GGR Innovation Programme: Phase 1

A low-energy approach to remove multiple greenhouse gases

(Sch202036)

Phase 1 Public Facing Report

31/12/2021

Table of Content

1. A detailed description of the science and engineering.

1.1 An overview of the proposed GGR solution.

The major barrier for removal of greenhouse gases (GHGs) is its high energy penalty. We are determined to design a low-energy and versatile approach to capture CO_2 and destruct non-CO_2 greenhouse gases (e.g. CH_4, N_2O, etc.) simultaneously at large scale and driven only by solar energy, as shown in Fig 1.

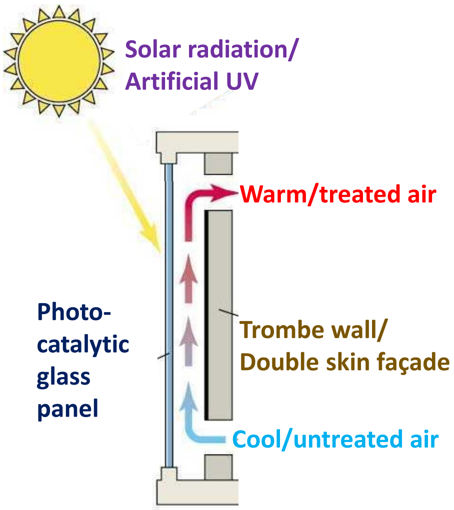

Figure 1 Sketch of a solar updraft Trambe wall.

The first step and one of the key components of this approach is solar updraft. The updraft is driven by solar energy utilising a design adapted from Trambe wall, as shown in Fig.1. We named the design as solar updraft Trambe wall (SUTW). With the presence of desired airflow, CO_2 capture can be realised by integrating CO_2 capture modules, removal of CH_4 and N_2O can be achieved by applying photocatalytic materials, also as indicated in Fig.1.

Activated carbon is the starting point as adsorbent in the CO_2 capture modules. Surface modified activated carbon provides enhanced adsorption capacity will be a more promising candidate.

CH_4 and N_2O are eliminated by photocatalysis transforming them into benign atmospheric gases, all of which are much less active GHGs than their precursors. (i.e. $CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$, $2N_2O \rightarrow 2N_2 + O_2$). Commercially available TiO_2 is the starting point as photocatalyst, and some advanced photocatalysts are expected to further enhance the removal efficiency.

Features of this integrated technology are included but are not limited to the following:

Low energy and low cost. The process is driven only by solar energy. These installations have virtually no moving parts and should therefore have a working life well in excess of 30 years, sufficient to secure their economic justification.

Versatile formats and wide applications. There are various derivations of solar updraft devices operating on the same principle. This project looks in particular to adapt Trombe wall to livestock buildings. Outcomes of this project will provide the design methodology and operation parameters for the development of all the other formats. This enables wide applications of the technology.

Measureable process. The monitoring, reporting and verification (MRV) of GGR systems is hampered by the complexity of measuring trace concentrations in the open environment. Measurable airflow induced by SUTW provides a solution. This allows in-situ monitoring and quantitative evaluation.

Easy up scaling. Up scaling can be achieved by duplication of a single unit, i.e. if a $1m^2$ device is built and verified, multiple duplicates will be the solution for up scaling to climate relevant scale.

1.2 Progress throughout Phase 1.

We have set out ambitious objectives and measurable deliverables for the entire programme spanning both Phase 1 and Phase 2. The most important objective for Phase 1 is to build up a testing rig according to initial design to provide data for a detailed engineering design for Phase 2.

Achievements in Phase 1 are summarised in Table 1, which shows that successful outcomes achieved will lead to a pilot project to be implemented in Phase 2. Detailed results from Phase 1 are discussed in Section 2.

Table 1 Summary of outcomes delivered in Phase 1

Technical components	At the beginning of Phase 1	At the end of Phase 1
Solar updraft	This project team had calculated that a 1 m^2 SUTW could draw 100 m^3 air per hour at solar radiation of 100 W/m^2, which was validated using literature data.	It is experimentally demonstrated that the 1 m^2 SUTW is able to generate an average of 100 m^3/h airflow at the solar radiation above 100 W/m^2, which is not a high threshold and achievable on 291 days in 2020 in Edinburgh.
CO_2 capture	Efficient adsorbents are available according to small scale lab tests.	CO_2 capture module designed and built based on activated carbon.
Photocatalysis	Photocatalytic removal of CH_4 had been proven to be very effective at lab scale and in batch-wise set up.	Photocatalytic removal of CH_4 has been tested in continuous flow reactor and at ambient conditions. Removal rate of 2 ppm methane can be as high as 98% at a residence time from few seconds to tens of seconds.
Integrated system	Initial design as shown in Fig. 1.	An integrated testing rig is designed and built, which is ready for pilot tests in Phase 2.

1.3 All chemical and physical processes used, materials and substances required.

The removal of methane is a chemical process of oxidation, driven by solar photocatalysis on a catalyst surface, i.e. $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$. The removal of CO_2 is a physical process of adsorption, i.e. CO_2 adsorbed onto active carbon. Materials required are commercially available glass panels, photocatalysts (e.g. TiO_2, ZnO) and adsorbents (e.g. activated carbon). These materials have either long lifetime or the ability to be recycled, regenerated and reused.

1.4 All energy and fuel requirements for each stage or process.

The process is driven by solar energy and does not need any other energy or fuel.

1.5 A description of its environmental impacts.

It is worth noting that the adsorption and oxidation processes are not limited to remove CO_2 and methane, they are capable of removing other undesirable species, like N_2O another potent GHG, ammonia from livestock building ventilations and air pollutions. Removal of these species will be conducive to GGR, biodiversity and air quality.

2. A detailed engineering design for a pilot project

2.1 The credibility of the design and its costs.

2.1.1 Solar updraft capacity

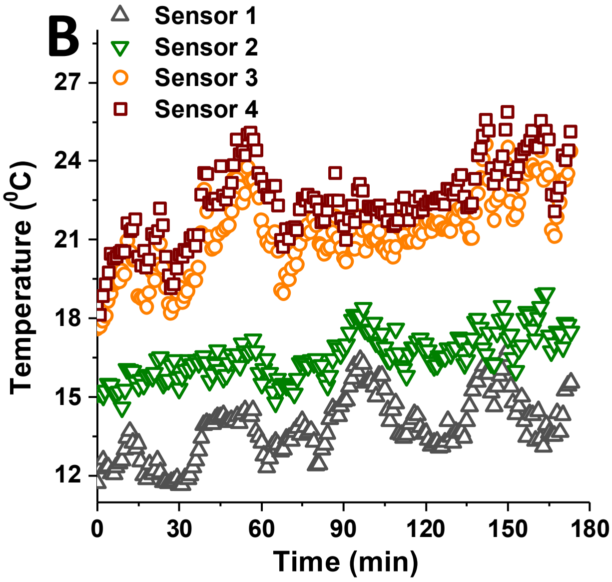

Fig 2. Temperature in the unit.

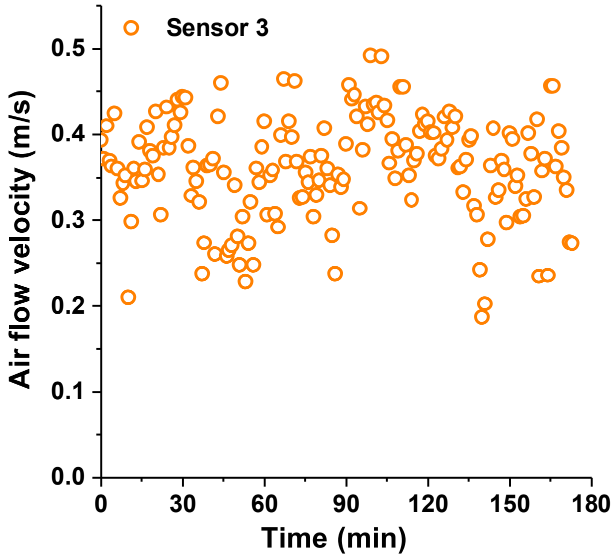

Fig 3. Air velocity in the unit

Fig 2 indicates the temperature distribution in the gas processing unit under sunshine. Four different sensors are allocated in the unit to measure the temperature inside. The inlet air temperature was around 14.0 ^oC at the time of experiment. Solar radiation was 100 W/m^2 in average. The average temperature readings from sensors 1, 2, 3 and 4 during the three hours measurement were 14.6 ^oC, 17.6 ^oC, 21.2 ^oC and 22.0 ^oC, respectively. The temperature increase due to solar radiation in the unit is 7.4 ^oC, agreed well with our modelling data of ~ 7 ^oC.

Fig 3 demonstrates the air velocity in the gas processing unit measured by sensor 3. The air velocity data are in the range of 0.2 – 0.5 m/s with an average of 0.35 m/s, which again matched well with modelling data of 0.4 m/s.

Table 2 Summary of data after multiple tests under different weather conditions

Date of experiment		06/10/21	01/10/21	25/09/21	25/08/21	23/08/21
Weather conditions	Solar, W/m^2	102	192	397	583	612
	Wind, m/s	0.02	0.73	0.03	1.22	1.36
	Temp., ^oC	14.0	21.1	24.1	24.1	22.1
Temperature rise, ΔT, ^oC		7.4	5.8	6.4	6.8	8.2
Airflow velocity generated, m/s		0.35	0.39	0.42	0.45	0.41
Volume of airflow, m^3/h		85.1	94.8	102	109	99.6

Table 2 confirms that the solar updraft has good reproducibility under different weather conditions (i.e. a wide range of solar radiation 102 – 612 W/m^2, ambient temperature 14 – 24 ^oC and wind speed 0.02 – 1.22 m/s.).

Overall, outdoor tests on the rig has confirmed the air volume that this solar updraft device can process. In the original proposal, we estimated that the rig could draw 100 m^3/h of air based on our initial modelling, and the above experimental data confirmed that an average flow rate of 100 m^3/h has been achieved by this rig.

2.1.2 CO_2 adsorption

For CO_2 adsorption, adsorbent materials should be able to provide good adsorption capacity but not induce significant pressure drop under an optimum packing. Large size activated carbon particles (~ 2.3 mm) can be a good candidate, which shows nearly zero pressure drop and 1.93 mmol/g adsorption capacity (as good as much smaller particles). Good recyclability is also observed. The adsorption capacity can be further improved by surface modification with Pentaethylenehexamine (PEHA).

2.1.3 Photocatalysis

We tested photocatalysis with ~ 2ppm of CH_4 in the atmosphere directly. Photocatalytic materials used are commercial P25 TiO_2 photocatalyst and more advanced photocatalysts synthesised in our lab, illuminated by 20 W/m^2 UV light (similar to UV intensity in solar radiation). Under an airflow of 0.4 L/min, which is equivalent to a residence time of 12 seconds, the removal rates of CH_4 for the three photocatalysts (i.e. TiO_2, modified ZnO and modified TiO_2) is 46%, 79% and 78%, respectively as shown in Fig 4.

Longer residence time gave higher removal rate, which can be as high as 98%. Removal rate decreases when residence time is shorter. The constructed rig can provide 5 seconds of residence time when the solar updraft airflow rate is 100 m^3/h. Fig 4 confirms that, at such a short residence time, the removal rate can reach 60% when the more efficient photocatalysts are applied.

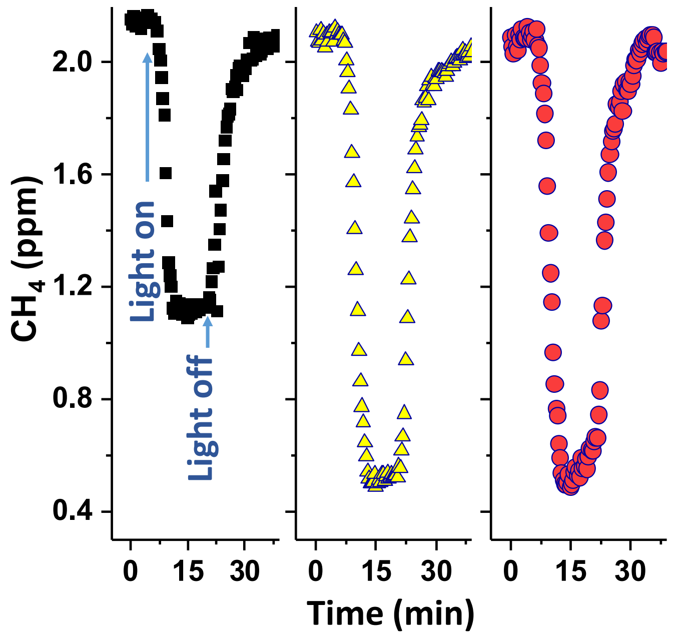

Fig 4. Photocatalytic removal of CH_4 in the continuous flow reaction system with three different photocatalysts (TiO_2, modified TiO_2 and modified ZnO, respectively)

We need to emphasise that these were our initial tests without much optimisation and the CH_4 concentration used is only 2 ppm which is much lower than that in a dairy farm house (typically, 40 – 100 ppm). The experimental results can be improved significantly by optimising the photocatalyst loading, using higher CH_4 concentration, etc.

In the Phase 2 pilot project, we will test and optimise the photocatalytic process on the site of Langhill farm under operational conditions.

2.1.4 Summary of calculations on removal costs to date

The original calculations on removal costs are summarised below.

An assessment of removal cost in 2030 in £/tCO_2e focusing on CAPEX and OPEX - Capex per tonne CO_2e is estimated to be £56. Opex per tonne CO_2e is estimated to be £76.

2.2 Relevant data informing the design.

Table 3 Summary of data of single unit and 100 t CO_2e pilot

	Capacity of airflow, m^3/h	Access to GHGs			Annual GGR capacity at a removal rate of 50 – 60%, (tonne CO_2e)
		CO_2	CH_4	Total, CO_2e	
Single unit	100	200 g/h	4 g/h	312 g/h	0.25 – 0.3
360 m^2 pilot	36000	72 kg/h	1.44 kg/h	112 kg/h	90 - 108

Airflow of 100 m^3/h of a single unit is taken from experimental measurement. Access to GHGs is calculated using GHGs concentrations of 1000 ppm CO_2 and 60 ppm CH_4 as measured on the farm. 100-year time horizon global warming potential (GWP) of CH_4 relative to CO_2 is 25, according to the IPCC Fifth Assessment Report, 2014 (AR5). The annual sunshine hours of 1600, a statistic data, is used to calculation Annual GGR capacity.

2.3 Cost savings compared with exclusive development contracts.

As an innovative and unique technology in its R&D process, it is difficult to find a reference in the open market to compare with or estimate the cost for an exclusive development contract. The nature of an SBRI contract is cost effective via the risk-benefit sharing IPR conditions.

3. A detailed and costed project plan for pilot.

3.1 The site location.

The Phase 2 pilot will be carried out on Langhill Farm, Roslin, Midlothian, as shown in Fig 5.

Fig 5. A set of images taken at the Langhill Farm

3.2 Project plan for Phase 2.

The Phase 2 pilot will be delivered by three work packages.

WP1 – Technical work. The single unit (which has 250 kg CO_2e/year GGR capacity) needs to be tested on the pilot site (i.e. under operational conditions) before being duplicated to construct the full pilot scale (i.e. 100 t CO_2e/year). The tests will be carried out on the pilot site as discussed in the above Section 3.1.

WP2 - Construction. Construction of the full pilot scale will begin in the fourth quarter of the first year. It will start with restructuring of the existing building structure, which will be followed by installation of single units. Full pilot scale will be constructed in two stages – 1) several units as a starting point and 2) the rest of all units.

WP3 - Evaluation & Optimisation. Monitoring, evaluation and maintenance will start immediately after the pilot commissioning. WP3 also includes important tasks of optimisation, wider applications and animal welfare, which can start in parallel with WP2.

3.3 How the GGR solution interacts with current or proposed use of the site or activities undertaken at it.

We have some insight into the implications for farm animal health and welfare of a solar updraft GGR device situated in the housing.

The ventilation of most buildings that house adult dairy and beef cattle relies on the stack effect. The use of a solar updraft GGR device is likely to supplement this effect.

As a consequence, the effects on the housing environment and the health and welfare of winter housed ruminants is likely to be minimal, but could be affected by the surface area of the solar updraft GGR device. For summer housed dairy cows then a solar updraft GGR device may have a beneficial effect on air flow, as the stack effect is less efficient at circulating air at higher environmental temperatures. As a consequence animal health and welfare may be improved.

The effect of a solar updraft GGR device on non-ruminant animals such as weaner pigs and broiler chickens that are housed in temperature-controlled, artificially ventilated buildings is more difficult to predict. Here, airflow for ventilation and to reduce the risk of respiratory disease has to be balanced with maintaining a suitable housing temperature. Normally the ventilation in these buildings is controlled via the use of fans, and airflow has to be constant and drafts avoided. However, very little research has been conducted on the effects of integrating solar updraft GGR devices on the airflow and subsequent health and welfare of housed farm animals, and this should form an important part of future studies.

4 A programme and business plan beyond the end of the pilot phase.

Our Business Plan is set within the parameters defined in the BEIS funding terms and conditions.

The University of Edinburgh will own all Arising Intellectual Property (AIP). On this basis UoE will be responsible for ensuring that opportunities to protect and commercialise the AIP is processed and validated by Edinburgh Innovations Ltd (EI), the University of Edinburgh's commercialisation service.

EI have a dedicated resource of business development professionals and technology transfer experts to assist UoE staff and researchers identify the route to commercialisation.

Route to commercialisation

It is the ambition of the University to commercialise the AIP within 3 years of the project. The most effective and efficient route to market will be via Licensing. Licensing enables technologies to be taken to market with the expertise and resources of an already established company and still provides revenue for the inventor. Furthermore licensing can increase adoption of new technologies. When a technology fits a company's product range its existing client base can be accessed immediately and good links with customers are established. In order to commence this process we need to define how to protect the Intellectual Property developed.

EI has established a robust invention disclosure process to guide clients through the various stages of exploiting the AIP from research, from evaluation of a new discovery through to negotiating a licence agreement.

AIP evaluation

EI will undertake preliminary due diligence work all inventors to:

1. Establish ownership and commercialisation rights to the invention
2. Evaluate the potential to protect idea, discovery or invention
3. Carry out an initial search and review of patents in the field
4. Carry out a preliminary review of the relevant market(s) to identify the product and market opportunity, assessing market need and the competition
5. Construct a proof of concept strategy to demonstrate the performance and commercial potential of the technology
6. Identify potential competitors, collaborative partners or licensees from industry
7. Determine the most effective commercialisation strategy for a new technology

The Technology Transfer Manager will prepare and present their findings to EI's Intellectual Property Approval Meeting (IPAM), who will make a final decision whether to fund patent protection as part of the commercialisation of a particular idea, discovery or invention. The processes of disclosure, patent filing, patent prosecution, IP development, and successful commercial exploitation, all require close cooperation and input from the inventors.

The Licensing process

EI will manage the complete licensing process, whilst working closely with academic researchers. For the Licencing processes the following five key steps form the basis of our process;

1. Carry out thorough market research to identify suitable licensee companies.
2. Develop appropriate marketing materials for approaching potential licensees
3. Undertake a process of due diligence on potential licensee companies to demonstrate that it has the necessary resources and expertise to fully exploit the technology.
4. Negotiate fair and reasonable commercial terms and conditions in any licence agreements to license the technology to an interested company.
5. Provide post-licence administration including revenue distribution.

Business model

We have commenced early engagement with Carbon Clean Solutions Ltd. Carbon Clean are a UK based company with offices in the North America, Europe and Asia, specialising in modular carbon captures and storages devices for industrial use. Prof Xianfeng Fan has a long standing relationship with Carbon

Clean. The integration of solar updraft and GGR technology would provide Carbon Clean with and additional service offering that does not presently existing in their portfolio.

Carbon Clean have an existing business model that allows for retrofitting of CCS devices to large scale buildings. Expansion into the agricultural market would represent a diversification of the existing company portfolio yet complementary to their existing business model.

We will also seek to identify other parties in order to maximise the commercial potentials of the GGR device. The University has strong link with Scotland Rural College (SRUC), Roslin Institute and Scottish Food & Drink, whereby can engage with leading members of the agriculture sector across both industry and government.

Edinburgh Innovations will provide relevant marketing support for all technologies born our collaborative research. The EI Technology web page will provide the initial landing page for the purpose of promoting the technology. The landing page will include provide interested partnering with an overview of the technology, IP status, commercial offering and describe the opportunity the technology can provide. Our team of Technology Transfer experts will engage with all interested parties in order to ensure we maximise each opportunity and ensure professional technology transfer management.

For the purpose of negotiation with potential licensees we would need to advise on the existing BEIS terms whereby, BEIS are granted royalty-free, non-exclusive licence to use the Arising IP for any purpose. Most likely we will need to define a field of operation, i.e. In the field of livestock management and agricultural buildings, in order to minimise barriers to entry.