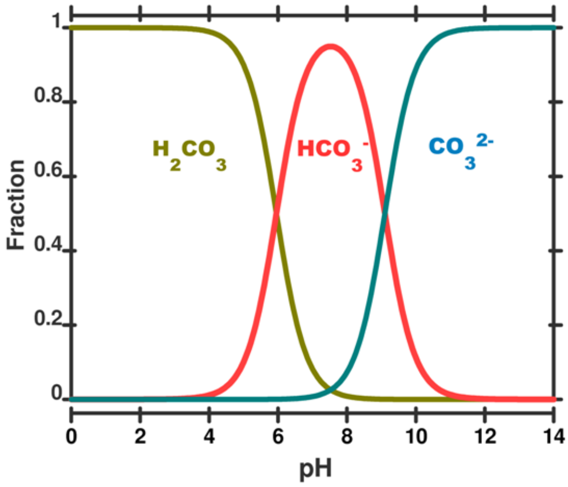


Figure 4: Distribution of CO_2, bicarbonate and carbonate vs pH

Other measurements

Flow rate, temperature, and pressure of the absorbent into the MGA module will be measured. Pressure control will take place behind the last MGA module.

2.3.2 EDBP unit

pH and conductivity changes

Process control of the EDBP unit is based on electric conductivity and pH measurements. In the acid compartment, the K_2CO_3 solution, having a pH of about 10 to 12, gradually converts to water, having a pH of about 7.

In the base compartment, water gradually becomes a KOH solution, which finally should meet the concentration requirement for use in the MGA unit, i.e., 4% wt. During regeneration, the pH of the fluid recirculating across the base compartment changes from about 7 (water) to maximum (range: ±14). The batch is ready when the target of 4% wt KOH has been met.

Other measurements

All EDBP recirculation vessels are attached with level measurement (with overflow alarm) and pH measurement. Only one flow measuring device is foreseen for measuring the throughput of the EDBP unit across the acid compartment and only one flow measuring device for measuring the throughput from the base compartment. Principally, the EDBP unit operates at a fixed fluid throughput for both compartments.

With respect to the CO_2 gas released from the EDBP unit: This effluent stream is measured with respect to i) mass flow rate and ii) CO_2 content (weight fraction). These are key measurements within the monitoring plan and are important measurements as they will indicate the amount of CO_2 captured during operation of the pilot plant

For determining the electrolysis power supply, voltage, current, and duration are continuously monitored and measured.

3. Pilot Plant Design (FEED)

Optimus undertook Front End Engineering and Design (FEED) level Engineering study on the proposed pilot plant. This involved developing the system identified in the Basis of Design (BoD) to a greater level of definition and maturing this to a level sufficient to provide a cost estimate for Detailed Design (DED), Procurement, and Construction (EPC) in Phase 2 of the GGR competition.

The engineering effort has added significant value to the project in that through maturing the concept and defining and laying out the required components on a 3D model, it became clear that the early design iterations were too large and complex and would therefore be too costly. This drove a value engineering exercise which sought to reduce complexity in the system, which was successfully achieved within the remaining time of Phase 1 and resulted in a substantially simpler plant ultimately being presented in the final version of this report.

This section summarises the key FEED engineering activities and outcomes.

3.1 FEED Summary

3.1.1 FEED Objectives

- The FEED study had the following objectives for the pilot plant design
- Generate Engineering, Procurement, and Construction Cost estimate.
- Further define the process system and equipment requirements from the supplied BoD and PFD.
- Define key discipline requirements (line, tank, and pump sizing).
- Identify and define instrumentation and control requirements.
- Generate FEED level layout of piping, vessels, mechanical equipment and structure.
- Ensure safety by design.

3.1.2 Plant Layout

A preliminary plant layout was generated during FEED. A key attribute of the pilot plant is modular construction, which allows much of the manufacturing and construction effort to be completed “off-site” within a more controlled shop environment, increasing the likelihood of positive outcomes in terms of cost, schedule, and quality. This also simplifies decommissioning or re-use of the plant.

A preliminary iteration was significantly revised and optimised during the “value engineering” exercise.

The process optimisation / value engineering exercise resulted in a substantially smaller plant in terms of equipment and footprint. Most of the pilot plant is still laid out on one level, with some elements stacked above including the MGA modules and CO_2 release vessel Error! Reference source not found.. This r esulted in a reduction in the number of containers to three. The length of required pipework also decreased by two thirds, and the number of large tanks (5000 litre) reduced to three with attendant pumps and instrumentation also reducing. The revised plant footprint should offer considerable advantage versus the early iterations in terms of supply of a suitable site, as well as maintaining any access requirements round the plant.

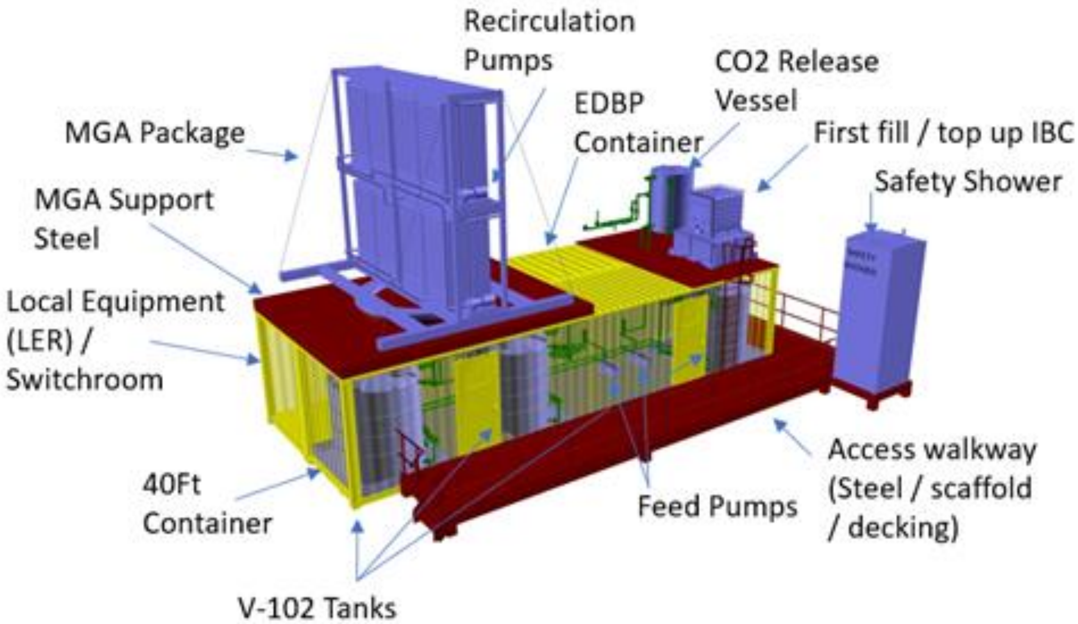


Fig. 5 : Optimised plant layout post value engineering

3.1.3 FEED Key Findings

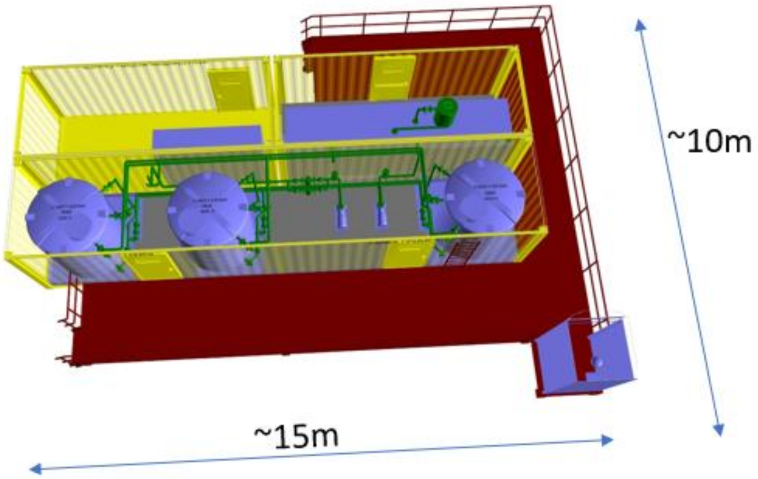
Total EPC Cost: **£1.2M** excluding VAT (see **Section 3.3** for full details). The cost estimate comprises of figures obtained from a deterministic engineering cost build up, vendor supplied estimates, and coarse and norms-based assessments. The construction cost estimating template was supplied by a third-party estimator and several line items were advised by CO2CirCulAir who have previous experience in designing and manufacturing these systems.

Lead Time: The total lead time for the pilot plant Engineering, Procurement, and Construction is estimated to be approximately 10 months.

Total Site Footprint: Approximately 15m x 10m (excluding any laydown, storage, or parking requirements). The footprint is based on most modules being on a single level

(see Figure 6)

Figure 6: Plant Footprint



Process Findings [2] The process finding are based on the supplied Basis of Design (BoD), with process schematics defining the system further for “at scale” deployment, with a capture capacity of 110 tonnes eq of CO_2 per annum from atmosphere. This includes a 10% margin over and above the competition requirements to allow for operational down time and adverse weather conditions.

Tank volumes and pump sizing was calculated during this phase, allowing the mechanical discipline to commence enquiries into the provision of these components. The consortium confirmed that simple centrifugal pumps are acceptable. Feed pumps are to be designed so as not to provide more than 0.5barg pressure, as an intrinsically safe measure to protect the membranes. The requirement for variable speed drive versus fixed speed will be considered further in detailed design during Phase 2. Additionally, pressure losses across the membranes were confirmed to be less than 0.5barg. The instrumentation required to safely operate the plant was also defined. Line sizing was confirmed to be universally 2” unless notified otherwise.

On review of the initial plant design the system has been substantially optimised reducing equipment requirements via a value engineering exercise. This has had a significant impact on plant cost and size and has resulted in a substantially improved plant design

Absorption Process Redesign: In the redesigned process system, there are three tanks replacing the two tanks on the absorption loop and the four buffer tanks between absorption and regeneration. In a departure from the BoD, these tanks are interchangeable in their function, meaning only one tank per function is required instead of two. The new tanks are the same volume (as they can perform all three functions) reducing the buffer volume between absorption and regeneration significantly. This reduces the number of tanks from ten to three (as dual tank arrangements had been required to achieve the required tank volumes) offering savings in terms of containers, pumps, pipework, instrumentation, and grillage. However, this arrangement requires both absorption and regeneration to work in unison due to the loss of buffer storage. (See Figure 7)

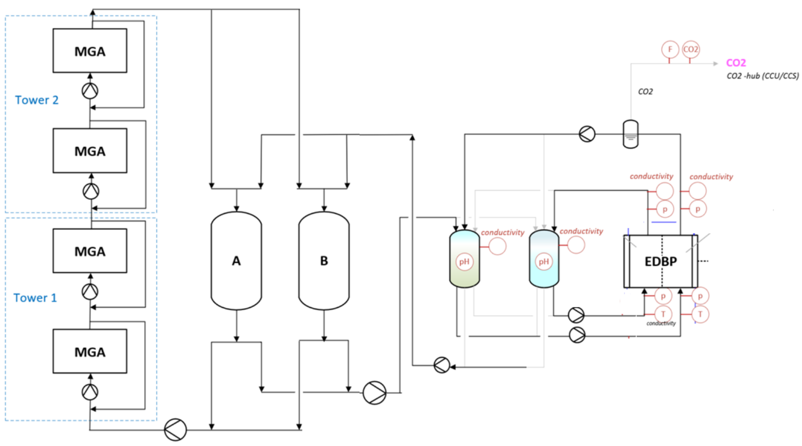


Figure 7: CO_2 absorption and regeneration process and tank layout

Instrumentation Findings:

The proposed design should not present any significant difficulties in terms of Instruments and Controls. Both Optimus and CO2CirCulAir have experience of specifying and procuring suitable control systems form established vendors. CO2CirCulAir have specified that the plant should be fully automated to reduce on-site operator requirements. The pilot plant will still require manning for 8hrs per day, 5 days per week and requires two operators on site. A Control System Specification [3] was produced, proposing a single simplex PLC for all control and trip functionality for the package.

Field instrumentation is expected to comprise of pH and conductivity probes, level transmitters, pressure safety valves, flowmeters, actuated valves, and control valves. In addition, temperature transmitters, differential pressure transmitters and pressure transmitters will also be required. High pressure alarm and trips were identified as a requirement on the pump discharges to protect downstream equipment, although the alarm output is TBC as the plant will not be continuously manned.

Electrical Findings: It is assumed that power requirements will be met by a suitable connection to grid: 400V 3phase 50Hz supply, connected to a dedicated switchboard. The switchboards / motor control centres will be located in a switchgear room supplied as a containerised package. The ground area for the plant is assumed to be suitable for earth pit construction. Trace heating has been selected as the most power-efficient means of maintaining suitable temperatures in the process fluids during colder weather conditions.

Material Selection: The use of polypropylene (PP) was agreed as suitable for both piping and storage tanks and has been selected on review of chemical datasheets for the absorption media. This has both cost and material property benefits to the project.

The design in piping and layout resulted in a total of 3 containers: one 40ft and two 20ft containers plus ancillaries and access. The containers will house:

1. 40ft Container – three tanks plus pumps and pipework
2. 20ft Container – EDBP package unit
3. 20ft Container – electrical switchboard and control panels

Additionally, some items have been arranged on the upper level (on top of the containers). These include the CO_2 release vessel, the first fill and top up IBC, and the MGA package(s) plus supporting steelwork.

Mechanical Findings: Pumps are expected to be magnetic drive, close coupled, electrically driven, and seal-less to negate the possibility of mechanical seal leaks (stainless steel for intended chemical solutions). Pump quotations were sourced from two separate vendors on a budgetary basis.

The proposed bulk chemical storage tanks are manufactured from Polypropylene (PP) and have been selected based on standard sized "off the shelf" items. The tanks have been specified with PN16 connections, have a wall thickness rating of 1.5G, and are self-supporting. The number of tanks required was reduced substantially via the value engineering exercise. **Figure** presents the final tank and pipework arrangements.

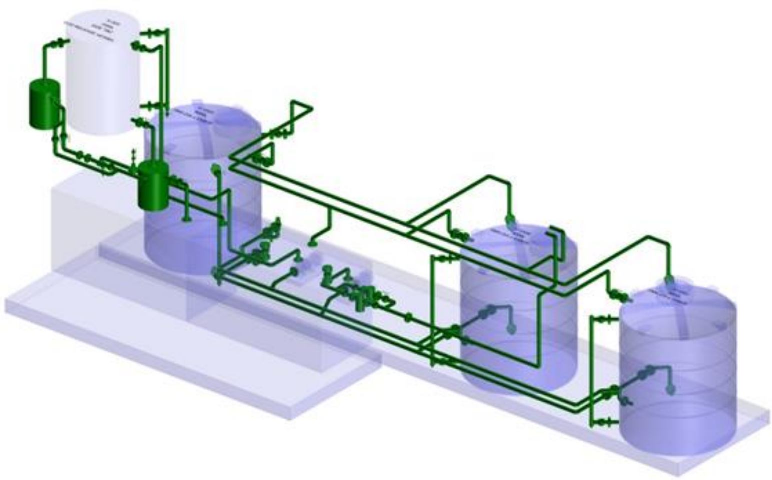


Figure 8: Tank and pipe layout post plant redesign

Civil/Structural Findings [4]: A modularised container-based structure has been proposed. Benefits include weather protection, transportability, integrated drainage and bunding, load distribution, and the ability to off-site much of the manufacturing effort/costs to a more controlled "shop" environment. Containers are required to be of a "high cube" type to give sufficient internal height to install the tanks (tanks in many cases have top hatches). The following number of containers is expected to be required: 1 x 40ft high-cube, 2 x 20ft high cube container. Note: this includes the switchgear / control room which is anticipated to be supplied as a complete package.

A grillage structure was initially proposed to "lift" the superstructure allowing integrated drainage and bunding (and negating the requirement for extensive civils site works). However, in order to minimise the cost of this element, it was proposed that the inside of the containers be "tanked" with integrated internal bunding (and raised doorways etc), to negate the requirement for this relatively expensive steelwork (**Figure 3**). The containers will be laid direct to ground assuming a suitable sub-base at the host site.

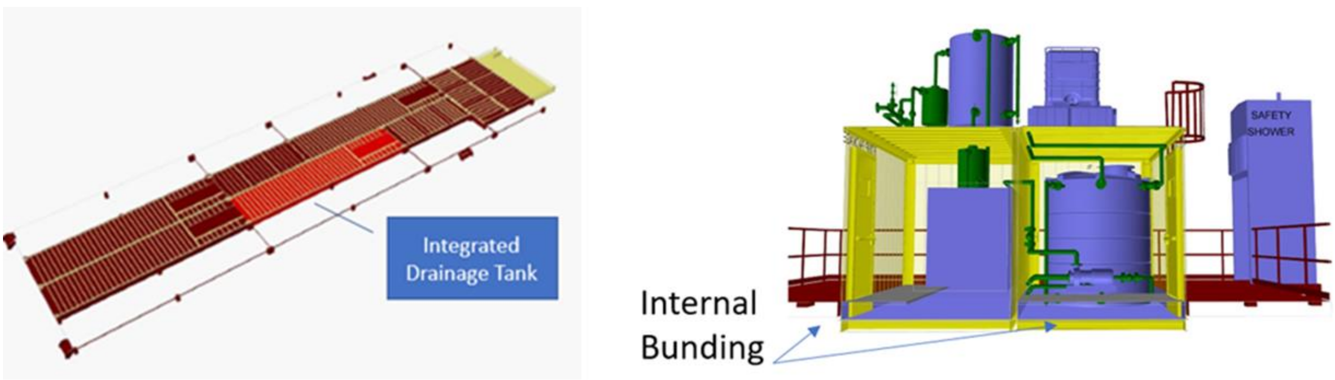


Figure 3: Initial and proposed support structure and liquid bunding

The MGA package has been extensively developed by CO2CirCulAir during Phase 1, and sizes/weights of the individual modules are now known. The MGA package has evolved from a series of towers to a single structure containing the individual modules which is required to rotate by up to 180 degrees to ensure optimum wind capture during the pilot plant operating phase (**Figure 4**). The rotating part of this structure is anticipated to be supported on some form of “slew ring” similar to a crane, with the supporting steelwork forming a bund suitable of capturing released liquids from the MGA in a loss of containment scenario.

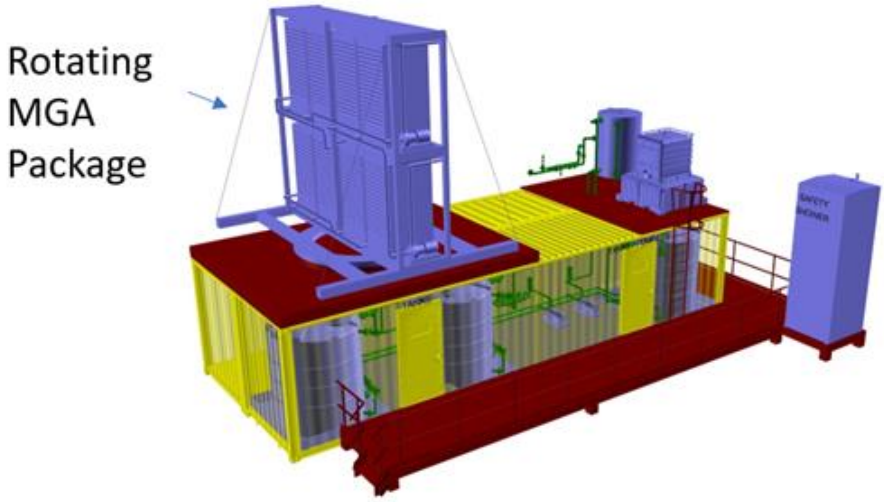


Figure 4: Single rotating tower MGA module

3.2 Detailed Design (DED)

A detailed engineering design (DED) is proposed at the start of Phase 2 should further grant funding be awarded. The purpose of this work is to

- Finalise construction estimate to a reasonable tolerance
- Complete detailed design sufficiently to allow material order placement, manufacturing and fabrication, and for construction
- Place orders for long lead procurement items
- Maximise ex-situ manufacturing, packaging and fit out to minimise in-situ site time (by design)
- Plan construction / hook up to minimise site time and in-situ construction effort and likelihood of successful construction outcomes (safety by design)
- Exercise sufficient planning and control to maintain budget / schedule to agreed tolerances while ensuring quality standards are preserved

Estimated time to deliver the DED is study is five months.

3.2.1 DED Activities

Detailed Design will further the maturity of the proposals sufficiently to allow procurement and construction of the pilot plant. This will be led by Optimus and is likely to involve third party services. This is detailed in the FEED Report and includes a project execution statement, as well as details on procurement and construction. Appended to the FEED Report are the detailed engineering CTRs (detailed to activity level), as well as a Level 2 Gantt chart format schedule.

3.2.2 Design Opportunities and Risks

A project risk register has been generated at FEED: Key opportunities and risks are summarised below:

- Market derived estimates may be less than current pricing which is in some cases based on norms. Compression – may not be required or may only require minimal compression. Increased industry knowledge generated within timeline for construction which assist with "lessons learned", and supplier confidence or number of suppliers willing to engage increases (i.e., more competitive pricing).
- Increased inflation versus recent historical trend, Brexit & COVID related supply chain issues. HAZOP workshop in DED identifies requirement for substantial additional process safety measures currently not allowed for in design. Items noted as cost options become requirements through detailed design. Market derived estimates may end up *higher* than the currently stated costs, which in some cases are based on norms. Lack of engineering / supplier experience in CO_2 applications. Assumptions on costs. Assumptions relating to provision of services by host site. Assumption of suitability of host site.

4. Life Cycle Assessment

4.1 Life Cycle Assessment (LCA)

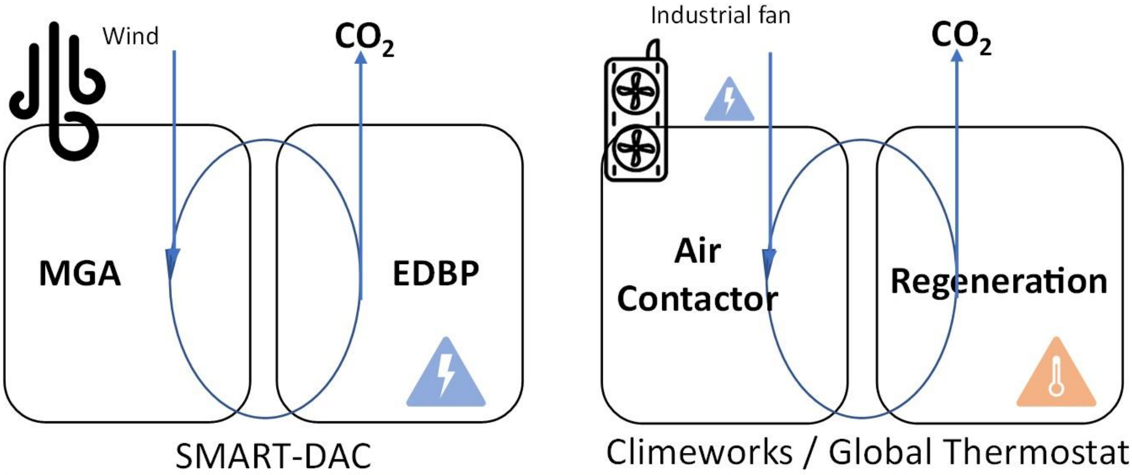
LCA is a tool used to evaluate the environmental impacts of a product or process across the supply chain throughout its lifetime (i.e., from raw materials to end use and disposal). A baseline must be estimated which is followed by a detailed sensitivity analysis to test the impact on the performance of the system due to variation in different parameters, such as carbon intensity (CI) of the energy used as well as the uncertainty associated with projected performance at different scales. The Life Cycle Assessment for the project plant was established by using SimaPro software which will be used to quantify environmental impacts. For this purpose, up to date libraries were acquired and reviewed such as Ecoinvent 3.7.1, Agri-footprint 5, Industry data 2.0 and Life Cycle Inventory Database.

To understand the performance of the SMART-DAC system, a summary of the key systems characteristics was compiled and compared with commercial DAC systems from literature (based on Carbon Engineering technology). This is shown in **Table** . The carbon footprint for the electrical energy source was based on Energy Statistics for Scotland Q1 2021 [5] while the carbon footprint for the heat energy source was based on UK Government GHG Conversion Factors for Company Reporting for 2020 [6]. The latter reflects the use of mainly natural gas to raise heat/steam.

Description	Units	Technology					
		Carbon Engineering (de Jonge 2018)			*SMART-DAC*		
		Baseline	Optimistic	Pessimistic	Baseline	Optimistic	Pessimistic
Lifetime	(yr)	20	40	10	20	40	10
Percentage year operations	(%)	85	-	-	85		
Mass transfer coefficient	(KL, mms^{-1})	1.5	2	0.8	1.5		
Air velocity	(v, $m\ s^{-1}$)	1.6	-	-	4.5	5.84	12
Sorbent flow	(f, $L\ m^{-2}\ s^{-1}$)	0.41	-	-	0.5		
Ambient CO2 concentrations	(ppm)	400	-	-	412.5	-	-
Membrane Gas Absorption efficiency	(%)	-	-	-	30	-	-
Packing efficiency	(ε, %)	80	-	-	-	-	-
Specific packing area	(SSA, $m^2\ m^{-3}$)	210	-	-	-	-	-
Air travel distance	(d, m)	8.6	-	-			
Fan efficiency	(η_{fan}, %)	56	-	-	-	-	-
Liquid pumps efficiency	(η_{pump}, %)	75	-	-	75	-	-
Relative humidity	(R_H, %)	65	82	38	78	82	40
Temperature	(T, °C)	13	9.4	21	8	15	-3
NAOH recycling efficiency	(%)	99.9	-	-	-	-	-
CaCO3 recycling efficiency	(%)	90.9	-	-	-	-	-
KOH recycling efficiency	(%)	-	-	-	99.9	-	-
Efficiency heat transfer	(%)	90	-	-			
Carbon footprint electrical energy source	(kg CO_2 eq. kWh^{-1})	0.08	0.02	0.36	0.08	0.02	0.36
Carbon footprint heat energy source	(kg CO_2 eq. kWh^{-1})	0.20			-	-	-

Table 1: Summary of system characteristics and comparison to commercial DAC systems based on information in public domain

An energy consumption comparison was also carried out between SMART-DAC and two commercial DAC systems based on literature data (**Figure 5**). A learning factor of 0.7 has been applied for SMART-DAC in order to compare with the commercial units due to 1 order of magnitude different scale. The comparison shows that energy requirements for SMART-DAC are on the whole lower due to being purely reliable on electricity for sorbent regeneration while the commercial technologies rely on heat.



Company	Low (kWh/ton CO_2)	High (kWh/ton CO_2)	Heat	Electricity
Climeworks	1700	2300	90%	10%
Global Thermostat	1330	1670	80%	20%
SMART-DAC	1260	1960	0%	100%

Figure 51: Energy consumption comparison between SMART-DAC and two commercial DAC systems based on publicly available information

Looking at the future, Scotland is aiming to achieve close to carbon free electricity production as possible. The carbon footprint from electricity for Scotland in 2017 was 22.7 gCO_2/kWh so an optimistic scenario for SMART-DAC would be a further carbon footprint reduction of over 50% using grid electricity in Scotland. Companies such as Climeworks are addressing the high carbon footprint by using renewable heat to power direct air capture, such as geo-thermal heat at their Orca plant in Iceland [7]. However, scale-up remains an issue for heat-based technologies which is avoided using purely electricity-based approaches, such as SMART-DAC.

5. Site Location

5.1 Site Location

The pilot plant will be located at the offices of B9 Energy Ltd in Northern Ireland. An arial view of the site can be seen in **Figure 6** taken from Google Earth.

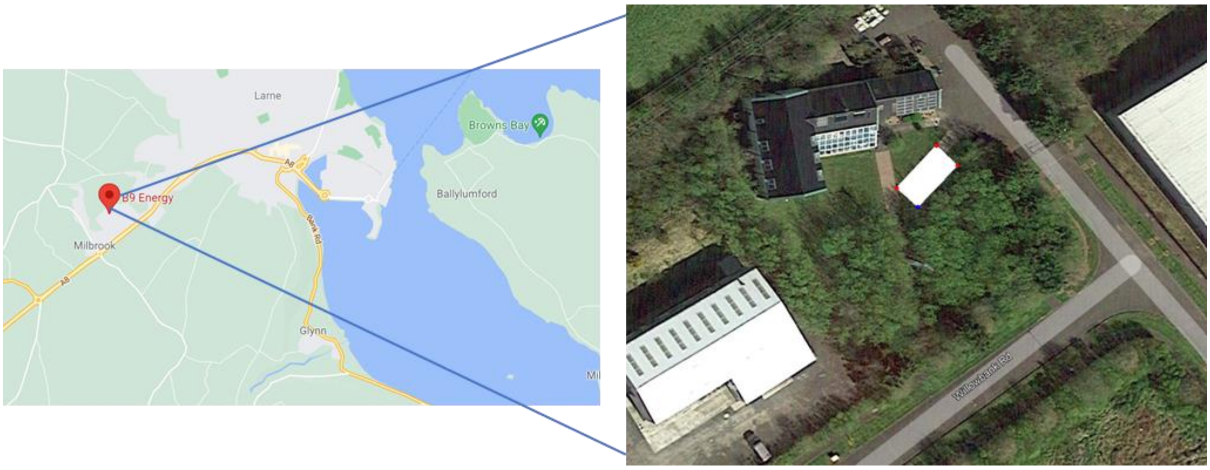


Figure 6: Proposed pilot plant site location, Larne Northern Ireland. Proposed location is marked by the white rectangle

Located to the north of Belfast and adjacent to the **Port of Larne** the site offers excellent transport and supply chain links to facilitate the operation of the pilot plant. The two international airports for Belfast are within ½hr travel time by car / taxi.

B9 Energy Ltd is made up of a group of companies covering B9 Solutions (Renewable Energy & Environmental Consultants), B9 Resource, B9 Energy Control, B9 Shipping and B9 Energy Storage. All the companies share the common goal of tackling climate change to smooth the transition to a low carbon and diverse economy through the development of renewable energy projects.

As environmental entrepreneurs B9 has been operating successfully for nearly 30 years in the emerging renewables sectors that have included onshore and offshore wind, landfill gas, commercial and industrial scale Anaerobic Digestion, compressed biomethane distribution by tube trailer, solar PV and longer duration energy storage in the form of Power-to-X. Over that time, they have built up an expertise and knowledge in developing novel and ground-breaking projects and engaging with key stakeholders to deliver projects from the small scale working with individuals to advising on national infrastructure programmes with long term strategic goals in wide ranging, long term developmental projects.

With their track record in the renewable arena, B9 will bring expertise currently not in the consortium providing knowledge and vision to develop this novel technology to the next stage.

Also, with established connections to Queens University in Belfast there is the potential to connect with ongoing research programmes in the production of synthetic fuels to further the commercial and business cases for the use of SMART-DAC as well as the potential to provide chemical engineering support in the operation and technical development of the pilot plant during phase 2.

5.2 Weather Profile Analysis

Located to the north of Belfast, the Port of Larne was one of the locations modelled by Heriot Watt during the wind profile analysis of various locations in the UK to identify the most appropriate locations.

Analysis shows that the area is very favourable for the location of SMART-DAC. The B9 office is located on an exposed site at 87m above sea level and so will see higher wind speeds as a result. The site already has a 6kw wind charger located on an 18m high tower, 12kW of roof mounted solar PV and a 3-phase grid connection with sufficient capacity to drive the SMART-DAC at any/all times of day.

The site is characterized by a prevailing wind direction from the south-west with an average yearly wind speed of 6.79ms^{-1}. Average yearly temperatures range from 3-17 deg C so protection against freezing should not be required. Located in west of the UK, average rainfall is slightly higher than locations studied on the east coast but remains comfortably within the operating envelop of SMART-DAC. **Figure 7** shows prevailing wind direction and speed for the Port of Larne while **Figure 8** shows average monthly wind speed, rainfall, and temperature.

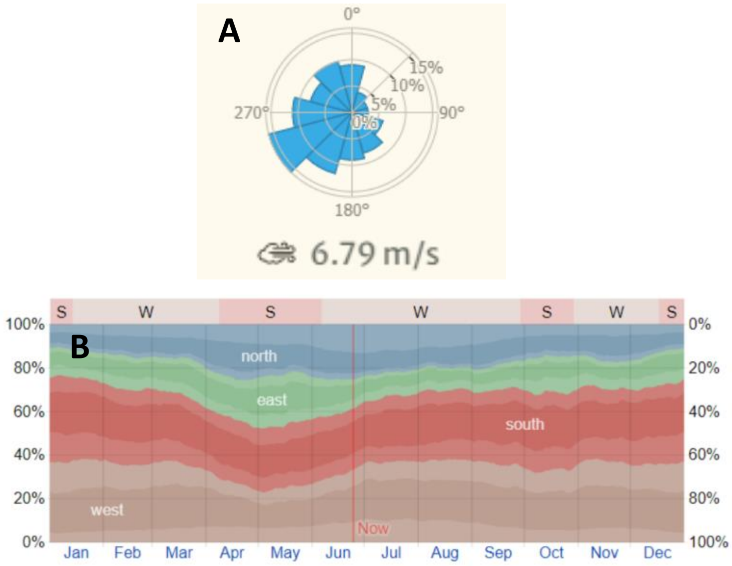


Figure 7: A) Rose diagram showing prevailing wind direction and speed, B) Average monthly wind direction for Port of Larne

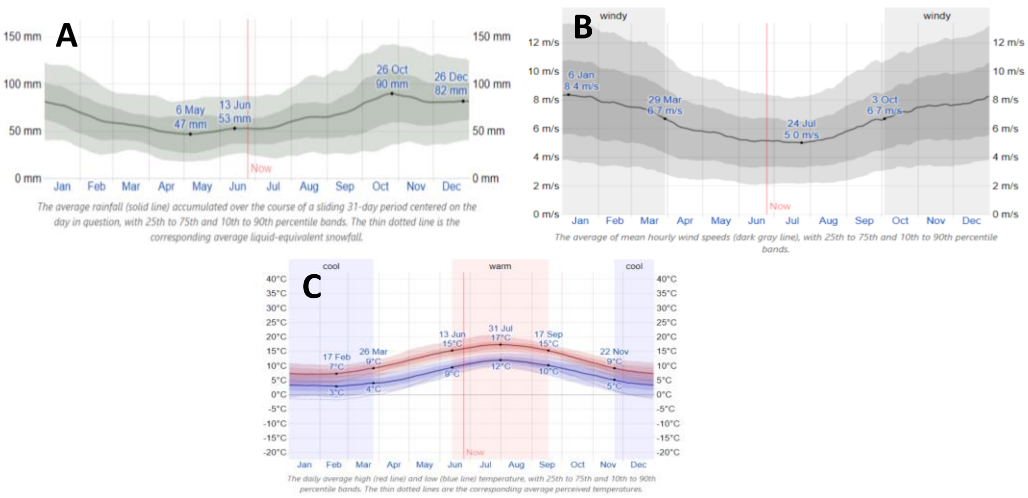


Figure 8: A) Average monthly rainfall, B) Average monthly wind speed, C) Average monthly temperatures for Port of Larne

5.3 Site Facilities

The site will purely act as a test site for the pilot plant and will not form part of an end-to-end process demonstration. However, the intention is to make use of the captured CO_2 in either the local food or agriculture industry to investigate the social impact, volume requirements and economics of the use of green CO_2 in these businesses. The food/drinks industry is a heavy user of CO_2 and direct air capture could play a key role in the decarbonization of the industry as CO_2 produced from technologies that digest waste cannot be used due to the source material and inferred purity of CO_2. For example, B9 was the developer of, and remains the operator of, the Granville Eco-Park AD project at Dungannon which produces up to 6 tonnes of high purity Green CO2 per day and has to vent it all to atmosphere because of perceptions around bio-security.

The Larne site is ideal to facilitate the pilot plant. There is a sufficiently large existing large grid connection to support the maintenance of hydrogen fuel cell powered buses. Workshop facilities will enable maintenance on site and the offices could provide meeting room space to host workshops to engage the local food and agriculture industries in the potential use of SMART-DAC to decarbonize their businesses.

The site has heavy vehicle and crane access and is a secure facility with a perimeter fence. Being an active office, the site is manned during the day so the plant could be monitored.

The B9 offices also act as a demonstration site for some of their renewable technology initiatives. Wind, solar, willow coppicing and biomass pellet boiler demonstration plant is co-located at the site so there is a constant footfall of experts working in the renewables arena visiting the site. The willow trees are coppiced every 3 years at present, but this can be done annually for the duration of the demonstration to reduce tree height and associated wind drag.

It is expected that there will be no issues with obtaining the required planning permission to locate the pilot plant at the chosen site having already located a wind turbine and biomass demonstration plant at the location. B9 have extensive knowledge and experience in working with the local authorities on permitting through their other initiatives.

Due consideration, permissions and provision will also be made for any emissions to air and discharge of material or fluids to water causes. The SMART-DAC plant has been designed to prevent any discharge to the environment so this will not require any major site preparations or permitting.

5.4 Pilot Plant Time and Cost Estimates

As described in Section 3.2 a detailed engineering design (DED) is proposed at the start of Phase 2 should further grant funding be awarded. The purpose of this work is to finalise design requirements to enable procurement, manufacture and fabrication of the pilot plant, to control schedule and budget, and ensure quality of standards and design. This is expected to take approximately 5 months.

The MGA and EDBP modules will be supplied ready-made to the requirements determined during Phase 1. The lead time is approximately 8 months for the modules by which time the DED will be complete, and procurement and manufacture of the pilot plant started.

The pilot plant is expected to be complete and on site within the first 12 months of the project. This builds in sufficient contingency for extension of lead times for materials in the construction of the pilot plant to enable operation for at least one year.

6. Business Plan

The captured CO_2 from DAC is a valuable commodity that, as well as being sequestrated, can be used by emerging carbon utilisation technologies. This is driving considerable downstream demand from environmentally conscious consumers which in turn is attracting investments from ventures, corporations, and governments through the increase in start-up and corporate activity.

This is one of the long-term visions of CO2CirculAir and SMART-DAC to use the captured CO_2 to generate a non-fossil based green carbon source to assist in decarbonising industries like the chemical industry, agriculture, and the food and drink industries.

To enable this vision CO2CirculAir have signed a Memorandum of Understanding (MoU) with B9 Energy to investigate ways in which the green CO_2 produced by SMART-DAC can be combined with the renewable projects that B9 already have under development.

One of these projects is a partnership to manufacture and distribute electrolysers that will contribute towards the green hydrogen economy in Northern Ireland supporting efforts to decarbonise transport and ultimately decarbonise heating and powering the country. Using the electrolyser B9 see an opportunity to combine the streams of green hydrogen and green CO_2 to produce green methanol.

B9 have proposed using one of the 5MW electrolyser plants that are being installed in Northern Ireland. The suggested location at the moment is Ballymena where a hydrogen hub is being planned. To produce sufficient CO_2 SMART-DAC would require scaling up by up to a factor of 30 to capture 3000 tonnes CO_2 per annum.

This is a considerable scale up from the pilot plant and will require financial investment from external parties. With B9 embedded in the renewables economy of Northern Ireland and with hosting the pilot plant at their offices, CO2CirculAir will work with B9 to lobby and attract investment during Phase 2 to secure funding for the next stage on the road to commercialisation of SMART-DAC.

The pilot-plant has been designed to perform testing in an operational environment on various aspects of the technology in development. The design for the pilot-plant therefore includes additional instrumentation, valves and piping to enable the gathering of information that would not be part of the design of a commercial plant.

The design of the pilot plant is based on various assumption derived from previous and documented work on direct air capture of CO_2 and on regenerating the absorbent. By testing in the pilot plant both the absorption step and the regeneration of the absorbent will be subject to improvement. Optimisation of the MGA and regeneration process and lessons learned during a Phase 2 will be critical to enable scaling up to a larger plant.

It is expected that operation of the pilot plant will lead to greater understanding of the absorption process and how optimal absorption at times of high and low wind velocities while protecting the absorption unit from high winds. Better (thinner) membranes can improve the mass transfer rate for absorption of the CO_2, resulting in a reduction of the number of absorption modules and therefore a smaller footprint on scaling up to capture larger volumes of CO_2.

Process optimisation of the regeneration step in the EDBP stacks in terms of operation (one step or two-step, or to run lean when unit cost of electricity is high and increase production when the unit price is low) and the composition of the feed into the unit will lead to higher capacities and lower energy consumption within the unit.

On further scaling up it is expected that the CAPEX for the plant will strongly decrease because of lower production cost of the absorption modules due to automation of the production and lower material costs at higher volumes.

Commercialisation and scaling up of the technology for the manufacture of the large numbers of modules required will result in a reduction of cost per module. Scaling up by numbers instead of by size (more modules, not larger) will not require a similar increase in the amount of instrumentation or manpower to operate the plant. Based on experience with scaling up of membranes plants, a large-scale plant in 2030 will therefore have proportionally lower investment and operational costs per tonne CO_2 removed due to the economies of scale. we therefore expect a strong decrease of costs per unit of product.

7. Conclusions & recommendations

Funding through the BEIS GGR Innovation Programme has supported development of the SMART-DAC technology from the formulation of technical concept and feasibility to component validation in laboratory and simulated environments, enabling a complete Front End Engineering Design (FEED) for a pilot plant.

Phase 1 funding has advanced technology readiness levels (TRL) in two key areas of SMART-DAC, membrane gas absorption from TRL 4 to TRL 5 and the regeneration process from TRL 4 close to TRL 6.

Membrane Gas Absorption Module – testing has demonstrated the potential to apply hollow fibre membranes in the modules, allowing for a larger surface area to be installed in the membrane module without reducing the 'free' space within the module which is critical to allow for air flow through the module and therefore efficiency of CO_2 capture. Originally the volume of the membranes has decreased with more than 20%. This is an important breakthrough as it means that the surface area for mass transfer of CO_2 to absorbent in the module can be increased by a factor of 2 or even 4 improving the effectiveness of the MGA step even at low wind velocities.

Regeneration Module – Two key advances were made in this area of the pilot plant during the project. Firstly, the realisation that using $KHCO_3$ leads to approx. half the energy consumption than before. Secondly, the change from Electro-dialysis (ED) to Electro-dialysis Bi-polar membranes (EDBP) has led to significant energy consumption savings by not having to separate the CO_2 from O_2.

On top of the reduction in energy moving to an EDBP process gives greater flexibility in the operation of the pilot plant. It creates the potential to cease the absorption process at a higher pH leaving a mixture of carbonate and bicarbonate in the absorbent with a lower residence time in the absorber. If low-cost electricity is available this can reduce CAPEX as the plant can be designed with fewer absorption modules.

A FEED study has added significant value to the project by maturing the concept defined in the Basis of Design (BoD). Through 3D modelling it became clear that the early design iterations were too large and complex and would therefore be too costly. This drove a value engineering exercise to reduce complexity in the system, which was successfully completed resulting in an optimised plant design with a significantly reduced footprint while not compromising capture capacity or efficiency.

Recommendations for the next stage of development is a detailed design study to further the maturity of the proposed design parameters sufficiently to allow procurement and construction of the pilot plant.

Although tested and ready for application in the pilot plant, continued testing and optimisation of the MGA and EDBP modules will continue in parallel to the operation of the pilot plant. Improving the mass transfer rate within the MGA process will be one area of focus.

Finally, an ideal test site and partner to operate and develop SMART-DAC has been secured. B9 Energy have been operating successfully for nearly 30 years in the emerging renewables sector. Over that time, they have built up an expertise and knowledge in developing novel and ground-breaking projects and engaging with key stakeholders to deliver projects from the small scale working with individuals to advising on national infrastructure programmes with long term strategic goals in wide ranging, long term developmental projects. With their track record in the renewable arena, B9 will bring expertise currently not in the consortium providing knowledge and vision to develop this novel technology to the next stage.

B9 will host the pilot plant at their offices in Larne, Northern Ireland. Analysis shows that the area is a very favourable location for SMART-DAC. The B9 office is located on an exposed site at 87m above sea level and so will see higher wind speeds as a result. The site already has a 6kW wind charger located on an 18m high tower, 12kW of roof mounted solar PV and a 3-phase grid connection with sufficient capacity to drive the SMART-DAC at any/all times of day. Workshop facilities will enable maintenance on site and the offices provide meeting room space to host meetings or workshops to engage potential users/industries of green CO2 industries in the use of SMART-DAC to decarbonize their businesses.

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