Direct Air Capture and Greenhouse Gas Removal Programme

GreenShed
Phase 1 - Final report

Lead organisation:	SAC Commercial
Project partners:	University of Strathclyde
	Agri-EPI Centre
	No Pollution Industrial Systems
Project Reference:	SAC202091

Contents

Introduction – Phase 1

Competition objective

The aim of the Direct Air Capture and Greenhouse Gas Removal (GGR) Innovation Programme is to identify approaches to removing carbon dioxide (CO_2) or other Greenhouse Gases (GHGs) from the atmosphere and drive innovation in these. The objective of this Programme is to identify one or more ways in which to achieve removals at the $MtCO_2e$ scale or greater, at a cost of <£200 per tonne CO_2e removed and undertake innovation activities that help to achieve this outcome.

Deliverables

Phase 1 projects were required to deliver a design study containing:

- A detailed description of the science and engineering underpinning the proposed GGR solution.
- A detailed engineering design for a pilot project that could be taken forward between 2022 and 2025.
- A detailed and costed project plan setting out how and where the GGR solution will be piloted if selected for funding.
- A programme and business plan detailing how the GGR solution could continue to be developed beyond the end of the pilot phase.

GreenShed scope

The ambition of GreenShed is to reduce the environmental impact of beef production by integrating a number of independently innovative technologies, in a multi-disciplinary approach. GreenShed will develop an integrated low-carbon, circular, cattle and vertical farming system, which captures methane (CH_4) from housed cattle and utilises its combustion outputs (heat, power, CO_2) to yield low-carbon produce (meat, vegetables/fruits) and optimise resource efficiency. We propose to combine five core proven technologies to create the "GreenShed system".

1. High-volume air recirculation/conditioning/sterilisation system, aligned with a novel engineered solution to capture CH_4 from cattle sheds.
2. Micro-anaerobic digester (AD) with built in feedstock pre-treatment to improve efficiency. This produces combustible biogas from manure and waste feed.
3. Novel ultra-lean combined heat and power (CHP) engine.
4. Plasma reactor to produce nitrogen-enriched fertiliser from AD waste and atmospheric nitrogen.
5. Vertical farming to utilise low-cost, low-carbon AD/nitrogen fixing outputs and return oxygen-rich air to the shed.

Phase 1 was focussed on the design phase. The objectives included:

- Provision of historical data and new animal-based emissions data to identify optimum airflow requirements within the GreenShed design.
- Mathematical modelling of the GreenShed concept to generate design data (e.g., heating and cooling loads), test building performance against agreed operating

scenarios and provide design information for development of the physical prototype (including ventilation flow rates, heating, cooling and air conditioning (HVAC) component capacities and system operating strategies).
- Customer and stakeholder research with key players across the supply chain to obtain acceptability feedback and understand key commercial, ethical, and operational considerations.
- Refined commercialisation plans based on market research and competitor analysis.

Summary of achievements

A mathematical model of the GreenShed concept has been established and populated with validated data from SRUC experiments or data from the literature. The model has been simulated using four different UK climates, different building materials and different cattle gains levels to establish the operating requirements for the HVAC system. The model has been adapted to investigate different approaches to meeting the cooling energy demand and offsetting primary energy usage. Duties for primary environmental system components have been derived from the modelling results. Simulation of the model has indicated that:

1. The environmental conditions for the housed cattle are acceptable.
2. Resulting cooling and heating loads are high (e.g., 175 kW cooling load), but alternative HVAC configurations that make use of waste heat can dramatically reduce primary energy requirements.
3. A rooftop PV installation can offset the primary energy demand from the cooling system.

When the different building model results were analysed for optimum financial and carbon returns, we produced a revised design which has sufficient financial returns to attract farmers and maximises carbon removals and reduction to give full weight to the marketing potential of low carbon beef.

Customer and stakeholder research has been conducted through qualitative interviews with representatives across the beef value chain, including farmers, processors, retailers and wider industry stakeholders. This has attracted excellent engagement and a high level of interest in GreenShed. Analysis of interviewee feedback and outcomes from this report underpin the commercialisation plans and dissemination activities envisioned for Phase 2. Respondents recognised the need for technology to address the GHG impact of beef production, and the potential for GreenShed to provide a solution for sustainable beef. The key opportunity identified for GreenShed was for specialist beef finishing units, where cattle are housed and fed intensively for the final stage of the production cycle. Two areas emerged which warrant further research, to be conducted in Phase 2: consumer perceptions of the system and return on investment for farmers.

Phase 2 - Pilot plant

Technical requirements

Science and engineering: system components and processes

Physically this process is carried out, optimised and controlled by integrating discrete off-the-shelf components.

Methane capture: Galebreaker / No Pollution (GB / NP)

- Standard livestock sheds will be retrofitted with a removable membrane system – this will not seal the shed. Combined with a small negative air pressure within the shed, this will maximise the capture of CH_4.
- An Air Handling Unit (AHU) will be used to recirculate most of the air and "condition" it to maintain temperature and humidity for the animals.
- The environmental conditions in the shed will be closely monitored for all parameters relating to welfare and health – temperature, humidity and CO_2 concentrations, and the AHU will automatically maintain them within defined safe limits (15°C, 80%RH and 1,500ppm respectively). The modelling carried out by the University of Strathclyde (UoS) (detailed later in the report) has gauged the various loads, duty and flow rates required of the components of the AHU and ancillary fans to easily maintain suitable conditions.
- A smaller amount of air is removed from the shed with exhaust fans. This will create a slight negative pressure, and fresh air will infiltrate through the inevitable small gaps in the building envelope. This air is the fresh air required by the cattle.
- In addition, back-up monitoring systems and failsafe's will be installed, such as passive pressure balanced vents which will automatically open to allow air in if sufficient air isn't entering through the gaps in the building envelope. This will include an emergency curtain release mechanism to lower/raise the enclosing membrane to allow natural airflow in the shed.

Power generation / methane reduction: Organic Power Ireland (OPI)

- The main energy for the system is produced by a low carbon biogas CHP engine, using biogas made in a micro AD plant. The AD plant utilises the used straw bedding and dung as feedstock.
- A small amount of air is sucked out of the shed.
- The suction of the air out of the shed will create a slight negative pressure, and fresh air will infiltrate through the inevitable small gaps in the building envelope. This air is the fresh air required by the cows.

System maximisation: N2 Applied / Saturn Bioponics (N2 / SB)

- Beyond the core components above, we have two key technologies, which modelling has shown, further enhance the carbon savings of the system and increase the economics:

- A plasma reactor to fix volatile nitrogen in the digestate, and a natural light vertical farming unit.
- The plasma reactor splits nitrogen and oxygen from the air into atoms, which in turn form nitrogen oxides. These react with the ammonium in the digestate to form stable nitrates, which stops the loss of nitrogen as ammonia gas and effectively doubles it by extracting and fixing nitrogen from the air.
- The vertical farming unit is based in a polytunnel, supplied fertiliser from the plasma reactor and heat from the CHP engine, to produce high value salad and herb crops.

Energy and fuel requirements

Modelling carried during Phase 1, has calculated the major loads and energy requirements for heating, cooling and dehumidification (modelling process detailed later in the report). The energy summary below is based on the preferred pilot design using a desiccant wheel to carry out dehumidification rather than a chilled coil-based dehumidifier, and is scaled down to the 40-animal shed intended for the pilot and assumes it is located in the North East of the UK.

- Shed heating load, winter peak = 7 kW with an annual energy use of 6 MWh. The heat will be provided by hot water from the heat recovery on the CHP engine (~30 kWth) using 3% of the available heat.
- Shed cooling load, summer peak = 25 kW. Annual cooling energy of 70 MWh. However, this is not the primary energy use as the cooling will be provided by a standard compression cycle chiller which uses electricity to drive the compressor. Typical air conditioning chillers have a ratio of electricity to cooling of about 1:3, this is known as the Coefficient of Performance (COP). Therefore, the peak electrical power is 9kW with an annual electrical use of 21 MWh. On average over the year the solar PV on the roof can match this usage. However, when the detailed hourly loads and PV production in the model is assessed, there are periods when there is a deficit. During these periods the constant electrical output from the 25 kWe CHP engine is available to power the chiller.
- Desiccant wheel peak recharge heat = 60 kW, with an annual energy usage of 350 MWh. The heat will be provided by a combination of the low-grade heat from the ~30 kW condenser coil of the chiller unit (heat recovery) and the high-grade heat from the ~20 kWth surplus heat from the CHP engine.

Whilst between these sources they can meet the annual energy demand, there may be short periods when an auxiliary electrical heater may be required to top it up, which will be powered by the PV/CHP electricity.

Environmental impacts

Below details the positive environmental impacts over and above the carbon removal:

- The plasma reactor reduces gaseous ammonia emissions by up to 95% from the digestate, these are ammonia emissions which would happen from the raw dung and bedding regardless if it goes through an AD plant. Ammonia is linked to eutrophication of the land, which is hugely detrimental in environmentally sensitive sites, and has negative impacts on biodiversity. Additional there are human health concerns linked to air quality from gaseous ammonia and particulates forming smog. For these reasons, ammonia emissions are already legislated for in the pig and poultry sectors, and it is likely these types of legislation will apply to the beef sector in the near future.
- Another benefit of fixing nitrogen and stabilising it via the plasma reactor, is increasing organic nutrients, which in turn reduces reliance on bagged fertiliser.
- Cattle play a key role in sustainable and regenerative farming systems, providing manure to reduce or eliminate dependency on artificial fertiliser, and improve soil health and biodiversity.

Detailed engineering design

Cost

Our detailed Phase 2 cost breakdown can be found in the “Detailed and costed project plan” section (page 16). Beyond 2025, based on the plant sizing work carried out under the modelling in Phase 1, and input from our commercial partners (No Pollution, Galebreaker, Organic Power Ireland, N2 Applied and Saturn Bioponics) we have arrived at budget estimates of capital for the commercial deployment by 2030 as seen in the section “Programme and business plan”. This gives an approximate payback of just over 8 years. Based on experience with renewables adoption in the farming sector, an 8-year payback is acceptable.

Pricing of the capital items is based on the experience of our technology partners who develop, manufacture, and supply their respective components, therefore having the best possible gauge on likely costs beyond the development Phase based on their specific business model. Some partners have large scale in-house manufacturing capability (Galebreaker), others will adopt the common SME model of licenced manufacturing by fabrication partners. This allows for rapid expansions of production by simply licensing additional existing fabrication and engineering companies. Some components are simple existing off-the-shelf items with no or short lead time (the various AHU components). The sales, installation, and maintenance of the systems will be via the wide-ranging partner network across the UK and Europe. The partners will form a Joint Venture (JV) to sub-contract a single central maintenance contractor to ensure there is a single point of contact for purchasers rather than having to deal with the individual technologies separately.

Using the “*GGR_workbook_V 3.0_GREENSHED_202076*” spreadsheet values and scaling to 500 installations averaging 80 animals per shed, gives an annual CH_4 capture of 4,737 tonnes = 118,423 tCO_2eq/yr based on the out-of-date GWP of 25, or 132,633 tCO_2eq/yr based on the current IPPC CH_4 GWP of 28.

The levelised costs in 2030, before incomes = £216/t of CO_2 after incomes from green beef premium, vertical farm produce sales, offset fertiliser, offset heating are factored in the levelised cost is -£92/t of CO_2 i.e., a £92 profit. Sensitivity on the green beef premium and produce sales based on +-30% shows a range of levelised net costs of -£15/t through to -£169.

Technical drawings

Full technical drawings are provided in Appendix A. Further technical drawings.

Modelling

Aim and objectives

The aim of the modelling work package was to develop a detailed, mathematical model of the GreenShed concept, determine its heating and cooling energy requirements, the likely indoor environmental conditions that would occur under a range of different operating scenarios, especially under the optimised fresh air input required for integration with the CH_4 removal system, and ultimately determine the duty required of the components in the environmental conditioning system. This section summarises the outcomes of the modelling work, where this feeds directly into the design of a full-scale prototype. A more extensive modelling report (provided in Appendix B. Development of a detailed simulation model) gives more details of all modelling work undertaken.

The specific objectives for the modelling work were as follows:

- Data collection for the development of a model.
- Development of the mathematical model of the GreenShed concept.
- Development of operating scenarios for investigation using simulation.
- Simulation of performance and extraction of systems design data.

Model

The energy and environmental performance of the GreenShed concept was assessed against a range of operating conditions using the ESP-r building simulation software[1]. ESP-r is a long-established tool that explicitly computes the transient energy and mass transfer processes in a building over a user-defined time interval (e.g., a day, a year, etc.). The basic ESP-r GreenShed model comprised details of the shed form and fabric, details of the heat and other emissions from the cattle. This was augmented with a detailed sub-model of the heating, ventilation, and air conditioning system (HVAC) serving the shed and which supplies the CH_4 extraction system. The model was used to compute sizes of key components and to determine the environmental conditions inside the shed under a range of operating conditions.

The building model featured a pitched roof, with a maximum eave height of 5m and a 15^o roof slope. The floor area was $720m^2$ and the internal volume was $4760m^3$. The included external constructions, typical of a UK cattle shed: a roof of corrugated steel sheet; upper external wall surfaces of slatted timber with a thin layer of impermeable flexible material (1mm thick) to reduce leakage of CH_4-rich internal air to outside; the lower 2.4m of external wall were block construction; and the floor was concrete slab, 150mm thick with hardcore and gravel below this.

---

[1] ESRU. (2021). *ESP-r download page*. Retrieved from Energy Systems Research Unit (ESRU) website: http://www.esru.strath.ac.uk/Programs/ESP-r.htm. Accessed July 28.

Two animal gains scenarios were developed from data provided by SRUC[2] and the literature, these covered the likely range of cattle sizes that could be encountered in the UK. **Table 1** shows the gains for 100 cattle, which is the notional capacity of the GreenShed system.

Table 1. Heat, moisture, and contaminant emissions for 100 cattle

	Sensible heat gains (W)	Moisture gains (g/s)	CH_4 release rate (g/s)	CO_2 release rate (g/s)
High scenario	68,900	26.3	0.21	5.3
Low scenario	55,300	24.8	0.14	3.5

Two different configurations of environmental conditioning system were tested with the model: shed humidity control using a combined cooling/dehumidification coil and using a dedicated desiccant wheel. The component capacities used in the model are shown in **Table 2**.

Table 2. Details of components used in ESP-r GreenShed HVAC model

Component	Capacity	Comments
Fresh air supply & extract fans	2.9 m^3/s	Flow rate was determined based on the 1500 ppm limit (determined from pre-simulation calculations and documented in the appendices)
Recirculation fan	8.9 m^3/s	Flow rate determined based on pre-simulation calculations of cooling load
Heating coil	200 kW	Coil capacity based on initial simulation of heating requirement and set so capacity > likely maximum load, so maximum duty can be determined
Cooling/dehumidification coil	200 kW	Coil capacity based on initial simulation of cooling and dehumidification requirements, capacity > likely maximum demand so maximum duty can be determined
Desiccant wheel	150 kW	Based on the initial simulations of dehumidification requirements.

---

[2] Miller G (2021) SRUC test chamber environmental conditions [dataset].

The supply and extract fans were controlled to maintain indoor CO_2 below 1500 PPM, which is the limit of acceptability for cattle. The cooling coil was controlled to maintain the relative humidity in the shed to below 80%. The heating coil was controlled to maintain indoor temperatures between 4 and 22°C, which is an acceptable range for cattle[3].

The performance of the model was assessed by simulating against a year's worth of climate data for both of the gains levels and HVAC configurations indicated previously. Four separate climate sets were investigated, which were representative of the UK's Northeast (NE), Northwest (NW), Southwest (SW) and Southeast (SE) climate zones.

The results that follow were therefore derived from a total of 16 simulations, with all heat and mass exchanges and state variables calculated at each hour of the simulated year. A large number of precursor simulations were also undertaken, which are reported in Appendix B. Development of a detailed simulation model..

Results

Table *3* to Table 6 show the key environmental metrics extracted from the modelled data. This shows that CO_2 and CH_4 concentrations are within acceptable levels (<1500 ppm and 1000 ppm, respectively), while peak temperatures[4] are within comfort limits for cattle, and RH* is less than 80%.

Table 3. Peak CO_2 levels (ppmv) calculated from simulation

CO_2 PPM	NE	NW	SW	SE
HI GAINS CO_2	1435.4	1438	1439.2	1441.5
LO GAINS CO_2	1083.4	1085.1	1084.4	1084.9

Table 4. Peak CH_4 levels (ppmv) calculated from simulation

CH_4 PPM	NE	NW	SW	SE
HI GAINS CH_4	114.4	114.6	114.9	115.3
LO GAINS CH_4	76.7	76.9	77.1	77.2

---

[3] Discussion on cattle physiology with SRUC experts. (A. Cowie, Interviewer, September 16)

[4] 95th percentile temperature and RH values were used here to remove the influence of short duration outlier conditions of system design and sizing.

Table 5. Peak Temperatures (°C) calculated from simulation

PEAK TEMPERATURE °C	NE	NW	SW	SE
HI GAINS	17.9	17.4	18	19.1
LO GAINS	17.4	17	17.6	18.6

Table 6. Peak RH (%) calculated from simulation

PEAK RH (%)	NE	NW	SW	SE
HI GAINS	76.3	77	78	76.7
LO GAINS	76.2	76.9	78	76.6

Table 7 – Table 12 show the HVAC peak loads[5] and energy use required to maintain conditions within the tabulated environmental conditions for the different climate gains levels and HVAC configurations tested. The results show that with cooling coil dehumidification, cooling coil and heating coil loads and energy use are very high, with the cooling coil requiring significant primary energy input.

With desiccant dehumidification, coil loads are dramatically reduced, but this is offset by the heat needed to re-charge the desiccant.

Table 7. Heating coil peak load (kW) calculated from simulation

PEAK LOAD KW	NE	NW	SW	SE
HI GAINS – COIL	111.3	102.4	111.4	110.3
HI GAINS – DESICCANT	6.4	8	6.1	12.4
LO GAINS – COIL	116.5	108	116.8	116
LO GAINS -DESICCANT	10.9	12.7	10.9	17.3

Table 8. Heating coil annual energy use (MWh) calculated from simulation

ENERGY MWh	NE	NW	SW	SE
HI GAINS - COIL	634.2	577.8	570.6	548
HI GAINS -DESICCANT	6.9	9	6.5	13.4
LO GAINS – COIL	684.9	630.3	621.5	599.2
LO GAINS – DESICCANT	13.7	16.4	10.8	20.8

---

[5] again, these are 95th percentile values to ensure sizing isn't undertaken for outlier conditions.

Table 9. Cooling coil peak load (kW) calculated from simulation

PEAK LOAD KW	NE	NW	SW	SE
HI GAINS – COIL	137.3	138.6	139.1	140.9
HI GAINS - DESICCANT	69.8	81	78.9	92.4
LO GAINS - COIL	136.8	138	138.4	140.4
LO GAINS - DESICCANT	61	58.6	69.9	83.3

Table 10. Cooling coil annual energy use (MWh) calculated from simulation

ENERGY MWh	NE	NW	SW	SE
HI GAINS – COIL	997.1	981.5	991.1	996.3
HI GAINS - DESICCANT	187.1	195.2	273.1	254.2
LO GAINS - COIL	984.4	971.9	983	991.4
LO GAINS -DESSICANT	148.4	155.2	223.6	211.9

Table 11. Peak desiccant recharge load (kW) calculated from simulation

DESICCANT RECHARGE KW	NE	NW	SW	SE
HI GAINS	155.6	165.3	173.1	158.4
LO GAINS	154	164	175.3	157.9

Table 12. Desiccant recharge energy (MWh) calculated from simulation

DESSICANT RECHARGE MWh	NE	NW	SW	SE
HI GAINS	1002.8	1116	1147.6	1030
LO GAINS	998.5	1114	1148.4	1033.2

An additional simulation was used to calculate the potential energy yield from a PV system, and this, along with data on the CH_4-removing engine from SRUC was used to undertake a primary energy balance of the GreenShed system (**Table 13** and **Table 14**). The assumptions behind this were as follows: i) the inverter efficiency for the simulated PV output (from DC-AC) was 95%; ii) the engine power output was 50 kW, with 55 kW thermal output iii) the heat from the cooling coil was recovered using a heat pump with a coefficient of performance (COP) of 3 for heating and 2 for cooling; and iv) the total fan power consumption was 2.8 kW assuming a typical fan pressure rise of 200 Pa. The engine and fans ran continuously. In the tables that follow a –ve value denotes an energy demand and a +ve value an energy source.

Table 13. Energy balance (MWh) for HVAC with cooling-coil dehumidification

Cooling-Coil Dehumidification Annual Energy Balance (MWh)				
Electricity				
Climate	NE	NW	SW	SE
Cooling electricity (Hi)	-498.6	-490.8	-495.6	-498.2
Cooling electricity (Lo)	-492.2	-486.0	-491.5	-495.7
Fan electricity	-21.0	-21.0	-21.0	-21.0
PV electricity	92.3	91.5	108.1	104.6
Engine electricity	438.0	438.0	438.0	438.0
Electricity balance (Hi)	10.8	17.7	29.5	23.4
Electricity balance (Lo)	17.1	22.5	33.6	25.9
Heat				
Climate	NE	NW	SW	SE
Heating coil heat (Hi)	-634.2	-577.8	-570.6	-548
Heating coil heat (Lo)	-684.9	-630.3	-621.5	-599.2
Cooling recovered heat (Hi)	1495.7	1472.3	1486.7	1494.5
Cooling recovered heat (Lo)	1476.6	1457.9	1474.5	1487.1
Engine recovered heat	481.8	481.8	481.8	481.8
Heat balance (Hi)	1343.3	1376.3	1397.9	1428.3
Heat balance (Lo)	1273.5	1309.4	1334.8	1369.7
Net all energy (Hi)	1354.0	1394.0	1427.4	1451.7
Net all energy (Lo)	1290.6	1331.9	1368.4	1395.6

Table 14. Energy balance (MWh) for HVAC with desiccant dehumidification.

Desiccant Dehumidification Annual Energy Balance (MWh)				
Electricity				
Climate	NE	NW	SW	SE
Cooling electricity (Hi)	-93.6	-97.6	-136.6	-127.1
Cooling electricity (Lo)	-74.2	-77.6	-111.8	-106.0
Fan electricity	-21.0	-21.0	-21.0	-21.0
PV electricity	92.3	91.5	108.1	104.6
Engine electricity	438.0	438.0	438.0	438.0
Electricity balance (Hi)	415.8	410.9	388.5	394.5
Electricity balance (Lo)	435.1	430.9	413.3	415.6
Heat				
Climate	NE	NW	SW	SE
Desiccant re-heat & heating coil (Hi)	-1009.7	-1125.0	-1154.1	-1043.4
Desiccant re-heat & heating coil (Lo)	-1012.2	-1130.4	-1159.2	-1054.0
Cooling recovered heat (Hi)	280.7	292.8	409.7	381.3
Cooling recovered heat (Lo)	222.6	232.8	335.4	317.9
Engine recovered heat	481.8	481.8	481.8	481.8
Heat balance (Hi)	-247.3	-350.4	-262.7	-180.3
Heat balance (Lo)	-307.8	-415.8	-342.0	-254.4
Net all energy (Hi)	919.8	919.8	919.8	919.8
Net all energy (Lo)	168.5	60.5	125.9	214.2

For the HVAC system with cooling-coil based dehumidification, the electricity consumption could be offset by the output from the engine unit and a roof top PV array and there is a substantial surplus of heat. With desiccant dehumidification there is a large surplus of electrical energy, but a small deficit in heat. However, in both cases the net energy balance (electricity and heat) is in surplus.

Conclusions

The results from the modelling indicate that with a HVAC system with cooling-coil-based dehumidification, temperatures, humidity, and contaminants could all be kept within acceptable levels, for all UK climates and gains levels tested. However, this was at the expense of high cooling and heating loads and energy requirements (in excess of 100 kW and 1 GWh per annum, respectively), energy for the high cooling load would be primary energy from the electricity network.

An alternative HVAC configuration with desiccant dehumidification massively reduced both the total cooling coil energy requirement and heating coil energy requirement, though this was offset by the heat energy needed to recharge the desiccant.

Analysing the energy balance of the GreenShed system, both the energy consumption of the cooling-coil-based HVAC system and the desiccant-based system could be offset using heat recovery from the engine and cooling coils, along with the electrical output form the engine unit and rooftop PV array.

The system component parameters derived from the simulations are as follows:

Table 15. Maximum component duties extracted from the simulation

Component	Approx. Maximum Duty	Comments
Recirculation fan	8.9 m^3/s	Required to maintain adequate indoor temperatures and humidity levels.
Fresh air supply/extract fan	2.9 m^3/s	Required to maintain CO_2 levels below 1500 ppm
Cooling coil dehumidification		
Cooling/dehumidification coil	141 kW	Required to maintain adequate humidity levels
Heating coil	117 kW	Required to maintain temperatures
Desiccant dehumidification		
Cooling coil	92 kW	Required for temperature control
Desiccant (recharge)	176 kW	Required to maintain humidity levels
Heating coil	18 kW	Required for temperature control
PV array	126 kW (peak capacity)	Offsetting cooling system primary energy demand.

Cost savings (compared with exclusive development contracts)

Our proposed system relies heavily on off-the shelf components purchased from external suppliers; therefore, these are fixed costs with no room for price reductions.

However, for the novel micro-AD system from Organic Power Ireland and the innovative membrane system from Galebreaker, the development of these is done as cost, with no “markup” added to compensate for the risk in developing these without funding.

Likewise, the academic partners SRUC and University of Strathclyde, have priced time based on the standard academic non-profit costing model “Full Economic Costs” (FEC). And again, does not include any risk markup.

If this system were to be developed as a commercial product, it is unlikely the partners would proceed at this risk level, but for calculation of a nominal saving, in normal commercial risk projects, we would expect the final product to have an additional 10%-15% added to price to cover development risks.

Detailed and costed project plan

The Phase 2 pilot is designed around a 40-animal shed. Taking data from the building modelling carried out for Phase 1, along with the results of the previous proof of concept study, we have calculated the expected CH_4 capture rate at 5.92t/yr, equating to 148t CO_2eq/yr. Please note, this is using the out-of-date GWP of 25 as per the "*GGR_workbook_V 3.0_GREENSHED_202076*" calculation spreadsheet issued with this project, if we were to use the current IPCC GWP of 28 it would equate to 166tCO_2eq/yr.

Pilot site

The demonstrator for GreenShed will be piloted at SRUC's Beef and Sheep Research Centre, Easter Howgate Farm, Easter Howgate, Midlothian, EH26 8DD. The facility lies eight miles south of the centre of Edinburgh, within the Pentland hills. The site has a total farms area of 1,013ha (mixture of hill, improved upland and lowland) with of a total of ~400 suckler cows, consisting of three commercially representative breed types (Aberdeen Angus cross, Limousin cross and pedigree Luings). All calves born are reared as replacement breeding heifers or finished on-site. See Appendix A. Further technical drawings.

Benefits of the site

- The facility has a long-standing reputation for delivering research, teaching and demonstration, such that research and education can be seen within the context of a realistic farming enterprise.
- The facility provides access to the scientific and technical expertise required to test the design (including animal welfare scientists, ruminant specialists, renewable energy consultants, GHG emissions researchers and a skilled technical team).
- SRUC's aligned consultancy division already provide an advisory service to this farm (and wider farming community), therefore a new build on this facility under the supervision of SAC consulting should prove unproblematic.
- Home Office licencing required for the initial test Phase of GreenShed is already in place on this facility (including establishment licence, project licence and personal licencing). Following testing and with underpinning evidence associated with animal health and welfare, this will not be required for subsequent builds on commercial farms.
- One of the key ambitions of the research farm is to facilitate demonstration of research and education. Visitors to the facility regularly include a range of key stakeholders which are our target audience for disseminating GreenShed outputs (e.g., farmers, farming bodies, government representatives, retailers, processors).
- Existing working relationships already exist with contractors such as NP who built SRUC's internationally recognised research facility for measuring CH_4 emissions from cattle ("GreenCow") on this site.

Risks associated with the site

A comprehensive risk register associated with Phase 2 activities is included within Appendix D. Risk register. The key risks of the site itself are outlined below where likelihood (L) is defined as 1=Unlikely, 2= Likely and 3=Highly likely; and Severity (S) as 1=Minor, 2=Moderate and 3=Major. Please see the risk register for residual risks post-mitigation.

1. Poor farmer confidence in commercial application as demonstrated on a research farm (L=2, S=2). Mitigated through robust underpinning scientific testing and evidence provided by SRUC, SAC consulting's trusted relationship with a large network of farm subscribers (~7500), wide farm networks and stakeholders associated with each partner, support from partner communications and marketing teams and targeted stakeholder engagement activities.
2. Capacity of available utility supply (backup power, drainage) (L=1, S=3). Mitigated through access to two power supply points and drainage on two nearby steadings (controlled by SRUC).
3. Delays in securing appropriate permitted development notification approvals (L=1, S=2). Mitigated through a speculative pre-Phase 2 application which will be sought, and appropriate time built into the workplan (see Gantt chart, **Table 16**) for securing permissions.
4. Outbreak of notifiable disease restricting access to site (L=1, S=3). Mitigated through strict biosecurity protocols on selected site.

Interactions with current and proposed site use

Alongside supporting research and education activities at SRUC, the site operates as a commercial working farm. As GreenShed is designed with commercial applicability in mind (either new build or retrofit options), the development will easily integrate within the commercial farm business. The farm system operates both a spring calving herd and autumn calving herd, thus growing-finishing animals will be available for housing within the GreenShed all year round which is important for testing and to demonstrate the benefits that can be achieved through adoption of GreenShed. The expectation for this demonstrator unit is that cattle will be managed as per normal practice by the stockmen on the farm, to demonstrate commercial applicability and engage feedback from those directly working with the system. In addition, one of the key areas of priority for SRUC's farms includes implementing a plan for reducing the farm carbon footprint (utilising the expertise of SAC consulting's Agrecalc carbon footprinting tool and advisors). This GreenShed facility aligns with their short-term and long-term ambitions of supporting Net-Zero targets.

GreenShed also aligns with the key research themes at SRUC's Beef and Sheep Research Centre. The site operates as a world-class facility for beef cattle research, with a focus on GHG emissions, resource use efficiency, development and use of data-driven innovations and optimised animal health and welfare. The site is also home to SRUC's specialist emissions recording facility for individual cattle - "GreenCow" - in operation since 2010. This facility was designed and built as a collaboration between project partners SRUC and NP who have a long-standing and continued working relationship in this area. GreenShed will extend this facility from individual monitoring of cattle to group-housed monitoring and CH_4 capture, allowing for further innovation in this area.

In addition, the facility operates in both an education and dissemination capacity to disseminate key messages from both the research and farming business to students, farmers, and the wider farming industry (from farm to fork). The farm supports a range of stakeholder engagement activities including farmer-focussed events, larger open-days with key stakeholders, and the use of mixed media platforms (e.g., social media, podcasts, broadcast media, video-hosting platforms, panel discussions). The site will therefore support effective dissemination of GreenShed – with respect to economic performance, environmental conditions, GHG reduction potential and animal welfare.

Decommissioning costs

As the pilot system will in effect be a fully functioning CH_4 capture system, with all the benefits, SRUC intend to continue to run it as such beyond the end of the pilot phase, therefore there will be no decommissioning costs involved with this project.

Phase 2 project plan

Phase 2 consortia will include (see Appendix E. Phase 2 partners for project partner details):

- Scotland's Rural College (SRUC) – academic lead, site provision and consultancy, systems testing
- University of Strathclyde (UoS) – academic – building design and testing
- Agri-EPI Centre (AEC) – Project management and commercial research
- No Pollution (NP) – design and provision of AHU technology
- Galebreaker (GB) – design and provision of shed membrane
- Organic Power Ireland (OPI) – design and provision of AD plant and CHP engine
- Saturn Bioponics (SB) – provision of vertical farm
- N2 Applied (N2) – provision of plasma reactor
- Retailer 1 – provision of supply chain intelligence and route to market
- Retailer 2 – provision of supply chain intelligence and route to market

The objectives of Phase 2 are to:

- Build a prototype GreenShed system at SRUC's Beef and Sheep Research Centre.
- Conduct pilot testing of CH_4 capture and conversion combined with vertical farming and nutrient production unit.
- Conduct animal welfare assessments (SRUC's Animal Behaviour and Welfare team) of cattle housed within the GreenShed.
- Validate design and conduct full life-cycle-analysis (heat, nutrients, power, carbon savings).

- Finalise business model: pricing and ROI strategy - tested with farmers and processors/retailers.
- Create case studies covering various legacy infrastructure and production systems.
- Demonstrate and disseminate the benefits (animal health and welfare, environmental) of the proposed system.

The work is split across six work packages (WP's) described below. **Table 16** shows the Gantt chart and **Table 17** a description of each WP, lead and cost per WP, list of deliverables (D) and milestones (M) with clear delivery dates associated with Phase 2 work.

WP0: PROJECT MANAGEMENT (PM). LEAD=AEC. MONTHS 1-36.

- Project Lead (PL) delivered by SRUC with responsibility for strategic direction and project delivery with oversight of project management.
- PM delivered by AEC using proven techniques and tools (PRINCE2, Scrum) and standard software (Microsoft Teams, Project, Office 365 applications) to support collaboration, communication, task scheduling, resourcing, and budget management.
- Fortnightly technical updates between all project partners using online platforms and in-person on-site meetings as required.
- Monthly project progress meetings with project monitoring officer (PMO) (and BEIS representative as required) using a mixture of online platforms and in-person meetings.
- WP leads report directly to AEC, issues identified quickly and mitigated. Project deliverables, milestones and risks reviewed and updated monthly.

OUTCOMES: Technical, project, interim and final progress reports; updated risk register.
DEPENDENCIES: ALL WPs.

WP1: PERMISSIONS AND CONTRACTORS. LEAD=SRUC. MONTHS 1-16.

There are three key activities associated with permissions and contractors within WP1. These include:

- Development and submission of the permitted development notification to the local authority for the new shed to be installed at SRUC's Beef and Sheep Research Centre (D1.1).
- Select contractor for shed build in WP2 (D1.2). Quotes will be obtained from a range of agricultural shed contractors (and electricians) and contract agreed with favoured contractor.
- Development and submission of planning permission for polytunnel (for the vertical farm installation in WP4) (D1.3).

OUTCOMES: Approvals in place for shed build and permissions in place for polytunnel.
DEPENDENCIES: CAD designs and specifications.

WP2. SYSTEMS INSTALLATION– CORE TECHNOLOGY. LEAD=NP. MONTHS 5-11.

WP2 will focus on the installation of the core GreenShed technologies onto selected site. The key activities will focus on:

- Installation of shed using chosen contractor in WP1 (D2.1). The build will be managed by SAC consulting (part of SRUC) with regular (minimum fortnightly) meetings on-site with the contractor.
- Installation of GreenShed technologies: Anaerobic digester (AD), removable shed membrane and air handling unit (AHU) (D2.2, 2.3 and 2.4). Design meetings will be held with all consortia and fabricators to ensure design is optimised for the specific purpose. Construction and fabrication of each technology will be owned by each technical lead (OPI, GB and NP). Technology installations will be over-seen by SAC/SRUC.
- Installation of environmental sensing and monitoring equipment for large scale testing in WP3. This will involve the procurement of sensing equipment (respiratory gases, CH_4 emissions, environmental parameters) and installation (D2.5).

OUTCOMES: Completed core systems installations for testing in WP3.
DEPENDENCIES: Permissions and contractors from WP1. Access to technology from consortia.

WP3. GREENSHED TESTING. LEAD=SRUC. MONTHS 6-21.

Two levels of testing will be carried out in WP3:

- Animal-free testing (D3.1) will assess airflows, pressures, and failsafe/safety mechanisms against agreed performance criteria.
- Larger scale testing with animals housed in the facility. Animal-based testing in this facility will require approvals from SRUC’s local animal ethics committee and home office licencing approvals. The latter is already in place, but approvals will be sought from SRUC’s animal ethics committee approvals before data capture commences (D3.2). Animal-based testing will involve an iterative cycle of data capture (D3.3) and analysis. Data will be assessed on shed performance (environmental parameters and GHG reduction efficacy; D3.4) and animal welfare (through animal welfare assessments in D3.5).

OUTCOMES: Assessment and optimised shed performance. Design ready for integration with further circular farming technologies in WP4.
DEPENDENCIES: Completed core installations (WP4), experimental licencing and approvals.

WP4. SYSTEMS INSTALLATION – ADD ON MODULES. LEAD=NP MONTHS 16-21.

WP4 will integrate the remaining technologies to create the low-carbon circular farming operation combining cattle and crop production:

- The plasma reactor will be installed by N2 to utilise digestate from the AD (unavailable nitrogen) and convert to available nitrogen (D4.1).

- Vertical farm installation (including polytunnel) will be managed by SAC and SB. The vertical farming system will utilise the excess outputs (power, heat, CO_2) and low-cost nutrients (nitrogen). Oxygen-rich air from the vertical farm will be supplied to the cattle shed (to optimise resource use) (D4.2).

OUTCOMES: Plasma reactor and vertical farm in place for demonstration within WP6.
DEPENDENCIES: Completed core installations (AD unit) (WP4).

WP5.SUPPLY CHAIN ENGAGEMENT. LEAD=AEC. MONTHS 6-36.

WP5 will build on the commercial research conducted in Phase 1 (report included in Appendix C. Market report). This showed widespread support for GreenShed from across the beef industry (farmers, processors, retailers, and industry stakeholders) as a potential solution for low carbon, sustainable beef production. However, two key areas of uncertainty emerged from the Phase 1 research: consumer acceptability and commercial viability (ROI). WP5 will address these.

- Consumer research (D5.2): a third-party agency will be subcontracted to undertake detailed research on consumer perceptions of GreenShed and acceptability of beef products from this system, and on consumer willingness-to-pay for low carbon beef products.
- Supply chain research: A deep-dive approach will be taken with two specific supply chains. We will work with them throughout Phase 2, scoping metrics to validate animal health and welfare outcomes, in addition to GHG and broader sustainability impacts (D5.1). Working with retailer and processor agriculture and commercial teams and representatives of their aligned farmer groups, we will design and model potential incentive schemes and supply chain scenarios (D5.3). In tandem, accurate capital and operating cost analysis, as well as quantification of animal performance and efficiency gains, will enable ROI to be calculated (D5.4). This will raise supply chain confidence to develop pilot incentive programmes for GreenShed adoption and integration into the supply chain post-project (D5.5).

OUTCOMES: Report detailing consumer acceptability of GreenShed and willingness to pay for low carbon produce. Design of pilot supply chain schemes ready for post-project implementation.
DEPENDENCIES: Supply chain commitment; GreenShed performance data from WP3; dissemination materials from WP6.

WP6. DEMONSTRATION AND DISSEMINATION. LEAD=GB. MONTHS 15-36

Of key importance to the success of the GreenShed project is an effective dissemination and commercialisation plan. SRUC have significant experience of effective dissemination through their consultancy division (SAC consulting) with >7500 farm subscribers. At appropriate points in the project the team will target dissemination through the following routes:

- A series of on-farm demonstration events (D6.1). These will be structured depending on the target audience but will involve a series of smaller targeted meetings with farmers to demonstrate the system and discuss perceptions, and larger open days to target the wider industry (farmers, processors, retailers, farming bodies (e.g., national farmers union, levy boards, beef producer groups), agricultural press and government representatives).

- To maximise dissemination throughout the project, mixed media platforms will be used to disseminate key messages as they arise (D6.2). The format will depend on the outputs, but we anticipate a series of blogs (facilitated by SRUC and AEC communications department), release of digital material through SAC Consulting's Farms Advisory Service (FAS) and the Farming for a Better Climate platform, scientific outputs (to robustly underpin the design) and policy recommendations to support uptake. Project outputs will be highlighted through project partner websites, twitter, and social media platforms.
- A detailed commercialisation plan will also be developed within this WP (D6.2) led by GB. The team will develop a robust business/operating model, refine target markets, develop marketing plan and refine their pricing/service model.

OUTCOMES: Finalised dissemination materials; agreed commercialisation plan.
DEPENDENCIES: GreenShed demonstrator (WP2 and 4), data outputs from WP3, project specific material (hard and digital).

Table 16. Gantt chart

		Yr 1 (2022)												Yr 2 (2023)												Yr 3 (2024)											
Work Packages	**Deliverables / Milestones**	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
WP0. PROJECT MANAGEMENT	Project Management	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Monthly project monitoring meetings PMO	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Milestones	**M1**													**M7**									**M12**							**M13**						**M14**
WP1. PERMISSIONS / CONTRACTORS	Develop and submit permit notification to LA	■	■	■	■	■																															
	Select contractor for shed	■	■	■	■	■																															
	Develop and submit planning permission for polytunnel (vertical farm)											■	■	■	■	■	■																				
	Milestones					**M2**											**M8**																				
WP2. SYSTEMS INSTALLATION - CORE TECHNOLOGY	Installation - shed					■	■	■	■																												
	Installation - AD						■	■	■	■																											
	Installation - Shed membrane								■	■	■																										
	Installation - AHU									■	■	■																									
	Installation - envirnonmental sensing/monitoring										■	■																									
	Milestones								**M3**			**M4**																									
WP3. GREEN-SHED TESTING	Animal-free test											■	■																								
	Experimental design and approvals						■	■	■	■	■	■	■																								
	Animal trials - data capture													■	■	■	■	■	■	■	■	■															
	Data analysis - environmental GHG removals														■	■	■	■	■																		
	Animal welfare assessments																		■	■	■	■															
	Milestones												**M5**									**M9**															
WP4. SYSTEMS INSTALLATION - ADD-ON MODULES	Installation - plasma reactor																■	■	■	■	■	■															
	Installation - vertical farm																■	■	■	■	■	■															
	Milesones																					**M10**															
WP5. SUPPLY CHAIN ENGAGEMENT	Recruit supply chains and agree workplan						■	■	■	■	■	■	■	■	■																						
	Conduct consumer research										■	■	■	■	■	■	■	■	■																		
	Agree supply chain model scenarios																			■	■	■	■	■	■	■	■										
	Test model scenarios																										■	■	■	■	■						
	Develop incentivisation model and pilot programme																														■	■	■	■	■	■	■
	Milestones														**M6**							**M11**															**M18**
WP6. DEMONSTRATION AND DISSEMINATION	On-farm demonstration events																					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Dissemination activities (mixed media)															■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Development of commercialisation plan																												■	■	■	■	■	■	■	■	■
	Milestones																																				**M15** **M16** **M17**

Table 17. Work package (WP) details with lead partner, cost per WP, deliverables (D) and milestones (M)

WORK PACKAGES		MILESTONE / DELIVERABLE	TASK/ACTIVITY	COMPLETION DATE	RESOURCES REQUIRED	SUCCESS CRITERIA
WP0. PROJECT MANAGEMENT. LEAD: AEC. COST: £219k.	D0.1	Project kick-off meeting successfully completed	Meeting arranged and co-ordinated by PM (AEC) with lead (SRUC), sub-contractors (NP, AEC, GB, OPI, SB, N2 and SB) and project monitoring officer (PMO); Meeting chaired by project lead (SRUC); Minutes/actions with a clear plan for Phase 2 delivery (PM AEC)	15/04/2022	Collaborative working, online-meeting, and PM software (Microsoft Teams; staff time (all participants)	Project kick off report detailing clear plan for delivery of Phase 2
	D0.2	Fortnightly technical meetings	Fortnightly meetings using online-platforms (Microsoft teams) and on-site meetings; arranged by PM (AEC), chaired by SRUC; technical updates from lead and sub-contractors; milestones and deliverables review; risk register/competitive landscape reviewed and updated	31/03/2025	Collaborative working and PM software (Microsoft Teams); project documentation (risk register/ competitor analysis, progress)	Technical meeting reports; risk register; competitor analysis
	D0.3	Completion of end of Phase 2 report	Summary of all activities and outcomes detailed in WP1-WP6 to include GreenShed performance (animal welfare, environment, GHG reduction, economics), supply chain models and commercialisation plan	31/03/2025	Outputs from WP1-6; final project documentation (risks, competitors)	End of Phase 2 report submitted: successful delivery
	M1	**Completion of project kick-off meeting**		**15/04/2022**		
	M7	**Interim report: core systems installation**		**31/03/2023**		
	M12	**Interim report: core systems performance**		**28/02/2024**		
	M13	**Interim report: combined systems performance**		**30/09/2024**		
	M14	**Submission of final report**		**31/03/2025**		
WP1. PERMISSIONS AND CONTRACTORS. LEAD: SRUC. COST: £43k.	D1.1	Submit permitted development notification	Produce CAD designs and specifications: complete notification (online)	31/08/2022	SAC planning team; design drawings	Approvals obtained for WP2
	D1.2	Select contractor for shed installation	Designs and specifications to agricultural contractors; obtain quotes; select contractors (build/electrical)	31/08/2022	SAC planning team; design drawings; contracts team	Contract in place
	D1.3	Planning permission for vertical farm	Develop and submit planning permissions for polytunnel	31/07/2023	SAC planning team; design drawings	Permissions approved ready for WP4

WORK PACKAGES		MILESTONE / DELIVERABLE	TASK/ACTIVITY	COMPLETION DATE	RESOURCES REQUIRED	SUCCESS CRITERIA
	M2	**Finalise permissions for shed installation**		**31/08/2022**		
	M8	**Finalise permissions for vertical farm installation**		**31/07/2023**		
WP2. SYSTEMS INSTALLATION - CORE TECHNOLOGY. LEAD: NP. **COST: £1,129k.**	D2.1	Shed installation	Build managed by SAC consulting; fortnightly progress meetings on-site with contractor	30/11/2022	SAC, electrical contractor, SRUC's properties and estates	Completed shed ready for systems installations
	D2.2	Anaerobic digester (AD) installation	Design meetings with consortia and fabricator (OPI) to optimise design for specific purpose; construction controlled/monitored by OPI at factory; on-site build managed by SAC consulting and OPI	31/12/2022	Fabricator; SAC, OPI design team	AD plant in place ready for WP3
	D2.3	Installation of removable shed membrane	Design meetings with consortia and fabricator (GB) to optimise design for specific purpose; fabrication at GB factory; installation at SRUC controlled/monitored by GB	31/01/2023	GB design team, GB installation team	Shed membrane in place ready for WP3
	D2.4	Installation of air handling unit (AHU)	Design meetings to determine physical structure of AHU; installation managed by NP	28/02/2023	NP design team and NP installation team	AHU installed ready for WP3
	D2.5	Installation of environmental sensing	Specify sensing equipment requirements; procure monitoring equipment; installation by SRUC/SAC	28/02/2023	SRUC research team, installed shed and systems	Sensing equipment ready for WP3
	M3	**Completion of shed installation**		**30/11/2022**		
	M4	**Completion of GreenShed installations (AD, shed membrane and AHU) and monitoring equipment**		**28/02/2023**		
WP3. GREENSHED TESTING. LEAD. SRUC. **COST £773k.**	D3.1	Animal-free test	Agree performance specifications and testing procedure; conduct testing; test failsafe's	31/03/2023	Installed GreenShed; sensing equipment; monitoring/verification equipment	System maintains environment as per specification; all fail-safes work
	D3.2	Experimental and ethics approvals/experimental protocols	Design experiment; submit for animal ethics committee approvals and Home Office licence approvals; Animal identification/pre-trial management	31/03/2023	Staff time/labour resource for planning; animal ethics committee; home office inspector	Animal ethics committee approvals and home office licencing in place
	D3.3	Animal trials - data capture	Identify animals and house within GreenShed; iterative testing and review of environment	31/12/2023	GreenShed; cattle, animal ethics and home office licencing, animal care, technical and scientific staff	Dataset from animal tests
	D3.4	Data analysis - environmental parameters / GHG removal efficacy	Data cleaning and collation into database; analysis of environmental parameters/sensing; assessment of GHG removal efficacy	30/09/2023	Database (SQL) of parameters from D3.3, research scientists to conduct analysis	Completed analysis; exact airflow, power and feedstock requirements determined

WORK PACKAGES		MILESTONE / DELIVERABLE	TASK/ACTIVITY	COMPLETION DATE	RESOURCES REQUIRED	SUCCESS CRITERIA
	D3.5	Animal welfare assessments	Animal welfare assessments within the GreenShed (and baseline); collation of data and analysis.	30/12/2023	Animal welfare scientists; animal welfare technicians; activity/health monitors	Completed welfare assessment of cattle
	M5	**Completion of animal-free testing**		**31/03/2023**		
	M9	**Completion of data capture and assessments (environmental parameters, GHG removal efficacy and animal welfare)**		**31/12/2023**		
WP4. SYSTEMS INSTALLATION - ADD-ON MODULES. LEAD: N2. COST £395k.	D4.1	Plasma reactor installation	Modular unit installation on-site managed by N2.	30/12/2023	AD unit (power)	Plasma reactor in place ready for WP6
	D4.2	Vertical farm installation	Specifications for polytunnel provided by SB, vertical farm installation managed by SAC and SB.	30/12/2023	AD unit (heat)	Vertical farm in place ready for WP6.
	M10	**Completion of systems installations for circular farm (plasma reactor and vertical farm)**		**31/12/2023**		
WP5. SUPPLY CHAIN ENGAGEMENT. LEAD: AEC. COST: £142k.	D5.1	Scope supply chain development	Recruit (2) supply chains and agree detailed workplan including objectives and outcomes	31/03/2023	Commitment from two supply chains: retailer, processor, farmer representatives	Workplan confirmed with 2 supply chains. MOU/LOI in place
	D5.2	Consumer research	Consumer research complete (acceptability and willingness to pay)	31/09/2023	External consumer research agency	Report: consumer acceptability and willingness to pay
	D5.3	Supply chain model scenarios	Supply chain scenarios for GreenShed integration agreed (e.g., producer price premium, product positioning within range, volume projection, consumer price-point)	31/03/2024	Labour (AEC), input from supply chain partners	Candidate model(s) developed for each supply chain
	D5.4	Test scenarios	Model adoption of scenarios using GreenShed performance data	31/09/2024	Animal / carcase data; labour; (AEC/SRUC/supply chain partners)	Economic and commercial analysis of each scenario
	D5.5	Plan and agree pilot programme	Based on scenario testing design pilot GreenShed incentive for post-project implementation	31/03/2025	Supply chain partners	Pilots agreed for post-project implementation
	M6	**Supply chain groups established (retailer, processor, farmers)**		**31/03/2023**		
	M11	**Evidence-base complete & presented to supply chains (D3.4, 3.5, 5.2)**		**31/12/2023**		
	M18	**Post-project supply chain pilot agreed (letter of intent)**		**31/03/2025**		
WP6. DEMONSTRATION AND DISSEMINATION. LEAD: GB.	D6.1	Demonstration	On-farm demonstration events (farmer meetings, industry events and retail)	31/03/2025	Farmer/industry contact list; communications team; catering	Attendance (number and role within the sector); Feedback.

WORK PACKAGES		MILESTONE / DELIVERABLE	TASK/ACTIVITY	COMPLETION DATE	RESOURCES REQUIRED	SUCCESS CRITERIA
COST: £258k.	D6.2	Dissemination	Dissemination to wider; conference proceedings / scientific outputs; policy recommendations industry	31/03/2025	Project specific literature, media material, GreenShed economics;	Social media and website engagement; peer-reviewed publications; and policy briefs
	D6.2	Commercialisation plan	Develop business/operating model, refine target markets, develop marketing plan; refine pricing/service model	31/03/2025	Market and competitor analysis; finalised costings and agreed JV model	Commercialisation plan and route to market
	M15	**Completion of on-farm stakeholder engagement events**		**31/03/2025**		
	M16	**Completion of dissemination activities**		**31/03/2025**		
	M17	**Completed commercialisation plan**		**31/03/2025**		

Programme and business plan

Next steps of development

Roll out of GreenShed after completion of Phase 2, will be through the commercialisation of the integrated technologies into the beef farming sector. This will be facilitated through a Joint Venture of the technology consortium members. The key market opportunity, and initial target market, for GreenShed which has already been identified through Phase 1 research, is specialist beef finishing units. Following Phase 1, an outline ROI projection has been calculated (**Table 18** and **Table 19**).

Table 18. Summary of capital, operational costs, and incomes

	Capital Cost	Annual Running costs	Annual income / benefit
Shed "Galebreaker" sealing system	£38,000		£-
Heatpump / Air handling unit for shed	£65,000		£-
50 kW AD system	£125,000		£-
N2 plasma reactor	£62,000	£4,800	£9,200
Vertical farming unit	£30,000	£1,200	£24,000
100 kW Solar PV	£75,000		£1,500
Crop feedstock for AD system	£-		£-
Maintenance	£-	£20,000	£-
Beef sales "premium" for low carbon beef	£-	£-	£36,750
CHP Export electricity sales	£-	£-	
Heat usage	£-	£-	£3,000
Total	**395,000**	**£26,000**	**£74,450**

Table 19. Farmer rationale and target market

FARMER RATIONALE: 100-animal finishing unit	**TARGET MARKET: 5 yrs post-Phase 2 (2030)**
£320k capital; £50k increase in output: - fertiliser reduction - yield gain; horticulture output - beef sales premium (+20p/kg); export heat With operational costs = payback of c.8-9 years	UK: • 2,600 farms of 100+ head of cattle • 3% market penetration = 180 sheds EU: • 64,200 farms of 50-100 head of cattle • 0.5% market penetration = 320 sheds This yields ~90kt removal

How will this be informed by Phase 2

Phase 2 will firm up these calculations, based on the actual capital cost, operating cost and efficiencies measured within the pilot unit.

A critical component of this will be any “green beef premium” which can be secured from the beef supply chain in return for a sustainable, low carbon, high animal welfare beef product. Initial engagement with the supply chain, and particularly retailers, during and in the lead up to Phase 1, suggests a strong case for such a premium. Retailers and processors expressed an interest in further exploration (made possible by Phase 2) into the GHG and animal health impacts of the system, upon which such a premium would be contingent.

Phase 2 will enable the quantification of the price incentive that would be required to justify farmer investment, as well as an opportunity to carry out consumer research and engagement around the acceptability of the technology and willingness to pay for the benefits of reduced GHGs. Retailers and processors are clear that an “evidence-base” is critical for any firm commitment to such a premium can be made. This would include objective animal health and welfare outcomes, verification of GHG savings, and the initial and ongoing costs and savings arising.

Dependencies and assumptions

Successful roll out of GreenShed across the sector will depend upon:

- A producer incentive (most likely a price premium for low carbon beef) to justify producers to invest in the system, supported by the downstream beef value chain.
- A willingness from consumers to pay more for a low carbon beef product.

The commercial model is also based on the following assumptions:

- Beef production will continue to become more specialised: a polarisation between extensively produced suckled beef from mainly upland areas, and intensively reared commercial beef produced from dairy-bred calves on largely indoor production systems.
- The beef industry will strive towards achieving its net zero ambition, through production efficiencies and technology solutions. The cost of these will be shared along the value chain.
- Society will continue to demand beef as a protein source, with increasing scrutiny on its sustainability credentials and GHG impact in particular.

APPENDICES

Appendix A. Further technical drawings

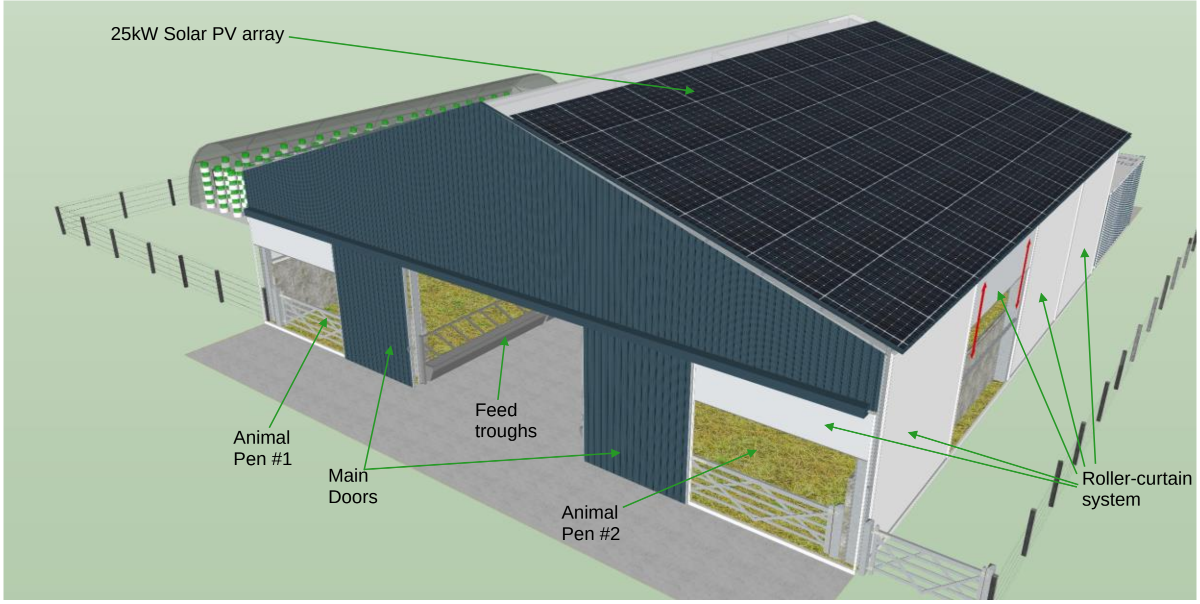


Figure 1. 3D external layout from the southwest

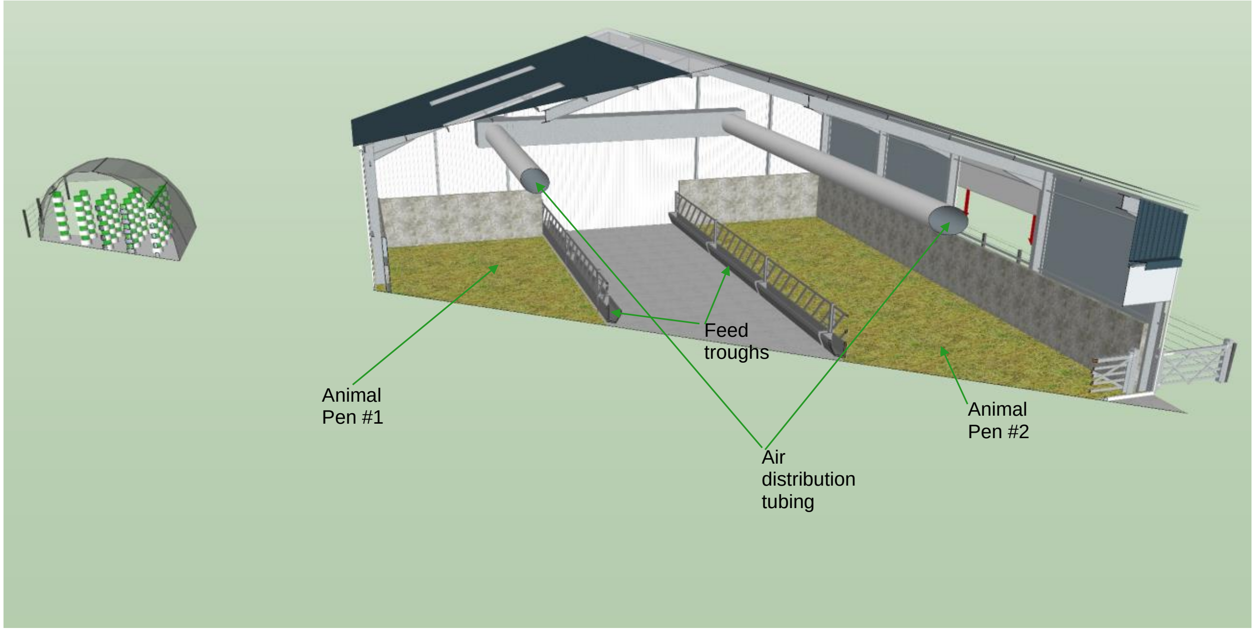


Figure 2. 3D internal section layout from northwest

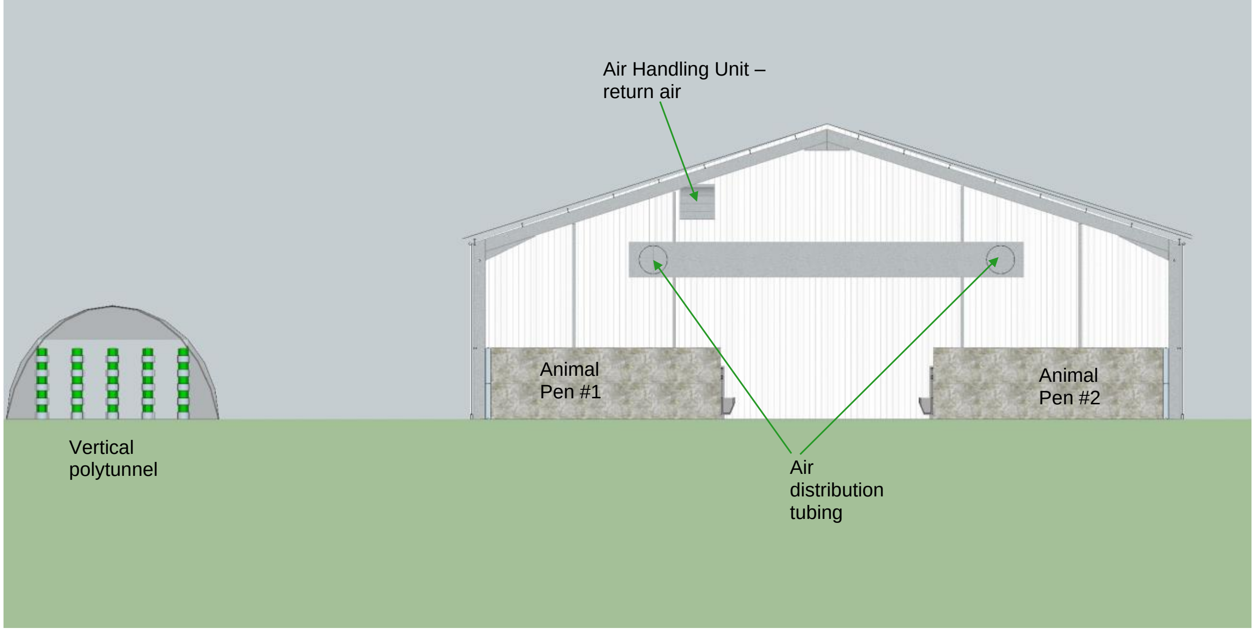


Figure 3. End plan section internal

Appendix B. Development of a detailed simulation model. Performance simulation of the GreenShed concept

Lead authors: Dr Nick Kelly & Dr Andrew Cowie, Energy Systems Research Unit, Dept. Mechanical and Aerospace Engineering, University of Strathclyde.

Summary

The report describes the modelling and performance simulation of the SRUC GreenShed concept. The goals of the simulations were to assess if 1) suitable indoor conditions could be maintained given the reduced fresh air required for CH_4 emissions control; 2) the energy requirements of the environmental control system, and 3) initial duties for heating, ventilation and air conditioning (HVAC) components.

Data collection was undertaken to gather information on the shed design and details of heat and contaminant gains from cattle. The GreenShed design was intended to house 100 cattle. Data on cattle carbon dioxide (CO_2) and CH_4 (CH_4) emissions were derived from test chamber data supplied by SRUC, data for cattle heat and moisture gains was derived from the literature. Using the collected data, high and low gains scenarios for cattle emissions were developed.

Modelling and simulation of the GreenShed concept was undertaken on the ESP-r building simulation software. An initial model was created in order to determine the likely indoor conditions, along with heating, cooling and dehumidification requirements over the course of a typical year. Four separate UK climates were analysed (in addition to the high and low cattle gains) in order to gauge the impact of location.

In these initial simulations, indoor conditions were maintained at those deemed comfortable for cattle, 15ºC, <80% RH and CO_2 levels < 1500 ppm. To maintain the required CO_2 level under the high cattle gains scenario, a fresh air flow rate of 2.9 m^3/s (10440 m^3/hour) was required. The simulation results indicated that comfort and contaminant criteria were met, at the expense of a high energy requirements and high maximum cooling and dehumidification demand of > 120 kW in all of the cases modelled. Heating demands were also appreciable at > 40 kW in all cases.

Subsequent simulations to reduce or offset heating and cooling demands, assessed the impact of reducing solar gains using a low emissivity material on the shed roof, putting photovoltaic (PV) panels of the shed roof, and relaxing the indoor temperature and relative humidity (RH). The low-emissivity roofing material had only a marginal effect on peak loads. However, the rooftop PV generated up to 100 kW of power and could offset up to 50% of cooling primary energy demand. Relaxing heating, cooling and humidity constraints eliminated the heating requirement and reduced sensible cooling demand by up to 90%. However, the dehumidification demand and energy use were still substantial at >40 kW and 250 MWh, respectively in all cases modelled.

To further investigate dehumidification and likely heating, ventilation and air conditioning (HVAC) component duties, two alternative versions of the model were created with

detailed representations of the HVAC system: one with cooling-coil-based dehumidification and the other with desiccant-wheel-based dehumidification. In these more detailed representations, the HVAC system was a separate recirculation loop from the aforementioned fresh air supply, operating at a flow rate of 8.9 m^3/s; this was calculated based on the amount of air required to supply to necessary cooling load. Recirculated air was extracted from the shed, cooled, dehumidified, and heated as required, and then supplied back to the shed.

Simulation of the more detailed model indicated that with dehumidification using the cooling coil (which cools the air to its dewpoint temperature), temperatures, humidity, and contaminants could all be kept within acceptable levels, for all UK climates and gains levels tested. However, this was at the expense of high cooling and heating-coil component loads and energy requirements (>100 kW cooling >100 kW heating, and in excess of 1 GWh per annum, respectively). With this system configuration, heat input from the heating coil was required to re-heat the air to an acceptable temperature for cattle comfort after it had been passed over the cooling coil for dehumidification.

The configuration with the desiccant dehumidification also maintained acceptable conditions and contaminant levels, but massively reduced both the total cooling coil energy requirement and heating coil energy requirement (in both cases by more than 90% as there was no need to cool the air to its dew point or re-heat), though this was offset by the heat energy needed to recharge the desiccant, of approximately 1 GWh per annum.

For both configurations, the duties for the main components have been calculated.

Finally, analysing the energy balance of the GreenShed system using the detailed model indicated that the energy consumption of both the cooling-coil-based HVAC system and the desiccant-based system could be offset using heat recovery from the engine and cooling coil, along with the electrical output of the engine and rooftop PV array.

Overview

The GreenShed concept relies on recovering CH_4 emissions from cattle housed indoors using a combination of a heating, ventilation, and air conditioning system (HVAC) and an engine unit. The HVAC system extracts the CH_4-rich air from the shed, heats or cools and de-humidifies it and then recirculates most of it, to maintain comfortable conditions for the cattle.

Aim

The aim of this work package was to develop a detailed model of the GreenShed concept to determine its heating and cooling energy requirements, along with the likely indoor environmental conditions that would occur under a range of different operating scenarios, including different climates and cattle emissions levels under the optimised fresh air input.

Objectives

The specific objectives for the modelling work were as follows.

- Data collection for the development of a model.
- Development of the mathematical model.
- Development of operating scenarios for investigation using simulation.
- Simulation of performance and extraction of systems design data.

Modelling strategy

The goal of the modelling work was to determine the heating and cooling required to maintain comfortable conditions in the GreenShed, given the need to optimise the flow of fresh-air and extracted air. The means to assess both the indoor environmental conditions and the likely energy demand was to simulate the performance of a GreenShed against a range of operating conditions using a building simulation tool: ESP-r (ESRU, 2021). This is a long-established tool that explicitly computes the transient energy and mass transfer processes in a building over a user-defined time interval (e.g., a day, a year, etc.).

A basic ESP-r building model comprises a 3-D building geometry, coupled with explicit details of constructions, internal heat gains and heating/cooling control requirements (set points). This basic model can also be augmented with a detailed sub-model of 1) any heating, ventilation, and air conditioning system (HVAC) serving the building, and 2) the building's air flow and contaminant dispersion. The technical basis of ESP-r is described in detail by Clarke (2001). ESP-r's has been extensively validated and many of these validation efforts are summarised by Strachan et al (2008).

Collection of data for model development

Prior to development of the simulation model, the data needed to build the model and assess its performance had to be collated. Information required included the following:

- Information on the geometry and constructions of the building.
- Details of the HVAC system required to service the building and intended indoor conditions (e.g., conditions set points).

- Details of likely heat, moisture and other metabolic emissions from the cattle housed in the shed.
- Climate data.

Geometry and constructions

The majority of the building information was derived from the initial design concept of SRUC, (2021a). This comprised a building featuring a pitched roof, with a maximum eave height of 5m and a 15° roof slope. The floor area was 720m^2 and the internal volume was 4760m^3. The building also featured basic external constructions, typical of Scottish cattle lairing. The roof was corrugated steel sheet. The upper vertical surfaces were slatted timber with a thin layer of impermeable flexible material (1mm thick) to minimise the risk of the leakage of CH_4-rich internal air to outside. The lower 2.4m of external wall are block construction. The floor is concrete slab, 150mm thick with hardcore and gravel below this.

HVAC system and set points

Similarly, the form of the HVAC system was derived from the initial GreenShed concept (SRUC, 2021a). The bulk of the environmental conditioning would be achieved by recirculating most of the air inside the shed through an air handling unit and cooling/dehumidifying it to off-set heat and moisture gains from the cattle.

To minimise the escape of CH_4 from the interior, the shed could be slightly depressurised, with the supply air flow rate 10% less than the extracted flow rate, with the balance airflow infiltrating from outside through gaps in the building fabric. This infiltrating air and the air entering via the supply fan would provide a minimum of 104 m^3/hour of fresh air supplied per animal.

In the preliminary simulations, the shed indoor temperature had to be maintained at 15°C and the relative humidity (RH) was limited to approximately 80%. According to SRUC (2021b), these constitute typical conditions where cattle are comfortable.

Heat and moisture gains

The GreenShed concept is intended to house 100 cattle each of which would be a source of heat, moisture, CO_2 and CH_4, that would have to be mitigated by the HVAC and engine system.

Data on cattle emissions was available from the SRUC's test chambers at Easter Howgate farm (Miller, 2021), this comprised a dataset of test results from approximately 140 animal tests. In these tests an animal was kept in a test chamber, with inlet and outlet air flow conditions monitored. For each test the airflow rate to and from each test chamber was recorded along with inlet and outlet temperatures, relative humidity, CH_4 and CO_2 levels. The data was processed to determine heat gains, moisture gains, CH_4 emissions and CO_2 emissions from each animal tested. This provided 120 reliable data points for each measured quantity. **Figure 4** shows the calculated CO_2 emissions from the test data plotted against animal live weight.

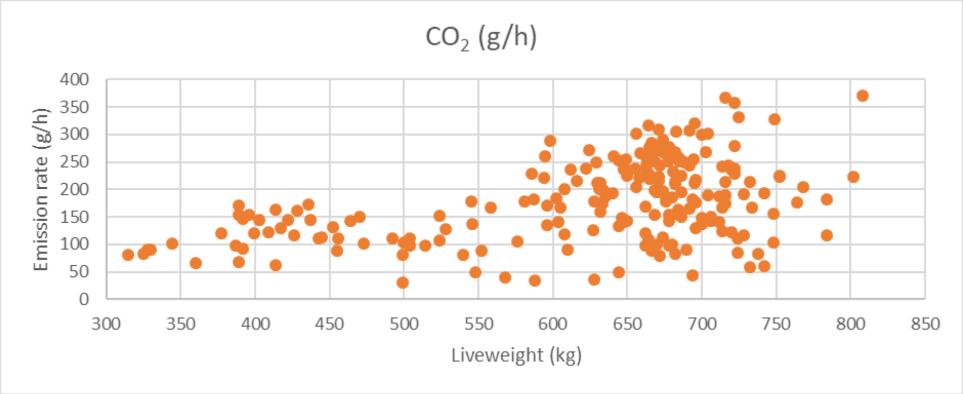


Figure 4. CO_2 emissions against animal live weight

The data shows a significant spread in the weight of animals tested and some correlation between body weight and CO_2 emissions. The test data indicates an average emission level of 177.8 g/h per animal, with a standard deviation of 72.8 g/h. This lies within the range of values observed in the literature e.g., 125.4 g/h from Australian research (Donoghue et al, 2020) and 396 g/h from Belgian Research (Jerome et al, 2014).

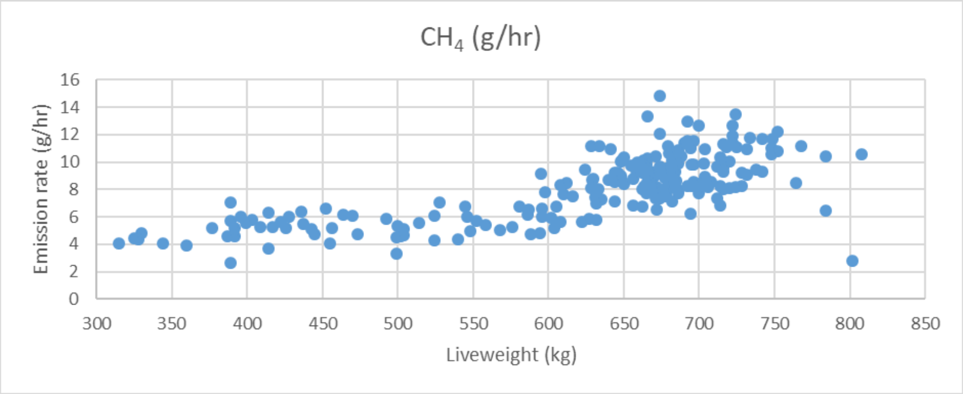


Figure 5. Methane (CH_4) emissions against animal live weight

As with the previous case, the data showed some correlation between body weight and CH_4 emissions from cattle (**Figure 5**). Average CH_4 emissions from SRUC tests indicated average emission levels of 8.1 g/h per animal with a standard deviation of 2.4 g/h. This is corroborated by Richmond et al (2015), who indicate that a typical CH_4 emission rate for cattle is 7.5 g/h per animal.

Due to the configuration of the test chamber monitoring system, it was not possible to extract reliable heat and moisture gain data from the test data. This was due to a cooling coil being placed between the monitored inlet air to each chamber and the inlet air temperature sensor. However, data is available from the literature:

- Webster (1973) reported total sensible and latent heat gain values between 578 and 1034 W. Neinaber et al (1993) report total gains of approximately 900W (640 W sensible 260 W latent).
- McLean et al (1972) undertook an experimental study that apportioned the different components of latent and sensible heat gain from cattle at 15 and 35°C. At 15°C, 82% of heat from cattle was sensible and 18% latent; the latent was split into 46% evaporative loss from the skin and 54% evaporative respiratory loss.
- In addition to moisture gains from the cattle, Jeppson (2000), measured an evaporative load of 130 g/hr per m^2 of cattle bedding. Assuming a bedding area of $5m^2$ per animal, this gives an additional load of 65 kg of moisture to the air per hour over and above that from the cattle.

Climate data

Building simulation is typically undertaken using hourly climate data as a boundary condition. The data used with ESP-r is: air temperature (°C), wind speed (m/s), wind direction (°), direct solar radiation (W/m^2), diffuse horizontal solar radiation (W/m^2) and relative humidity (%). Optionally, values of atmospheric pressure (Pa) and cloud cover can also be given. Annual climate data sets with hourly reading of the parameters listed were sourced for 4 different locations, which characterise the types of climate found in the UK.

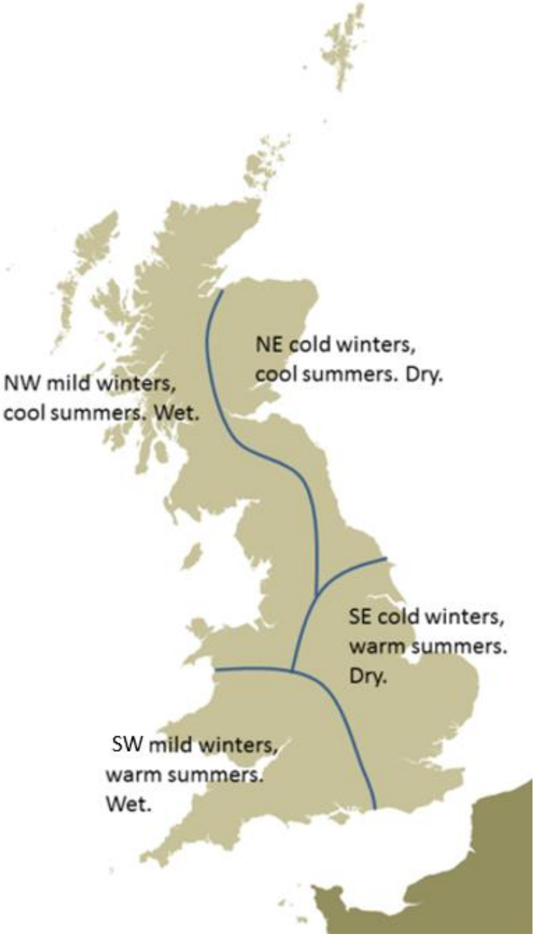


Figure 6. Basic UK climatic regions analysed in the simulations

Scenarios for performance analysis

The simulations are intended to assess the performance of the sheds environmental systems, of particular interest are the energy requirements for heating and cooling and the environmental conditions inside the shed (temperature, humidity, contaminant concentration levels, etc.), and whether or not these are conducive to bovine comfort.

As the GreenShed concept relies on a reduced intake of fresh air and limited extraction of indoor air, contaminant levels will be investigated. Additionally, given the relatively high heat and moisture gains from the cattle and the need to condition recirculated air, heating and cooling/dehumidification loads are of interest, along with conditions that may affect them. Consequently, the cases examined were:

- High and low gains and emissions from cattle – reflecting the different sizes of cattle that could be housed and their impact on energy requirements and conditions. The gains modelled were as shown in **Table 20** and represent gains from 100 animals. Both the CH_4 and CO_2 release rates were derived from the SRUC chamber data (**Figure 4** and **Figure 5**) and the heat and moisture gains were derived from SRUC (2021c), Miller (2021) and the literature sources cited previously.

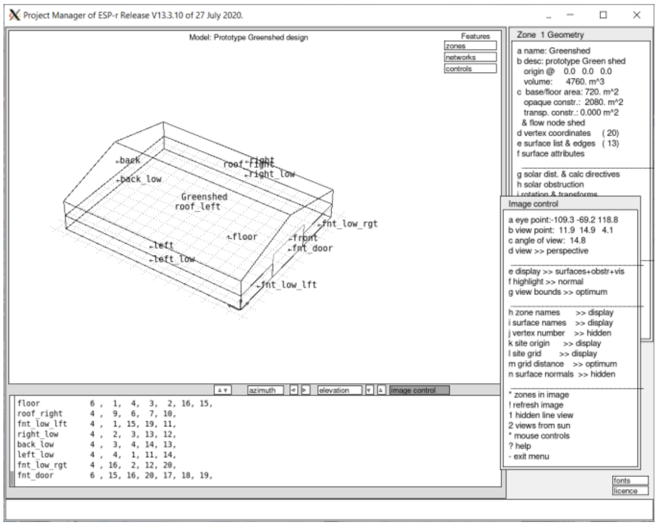
Table 20. High and Low Scenario Emissions from 100 cattle (derived from SRUC tests)

	Sensible heat gains (W)	Moisture gains (g/s)	CH_4 release rate (g/s)	CO_2 release rate (g/s)
High scenario (Hi Gains)	68,900	26.3	0.21	5.3
Low scenario (Lo Gains)	55,300	24.8	0.14	3.5

Modelling and simulation

Initial model

The initial model of the GreenShed concept (**Figure 7**) comprised the building geometry and materials, along with representative heat gains from cattle and a simplified representation of the environmental conditioning system, which mimicked the effect of the conditioning system on indoor conditions. ESP-r solved for the user-defined heating/cooling and humidity set points and then determined the heating/cooling demands[6] and energy required to deliver those conditions.



```
Zone  1 Geometry
a name: Greenshed
b desc: prototype Green shed
  origin @    0.0   0.0   0.0
  volume:      4760. m^3
c  base/floor area: 720. m^2
  opaque constr.:  2080. m^2
  transp. constr.: 0.000 m^2
 & flow node shed
d vertex coordinates     ( 20)
e surface list & edges   ( 13)
f surface attributes
 ____________________________
g solar dist. & calc directives
h solar obstruction
```

```
Image control
a eye point:-109.3 -69.2 118.8
b view point:  11.9  14.9   4.1
c angle of view:  14.8
d view >> perspective
 ____________________________
e display >> surfaces+obstr+vis
f highlight >> normal
g view bounds >> optimum
 ____________________________
h zone names      >> display
i surface names   >> display
j vertex number   >> hidden
k site origin     >> display
l site grid       >> display
m grid distance   >> optimum
n surface normals  >> hidden
 ____________________________
* zones in image
! refresh image
1 hidden line view
2 views from sun
* mouse controls
? help
- exit menu
```

```
floor          6 ,  1,  4,  3,  2, 16, 15,
roof_right     4 ,  9,  6,  7, 10,
fnt_low_lft    4 ,  1, 15, 19, 11,
right_low      4 ,  2,  3, 13, 12,
back_low       4 ,  3,  4, 14, 13,
left_low       4 ,  4,  1, 11, 14,
fnt_low_rgt    4 , 16,  2, 12, 20,
fnt_door       6 , 15, 16, 20, 17, 18, 19,
```

Figure 7. ESP-r model of the GreenShed building

---

[6] This is the energy that needs to be delivered to the interior of the shed to maintain conditions, not the energy consumed by the environmental conditioning plant, this is determined in later simulations.

Simulations

The simulations undertaken with the initial model are as shown in **Table 21**.

Table 21. Initial simulations

Model variants	NE Climate		NW Climate		SW Climate		SE Climate		Performance Metrics
	Lo	Hi	Lo	Hi	Lo	Hi	Lo	Hi	
1. Initial model	X	X	X	X	X	X	X	X	cooling requirement at high & low gains.

X – case simulated

The performance of the shed was simulated over a calendar year, with environmental conditions and energy exchanges calculated at half-hourly time intervals.

Results and comments

Figure 8 shows the maximum[7] sensible cooling (for temperature control) demand experienced in the shed over the year in order to maintain the indoor set point of 15°C. This indicated that whilst the cattle gains dominate, the influence of the climate is apparent with the southerly climates having a markedly higher cooling requirement, with a peak demand of over 80 kW.

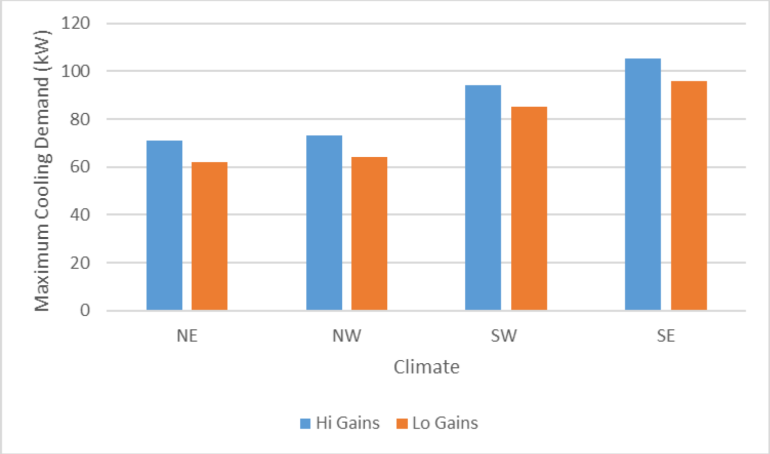


Figure 8. Maximum cooling demand

---

[7] Maximum cooling demands are the 95% percentile cooling demand, selected to reduce the influence of outlier cooling requirements.

The annual cooling energy demand is shown in **Figure 9** and follows a similar pattern.

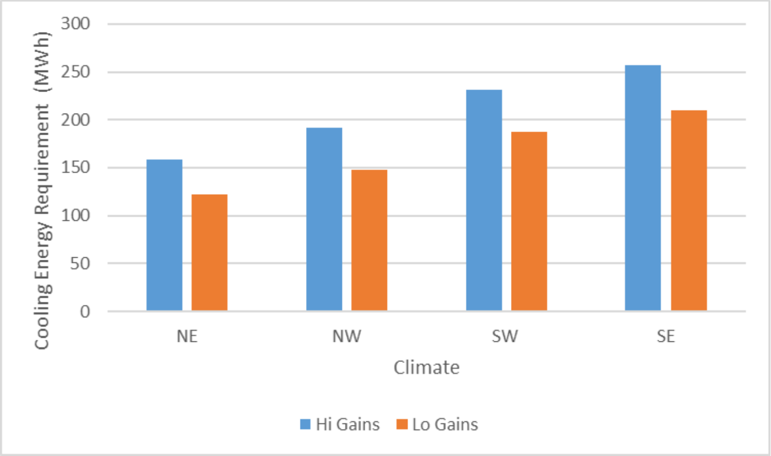


Figure 9. Annual sensible cooling energy requirement (MWh)

Figure 10 and **Figure 11** show the maximum latent cooling (dehumidification) demand (kW) and energy use (MWh), needed to keep the indoor humidity in the shed below 80% humidity. The load varied between 50-60 kW. The load is determined by moisture gains from the cattle and their bedding, there is limited influence from the local climate. Both dehumidification and sensible cooling will be required to maintain acceptable conditions.

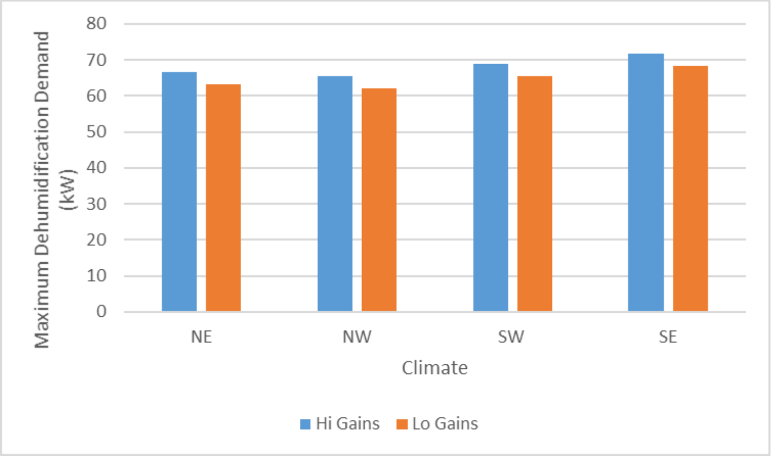


Figure 10. Maximum dehumidification (latent cooling) load (kW)

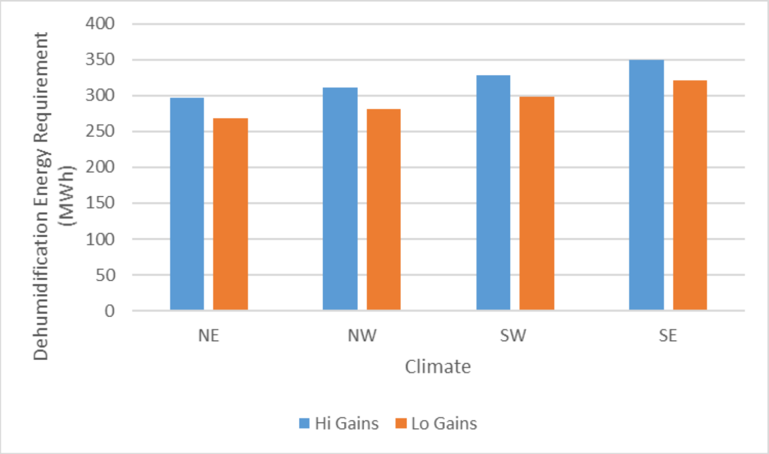


Figure 11. Annual dehumidification (latent cooling) energy requirement (MWh)

Figure 12 shows the maximum heating demand (kW) in the shed which is highest in the coldest region (North East) and ranges between 40-60 kW.

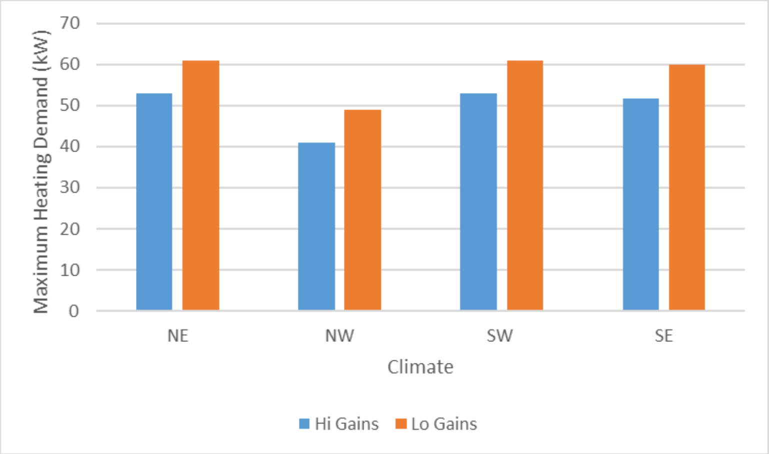


Figure 12. Maximum heating demand

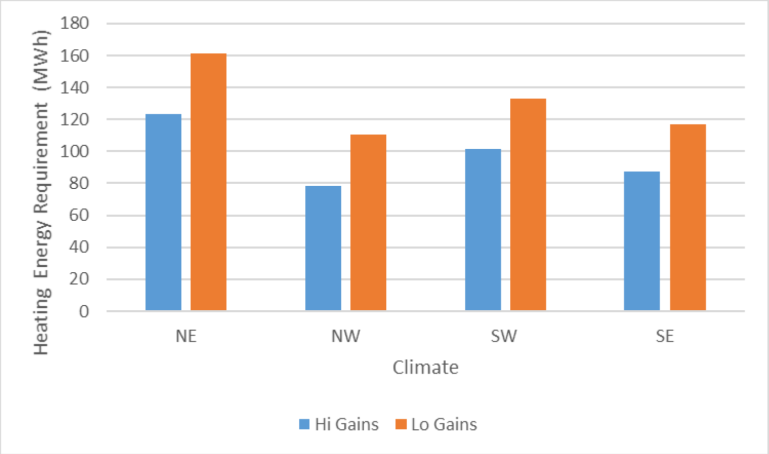


Figure 13. Annual heating energy requirement

Figure 14 and **Figure 15** show the maximum contaminant levels - CO_2 and CH_4, that were calculated over the simulated year.

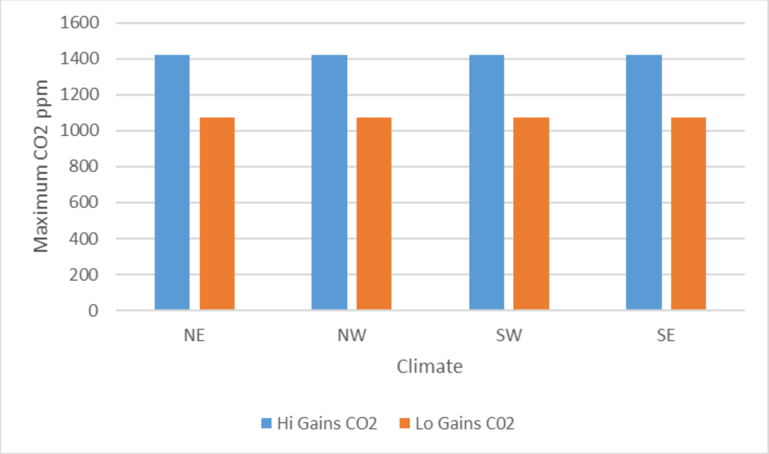


Figure 14. Maximum indoor CO_2 calculated in the annual simulation

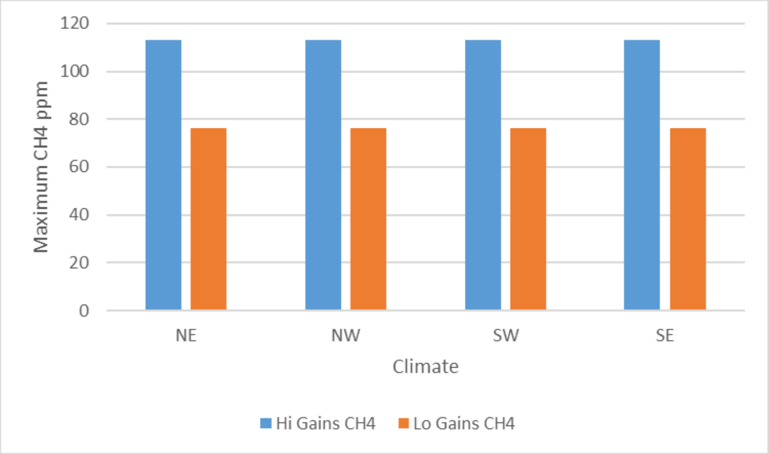


Figure 15. Maximum indoor CH_4 levels calculated in annual simulations

Contaminant levels maintained within the shed are acceptable, despite the limited fresh air in flow required in order to capture CH_4 emissions. Methane levels are well below the maximum exposure limit of 1000 ppm and CO_2 levels are below the maximum recommended value for cattle of 1500 ppm (SRUC, 2021c).

These preliminary results show that the heating, cooling and dehumidification demands are substantial, with combined cooling and dehumidification demand well in excess of 120 kW for the cases simulated. Additional simulations were undertaken to investigate ways to mitigate these high loads.

Solar load reduction, PV self-generation and constraints relaxation

The results indicated that whilst the majority of the cooling/ dehumidification load was removing the heat and moisture gains from the cattle, another contributor to the sensible cooling load was the solar gain on the roof of the shed. Further simulations were undertaken in order to attempt to reduce this load. These were:

1. Replacement of the existing metallic roof sheet material with a lower absorptivity/emissivity version (i.e., a reflective surface finish) to reduce the peak cooling requirements seen in the middle of the summer. The emissivity of the original roofing material was 0.75, this was replaced with a coated steel with a lower emissivity of 0.2
2. Addition of solar photovoltaic panels (PV) to the roof structure of the ESP-r model to produce electricity to attempt to offset or that required for the cooling plant. ESP-r calculates the electrical output of the rooftop PV array as a function of the incident solar radiation and material temperature. The development of the model and its validation is discussed at length by Kelly (1998). The details of the photovoltaic panels used are as shown in the Table below.

Table 22. PV panel details[8]

Open circuit voltage (V)	45.33
Short circuit current. (A)	13.79
Voltage at maximum power point (V)	37.99
Current at maximum power point (A)	12.9
Reference insolation (W/m^2)	1000
Reference temperature (K)	298
Number series connected cells (-)	22
Number of parallel connected branches (-)	6
Empirical temperature factor	10
H/W/D	2094x1134x35mm

3. Relaxation of indoor condition requirements. Following advice from SRUC (2021c), the model was adapted so that heating was used to heat the shed to a minimum of 4ºC in cooler weather and cooling was employed to keep peak temperatures below 22ºC. Between these conditions, temperature was allowed to ‘float’, with minimal heating or cooling input. Humidity was controlled to maintain conditions to 80% relative humidity or below.

---

[8] www.viridiansolar.co.uk

Simulations

As previously the simulations were run over a calendar year using the same climate datasets are outlined previously.

Table 23. Cooling load reduction/mitigation simulations

Model variants	Climate 1		Climate 2		Climate 3		Climate 4		Performance Metrics
	Lo	Hi	Lo	Hi	Lo	Hi	Lo	Hi	
2. Low emissivity roof	X	X	X	X	X	X	X	X	Heating and cooling requirement at high & low gains.
3. PV roof	X	X	X	X	X	X	X	X	Electrical power output from rooftop PV array.
4. Relaxed constraints	X	X	X	X	X	X	X	X	heating and cooling requirement at high & low gains.

X – case simulated

Results and comments

The sensible cooling demand[9] and total cooling energy use from the initial simulations and new simulations with more reflective roof, are shown in **Figure 16** and **Figure 17** respectively. These showed a small reduction in the peak cooling demand of between 4-12%. However, the cooling energy requirement over the year showed a slight increase. The reason for this is that reduced solar gains and daytime cooling loads due to reduced absorption of solar gains were offset by reduced heat radiated from the roof to the night time sky (as reduced absorption materials also have a lower radiative emissivity), resulting in slightly higher cooling loads at night. So, whilst this measure would be effective at slightly reducing the cooling capacity required for the shed, the overall impact is detrimental in terms of energy use.

---

[9] Reducing solar gain has a direct effect on sensible cooling requirements, but little or no effect on latent cooling loads which is dominated by cattle moisture emissions.

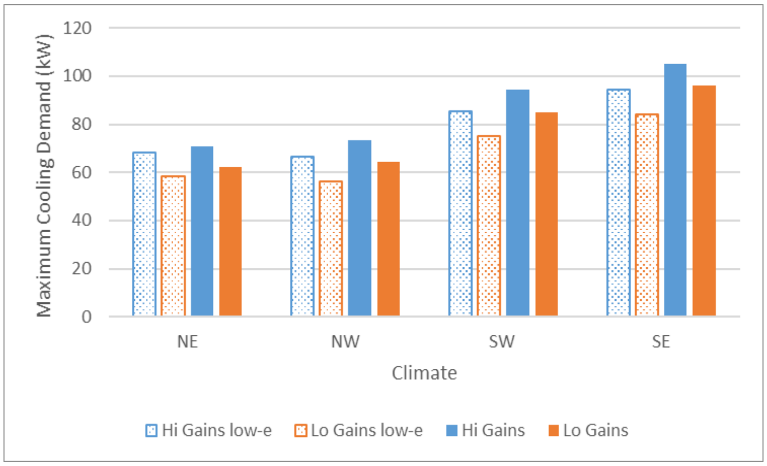


Figure 16. Sensible cooling demand (kW) with low-e roofing and original roofing

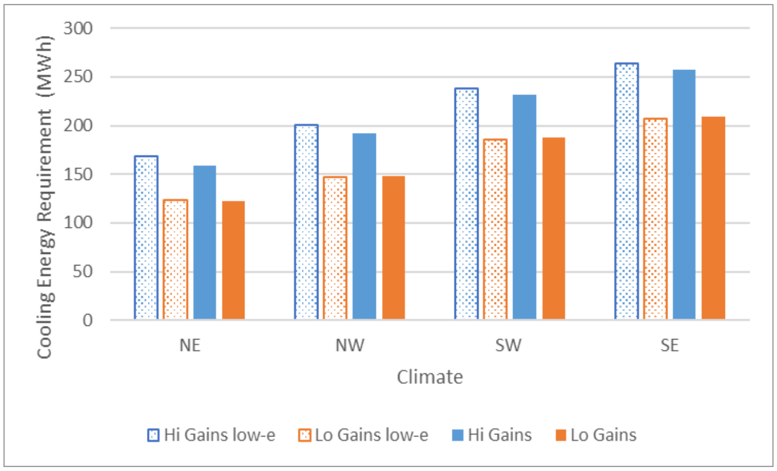


Figure 17. Sensible cooling annual energy demand (kWh) with low-e roof

Figure 18 shows the calculated peak powers from the PV array on the rooftop of the shed. These were broadly similar for all of the UK climates simulated, at around 100 kW. The peak power output was of the same order of magnitude as the combined cooling and dehumidification load. The average over the simulated year was significantly lower at 11-13 kW. Note that levels of cattle gains have no impact on the PV output and so the hi/lo gains cases are not shown on the graphs.

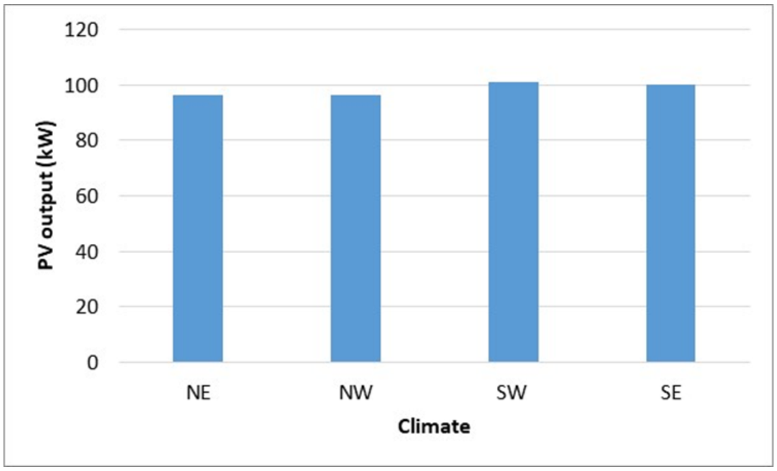


Figure 18. Peak and average power output from PV array

The annual energy output from the PV array is shown on **Figure 19**. The PV output was equivalent to 18-25% of the cooling requirement. If vapour-compression cooling plant with a coefficient of performance of 2 was used to provide the cooling, then the PV output could potentially cover 36-50% of the cooling energy requirements.

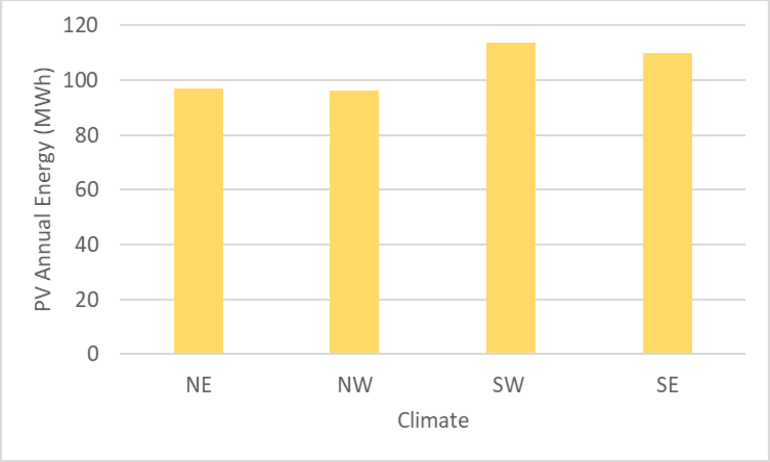


Figure 19. Annual energy yield from PV array (MWh)

The effect of relaxing temperature and humidity control constraints was to drop the heating load required for the GreenShed to zero, the heat from the housed cattle was sufficient to being the temperature up to the minimum of 4^{o}C.

The sensible cooling requirements were similarly dramatically reduced, as shown in **Figure 20** and **Figure 21**. Maximum cooling demand dropped to between 18-48% of the values seen in the initial simulations and the energy requirements were 10-30% of those seen in the initial simulations.

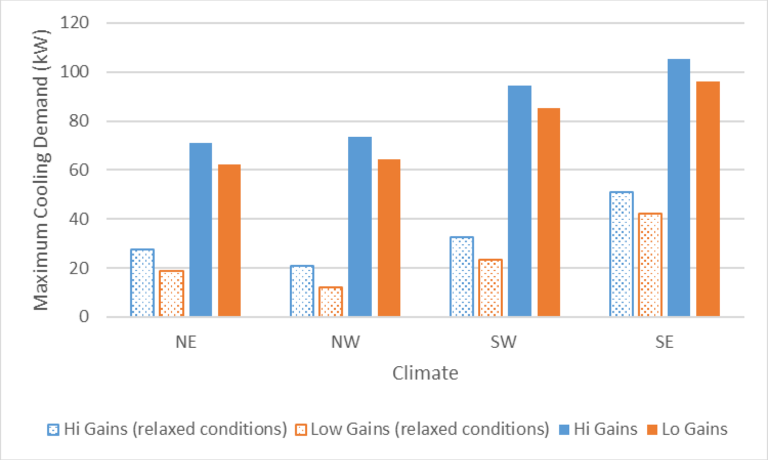


Figure 20. Maximum cooling demand (kW)

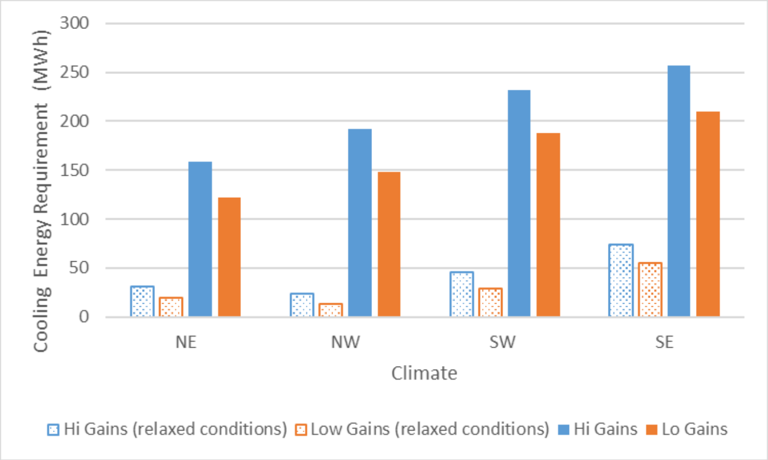


Figure 21. Cooling energy requirement (MWh)

The greater range of temperatures allowed in the shed had a small impact on the maximum dehumidification demand and dehumidification energy requirements. As shown in **Figure 22** and **Figure 23**. The maximum dehumidification demand dropped by 10-20 kW, however the dehumidification energy requirement was broadly similar, indeed in some cases with lower cattle heat gains, the energy requirement increased very slightly. This is likely because lower temperatures in the shed in spring and autumn due to the relaxed heating constraint resulted in increased time over which dehumidification was required.

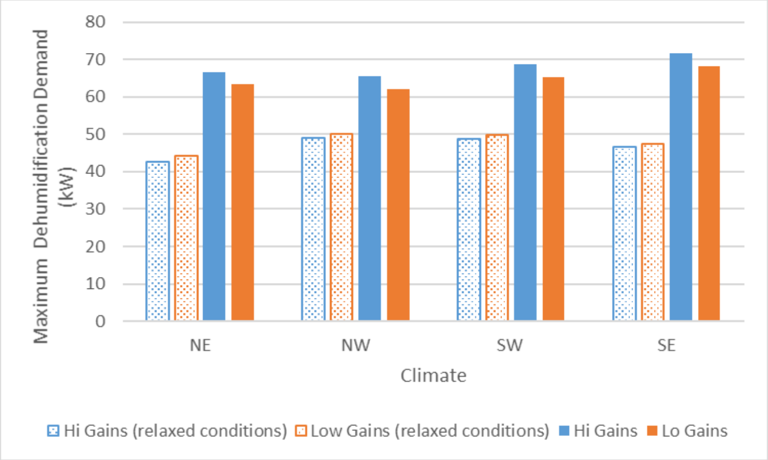


Figure 22. Maximum dehumidification demand (kW)

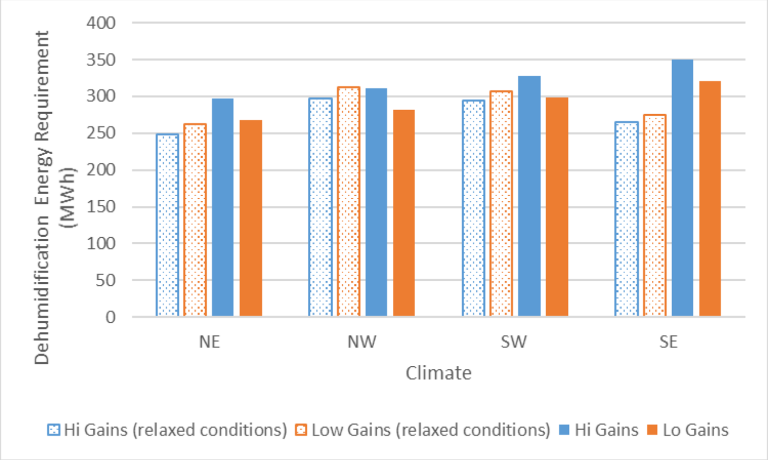


Figure 23. Dehumidification Energy Requirement (MWh)

Detailed model – explicit HVAC modelling

More detailed modelling of the GreenShed concept was undertaken, where the HVAC system servicing the shed was modelled in more detail, with primary components such as fans, heating and cooling coils explicitly modelled. Whilst the previous model could deliver information on energy requirements only, the more detailed model could determine the likely duty (kW) for heating, cooling and dehumidification components, which will be required when specifying the equipment for a prototype facility.

Two different HVAC system models were developed, to assess different approaches to dehumidification. The first, included a combined cooling and dehumidification coil and re-heat coil. The cooling coil cooled the recirculated air to its dew point to remove excess water vapour and a re-heat coil heated the air leaving the cooling coil to the temperature required to maintain comfort conditions in the shed. The second version used a desiccant dehumidification system (desiccant wheel), where the desiccant material removed the excess moisture from the recirculated air and the cooling coil was only responsible for sensible cooling. The desiccant was then recharged by heating.

Prior to undertaking these more detailed simulations, a number of pre-simulation steady-state calculations were undertaken to establish the likely HVAC flow rates of conditioned air needed to maintain stable temperatures, relative humidity (RH) and contaminant levels (CO_2, CH_4).

The results from this exercise indicated that supplying the flow rate of conditioned air needed to maintain temperature levels in the GreenShed should also be sufficient to allow control of moisture. This flow rate was calculated as 8.9 m^3/s for a CAV system. Similarly, it was concluded that a fresh air supply rate sufficient to maintain the CO_2 limit of 1500 ppmv (2.9 m^3/s) was more than sufficient to maintain safe levels of CH_4.

Simulations

A similar set of simulations to those undertaken with the basic model were performed. These featured the four UK climate zones and high and low cattle gains. Again, performance was assessed over a simulated calendar year.

Table 24. Detailed HVAC simulations

Model variants	Climate 1		Climate 2		Climate 3		Climate 4		Performance Metrics
	Lo	Hi	Lo	Hi	Lo	Hi	Lo	Hi	
5. HVAC w/ coil dehumidification	X	X	X	X	X	X	X	X	Coil loads, humidity, CO_2, CH_4
6. HVAC w/ desiccant dehumidification	X	X	X	X	X	X	X	X	Coil loads, humidity, CO_2, CH_4

X – case simulated

The component capacities used in the model are shown in **Table 25**.

Table 25. Details of components used in ESP-r GreenShed HVAC model

Component	Capacity	Comments
Fresh air supply & extract fans	2.9 m^3/s	Flow rate was determined based on the 1500 ppm limit (determined from pre-simulation calculations)
Recirculation fan	8.9 m^3/s	Flow rate determined based on pre-simulation calculations of cooling load
Heating coil	200 kW	Coil capacity based on initial simulations of heating requirement and set so capacity > likely maximum load, so maximum duty can be determined
Cooling/dehumidification coil	200 kW	Coil capacity based on initial simulation of cooling and dehumidification requirements, capacity > likely maximum demand so maximum duty can be determined
Desiccant wheel	150 kW	Based on the initial simulations of dehumidification requirements.

The supply and extract fans were controlled to maintain indoor CO_2 below 1500 PPM, which was the limit of acceptability for cattle (SRUC, 2021c). The cooling coil was controlled to maintain the relative humidity in the shed below 80%. The heating coil was controlled to maintain indoor temperatures between 4 and 22^{o}C.

The performance of the model was assessed by simulating against a year's worth of climate data for both of the cattle gains levels and HVAC configurations.

Four separate climate sets were investigated, which were representative of the UK's Northeast (NE), Northwest (NW), Southwest (SW) and Southeast (SE) climate zones.

The results that follow were therefore derived from a total of 16 simulations, with all heat and mass exchanges and state variables calculated at each hour of the simulated year.

Results and comments

Table 26-Table 29 show the key environmental metrics extracted from the modelled data. This shows that CO_2 and CH_4 concentrations are within acceptable levels (<1500 ppmv and 1000 ppmv, respectively), while peak temperatures[10] are within comfort limits for cattle, and RH is less than 80%.

---

[10] 95th percentile temperature and RH values were used here to remove the influence of short duration outlier conditions of system design and sizing

Table 26. Peak CO_2 levels (ppmv) calculated from simulation

CO_2 PPMV	NE	NW	SW	SE
HI GAINS CO_2	1435.4	1438	1439.2	1441.5
LO GAINS CO_2	1083.4	1085.1	1084.4	1084.9

Table 27. Peak CH_4 levels (ppmv) calculated from simulation

CH_4 PPMV	NE	NW	SW	SE
HI GAINS CH_4	114.4	114.6	114.9	115.3
LO GAINS CH_4	76.7	76.9	77.1	77.2

Table 28. Peak Temperatures (°C) calculated from simulation

PEAK TEMPERATURE °C	NE	NW	SW	SE
HI GAINS	17.9	17.4	18	19.1
LO GAINS	17.4	17	17.6	18.6

Table 29. Peak RH (%) calculated from simulation

PEAK RH (%)	NE	NW	SW	SE
HI GAINS	76.3	77	78	76.7
LO GAINS	76.2	76.9	78	76.6

Table 30 to **Table 35** show the HVAC peak loads[11] and energy use required to maintain conditions within the tabulated environmental conditions for the different climate gains levels and HVAC configurations tested. The results show that with cooling coil dehumidification, cooling coil and heating coil loads and energy use was very high, with the cooling coil requiring significant primary energy input.

With desiccant dehumidification, heating and cooling coil loads were dramatically reduced, but this is offset by the heat needed to re-charge the desiccant.

---

[11] 95th percentile values to ensure sizing isn't undertaken for outlier conditions.

Table 30. Heating coil peak load (kW) calculated from simulation

PEAK LOAD KW	NE	NW	SW	SE
HI GAINS – COIL	111.3	102.4	111.4	110.3
HI GAINS – DESICCANT	6.4	8	6.1	12.4
LO GAINS – COIL	116.5	108	116.8	116
LO GAINS -DESICCANT	10.9	12.7	10.9	17.3

Table 31. Heating coil annual energy use (MWh) calculated from simulation

ENERGY MWh	NE	NW	SW	SE
HI GAINS - COIL	634.2	577.8	570.6	548
HI GAINS -DESICCANT	6.9	9	6.5	13.4
LO GAINS – COIL	684.9	630.3	621.5	599.2
LO GAINS – DESICCANT	13.7	16.4	10.8	20.8

Table 32. Cooling coil peak load (kW) calculated from simulation

PEAK LOAD KW	NE	NW	SW	SE
HI GAINS – COIL	137.3	138.6	139.1	140.9
HI GAINS - DESICCANT	69.8	81	78.9	92.4
LO GAINS - COIL	136.8	138	138.4	140.4
LO GAINS - DESICCANT	61	58.6	69.9	83.3

Table 33. Cooling coil annual energy use (MWh) calculated from simulation

ENERGY MWh	NE	NW	SW	SE
HI GAINS – COIL	997.1	981.5	991.1	996.3
HI GAINS - DESICCANT	187.1	195.2	273.1	254.2
LO GAINS - COIL	984.4	971.9	983	991.4
LO GAINS -DESSICANT	148.4	155.2	223.6	211.9

Table 34. Peak desiccant recharge load (kW) calculated from simulation

DESICCANT RECHARGE KW	NE	NW	SW	SE
HI GAINS	155.6	165.3	173.1	158.4
LO GAINS	154	164	175.3	157.9

Table 35. Desiccant recharge energy (MWh) calculated from simulation

DESSICANT RECHARGE MWh	NE	NW	SW	SE
HI GAINS	1002.8	1116	1147.6	1030
LO GAINS	998.5	1114	1148.4	1033.2

Finally, the likely primary energy balance of the GreenShed system (**Table 36** and **Table 37**) was assessed using the simulated demand data, PV output and engine specifications. The assumptions behind this exercise are as follows: i) PV inverter efficiency was 95%; ii) the engine power output was 50 kW, with 55 kW thermal output iii) the heat from the cooling coil was recovered using a heat pump with a COP of 3 for heating and 2 for cooling; and iv) the total fan power consumption was 2.8 kW assuming a typical fan pressure rise of 200 Pa. The engine and fans were assumed to run continuously. In the tables that follow a –ve value denotes an energy demand and a +ve value an energy source.

Table 36. Energy balance (MWh) for HVAC with cooling-coil dehumidification

Cooling-Coil Dehumidification Annual Energy Balance (MWh)				
Electricity				
Climate	NE	NW	SW	SE
Cooling electricity (Hi)	-498.6	-490.8	-495.6	-498.2
Cooling electricity (Lo)	-492.2	-486.0	-491.5	-495.7
Fan electricity	-24.5	-24.5	-24.5	-24.5
PV electricity	92.3	91.5	108.1	104.6
Engine electricity	438.0	438.0	438.0	438.0
Electricity balance (Hi)	7.3	14.2	26.0	19.9
Electricity balance (Lo)	13.6	19.0	30.1	22.4
Heat				
Climate	NE	NW	SW	SE
Heating coil heat (Hi)	-634.2	-577.8	-570.6	-548
Heating coil heat (Lo)	-684.9	-630.3	-621.5	-599.2
Cooling recovered heat (Hi)	1495.7	1472.3	1486.7	1494.5
Cooling recovered heat (Lo)	1476.6	1457.9	1474.5	1487.1
Engine recovered heat	481.8	481.8	481.8	481.8
Heat balance (Hi)	1343.3	1376.3	1397.9	1428.3
Heat balance (Lo)	1273.5	1309.4	1334.8	1369.7
Net all energy (Hi)	1350.5	1390.5	1423.9	1448.2
Net all energy (Lo)	1287.1	1328.4	1364.9	1392.1

Table 37. Energy balance (MWh) for HVAC with desiccant dehumidification

Desiccant Dehumidification Annual Energy Balance (MWh)				
Electricity				
Climate	NE	NW	SW	SE
Cooling electricity (Hi)	-93.6	-97.6	-136.6	-127.1
Cooling electricity (Lo)	-74.2	-77.6	-111.8	-106.0
Fan electricity	-24.5	-24.5	-24.5	-24.5
PV electricity	92.3	91.5	108.1	104.6
Engine electricity	438.0	438.0	438.0	438.0
Electricity balance (Hi)	412.3	407.4	385.0	391.0
Electricity balance (Lo)	431.6	427.4	409.8	412.1
Heat				
Climate	NE	NW	SW	SE
Desiccant re-heat & heating coil (Hi)	-1009.7	-1125.0	-1154.1	-1043.4
Desiccant re-heat & heating coil (Lo)	-1012.2	-1130.4	-1159.2	-1054.0
Cooling recovered heat (Hi)	280.7	292.8	409.7	381.3
Cooling recovered heat (Lo)	222.6	232.8	335.4	317.9
Engine recovered heat	481.8	481.8	481.8	481.8
Heat balance (Hi)	-247.3	-350.4	-262.7	-180.3
Heat balance (Lo)	-307.8	-415.8	-342.0	-254.4
Net all energy (Hi)	919.8	919.8	919.8	919.8
Net all energy (Lo)	165.0	57.0	122.4	210.7

For the HVAC system with cooling-coil based dehumidification, the electricity consumption could be offset by the output from the engine unit and a roof top PV array and there is a substantial surplus of heat. With desiccant dehumidification there is a large surplus of electrical energy, but a small deficit in heat. However, in both cases the net energy balance (electricity and heat) is in surplus.

Conclusions

The results from the more detailed modelling (which builds on the results from the initial model) indicate that with a HVAC system with cooling-coil-based dehumidification, temperatures, humidity, and contaminants could all be kept within acceptable levels, for all UK climates and gains levels tested. However, this was at the expense of high cooling and heating loads and energy requirements (in excess of 100 kW and 1 GMWh per annum, respectively), energy for the high cooling load would be primary energy from the electricity network.

An alternative HVAC configuration with desiccant dehumidification massively reduced both the total cooling coil energy requirement and heating coil energy requirement, though this was offset by the heat energy needed to recharge the desiccant.

Analysing the energy balance of the GreenShed system, both the energy consumption of the cooling-coil-based HVAC system and the desiccant-based system could be offset using heat recovery from the engine and cooling coils, along with the electrical output form the engine unit and rooftop PV array.

The system component parameters derived from the simulations are shown in **Table 38**.

Table 38. Maximum component duties extracted from the simulation

Component	Approx. Maximum Duty	Comments
Recirculation fan	8.9 m^3/s	Required for a CAV system to maintain adequate indoor temperatures and humidity levels.
Fresh air supply/extract fan	2.9 m^3/s	Required to maintain CO_2 levels below 1500 ppm
Cooling coil dehumidification		
Cooling/dehumidification coil	141 kW	Required to maintain adequate humidity levels
Heating coil	117 kW	Required to maintain temperatures
Desiccant dehumidification		
Cooling coil	92 kW	Required for temperature control
Desiccant (recharge)	176 kW	Required to maintain humidity levels
Heating coil	18 kW	Required for temperature control
PV array	126 kW (peak capacity)	Offsetting cooling system primary energy demand.

References

Clarke, J. A. (2001). *Energy Simulation in Building Design* (2nd ed.). Butterworth-Heinemann.

Clarke, J. A., McLean, R. C., Kelly, N. J., & Johnstone, C. M. (1997). The prediction of mould growth in buildings. *Building Services Engineering Research and Technology*.

ESRU. (2021, July 28). *ESP-r download page*. Retrieved from Energy Systems Research Unit (ESRU) website: http://www.esru.strath.ac.uk/Programs/ESP-r.htm

Farquhar, J. (2019, February 21). Conversation on low carbon cattle shed details. (N. Kelly, Interviewer)

Jeppson, K.-H. (2000). Carbon Dioxide Emission and Water Evaporation from Deep Litter Systems. *journal of Agricultural Engineering Research*, 429-440.

Mclean, J. A., & Calvert, D. T. (1972). Influence of air humidity on the partition of heat exchanges in cattle. *Journal of Agricultural Science*, 303-307.

Neinaber, A. J., Hahn, G., & Ehrlehark, A. (1993). *Heat and Moisture Production and Dissipation in Beef Cattle.* Nebraska: U.S. Meat Animal Research Center.

Richmond, A. S., Wylie, A. R., Laidlaw, A. S., & Lively, F. O. (2015). Methane emissions from beef cattle grazing on semi-natural upland and improved lowland grasslands. *Animal*, 130-137.

Strachan, P., Kokogiannakis, G., & Macdonald, I. (2008). History and Development of Validation with the ESP-r Simulation Program. *Building and Environment 43 (4)*, 601-609.

Webster, A. J. (1973). Heat Loss from Cattle with Particular Emphasis on the Effects of Cold. In L. E. edited by J. L. Monteith, *Heat Loss from Animals and Man: Assessment and Control represents the Proceedings of the Twentieth Easter School in Agricultural Science.* Butterworths.

Appendix C. Market report

Objectives and scope

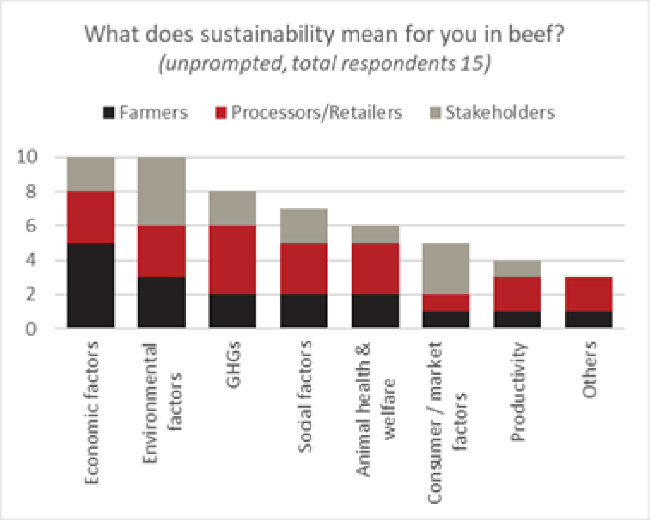
The commercial research aims to help inform the project by exploring the market perceptions of the GreenShed concept. This also highlights drivers and barriers to uptake, including considerations for technical design and business model.

The objective was to engage a cross-section of the beef supply chain: including farmers, processors, retailers and other industry bodies and stakeholders, with individuals responsible for production, sourcing, or sustainability. The research was conducted via one-to-one interviews, mainly conducted online, using a semi-structured topic guide (a copy is included at the end of this appendix).

The topic guide structure explored the background and context of the organisation being represented. This focussed on their role and remit in the beef supply chain; their understanding and perception of key sustainability issues for the UK beef sector and future vision for the industry; their initial reaction to an overview of the GreenShed concept; and an exploration of how their view of sustainable beef reconciles with GreenShed.

In total 16 interviews were conducted, including: 5 farmers; 2 processors; 4 retailers and 5 industry stakeholders.

Sustainable beef production



Respondents recognised a broad range of factors associated with sustainable beef production. **Economic and financial factors** (67%), **environmental factors** (67%), **GHG emissions** (53%), social factors (47%), animal health and welfare (40%), market/consumer factors (33%), productivity (27%) were all highlighted in unprompted responses.

There were differences by respondent type, with all farmers interviewed identifying economic factors as critical to sustainability in beef, while processors and retailers most frequently identified GHG emissions (67%), and stakeholders most commonly identified environmental (100%) and consumer factors (75%).

Universally, respondents were clear that sustainable beef production should not become dominated by a single issue, such as GHG emissions, but should recognise a wide range of contributions made by the sector as well as challenges.

Sustainability must be hand-in-hand with profitability. If you do things in the right way you will look after the environment. When profitability is poor, corners are cut and the environment falls down the pecking order.

Farmer

Sustainability often never gets further than carbon. But there is a bigger picture, including social and financial areas too. Beef and sheep produce quality food that is cognisant in terms of the environmental jigsaw.

Stakeholder

Methane emissions is the main focus but there are others on the agenda as well. Sustainability means having engaged, innovative farmers who have the capital and support to invest. Sustainability is delivering what the customer wants.

Processor

Drilling down into specific aspects of sustainability also reinforces the recognition of the complexity of issues contributing to sustainable beef production. Processors, retailers and industry stakeholders saw **GHG emissions** as being more important than did farmers. While farmers recognise GHGs are high on the agenda, they feel less able to influence this and are defensive in their language when discussing GHG emissions from cattle. For processors, retailers and stakeholders, there is a frustration that there is not a universal way to quantify GHG emissions holistically to measure progress and benchmark between food sectors.

I am not seeing the connection personally; we can't see it or quantify it and until then I can't do much about it.

Farmer

It is a bigger direct threat to public perception, policy and retailers. GHGs are not going to put anyone [farmers] *out of business unless there is a tax or levy on emissions.*

Stakeholder

The industry is challenged on this from all sides, it is THE climate change challenge, but there is a lack of research about individual gases and how livestock fits into the overall balance.

Processor

It is a significant issue, but it is claimed to be a bigger problem than it really is. Cattle emissions have a short cycle, and there are less cows on the planet than ever before. Cars are much worse, producing long-cycle gases. It is a big issue for the public, but there needs to be more understanding.

Farmer

In terms of farmers - there is a broad spectrum of awareness of sustainability, and there is a higher awareness than there was 3 - 4 years ago. They feel like they are scapegoats. They feel that they are ok as grassland sequesters carbon. There needs to be a way to measure where they are now to move forward, it is hard to motivate without a starting base.

Stakeholder

The biggest challenge is that there is no standardisation for measuring GHG emissions on farm.

Processor

Regardless of arguments about how GHGs are measured, by which methodology, cows still emit methane. We need to work on efficiency, days to finish, and how we are feeding cattle.

Retailer

Respondents identified complexities of **beef production systems** (especially the merits of **indoor vs outdoor production**), which they noted are not well understood outside of the industry. Regarding indoor and outdoor production systems, they recognise the value of diverse farming types and of farming systems being best suited to the land farmed. However, they acknowledge consumers in general prefer to see cattle at grass, but do not fully comprehend the advantages and disadvantages of each system.

Consistent beef finishing needs to be indoors. For reduced GHG emissions you need to keep the cattle for the least amount of time. The [suckler] *cows stay outside all year, it's about maintaining health and body condition as cheaply as possible – but the finishers need to be inside.*

Farmer

All cattle are indoor in the winter.

Farmer

We like to have them out to graze, but for bull beef it needs to be done intensively indoors, getting them finished to specification by 16 months or earlier – this is not possible outside.

Farmer

It's a dilemma. The image of Scottish beef is pasture-based. But in reality the vast majority have cereals in their ration. The most efficient beef system is indoor finished at a year old versus a 3 year animal on the hills.

Stakeholder

There is a place for both. If there was a total focus on GHGs all production would be intensive indoor, but this needs to be balanced.

Stakeholder

Consumers associate beef with outdoor production and want cattle to be outdoors. But the easiest way to reduce carbon footprint is to reduce days to slaughter on faster indoor systems. But there are good environmental arguments for longer life animals. There needs to be a middle ground: grazing and consumer acceptability versus short finishing periods. Also the industry is very segmented – an animal could live on 4 different farms before ending up in retail.

Stakeholder

For efficiency and reduced GHGs, they should be indoor; however consumer preference is not to see animals indoors but for them to be outdoors – we have seen this in dairy, pigs and other sectors.

Stakeholder

Consumers like to see that their food has been grazed outdoors so we will produce beef outside for at least part of their lifecycle. But there are many health and welfare benefits of indoor production, but this needs balancing with consumer demand.

Processor

We don't support one system over another – it is evidence-based and we respect that different systems work for different people in different environments.

Retailer

This is a big consumer issue rather than an actual sustainability problem. Customer perception is that indoor production is not sustainable, they expect cattle to be outside, although they do accept winter housing. Regenerative agriculture with outdoor grazed or mob grazing fits in well with reduced emissions. We need to look at how cattle are fed inside – increased soya can be damaging, but grass and forage-based diets much less so.

Retailer

Respondents identified related issues linked to the **impacts of feed** of sustainability, particularly a lack of general understanding of how different feeds are used in beef production. Farmers associate more closely to the practicalities and costs of feeding cattle in order to achieve required finish, whereas stakeholders, processors and retailers are more concerned with the public's perception of feeds and how they fit into the wider food system.

We try and utilise grass and silage in the ration as much as possible to reduce purchase feeds

Farmer

It links to breeding – you can finish traditional breeds off a grass based system, but larger Continental breeds are more difficult.

Farmer

Grass alone wouldn't get animals to market specification. We feed grain (mostly home-grown), a small amount of soya, molasses, beet pulp in winter and minerals. We buy straights to keep costs low and grow as much ourselves as possible. Calves get a pellet for the first 6-10 weeks.

Farmer

There is a huge opportunity for by-product feeds. For example soya use - we don't actually use that much of it but it always gets jumped on. It is always the US system quoted, whereas UK systems are very different. Feed is not that big an issue, but perceptions make it bigger.

Stakeholder

87% of cattle are on a predominantly forage (grass or silage) based diet. We have quite low soya use (though most people would rather it was zero) – according to the Roundtable for Sustainable Soya around 5% goes into beef diets. However there are few alternatives. Cattle are very good at converting waste products into useful protein; consumers don't understand this: most barley and wheat is grown for human consumption, only the low grade goes to cattle – this is a waste product. Many waste products from the food industry are fed to cattle – from surplus dough to orange peel. In this way cattle are in fact very sustainable.

Stakeholder

We need to optimise growth and days to slaughter. The intensive feed period is only short, less than 10% of total life. Underfed, under finished animals cost more to finish and process. They need the most appropriate protein source, which could be soy, for this short period. Generally livestock feed is waste from other processes. Can we grow enough of alternative proteins (lupin, beans and so on) sustainably to replace soya? The focus should be on efficiency – a shorter time on farm gives both environmental and financial savings.

Processor

We encourage farmers onto forage-based diets, and looking into herbal leys and mixed swards. Imported feed is a challenge – we shouldn't need soya to produce beef – we don't ban it but discourage its use, we want to move away from feeding soya. It's also about measuring feed and its impact on performance.

Retailer

Soil and water impacts were seen as important but in different ways. Several issues were identified, including manure management, soil fertility, soil carbon sequestration, water supply and use – with both surplus and deficits identified depending on individual experience. Overall the role of livestock (manures) in healthy soil systems was recognised and valued, though some areas, particularly around soil carbon, are not fully understood.

If you don't look after the soil the farm won't look after you. It is vitally important. We do soil mapping and soil testing to try to look after the soil.

Farmer

Manure is a huge source of nutrition for soils and reduces fertiliser purchases.

Farmer

Soil is increasingly important. We need better data on carbon sequestration – claims are not always backed up by good science. 99% of food comes from the soil – it is a finite resource and there will be increasing focus on how to maintain it.

Stakeholder

It is quoted that it takes about "17,000litres of water to produce 1kg of beef" but only 0.4% is water that humans could consume - it is mainly rain that falls onto the grass the cattle eat, so actual water consumption is low.

Stakeholder

We are doing research around soil and manure management, and we accept there are sustainability issues with run-off and effluent. We place huge focus on grass and grassland management, which feeds into economic sustainability as grass is cheap.

Processor

There is very variable soil health across farms, and beef has an opportunity to contribute positively to soil health. Beef as part of a regen livestock system, or supplying manures to arable systems.

Retailer

Animal disease is recognised by all as a major barrier to productivity and sustainability due to lost performance and financial impacts of disease and mortality.

This is a major problem, we vaccinate for many diseases and have started to see a response – using less antibiotic, but it is hard to get through a winter without any trouble and we still have to jab some. Variability in the temperature animals experience doesn't help, and stress is a big factor – moving cattle from different farms and into different groups, the weaning period. Stress in turn impacts the vaccine efficacy so we aim to reduce stress as much as possible. We have to learn from mistakes.

Farmer

At present this relates to issues like medicines use, AMR [antimicrobial resistance] *but in general the public assumption is that animals are generally healthy. There is a knowledge gap on the economic and GHG impacts diseases; data is often out of date – we haven't invested in quantifying the impacts beyond (and to limited extent) productivity.*

Stakeholder

This is a major issue, having both financial and productivity impacts. Diseases like BVD, Johnes and IBR cause diminished output over the animal's lifetime and increased time on farm which may not be recognised. It needs a much greater focus.

Processor

There is no silver bullet but healthy cattle are more productive and efficient – disease is a major blocker to productivity – wasted effort and resources, especially where it leads to mortality.

Retailer

This is a major problem. Government doesn't have a grip on it, whether it's BVD in Scotland or TB in England. We are not going to manage it without proper controls, persistent infectors are not being culled, people are working around the system. Technology to track movements and contacts has a significant role to play, it isn't a huge cost to put in place.

Farmer

Disease has a huge impact on production efficiency – mortality massively increases a farm's environmental footprint – not just late mortality but also calf losses. Antibiotic and anthelmintic use is not sustainable – there needs to be more accountability. There is a real need to join up environment and health and welfare. Endemic disease is the biggest contributor to animal welfare.

Stakeholder

The **economic sustainability** of the beef sector was by far the major threat highlighted by all respondents. Uncertainty around the future of public payments to agriculture is a significant concern to all respondents.

We have brought on a new enterprise, which has taken up winter accommodation from about 100 cows. We looked at reinvestment into cow housing but find this difficult to justify in the current trading environment and the lack of security of any farming subsidies. Without subsidies, our two herds are currently losing between £210-334 / head versus an industry figure of £276 loss based on the 2019 figures.

Farmer

This is a huge threat. Beef is more expensive than other meats, many consumers still buy on price. It would not necessarily be a bad thing if everyone cut their beef intake by 20% but spent more on British beef – a better opportunity for high welfare, low GHG product. Uncertainty around ELMS and the economics of beef production is the biggest threat.

Stakeholder

In the beef supply chain farmers are not tied into contracts like in dairy, pig or poultry, minimising integration, security and efficiency. We have an 80/20 rule – 80% of product comes from 20% of suppliers who are loyal. The remaining 80% of suppliers have no integration. We (like other processors) have some integration, buying calves to place with a rearer then a finisher, but farmers need a financial stake in the animal to get the best performance.

Processor

Margins are very tight and not sustainable. Subsidies have created very cheap food. Pence changes in price have a huge impact of profitability as margins are so thin. Low margins reduce NPD – vegan foods have shown lots of NPD which drives consumer interest. Lockdown has seen a return to scratch cooking for many and driven retailer interest in targeting the market but NPD remains a challenge.

Stakeholder

The Number 1 issue. Farmers are looking to make capital investments unless something is absolutely proven and will make quick returns. They are very risk averse. Government financial support will be crucial and the appetite is there from farmers to invest for the future if they have confidence.

Retailer

You can't be in the green if you're in the red. There is a role of future public funding and changing agricultural payments.

Retailer

Variability in productivity between farms is seen as holding back overall supply chain and beef sector efficiency and sustainability. There is some frustration from those in the supply chain about the slow progress from some farmers in improving productivity and production efficiency – this is identified as a human rather than technical challenge. Farmers see that the segmented structure of the industry does not always drive effective decision making as not all farmers are connected to the market. At the same time, the wide range of production systems are also recognised, each with different productivity challenges and solutions.

I am an advocate of getting more uniform production linked to market requirements. Store cattle producers are not linked to the market and they get a premium through auctions that is not aligned to what the market wants.

Farmer

There is no 'one size fits all' – it is an individual approach to each farm. There is a huge opportunity to improve, but we need to benchmark the data and improve. Globally, UK has quite good productivity, but it could be better. Improving the bottom 25% is a challenge, although they may drop out with support changes and economics.

Stakeholder

The main barrier is psychological – getting farmers to recognise a need to change. The messages haven't changed for years – weighing, getting one calf per year, monitoring daily liveweight gain, pasture management… Subsidies have been a barrier to effective decision making.

Processor

There is an enormous bell curve of producers and productivity measures. Hobbyists, pedigree breeders, commercial beef producers all have different motivations, as well as skill levels, between producers.

Retailer

Trade and regulatory issues were identified as an important consideration though out of direct control of the beef sector. There were mixed views whether these present as challenges or opportunities, and the extent to which the market (driven especially by retailers) can ‘over-ride’ any potential threats from cheaper, lower-standard imports which may arrive through new trade agreements. There is concern from some that despite the important role of policy and regulation, policy-makers lack a good understanding of the complexities of the beef industry and its role in the wider farming and rural economy.

Legislation will be a big driver. Civil servants want fewer cows for the carbon footprint but don’t understand you can’t grow crops in place of cows, and you can’t grow nuts in Scotland! There is lots of naivety. They need to value local and British more.

Farmer

We need a strong brand, a ‘sellable’ product which is sought after worldwide, not having imports of less-scrutinised beef. We need support from Government – not to be reliant on payments but they have to provide support for certain practices, for the environment.

Farmer

I get fed up of hearing about getting rid of cows to hit sustainability goals; and Government talking about off-shoring targets. We can't rely on stopping production to reduce carbon. There needs to be more balanced knowledge at a ministerial level and civil servants - there is a lack of knowledge. They just think that cows are bad. Policy is being created with a lack of understanding.

Stakeholder

Retailers and processors can have a big role in setting buying policies which can impact the industry overnight – since often where one leads others follow.

Stakeholder

We service 50 markets with sales offices around the globe, both under trade deals and outside of those. The more markets are open to the UK, the more opportunities there are to add value. Government regulations are the only lever that will drive real change on farm, but there must be scalable change, not one size fits all. Assurance schemes are too slow. Retailers have too small influence with only a small number of farms they work with closely, and also they don’t buy the whole carcase.

Processor

There will be opportunities, especially in Asia-Pacific, but more for lamb than beef. We are 67% self-sufficient in beef. With more animals coming through due to changes in the dairy sector with dairy-bred calves, there is an opportunity to displace Irish beef (our main supply with a similar product), but many of our processors are Anglo-Irish. Australia, New Zealand and US are the largest global exporters with lots of available product – this is a dangerous situation. Not so much in the retail sector as they have all made commitments to British and consumers will hold them to account, but foodservice is a big unknown. UK is a high value target for these exporters.

Stakeholder

The Australian trade deal has created a lot of disquiet among farmers. However retailer buying standards are very different from legislative standards. Foodservice markets have less transparency and attention on standards, but retailers set their own standards which go well beyond legislation – it is not the only driver.

Retailer

Respondents recognise **changing consumer habits:** food choices, shopping and buying patterns and ethical preferences. There is a growing trend towards reducing meat consumption (as opposed to excluding meat altogether) which some respondents interpret as a threat, and others an opportunity to 'trade-up' buying choices. The impacts of Covid lockdowns are well noted, though respondents are unclear how long-lasting these will be.

It is difficult for processors, hard to balance the carcase. With a more uniform product it would be easier. Weather also impacts, like at the moment with the hot weather everyone has a barbeque – burgers are in high demand but not other cuts. Price is very important and beef is quite a high-priced protein.

Farmer

2019 data shows only 1-2% identify as vegan, 3% vegetarian, but 15% flexitarian – this is gaining momentum. It is not a threat if people eat less beef but better – spending more on quality and British.

Stakeholder

During lockdown beef and lamb sales went up as people reverted to comfort food, and spent more time preparing and cooking food and batch cooking – leading to larger packs, which is more efficient. It will be interesting to see which trends stick towards the end of the year.

Processor

Vegans haven't made a huge impact. With Covid people went back to meat and traditional cooking. Beef is still wanted and valued. Weather and seasonal changes have more impact. Butchers and farmers' direct sales did well during Covid, farm shops and local are doing well. It's now about keeping people engaged and enthusiastic, making it easy for them to buy local.

Farmer

Beef is increasingly seen as premium, luxury product, which gives challenges for carcase balance. Anecdotally a new restaurant opened up in our village which had on the menu 'ex-dairy cow rib eye steak'. There needs to be greater awareness and utilisation of the whole carcase and animal.

Stakeholder

Vegan and plant-based has a loud but very small impact. The more worrying trend is those 'unconscious reducers' of meat – they are never going to be vegetarian but just cut back a little for health or environmental reasons. Small cuts add up to a big difference across a lot of people.

Processor

With regard to industry **action on sustainability**, respondents recognise and cite a lot of activity, but there is a sense that this can be disparate and lacking in genuine collaboration and co-ordination across the industry. Retailers and processors have often set their own targets for sustainability and GHG emissions, while farmers are taking actions based on their own business or production system priorities.

We closely monitor production performance and the health status of the herd.

Farmer

With careful evaluation of feedstuffs we have purchased no protein in the last 12 months.

Farmer

There is a lot of 'scrabbling around' to try to find solutions. There needs to be an industry or global standard calculator on carbon footprint. There are too many labels which create siloes and barriers – regen, organic – whereas most farms will be doing a bit of all of these things. There needs to be more data and research which needs to be shared in a pre-competitive way.

Stakeholder

We have a sustainable farming group for each major farming sector including beef – this is still in its infancy but it is supporting better engagement with farmers around sustainability issues.

Retailer

As well as lots of ongoing work in our own supply chain, we engage with UK Cattle Sustainability Platform, EU Roundtable on Beef Sustainability, WRAP and Meat in a Net Zero World.

Retailer

Vision for the UK beef industry

A number of themes emerged as respondents described their vision for the future of the UK beef industry. One area in which views were split was around the future size of the sector. In general, they were positive, and five respondents anticipated increased beef production and consumption, whether driven by the UK or export markets. Two respondents aspired to maintaining the current size of the sector, while only one envisioned a decline in beef production. Many respondents envisioned reduced or sustained beef consumption in tandem with a trading-up on quality and sustainability.

Related to this was a vision for improved understanding of beef production and wider agriculture from the general public as well as policy-makers.

> *Our vision is to maintain beef consumption (it is unrealistic to grow this further), based on the Eat Well Plate as part of a balanced diet. Beef will need to have the credentials and information making a positive contribution to economic, environmental and social sustainability measures. A high quality, added value product, not eaten as often as we are used to*.
>
> ~ Retailer

> *A profitable beef industry, producing uniform animals in an efficient way to get the best from the land on each farm. A recognition of the role of cattle and support for local and British production - better understanding from government and the public*
>
> ~ Farmer

More aligned was a view that the beef sector, especially at farm level, would continue to polarise, with an increase in largely dairy-bred beef finished intensively and efficiently supplying the mainstream market, contrasted with a smaller but added-value, premium and high quality beef production from slower-grown, grazed animals from upland and suckler-cow systems. Linked to this, respondents' vision was for a beef industry which includes a range of production systems: upland and lowland, grazed and housed and suckled and dairy-bred beef production. Some respondents' vision included beef as part of an integrated production system recognising the role it plays in contributing to the sustainability of other agricultural outputs such as arable or sheep production.

> *Productive farms on a range of systems suited to the land such as upland and hill grazing, intensive finishing on the lowland.*
>
> ~ Processor

Another common area was the need for the industry to improve and build its sustainability credentials, and to ensure that these are well validated and communicated to consumers to enable an informed and confident choice of beef as a sustainably produced protein. In tandem with environment or climate sustainability, was a vision for a profitable beef industry.

> *Agriculture is as environmentally sustainable as possible. Facing the hard challenges - meeting tough net zero targets, straining every sinew to get there, and supporting farmers to make changes. An even landscape for judging sustainability - an equal lens on all products - so that consumers can make informed decisions on what products they buy and what impacts they have. Consumers who want to eat beef can do so with a clear conscience.*
>
> ~ Retailer

Also highlighted was a need for greater innovation, recognising the role of technology and data, in beef production, processing and marketing.

For the whole carcase to be used - less waste, and more awareness of the value and usefulness of the whole animal: it isn't just a steak. Precision, innovative, high standard premium product.

~Stakeholder

Data-driven systems which promote biodiversity, enhance circularity & improve efficiency

~Processor

GreenShed perceptions

GreenShed attracted interest and excitement in respondents' initial reactions to the high-level concept. They had initial questions about aspects of the integrated technologies and identified both opportunities and some potential concerns.

Questions related to the **physical set up and operation** of the shed, as well as its **technical efficacy and impact**, and the **financial cost and return**.

Where are the investment opportunities going to come from? Could this work with carbon offset/capture scheme?
Retailer

[Referring to horticulture module]
What about skills, packhouse infrastructure? Is the cropping seasonal; is the demand seasonal?
Stakeholder

On the circularity, does it incorporate the packaging wastes from feeds and other inputs? What about the diets fed to cattle, will it work with additives to reduce methane emissions?
Retailer

What is the cost of the setup?
Farmer

How big is it? Over what period should animals be housed?
Processor

What does it look like? If it's a big airy shed with good ventilation, windows with natural light, it can be "natural" - not like a pig or poultry building.
Retailer

What would be the impact on the lifetime emissions for cattle? It should be modelled for the full cycle vs the finishing or over-wintering period only.
Retailer

Concerns were in two areas only: **public acceptability** and **economic viability**.

It is highly unlikely to be cost effective and there may be alternative or more natural ways to achieve the same thing.
Farmer

You will need to be careful over image, but animals do need to be housed anyway; you have to manage outward perception
Processor

It seems like an expensive solution. ROI and cost:benefit analysis must be prioritised as part of a demonstrator.
Processor

Worried that consumer pressure for grazed animals might get in the way.
Processor

Customer perception is a real challenge - this is far from a natural environment for cattle. Consumers like to think of cows at grass, even with metrics to demonstrate the welfare and health of indoor cattle it is very difficult to market. We already struggle with the housed finishing units - customer perception surveys will be really important.
Retailer

Marketing will be a big issue – we don't want beef to be the new pigs and poultry: a Eurobarometer survey showed public perception of animal welfare is that beef is best followed by dairy then pigs and poultry. We don't want this to be considered a battery shed for cattle.
Stakeholder

Consumers won't want it. For housed or enclosed systems, in dairy we see an increasing move for cows at pasture.
Stakeholder

The drawbacks include the capital outlay, and how to integrate into existing buildings.
Farmer

The level of investment required would never achieve a return in the foreseeable future.
Farmer

The clear **opportunity** for GreenShed that emerged was for **specialist beef finishing units**. This aligns with our vision for GreenShed, focusing on the final stage of the beef production cycle in which almost all beef cattle are routinely housed, regardless of how they have been reared up to that point. However **wider opportunities** also recognised the contribution GreenShed could make to the overall sustainability of the sector and its alignment with the way the beef sector is already starting to evolve.

> I can see it working for specialised finishers – having a few finishing hubs dotted around the country – for the more intensive feeding period, the larger animals emit more. It could be a finishing hub for grass farmers. This is not what we are doing now but we have to think differently.
>
> Processor

> It would be suited as a 'partial' solution during finishing (perhaps as a cooperative asset) or rearing.
>
> Processor

> There is a place for all systems including intensively finished beef – this is a good use of technology to produce valuable products including the vertical farm, fertiliser and beef.
>
> Stakeholder

> It shows there can be a circular economy for beef – we see this in poultry, but not yet in beef and dairy
>
> Retailer

> Technically it looks like an effective measure in allowing beef production to contribute to Net Zero
>
> Farmer

> The beef supply chain is changing - there will be fewer suckler cows, more integrated supply chains, which can lead to new units and new infrastructure. Think of chicken shed design - outwardly it hasn't changed but inside there is much more technology. We have an aligned production chain - high specification calf units with links to dairy farms and bespoke genetics, dedicated rearers and finishers, all on our contracts. It is currently relatively niche, but these types of supply chains provide the opportunity to do things differently.
>
> Retailer

Following their initial perceptions, respondents were probed further on their views on the controlled environment, animal health and welfare, and GHG emissions reductions.

The controlled environment and animal health and welfare were strongly associated with respondents identifying that effective environmental controls would promote good animal health and welfare outcomes, as well as improved biosecurity. In particular the link between the efficacy of the ventilation system and respiratory disease was noted. However, provided the technology controlling the environment was effective, respondents had no concerns for animal health.

Animal welfare had a more mixed response. Overwhelmingly respondents had no major concerns for animal welfare, provided it was properly monitored, and the building had sufficient space for the animals to interact naturally, and provided enrichment, natural light and ‘fresh air’. One respondent noted that in research more animals generally choose to stay inside than go outside. Respondents supported an evidence-based empirical approach to the assessment of animal welfare. Of greater concern was the perception of animal welfare by consumers and the general public.

Regarding GHG emissions, the main queries were around whether there was any place in the system for dietary GHG inhibitors, and on the efficiency and reliability of the AD technology – which has historically gained a poor reputation for technical problems on farm, yet more recently has been the subject of further R&D to make the technology more suitable for smaller, modular systems – such as that proposed in GreenShed. The combination of enteric CH_4 capture with manure CH_4 was seen as highly positive, and this addresses both key sources of GHGs in cattle production, as well as offsetting the embedded GHGs in nitrogen fertiliser.

Some respondents wanted to see the level of ambition and capability of the system: could it produce carbon neutral, or even carbon negative beef? This underlines the ambition of the sector to address GHG emissions, and recognition of the need for new approaches. However, it was also pointed out that beef carbon footprint still has significant scope to be reduced through improved farm management practices targeting technical efficiency: such as improving conception rates, reducing mortality and animal disease, improving grassland management. The adoption of best practice on farm would indeed drive further efficiency and GHG reduction per unit of output, yet widespread behaviour change has long been challenging. GreenShed would enable commercial farmers already achieving good technical performance, businesses which are most likely to play a role in the future of beef production, to further drive down GHG emissions. It was recognised that GreenShed is not a 'silver bullet', but in combination with good farm management and animal husbandry it has a part to play in addressing the environmental footprint of beef production.

This was reflected in the way respondents felt GreenShed aligns with their vision for the beef sector: it is seen as a promising "part of the solution". The key concerns that are highlighted are once again related to the public image of the system, and its commercial viability.

> *This will be part of a suite of tools available to farmers. This is a system approach – a whole farm system of managing gases and outputs. However, it is at odds with 'grass fed' labels - consumer perception needs to be managed.*
>
> ~Processor

> *It aligns on most fronts except the consumer drive towards grazed beef.*
>
> ~Processor

> *I can see that it is a potential part of the jigsaw...however cows in fields are also part of the vision. But the feeder calves that go into unit would come from the highlands and the dairy industry.*
>
> ~Stakeholder

> *It covers the low carbon beef aspect (...) but it doesn't cover the environmental side so well, which is important for consumers. They want both, but probably want the environmental benefits more. Recent research showed consumers want to see rolling hills, green pastures with animals, not rewilding effects, lots of trees, turbines etc. Basically, traditional farming even if they don't want to eat meat.*
>
> ~Stakeholder

> *It could definitely have a place – it isn't shooting for the stars. The key elements are right environmentally, but scale is key for profitability; it must make a return.*
>
> ~Farmer

> *It raises concerns around perceived issues with animal welfare and (mis)understanding of climate change.*
>
> *It has the potential to significantly damage the Scotch Beef brand..*
>
> ~Farmer

> *It's a no-brainer - but it needs assessment on the commercial viability.*
>
> ~Retailer

> *It could be part of the solution. Part of our problem statement on net zero includes looking at cyclical production systems, buildings and gas utilisation..*
>
> ~Retailer

Respondents were interested to remain informed about the progress of the project and onward development of the technology and potential demonstrator.

Conclusions

Key conclusions from the commercial research are as follows:

- The sector recognises the importance of addressing its GHG emissions, alongside other important areas including wider environmental impact, animal health and welfare, consumer perceptions of beef.
- However, one of the greatest concerns is the economic sustainability of beef production.
- Farmers are unsure how to tackle GHG emissions, and are unlikely to do so without a clear route and economic incentive
- The industry sees an urgent need for a unified way of measuring GHG emissions across food production, recognising the wider contributions of the sector to social, environmental and economic sustainability.
- A sustainable beef production system should not only focus on one area; the challenges are wider than just the reduction of carbon footprint
- There are problems within the sector with run-off and effluent; could this be a positive to the GreenShed concept?
- There is significant scope to improve productivity: through improved animal health, genetics, nutrition, soil management and monitoring of animal performance. It is recognised that productivity directly influences GHG emissions, with more productive and efficient farms having a lower footprint.
- The diversity of beef production systems is valued and enables land to be used in the most appropriate and productive way. It is clear there is no single blueprint for beef production.

- The importance of consumers and their preferences and needs was acknowledged universally. There is a need to assure quality, sustainable and affordable beef, and to communicate this effectively with the public; how will this transcend post COP26?
- Respondents were positive about the future of beef and recognise forces for change. The trajectory of the beef sector is towards specialisation, with increasing numbers of animals derived from the dairy sector, and a reducing suckler herd. This is likely to lead to a polarisation between premium suckled, grass-fed beef and mainstream beef produced by more intensive indoor systems.
- GreenShed is seen as having a role in the future of the beef industry, particularly for specialist, intensive beef finishing units.
- With changes to the structure of farm subsidies; reduction in financial support to farmers, and continuation of low margins, there is apprehension on how farmers can invest in the GreenShed infrastructure.
- There remains uncertainty around both the commercial viability of GreenShed, in terms of the return on investment to producers, and the consumer acceptability of the system. This will require further research to fully address.

Recommendations

It is clear that further research is required into two aspects of GreenShed in order to fully establish the commercial feasibility:

- The commercial model for adoption by farmers and the supply chain.
- Consumer perceptions and acceptability of beef produced from GreenShed.

This is further elaborated below:

Commercial model for adoption:

- A clear understanding of capital cost for installation.
- A clear understanding of the running costs of the system.
- Quantification of technical efficiencies derived from anticipated improvements in animal health and productivity.
- Quantification and assurance of a “green beef premium” available to farmers who adopt the system, in return for a sustainable low-carbon beef product.
- The creation of models that demonstrate the cost and savings (£ and Carbon Reduction/Zero Carbon) taking into account of different systems (e.g., intensive indoor system; grass fed system). This modelling should also consider optimum cow numbers within the system.

Consumer acceptability:

- Data collection and independent assessment of animal health and welfare in the GreenShed system.
- Data collection and independent assessment of the holistic environmental impact of beef produced from GreenShed.
- Further processor and retailer engagement and exploration of this data
- Consumer research on perceptions and a depth of insight from focus groups

These two aspects are not mutually exclusive since the commercial viability will depend on consumer and supply acceptance and associated premium on the product.

This further research can only be carried out with a pilot demonstrator GreenShed system, allowing actual performance and financial data to be collected. It is unlikely that supply chain commitment to a premium will be secured without a demonstrator unit that retailers and processors can review and assess: GreenShed will not progress further unless a demonstrator unit is secured.

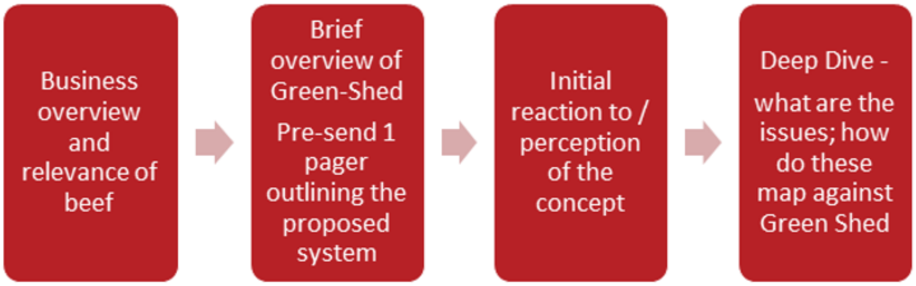
Customer and stakeholder research: topic guide

Research objectives and scope

Target 15-20 interviews across the value chain: farmers and farming representatives; beef processors; retailers; foodservice operators; animal welfare organisations

Targeting interviewees with responsibility for production, sourcing, or sustainability

Discussion scope



Topic guide

Note this is a guide for the interviewer, not a script, and is not shared with the interviewee

Interviewee name, job title and role/responsibility within the organisation

1. Overview of the business

PROCESSORS/RETAILERS/FOODSERVICE

  a. Scale of beef products within the business (volume or ££).
  b. Customer base
  c. Beef products – product ranges and specifications. Any premium pricing for specific ranges (at customer/consumer or producer level). Indication of relative scale of each product type
  d. Profile of beef – how significant is it to company reputation

FARMERS

    e. Scale of production – number of head etc
    f. Any other enterprises on the farm; how does beef fit into the overall farming system
    g. Production system details: e.g., dairy/suckler beef; age on entry/exit from system; extent of grazing; feeding system; finishing weights etc; source of calves/animals; breeds
    h. Supply chain: who do they sell to and how; are they part of any particular supply chain – if so, how does this work (is there a contract for specific production system, specification, pricing system etc)

NGO/STAKEHOLDERS

- Background to the organisation and role/scope
- Remit in beef: what is their role in the beef industry
- Who do they represent: farmers, consumers/society, supply chain etc.

2. Beef production
    a. What does sustainability mean for you in beef?
    b. What are the key challenges around sustainability (emphasise this includes environmental, animal welfare, social/political and economic) of beef production
    c. How significant are the following issues with beef production
        i. GHG emissions from cattle and manure
        ii. Indoor vs outdoor production (grazed/housed)
        iii. Feed impacts
        iv. Soil/water impacts
        v. Disease
        vi. Economic sustainability – ability of producers and supply chain to invest in their business; cost of production / gross margin
        vii. Productivity issues: carcase variability, breed, age etc
        viii. Consumption trends (flexitarianism/veganism/changing eating habits/behaviour)
        ix. Trade and regulatory landscape
        x. Other issues?
    d. What is the most important issue?
    e. Any action taken to address these issues in the business or supply chain – please describe
    f. What is your vision for the future of UK beef production and consumption
3. GreenShed perceptions
    a. Referring to GreenShed one-pager: what is your initial reaction / opinion / thoughts on the GreenShed concept?
    b. What are your views on:
        i. The controlled environment shed for housed cattle

        ii. Animal health/welfare considerations within the shed
        iii. GHG / carbon footprint reduction
        iv. Any other technological, operational or market considerations
    c. From your understanding of the GreenShed concept, to what extent does it address your vision for the beef industry? And why
4. Any other comments/issues not covered already.

Appendix D. Risk register

Table Key			
Likelihood (L)	**Unlikely: 1**	**Likely: 2**	**Highly Likely: 3**
Severity (S)	**Minor: 1**	**Moderate: 2**	**Major: 3**
Risk Rating (RR) **(Likelihood x Severity)**	**Low Risk: 1 – 2**	**Medium Risk: 3 - 4**	**High Risk: 5 - 6**
Residual Risk	**Risk rating after mitigation applied**		

Managerial Risks

Risk Description	**L**	**S**	**RR**	**Mitigation**	**Residual Risk**
The absence of a structured project management strategy compromising the project.	1	2	2	• SRUC will be in overall control of the project. • AEC will lead the Work Package and has extensive experienced in this role. • Individual WPs will be under the control of different partners. • Standard tools (e.g., MS Project, Microsoft Teams) will be utilised to track progress • Fortnightly Project Update Meetings • Monthly Monitoring Meetings ○ Partner Progress Reports ○ Progress Presentation ○ Project Plan	1

Risk Description	L	S	RR	Mitigation	Residual Risk
Delay to achievement of milestones or deliverables	1	2	2	• A detailed and realistic project plan has been created with clear milestones and deliverables associated with each WP. • Recovery plans will be developed when there is progress slippage.	1
Team member not technically capable of delivering on the work required.	1	3	3	• Each team member has a clear understanding of the input required with a track record in similar developments. • Shortcomings will be identified, and additional support provided where required.	2
Costs higher than expected.	2	2	4	• Cost targets set for each WP will be reviewed at Project Update Meetings so that overruns can be tackled early. • Claims will be submitted regularly and spend profiles adjusted.	2

Technical Risks

Risk Description	L	S	RR	Mitigation	Residual Risk
Design does not achieve GGR	1	3	3	• The proposed design is based on robust underpinning evidence from research at SRUC and modelling work from UoS. ○ SRUC has significant expertise in GHG emissions from agriculture and mitigation strategies ○ Phase 1 study (and previous feasibility work), conducted at SRUC's internationally recognised GreenCow facility.	2
Delay due to technology integration	2	3	6	• The proposed system, and aligned consortium, has been carefully selected to ensure availability of technical	3

Risk Description	L	S	RR	Mitigation	Residual Risk
				components and suitability for retrofitting onto commercial farm buildings.	
Build issues (power, foundations, accessibility).	2	2	4	• Build specifications and site planning will be conducted prior to installations. • The build will be controlled by No Pollution and co-ordinated by SAC consulting Ltd. (part of SRUC), with expertise in planning and installations of this type.	2
Capacity of available utility supply (backup power, drainage)	1	3	3	• Mitigated through access to two power supply points and drainage on two nearby steadings (controlled by SRUC).	2
Delays in securing appropriate permitted development notification approvals	1	2	2	• Mitigated through a speculative pre-Phase 2 application will be sought and appropriate time built into the workplan for securing permissions.	1
Delay due to animal availability	1	3	3	• Experimental activity will be handled by SRUC who have extensive experience in data gathering, animal experimentation. • Animals will be selected from current stock housed on the SRUC research farm.	1
Delay due to experimental permissions	1	2	2	• Experimental activity will be handled by SRUC who have extensive experience in data gathering, animal welfare assessments, animal experimentation and home office permissions.	1
A serious outbreak of notifiable disease	1	3	3	• Strict biosecurity protocols on experimental site will significantly reduce this risk.	2

Risk Description	L	S	RR	Mitigation	Residual Risk
Key personnel leave the project.	2	2	4	• There are extensive expertise overlaps within and between project partners. • Where required, additional resources will be identified from within the team or an external provider until a replacement is in place.	2
Government travel restrictions due to COVID-19	2	2	4	• Appropriate risk assessments and working policies are now in place on partner sites to allow for delivery of the work within COVID-19 restrictions. • Animal-based work will be conducted current SRUC H&S Guidelines and implemented in a manner which will accommodate social distancing with appropriate PPE as required.	2

Commercial Risks

Risk Description	L	S	RR	Mitigation	Residual Risk
Farmers are cautious about investing in new technologies.	2	3	6	• AEC and SRUC will lead on disseminating the positive benefits of the system to promote adoption. • Involvement of retailers will help with effective dissemination to the farming community through their current active and wide client base. • Dedicated work package to engage dedicated supply chains to develop and test model scenarios for incentivisation • Series of planned dissemination activities at key points throughout Phase 2 will include farmer meetings, open-days and mixed media platforms. • Market penetration will be effective as consortium includes key players from across the supply chain.	4

Risk Description	L	S	RR	Mitigation	Residual Risk
Supply chain engagement due to commercial sensitivity	2	3	6	• Two retailers have signed an NDA to participate in the project and have both engaged in Phase 1. Additional retailers and processors have engaged throughout Phase 1 with an ambition to participate in Phase 2.	3
Poor farmer confidence in solution as demonstrated on a research/education facility	2	2	4	• Mitigated through robust underpinning scientific testing and evidence provided by SRUC, SAC consulting's trusted relationship with network of farm subscribers (~7500), wide farm networks and stakeholders associated with each partner, support from partner communications and marketing teams and targeted stakeholder engagement activities.	2
An insufficient range of routes to market access.	1	2	2	• Access to UK and international markets provided by access to end users through ○ AEC membership ○ Retailer 1 and 2 supply chain ○ Partner networks.	2
IP - Freedom to operate.	2	2	4	• Freedom to operate has been established through full competitor analyses and patent search, which will be regularly updated throughout the project.	2
Design / Concept - IP protection	2	3	6	• Each partner has IP protection for their technology. • The partners will seek professional advice on the correct IP protection required to protect this unique design. If required Patent applications will be filed.	4

Appendix E. Phase 2 partners

SRUC. ACADEMIC LEAD

SRUC has a proven and highly respected track-record in delivering international quality research that has substantial impact on the UK agricultural industries. SRUC team members have scientific skills in ruminant production and efficiency, greenhouse gas (GHG) emissions from agriculture and measurement techniques, health and welfare, renewable energy, engineering for agricultural applications and advanced data analytics (including machine learning techniques). In terms of project management, the team has over 20 years' experience in running successful multi-partner projects from initial applications, and including project management, problem solving and partner and funder communication. SRUC will provide access to a dedicated beef research facility, including SRUC's GreenCow facility, an internationally leading GHG emissions research facility, as well as expert technical support for research farm trials.

Name:	**Dr Carol-Anne Duthie; PI**
Organisation:	Research Division, SRUC
Present position:	Researcher
Key areas of expertise:	Ruminant production systems; Optimising production efficiency; Environmental impact of ruminant systems; GHG mitigation strategies; GHG measurement techniques; Precision livestock farming, in particular monitoring technologies for individual animals (sheep, beef cattle and dairy cattle).
Professional profile:	Conducting and managing a portfolio of research projects. Extensive experience of collaborating in multidisciplinary programmes of work engaging across both industry and academia (>15 years). Over 40 peer-reviewed scientific publications. Former chair of the British Society of Animal Science Strategy and Innovation Committee, current member of the British Society of Animal Science Awards committee, current director of the Scottish Accreditation Board, current member of KTN's Animal Sector advisory board, and review editor for Frontiers in Animal Science (Precision Livestock Farming).

Name:	**Dr Gemma Miller; CO-I**
Organisation:	Research Division, SRUC
Present position:	Researcher
Key areas of expertise:	GHG measurement techniques, including development and testing of novel methods to measure enteric methane; Environmental impacts of ruminant production systems, including GHG mitigation strategies; Precision livestock farming, including sensors for automated and continuous monitoring of animals; Advanced data analytics, including machine learning techniques.
Professional profile:	Facility manager for SRUCs ‘GreenCow’ respiration chamber facility. Member of the National Farmers Union Scotland’s Climate Change Advisory Panel. Background in GHG emissions and mitigation from agriculture and the wider land-based sector. Member of reviewer board for Animals.

Name:	**Mr John Farquhar; Consultant/Researcher**
Organisation:	Consulting Division, SRUC
Present position:	Senior Renewables Consultant
Key areas of expertise:	Energy, mechanical design and engineering, carbon foot-printing.
Professional profile:	Senior renewables consultant with broad expertise and interest in mechanical engineering, sustainability, life cycle assessment and renewable energy. Technical support and design work for clients involved with renewable energy and energy recovery. Technical lead on the Innovate UK - Enerwater project, researching energy recovery from dairy processing refrigeration plant; Designer of the simplified GHG calculator for the RHI Biomass Suppliers List (BSL); Over 70 successful renewables installations, totalling over 50MW.

Name:	**Prof Marie Haskell; CO-I**
Organisation:	Research Division, SRUC
Present position:	Senior Researcher
Key areas of expertise:	Animal welfare and welfare assessment, animal behaviour,
Professional profile:	Marie Haskell has been involved in research into animal welfare and behaviour, with a focus on cattle, for over 30 years. She has expertise in the development and use of welfare assessment indicators and protocols and is also involved in research into the use of enrichment, animal emotional state and motivation. She has supervised over 15 PhD students to completion and lectures on a number of MSc and undergraduate programmes.

University of Strathclyde (UoS)

UoS - Energy Systems Research Unit (ESRU): has an international reputation for energy systems modelling and development and testing of low-carbon technologies. The ESRU team develop and maintain the ESP-r building simulation software, deployed by organisations around the world investigating the performance of buildings and their supporting electrical and heating systems and embedded renewables. Used to study a wide range of applications, from hydrogen-powered buildings to solar crop dryers. The group also has expertise in low-carbon combustion and cogeneration, developing the biomass boiler tool for the Carbon Trust and leading modelling activities in the International Energy Agency's Energy Conservation in Buildings Research Annex 42, developing calibrated models for fuel cell and other cogeneration technologies

Name:	**Dr Nicolas Kelly**
Organisation:	University of Strathclyde
Present position:	Reader in Mechanical and Aerospace Engineering; co-director ESRU
Key areas of expertise:	the built and indoor environment, building environmental conditioning, building-integrated microgeneration and renewable energy systems, technical software development, modelling of buildings and energy systems performance.
Professional profile:	25+ years' experience in built environment and energy systems engineering, extensive experience in multi-discipline research projects, including UK (EPSRC), EU Framework programmes, H2020 projects and International Energy Agency research annexes. Over 80 peer-reviewed publications. Coordinator of the University of Strathclyde's Energy Theme, Board Member of the Scottish Universities Energy Technology Partnership (ETP) and Scottish Chair of the International Building Performance Simulation Association (IBPSA).

Name:	**Andrew Cowie**
Organisation:	Energy Systems Research Unit, University of Strathclyde
Present position:	Research Associate
Key areas of expertise:	Building Energy Modelling, Computational Fluid Dynamics, Design Optimisation, Software Development
Professional profile:	Dr Cowie has an MEng in Civil and Structural Engineering and PhD from the University of Leeds focusing on building optimisation using simulation tools. He has been a member of ESRU since 2014 working on a range of projects including the EPSRC funded FITS project - modelling fabric integrated thermal storage in buildings, IEA Annex 66 on advanced occupancy modelling, the EU funded RUGGEDISED project, deploying smart energy solutions in cities and the GreenShed project, mitigating methane emissions from beef production.

No Pollution Industrial Systems Ltd. PROJECT LEAD

No Pollution has over 30 years' experience in custom mechanical and electrical engineering design and offer a comprehensive service in optimising production processes via maximising heat recovery and energy savings, with a specific focus on the food processing, agricultural and cardboard industries. In the last 10 years, the focus has been on precision-controlled climate chambers for research on gas emissions from livestock, which have been designed and installed in the most advanced agricultural institutes worldwide from the UK to Brazil and Australia. Its technical role in the project is to provide the air handling systems and installation support and maintenance for the commercial farm builds.

Name:	**Mr Giorgio Rivolta**
Organisation:	No Pollution Industrial Systems Ltd
Present position:	Technical Manager
Key areas of expertise:	Engineering Design, Energy Recovery, Precision Heating Ventilation and Air Conditioning
Professional profile:	Mechanical Engineer with 20 years' work experience in design and installation of bespoke soundproofing and thermo-insulating enclosures, heat recovery, precision HVAC and energy optimisation systems.

Galebreaker Agri Ltd. INDUSTRY PARTNER

Galebreaker designs and manufactures ventilation systems that optimise natural ventilation for livestock housing using the latest fabric with in-built UV protection and access technology to enhance housing conditions. Thirty years of experience has enabled the development of a range of environmental weather screen systems which provide ideal housing conditions for healthy, productive livestock. The systems provide variable ventilation, protection and light for the ideal environment, whilst meeting legislative requirements for excluding birds from crop storage and for milking parlours. Galebreaker is an ISO9001 accredited company operating from a purpose-built laboratory in Herefordshire and will be responsible for design and build of the shed seal, new fabric and manufacturing process and farm installation support and maintenance.

Name:	**Andrew Gardner**
Organisation:	Galebreaker Agri Ltd
Present position:	Senior Engineer
Key areas of expertise:	Responsible for the Engineering Department that carries out the design, development and project management for the Galebreaker product range. Product CAD for fabric doors, wind shields, automatically controlled ventilation curtains and ventilation light ridges.
Professional profile:	Senior product design engineer with 15+ years' experience developing hardware solutions for use in hostile outdoor conditions.

Saturn Bioponics Ltd. INDUSTRY PARTNER

Saturn Bioponics is a multi-award winning company dedicated to delivering sustainable soil-less crop production solutions globally. A highly innovative company, having over 8 years of pioneering R&D experience, featured in the UK government's 25-year Environment Plan. Innovations include a vertical hydroponic crop growth system demonstrating 3-4-fold increase in crop yield on the same land area, with reduced input requirements and improved crop quality. Saturn is shaping future policy for research and innovation in this sector as 1 of only 6 stakeholders in the BBSRC Horticulture Strategy Working Group and advising in the consultation by the government Department for Science and to Michael Gove/DEFRA on the future of UK agriculture. The company has also been promoted as one of InnovateUK's previous success stories in: e.g., KTN Case Study "Increased crop yield, quality and sustainability through collaborative innovation in hydroponics"; InnovateUK Case Study "UK success just the start for 3D crop-grower" and the BBC documentary "The Future of Farming". Saturn has a dynamic team with extensive experience across hydroponic science, agricultural engineering and plant biochemistry as well as commercial / business development experience delivering agricultural technology into international markets. Saturn's role will be to design and build the vertical farm and support new business model development for the net carbon zero farm.

Name:	**Arnoud Witteveen**
Organisation:	Saturn Bioponics Ltd
Present position:	Chief Technical Officer
Key areas of expertise:	Leading research into the vertical hydroponic system, optimising crop conditions leading to increased yields and premium quality produce.
Professional profile:	Qualified as a plant breeder, with a profound understanding of plants down to a genetic level, with 5 years' experience leading hydroponic science research to manipulate the controllable variables delivering improvements in crop yields and quality, including colour, flavour and shelf-life.

Organic Power Ireland Ltd. INDUSTRY PARTNER

Organic Power Ireland (OPI) is a carbon management company dedicated to optimising production of sustainable energy from local wastes. Robert Brennan (owner) was the instigator and developer under a separate company vehicle for the first and largest commercial Waste to Energy plant in Ireland, which accepts 100,000 tons of waste pa to produce ~5MW of electrical power. OPI is now developing a modular plug-and-play small-scale anaerobic digester (AD) for off-grid operation with energy storage rated at 20 kW/h to create green energy from farm manure/slurries. The company adopts a holistic 'closed-loop' approach to deliver advanced, cost-effective, sustainable solutions to the management and treatment of a variety of agricultural waste streams. It currently has prototype AD technology undergoing research farm trials with cattle slurries, (primarily dairy) and will further develop and optimise this for the beef sector.

Name:	**Mr Robert Brennan**
Organisation:	Organic Power Ireland Ltd
Present position:	Managing Director
Key areas of expertise:	Closed loop food production aimed at the Carbon Neutral Farm; nutrient recycling; modular AD systems; sustainable energy production
Professional profile:	Graduate from a Farming background with 20 year history in environment and renewable energy and has set up a number of businesses in this sector.

N2 Applied. INDUSTRY PARTNER

N2 Applied is a UK-based SME whose objective is to improve global food production by enabling farmers to produce their own low-carbon fertiliser. N2 has developed a game-changing patented technology to produce nitrogen fertiliser on-farm, through fixing nitrogen from air and reaction with ammonia in manure or biogas digestate. N2's scalable process eliminates dependence on fossil gas for fertiliser production and reduces ammonia emissions from agriculture, offering sustainable food production that is profitable to the farmer. Initial calculations show that implementation of N2's technology leads to a 27% reduction of the dairy supply chain carbon footprint (Danish farm data). N2's role will be to implement a prototype plasma unit onto research and pilot farms, integrate with other technologies and farm management tools and optimise strategies to reach carbon zero.

Name:	**Mr Chris Puttick**
Organisation:	N2 Applied Ltd
Present position:	Business Development Manager
Key areas of expertise:	Commercialisation of N2 Applied in the UK. Executing go to market strategy in key industry verticals of Livestock Farming, Biogas, Organics and Sewage Treatment.
Professional profile:	Experienced EMEA Manager in the AgTech industry, working with world class IP and highly disruptive concepts. Executed substantial growth in early stage AgTech companies to the point of exit, managed EU expansion for NASDAQ companies.

Agri-EPI Centre Ltd. RTO - PROJECT MANAGER

Agri-EPI Centre is an Agri-Tech Innovation Centre established by the UK government. Agri-EPI is a public innovation centre and established as a consortium of key organisations in the field of precision agriculture and engineering, which brings together expertise in research and industry, as well as data gathering capacity in all areas of the Agri-Food supply chain. Agri-EPI Centre brings its dedicated network of "Satellite" instrumented commercial farms, which have capacity to test and monitor the proposed system. Agri-EPI has extensive experience managing several interdisciplinary InnovateUK projects and will assist and facilitate the project lead in ensuring project deliverables are met within budget.

Name:	**Mr Dave Ross**
Organisation:	Agri-EPI Centre Ltd

Present position:	Chief Executive Officer
Key areas of expertise:	Precision Livestock Farming and engineering technology applied to agriculture Project management involving multiple partners; Sensors and systems for monitoring agricultural and food products
Professional profile:	Over 25 years in agricultural engineering and technology research. Management of multi-£M R&D projects; Experienced presenter to agri-food sector; published many conference papers and patents.

Name:	**Mr Stephen Burns**
Organisation:	Agri-EPI Centre Ltd
Present position:	Senior Project Manager
Key areas of expertise:	Electronic & Electrical Engineering and product development project management implementation, APM & PRINCE2 principles and methodology
Professional profile:	Over 25 years of electronic engineering projects and development across multiple industry sectors. Management of small, medium and large-scale R&D projects.

Name:	**Rebecca Lewis**
Organisation:	Agri-EPI Centre Ltd
Present position:	New Business & Proposals Manager
Key areas of expertise:	Agrifood value chain Strategic market research / business engagement
Professional profile:	Background in agriculture, with 10 years' experience in value chain research and analysis across livestock, dairy and horticulture. Now engaged in supporting agri-tech R&D.