GreenShed

Low carbon beef / Sustainable / Circular farming

Phase 2 Public-Facing Final Report

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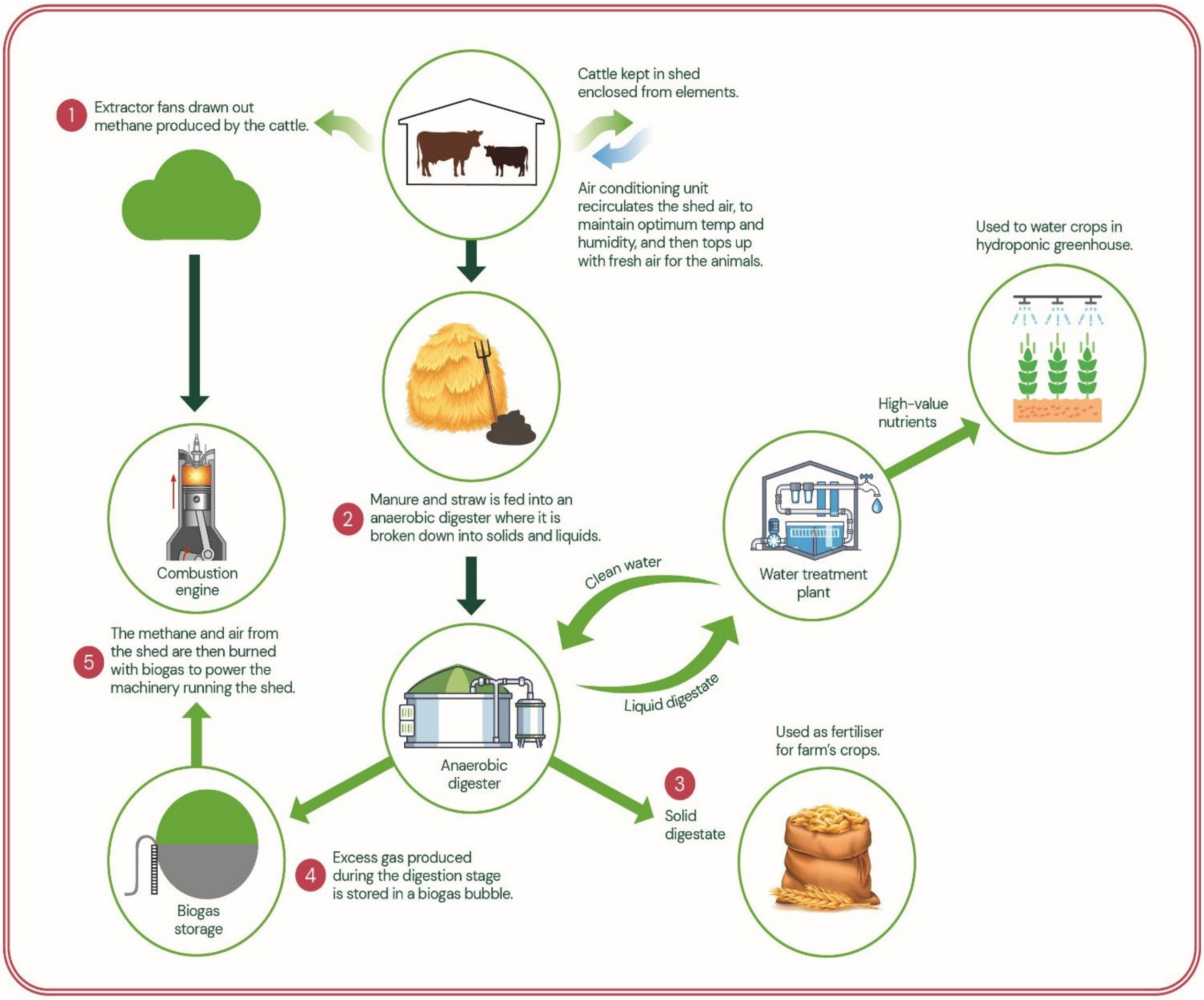
Project background and scope

Funded by the Department for Energy Security and Net Zero's (DESNZ) Direct Air Capture and Greenhouse Gas Removal (GGR) Innovation Programme, the project's ambition was to reduce the environmental impact of beef production by integrating several independently innovative technologies, in a multi-disciplinary approach. GreenShed addresses the need for the livestock farming sector to reduce its GHG emissions whilst improving productivity by creating a low-carbon, circular, cattle and vertical farming system, which captures methane (CH_4; global warming potential 27 times greater than carbon dioxide (CO_2) over 100 years) from housed cattle and utilises its combustion outputs (heat, power, CO_2) to yield low-carbon produce (meat, vegetables/fruits) and optimise resource use efficiency. The combination of five core proven technologies created the "GreenShed System":

- High-volume air recirculation/conditioning/sterilisation system, aligned with a novel engineered solution to capture CH_4 from cattle sheds.
- Bespoke micro-anaerobic digester (AD) with built in feedstock pre-treatment to improve efficiency. This produces combustible biogas from manure and waste feed.
- Novel ultra-lean combined heat and power (CHP) engine for combustion of biogas and CH_4-rich air.
- Wastewater Treatment System (WWTS) to remove and clean water from the digestate, reducing the storage requirements for liquid digestate and providing re-usable water.
- Vertical farming to utilise low-cost, low-carbon AD outputs (nutrients, heat).

The infographic in Figure 1: Infographic of the GreenShed model, shows how the combined technologies work together to capture CH_4, and generate usable products (beef, fertiliser, crops) from waste streams.

Figure 1: Infographic of the GreenShed model



Key changes to original scope

The original scope intended to integrate plasma reactor technology, developed by N2 Applied, to produce nitrogen-enriched fertiliser from AD waste and atmospheric nitrogen. This technology uses electricity to heat air until it forms a plasma of reactive oxygen and nitrogen ions which then combine with the unstable ammonia in the digestate, to form the stable fertiliser, ammonium nitrate. Ammonia in the digestate is not readily available to plants, as it is volatile and lost to the atmosphere - fixing it in combination with atmospheric nitrogen more than doubles the plant available nitrogen of the treated digestate. This has the potential to decrease bagged fertiliser use - offering carbon savings. During the early stages of the project (Year 1), the small-scale plasma reactor intended for use was no longer available. The larger units have a much higher power demand (~90kW compared to ~20kW peak). This resulted in the removal of N2 Applied. If developments achieve the required levels of power demand, the system could be easily integrated into GreenShed in the future.

In addition, new regulations on slurry storage[1] meant that the volume of liquid digestate produced by the AD would require installation of a costly storage solution which would negatively affect commercial adoption. The project had initially proposed storing the liquids (digestate) in relatively cheap "Ag-bags" (high volume flexible bags which simply lay on even ground), however, incoming regulations stipulate that Ag-bags require bunding /lagoon /concrete storage for the full bag volume - the cost of which, volume dependant, would have been prohibitive (~£300k-£500k). This was mitigated through inclusion of a lower-cost wastewater treatment system (developed by Circular Values Industries, the Netherlands). This reverse osmosis unit removes and cleans the water from the digestate. The cleaned water is re-used within the AD, reducing reliance on mains water.

The objectives of Phase 2 were to:

- Build prototype GreenShed.
- Conduct pilot testing of CH_4 capture and conversion combined with vertical farming and nutrient production.
- Conduct animal welfare assessments of cattle within GreenShed.
- Develop a "digital twin" of GreenShed and validate using prototype data.
- Validate design and conduct full Life-Cycle-Analysis (i.e., 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 GreenShed

[1] https://www.legislation.gov.uk/ssi/2021/412/made/data.pdf

Design and development of the pilot

Work package 2: specifications, permissions and contractors

Key activities

- Development and submission of the permitted development notification to the local authority for the new shed.
- Development of initial model and finalised design specifications: setting design parameters specific to chosen site (airflows, power requirements, dehumidifying, cooling, and heating requirements) and setting all component performance criteria.
- Select contractor for shed build in WP3. Quotes were obtained from a range of agricultural shed contractors (and electricians) and contract agreed with favoured contractor.
- Develop a digital twin of the full GreenShed system, calibrated using data from WP4.
- Development and submission of planning permission for polytunnel (for the vertical farm installation in WP5).

Planning permissions

SRUCs research farm is not deemed a commercial farming business, and as such, not eligible for agricultural permitted development rights. As a result, full planning permission was applied for. Planning application was submitted to Midlothian Council in October 2022, and a response received at the end of February 2023 (two months behind their target date). This included a series of conditions prior to commencing works – programme of archaeological work, surface water drainage scheme, air quality impact assessment and a biodiversity enhancement plan. All project surveys, plans and evidence were submitted to the Local Authority (LA; 24/04/2023), and full planning permission (which included the polytunnel) received on 10/05/23. For a commercial farm installation, a simpler notification to the LA would be required.

Building simulation model and finalised design specifications

Design specifications for the operation of the shed heating ventilation and air conditioning (HVAC) system were determined using modelling and simulation. A dynamic building simulation model was developed by Strathclyde University's (UoS) Energy Systems Research Unit (ESRU), featuring the shed geometry and materials, control systems and cattle. The characteristics of the cattle were created from SRUC test data. The model was simulated using an Edinburgh climate data set (hourly data on ambient solar, wind, humidity and temperature conditions) to determine air extract rates to maintain CO_2 levels below 1500ppm, recirculation air flows and resulting loads on cooling and reheat coils to maintain cattle comfort. The model was also used to select between a desiccant or coil-based dehumidification strategies model and later formed the foundation of the GreenShed digital twin.

A complementary computational fluid dynamics (CFD) model of the shed ventilation system was also developed using the ANSYS/FLUENT tool. This complemented the building simulation model and was used to assess the efficacy of the shed ventilation system layout (the porous fabric supply ducts running the length of the shed, and extraction of air at the corners). Flow velocities and temperature distributions were assessed along with a check for short circuiting of air flows (cool supply air from the HVAC system, being extracted without mixing with/cooling the shed air) and resulting temperature hot spots.

Shed build and contractor

Site selection and shed design was carried out by SRUC's research staff (beef specialists and skilled technicians), agricultural consultants and farm staff. The build tender was released to four companies (28/11/2022) with one contractor submission, who were appointed to deliver the works.

Digital twin

The digital twin was developed from the simulation model of GreenShed, used in the initial design of the shed and systems. Digital twinning involved calibrating this model using operational data (captured in Work Package 4) and extending its remit to cover the balance of plant (biogas digester, polytunnel, etc). The digital twin has been used for a range of post design tasks, including: (i) assessing the actual air leakage characteristics of the shed and effectiveness of sealing solutions; (ii) developing more complex environmental control strategies, which link humidity, temperature, and thermal stress (THI), rather than using conventional single setpoint values, achieving significant energy savings when simulated; (iii) testing the resilience of the environmental system design, by simulating the impact of housing different sized cattle (which have different levels of emissions of CO_2, CH_4, heat and moisture) - the selected environmental conditioning system dealt adequately with all cases modelled and in all but the case with the largest cattle, kept indoor CO_2 levels below 1,500 parts per million (ppm) (see section on "*Demonstration and trials results*"). The final application of the digital twin in the project was to assess approaches to energy savings through operational optimisation. This required the development of a platform to optimise the operation of the shed HVAC system and to investigate the best use of products and wastes of the different processes to maintain circularity. Finally, a data acquisition system has been constructed and installed for indoor and outdoor conditions. This data was required firstly to assess the as-built performance of the shed and its systems and to calibrate the digital twin.

Modelling and simulation for design guidance

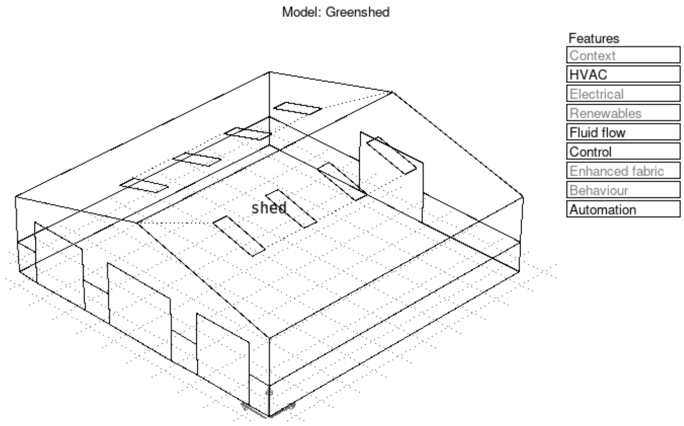
Simulation model development

This section summarises the application of the building simulation model in the initial design of the GreenShed's HVAC system. To inform the initial design of the GreenShed's HVAC systems, a model of the GreenShed prototype was developed on the ESP-r building simulation platform[2]; this is Open-Source software that has been extensively validated in a range of UK and EU projects.

Model elements

A basic ESP-r building model comprises a 3-D building geometry, coupled with explicit details of constructions, internal heat gains and heating/cooling set points. It can be augmented with detailed sub-models of (i) the HVAC system, and (ii) the building's air leakage characteristics. The GreenShed prototype model is shown in Figure 2.

Figure 2: ESP-r model of the GreenShed Concept



Data on air infiltration for agricultural buildings was scarce, therefore, leakage characteristics were derived from information on warehousing, as this type of building was deemed to be a close match to the envisaged GreenShed construction. An air leakage value of 1.2 air changes per hour (ac/h)[3] was applied in the model. Initial heat and moisture gains from the cattle were based on those reported in Cowie and Kelly[4] and are summarised below. These gain levels are assumed to persist for over the entire simulated period.

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[2] Energy Systems Research Unit [ESRU] (2022), ESP-r Software, Available at: https://www.esru.strath.ac.uk//Downloads/downloads.htm#ESP-r, Accessed: 16-12-24.
[3] Brinks, P., Kornadt, O., & Oly, R. (2015). Air infiltration assessment for industrial buildings. Energy and Buildings, 86, 663-676.
[4] Cowie A, Kelly N J, Greenshed Phase 1 Final Report, Appendix B – Development of a Detailed Simulation Model. Available at:

Table 1: Heat and moisture gains used in the model (per animal)

Sensible heat gain (W)	Latent gain (g/hr)	Latent gain from bedding (g/hr)
640	380	645

A climate file appropriate to the local (Edinburgh) area was sourced from https://climate.onebuilding.org/ which features climate test meteorological years (TMY) for many global locations. The basis of TMY climate files are described by Crawley and Lawrie[5].

The basic environmental control of the shed comprised two components: (i) an air extraction system that removed warm, moisture and CH_4-laden air from the shed and directs this to an engine unit for combustion, the extracted air is made-up by infiltration through the shed fabric; and (ii) an environmental control system that extracts, cools, dehumidifies and recirculates air from the shed interior. Two variants of the environmental control system were created for the model: (i) conventional cooling, a dehumidification system based on a cooling coil and (ii) a desiccant-based system, using warm air to re-charge the desiccant. The set points that these systems attempt to maintain in the model are shown in Table 2. These were derived from discussions with SRUC.

Table 2: Control set point for environmental system

	Internal Dry bulb temperature	Relative Humidity
Cooling-coil dehumidification	$4 < \theta < 22^{o}C$	<70%
Desiccant dehumidification	$4 < \theta < 22^{o}C$	<70%

The characteristics of the HVAC systems are shown in Table 3, derived from earlier work in developing the GreenShed prototype[6].

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1075309/sac-commercial-greenshed-phase-1.pdf

[5] Crawley, D. B., & Lawrie, L. K. (2015, December). Rethinking the TMY: Is the 'typical'meteorological year best for building performance simulation. In *Proceedings of the 14th Conference of International Building Performance Simulation Association BS2015* (pp. 2655-2662).

[6] Cowie A, Kelly N J, Greenshed Phase 1 Final Report, Appendix B – Development of a Detailed Simulation Model. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1075309/sac-commercial-greenshed-phase-1.pdf

Table 3: HVAC component characteristics

Cooling Coil Dehumidification		Desiccant Dehumidification	
Extract fan flow	0.87 m3/s	Extract fan flow	0.87 m3/s
Recirculation fan flow	2.67 m3/s	Recirculation fan flow	2.67 m3/s
Cooling/dehumidification coil capacity	150kW	Cooling fan flow	1.75 m3/s
Cooling/dehumidification coil set point	<70% RH	Gas burner	65 kW
Re-heat coil capacity	150kW	Gas burner set point	80^{o}C
Re-heat coil set point	12^{o}C	Cooling coil	150 kW
		Cooling coil set point	22^{o}C
		Re-heat coil	150 kW
		Re-heat coil set point	12^{o}C
		Spray cooler max flow rate	0.1 kg/s

**NB capacities indicated in the table are for sizing studies and peak required capacities will be significantly less. Eventual installed capacity will reflect the peak capacity calculated in the simulations.*

Simulation results

The performance of the two systems was simulated over a one-year time interval using an Edinburgh climate data set and the system characteristics indicated in Table 3.

Cooling coil dehumidification
The results (Table 4 andTable 5) showed that humidity exceeded the target for 25% of the simulated year, though only marginally.

The energy requirement for cooling and dehumidification was 536 kWh, and the energy required to re-heat the recirculated air (cooled to its dew point) was 278 MWh. The cooling load resulted in the cooling coil reaching its maximum capacity of 150kW for six of the simulated hours. However, the mean cooling load was significantly less at 79.2kW. The maximum reheat coil load was 70.5 kW, and the mean coil load was 34.3 kW.

Table 4: Average environmental conditions with cooling-coil dehumidification from cooling coil dehumidification simulation

Cooling Coil Dehumidification	Average	Min	Max	Hrs > 22ºC	Hrs < 12ºC
Air Temperature	13.48	11.59	27.21	143.00	417.00
				Hrs > 70% RH	
Relative Humidity	68.59	35.79	73.47	2216.00	

Table 5: Energy use and component loads from the cooling coil dehumidification simulation

Cooling Coil Dehumidification	Delivered cooling/ heating (MWh)	Primary energy Demand* (MWh)	Coil Rating	Average cooling/ heating power (kW)	Maximum Cooling/ heating power (kW)	Hrs On	Hrs at peak
Dehumidification and cooling	535.7	267.8†	150	79.2	150	8521	6
Reheating	277.6+	92.5 (0)	150	34.3	70.5	665	0
Total primary Energy (MWh)		267.8+					

**Assuming a COP of 2 for a cooling system and 3 for heating. †Electrical demand. +Re-heat energy can be recovered from dehumidification/cooling.*

Desiccant dehumidification

The average shed temperature was 17.8ºC with 145 hours above 22ºC. The relative humidity (RH) was below 70% for all the simulated hours and the average RH was 51%. The results show that the energy use of the cooling coil was 61 MWh and 17 MWh for the re-heater. The heat demand (to recharge the desiccant wheel) was 645.2 MWh. The peak cooling coil load in this simulation is 109kW, but the average cooling coil load was 19 kW. The recharge burner was active for the entire simulation, as there was always a dehumidification requirement, and the average burner heating requirements was 66 kW.

Table 6: Average environmental conditions with cooling-coil dehumidification from cooling coil dehumidification simulation

Cooling Coil Dehumidification	Average	Min	Max	Hrs > 22ºC	Hrs < 4ºC
Air Temperature	17.85	11.95	26.32	145	0.00
				Hrs > 70% RH	
Relative Humidity	51.05	31.12	65.29	0	

Table 7: Energy use and component loads from the desiccant dehumidification simulation

Desiccant Dehumidification	Delivered cooling/ heating (MWh)	Primary energy Demand* (MWh)	Coil Rating	Average cooling/ heating power (kW)	Maximum Cooling/ heating power (kW)	Hrs On	Hrs at peak
Cooling	61.45	30.72†	150	19.29	109	3185	1
Heating	17.08+	5.69 (0)	100	11.52	52.58	1482	0
Recharge Burner	580.70	645.20^	75	66.3		8760	0
Total primary Energy (MWh)		30.72 (electrical) 645.2 (gas)					

**Assuming a COP of 2 for a cooling system and 3 for heating. †Electrical demand. +Re-heat energy can be recovered from dehumidification/cooling. ^Assuming a gas burner efficiency of 0.9.*

Outcome: based on the results of these simulations, despite the desiccant system performing well, it was discounted, due to the high gas demand for the recharge system. This was significantly more gas than could realistically be supplied from an on-site biogas system.

Attention therefore focused on the cooling-coil system and efforts to reduce the substantial electrical power requirements of the chiller system needed to dehumidify the recirculating air.

Analysis of THI control

The dehumidification of the shed air resulted in high energy requirements for both cooling and re-heating, with cooling-coil dehumidification. An alternative approach was investigated, (suggested by SRUC) which involved controlling the shed temperature-humidity index (THI) by dynamically altering the relative humidity (RH) set point based on shed temperature in the shed. The revised system control requirements are shown in Table 8.

Table 8: THI control set points

Dry bulb temperature range °C	θ <14	14≤ θ<18	18≤ θ<21	21 ≤ θ < 23	23 ≤θ < 24	≤24
Max RH%	90	90	75	50	40	40
THI	57	57-64	64-68	68-69	69-69.4	69.4

The other component capacities and flow rates remain the same as previously indicated.

Results: Implementing the THI control regime, substantially changed the shed indoor conditions and the energy usage characteristics of the environmental conditioning plant (Table 9 and Table 10, respectively).

Table 9: Average environmental conditions with cooling-coil dehumidification with revised control

Cooling Coil Dehumidification	Average	Min	Max	Hrs > 22°C	Hrs < 4°C
Air Temperature	14.47	11.88	27.83	137	0
				Hrs > 70% RH	
Relative Humidity	84.34	35.85	91.56	7978	

Table 10: Energy use and component loads from the cooling coil dehumidification simulation with revised control

Cooling Coil Dehumidification	Delivered cooling/ heating (MWh)	Primary energy Demand* (MWh)	Coil Rating	Average cooling/ heating power (kW)	Maximum Cooling/ heating power (kW)	Hrs On	Hrs at peak
Dehumidification and cooling	290.8	145.4†	150	33.2	97.0	8758	1
Reheating	106.2+	35.4 (0)	150	12.12	56.3	6595	1
Total primary Energy (MWh)		145.4+					

The revised THI humidity control regime tolerated higher humidity at lower temperatures, and the average shed temperature of 14.5°C corresponded to a humidity limit of 90%. The impact of these more relaxed humidity requirements at lower temperatures was that cooling coil primary energy demand (electrical) dropped to 145.4 MWh and heating demand dropped to 35.4 MWh. Peak component loads were also reduced - the peak cooling demand fell to 97 kW, and the peak heating demand fell to 56.3 kW.

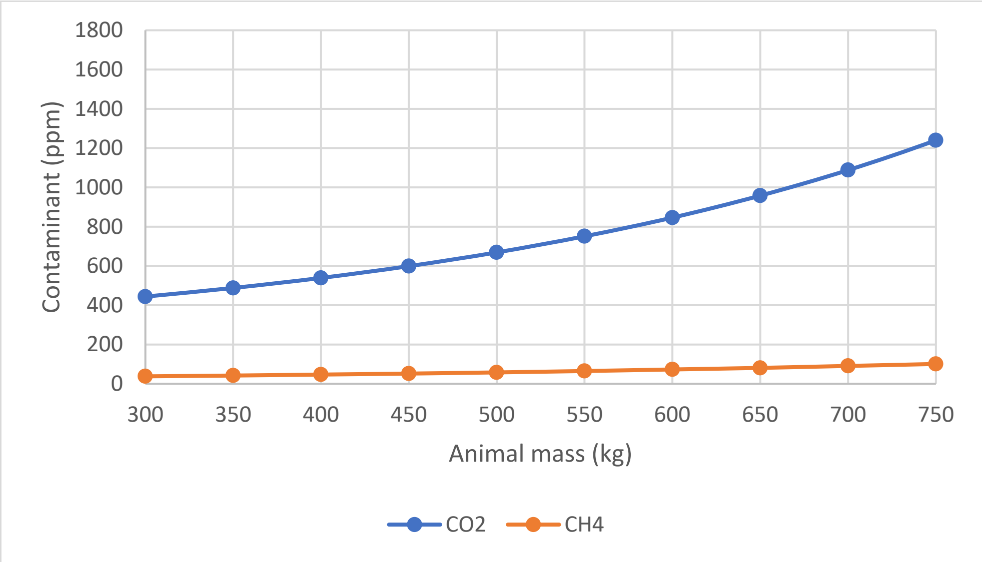
Outcome: The revised dynamic RH set point control results in significantly lower energy use and cooling/heating coil loadings of approximately 100kW and 56 kW, respectively. The THI strategy was adopted for indoor conditions control.

Sensitivity and resilience

To test the resilience of the HVAC parameters emerging from the modelling work, a sensitivity analysis of the HVAC system operation was undertaken with different animal sizes, as size affects heat gains, CO_2, CH_4 and ammonia emissions. Experimental data from SRUC, quantifying emissions from cattle sizes between 300 and 850kg were used to generate different model variants with increasing levels of cattle heat, moisture and contaminant load. The results are illustrated in Figure 3 and indicated that the HVAC system capacities indicated in the initial modelling work would be sufficient to maintain suitable reasonable indoor conditions with cattle sizes up to 750 kg. Above 750kg, CO_2 limits breached the 1500 ppm limit, but this would be well beyond the typical maximum size of cattle housed in the shed, with liveweights ranging from 530-730kg, the ideal weight being 600 kg[7].

[7] https://www.fas.scot/article/a-practical-guide-to-selecting-finished-cattle/

Figure 3: Variation in shed contaminant levels with animal mass

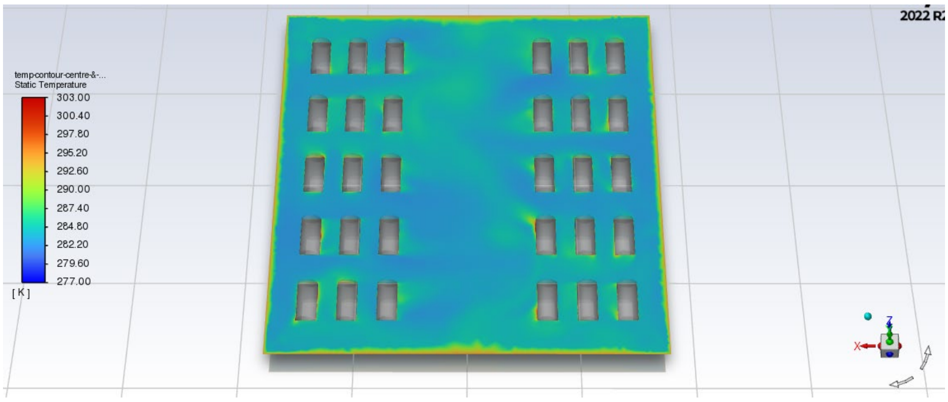


CFD modelling for ventilation design

A computational fluid dynamics (CFD) model of the GreenShed was developed to assess the expected distribution patterns for the ventilation distribution system design. The aim of the work was to provide a qualitative view of ventilation system's ability to providing conditioned air throughout the shed interior. To assess the effectiveness of the conditioned air distribution system a scenario was developed to represent typical cooling characteristics with supply air at 4°C, surrounding surfaces at 22°C (both extracted from the shed building simulation model), and heat transfer from each animal of 600 W. Radiation heat transfer was not solved as part of the model and so all of this heat is transferred via convection. The results from the CFD model are a steady-state solution of the flow indoor field, that reflect the boundary conditions outlined previously.

Outcome: the results from the CFD analysis indicated that the design for conditioned air distribution inside the GreenShed provided excellent mixing of conditioned (cool) air to the space, with limited stratification and no evident hot spots around cattle. There was some evidence of short circuiting close to the air extraction points (situated) at the corners of the shed, but its effects on performance were minimal. A typical temperature distribution plot from the analysis is shown in Figure 4.

Figure 4: Small temp variations around cattle (modelled as cylindrical objects), plan view



Work package 3: System installation – core technology

Key activities

- Installation of shed using chosen contractor in WP2. The build was managed by SAC consulting (part of SRUC).
- Installation of core technologies: Anaerobic digester (AD), removable shed membrane and air handling unit (AHU). Design meetings were held with all consortia and fabricators to ensure design was optimised. Construction and fabrication of each technology were owned by each technical lead and technology installations were overseen by SRUC.
- Installation of environmental sensing and monitoring equipment for large scale testing in WP4. This involved the procurement of sensing equipment (for respiratory gases, CH_4 emissions, environmental parameters), metering (to evaluate HVAC loads and disaggregate primary energy inputs) and installation.

Shed installation

All aspects of the shed build (from procurement through to completion) were managed by external construction project managers, appointed by SRUC. The building works commenced on 12/06/23 and were completed by 30/09/2023. Figure 5 shows aerial images of GreenShed.

Figure 5: Aerial images of GreenShed

Core technology install

Shed membrane

The design, fabrication and installation of the shed membrane was led by Galebreaker (GB) (Figure 6). The flexible membrane had to seal the openings in the building construction to ensure the air is captured by the Air Handling Unit but also move/open to allow the building to naturally ventilate in the event the AHU was not in operation. Natural ventilation of a livestock building functions under the ‘stack effect’, whereby warm stale air rises and exhausts through the ridge with fresh air drawn through the side openings. This natural stack effect is enhanced in windy conditions where air passing over and around the building causes low pressure regions that draw air from the building. Materials fabrication was undertaken at a time when the shed’s steel frame was sufficiently complete to carry out a site survey and obtain as-built dimensions (02/08/2023). The installation of GB’s ventilation light ridge, Variable Ventilation System (VVS) curtains, doors and ridge closing flaps was undertaken between 07/08/2023 and 08/09/2023. Even though these were similar to GB’s standard product range, several adaptations were made to for the purposes of GreenShed. Mechanical closing flaps along the full length of the building were developed for the ventilation light ridge, meaning the ridge opening could be closed through activation of linear actuators. A VVS curtain sealed the 2m gap above the concrete wall on both sides of the shed up to the building eaves. The top rail of the curtain is suspended from cables which are hoisted from a single motor, allowing the curtain to open from the top and dropping to the top of the lower concrete wall. To ensure the curtain was able to withstand wind when closed, vertical control tubes were set at intervals along the length to support the impermeable fabric curtain. When closed the top edge of the curtain closed to a longitudinal sealing strip. The impermeable fabric doors at the end of the central feed passage, and access doors to each pen used GB fabric doors. Additional seals were provided along the vertical edges of the door, and a cowling provided a seal around the top rolling barrel. The lower edge of the door had flaps which sealed to the floor when closed.

Figure 6: Shed flexible membranes

An Uninterruptable Power Supply (UPS) (including a back-up power supply) ensured the emergency failsafe opening of the two side curtains and ridge flaps from the control input (e.g., loss of mains or an alarm signal from the AHU). The west central passage door was also powered from the UPS allowing access to animals (e.g., feeding) if mains power was lost. Two GB positive pressure ventilation tubes (VentTubes) ensured the returned air from the AHU was distributed throughout the cattle pens with the correct volume flow rate and pressure delivery.

During the testing of the system, it was identified that air leakage was above expectations during windy conditions, as evidenced by monitored CO_2 and CH_4 levels. Modelling and simulation using the digital twin indicated average, closed shed leakage rates of around 3.5 air changes per hour (ac/h); considerably more than the 1.2 ac/h assumed in the initial modelling. Throughout the project improvements in the shed seal was carried out:

- Additional sealing of the ventilation ridge closing flaps.
- A new profile to stop the ends of the side curtains pulling away from the inner seal whilst still allowing them to freely open when required.
- Mitigating the lifting of lower flap in the east feed passage door.
- Fitting of seal above eave purlin.
- Filling of gaps across steel roof profile eave and at gable-ends

These modifications have resulted in reducing the air escape in windy conditions (see section on "*Demonstration and trials results*") from 3.5 air changes per hour (ac/h) to a more acceptable 1.35 ac/h. Any further leakage would likely be from joins between the general construction of the building (e.g., overlapping roof panels). To seal these would require a more continuous fabric seal which was not considered practical or cost-effective at this stage.

Air handing unit

The design, fabrication and installation of the AHU was managed by No Pollution Industrial Systems (NP). The main unit of the AHU was fabricated and delivered to site on 24/05/2023. In November 2023 the AHU was positioned on its supporting skid, and all auxiliary systems installed, including the buffer tank, the mains power and control cabinets, the supply and return ductwork connected, and the supply and return shed penetrations dressed and sealed to the building walls. Furthermore, the exhaust air ductwork was routed to the far external corner of the building and connected to the Combined Heat and Power (CHP) engine. Electrical and plumbing connections of AHU and chiller were completed by 24/11/2023, after which commissioning was carried out.

Once the basic configuration and operation was thoroughly tested, the system was pushed further towards its limits to improve the performance and establish baseline limits for future tests. Specifically, the AHU has been extensively tested under different conditions, both with and without animals in the shed, and with different thermal loads and operation set-points, to make sure the system was performing correctly in the various operation conditions. Testing of the system showed how under certain conditions (warm days, with outside temperature around 22^{o}C), the AHU struggled to control both temperature and humidity sufficiently. The primary reason proved to be the insufficient sizing of the buffer tank. Although often considered a secondary component, this is crucial to avoid the continuous on/off of the chiller, and as the name says, create a buffer to the system by substantially increasing the volume of fluid flowing through the coils and chiller unit. The original tank had a volume of 300 litres and was replaced with one 3 times the original size (900 litres). This significantly improved control of water temperature at the inlet to the cooling coil and eliminated fluctuations seen previously; water temperature at the coil inlet was maintained between -1 and 1^{o}C, compared to 2 to 10^{o}C.

Further to the replacement of the buffer tank, modifications were also carried out to the configuration of the cooling coils. This has been changed by adding a 40kW pre-cooling coil and increasing the power of the original coil by adding an extra section with a cooling power of 23kW. The first provides pre-cooling to the return air before passing through the free-cooling heat exchanger; the second increases capacity at the primary cooling coil. Both have been connected in parallel to the existing cooling circuit, and each with independent 0-10v proportional control, to maintain optimal conditions. These modifications considerably improved the unit's overall cooling capacity (i.e., temperature control), as well as the control of relative humidity (RH). Most importantly, they make better use of the available chiller power.

The volume of extracted air, typically set at 2500 m3/h, proved sufficient to control CO_2 concentration inside the shed and keep CO_2 below the required levels. The filtering system also proved effective at capturing large (bedding straw) and fine (dust) particles, although the interval between the cleaning of the filters could be increased by adding an automatic filtering unit, or regenerative filtration. The installed UV filtration system proved effective at controlling pathogens inside the shed (pathogen load was not measured, but animals did not show signs of respiratory disease).

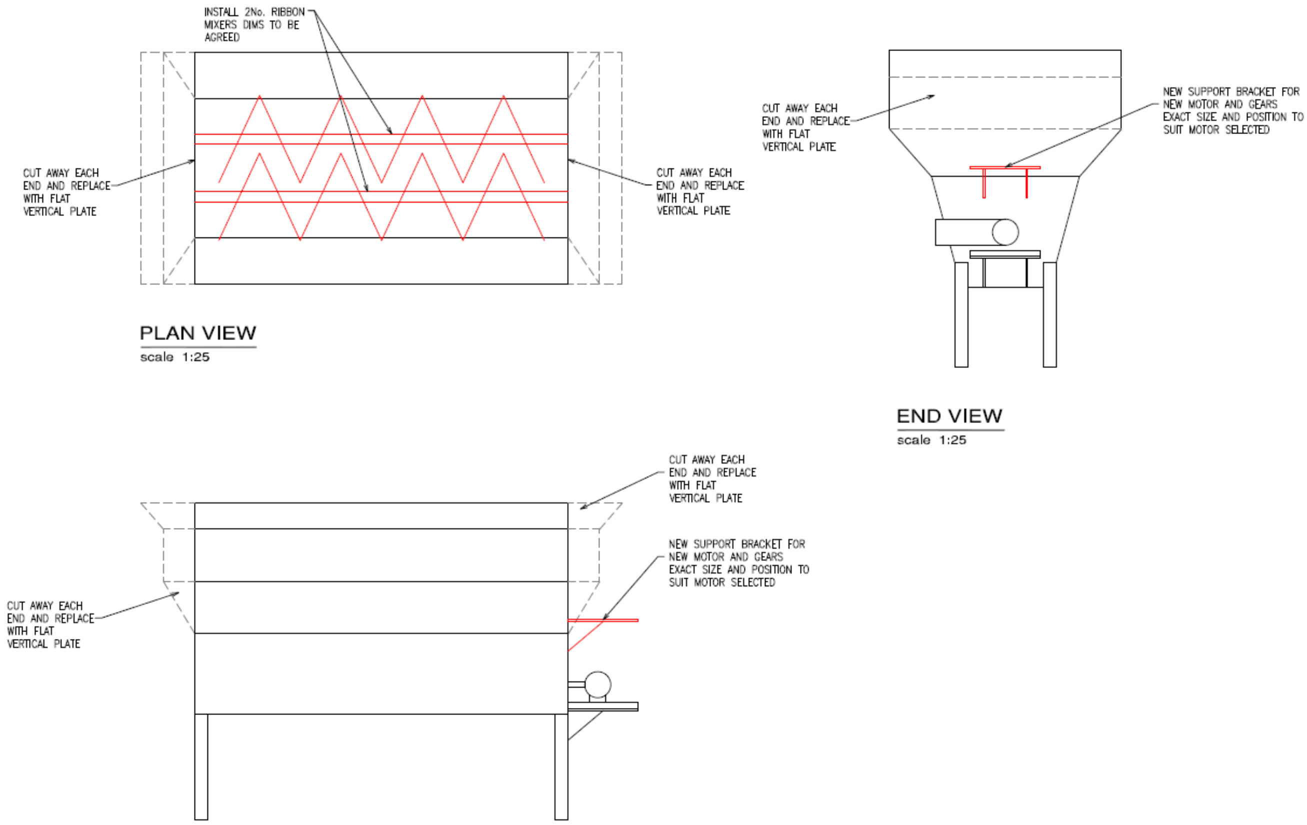
Anaerobic digester

The design, fabrication and installation of the AD unit was managed by Organic Power Ireland (OPI). This unit is entirely novel, with the capability of using solid feedstocks rather than slurries which is unique for micro-AD systems, normally only available in much larger AD systems. It achieves this by separating the solid and liquid fractions and digesting them separately. This allows for the sheds straw-bedding to be accommodated more easily as straw takes longer to digest than the liquid fraction; separating them allows the system to have the optimum retention time for each fraction. In addition, the digester for the wet fraction incorporates a plastic media with a high surface area to increase the available establishment sites for the non-suspended micro-organisms essential to the digestion process.

Overall power sizing was determined by the annualised average power needs modelled in the Digital Twin (16.7kW). It was decided not to size the CHP system at peak power load, due to capital costs, and accept that there would be times when the system would require electricity import, and times that it would export electricity with net overall zero import. OPI sourced a biogas CHP close to modelled.

OPI developed their own feedstock feed system to save significant capital costs, a key factor in making the GreenShed system economically viable. There are several off-the-shelf feed systems for AD systems, however they are generally very expensive. The design was based on a gravity fed hopper system with mixers to allow solid muck to be mixed with water (to allow it to be macerated and be pumped in pipes rather than moved with augers and conveyors which is more complex and expensive), which then feeds the mixture through a macerator to chop the straw finely to increase the active surface area available to microbes and release all the water soluble digestible materials and wet fraction from the feedstock. Later on the feedstock is separated into the wet fraction and dry fraction to allow different digestion pathways, however this initial mixing with water is essential to allow it to be macerated successfully.

Figure 7: Drawing of AD feed hopper



The AD unit was fabricated in two stages; (i) building the frames and main steel structures off-site (completed 30/07/2023), and (ii) pipework, electrics, and ancillary components fit out on-site (completed 29/02/2024). To speed up the establishment of the AD microbial community, seeding the system with externally sourced digestate was undertaken (24/07/2024). Seed digestate was sourced from a local farm AD system that uses straw-based manure in the mixture of feedstocks, so would have the specific microbe community capable of digesting straw. During commissioning, it became apparent that the feedstock intake hopper did not cope well with the long straw in the shed manure and resulted in manual intervention. Following consultation with a materials handling specialist, additional “choppers” were fitted to the hopper, in the form of two overlapping ribbon augers.

Installation of environmental sensing/monitoring

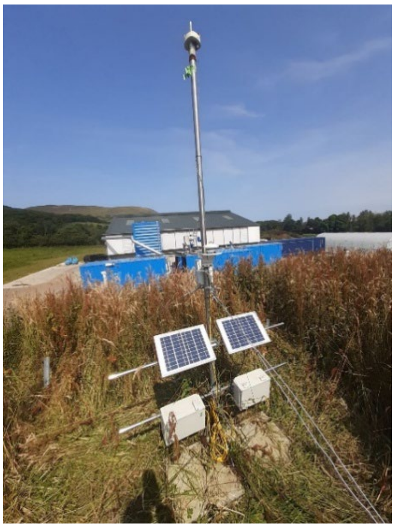
Two sets of operational data were required, climate data and data on internal conditions.

External data
ESRU refurbished, re-calibrated and installed a weather station to capture high resolution (sub-hourly) micro-climate data and better understand shed performance (Figure 8). The system components are indicated in Table . The weather station is self-powered, using 2 x 9W solar panels powering the TMET NiMH batteries. Additionally, UoS had access to data from three neighbouring weather stations for supplementary environmental data and to corroborate on-site readings.

Table 11: Weather station components

Global horizontal solar radiation (W/m2)	Kipp and Zonen Class 2 Pyranometer
Temperature (°C)	Eltek temperature sensor (+/- 0.4°C)
Relative humidity (%)	Eltek relative humidity sensor (+/- 2%)
Wind Speed (m/s)	Vaisala sonic anemometer (+/- 0.3ms)
Wind direction (o)	As above (+/- 3o)
Transmitter	2 x Eltek TMET RF transmitters and enclosure
Logger	Eltek squirrel logger (274 K reading capacity)

Figure 8: An image of the GreenShed weather station



GB also installed a separate weather station, providing additional temperature, relative humidity, wind speed, wind direction and rain events data in the immediate environment of the shed. The ESRU, Galebreaker and 3rd-party weather station data has been used to compile a comprehensive, validated, climate dataset for the shed.

Internal data

GB have installed two key sensor systems inside the shed (i) Temperature and Humidity Index (THI) monitoring matrix – to provide a 3D picture of shed environmental conditions, and (ii) CO_2 sensor line – to create a 1D picture of CO_2 distribution in the shed These systems are part of the GB iSeries monitoring platform, which is connected to the buildings internet via the LAN, and uploads THI sensor data to the cloud every 15-mins. This data is accessible via their 'Barn Report Pro' (BRP) web portal.

Work package 4: GreenShed testing

Key activities

- Assessment of failsafe/safety mechanisms against agreed performance criteria.
- Larger scale testing with animals housed in the facility. Animal-based testing in this facility required approvals from SRUC's local animal ethics committee and home office licencing approvals. Animal-based testing involved an iterative cycle of data capture and analysis. Data was assessed on shed performance, stability, and optimisation (environmental parameters) and animal welfare (animal welfare assessments).
- Monitoring, Verification and Reporting. Once the system was optimised and performing to specification based on environmental conditions, data capture continued to assess the carbon reduction benefits of the system and longer-term effects on animal welfare. Data captured was used to develop the LCA model demonstrating the carbon reduction efficacy. For commercial application, this model will be incorporated into a computerised monitoring system to provide real-time carbon savings based on the automated monitoring of outputs and inputs. Data from the monitoring exercise was also used to calibrate the digital twin, ensuring its energy and environmental predictions are reconciled with actual performance. This calibrated model can then be used with confidence to assess the scale-up and variation of GreenShed and its value in markets outside the UK.

Experimental approvals and licencing

Research activities were subject to a series of approvals from the Home Office (HO) and SRUC's Animal Experiments Committee (AEC). Home office approvals were required for the building (establishment licence), the project (project licence holder – held by animal science lead), and the individual staff members conducting regulated procedures (personal licence holders – held by both scientific and technical staff at SRUC). In this instance enclosing an animal in a semi-sealed shed was considered a regulated procedure. All HO approvals were in place by 01/03/2023. Throughout the project, small amendments to the project licence were applied for and approved, based on results from assessments of building performance, and animal assessments (e.g., revisions to set point values for environmental failsafes). Experimental work with animals also required approvals from SRUC's AEC (received 22/03/2025). The AEC ensures that all SRUC's research involving animals upholds the highest welfare standards. The purpose of the AEC is to assess and ensure the health and wellbeing of all experimental animals within SRUC. The ethical review process is a statutory requirement at all UK establishments designated under the Animals (Scientific Procedures) Act 1986.

Failsafes

The failsafe/safety mechanisms were tested against agreed performance criteria. Testing parameters included temperature, CO_2, loss of power and Temperature-Humidity-Index (THI). There were two levels of testing carried out for the failsafes: (i) individual sensor testing, where we would heat up, make more humid or increase gas levels locally around the system sensors to test the sensitivity at the designed alarm levels, levels were verified on calibrated handheld testing equipment; (ii) to test the responsiveness during normal running at alarm condition levels was not possible for most parameters, we couldn't heat up the entire shed in the winter testing period sufficiently, nor humidify it. Therefore, for most testing parameters (except loss-of-power and CO_2) the alarm condition parameter was manually adjusted (using in-built controls) to simulate a breach of limits to assess the functionality and reliability of failsafe systems (e.g., opening of roller curtain system within specified 2 min period; increasing exhaust fan and air recirculation to 100%; increasing cooling system 100% - for temperature breach only). All failsafes (except CO_2) were tested without animals in the shed (between 19/02/2024 and 07/03/2024) and all received a PASS over 5 runs. For testing of CO_2 breaches, animals were housed in the shed and airflows reduced to increase CO_2 levels accordingly. The CO_2 failsafe limits implemented (1,500 ppm at earlier stages of testing) are significantly below animal health concerns (>3,000 ppm for longer-term exposure; >5000ppm for short term exposure). As confidence in the building operation was achieved the environmental set point values were continually reviewed. Upper CO_2 limits were increased to 2,500 once confidence in the system was achieved (i.e., no adverse effects were observed). In addition, RH ranges were revised to account for the "uncertainty of measurement". The sensors employed in the project have a tolerance of ± 5-6%. Following continued testing throughout 2024 and 2025, an additional failsafe was included to ensure cattle safety in the event of control systems failure (where the controls system crashed this could not send an alarm signal). This was an independent CO_2 sensor, set at 2800ppm, which triggered an alarm and signalled the operation of the same failsafes.

Animal welfare

Welfare assessments were conducted using a welfare assessment protocol that included indicators most likely affected by continuous housing. Following the guidelines of the Welfare Quality ® protocol for fattening cattle (2009, Welfare Quality® Consortium, Lelystad, Netherlands), these fall into four categories: good feeding, good housing, good health and appropriate behaviour. The welfare measures were chosen to reflect the range of possible welfare impacts that may occur in the GreenShed environment.

It was considered that the closure of the shed may affect physiology, performance of normal behaviour and mental state of animals. Respiratory disease, lameness and injury may be present due to the enclosed housing conditions and mechanical ventilation (although recirculated air is filtered/UV-treated). The performance of normal behaviours such as standing and lying were assessed, so that they could be compared between open and closed situations. Cattle are known to perform abnormal behaviours (such as tongue-rolling, navel sucking or urine drinking), increase the level of displacement behaviours (such as pen- or wall-licking, and drinker manipulation, self-grooming or grooming of others) under restricted or stressful conditions. Therefore, these behaviours were included in the assessment protocol. Several methods were used to gather the data. Instantaneous scan sampling was used to assess the posture and behaviour of the animals. The number of animals standing or lying and performing each behaviour was tallied across the group. At each assessment day five samples were carried out for each of the two pens in the shed at approximately 5-min intervals over a 30-minute period. Between each scan, one focal animal per pen was assessed for respiration rate, and the sweating, cleanliness, and disease and injury indicators[8]. This was repeated after every scan for a total of 10 animals. During this 30-minute period, any incidence of coughing was recorded, as well as any observation of any animal performing any of the displacement behaviours, abnormal behaviours or grooming behaviours listed in Table 12.

Finally, a qualitative behavioural assessment[9] was carried out for each side (pen) of the shed. A total of twenty-four sessions of observations were carried out (May 2024-February 2025). During this period, the shed was closed for eleven of the observations and open for thirteen of them.

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[8]Welfare Quality® (2009). Welfare Quality® assessment protocol for cattle. Welfare Quality® Consortium, Lelystad, Netherlands
[9]Rousing, T., & Wemelsfelder, F. (2006). Qualitative assessment of social behaviour of dairy cows housed in loose housing systems. Applied Animal Behaviour Science, 101, 40 - 53.

Table 12: List of welfare indicators assessed

Category	Indicator	Method
Performance of normal behaviour	Standing/Lying	Scan sampling
	Eating/Drinking	Scan sampling
	Ruminating	Scan sampling
Housing effects	Dirtiness	Focal animal scoring
Air quality/thermal responses	Respiration rate / sweating	Focal animal scoring
	Panting/drooling	Behaviour sampling
Mental state	Qualitative behavioural analysis	Group level assessment
Disease	Nasal/ eye discharge	Focal animal scoring
	Lameness	Focal animal scoring
	Coughing	Behaviour sampling
Injury	Lesions / swellings	Focal animal scoring
	Hairless patches	Focal animal scoring
Abnormal behaviour	Tongue rolling	Behaviour sampling
	Urine drinking	Behaviour sampling
	Navel sucking	Behaviour sampling
Displacement behaviour	Wall licking	Behaviour sampling
	Pen licking	Behaviour sampling
	Playing with drinker	Behaviour sampling
Grooming	Self-grooming	Behaviour sampling
	Grooming others	Behaviour sampling

Longer-term data capture

Following failsafe testing, data capture continued (19/07/2024 - project end) to assess technical performance of the system, and carbon reduction benefits of the system. The data from this monitoring exercise was used to validate the digital twin model, ensuring its energy and environmental predictions were reconciled with actual performance. Data was used within section "*Life cycle assessment (LCA) and monitoring, reporting and validation (MRV)*".

A substantial volume of data was collected through a combination of automated and manual recordings. Details of the instrumentation and measurements are outlined in Table 13. The frequency and volume of data collection varied across sources. For example, GB system data was recorded at 15-minute intervals, resulting in over 40,200 data points for 42 measured variables from 18 internal sensors and the weather station. Eltek weather station data, recorded at 5-minute intervals, has accumulated more than 120,600 data points for 8 weather-related variables. Gas analyser and AHU data were logged every minute, yielding over 603,000 data points for 19 columns. Electricity and water meter readings were recorded weekly, with additional electricity readings taken whenever the shed was switched on or off. Cattle data was updated any time animals entered or exited the shed and datetime records of any events recorded (e.g., feeding, bedding).

To manage and align this complex dataset, a database was developed in Microsoft SQL Server. This central database ensures easy access and facilitates efficient data analysis. Data is initially uploaded into a staging table where it undergoes quality checks before being integrated into the main database. Some data streams required scripts for cleaning, such as standardising file delimiters and removing "stuck" values resulting from connectivity issues, particularly when data points were frozen for more than two hours.

Currently, the database includes 84 columns and, when aligned to 15-minute intervals, contains over 40,200 rows per column, equating to 10,000 hours of data. Additional columns were added to capture feeding/bedding events based on the times recorded in the log, and a classification column was implemented to indicate the shed's operational status. This classification is based on key criteria, for example, if the shed was closed, the AHU and chiller were operational, no feeding and bedding events were recorded and animals were present, the shed was marked as fully operational. If only some conditions were met, for example, the shed was open, but the AHU and chiller were operational, the shed was marked as partially operational. This high-resolution dataset enables in-depth monitoring and analysis of building performance.

Table 13: Overview of Greenshed data streams

Data source	Instruments	Measured variables	Rec freq.
Galebreaker system	18 RuuviTag wireless sensors, weather station	Internal temp (°C) + humidity (%RH); External temp (°C) + humidity (%RH), wind speed (m/s), wind direction (°), rain events.	15 mins
Eltek weather station	Vaisala anemometer, Kipp & Zonen pyranometer, Eltek Tx/Rx sensors	Wind speed (m/s) and direction (°), global solar radiation (mV), temperature (°C), relative humidity (% RH)	5 mins
Air handing unit	Johnson Control combined Temp & RH sensor SHT-1301-UD1, Johnson Control differential pressure sensors SDP2500-R8, EEPlusE EE850 CO_2 sensor	Fresh, supply, exhaust and return air temp (°C) and humidity (% RH), supply, exhaust and fresh air flow (m^3/h), exhaust air CO_2 (ppm), cooldown air temperature (°C), shed differential pressure (Pa), heating control (%)	1 min
Gas analyser	ADC multi-gas analyser and sequencer, HOBO data logger	DC current (mA), methane concentration (ppm)	1 min
Electricity readings	3 x MID-compliant 3-phase meters (whole site/AHU/chiller)	Electricity usage for whole site, AHU, and chiller (kWh)	Weekly
Water meter readings	2 x MID compliant single jet water meters (polytunnel and AHU)	Water usage for polytunnel and AHU (m^3)	Weekly
Shed events	Recording sheet	AHU on/off, chiller on/off, shed open/closed, alarms, feeding and bedding records	At time of event
Cattle data	Recording sheet	EID no, animal type, sex, breed, date of birth, entry/exit date and weight (kg)	At cattle entry/exit

Work package 5: Systems installation – add-on modules

Key activities

- Installation of a Wastewater Treatment System (WWTS) to remove and clean the water from the digestate, reducing the storage requirements and providing re-usable water.
- Install of vertical farm (including polytunnel) to utilise excess outputs (power, heat, CO_2) and low-cost nutrients (nitrogen).

Waste water treatment system (WWTS)

Circular Values Industries' reverse osmosis plant works on the principle of membrane filtration using high pressure. Dissolved particles cannot pass through the membrane, and these particles (ions, viruses, bacteria and other dissolved substances) are stopped and enter a concentrated stream - only water is allowed to pass through the membrane. Within GreenShed the outgoing streams from the process are concentrated high value nutrients intended for use within the vertical farm and dischargeable "clean" water on the other. Within GreenShed the clean water from the liquid digestate can be either recycled within the AD system, used for irrigation in the vertical farm and/or discharged into the nearby watercourse (with appropriate inexpensive SEPA consent). In the current project, installation was complete in May 2024.

Vertical farm

The objective of the vertical farming system within GreenShed is to utilise excess outputs (power, heat) and low-cost high-quality nutrients (nitrogen) from the AD to grow high value, high quality produce such as herbs, leafy greens or soft fruit, dependent on market. The extra profits from the sale of high value low-carbon GreenBeef, and high-value leaf crops from the vertical polytunnel are an important aspect of commercialisation (in section - "*Commercialisation Plan, Barriers and Risks*"). The Saturn Grower hydroponic system was installed, tested and commissioned (15/07/2024, Figure 9) and first set of seedlings received, graded and planted (21/08/2024, - 2,500 plants, butterhead lettuce, variety Euler).

Figure 9: Images of the vertical farm


Demonstration and trials results

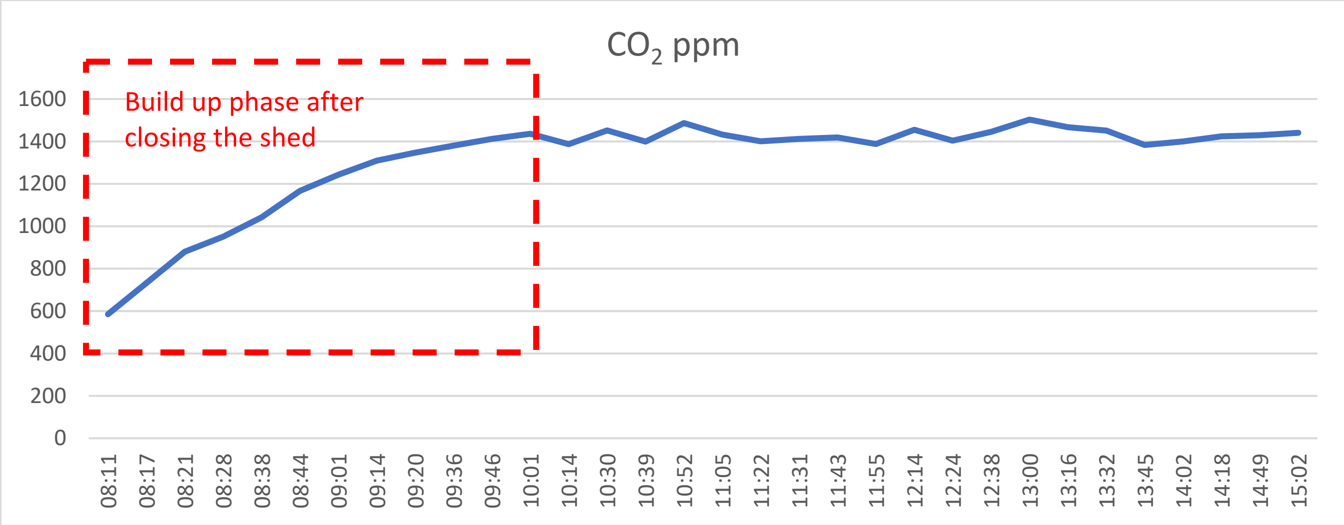
Building performance

Temperature humidity index and CO_2 control

To assess performance of the shed in maintaining optimum conditions and maintaining sufficient seal to allow CH_4 capture, data was continually captured during the test period for temperature, humidity, and gas levels inside the shed, alongside external temperature, humidity, wind speed, wind direction, rain events, rainfall, and solar radiation levels. This allowed for accumulation of data on conditions in the shed when open (replicating conditions in normal livestock sheds that are naturally ventilated) and when closed throughout the year.

During initial testing of the closed shed, CO_2 levels were generally maintained within limits that were initially set at 1,500 ppm (Figure 10). However, it was noticed that CO_2 levels dropped significantly during windy spells, leading us to infer that the sealing of the shed was not sufficient to suppress outside air infiltration.

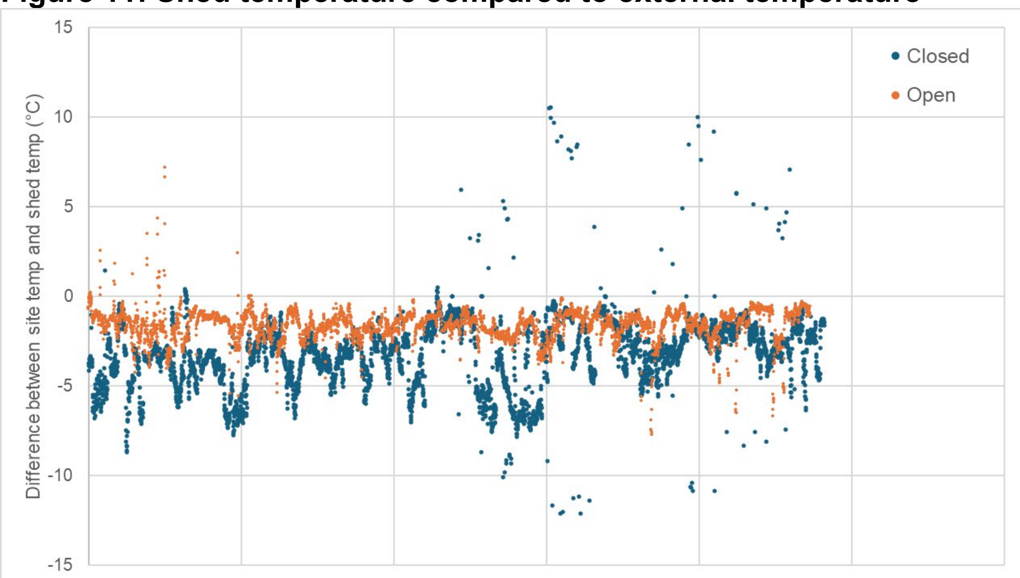
Figure 10: CO_2 level control



Further investigations through visual inspection and smoke testing, revealed that leakage at the ridge needed to be improved, along with structural gap filling. Modification work and re-design was carried out as detailed in section "*Design and development of the pilot*". These modifications improved the seal, reducing the infiltration by over 60%.

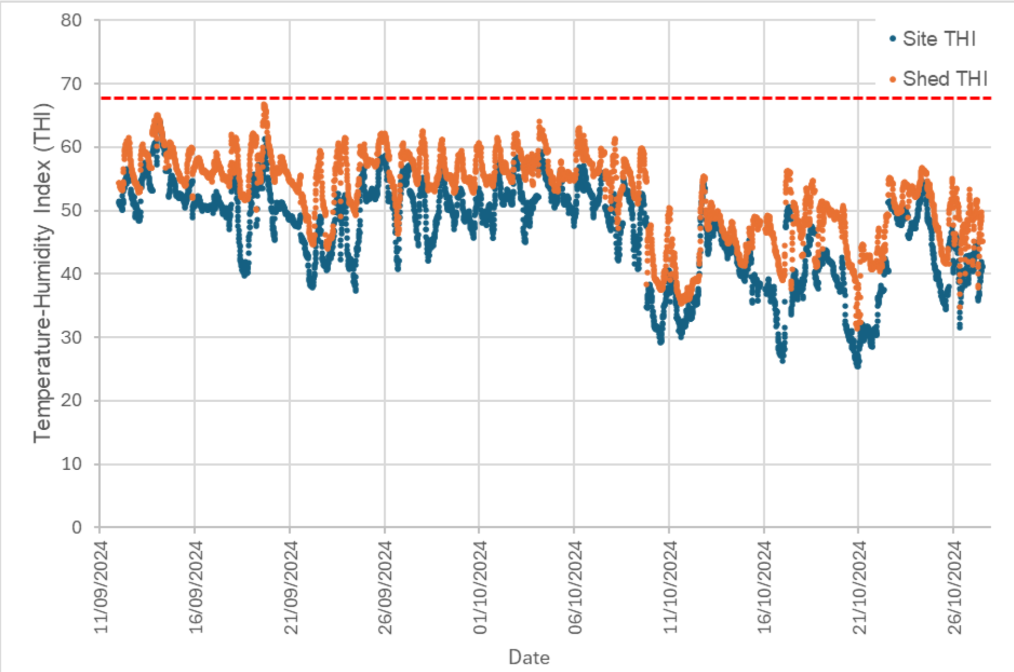
During assessments of temperature and humidity control, they were considered relative to external conditions, i.e., are they significantly better or worse than outside conditions. Whilst it is possible to maintain conditions within a very narrow window regardless of outside conditions, from an energy use point of view this would not be sensible. Therefore, one of the key aims of the development stage was to assess internal conditions that would minimise energy use whilst maintain optimum conditions for the animals. Figure 11 shows the difference between the shed temperature and the outside temperature i.e. is it better inside than out, both when closed and open conditions and when the AHU was not operational (i.e., like a normal naturally ventilated shed). Generally as cattle suffer from more heat than cold, it is better if cooler. With the latest configurations, the technologies were able to maintain conditions within the shed to within a few degrees of the external conditions and several degrees better than a normal shed.

Figure 11: Shed temperature compared to external temperature



Humidity is considered slightly differently to temperature as the effect of humidity on an animal is temperature dependent. Therefore, we use a metric of Temperature and Humidity Index (THI). This index is widely recognised for assessing livestock buildings, and factors in the importance of lower humidities as the temperature rises to enable an animal to lose heat through sweating or convection. It is considered that any THI below 68 will not cause heat stress in any type of cattle. Figure 12, showing the comparison of inside and outside temperatures over a hot period in June (this was monitored throughout the year, the sample below shows one of the hottest extended periods), demonstrates the system's ability to sufficiently control humidity to maintain optimum conditions for the animals, and better conditions than if the animals were outside.

Figure 12: THI inside and outside the shed

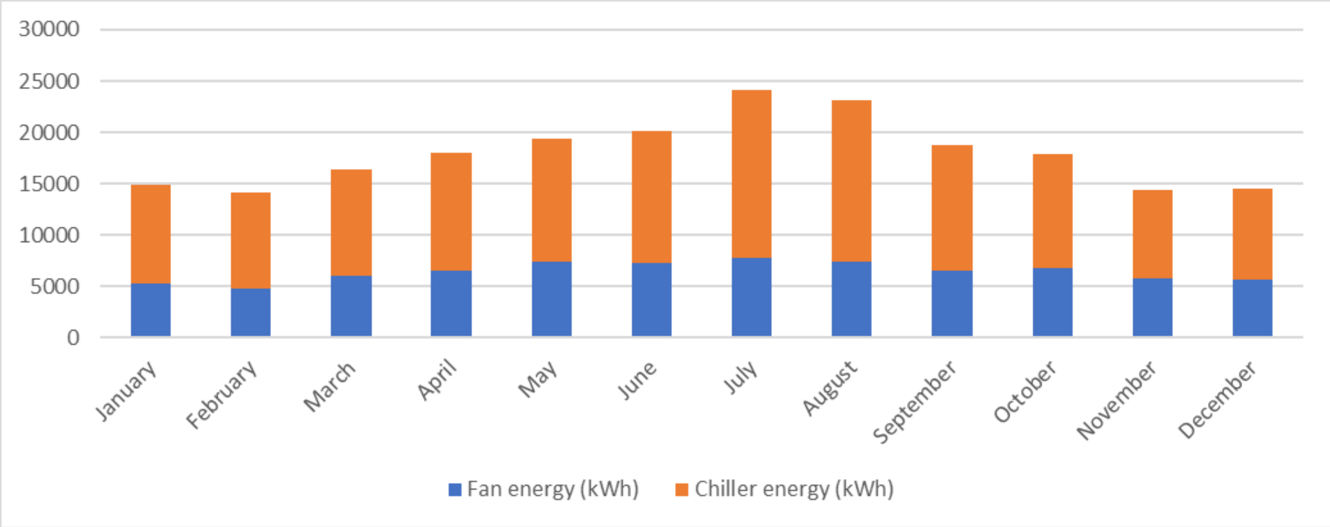


Energy usage

Annual energy demand data was extrapolated from trials when the shed was closed each month. However, due to the initial optimisation phase giving unrepresentative energy use data, we have estimated energy use for July and August based on other months and mean temperatures. The main energy use is the AHU unit; the data is presented in Figure 13. The variation in energy use across the year is not as large as for most buildings, this is due to the relatively stable base load for dehumidification from the animal's vapour outputs (breath, sweat, and urine), and the constant recirculation fan load. The variation that was observed is due mainly to outside temperature changing the cooling load, especially when it was sunny.

Our extrapolated energy demand for annual operation of the pilot system is 76,752kWh for the fans, and 145,000kWh for the chiller. We were surprised that the chiller was only less than double the energy use of the fans, but this is mainly due to the free cooling aspect of the AHU (using ambient air via a heat exchanger to cool the shed air) needing an additional fan, increasing the fan load, and conversely also reducing the chiller load.

Figure 13: Energy use in the Air Handling Unit over the year (2024)



Digital twin

The building simulation model of the GreenShed described was further developed as a Digital Twin[10]. This comprised two key elements: (i) the underpinning building simulation model, which has been calibrated using monitored data, and (ii) a wider optimisation model, described later, which has been used in the latter stages of the project to suggest optimum approaches to the operation of the existing GreenShed system and to signpost design improvements for future iterations of the concept.

Model calibration

A key element of digital twinning is calibration of building simulation model parameters against operational data. The model used data on shed geometry, materials thermal properties, construction characteristics, environmental control systems and their settings, cattle and bedding heat and contaminant emissions, and the shed air leakage characteristics. The majority of the information used was reasonably well defined and derived from design data (e.g. architects and engineering drawings) or from existing construction databases[11]. Further, test data from SRUC[12], was used to create a model of the heat and contaminant emissions from the housed cattle.

However, a key uncertainty in the model was its air leakage, which relates to the air flow into and out of the shed and is the result of gaps and cracks in the shed structure, purpose-built vents and the opening and closing of doors. Leakage characteristics used in the initial

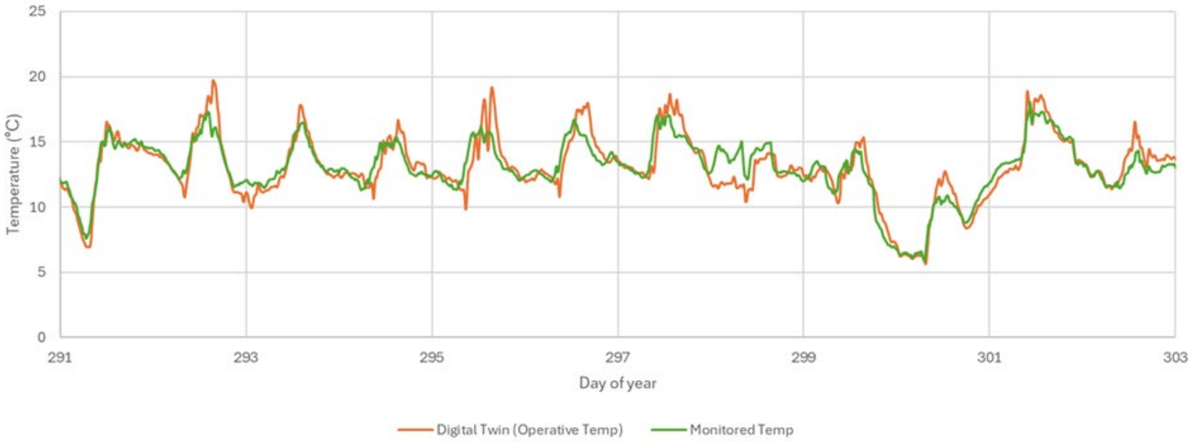
[10] A digital twin is a mathematical model of an entity such as a building, that evolves as the twinned entity develops. In the case of GreenShed, the digital twin was developed based on the initial concept (SAC, 2022), this was then revised to mimic the as-built shed. This report deals with a further revision, calibrating the twin using monitored data.

11 Clarke J A, Yanneske P P, Pinney A A, (1991) The harmonisation of Thermal Properties of Building Materials, BEPAC Technical Note 91/6.

12 Miller J, (2021). GreenCow animal emissions private data set. SRUC.

modelling were derived from information on warehousing[13], as this type of building was deemed to be a close match to the GreenShed construction, with a value of 1.2 ac/h applied. To facilitate calibration of this model parameter, a flow path network was added to the building simulation model, that computed time varying air flows into and out of the shed and time-varying contaminant levels. The calibration process involved the use of optimisation algorithms[14] that iteratively adjusted the leakage model to minimise differences between computed and measured parameters. Both CH_4 levels and temperature were used in the calibration process, which delivered a model for leakage that behaved in a similar way to the air leakage of the real shed. Figure 14 shows the temperature predictions of the calibrated model against measured data.

Figure 14: Monitored (green) vs. simulated temperatures (orange)



Using the updated leakage characteristics in the model, and simulating using the Edinburgh climate allowed the average air leakage (when the shed was closed) to be determined. The results indicated a leakage rate of 3.5 ac/h, which was considerably higher than the initial assumption of 1.2 ac/h. This finding prompted a programme of improvements to the fabric, to reduce infiltration. Two subsequent calibration exercises were undertaken, using data collected after improved sealing of the rooftop ridge vents and sealing of substantial gaps between the profiled roof and side walls was done. The results are shown in Table 14, indicting progressive reduction in average air leakage, such that the final leakage rate is close to initial assumptions made with the model.

Table 14: Computed leakage rates (ac/h) calculated using calibrated model

As-built shed	With improved ridge vent seal	With sealed roof profile
3.5	2.9	1.35

13 Brinks, P., Kornadt, O., & Oly, R. (2015). Air infiltration assessment for industrial buildings. Energy and Buildings, 86, 663-676.
14 Two algorithms were used in this case, which allows cross-validation of the model characteristics arrived at by each.

Outcome: Use of the digital twin has demonstrated that sealing has improved air leakage rates, which will result in significantly less exfiltration of CH_4, when the shed is closed. It also indicates that with improved build oversight, a relatively airtight construction can be achieved.

Adjusting other model parameters

Other parameters adjusted included gaseous emissions from cattle (CO_2 and CH_4), which was more straightforward than leakage, as this was a single data input point to the model. Again, each parameter was iteratively adjusted within a range until the root mean squared error between measured and monitored CO_2 and CH_4 levels was minimised.

The CO_2 level emerging from the calibration was consistently higher than the 200 g/h/animal assumed in initial modelling. Further investigation indicated that ageing bedding could be contributing to the CO_2 load in the shed. With emissions rates of up to 1.8 kg/hr after 30 days[15]. This is the equivalent of another 9 cattle in the shed. The simulation model was adjusted to include the higher bedding emissions rate, increasing the emissions per animal by 50g. This increased nominal CO_2 levels in the shed with 30 cattle from around 800 ppm to 1100ppm, with 30-day-old bedding, which is still below the initial 1500 ppm limit. However, emissions from aging bedding will need to be accounted for in future upgrades to the GreenShed air extraction system. We did consider the use of alternative bedding systems which would produce less or no CO_2 ,such as zero bedding systems, sawdust or inert bedding like shredded carpets. However, they were discounted as none of them would allow us to generate biogas from the waste products of the shed, a key concept of the circular system.

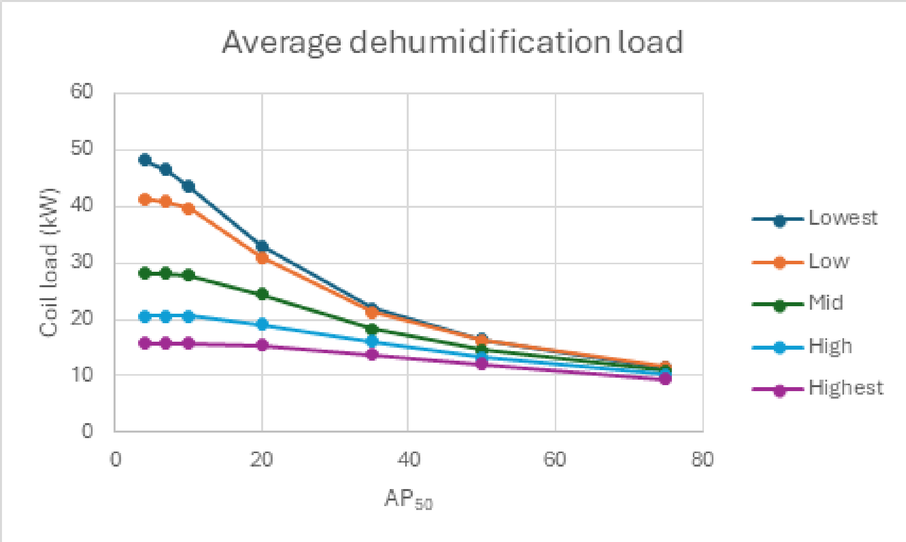
Further Analysis

Finally, simulations were undertaken with the digital twin to assess the effect of variation in air leakage, animal and bedding emissions and increasing air extraction from the shed.

All of these simulations indicated that increasing the air extraction rate significantly reduced the requirements for cooling and dehumidification, irrespective of gains from cattle and bedding and shed fabric quality. This was due to outside air almost always being cooler and drier than the air in the shed. So infiltration balancing air extracted provided “free” cooling. For example, Figure 15 shows that increasing extraction rates to 3 x the current levels (highest and lowest levels in the figure) significantly reduced the cooling and dehumidification load, with the average reducing from over 30kW to around 15kW at design shed leakage rates (20@AP50)

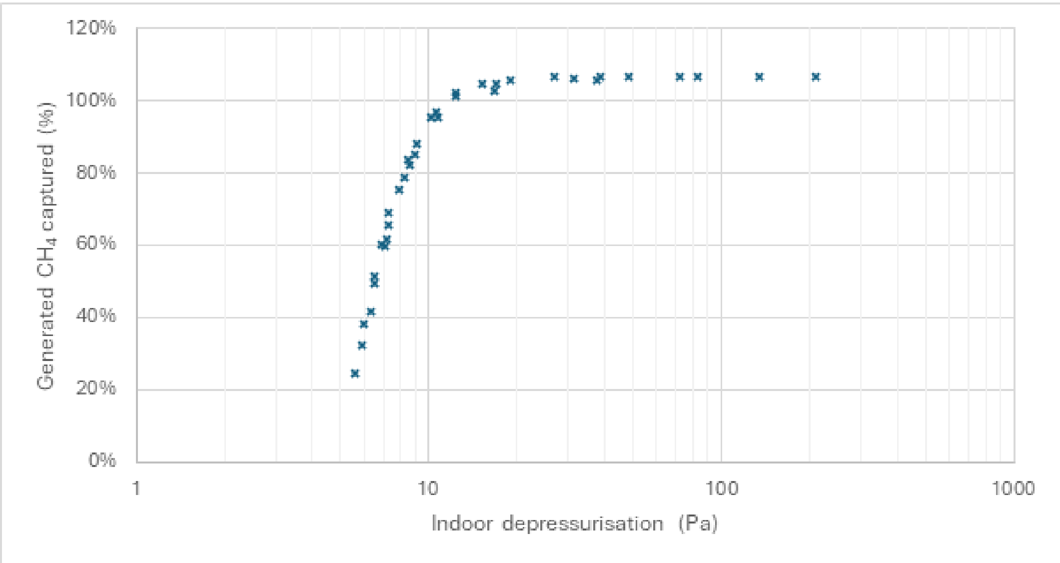
Figure 15: impact of shed air extraction on energy use (highest extraction rate to lowest)

[15] Spiehs, M. J., Woodbury, B. L., & Parker, D. B. (2019). Ammonia, hydrogen sulfide, and greenhouse gas emissions from lab-scaled manure bedpacks with and without aluminum sulfate additions. *Environments*, *6*(10), 108.



The simulations also indicated the depressurisation level needs to eliminate net methane emissions from the shed. Figure 16 shows that at -12Pa depressurisation methane processed by the shed's systems wholly offsets emissions from the cattle and leakage to the outside environment, when closed. A higher extract rate and improved airtightness would make this level of depressurisation achievable. Beyond -12Pa depressurisation, levels of infiltration of ambient methane from outside is such that the shed's systems process more methane than is produced inside the shed and escapes to outside.

Figure 16 shed depressurisation vs methane captured



GreenShed optimisation modelling

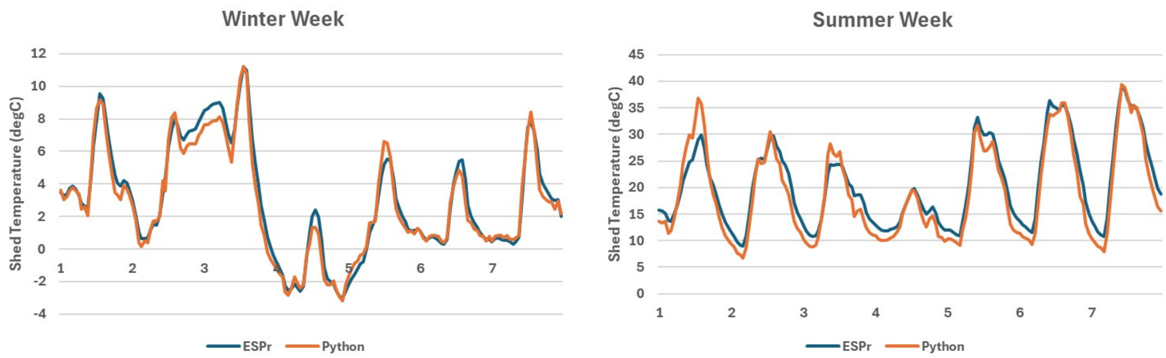
An optimisation-based model (complimenting the digital twin previously described) was developed to investigate shed design variants and operating strategies. The optimisation engine was developed using the GEKKO library in Python, which uses the APMonitor linear programming engine. The cost function used as the basis of the optimisation was:

$$'Cost' = Grid\ Electricity\ kWh + [S1 * (THI - 69)] \quad \text{(Eqn 1)}$$

S1 is a penalty value (50), applied if the shed THI exceeded the maximum value set by SRUC of 69.

The optimisation analysis required the shed thermal model was simplified to a series of linear or non-linear equations that could be solved to find the optimal, least ‘cost’ operating strategy based on current conditions. The simplified optimisation model was calibrated using data from the digital twin. Figure 17 shows that the simplified linear model was able to track the building simulation model results with sufficient accuracy to allow assessment of design variations and operating strategies.

Figure 17: Winter and summer week comparison of shed temperature for the simplified optimisation (python) model and digital twin (ESP-r)



Optimisation model application

The optimisation model was used to assess potential improvements in the Greenshed design and operation. Specific investigations focused on, first, the use of look-ahead optimisation, the impact of improved sealing of the shed on optimum operation, the impact of heat recovery, and control of heat gains from the shed roof.

Lookahead optimisation time horizon

Linear optimisation analysis can be run with different lookahead ‘horizons’ (i.e., the model is optimised over single or multiple timesteps). A single timestep horizon assesses the optimal operating strategy for only the following timestep. The horizon can be extended to multiple timesteps, incorporating weather forecast data etc., to determine if the strategy in the next timestep should be altered in the context of expected future performance over the assessed time horizon. To assess if lookahead optimisation would be of benefit in the operation of the GreenShed, a sensitivity analysis was undertaken with 1-hour and 24-hour look-ahead horizons (Table 15). The metric assessed was the energy use required to maintain shed THI within limits.

Table 15: Optimisation time window vs heating and cooling energy use

Horizon (hrs)	Average Temp (°C)	HVAC Cooling Energy (MWh)	HVAC Heating Energy (MWh)	Electricity (MWh)	HVAC Moisture Removal (t)
1	14.86	308.3	138.3	311.8	185.4
24	14.37	339.7	124.7	307.9	205.1

The results indicated that extending the optimisation horizon to 24 hours did give a slight reduction in overall energy use. However, the benefits are marginal and in the assessments that follow, performance optimisation performance was be focused on short term requirements.

Improved shed sealing

As indicated by the detailed model calibration exercise, the GreenShed system, as-built, was seen to have significantly higher air infiltration than initially anticipated – 3.5 air changes per hour (ac/h) as opposed to the 1.2 ac/h initially anticipated. The impact of reducing the infiltration levels on optimum operation of the GreenShed was analysed.

An as-built model was simulated with the current shed leakage (3.5 ac/h) and with a target of optimally maintaining THI below 69. The average shed temperature over the simulated period was 15.4°C and the target THI was exceeded for 93 hours, due to infiltration of large quantities of air at temperatures above the shed interior. With the design infiltration rate (1.2 ac/h), optimum THI control resulted in the shed temperature increasing significantly, with increased heating; this reduced the RH and the need for dehumidification (the largest component of the cooling requirement). However, as less moisture was lost through exfiltration, so mechanical moisture removal increased compared to the leaker shed case. Even with optimised operation, the HVAC energy requirements increase as leakage rates drop. Conversely CH_4 lost to the environment would be reduced.

Table 16: Optimum annual energy use with as-built and target infiltration

	Average Temp (°C)	Hours THI > 69	HVAC Cooling Energy (MWh)	HVAC Heating Energy (MWh)	HVAC Moisture Removal (t)
3.5 ac/h	15.4	93	62.3	154.1	22.5
1.2 ac/h	18.2	136	104.6	242.5	48.0

Adding roof insulation

The current shed has a roof comprised of thin, metallic profiled sheet. This has the potential to increase summer overheating, as the roof surface heats quickly with solar gain, to a temperature significantly higher than the ambient and the shed internal temperature. The impact of adding 100mm of internal roof insulation to the existing structure on optimum shed operations was assessed and the key results shown in Table 17. The results are presented for the as-built and improved air infiltration levels, after the gaps in the shed fabric were sealed.

Table 17: Optimum annual energy use with roof insulation for as-built and design infiltration

Shed Design	Infiltration (ac/h)	Average Temp (°C)	HVAC Cooling Energy (MWh)	HVAC Heating Energy (MWh)	HVAC Moisture Removal (t)
Current	3.5	14.29	187.7	128.3	104.9
Insulated	3.5	15.24	49.1	96.4	15.7
Current	1.2	14.37	339.7	124.7	205.1
Insulated	1.2	15.82	207.6	94.9	128.7

In all cases, running to minimise operational ‘cost’, insulating the roof surface resulted in a significant reduction in energy use and required less moisture removal, particularly for the as-built case. Increased insulation allowed higher temperatures to be maintained in winter, reducing the need for moisture removal and reheating. Summer overheating and cooling requirements are also reduced, due to reduced solar gain to the shed interior from the roof.

Cooling coil heat recovery

The HVAC dehumidification process requires cooling of recirculated air to below the recirculated air saturation temperature to remove moisture and then reheating to increase the return the air to maintain shed temperature and suitable THI levels. A heat pump system can be used to recover heat removed during the dehumidification and cooling or recirculated air for reheating of the dried air (Table 18).

Table 18: Optimum annual energy use with heat recovery

HVAC Design	Infiltration (ac/h)	Avg. Temp (°C)	HVAC Cooling Energy (MWh)	HVAC Heating Energy (MWh)	Electricity (MWh)	HVAC Moisture Removal (t)	Heat Recovered (MWh)
Current	3.5	14.29	187.7	128.3	264.7	104.9	0
Recovery	3.5	14.57	162.4	140.2	134.7	84.5	103.7
Current	1.2	14.37	339.7	124.7	307.9	205.1	0
Recovery	1.2	16.06	240.4	180.6	139.8	137.6	149.6

The results emerging from running the GreenShed model to minimise operational cost indicated that using heat recovery could provide over 70% of the optimal re-heating input, reducing the required input electricity by 55% for the design infiltration case.

Outcome: The application of the optimisation model has indicated that there are potential energy savings to be derived in the operation of the GreenShed:

- 24-hour lookahead control delivers some energy benefits in operation of the GreenShed system but look-ahead control of for as little as 1-hour can deliver operational energy savings compared to reactive control.
- Increasing the air tightness of the shed decreases CH_4 leakage but increases cooling and dehumidification load on the HVAC system, even with optimised operation; the as-built leaky construction delivered ‘free’ cooling in the form of infiltration of outside air; however, this could also lead to summertime overheating.
- Optimum HVAC control tended to maintain shed temperatures at their upper limits which reduced RH levels in the shed; this strategy decreased sensible cooling and latent cooling loads.
- The addition of roof insulation can lead to a substantial reduction in optimum cooling energy requirements preventing gains manifesting themselves as convective and radiant heat gains to the interior of the shed.
- Heat recovery from the cooling/dehumidification coil can cover over 70% of shed heating and HVAC re-heat load.

Animal welfare assessments

The means and estimates of variance are shown in Table 19 for the welfare indicators assessed on individual animals for each session. No animals were lame or had any swellings or lesions. There were only two observations of animals with a single hairless patches (both in the “open” condition) or that were dirty (both in the “closed” condition), but the frequency was very low and did not warrant statistical analysis. The respiration rate ranged from 24 to 58 breaths/min with a mean of 38.5. There was no difference in respiration rate between the ‘open’ and ‘closed’ condition ($P<0.05$). Nasal discharge was recorded on a scale from 0 to 2, where 0 represented the absence of discharge and 2 showed a significant presence. Ocular discharge was scored in the same way. Of the 240 observations of the animals, there were 35 animals observed with nasal discharge and 205 observations in which the animal had no nasal discharge. For ocular discharge, there were 17 observations of ocular discharge out of 240 observations. There was no effect of whether the shed was open or closed on the level of nasal or ocular discharge ($P<0.05$). There was no effect of the shed being open or closed on sweating ($P<0.05$). There were 35 observations of sweating out of 240 total animal observations.

Table 19: Descriptive statistics

Indicator	Scale	Mean	SEM	Min observed score	Max observed score	No. obs
Cleanliness	0-2	0.017	0.012	0	2	240
Hairless patches	Counts	0.008	0.006	0	1	240
Lameness	0-2	0	0	0	0	239
Lesions	Counts	0	0	0	0	240
Nasal discharge	0-2	0.32	0.05	0	2	240
Ocular discharge	0-2	0.140	0.03	0	2	240
Resp. rate	Counts	38.51	0.42	24	58	240
Sweating	0-2	0.15	0.02	0	2	240

Swellings	Counts	0	0	0	0	240

The descriptive statistics for scan sampling are shown in Table 20. There was an interaction between season and the open/closed condition that indicated that there was more standing during the autumn in the closed condition (P<0.001). Similarly, there was an interaction between season and the open/closed condition that indicated that there was less lying during the autumn in the closed condition (P<0.001). There was no effect of the open/closed condition on the performance of abnormal behaviour. There was a very low level of abnormal behaviour and it mostly consisted of licking the pen and walls and playing with water. This may be associated with housing per se, as abnormal behaviours are observed less in cattle at pasture. There was no effect of whether the shed was open or closed on the amount of aggressive behaviour seen. There was not a high level of aggression. However, more of these behaviours were shown in the autumn (P<0.05), which may explain the higher level of standing. The amount of coughing was not affected by whether the shed was open or closed (P>0.05).

Table 20: Means, standard error of the mean, minimum and maximum values for the behaviours scoring using instantaneous scan sampling

Indicator	Unit	Mean	SEM	Min	Max	No. obs
Lying	Proportion of group	0.31	0.01	0	0.93	240
Standing	Proportion of group	0.69	0.01	0.07	1.0	240
Abnormal behaviour	Proportion of group	0.03	0.004	0	1.0	240
Aggressive behaviour	Count/session	0.02	0.003	0	0.38	240
Coughing	Count/session	21.9	1.21	3	76	240

From the Qualitative Behavioural Analysis, a principal components analysis showed two main components. The first component was emotional valence (negative to positive), and the second component was activity (low to high). The analysis showed that there was no effect of whether the shed was open or closed on the emotional state of the animals (P>0.05). However, as before, there was an interaction between shed condition and season (P<0.05), with animals being more active when the shed was closed in the autumn.

In conclusion, there appears to be no effect of being housed in a closed shed on any health parameters assessed. Animals do not suffer from more lameness, injury or increased respiration. There does not appear to be visible signs of thermal stress. No more sweating was observed in the closed conditions vs the open conditions. Mental state was not affected by being housed in the closed shed, as shown in the qualitative behavioural analysis, and performance of abnormal behaviours (which are associated with boredom) were no higher in the closed condition than in the open condition. There were some differences in activity levels and aggression, but this was limited to a single season (autumn). This may be due to a particular group or type of animal housed in the shed in that period. There were more observations in autumn than in other seasons. The results suggested that activity was 10% higher in the closed condition than the open condition. Aggression levels were generally low in comparison to other types of housing systems. Published data on behaviour of beef cattle is sparse in the literature (much more work has been done with dairy cattle), thus no reference to published data could be made.

Challenges overcome

- Components delivered not fabricated to the correct design - many components were bespoke and manufactured by specialist fabrication companies to specific designs from the technology partners, however several of these arrived on site manufactured incorrectly. This was not due to errors with the designs and drawings, but always a mistake during fabrication when translating the drawings into manufacturing details. Whilst this did not cause increased costs to rectify, it did introduce delays. To overcome this, technical partners initiated an intermediate step to review fabrication plans from manufacturers before fabrication commenced.
- Quality-control/performance on external contractors' delivery – some aspects of the project were carried out by non-technical partners as specialist work, such as shed fabrication, and controls electricals. These were often the aspects that initially did not meet the required standard. The underlying cause was often the contractors understanding of what the project was trying to achieve, leading to assumptions about what was required. To overcome this the project partners issued more detailed performance criteria, and included higher level aims and goals of the project.
- ATEX regulations (controlling explosive atmospheres) - during commissioning of the AD system, external biogas gas engineers were bought in, and they required a separate ATEX plan to be carried out. This was a surprise to the project, as in terms of gas usage, the system was approximately the same size as a large domestic heating system, which are not covered by ATEX regulations. This ATEX plan requirement necessitated the AD system being shut down, and an ATEX specialist bought in who suggested design changes to comply with regulations. This process took > 3 months. The result however is a design which in future will comply with ATEX regulations at the lowest possible cost.

- Full planning application was required instead of a simpler notification to council that would be required by a commercial farming business, which resulted in approximately a 6-month delay to commencing the shed build.
- Global increases in materials costs resulted in a budget shortfall for the build, resulting in a site re-design to reduce concrete and sub-base costs.
- The weather logging system has proved reliable, however the power supply to data logging equipment was subject to interruption, resulting in occasional data drop-put. This was mitigated by substituting validated data from neighbouring weather stations as needed. For wind speed data, this required adjusting measured wind speed by approx. +1m/s from neighbouring weather stations to account for the more open site conditions at GreenShed.

Life cycle assessment (LCA) and monitoring, reporting and validation (MRV)

LCA

Following carbon footprinting and LCA methods set out in ISO 14044, PAS 2050, and ISO 14067, all the processes, energy and resource movements involved in the system were mapped. This was used to define boundaries of the process that are included in the analysis.

Due to the pilot scale of our installation, we did not have sufficient heat from the CHP unit to provide heat to the AHU or vertical polytunnel, all heat is required to heat the digesters. However, the amount of heat required for the digesters does not increase linearly when you increase the size, therefore at full scale of a 100-animal shed and especially if the AD is over sized, there should be sufficient spare heat to export to the AHU and polytunnel, therefore we have modelled an LCA scenario based on heat from the CHP.

To scale up the results from the pilot scale shed to a 100 animal shed, we simply used a linear multiple based on inputs and outputs measured per animal in the shed. This is a worst case method, as some of the inputs would reduce per animal on a larger shed. Such as cooling load, especially when sunny as there is relatively lower external surface area.

- Manufacture of the system components are not included in the LCA. Whilst the CO2RE principles mention the inclusion of manufacturing, we have taken the view that this is aimed at large scale projects which would have far higher embodied carbon in the manufacturing. In addition, Under ISO 14044 there is a “cutting rule” which allows for the exclusion of activities which contribute a very low percentage of the total inputs to the system. The cutting criteria can be applied based on the contribution of that activity to mass, energy, or environmental importance. Assuming 1.54 kgCO_2e/kg of steel[16] and a total of 12 tonnes of steel in the AD unit and AHU and an assumed lifetime of 20 years, the manufacturing only accounts for approximately 0.924 tonnes of carbon/year, when considered against the estimated 200 tonnes of removal/year, this is less than 0.5% and would therefore qualify under the ISO 14044 cutting rule.

- The waste bedding and manure used as feedstock for the AD plant is considered to have no emissions up to the point it is placed in the storage pile as these emissions would happen anyway. Any emissions involved in handling and movement from the storage pile into the AD plant is included in the LCA.
- All imported electricity used in the air handling system, or vertical polytunnel, is included in the scope 2 emissions.
- Surplus electricity generated from the AD plant, or heat from the AD CHP engine and exported is not included as "avoided" emissions. However, we have taken a "net balance" approach, in that if net over the year, the system does not import electricity, we deem all electricity used in the GreenShed components to be effectively from the CHP.
- We have included CH_4 leaking from the digester tanks, but due to the difficulty of measuring the leakage directly, we have assumed the same rate as used in the Ofgem Biomass and Biogas Carbon Calculator[17] of 0.2g per MJ of electricity produced.

LCA flows, inputs and outputs

Electricity

- Total electricity generation from the AD CHP engine.
- Total imported mains electricity from the grid.
- Electricity usage in the AHU.
- Electricity usage for the AD unit parasitic load (stirrers, augers, pumps etc.)

Heat

- Heat from the CHP used in the AD digestor tanks.
- Heat from any other source used in the AHU.

Fuels

- Fuel usage in loader for handling the feedstock - not directly measured but estimated, based on the hours used for loading feedstock and standard figures for fuel usage from the [Farm Management Handbook (https://www.fas.scot/publication/fmh2022/)](https://www.fas.scot/publication/fmh2022/).

Water

[16] https://www.cisl.cam.ac.uk/files/sectoral_case_study_steel.pdf
[17] https://www.ofgem.gov.uk/publications/uk-biomass-and-bioliquid-carbon-calculator

- Total mains water usage to the shed.
- Water usage to the AD.

At this stage, without a full year of steady running, and without the CHP engine running, we have had to extrapolate some data and make assumptions for others.

LCA emission factors (EF)

Where possible we used government produced emission factors used for mandatory company reporting, specifically for mains electricity and water and fuels. Where this was not possible, it was sourced from the Ecoinvent (https://ecoinvent.org/) database, or where we deem that data was out of date, it was sourced from scientific literature.

Wider environmental and social impacts

In the case of the GreenShed system, we considered any potential biodiversity impacts of the very small construction footprint. At the scale of our system attached to existing sheds, the core activity of the shed does not change, it will still have animals in. Therefore, as far as the public or local community are concerned we would not envisage any social impacts with the exception of noise in situations where the farm sheds are close to non-farmhouses.

LCA Results

We have run the LCA based on a full-scale system, and modelled the scenario in the commercialisation plan i.e., a 100-animal shed, an oversized engine (to increase the income from export sales), or an existing AD plant.

The results, are not in a typical LCA format, where the emissions or savings are reported per “functional unit”, in the case of beef this would be per kg. However, As the aim of the project is to reduce emissions, we are more interested in total emissions, so are only reporting total emissions and reduction in tonnes of CO_2e.

Table 21: Annual inputs and Emission Factors (EF)

Annual Inputs	Quantity	Scope 1 EF	Scope 2 EF	Scope 3 EF
Mains water to AHU (L)	310,630	-	-	0.0002
Mains water to AD (L)	182,500	-	-	0.0002
Electricity to AHU Chillers (kWh)	335,520	-	0.207	0.068
Electricity to AHU Fans (kWh)	168,192	-	0.207	0.068
Electricity to AHU heaters (kWh)		-	0.207	0.068
Electricity to AD (kWh)	43,800	-	0.207	0.068
Electricity to WWT (kWh)	17,520	-	0.207	0.068
Fuel used to load AD (L)	535	2.755		0.627
Methane leakage from AD (kg)	407	27.000	-	-
N fertiliser into polytunnel (kg)	220			3.437
P fertiliser into polytunnel (kg)	96			1.700
K fertiliser into polytunnel (kg)	183			0.600
Electricity to polytunnel (kWh)	839	-	0.207	0.068
Mains water to polytunnel (L)	54,860	-	-	0.0002
Methane captured (kg)	4,698	27		

Table 22: Annual emissions (kgCO2e)

Annual Inputs	Scope 1	Scope 2	Scope 3	estimated,extrap.,actual
Mains water to AHU	-	-	48	extrapolated
Mains water to AD (top up)	-	-	28	estimated
Electricity to AHU Chillers	-	69,469	22,872	extrapolated
Electricity to AHU Fans	-	34,824	11,466	extrapolated
Electricity to AHU heaters	-	-	-	extrapolated
Electricity to AD	-	9,069	2,986	estimated
Electricity to WWT	-	3,628	1,194	estimated
Fuel used to load AD	1,474	-	335	estimated
Methane leakage from AD	10,984	-	-	extrapolated
N fertiliser into tunnel	-	-	756	extrapolated
P fertiliser into tunnel	-	-	163	extrapolated
K fertiliser into tunnel	-	-	110	extrapolated
Electricity to Polytunnel	-	174	57	estimated
Mains water to polytunnel	-	-	8	extrapolated
Total emissions (kgCO2e)	12,458	117,164	40,023	
Methane captured (kgCO2e)	-126,837			
Generation from CHP		-116,989.88	-38,518	estimated

NET C. balance (kgCO2eq/y)	-114,379	14	1,505	

From the results in Table 22 the net scope 1 removal is 114,379 kgCO_2e per year, however when we factor in the net emission from scope 2&3, the net removal across all scopes drops to 112,700 kgCO_2e. This is lower than modelled at the beginning of the project, at over 200,000 kgCO_2e, due to the far higher levels of CO_2 from the bedding than suggested by the literature, requiring higher ventilation rates and resulting in dilution of the CH_4 in the exhaust air.

MRV Methodology

Our Greenhouse Gas Removal (GGR) mechanism relies on the conversion of a high Global Warming Potential (GWP) gas (CH_4) to a lower GWP gas (CO_2), which is 27 times less potent. Therefore, it is possible to have net negative emissions – i.e., removals.

Using the four principles for defining GHG removals rather than avoidance, established by the Zero Emissions Platform (ZEP), and which are adopted in this programme:

1. The GHG is physically removed from the atmosphere.
2. The removed GHG is stored out of the atmosphere in a manner intended to be permanent.
3. Upstream and downstream GHG emissions, associated with the removal and storage process, are comprehensively estimated, and included in the emission balance.
4. The total quantity of atmospheric GHG removed and permanently stored is greater than the total quantity of CO_2 equivalents emitted to the atmosphere.

The system removes the CH_4 in the air produced from cattle (both enteric CH_4 from the animal digestive tract and the CH_4 produce from decomposing bedding). Therefore, we meet Principle 1.

The process then combusts the CH_4 to produce CO_2. As we use conversion of GHG rather than typical storage in a product, geologically or chemically, we do not face the challenges of verifying the permanence of that storage. The CO_2 will not convert back to CH_4. Therefore, we meet Principle 2.

As part of this pilot, we monitor a wide range of energy inputs and outputs, and resource flows. With this high-quality data, we are able to build a robust Life-Cycle Analysis (LCA), or technically a carbon footprint, as it does not include other environmental impacts commonly associated with an LCA. The LCA includes wider scope 3 emissions both upstream and downstream of our system. This comprehensive LCA allows us to estimate the net emissions from running the system. Therefore, we meet Principle 3.

We monitor CH_4 concentrations and flow at the inlet to the combustion process, which gives us the mass of CH_4 entering. Concentration and flow are measured again on the exhaust to allow calculation of the mass of CH_4 removed. Subtracting the net emissions from running the system calculated in the LCA demonstrate the net removals. Therefore, we meet Principle 4.

As our GGR process does not require "storage" we have a simplified MRV method that does not involve assessing or demonstrating the degree of permanence, as summarised below.

1. Quantify CH_4 removal -> convert to CO_2 equivalents = CARBON REMOVED FROM ATMOSPHERE
2. Full upstream and downstream LCA = CARBON RELEASED FROM THE GGR PROCESS
3. Carbon removed from atmosphere – Carbon released by the GGR process = NET CARBON REMOVAL

Methane removal quantification

To avoid any potential issues with leakages in long ducting, CH_4 concentration and flow is measured immediately before and after the combustion, in the air inlet to the engine and in the engine exhaust. The minimum read of most high-quality gas analysers is approximately 10ppm, therefore we assume for any reading at this level, or below, all CH_4 has been removed. We take a very conservative approach in the quantification of CH_4 removal:

- CH_4 concentration is measured in the engine air intake and engine exhaust using the same analyser with split sampling (it alternates between sampling the intake and exhaust). Using the same analyser lessens any potential errors between different analysers, the same error should be on the inlet and exhaust.
- If PPMexhaust_engine is below a predetermined level we assume all CH_4 has been combusted, therefore PPMreduction = PPMintake.
- Flow meter for engine air intake volume rate, pressure and temperature (V, P and T)
- Molar volume = (8.3145*T) /P
- Conversion to mass (g) = (V/Molar volume) x (6.022x1023) x (PPMreduction/1,000,000) x 44
- Conversion to CO_2 equivalent, CO_2reductiong = mass(g) x (GWP25-1**)
- All sampling periods when PPMexhaust_engine is above predetermined level, it is assumed no CH_4 has been removed (i.e., worst case)

**Accounts for the CO_2 produced from combustion.

Data storage for auditing MRV

All of the direct measurements and readings are centrally collected to the main controller and data storage, and this is also where the removals calculations are carried out. This data is stored locally on a central hard drive and also backed up to cloud-based storage. The storage will be sufficient for seven years of data in line with common auditing practices.

Commercialisation plan, barriers and risks

Consumer and supply chain research (work package 6)

A critical component of ROI will be any "green beef premium" 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 leading up to Phase 1, suggested a strong case for such a premium. Phase 2 work has explored in more detail the price incentive that would be required to justify farmer investment, alongside consumer research and engagement around the acceptability and willingness to pay for reduced GHGs. Retailers and processors are clear that an "evidence-base" is critical for any firm commitment to such a premium. This would include objective animal health and welfare outcomes, verification of GHG savings, and costs and savings arising. GreenShed lends itself to providing on-going real-time MRV data.

Consumer research - methodology

Throughout 2023 consumer research was conducted by a consumer research organisation. Firstly, they conducted a series of consumer focus groups in various parts of the UK with a cross section of the UK beef eating public (structured broadly by sex, age, and previous beef consuming practice). The objective of this qualitative assessment was to explore the feelings and behaviours of consumers around beef consumption as it relates to environmental concerns and to gain an insight into their perceptions of beef farming to gauge their reaction to the GreenShed concept. In total, six, 90- minute, face-to-face focus groups were conducted (Table 23).

These were split by age and a standard demographic classification/social grading model, often referred to as 'ABC1'. This system describes, measures and classifies people of different social grade and income and earnings levels, and is used for market research, social commentary, lifestyle statistics, and statistical research and analysis. For instance, 'A' equates to upper middle class, whereas 'C1' relates to lower middle class. From experience, ABC1s are more likely to be early adopters, and a greater proportion will have the ability, not just a willingness, to pay. Within groups participants were also required to be beef buyers and consumers, to consume a range of beef and to have a range of frequency of red meat consumption. The groups also included participants who were consciously reducing red meat consumption for environmental reasons.

Table 23: Focus groups for qualitative consumer research

	Red meat reducers*	Beef consumers**
Pre-family	Group 1 - London	Group 4 – Borrowash (Derby)
Family	Group 2 - Borrowash	Group 5 - Glasgow
Empty nesters	Group 3 - Glasgow	Group 6 - London

*All have consciously reduced red meat consumption for environmental reasons. All still consume beef; ** All eat beef at least once/week.

Secondly, an on-line survey of UK beef consumers was conducted by the same consumer research organisation. The objectives of this phase were to measure the willingness to pay for low carbon beef and consumer attitudes towards the GreenShed concept. In total 1,034 responses were received. Respondents were all UK adults aged 18 and over that buy and consume beef and were nationally representative of the UK. They were asked a series of questions about their beef consumption behaviour and how they would view the GreenShed concept and its focus on reducing GHG emissions. They were also asked what their concerns about such a GreenShed system might be, and what price premiums, if any, they would be willing to pay if such an environmentally focussed beef product was available in the marketplace.

Consumer research – current buying behaviour

Most consumers were concerned about climate change and of the actions tested (Figure 18), reducing emissions from farming was seen as lowest priority for tackling this issue (Figure 19):

Figure 18: Consumer concern regarding selected issues

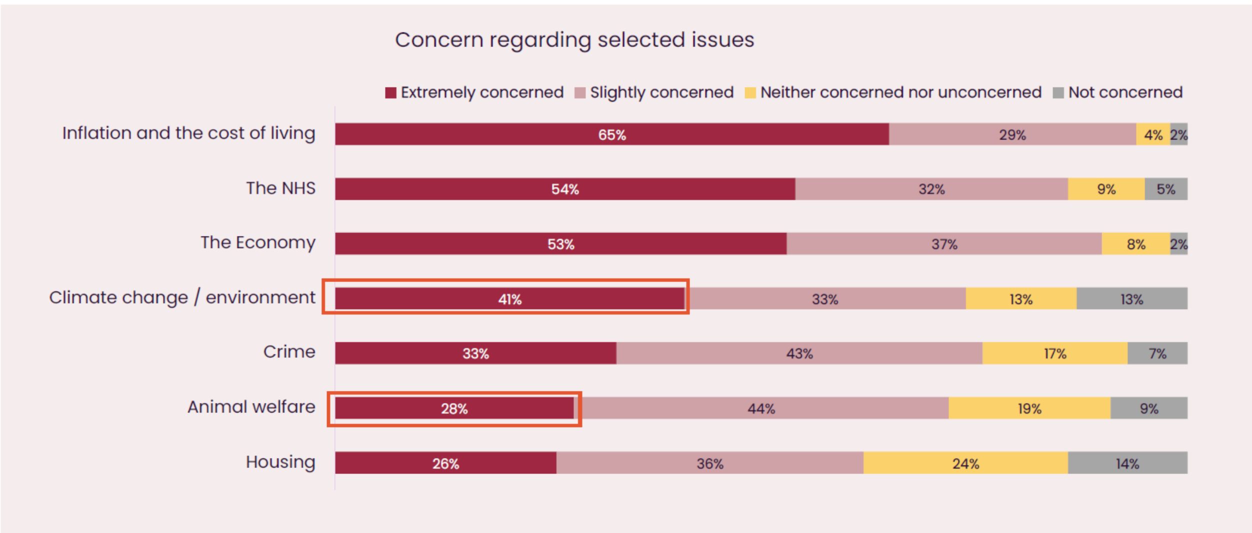
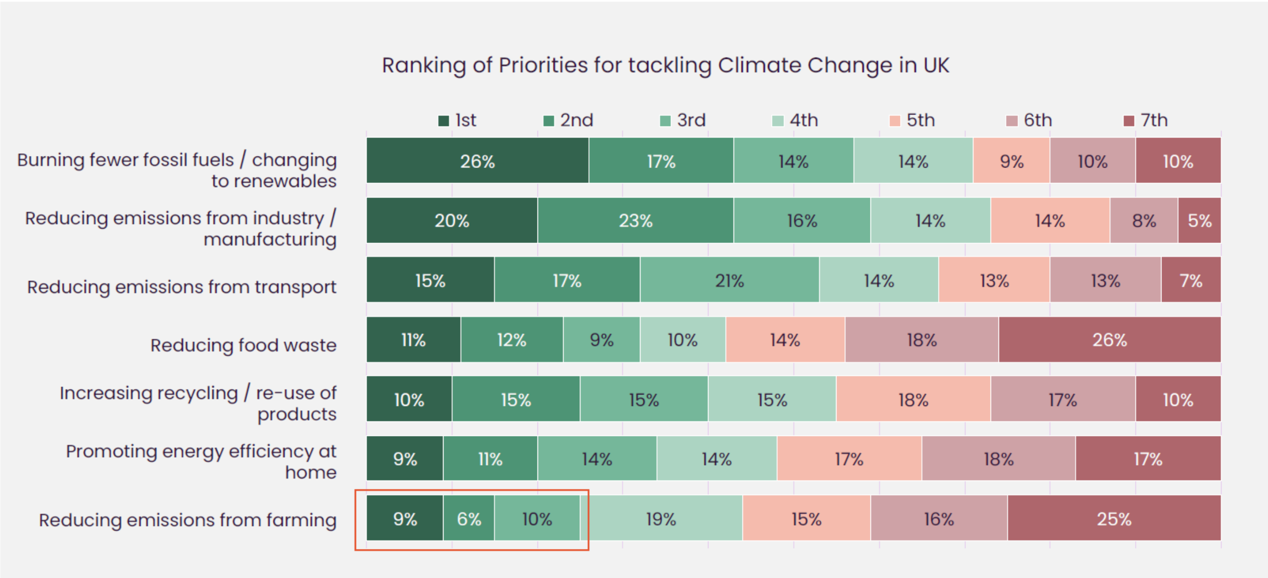
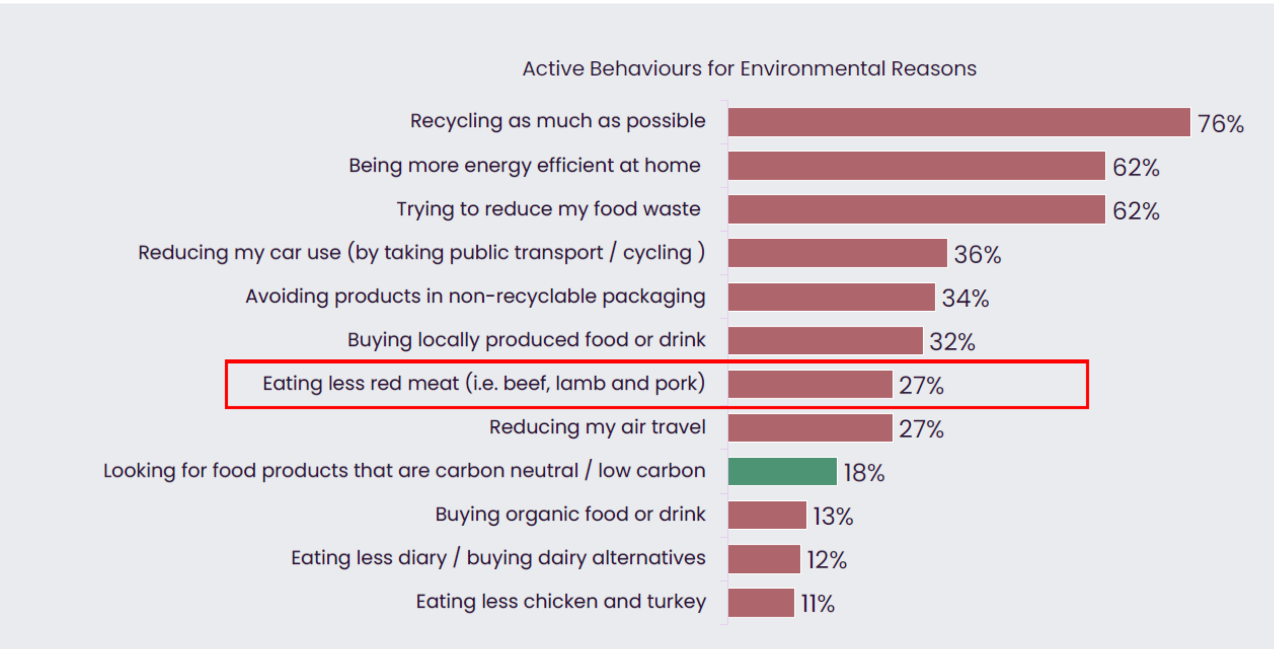


Figure 19: Consumer ranking of priorities for tackling climate change



Seeking out low-carbon food products was not high on the list of current environmentally friendly consumer behaviours. Recycling, energy efficiency, reducing food waste, reducing use of own transport (e.g., car), reducing non-recyclable packaging, purchasing locally produced food and drink all featured higher (Figure 20):

Figure 20: Current environmentally friendly behaviours



Currently, ~50% of beef consumers claimed to be limiting the amount of beef that they consume (Figure 21), and around one-third of beef limiters claimed to do so because of environmental concerns. Around 50% of those limiting for environmental reasons were also doing so for cost reasons (Figure 22), suggesting there may be a marginal willingness to pay for more environmentally friendly beef products.

Figure 21: Consumer attitudes towards beef

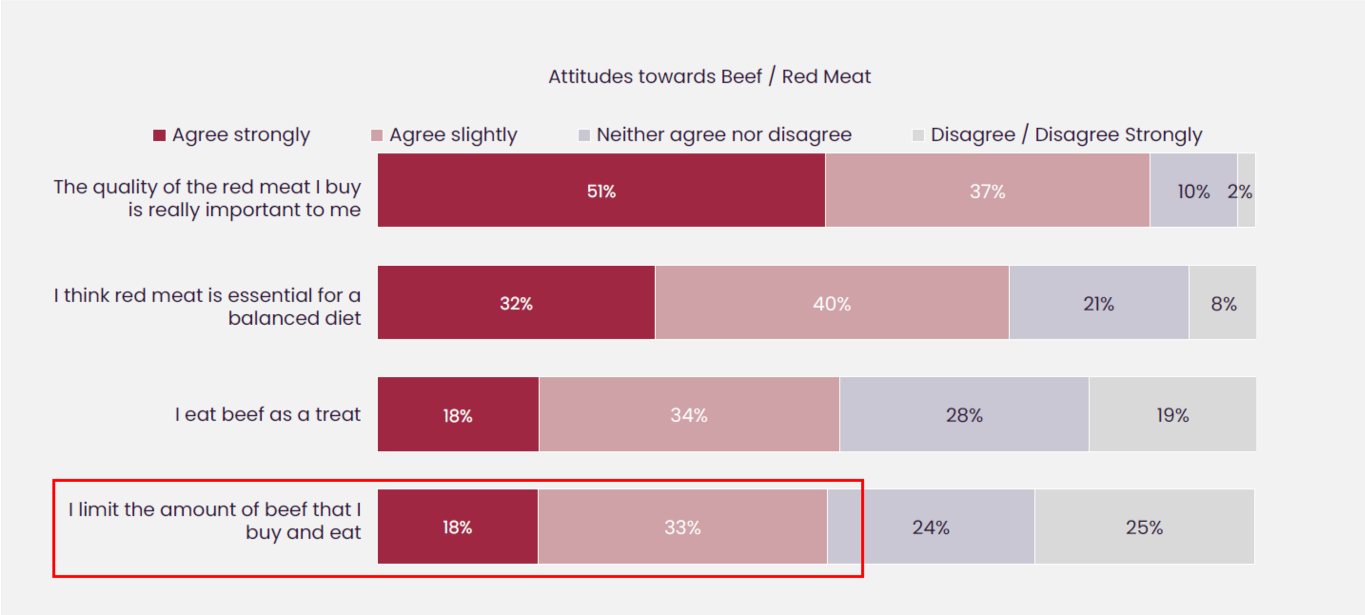
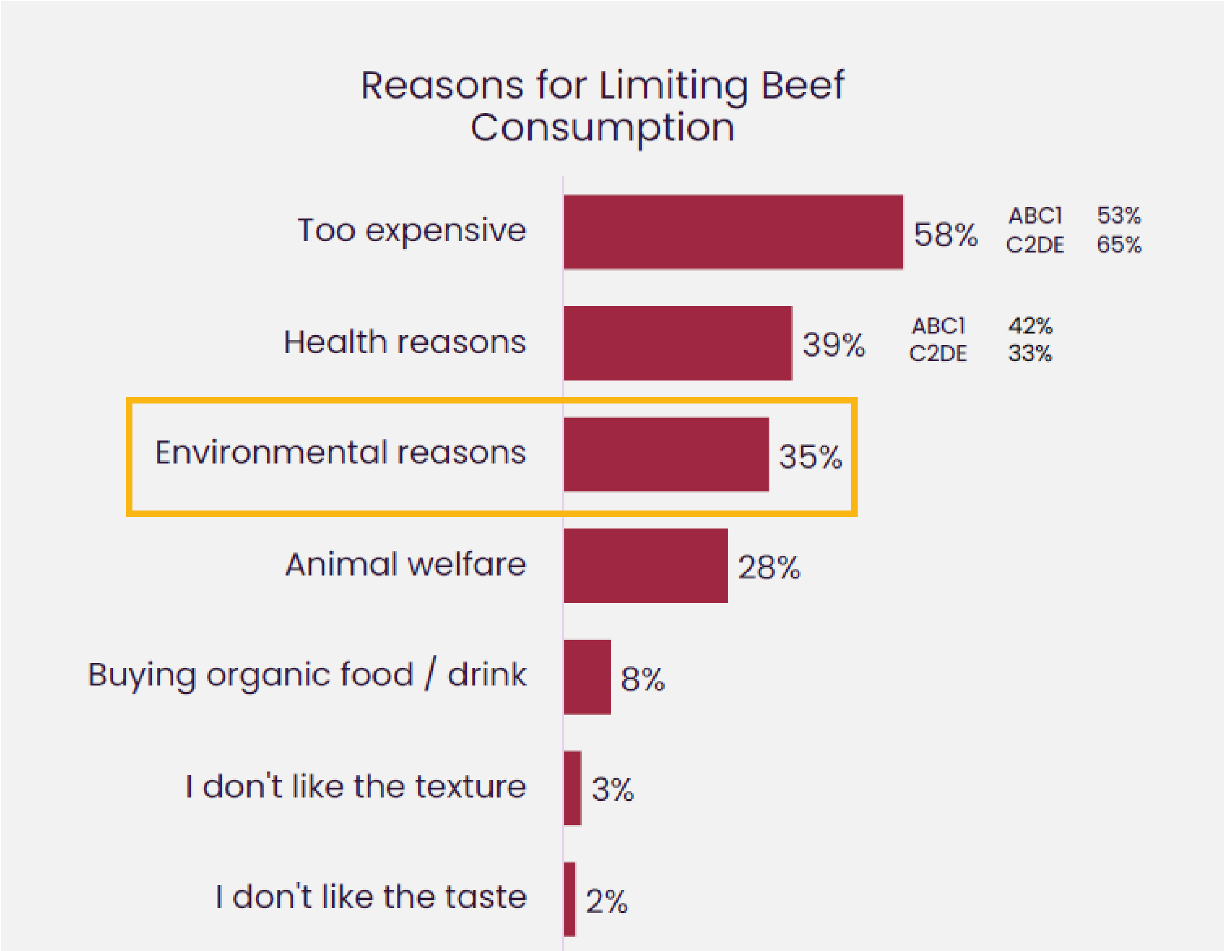


Figure 22: Consumer reasons for limiting beef consumption



Interestingly, those consumers reducing for environmental reasons were more likely to be shopping at Waitrose and Sainsbury's (Figure 23), where animal welfare is notably important for M&S shoppers:

Figure 23: Consumer reasons for limiting beef consumption by retailer

Too Expensive

	Too expensive
All	58%
Asda	64%
Aldi	63%
Tesco	62%
Lidl	62%
Morrisons	59%
Sainsbury's	56%
M&S	52%
Waitrose*	35%

Health Reasons

	Health reasons
All	39%
Waitrose*	47%
M&S	46%
Sainsbury's	44%
Lidl	43%
Asda	38%
Morrisons	35%
Tesco	35%
Aldi	33%

Environmental Reasons

	Environmental reasons
All	35%
Waitrose*	43%
Sainsbury's	42%
Asda	37%
Morrisons	37%
Tesco	37%
M&S	35%
Aldi	30%
Lidl	28%

Animal Welfare Reasons

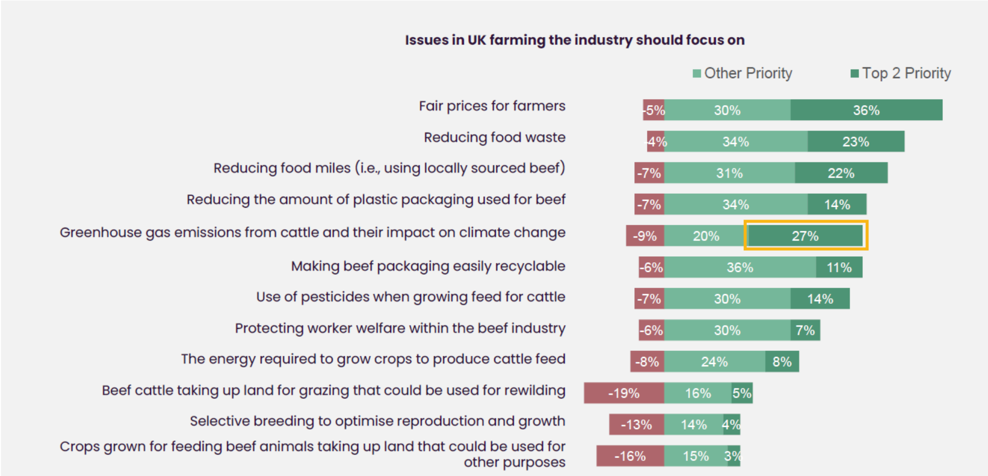
	Animal welfare reasons
All	28%
M&S	42%
Asda	36%
Morrisons	35%
Waitrose*	33%
Sainsbury's	33%
Tesco	31%
Lidl	26%
Aldi	25%

Currently, when shopping for beef, aside from price, consumer considerations were dominated by quality, provenance and fat content, and only ~1 in 20 actively considered the environmental impacts of the beef product they purchase (Figure 24).

Figure 24: Consumer considerations on buying choices

Most beef buyers (72%) felt that the UK beef industry's environmental reputation is at least good - but not excellent. When prompted cattle emissions in beef farming was seen as one of the top priorities (Figure 25:Figure 25). Similarly, animal welfare was considered to be at least good by the majority of beef buyers, but perceptions were more positive amongst older adults (79%):

Figure 25: Consumer priorities in UK farming

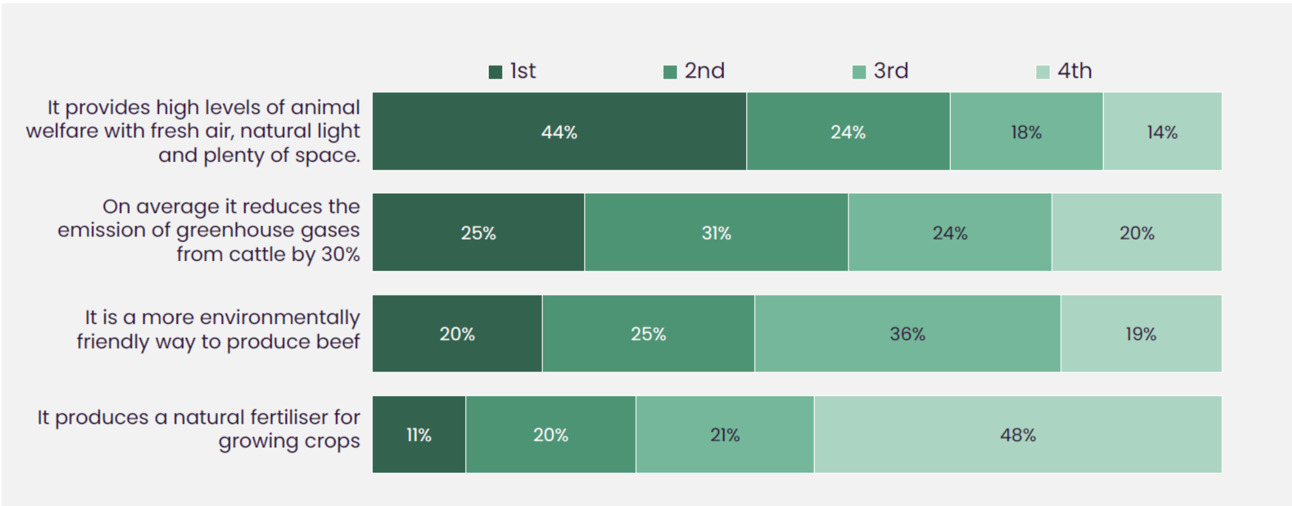


Consumer research – perception of GreenShed

The public are open to, and generally positive about, “low carbon” beef developments such as GreenShed but they need a careful explanation of its purpose, operation in practice and the benefits to not only them, but wider society, and it was notable that simple pictorial representations of how GreenShed works are preferred, rather than complicated flow diagrams of circular farming systems.

One area of concern relates to animal welfare of cattle being kept in “sheds” for long periods of time. A minority of respondents (7%) felt that GreenSheds would result in negative outcomes for animal welfare. Interestingly when prompted, the animal welfare benefit of GreenShed was clearly the most appealing to beef consumers, pushing environmental benefits into second and third place (Figure 26).

Figure 26: Consumer perception of GreenShed benefits



Most consumers seem re-assured by current farm assurance scheme standards and recognised logos such as Red Tractor. Provided no hint of “battery” cattle is conveyed during the explanation/marketing of such developments, then consumers would be happy to buy GreenShed beef rather than their current purchase.

Consumers were also concerned that any “claims” made about the “low carbon” nature of the GreenShed beef was backed up with real facts and figures about how much carbon was being “reduced” rather than simply accepting marketing materials. Overall, they were happy to see the figure of a 30% reduction in GHG output from GreenShed beef. The consumer survey also indicated that provided GreenShed beef was available at a reasonable price, 55% would choose it over ‘standard beef’, and one third felt they would buy more beef if it was available (Figure 27, Figure 28):

Figure 27: Impact of GreenShed on consumer buying behaviour

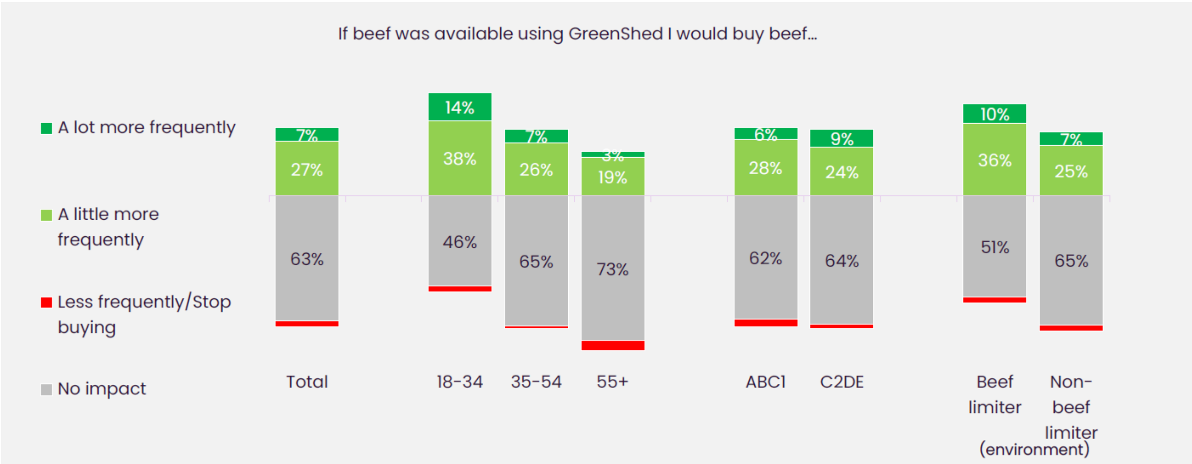
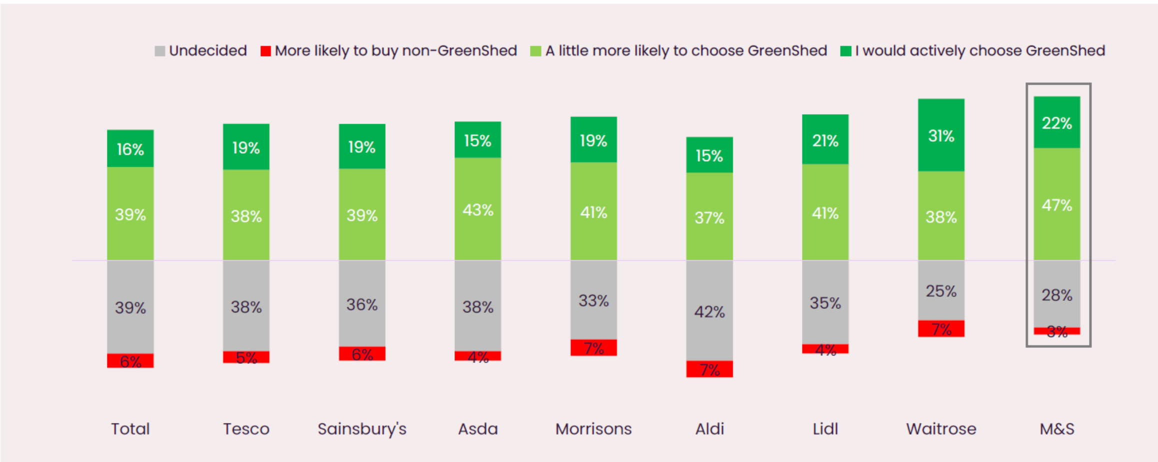


Figure 28: Impact of GreenShed on consumer buying behaviour by retailer



There was a clear willingness-to-pay for low carbon beef amongst a segment of the beef buying public, but this willingness was dependent on the degree to which there is a meaningful GHG reduction (Figure 29). Assuming GreenShed reduces “carbon” by 30%, consumers would be willing to pay around 16p more per 225g pack, compared to a pack of “standard sirloin steak”. This figure equates to approximately 71p/kg price premium for GreenShed sirloin steak. Unsurprisingly, there was a much greater willingness to pay for low carbon beef amongst those limiting beef consumption for environmental reasons:

Figure 29: Willingness to pay for low-carbon beef

As confirmed by the major processors and retailers, it must be acknowledged that consumer responses to questions and discussions in surveys and focus groups are not necessarily followed through by actual consumer buying behaviour. Consequently, it has been assumed that this willingness to pay a price premium for GreenShed produced beef will only apply to a minority of consumers who choose to value the “green” credentials of beef production highly in their actual buying practice. Some method of matching these willing consumers with a GreenShed beef supply chain must be found outside of the major processor/supermarket routes which form the bulk of the meat trade.

Supply chain engagement - GreenShed Interest Group

A GreenShed Interest Group (GSIG) was formed to:

- Provide the GreenShed project with inputs, insights, solutions, and metrics from external stakeholders who have a variety of roles within and allied to, food supply chains, and have both UK and international experience in these areas.
- Engage early with stakeholders prior to commercialisation, with whom the GreenShed project and concept may have future interactions.
- Hear and understand concerns, reservations, and enthusiasm, so they can be considered and addressed prior to commercialisation.
- Seek practical input and operational expertise from producers, beef value chains, assurance bodies, levy organisations and the financial investment sector about the concept and how it can be brought to the commercial marketplace.

To ensure a comprehensive view from across all sectors of the beef supply chain, the membership of the GSIG was deliberately compiled from a wide range of organisations which represent production, processing and marketing of beef from farm to retail shelf. The membership (22 organisations from across the beef supply chain) included: (i) R&D partners, retailers and processors, (ii) farming, farm assurance bodies and levy funded organisations and (iii) government, finance and other industry organisations.

The meetings discussed the key features needed to establish a dedicated GreenShed beef supply chain: (i) defining and adjusting on-farm production protocols for GreenShed beef and how farm and supply chain record flow could ensure authenticity and associated price premiums, (ii) understanding the technical operation of GreenShed and any necessary farm assurance standards/record changes, and (iii) the financial requirements of setting up a commercial GreenShed installation.

Modifications to existing beef supply chains

Key considerations raised included: management and verification of consumer sensitivities around animal welfare; quantification of GreenSheds capacity to reduce GHG emissions; and in particular, the financial costs and rewards necessary to ensure GreenShed investments were economically viable for producers. There was broad agreement that any amendments to on-farm production protocols, existing farm record flows and farm assurance standards and records could be achieved with relative ease.

On-farm GreenShed operational protocols

Grant and subsidy awarding bodies, as well as beef supply chains, require clear eligibility criteria. This may be needed for both Grant schemes and subsidy payments or for the purposes of branding, product differentiation, alternate product pricing schemes or consumer focussed marketing purposes.

GSIG discussions suggest the following eligibility criteria for verified GreenShed beef. Firstly, a set of basic “definitive” criteria for animals to be eligible to any “GreenShed beef scheme”. These should be simple, easily achieved and verified by existing means if possible. It was suggested that these basic criteria be that the animals were kept on a farm assured holding, managed under an existing animal health and welfare plan and be kept in a GreenShed facility during the final finishing phase of their lives for a minimum period, e.g., 10 weeks prior to slaughter. Secondly, there may be a range of factors that each marketing route/company may want to add to the definition/protocols for their own purposes (e.g. origin, breed, category, feeding/grazing, slaughter weight, fat and conformation grading ranges, etc.). These factors could be different for each marketing route and the GSIG could see plenty of scope for different supply chains to define a ‘GreenShed animal’, or GreenShed beef, relevant to them and their markets. The GSIG could also see scope for different types of beef animal being used within a GreenShed beef scheme with differences being accepted across different company or outlet-based schemes. However, it was also accepted that animals with a good level of overall efficiency would be preferrable since older, inefficient animals would be seen by consumers, Government and others as completely negating the point of finishing animals within a GreenShed facility designed to minimise GHG emissions.

The consensus amongst GSIG members was that these small changes to on-farm production protocols and practices could be achieved with relatively little difficulty to ensure consistent GreenShed beef supplies on a regular basis to any given supply/marketing route.

Food chain information forms and farm assurance standards

There was also consensus that existing on-farm records such as Food Chain Information (FCI) forms could be amended to incorporate any additional declarations, data or information that was required for verification as animals left the farm and entered the food processing sector. Each of the major abattoirs often have their own versions of FCI forms that could be amended to include GreenShed criteria as required.

Many discussions took place throughout the GSIG meetings around certification and verification and how the key issues could be addressed. Three main areas of concern included animal welfare, verification of actual GHG mitigation, and fresh produce supply. The existing farm assurance systems were considered the most appropriate route by which independent verification could be achieved. Animal welfare issues such as housing space and feeding trough requirements for indoor cattle, feed and water provision, vet and medicine treatment and recording, cattle handling and transport issues were all considered important. This was particularly, in relation to consumer perceptions of GreenShed, which to uninformed consumers might look like “factory farming”. It was noted that these issues are already covered by existing assurance schemes and no changes were needed to address these consumer concerns.

There was general agreement that existing FA beef standard could be modified to incorporate the principles of GreenShed production systems and on-farm record keeping providing independent verification of GreenShed protocols. In addition, the principles of existing pig sheds FA ventilation standards could be adapted for beef sheds where ventilation is controlled rather than natural. These standards would need to be modified to meet the biological parameters relevant to beef cattle. In principle, there was broad agreement that this approach should be possible. Farm Assurance standards also exist for fresh produce and a similar approach to their modification could be used where it was considered necessary.

Farm assurance standards currently have limited impact on GHG reduction. This is mostly addressed through “carbon footprinting” exercises , often with both retailer and Government encouragement. Measuring and monitoring GHG usage and savings within and by the GreenShed technology rather than modelling GHG output is the key to GreenShed. This can then be used to independently verify actual GHG reductions by organisations like Agrecalc, to support any environmental claims. If necessary, farm assurance scrutiny of these records could be easily incorporated into existing assurance schemes.

It was also stressed that comprehensive maintenance and servicing would be essential to ensure that equipment operated at maximum efficiency to maximise the GHG reductions achievable over time following installations on commercial farms. The costs of this would need to be factored into any cost / benefit calculations and farm assurance schemes could also review/inspect these farm records.

Supply chain considerations

One major element of perceived difficulty was price premium agreements for GreenShed beef. It was also widely acknowledged that farmers would be reluctant to make the considerable financial investments necessary to establish GreenShed production systems if no price premiums were available. Farmers commonly receive price premiums for specific classes of finished cattle such as organically produced or those sired by specific breeds (e.g., Aberdeen

Angus, Hereford or Beef Shorthorn). These price premium schemes are an established feature of the current marketplace and farmers can see no reason why the principle of such premiums could not be extended to GreenShed produced cattle. The major retailers and their aligned processers are not the only route to the consumer market for beef. Over recent decades, many much smaller supply chain routes to the consumer have developed across the UK. Often initiated by entrepreneurial farmers, working together with local abattoirs, smaller wholesalers and butchers etc. These routes may be direct from farm to consumer, or may operate through farm shop networks, farmers markets or via food catering outlets. These more direct marketing routes will need to be employed if the willingness of some consumers to pay extra for GreenShed beef is to be utilised by the farmer in meeting extra GreenShed financial costs. Once these routes establish a beef volume of supply that is of interest to the larger supply chain companies, then they may decide to get involved.

Favourable finance terms and conditions

It is envisaged that some financial benefit can be obtained through the availability of "Green Finance Initiatives", a term that usually refers to the financial activities that support "environmental sustainability". Typical projects that fall under the "Green Finance" umbrella include renewable energy and energy efficiency, pollution prevention and control, biodiversity conservation, circular economy initiatives and sustainable use of natural resources and land. Given the energy efficiency, pollution prevention via methane capture and usage, circular farming system and sustainable resource use objectives of a GreenShed system; it is certain that a GreenShed investment would qualify under such a "Green Finance" umbrella. These "Green Finance" initiatives would consequently provide some cost-saving benefits to farmers seeking capital for a GreenShed retrofit. Their ability to provide loans at both reduced arrangement fees (small saving), or more importantly through the provision of reduced long-term interest rates being the mechanisms delivering this benefit. Several of the high street banks already offer reduced terms for loans which meet their sustainability criteria and are considered on a case-by-case basis. Key to farmers accessing these better terms, is a robust MRV around the system, banks will not invest in unproven technologies.

Beyond farmers accessing better terms on finance, the commercial food retailers, who require significant levels of short-term finance from commercial banks to cover cashflow, can also benefit from lower interest rates from commercial banks (who are keen to meet their sustainable investment goals) when their sustainability performance improves, therefore this can give an incentive for supermarkets and retailers to purchase lower carbon products. It could be this driver which force the retailers to pay a “premium” for lower carbon beef. This premium may not always be seen by the consumers on the end price if they don’t think the market can take the extra cost, as the retailer gets the financial benefit of reduced interest payments.

Future “Green Income” schemes

In the longer term, it can be envisaged that new "Environmental Payment Schemes" are likely to develop where "carbon capture" can be monetised and "sold" by farmers operating such schemes. Some initiatives in this area already exist for arable, forestry or landscape systems where carbon captured in soils or woodland can be sold to commercial companies seeking to reduce their carbon footprint. One such system is the "Landscape Enterprise Network" scheme. It operates primarily at a landscape or water catchment level rather than an individual farmer or even animal level. While these schemes are in their relative infancy across arable and other land-based systems, there is not yet a UK livestock-based carbon trading system in operation. It remains to be seen if such a scheme does develop allowing livestock farmers to financially benefit from activities undertaken to capture carbon. There is no reason, in principle, why these commercial partners would not also seek to "buy" carbon capture from within livestock systems in the same way as they are doing for landscape systems. This would require these schemes to operate on a sufficiently large scale to be of interest to large commercial customers if they are to take off and flourish. It may be that if GreenShed systems can be successfully rolled out across the UK beef industry, that a GreenShed carbon capture scheme could be one of the first to develop within the livestock sector. However, since no such scheme yet exists, no financial benefit has been incorporated into the commercial scenarios.

GSIG - key considerations

- Management and verification of consumer sensitivities in relation to animal welfare.
- Quantification of GreenSheds capacity to reduce GHG emissions to the atmosphere.
- Evidence requirements and adherence to criteria for government grant schemes.
- Whether reductions need to be considered purely from a beef production perspective, or from that of a whole farm system, and as such part of a larger narrative.
- How different supply chains might define a ‘GreenShed animal’ relevant to themselves and their markets.
- The financial costs and rewards necessary to ensure that GreenShed developments are seen as economically viable options for producers in a commercial environment.
- The need for GreenShed to be sensitive, and nimble in its appeal, to a changing green-financing landscape.
- The ability for existing assurance and certification schemes to capture positives from, and therefore add value to, GreenShed beef production.

Commercialisation strategy

Return on Investment (ROI) calculations

Original estimates of the capital costs of retrofitting a GreenShed installation to an existing beef cattle shed were of the order of £330,000 to £400,000 in the early stages of the project in 2019-2020. A retrofit to an existing shed was chosen as the preferred marketing and installation route, as the full cost of a complete new shed build in addition to the capital costs of GreenShed equipment was considered expensive and difficult for farmers to justify. As a result of global disruptions (covid, inflation, energy crises and major global events) all major costs have risen considerably over the past five years with worldwide inflation rates resulting in a significant increase in most component costs for this type of investment.

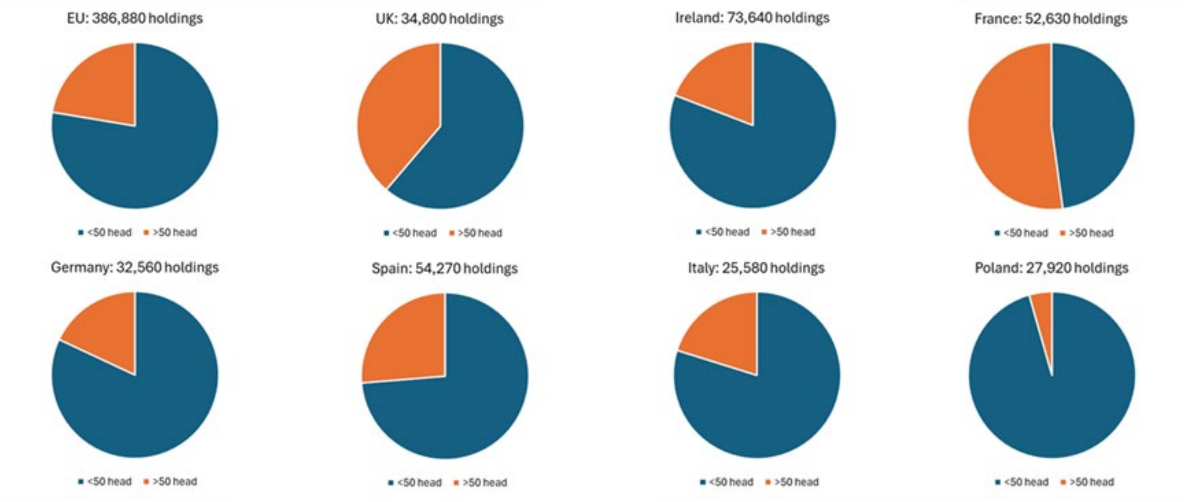
For a 100-animal scale operation the capital cost for installation has risen to £755k (an increase of >£350k from initial estimates). In our business model revised Phase 2 calculations have shown a c.£71k net increase in farmer output/annum, driven by horticultural output value, beef sales premium, export energy sales and heat; after all operating costs are accounted for (running costs. Maintenance and finance). It has been assumed that some government grant funding will be available for a retrofit GreenShed installation on commercial farms (at 40%, as this has been the historical limit on similar capital grant programmes). This provides a payback of 5.2 years, based on capital cost of £755k for the unit installation.

It is important to note that longer payback periods are not unusual for large scale farm installations (e.g., agricultural machinery/renewables/carbon). For scenario's where the farm has a pre-existing AD, the total capital cost reduces to £335k, with a payback period of 6.7 years (note in this scenario increased outputs are restricted to beef sales premium and horticultural output). When considering higher-value crop varieties (e.g., basil) we can reduce payback on the full-scale model (with AD), from 5.2 to 4.9 years, and when considering lower-value crops (e.g., butterhead lettuce) this increases to 5.6 years. Note all calculations above assume access to grant schemes. These estimates are conservative, as they only consider the value of horticulture outputs from one "mini-system" of 120 columns. The outputs from GreenShed will be able to support much larger scale horticulture outputs. These need to be more robustly quantified over a longer-time period (minimum of 12 months). Without grant support, the payback period on the full installation extends to >7 years.

Target markets and route-to-market

The initial target-market for GREEN-SHED outputs is the UK's c3.3M part-year housed beef-cattle, collectively producing 904,000t beef pa, worth £3.9B to the UK economy (85% self-sufficient) (DEFRA, 2017). The UK consumer spends \>£5.2Bpa consuming \>18kg of beef/related products (AHDB, 2018). We assume that a typical GreenShed installation will be for 100 finishing animals. Initial GreenShed installations will be considered most attractive to those beef farms who also have existing AD plants already installed and operational within their overall businesses. Consequently, farms with both an existing beef-finishing enterprise and AD plants firmly established, should be the obvious target customers for this first round of GreenShed commercial installations in the UK. Commercial development would start with a pan UK rollout of GreenShed sites, linked to specific niche marketing opportunities for beef and crop sales. Following successful development of a niche market for the GreenShed product(s) and concept; a JV company could be considered with the goal of further UK sales; progressing to EU and worldwide GreenShed sales. A conservative target market (Figure 30) has been identified of 3% initial market penetration of the specialist (100+ head) UK beef finishing farms, equating to 180 sheds; and 0.5% of EU specialist beef finishing farms, equating to 320 sheds; totalling 500 sheds. At 112tCO_2e/pa removed per shed, this will achieve 56kt CO_2e/pa removal.

Figure 30: Target market - specialist beef



Following beef-cattle, outputs can be applied to seasonally-housed dairy cattle and other housed ruminants, both in the UK, and globally, with further export potential (e.g. China's $26B beef market (CAGR 10%), where many animals are continually-housed). These markets can be accessed through wider stakeholder-consultation and via partners global supply-chain networks.

Post-project rollout

From supply chain engagement a sufficiently long period of MRV is required to gain supply chain confidence in the technology. This would require an MRV exercise of a minimum of 12-months before commercial rollout could commence. Commercial rollout will be facilitated through a Joint Venture (JV) of the technology consortium members. The consortium clearly understands that the key strength of this project, and future potential of GreenShed commercially, is in the combined strength of all technical partners and associated systems being brought together as a package. It is recognised that to commercially offer, supply, and maintain such a system a JV of the technical partners would be required – a legal entity where the partners are shareholders This legal entity would give the end user a single point of contact at the sales, installation and through life support of the system. The JV will be the legal entity to offer the maintenance and support contracts to the end user. This entity could then set up service contracts with existing partners and other 3rd-parties to ensure all farms have the local coverage and support they require. It is envisaged that the data and control systems will have the ability to be remotely monitored and have settings adjusted by the supply partners, giving the farmer further confidence in the unfamiliar systems. Rollout will be initially in the UK, followed by a European launch. Servicing and maintenance will be via an established national mechanical and engineering company.

Phase 1: modelling and initial market engagement

- Established technical and commercial feasibility

Phase 2: Pilot construction and operation

- Validation of animal and environmental data (Health and welfare / Productivity / GHG / other emissions and waste.
- Economic data: Capital and operating cost/ Cost-benefit and ROI calculation
- SC engagement: Awareness and buy-in to system / Model candidate producer incentives using real data.
- Design pilot incentive schemes for SC uptake post-project: Establish a GreenShed Interest Group
- Consumer research

Phase 3: longer term validation

- Funding to enable full 12-month MRV period.
- Updated system and commercial modelling.

GreenShed commercialisation and roll-out

- Joint Venture formation: UK roll-out / Pilot producer scheme within SC / EU sales launch

Key market drivers are shown in Table 24 and dependencies and assumptions in Table 25Table 25.

Table 24: Market drivers

Societal / Economic Drivers	Farmer Value	Supply Chain Value
Drive to net zero GHG food production. Increased scrutiny of animal health and welfare, GHG impacts of livestock production. Post-Brexit trade opportunities Alignment with trajectory of beef industry development (increased specialisation).	A net income benefit/year based a suitable scaled unit (~100 animals). An acceptable payback on capital cost (calculated at 5.2 years, in-line with other large on-farm infrastructure investments). Efficient and circular farming system. Safeguarding jobs, income, and skills diversification.	Desire to secure, implement and validate sustainable supply chains. Evidenced-based approach to supply chain interventions. Retailers seek to address Scope 3 carbon emissions. Precedent for price incentives for on-farm practices which deliver retailer/supply chain goals.

Table 25: Dependencies and assumptions

Dependencies	Assumptions
A price premium (or other incentive) for low-carbon beef products is secured. Access to government grant schemes for capital infrastructure.	Retailers and supply chain will share cost of delivering net-zero ambition. Consumers will accept the production system Retail supply chains will commit to paying a premium for low-carbon products.

Successful rollout of GreenShed will depend upon:

- A producer incentive (most likely a price premium for low carbon beef) to justify producers' investment in the system, supported by the downstream beef value chain. The business model is dependent on this price premium as without a price premium, the payback period would be too long (~9.5 years). These price premium schemes are an established feature of the current marketplace for finished cattle and farmers can see no reason why the principle of such premiums could not be extended to GreenShed produced cattle to cover the extra costs of production. As a comparison the organic price premium has been historically ~£1/kg above conventional. Organic is currently

~750p/kg DW compared to conventional at 680-690p/kg (60-70p/kg premium). This premium is not currently affected by cattle being housed indoors. Pasture for life (no grain feeding) can also be housed but only fed forage. Within integrated supply chains, there is a stipulation that cattle need to have one summer at grass (no stipulation for beef cattle general procurement). This has no impact on ability to house these cattle in GreenShed for the final months of finishing.

- A willingness from supply chain players to pay more for a low carbon beef product.

The commercial model is also based on the following assumptions:

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

Jobs creation

The commitment of participation from so many commercial partners reflects the benefit envisaged to boost the sustainability of the beef industry. The commercialisation and adoption of GreenShed will result in more diverse and higher-skilled rural employment opportunities, in addition to c.160 high-skilled jobs in the technology supply chain over five years from market entry. The project teams estimate of jobs creation has not changed from application stage. For owner/operators (farmers), the core system will require minimal additional labour (0.5hr/day) to load the AD system and perform basic maintenance. The vertical farming unit requires additional labour to manage and harvest produce, estimated at 0.5hr/day. Therefore, each system would require an additional 0.2 Full Time Equivalent (FTE) jobs. Extrapolated to 500 systems (intended to achieve 56kt GGR by 2030) equates to ~100 FTE jobs on-farm. System build and installation will require additional labour. Based on 100 new systems installed per year, each taking 5 weeks for a 5-person team, this supports 50 FTE jobs. The system will require skilled annual servicing by partners and/or their subcontractors. Based on our experience with commercial AD and environmental control systems, we expect each site to require servicing and/or breakdown support for 5 days/year. Across 500 sites this equates to 10 FTE jobs. In total, GreenShed commercialisation is expected to create 160 FTE jobs across the supply chain by 2030.

Business and marketing analysis; market barriers, and policy implications

Consumer market barriers: The focus groups raised issues, with the descriptor, ‘low carbon beef’ for instance. They demonstrated that consumers lack understanding on the housing of farm animals, remain uncertain about multiple sustainability and emissions logos, and the ownership/authenticity of those logos, as well as animal welfare concerns. In multiple recent surveys (AHDB and Ipsos for Yara International) consumers are requesting more information on the climate impact of their food. Animal welfare is a significant, over-riding concern to UK consumers and therefore it is important that UK Assurance bodies (Red Tractor, RSPCA) are engaged with the GreenShed project; hence their participation in the GreenShed Interest Group. Consumer research also indicated that consumers were willing to pay for low-carbon beef provided that their concerns relating to high animal welfare standards and definitive GHG reductions could be assured, rather than just theorised or claimed. It must be acknowledged, that what consumers say in a survey or focus group is not necessarily borne out when there buying behaviour in a supermarket is examined in detail. They will often buy on price and convenience rather than any additional market drivers identified during such consumers surveys. This feature of consumers buying behaviour was cited repeatedly by both supermarkets and beef processors during discussions as justification for their stated concerns in a producer price premium scheme that ensured a meaningful price premium for low-carbon beef back through the supply chain to the primary producer. Thus, a dependency on a consumer price premium, is an ongoing challenge. A preferential route is that supermarkets will pay a premium, to gain access to reduced interest rates from commercial banks. If such a consumer price premium is to be achieved in the real marketplace, more direct marketing routes between primary producer and consumer will have to be identified and developed in practice. Such routes as direct-from-farm box schemes, farm shops, farmers markets, internet selling, local butchers or meat wholesalers, catering outlets and direct sales to hotels, etc. could all be important routes to market for GreenShed produced beef as an alternative to the major processor/supermarket route. These would need to be an integral feature of commercial developments from a farm producer perspective as GreenShed moves from the R&D stage to commercial application.

Economic barriers: For an individual agricultural business, GreenShed could be seen as having a relatively high, initial capital cost. However, this level of investment is considered normal for farm businesses which regularly invest in machinery/renewables. However, from a supply chain perspective, the costs/benefits from such a system could be apportioned in various ways; apart from the positive environmental attributes GreenShed offers through mitigating GHG emissions, it has the potential to deliver optimised animal performance and improved animal welfare. The Defra Farming Transformation fund is one source of funding to mitigate the upfront capital cost. There are also investors interested in investing in green technology such as the Tesco / Santander initiative.

Competitors barriers: A full competitor analysis has shown that there are currently no direct competitors. Many possible competitors when seen or considered for the first time are offsetting emissions rather than reducing emissions directly. The Phase 2 project partners have been chosen based on their expertise, technology, complementarity and existing continental Europe market penetration. Therefore, we do not anticipate a fully formed consortium of competent competitors in the short-term.

Marketing barriers: the ‘brand’ GreenShed produced beef is a novel approach that will have resonance with some consumers due to its circularity, GHG mitigation and ability for MRV. One of the learnings from the consumer research, is lack of consumer knowledge and awareness surrounding beef rearing systems in the UK. UK beef systems already involve a period indoors which varies – a very small proportion are outdoors throughout their lives, whilst some are housed all their lives. Raising the awareness of this is a risk. New initiatives can often generate negative online material, that can spread quickly through social media channels. Care must be taken to ensure the positive benefits of GreenShed is not negatively affected by false online content.

Supply chains: standards across Europe and beyond are focussed on individual country markets and specific retailer-led supply chains. Identifying retailers / processor that are focussed on reducing their emissions will provide an easier market entry.

Regulatory: to the best of our knowledge there are no known legal barriers to the project. There are opportunities from the use of "Standards" such as BSI, and MRV, that the GreenShed more easily lends itself to, due to the close monitoring of animals, welfare, and emissions.

Technology: the project is working with leading, commercially internationally trading, and technology-proven companies to deliver the project. As such, we do not see a technology barrier to market entry. The modular nature of the project would allow additional companies to enter should new technologies become available. Throughout the project, the team has engaged in wider conversations with industry partners which would "add value" to GreenShed. Recent examples include the potential for inclusion of biofiltration technologies for CH_4. GreenShed will need to meet carbon reduction standards and be approved by Assurance schemes.

Environmental barriers: the project addresses concerns about GHG emissions, and as the consumption of red meats is forecast to increase, solutions such as GreenShed are an important contribution to a sustainable beef supply.

Policy implications barriers: GreenShed addresses GHG policy with a solution for part of the beef supply chain by mitigating CH_4 emissions in a circular way. GreenShed is complementary to other beef rearing systems, and it targets the period in an animal's life when the emissions generated are at their highest. In The Netherlands and the Republic of Ireland there are policies to reduce livestock emissions by reducing the number of animals. The GreenShed is a partial solution to this and removes the potential off-shoring of livestock production to other countries.

Process risks

Infrastructure/Technology failures:

- Insufficient performance of technology could result in reduced energy/technical efficiency of system components, and reduced carbon removal (not adhering to supply chain requirements or commitments to carbon reduction).

- Complexity of technology, and insufficient skillsets of on-site personnel may not ensure ongoing operations limiting carbon capture, providing insufficient conditions for animal requirements.

Supply Chain Disruptions:

- Manufacture/fabrication of required parts (for initial build, and for maintenance/breakdowns) affected by supply chain disruptions resulting in systems shut down for significant amounts of time.
- Partner loss (due to business closure, focus change) may require significant re-development to components of the GreenShed system – loss of support for ongoing maintenance of current systems, and delays with new installations, limiting the GGR potential.

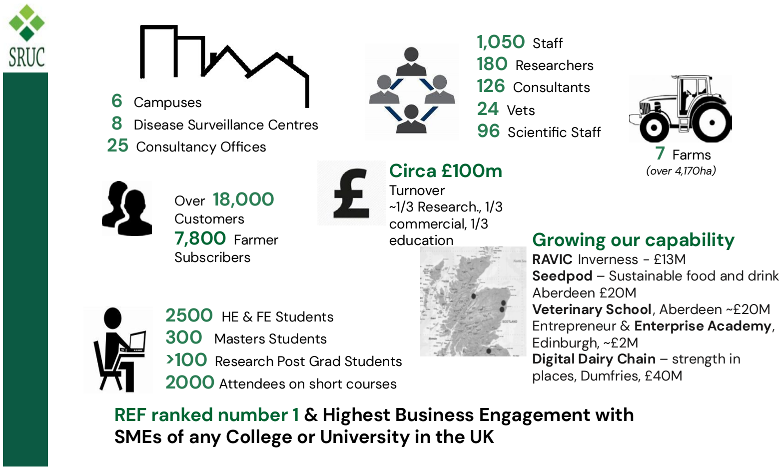
Regulatory or Non-Compliance:

- Insufficient technology performance may lead to failures to adhere to animal health and welfare standards.
- Retrofits to commercial installations on older buildings may not achieve sufficient shed seal, and lead to reduced carbon removals.
- Use of digestate in crop production may increase food safety risks (e.g., *E.coli*). Insufficient monitoring could lead to food safety risks and reputational damage from a system failure.

Demonstration, dissemination and social value

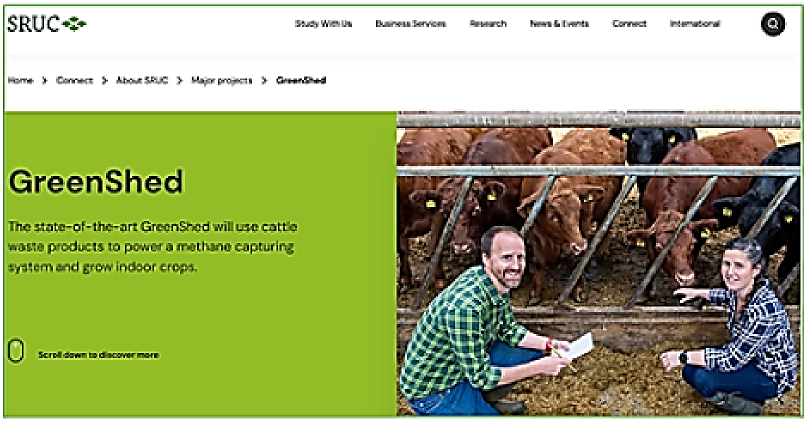
SRUC (Scotland's Rural College) activities are outlined in Figure 31. SRUC's unique structure allows for a wide range of engagement including students (from FE through to post-graduate level), farmers, public and wider industry/government. GreenShed has been build and demonstrated on SRUC's Beef and Sheep Research Centre near Edinburgh and has served as a "KE hub" since inception. The site itself has considerable history in research and teaching with a core focus on efficiency improvements and GHG measurement and mitigation (nutritional manipulation, genetic enhancement, precision livestock farming, technology advancements). In addition to a strong research portfolio, the site is actively used in training students - from basic agricultural skills through to more advanced research skills. GreenShed and the wider site has been widely used in teaching/training activities (student visits).

Figure 31: SRUC organisational structure



Throughout the project a robust Knowledge and Exploitation (KE) plan was implemented to engage directly with the farming community and wider industry (Figure 32). KE activities were developed to consider the challenges of engaging different target audiences including policy makers, advisors, farmers, farming organisations (e.g., NFUS, Levy boards), processors and retailers. KE activities included: GreenShed launch activities (press release, website/branding), articles (6 monthly e-Newsletter, articles in industry/farming press), podcasts, videos, webinars, social media engagement.

Figure 32: A selection of dissemination and knowledge exchange activities



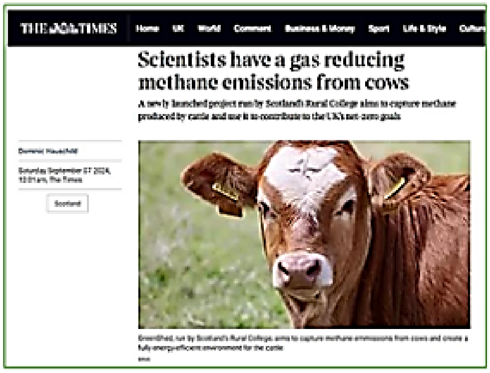
Timelapse video of the GreenShed build.

Five project newsletter updates released.

Project lead SRUC exhibiting GreenShed at the Royal Highland Show, June 2024.

GreenShed launch event, Sept 2024 – attended by more than a hundred beef industry stakeholders.

Podcast recordings.



THE TIMES

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Scientists have a gas reducing methane emissions from cows

A newly launched project run by Scotland's Rural College aims to capture methane produced by cattle and use it to contribute to the UK's net-zero goals

Dominic Hauschild

Saturday September 07 2024, 12.01am, The Times

Scotland

GreenShed, run by Scotland's Rural College, aims to capture methane emissions from cows and create a fully energy-efficient environment for the cattle

The Times GreenShed article published September 2024.

GreenShed: Shaping the future of livestock emissions

GhreenShed in SAC Consulting's Perspectives magazine, summer 2024.

Project lead SRUC has hosted almost 60 site visits from more than 30 individual companies and organisations, (inc. commercial farmers), a breakdown of which is given in Table 26.

Table 26: Sites visits to GreenShed

Type of visitor	No. of site visits
Student Group / Academic Institution	16
Government Body/Agency	17
Wider Industry	26

The project team have also been in attendance at trade/industry events and has generated wider scientific/policy outputs. Knowledge exchange will continue post project to maximise reach of key outcomes to a wide range of stakeholders.

Throughout the project, GreenShed has directly retained ~8 jobs and supported a further 4 across the consortium. Within SRUC alone, 2 researchers and 2 technicians were retained because of GreenShed.

Key successes, lessons learned, remaining uncertainties and next steps

Modelling and simulation

- Simulation of the GreenShed model provided key design data for the development of the prototype HVAC system, specifically air extraction rates and cooling and heating coil capacities. It also enabled a desiccant dehumidification to be discounted.
- CFD analysis indicated that the air distribution system designed for the GreenShed, featuring flexible conduit, delivered good mixing of conditioned air.
- The assumed air infiltration of 1.2 ac/h used in the model proved to be substantially different from the 3.5 ac/h as-built air infiltration, inferred from calibration of the model using measured shed contaminant data. Consequently, there was a significant performance gap between the as-built and modelled shed performance.

- Post construction sealing of the shed brought its inferred air infiltration rate to 1.35 ac/h, within 12% of the initially assumed value. This highlights that achieving a reasonably airtight shed build or retrofit will require close quality assurance of the build process.
- Calibration of the simulation model as part of the development of the GreenShed digital twin proved a very useful way to quantify the impact of shed sealing measures and suggests a possible new, passive means to characterise the air leakage of buildings in general.
- Bedding decomposition generated substantially more CO_2 than anticipated in the initial design process and, resulted in higher shed CO_2 concentrations than predicted by the simulation model. The decomposition process can also lead to the generation of CH_4. These additional bedding emissions have been included in the digital twin of the GreenShed.
- An optimisation model of the GreenShed has signposted potential future design and operational improvements, including insulation of the shed roof using 100mm internal insulation to reduce solar-driven overheating in summer, and running the shed HVAC system to favour higher indoor temperatures, resulting in lower indoor RH, reducing dehumidification loads and sensible re-heat loads, and reducing the overall energy consumption of the shed system.

Other considerations:

Anaerobic digester - reception/feed hopper:

- The feed hopper was designed and built by OPI because commercially available options at the time were too expensive for a low budget small-scale AD system.
- Feedstock handling and processing is key to the ease of running the GreenShed system as manual interventions take considerable labour resource. Whilst it was a key aim of the project to keep capital costs to a minimum by fabricating their own simple design feedstock hopper, it has become apparent that solid, fibrous feedstocks are a challenge to process.
- In this hopper the solid manure and bedding was added alongside water, with a stirrer at the bottom of the hopper intended to mix the material/water. This design resulted in the straw material floating to the top and not effectively mixing into the liquid without significant manual intervention. The situation improved with the installation of 'ribbon mixers' (Figure 33Figure 33: Ribbon mixers inside the feed hopper) but didn't solve the problem entirely.
- For this AD system to work effectively the straw needs to mix immediately with the liquid and not have the ability to float. This can be achieved using off-the-shelf mixers where the solid feedstock is coarsely chopped whilst dry, and this chopped material drops into a continuous flow of liquid which avoids floating. It then flows immediately through a macerator to become a homogenised slurry on a single pass. Using this system would

reduce operating time and is already proven to work with this material. A wider range of commercial mixers are now available at the size required and at much lower cost than at project start. Using these systems would slightly increase capex but are commercially tried and tested.

Figure 33: Ribbon mixers inside the feed hopper

Anaerobic digester - container construction and reinforcement:

- The containers were heavily reinforced with steel sections to withstand the hydraulic pressures generated by liquids and solids. Steel ribs were installed at varying heights, with closer spacing at the bottom where pressure is greatest. After reinforcement, the liquid enclosure tank was created inside the steel frame, heating pipework applied, and it was heavily insulated internally, then waterproofed with a flexible painted on plastic liner material.
- Most of this assembly occurred on-site, which proved very time-consuming. Also, possibly due to movement, the waterproof membrane failed on at least two of the tanks
- Recommended design revisions: the liquid enclosure would be fabricated using heavy-gauge, self-supporting steel. This ensures watertightness and eliminates all potential movement under pressure without the need for ribs. A lighter steel frame would then be welded around the tank, with heating pipes installed at the factory. Insulation can be efficiently applied in the gap between the liquid tank and the container envelope using solid and sprayed systems as appropriate.
- This factory-fitted approach is practical, cost-effective, and dramatically reduces on-site assembly time, and reduces chance of leaks due to thin membrane waterproofing.

Figure 34: Heavy tank structure with lightweight framing

Anaerobic digester - heating:

- The current design includes the heating pipes external to the tank that heat through the steel walls. The pipes are not in direct contact with the feedstock. This greatly reduces the heat transfer rate and therefore limits the rate at which the feedstock warms up or the ultimate temperature that can be maintained in colder periods. Design changes would ensure that the heating pipes run through the feedstock internally in the tanks.

Anaerobic digester - feedstock piping:

- The existing pipework for pumping the macerated feedstock around the system is 50mm diameter PVC. This did on several occasions cause blockages, especially in hot sunny periods when the liquid would dry out and block the pipe with the dried solids. We would increase the pipe diameter to 100mm to prevent this happening.

Anaerobic digester - dry digestate auger system:

- On the dry digesters, the current system to remove the digestate at the end of the process consists of a small exit hatch (500mm x 500mm) into a collecting box with an extraction auger set at 45 degrees to lift the digestate into a trailer. Based on the small amount of digestate produced in the trial, there were occasions when the auger would not extract the digestate until there was a considerable amount of pressure to push it out through the exit hatch. Design changes would include the extraction auger directly in the tank itself with no exit hatch and collecting box.

Air Handling Unit:

- The levels of dust produced in cattle sheds, especially during weekly bedding top-ups, cause conventional AHU wire and paper-based filters to clog after 1-2 weeks of running, requiring labour to clean them. Therefore future systems would include prefiltering system such as a cyclone to remove dust automatically before it reaches the filters.

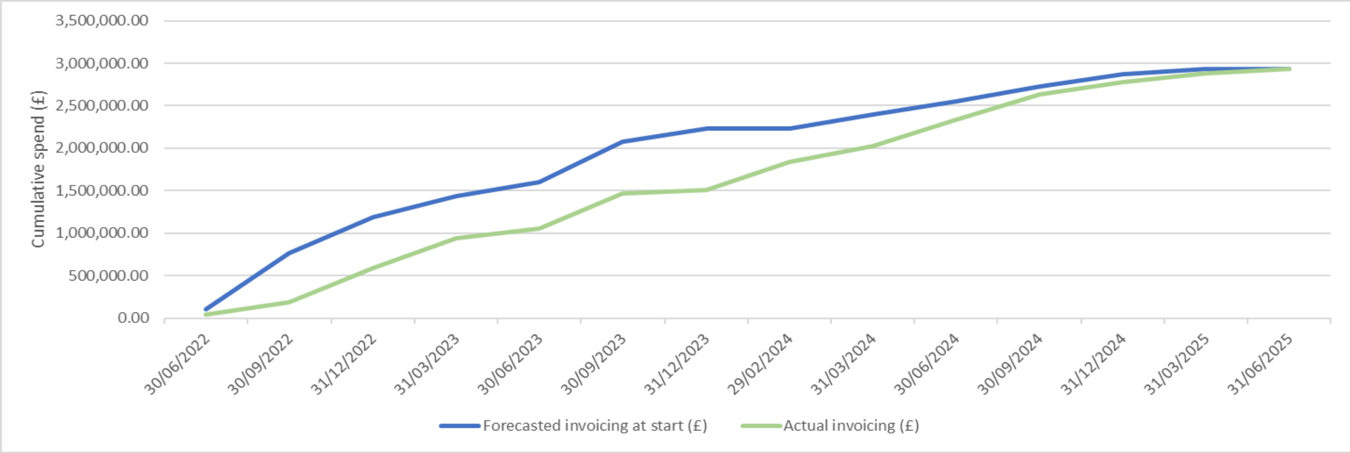
Next steps: immediate:

- In order to engage with retail supply chains on premium pricing, requires a longer-term MRV exercise (minimum of 12 months), quantifying CH_4 capture and conversion. The team are exploring options for further funding to run a long-term MRV exercise, and re-engage with retail supply chains, and wider routes-to-market (defined in the commercialisation plan).
- To understand the potential scale of the vertical farm within GreenShed we will explore further funding to characterise composition of digestate, run experimental trials in Saturn Hydroponics research facility (heated glasshouses) to assess any practical issues of the digestate within the irrigation system, and understand the impact of the digestate on yield/quality of different crop varieties.
- Due to it not being possible to get the current AD system fully functioning, and fully incorporated into the GreenShed system, engage with potential suppliers of commercial feedstock handling systems to incorporate into the AD system.
- Explore cyclone filtration options to pre-filter air before it gets to the main pathogen filters

Final project costs

The total SBRI contract was £2,934,428.75. A comparison of forecasted versus actual invoiced costs are shown in Figure 35. Finances have been continually revised at key stages throughout the project and budget re-distributed where necessary to fund specific shortfalls. We remain close to budget, however given the scale of the project, and the commitment of partners, the project has run over-budget in places. A revised estimate of build costs for a commercial 100-animal shed, based on learnings from the pilot installation and current market costs, is available in "*Commercialisation strategy - Return on Investment (ROI) calculations*".

Figure 35: Cumulative costs (as per invoiced) over the project (forecast vs. actual costs invoiced)



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Forecasted invoicing at start (£)
Actual invoicing (£)

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