DESIGNING FOR SUSTAINABILITY:

BLUEPRINT FOR A LOW-CARBON COLD ROOM

Exterior of low-carbon cold room, Homa Bay, Kenya.
Source: Charles Ogalo, WeTu, 2024.

A blueprint for off-grid solar companies and practitioners to design sustainable cooling solutions.

JUNE 2025

Efficiency for Access Coalition

This report serves as a blueprint for off-grid solar companies and practitioners to design sustainable cooling solutions. It draws on learnings from a low-carbon cold room design and implementation pilot in Kenya. The pilot was supported by the Siemens Cents4Sense initiative with the facilitation of Siemens Stiftung and the Efficiency for Access Research and Development Fund, with local implementation by We!Hub Victoria Limited (WeTu).

Efficiency for Access is a global coalition working to promote high performing appliances that enable access to clean energy for the world's poorest people. It is a catalyst for change, accelerating the growth of off-grid appliance markets to boost incomes, reduce carbon emissions, improve quality of life and support sustainable development. Efficiency for Access is jointly managed by Energy Saving Trust and CLASP. Efficiency for Access is funded by UK aid, from the UK Government via the Transforming Energy Access (TEA) platform, and the IKEA Foundation. This report has been funded by UK aid from the UK government; however the views expressed do not necessarily reflect the UK government's official policies.

WeTu is a social enterprise that uses innovative products and services to improve the quality of life in rural Western Kenya through sustainable solar powered solutions. Among WeTu's innovative solutions under solar cooling is the WeCool approach, which is piloting innovative solar cooling solutions to address food waste and loss in rural and peri-urban markets and increase the income of fresh produce traders.

CREDITS

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The low-carbon cold room project was a collaborative effort between a diverse range of experts. The lead design team consisted of the following specialists:

- Technical design: Victor Torres, Sonja Mettenleiter, Blessing Machokoto, Ana Salvatierra (Solar Cooling Engineering, Germany), Florian Martini, Géraldine Quelle (Phaesun, Germany),
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- Life Cycle Assessment: Stuart Walker (Energy Saving Trust / University of Sheffield, United Kingdom)

The low-carbon cold room design was informed by the following consultancy support:

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- Building physics consultancy: Maximilian Gester (ETH Zurich, Switzerland) Magda Posani (ETH Zurich, Switzerland)
- Timber construction engineering consultancy: Philipp Schmon (SJB Kempter Fitze, Switzerland)
- Food waste analysis: Jan Broeze (Wageningen University & Research, Netherlands)

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ABBREVIATIONS

°C	Celsius
AC	Alternating Current
Ah	Ampere Hour
BMS	Battery Management System
CAPEX	Capital Expenditure
CFCs	Chlorofluorocarbons
CO_2e	Carbon Dioxide Equivalent
COP	Coefficient of Performance
DC	Direct Current
DOD	Depth of Discharge
EPS	Expanded Polystyrene
GHG emissions	Greenhouse Gas emissions
GWP	Global Warming Potential
HCFCs	Hydrochlorofluorocarbons
IBC	Intermediate Bulk Container
kg	Kilogram
kWh	Kilowatt hour
L	Litre
LCA	Life Cycle Assessment
LEIA	Low Energy Inclusive Appliances programme
LFP	Lithium Iron Phosphate

ABBREVIATIONS

m	Metre
mm	Millimetre
MPPT	Maximum Power Point Tracking
OPEX	Operational Expenditure
PUR	Polyurethane
PV	Photovoltaic
SCE	Solar Cooling Engineering
T&G	Tongue-and-Groove
USD	United States Dollar
V	Volt
W	Watt

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Sub-Saharan Africa, which faces the highest absolute and per capita greenhouse gas (GHG) emissions from food loss, has much to gain from optimised cold chain management, with the potential to reduce these emissions by an impressive 66%[1]. However, if business as usual continues, the increasing demand for cooling also increases energy-related and product-embedded GHG emissions. Local assembly of cooling solutions presents a viable opportunity to mitigate GHG emissions while also delivering substantial social and economic benefits. Maintaining fresh produce like fruit and vegetables within the critical temperature range of 0—10°C and a relative humidity of 80-95% is essential for ensuring secure and efficient food supply chains. Yet limited access to reliable grid electricity in many regions of Sub-Saharan Africa poses a significant challenge, leaving underserved communities without the necessary cooling infrastructure to achieve the optimal food storage conditions. Solar-powered cold rooms with high local content are a promising solution to address this multifaceted challenge.

ALTHOUGH OPERATIONAL GHG EMISSIONS OF SOLAR-POWERED SYSTEMS ARE NEGLIGIBLE, THE EMBEDDED EMISSIONS FROM RAW MATERIALS AND MANUFACTURING CAN STILL BE SIGNIFICANT AS OUTLINED IN THE EFFICIENCY FOR ACCESS LIFE CYCLE ASSESSMENT (LCA) REPORT[2].

This pilot built upon the initial findings in the previous Efficiency for Access Life Cycle Assessment repor to demonstrate the technical and economic feasibility of a cold room made from locally available material, with minimal embedded GHG emissions. The goal was to create an energy-efficient, high-performing cold room consisting of solar photovoltaic panels, thermal and battery storage, and natural, environmentally friendly materials for wall insulation.

THIS PROJECT'S KEY INNOVATION WAS USING LIFE CYCLE ASSESSMENT AS A DECISION-MAKING TOOL IN REAL-TIME.

Immediate understanding of environmental impacts was essential for quick, data-driven design choices. This approach enabled rapid iteration and refinement of design variables. Detailed results per technical design element and for various impact categories are presented in the report, with final GHG emissions illustrated in Figure 1.

1. A. Friedman-Heiman, S. A. Miller. (2024). The impact of refrigeration on food losses and associated greenhouse gas emissions throughout the supply chain. Environmental research Letters, Volume 19, Number 6. https://iopscience.iop.org/article/10.1088/1748-9326/ad4c7b.
2. Efficiency for Access. (2023). Life Cycle Greenhouse Gas Emissions Assessment of Off- and Weak-Grid Refrigeration Technologies. https://efficiencyforaccess.org/publications/life-cycle-greenhouse-gas-emissions-assessment-of-off-and-weak-grid-refrigeration-technologies/.

THE FINAL COLD ROOM DESIGN RESULTED IN A COST REDUCTION OF 20% AND EMBEDDED GHG EMISSIONS OF 2,377 KGCO_2E, WHICH IS 63% LOWER THAN A SIMILAR SIZED COLD ROOM INSULATED WITH REGULATED POLYURETHANE SANDWICH PANELS[3].

The total GHG emissions of the cold room could be over 10 times higher if it used unsustainable design choices such as standard design configurations, older battery chemistries, and refrigerants with a high Global Warming Potential.

A COST REDUCTION OF

20%

EMBEDDED GHG EMISSIONS OF 2,377 KG CO2E

63%

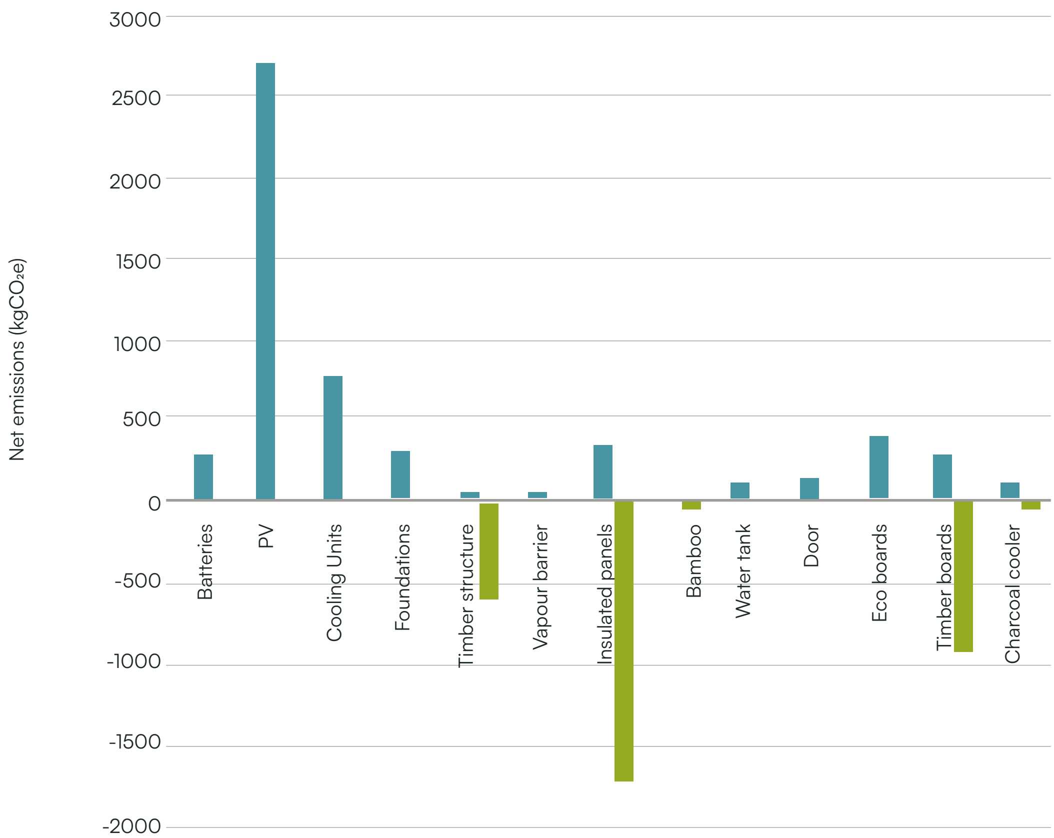
LOWER THAN USING POLYURETHANE SANDWICH PANEL INSULATION

WITHOUT SUSTAINABLE DESIGN

10x

HIGHER EMISSIONS

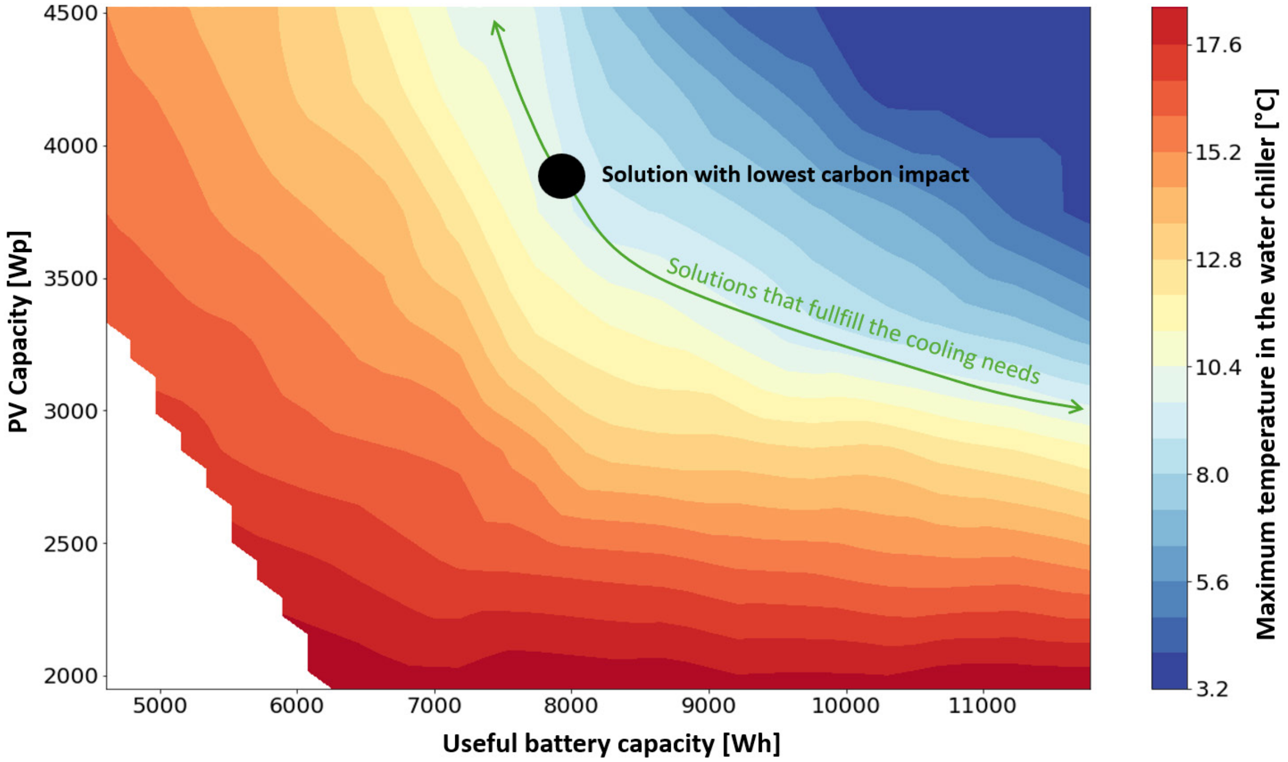
Figure 1. Net greenhouse gas emissions of the low-carbon cold room (product life cycle emissions excluding food loss avoidance)



3. Ibid.

A combination of solar photovoltaic panels, thermal storage, batteries, and evaporative cooling via a charcoal cooler provides the best solution for maintaining desired cold room temperatures below 10°C to store selected fresh produce. An optimisation tool was developed and used to assess the performance of each specific design throughout a typical year as shown in Figure 2. Results from the performance and cost optimisation and life cycle assessment revealed that a combination of thermal storage and small number of batteries is not only more cost-efficient, but also has a smaller carbon footprint compared to a battery-free system.

Figure 2. Results of the cooling system optimisation process for different solar PV and battery capacities



Over the course of 12 months, the biogenic cold cell design underwent significant evolution, with changes being made on a weekly basis through the consensus of three architects. A mock-up cold room was constructed to test various insulation wall elements, with relative humidity and temperature sensors employed to monitor the results. This process provided invaluable lessons that greatly informed the final decision to use a combination of straw, timber, and eco-boards as the best performing and most sustainable materials available at the deployment location in Western Kenya. The final conceptual design and installed cold room are shown in Figure 3.

Figure 3. Final low-carbon cold room design and installation

Despite these challenges, the climate mitigation benefits of avoided food loss are significant, with GHG emissions payback achieved in just two years, even under conservative assumptions.

The positive impact of the low-carbon cold room is particularly evident when considering grid connection and avoiding food losses. Although Kenya's electricity grid is relatively clean, with 90% of electricity coming from renewable sources, the GHG emissions saved by the standalone solar-powered cold room are 3.8 times higher compared to the grid scenario over its 20-year lifespan. Assessing food loss avoidance was challenging due to the lack of location-specific primary data. Secondary data was used, leading to assumptions that may not fully materialise during the operational phase. Despite these challenges, the climate mitigation benefits of avoided food loss are significant, with GHG emissions payback achieved in just two years, even under conservative assumptions.

Designing the cold room to be completely net-zero would affect commercial viability and scalability. Biogenic materials can help reduce the overall environmental impact, but achieving true net-zero status would require cost-inefficient decisions that may not be practical, such as significantly increasing the biogenic wall insulation. Therefore, the implemented solution was based on a fine balance between cost and environmental impact while achieving the optimal cooling requirements.

Construction of the low-carbon cold room, Homa Bay, Kenya

Source: Humphrey Anjila. 2024

KEY RECOMMENDATIONS FOR PRACTITIONERS

THE FOLLOWING RECOMMENDATIONS WERE JOINTLY PREPARED BY THE LEAD DESIGN TEAM FOR USE AS BEST PRACTICE FOR PRACTITIONERS WORKING ON EMBEDDED GHG EMISSION OPTIMISATION STRATEGIES FOR COLD ROOMS, BUT THEY APPLY TO OTHER PRODUCT CATEGORIES AS WELL:

1. LEVERAGE MULTIDISCIPLINARY EXPERTISE:
Assemble a diverse team of experts and local stakeholders early in the project to integrate specialised knowledge and regional insights.

2. ENSURE HIGH LOCAL INVOLVEMENT:
Engage local professionals and suppliers from the outset to ensure the design and material selection meet local needs and conditions.

3. OPTIMISE RELEVANT TOOLS AND TECHNIQUES:
Prioritise simple but effective design solutions such as using biogenic sandwich panels with moisture release features and integrate *optimisation tools* for the best outcomes such as the one developed for this project.

4. USE LIFE CYCLE ASSESSMENT AS A DECISION-MAKING TOOL:
Incorporate LCA tools from the beginning to enable swift and informed design decisions to reduce the environmental impact and cost of the final product.

5. BUILD A MOCK-UP TO TEST DESIGN AND PERFORMANCE:
Develop and evaluate mock-ups of key construction elements to ensure their effectiveness and address potential issues.

6. CONSIDER USE CASE LIMITATIONS:
Assess the suitability of selected design features for different types of stored produce and markets in line with relevant food safety compliance and regulations for different types of value chains.

7. CONTROL HUMIDITY LEVELS DURING CONSTRUCTION AND OPERATION:
Select an insulation material that can withstand humidity levels recommended for the relevant produce, in this case using straw insulation placed between eco-boards to store fruit and vegetables at a relative humidity of maximum 95%.

8. IDENTIFY AND MINIMISE CARBON FOOTPRINT HOTSPOTS:
Choose hybrid energy storage solutions that combine thermal storage with lithium-ion batteries to reduce the amount of solar PV required, improve performance and reliability, and minimise embedded GHG emissions and cost.

9. ADOPT GREEN BUILDING TECHNIQUES:
Implement green building techniques to reduce thermal losses through biogenic elements, avoid direct solar radiation to the walls to enable passive cooling, and improve aesthetics.

10. MAXIMISE COOLING EFFICIENCY:
Use evaporative cooling and thermal storage to boost energy efficiency and reduce the carbon footprint while managing storage space trade-offs within the cold room.

Architectural design of the low-carbon cold room

Source: Francis Maina. 2024

Low-carbon cold room seen from the back. Homa Bay, Kenya.

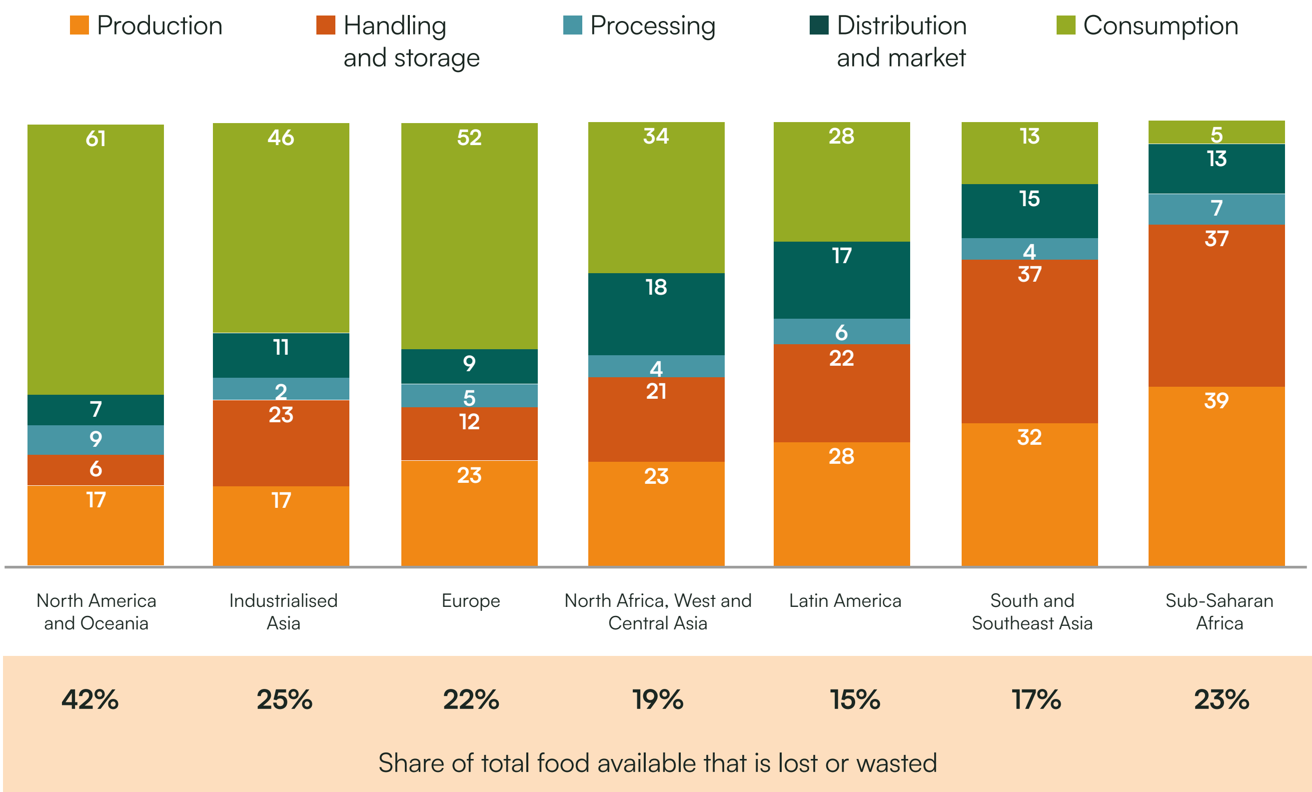
Source: Francis Maina. 2024

1. INTRODUCTION

1. INTRODUCTION

Food losses have significant global consequences, leading to an annual economic loss of USD 1 trillion, worsening food security, with one in ten people affected by hunger, and contributing 8 — 10% of GHG emissions[4]. In Sub-Saharan Africa, food losses are primarily concentrated in production, handling and storage, unlike in the Global North where most food waste occurs at the consumption phase, as shown in Figure 4.

Figure 4. Food loss per region and stage in value chain in 2009 (WRI and UNEP, 2013[5])



Efficient and sustainable cold chain management is crucial for reducing the 31% of food produced globally that is wasted[6]. A new study from the University of Michigan[7] estimates that improved cold chain infrastructure could avoid up to 1.8 $GtCO_2e$, which amounts to 5% of total global GHG emissions[8]. Given that Sub-Saharan Africa accounts for the largest absolute and per capita food loss GHG emissions, could particularly benefit from optimised cold chain management to reduce GHG emissions associated with food loss by a staggering 66%[9]. This potential is primarily driven by the meat value chain, which is to be expected given the high GHG intensity of meat production, but significant savings could also be made across milk, fish and seafood, fruit and vegetables, cereals, and roots and tubers as shown in Figure 5.

4. UNEP. (2024). World squanders over 1 billion meals a day - UN report. Nairobi, Kenya. https://www.unep.org/news-and-stories/press-release/world-squanders-over-1-billion-meals-day-un-report.

5. WRI and UNEP. (2013). Reducing Food Loss and Waste. http://pdf.wri.org/reducing_food_loss_and_waste.pdf.

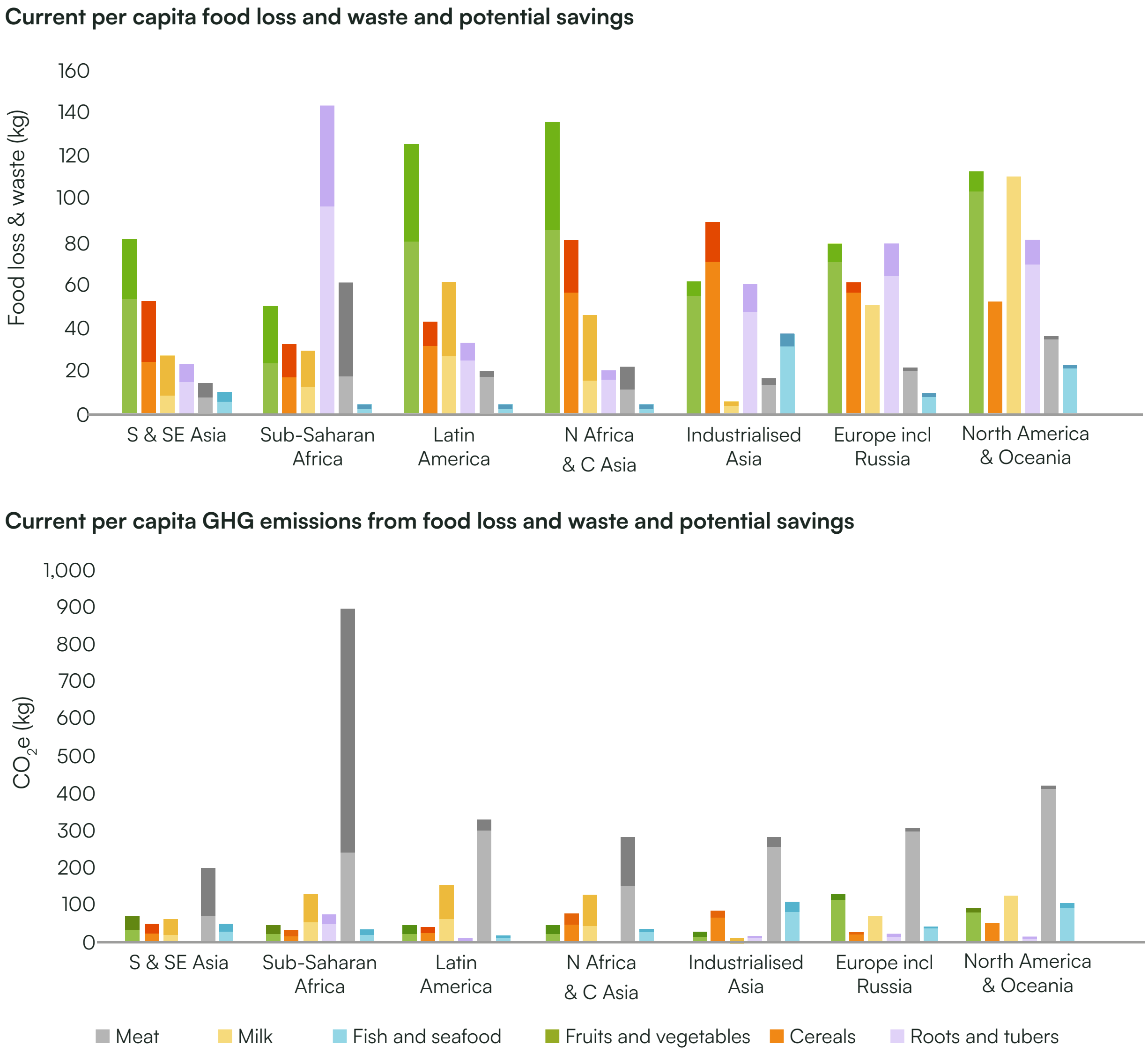
6. FAO. (2022). Tackling food loss and waste: A triple win opportunity. Food and Agriculture Organization of the United Nations. Rome, Italy. https://www.fao.org/newsroom/detail/FAO-UNEP-agriculture-environment-food-loss-waste-day-2022/en.

7. A. Friedman-Heiman, S. A. Miller. (2024). The impact of refrigeration on food losses and associated greenhouse gas emissions throughout the supply chain. Environmental research Letters, Volume 19, Number 6. https://iopscience.iop.org/article/10.1088/1748-9326/ad4c7b.

8. H. Ritchie, M. Roser. (2024). CO_2 emissions. https://ourworldindata.org/co2-emissions.

9. A. Friedman-Heiman, S. A. Miller. (2024). The impact of refrigeration on food losses and associated greenhouse gas emissions throughout the supply chain. Environmental research Letters, Volume 19, Number 6. https://iopscience.iop.org/article/10.1088/1748-9326/ad4c7b.

Figure 5. Regional food loss and waste, and associated GHG emissions under current and optimally refrigerated food supply chain conditions (darkened upper portions of the bars denote the potential savings through optimised cold chain)[10]



Due to limited grid availability and reliability in Sub-Saharan Africa and substantial solar resources, the solar-powered cold room is emerging as a promising technology. They are often located at the first mile to store produce for smallholder farmers and market vendors. The Walk-In Cold Rooms, A Practitioner's Technical Guide[11] provides step-by-step guidance on how to design conventional solar-powered cold rooms. Existing cold rooms vary in size and complexity but serve the same purpose — to extend the shelf-life of fresh produce and reduce post-harvest losses. Technology and business model innovations often work together to provide the most effective solution[12].

Although the embedded GHG emissions of solar-powered cold rooms are dwarfed by the food loss emissions avoided throughout their operational lifetime if they are sufficiently utilised *as shown in Chapter 4*, environmental life cycle and the use of local materials are important for long-term sustainability. However, these considerations are rarely the main drivers during the cold room design and deployment. This report serves as a blueprint for low-carbon cold room design, with environmental sustainability and local material availability at its core. This concept emerged from the previous Efficiency for Access Life Cycle Assessment research[13] delivered under the Low Energy Inclusive Appliances (LEIA) programme[14], aiming to reduce the embedded GHG emissions as close to zero as possible.

10. A. Friedman-Heiman, S. A. Miller. (2024). The impact of refrigeration on food losses and associated greenhouse gas emissions throughout the supply chain. Environmental research Letters, Volume 19, Number 6. https://iopscience.iop.org/article/10.1088/1748-9326/ad4c7b.

11. Efficiency for Access and the International Institute of Refrigeration. (2023). Walk-In Cold Rooms, a Practitioner's Technical Guide. https://efficiencyforaccess.org/publications/walk-in-cold-rooms-a-practitioners-technical-guide/.

12. Efficiency for Access, WRI, Wageningen University & Research. (2023). Keep it Cool. https://efficiencyforaccess.org/publications/keep-it-cool/.

13. Efficiency for Access. (2023). Life Cycle Greenhouse Gas Emissions Assessment of Off- and Weak-Grid Refrigeration Technologies. https://efficiencyforaccess.org/publications/life-cycle-greenhouse-gas-emissions-assessment-of-off-and-weak-grid-refrigeration-technologies/.

14. https://efficiencyforaccess.org/program/low-energy-inclusive-appliances/

Figure 6. Final low-carbon cold room design

Solar Cooling Engineering (SCE) is a global consultancy company based in Germany and the developer of the SelfChill[15] approach for modular cooling solutions in cooperation with the University of Hohenheim and the technology provider Phaesun GmbH. Since 2020, the SelfChill cooperation has deployed 19 solar cold rooms across eight African countries with different share of locally sourced materials. SCE has received support from the Efficiency for Access Research and Development Fund and WeTu to design and construct a low-carbon cold room using the SelfChill approach for local manufacturing. The aim of the pilot was to prove the feasibility of a cold room with minimal embedded greenhouse gas emissions over the cradle-to-grave scope. The vision was to develop an efficient, high-performing cold room, powered by solar photovoltaic panels coupled with thermal and battery storage, and using natural materials with biogenic storage of carbon dioxide to offset as far as possible the emissions of the technical equipment associated with active cooling.

This report describes the life cycle assessment (LCA) of the low-carbon cold room, undertaken during the design, testing and construction of the room. The report describes the design of the cold room, the methods used to assess the life cycle impact, and relevant assumptions and results. The results described are specific to the pilot project on Lake Victoria in Western Kenya as shown in Figure 3 but are applicable to other locations and cold rooms across Sub-Saharan Africa. In this pilot, life cycle assessment was used as a decision-making tool to inform material and component selection throughout the design, rather than using it as an evaluation of an existing product.

15. https://selfchill.org/

Construction of the low-carbon cold room. Homa Bay, Kenya.

Source: Humphrey Anjila. 2024

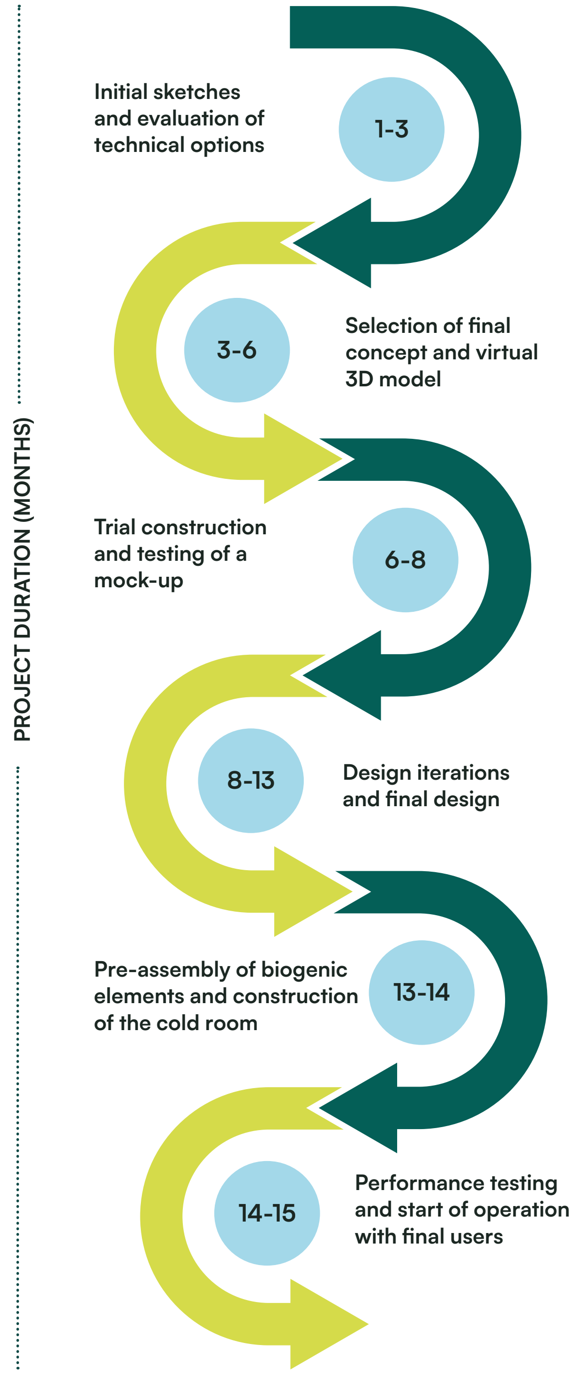
2. LOW-CARBON COLD ROOM DESIGN

2. LOW-CARBON COLD ROOM DESIGN

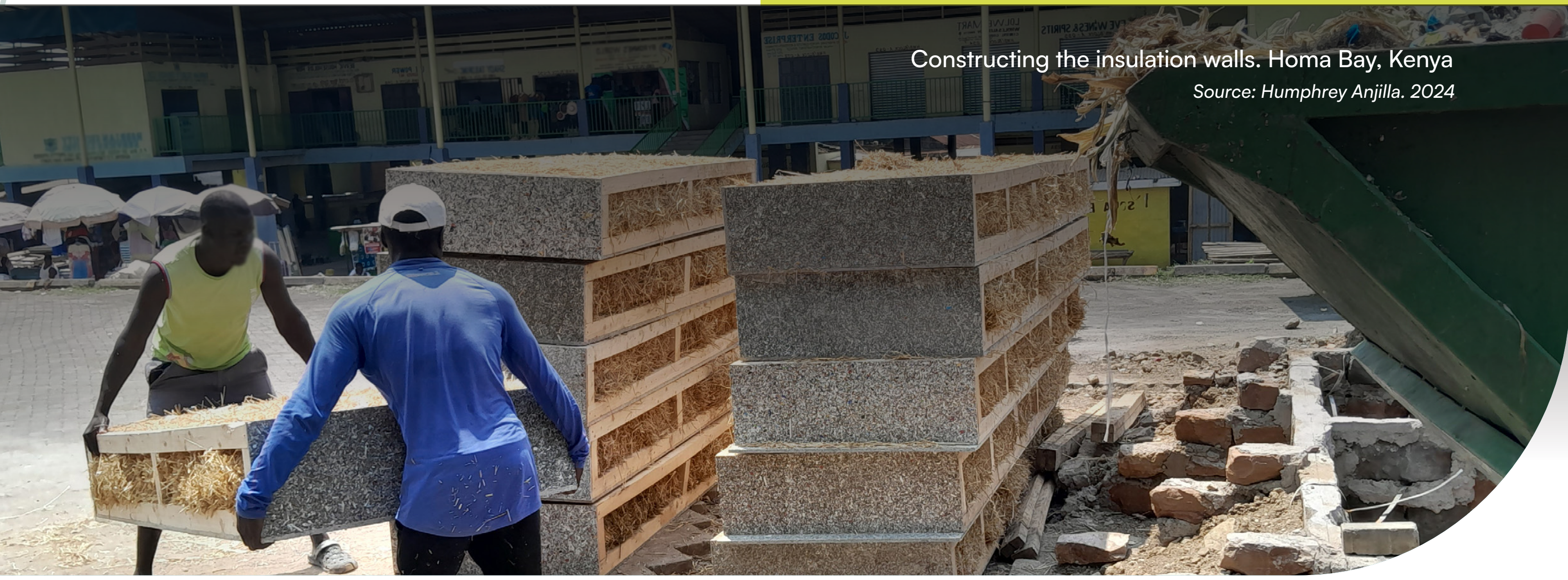
The low-carbon cold room was designed to offer the benefits of a conventional cold room while reducing environmental impact, using local materials, and supporting the local workforce. By minimising embedded GHG emissions, this approach not only mitigates risks associated with toxic or environmentally damaging materials, but also contributes positive social and economic impact through local manufacturing and the assembly of solar-powered cooling technologies, which are still relatively nascent in countries such as Kenya[16].

The design process meticulously integrated technical performance, cost implications, local manufacturing considerations, embedded GHG emissions, and overall life cycle impact as shown in Figure 7. This comprehensive approach ensured that every phase of the low-carbon cold room's development was scrutinised for sustainability and efficiency. By incorporating real-time LCA, the process evaluated environmental impacts from raw material extraction through to end-of-life during the design process. Cost analysis aligned economic feasibility with sustainability, while local manufacturing and assembly aimed to support workforce and skills development in-country and reduce transportation emissions. The detailed technical performance assessment ensured that the low-carbon cold room would meet the cooling demand for optional storage conditions of fresh produce. Pursuing this holistic method ensured a balanced approach to sustainable design, delivering a cold room that is high-performing, economically viable, and environmentally responsible.

Figure 7. The main phases of the project



16. Efficiency for Access. (2023). Examining Fiscal Environments for Increased Localisation of Solar Products. https://efficiencyforaccess.org/publications/examining-fiscal-environments-for-increased-localisation-of-solar-products/.



Constructing the insulation walls. Homa Bay, Kenya
Source: Humphrey Anjilla. 2024

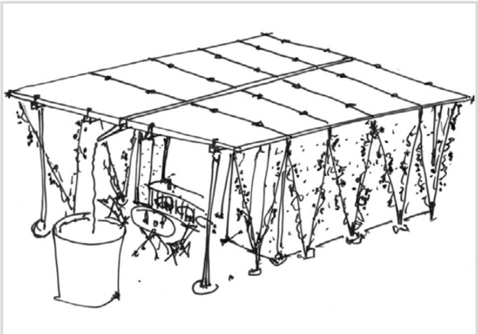
2.1. BIOGENIC COLD CELL

2.1.1. DESIGN EVOLUTION

The central vision of the project was to design a low-carbon cold 'room', in this case a biogenic cell, through the use of local materials and sustainable building techniques. This concept evolved over time through ongoing research and collaborative efforts within the team, resulting in a more customised, sustainable, and visually appealing cold room solution.

THE DESIGN EVOLUTION WAS AS FOLLOWS:

JUL 2023



The conceptual proposal highlighted the exterior design of the project, incorporating key sustainable features such as solar panels on the roof, a rainwater harvesting and storage system, and integrated outdoor greenery to enable passive cooling and enhance visual appeal.

AUG 2023

After extensive research and material selection, the first design proposal was developed.

This concept incorporated eco posts for the foundation, straw bale insulated floor, walls, and ceiling panels, and a solar panel system mounted on timber brackets for the roof.

SEPT 2023

Lateral overhangs were eliminated to enhance structural integrity for the roof-mounted solar panel system.

The foundation was upgraded to a natural stone construction, leveraging its local abundance and environmental benefits.

A technical room was incorporated to accommodate the equipment necessary for operating the cold room.

NOV 2023

The front overhang was reduced in size to integrate seamlessly with the technical room structure.

A charcoal-based cooling system was introduced in the technical room to alleviate excessive heat generation within the electrical components.

The technical equipment door was extended.

THE DESIGN EVOLUTION...CONT'D

JAN 2024

The technical room was enlarged to provide additional operational space.

The roof overhang was increased to mitigate rainwater damage to the wall.

The roof design was revised to incorporate a minimalist aesthetic while maintaining structural integrity.

Bamboo trellis was used to increase plant density.

EARLY FEB 2024

The roof pitch was adjusted to facilitate lateral water runoff rather than central collection.

A shaded entrance porch was created by extending the structure and adding a flat roof.

The technical equipment room was relocated to the rear of the cold room to minimise foot traffic in the front area and facilitate electrical connectivity.

A delivery ramp was implemented.

LATE FEB 2024

The roof structure was redesigned to butterfly configuration to mitigate water infiltration.

The delivery ramp inclination was adjusted to 15 degrees, and a natural stone staircase was added on the sides.

The entrance porch was enhanced with the addition of benches and wooden tables.

MARCH 2024

Existing tongue-and-groove wooden cladding was removed and replaced with wooden poles.

These poles serve the dual purpose of providing external cladding and supporting climbing plants.

APRIL 2024

A timber beam was installed to strengthen the roof structure at the entrance porch.

The wooden bench was replaced with a structure incorporating wooden poles to maintain a cohesive aesthetic with the existing wooden pole cladding.

The table support structure was modified from a cylindrical to a conical shape.

MAY 2024

3D renders were enhanced with a more realistic visual representation of the typical environments where cold rooms are deployed, including agricultural settings and marketplaces.

The door design was revised to create a more visually pleasing and energy-efficient configuration.

A foundation system made from lime replaced concrete for improved sustainability.

JUNE 2024

The final design was optimised with an improved lighting configuration to enhance visibility inside the cold room and at the entrance porch outside the main door.

The textural appearance of the ramp and stairs was standardised to match the ground surface.

SEPT 2024

THE COLD ROOM WAS INSTALLED AT THE HOMA BAY TOWN MARKET IN WESTERN KENYA.

2.1.2. FOUNDATION

The main design strategy for the foundation was to use more natural materials to reduce the embedded GHG emissions, which meant limiting or eliminating the use of common foundation materials such as steel and cement. Hence, the architects decided to use a natural stone foundation for the cold room to be placed on as shown in Figure 8.

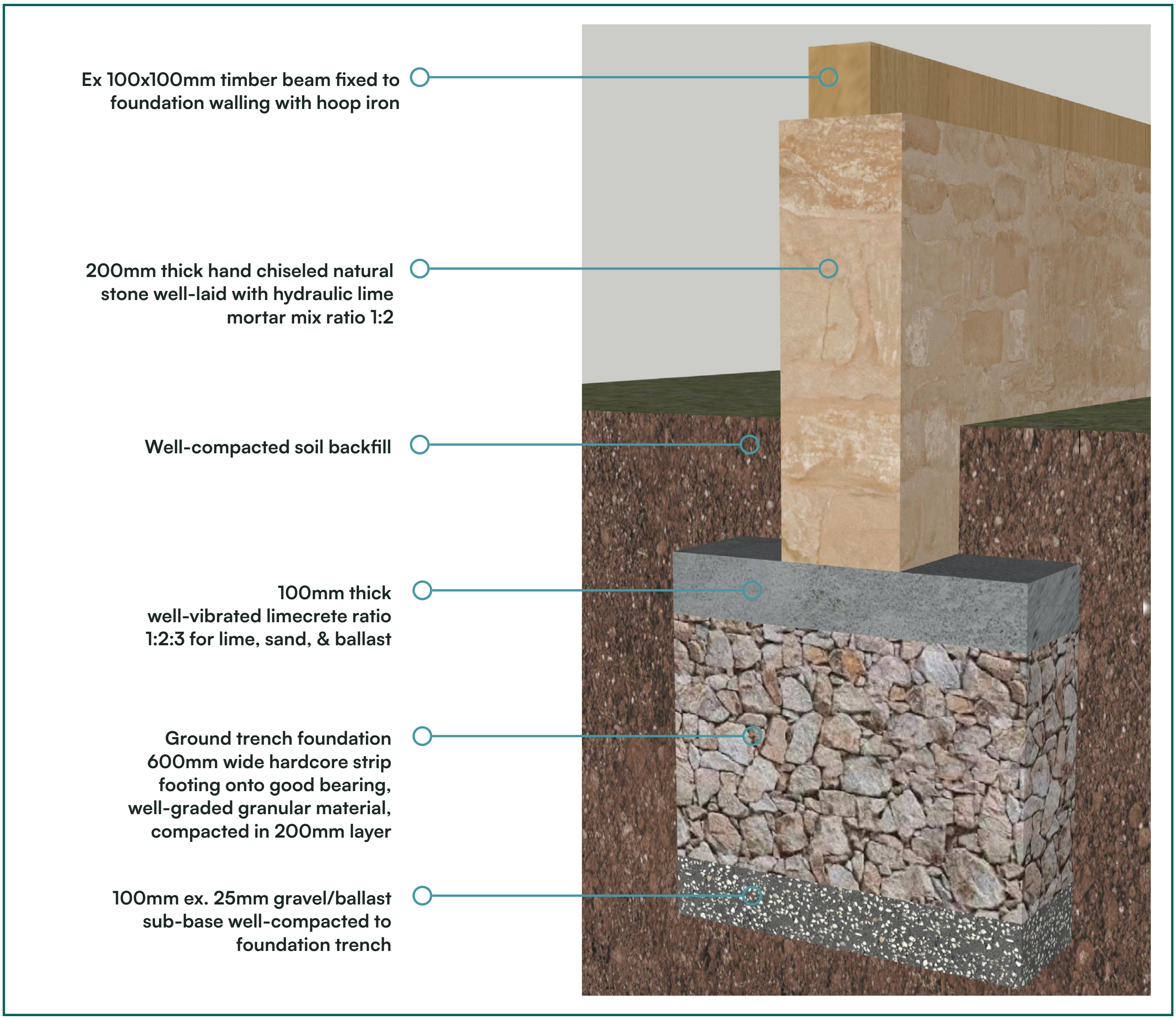
LINK FOR 3D VISUALISATION VIDEO OF THE LOW-CARBON COLD ROOM.

https://youtu.be/IARJ7C_dKFI

The selected materials included:

- **Ballast:** Smaller rocks were used as an aggregate for limecrete and to form a sub-base.
- **Hardcore:** Larger rocks formed the foundation's main base.
- **Hand chiselled stone:** Hand-shaped rocks forming the foundation walling, which the cold room will be placed on.
- **Hydrated lime:** Used to bind both lime mortar and limecrete, its production releases less emissions than cement used for the same purpose.
- **Local availability:** All the foundation materials are locally available.

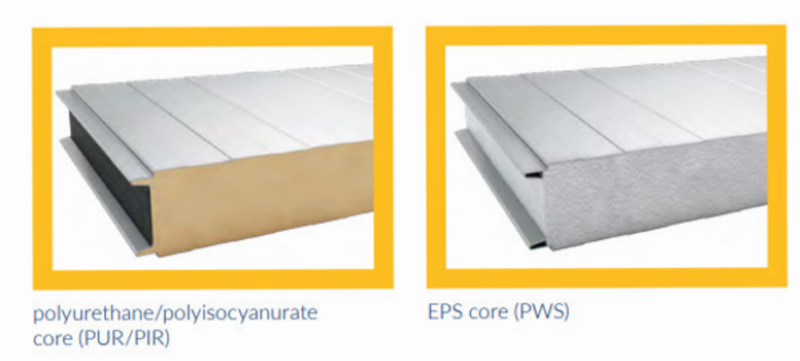
Figure 8. Natural stone foundation drawing



2.1.3. INSULATION ELEMENTS

Sandwich panels are typically used to construct cold room walls and internal partitions. These panels are typically made by layering a core insulation material between two outer layers of durable cladding, such as metal sheets. The core material plays a critical role in reducing heat transfer, ensuring that the cold room maintains its desired low temperature. The most used insulation materials in wall sandwich panels for cold rooms include polyurethane (PUR), expanded polystyrene (EPS), and mineral wool as shown in the figure below.

Figure 9. Typical sandwich panels (Source: PanelTech EU, 2024 Brochure)



The sandwich panels are commercially available in thickness sizes ranging from 40mm to 200mm. In general, **the thicker the insulation**, the less heat is transferred between the cold room and the ambient environment. However, the effectiveness of insulation is not solely determined by its thickness; it also depends on the **thermal conductivity** (λ, lambda value) of the material; the lower the lambda value, the better the insulation material. The table to the right shows typical λ values.

Table 1. Insulation materials and thermal conductivity

Typical insulation material	Thermal conductivity (λ) W/m·K
Polyurethane	0.020 — 0.025
EPS core	0.030 — 0.040
Mineral wool	0.035 — 0.045
Single panel glass	0.800 — 1.000
Concrete bricks	0.700 — 1.300

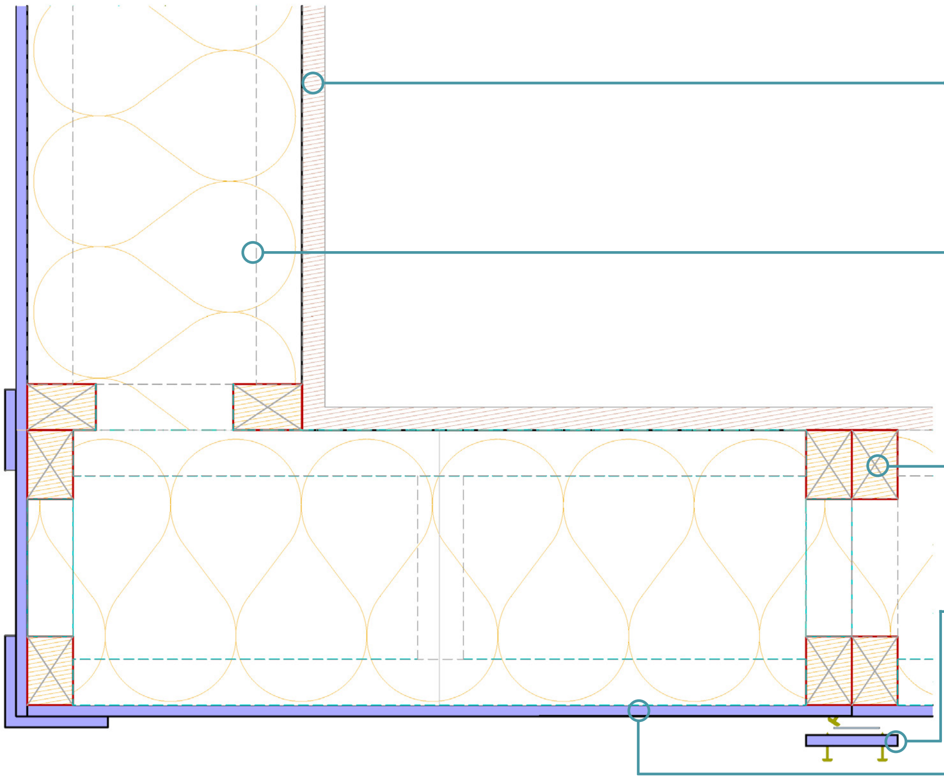
Figure 10. 3D visualisation of the key insulation materials

THE COLD ROOM WAS DESIGNED WITH A COMPOSITE INSULATION SYSTEM, PRIMARILY USING STRAW BALES FOR INSULATION AND PART OF THE STRUCTURAL ELEMENT AS SHOWN HERE.

THE DECISION TO USE STRAW BALE WAS BASED ON ITS FOLLOWING PROPERTIES:

- Excellent insulation - helps maintain a consistent temperature
- Sustainable and renewable resource
- Cost-effective
- Locally available
- Natural carbon sink
- Vapour permeability
- Low embodied energy - the total amount of energy used to extract, process, transport, and dispose of a building material or product
- Fire resistance

Figure 11. Wall panel showing the key insulation materials



The composite wall panel system for insulation comprises the following elements as shown in Figure 11:

- **12mm eco-board:** The outer face of the panel incorporates a 12mm thick layer of eco-board, made from plastic packaging waste. This water-resistant material helps prevent the ingress of external moisture, protecting the integrity of the straw bales within the insulation panel.

- **300mm timber-straw panel:** The core element of the panel is a 300mm thick timber-straw panel. This composite element functions as both the primary insulation layer and the structural component of the wall panel system.

- **25mm tongue-and-groove (T&G) timber cladding**: The interior face of the panel is clad with 25mm thick timber using T&G joints. This timber layer facilitates vapour permeability[17], allowing the straw bale to breathe and preventing moisture buildup that could lead to rot.

Below are other insulation materials that were considered earlier:

- **Structural insulated panels made of compressed straw:** The panels found by the design team were manufactured in northern Uganda and had been used in various projects in northern Kenya according to the manufacturer's website. We decided against using this material because the suppliers were unresponsive, making it challenging to obtain additional information on their insulative properties.

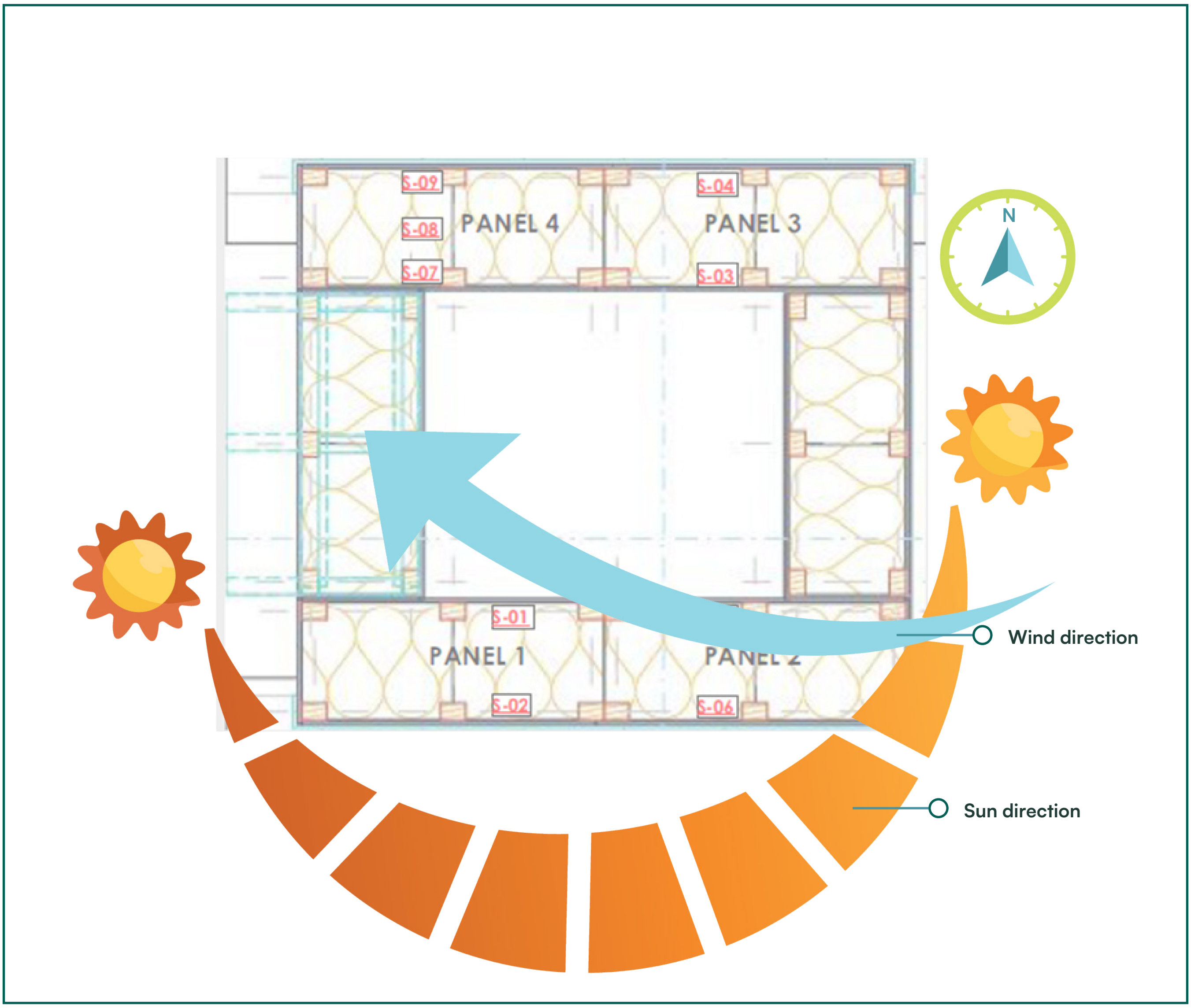
- **Seaweed:** This material was also considered for insulation, but the distance from the ocean, where it is sourced, would pose significant logistical challenges given the quantities required. Additionally, local seaweed is not commonly used for insulation purposes, necessitating further research into its insulative properties.

17. Vapour permeability is a material's ability to allow water vapour to pass through it, rather than blocking it or absorbing it.

2.1.4. TRIAL CONSTRUCTION

To validate the hypothesis and test the preliminary cold room design, a mock-up cold room was built in Kisumu. Creating a mock-up to test the cold room design is a more cost-effective approach than building the full solution without prior testing. This method allows for the identification and correction of any flaws before committing to the final build. Through installing sensors and conducting on-site tests near Lake Victoria, valuable data was gathered on the cold room's performance in real-world conditions. This process provided critical insights and improved the design, ultimately leading to a more reliable and effective solution. The cold room was constructed using heterogeneous wall panels as shown in Figure 10.

Figure 12: Insulation panel layout



The installation of the cold room mock-up took place at the WeTu facilities in Kisumu. The images document the mock-up construction from start to finish, beginning with the delivery of straw bales to the site, cutting the timber, and compacting straw bales into panels — Figure 13. Subsequent images capture the application of clay to the panels, the filling of panels with more straw, and the preparation of completed panels for assembly — Figure 14. Finally, the insulation panels were assembled onsite (see Figure 15), resulting in the completed cold room mock-up — Figure 10. This series of images highlights the key processes and techniques involved in using local materials and workforce.

Figure 13.
Straw bales delivery to site (top), timber frame fabrication (middle), and straw bale compaction into the insulation panels (bottom)

Figure 14.
Clay trial (top), filling up insulation panels tightly with more straw (middle), and completed panels ready for assembly (bottom)

Figure 15.
The assembly of the mock-up cold room

Figure 16. The completed mock-up cold room, Kisumu, Kenya

The mock-up cold room construction and assembly process proved to be successful, particularly from an economic perspective as the cost was lower than the one of conventional polyurethane (PU) sandwich panels. All the wall elements have temperature and humidity sensors installed to track the moisture content of the straw including different characteristics of the insulation panels as shown in Table 10. The Thermal Conductivity (λ) was observed to be around 0.1 W/m·K based on the cooling power provided by the cooling unit and the temperature differences given between the ambient and indoor air of the mock-up.

However, the humidity in the interior of the inside wall was too high. Therefore, the interior wall was cladded with T&G timber panels to replace the eco-boards. Since this change was made, the humidity had decreased, confirming the satisfactory performance of the updated elements as shown in Figure 13. Figure 14 depicts the process of replacing the eco-boards with T&G timber, revealing that the straw in the area where the eco-boards were replaced had been damp at the time of replacement.

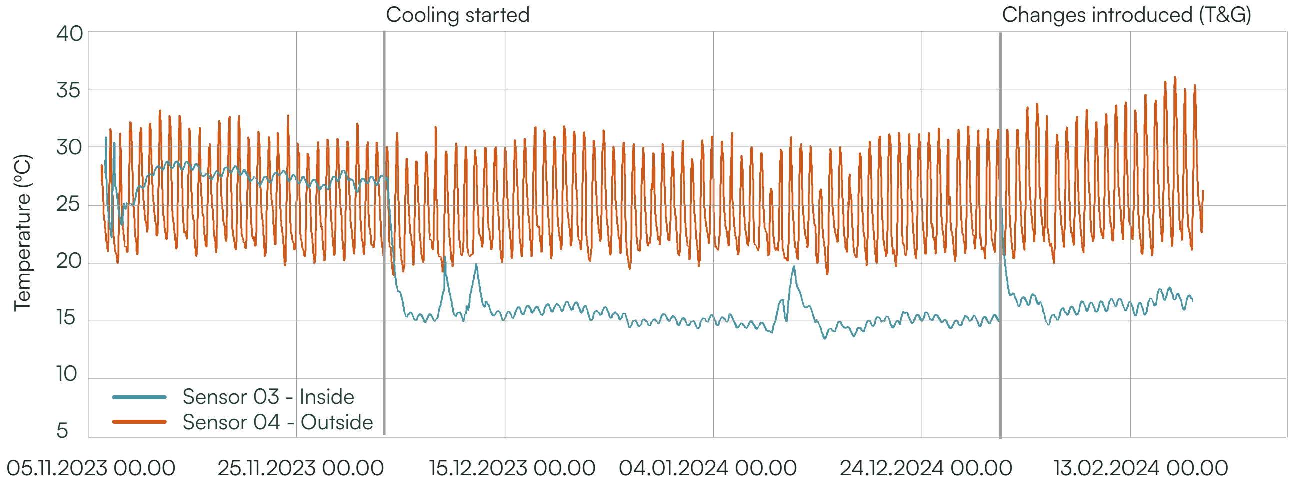
Table 2. Straw performance and humidity results from the cold room mock-up

Panel location	Panel characteristics	Sensor location	Results and findings
PANEL 1	Clay interior	Inside Outside	Performed well, regulated interior humidity considerably
PANEL 2	With a vapour barrier on all sides	Inside Outside	High humidity Internal straw conditions were moist
PANEL 3	With an external vapour barrier only	Inside Outside	High humidity Internal straw conditions were moist
PANEL 4	With no vapour barrier		Moderate humidity
BOTTOM PANEL	With a vapour barrier above	Inside Outside	High humidity Internal straw conditions were moist
TOP PANEL	With a vapour barrier above	Inside Outside	High humidity Internal straw conditions were moist
REVISED PANELS 3 & 4	T&G timber inside	Inside Outside	Moderate humidity Straw conditions were dry all through even after being moist initially

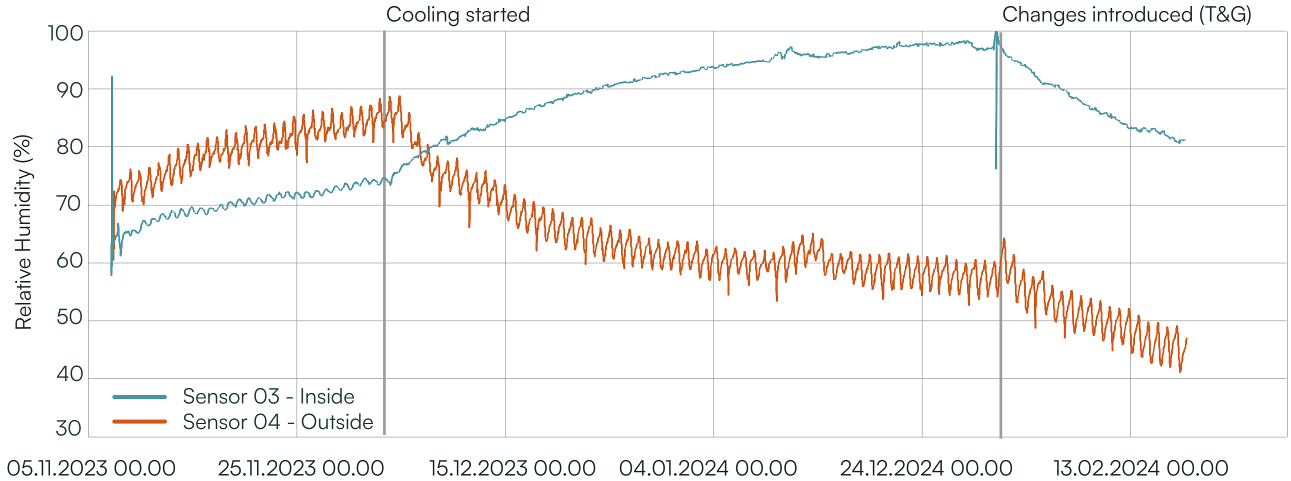
Figure 17. The location of sensors on the mock-up

Figure 18. Internal temperature (top), relative humidity (bottom) of the mock-up biogenic element before and after modifications (Sensors 3 and 4 of selected Panel 3)

Temperature inside biogenic element



Relative humidity inside biogenic element



The mock-up findings revealed that panels covered with eco-boards both internally and externally showed dampness at the contact points between the eco-boards and straw due to conduction as shown in Table 2. These panels also recorded very high humidity levels, indicating that eco-boards are not effective in maintaining a dry and low-humidity environment within the straw used as insulation material.

In contrast, panels with either T&G timber or clay plaster on the interior performed significantly better. These panels maintained completely dry straw at the contact points with the eco-boards and recorded humidity levels within the recommended range. This suggests that T&G timber and clay plaster are more effective in managing moisture and maintaining appropriate humidity levels inside the insulation wall.

Figure 19. Replacement of eco-boards with T&G timber to protect straw bale from high humidity

Source: Charles Ogalo, WeTu, 2024.

Figure 20. Replacement of eco-boards with T&G timber to protect straw bales from high humidity

Based on these findings, a timber interior was recommended for the internal walls of the cold room. Timber is easy to clean and disassemble, while allowing for better moisture and air passage. Although the clay plaster interior also performed well, it poses challenges in cleaning and maintenance, particularly if inspection of the straw is required at some point. Therefore, timber is preferred for its practical benefits and ease of maintenance.

Figure 21. An eco-board insulation panel with damp straw identified during the trial (top), and dry straw with clay plaster (bottom)

Source: Humphrey Anjilla. 2024

STAKEHOLDER CONSULTATION WITH STRAW EXPERTS REGARDING MOISTURE ISSUES

ISSUES THAT OCCURRED DURING THE MOCK-UP TESTING AND WERE RESOLVED AS PART OF THE FINAL DESIGN

Specialist studies recommend that relative humidity of the straw inside the insulation element wall should not exceed 85%[18]. Therefore, rain or condensation water should not be allowed to flow inside the elements[19,20]. High humidity can make the straw degrade quickly or in the worst-case cause fungus to proliferate.

The original solution with eco-boards being placed on both sides of the straw led to condensation on the inside of the inner eco-board panels as identified during the mock-up testing. Therefore, relevant experts were consulted to solve the condensation problem.

Working together with the ETH researcher and integrated design expert Maximilian Gester, Stefan Oeschger recommended the ILead dDesign team to involve additional straw insulation experts. Biogenic material expert Dr. Magda Posani from ETH and Thomas Dimov ETH architect from zoë circular were asked for their opinions.

According to Magda Posani, her simulations with WUFI Pro, a dynamic modelling software, have shown that a vapour barrier that is as diffusion tight as possible on the outside of a cold room seems to be essential to keep the moisture in the construction low.

According to Thomas Dimov, the moisture problem can be sufficiently controlled by using clay plaster on the inside and a slightly denser clay-lime plaster on the outside. The effectiveness of clay plaster on the interior of wall elements was demonstrated in the trial construction, which included an installed clay plaster element. Dimov notes that another option to consider is having a more open construction, without a vapour barrier on the outside. This alternative design involves the following composition: straw elements that have the width of only one straw bale module, with the outer clay layer and lime plaster prefabricated, and the inner clay layer created onsite, thus reducing weight during transport. Additionally, a lime plaster on the outside of the cold room would prevent moisture from entering the construction.

As the results of the simulations do not provide absolute certainty, the scientific findings regarding the moisture problem cannot guarantee absolute freedom from damage. Despite the uncertainties and the positive measured values from the revised mock-up, the lead design team opted for the element variant with eco-boards used as a vapour barrier on the outside, straw insulation in the core and diffusion-open wood T&G cladding on the inside. The solution of clay plaster on the inside, which was successfully tested in the mock-up, was rejected by the Kenyan team members as too prone to dirt and old-fashioned.

The functionality of the cold room was successfully tested in practice with the new T&G concept. Readings from the humidity sensors inside the insulation elements at the final installation have shown that the straw of the final insulation elements installed remains below 80% even at high relative humidity levels of up to 95% inside the cold room, which is required for the storage of most agricultural products. The success of this concept is due to the use of the inner wood of the T&G layer, which allows moisture from the straw to be released to the cold room air, while at the same time protecting the straw from low temperatures inside the cold room.

18. This limitation only applies to the internal part of the insulation wall. The relative humidity in the actual cold room can still be significantly higher - up to 95% - in line with the ideal storage conditions for most fruit and vegetables.

19. A. Mesa, A. Arenghi. (2019). Hygrothermal behaviour of straw bale walls: experimental tests and numerical analyses. Sustainable Buildings. https://wufi.de/de/wp-content/uploads/sites/9/Hygrothermal_behaviour_of_straw_bale_walls-experimental-tests-and-numerical-anlyses.pdf.

20. J. Robinson, H. K. Aoun, M. Davison. (2017). Determining Moisture Levels in Straw Bale Construction. Procedia Engineering, Volume 171, Pages 1526-1534. https://www.sciencedirect.com/science/article/pii/S1877705817304009.

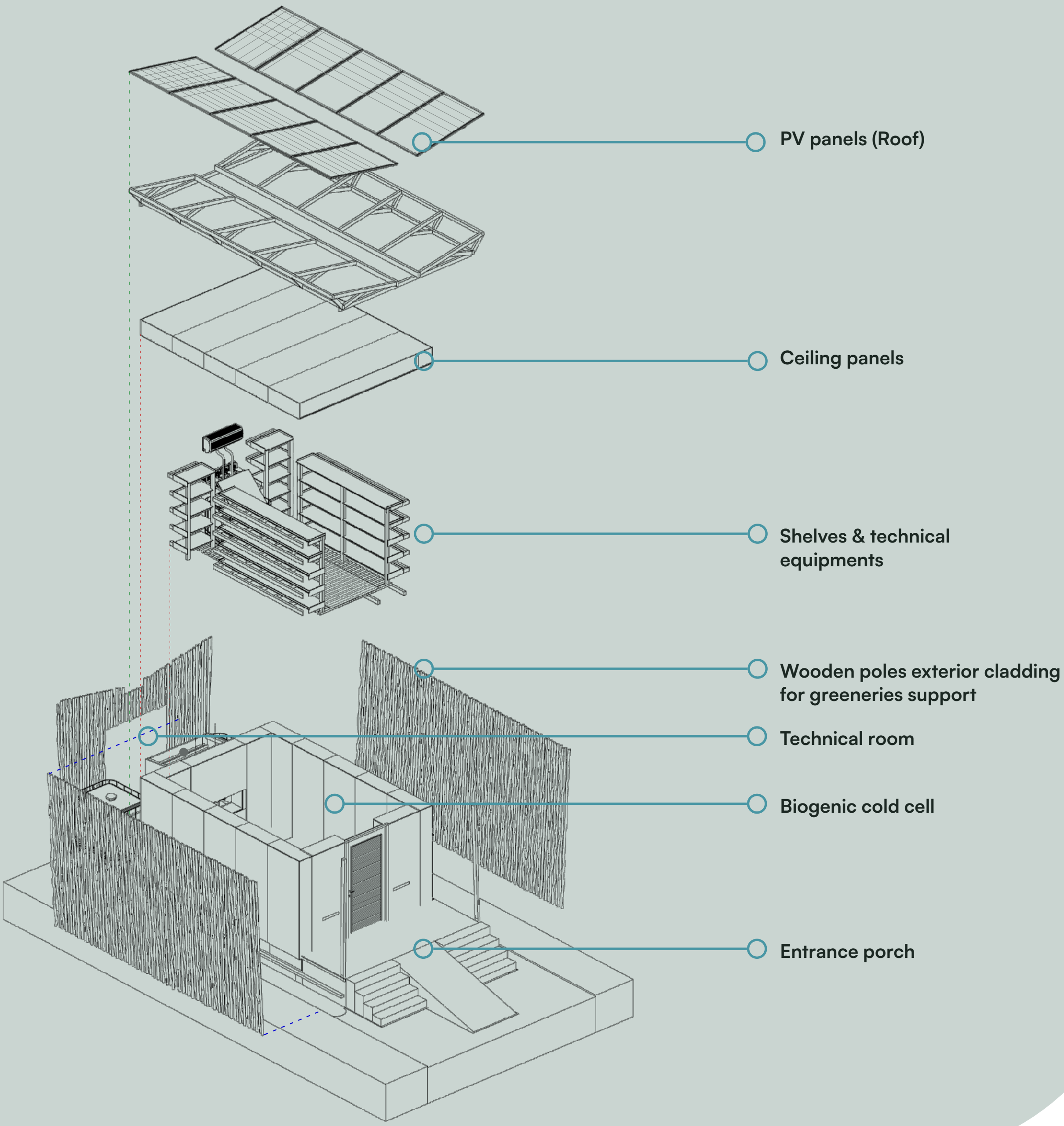
2.1.5. FINAL DESIGN

After the iterative design process including learnings from the trial cold room construction, a final design was proposed, which comprised **three main sections:**

The virtual assembly of the low-carbon cold room is shown in Figure 22 and the final design in Figures 23-25.

1. **A technical room** comprising all the electrical components, including batteries and the remote monitoring system.
2. **A biogenic cold cell** to accommodate shelves stocked with crates for fresh produce, ice storage tank, and air heat exchanger.
3. **An entrance porch**, enhanced with wooden benches and tables.

Figure 22. The low-carbon cold room's assembly visualisation



LINK FOR 3D VISUALISATION VIDEO OF THE LOW-CARBON COLD ROOM.

https://youtu.be/IARJ7C_dKFI

Figure 23. Floor plan for the final design

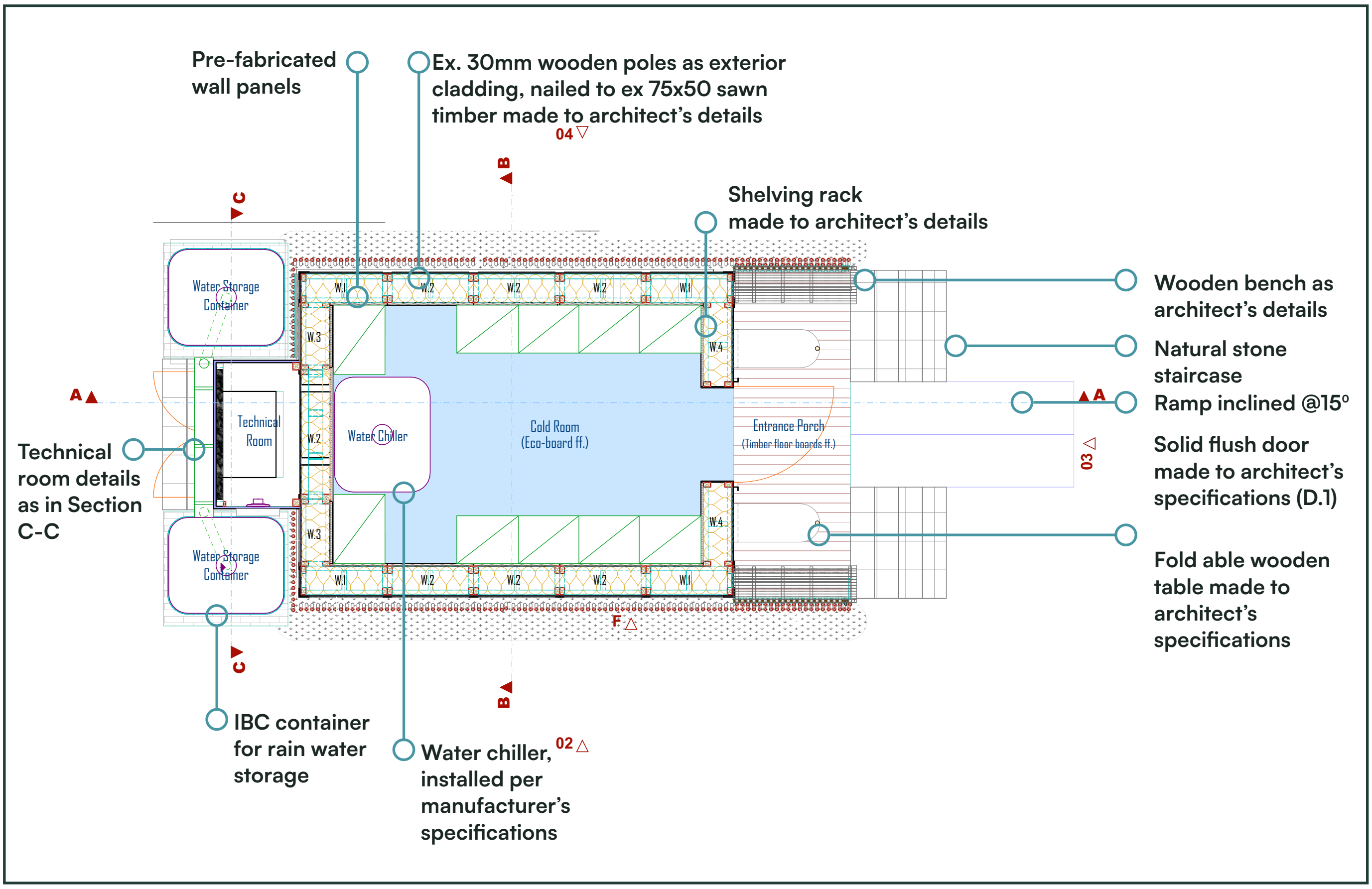


Figure 24. A-section across the cold room (side view)

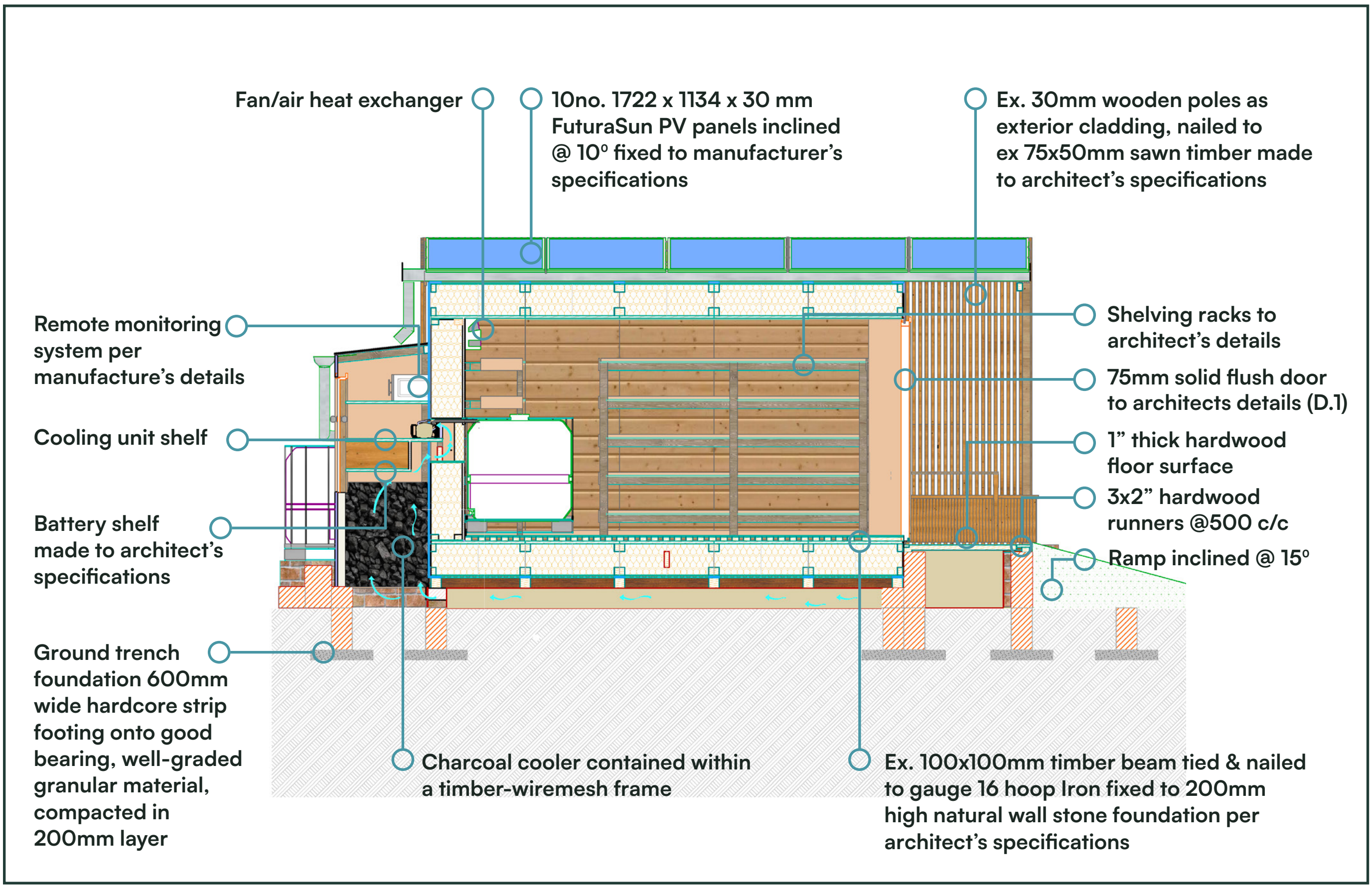


Figure 25. A-section across the cold room (back view)

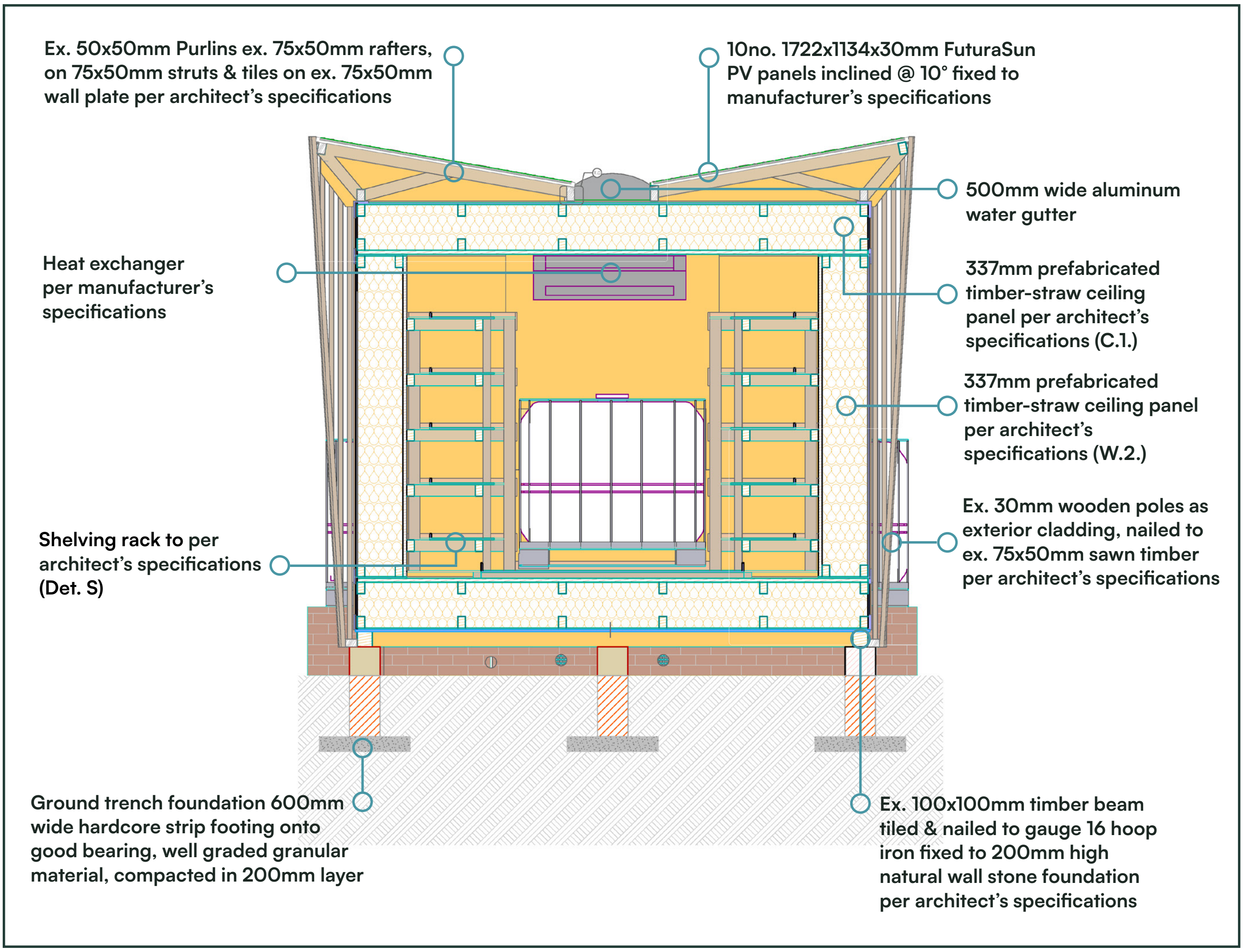
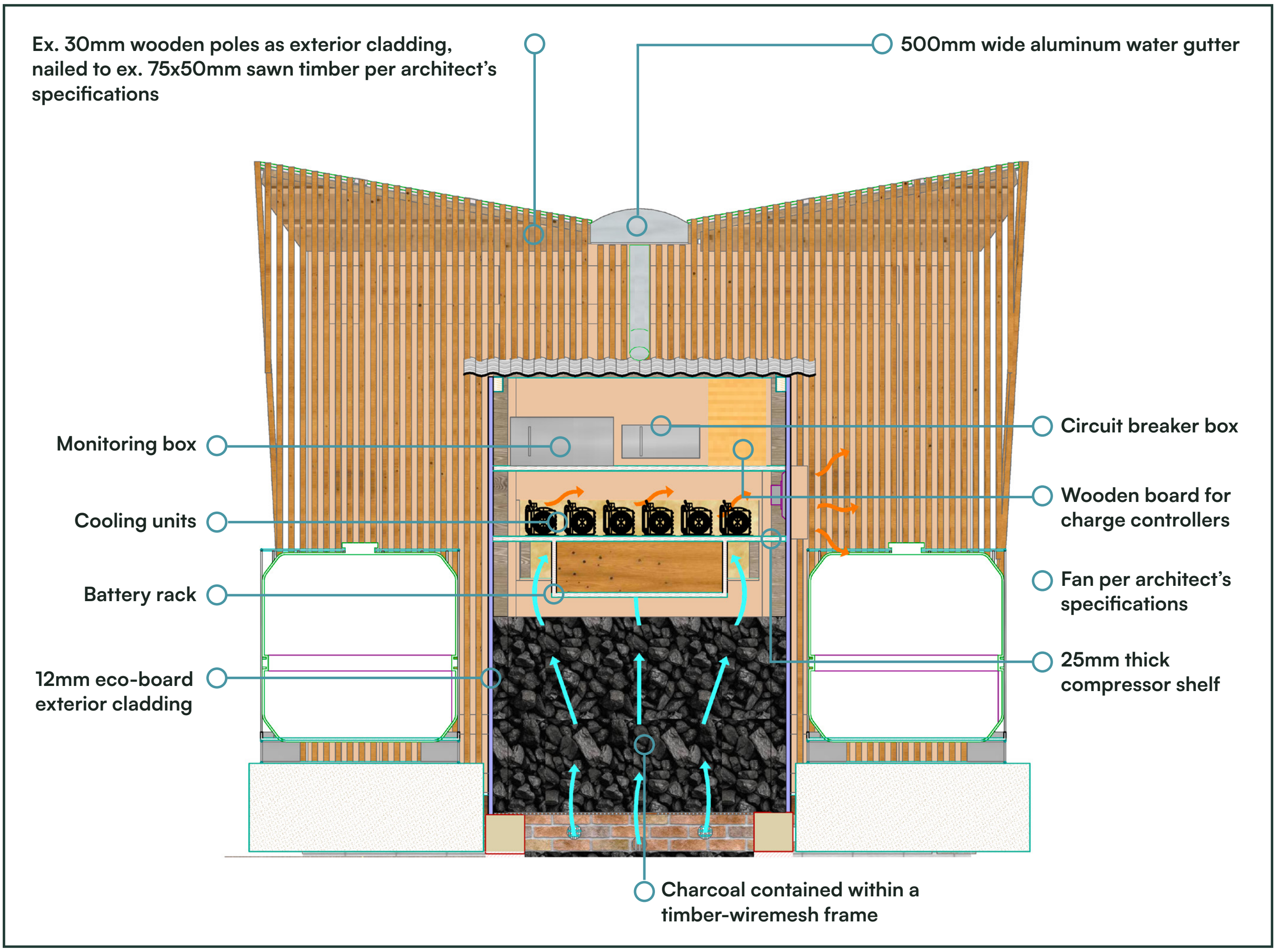


Figure 26. A-section across the technical room



To increase the coefficient of performance (COP) of the cooling units and at the same time maintain optimal operating temperatures for batteries and other temperature-sensitive components, a passive cooling system using evaporative cooling principles was integrated in the design as shown in Figure 26 on page 40. This system relies on the heat absorption properties of charcoal, where ambient air circulates through water-saturated charcoal, causing the moisture to evaporate and absorb heat from the air. This evaporative cooling process results in a temperature reduction of 5-10 °C depending on the ambient temperature. The cooled air is extracted from the ground air below the cold room and then circulated directed into the technical room, effectively mitigating heat buildup within the enclosures that house the condensing units of the cooling units, batteries, and other electrical components. This method ensures that the cooling units use less energy, and other components are protected from overheating. The warm air from the cooling units is then extracted from the technical room with the help of a fan.

ROOF DESIGN

The roof design incorporates the following elements:

- 10 photovoltaic panels — see Figure 27
- T-strip rubber seals installed at the joints between the solar panels to prevent water entering and ensure the integrity of the underlying ceiling panels
- A 500mm water gutter positioned centrally to direct rainwater collected from the solar photovoltaic panels to water storage tanks as shown in Figure 28

Figure 27. Roof design including the integration of solar photovoltaic panels

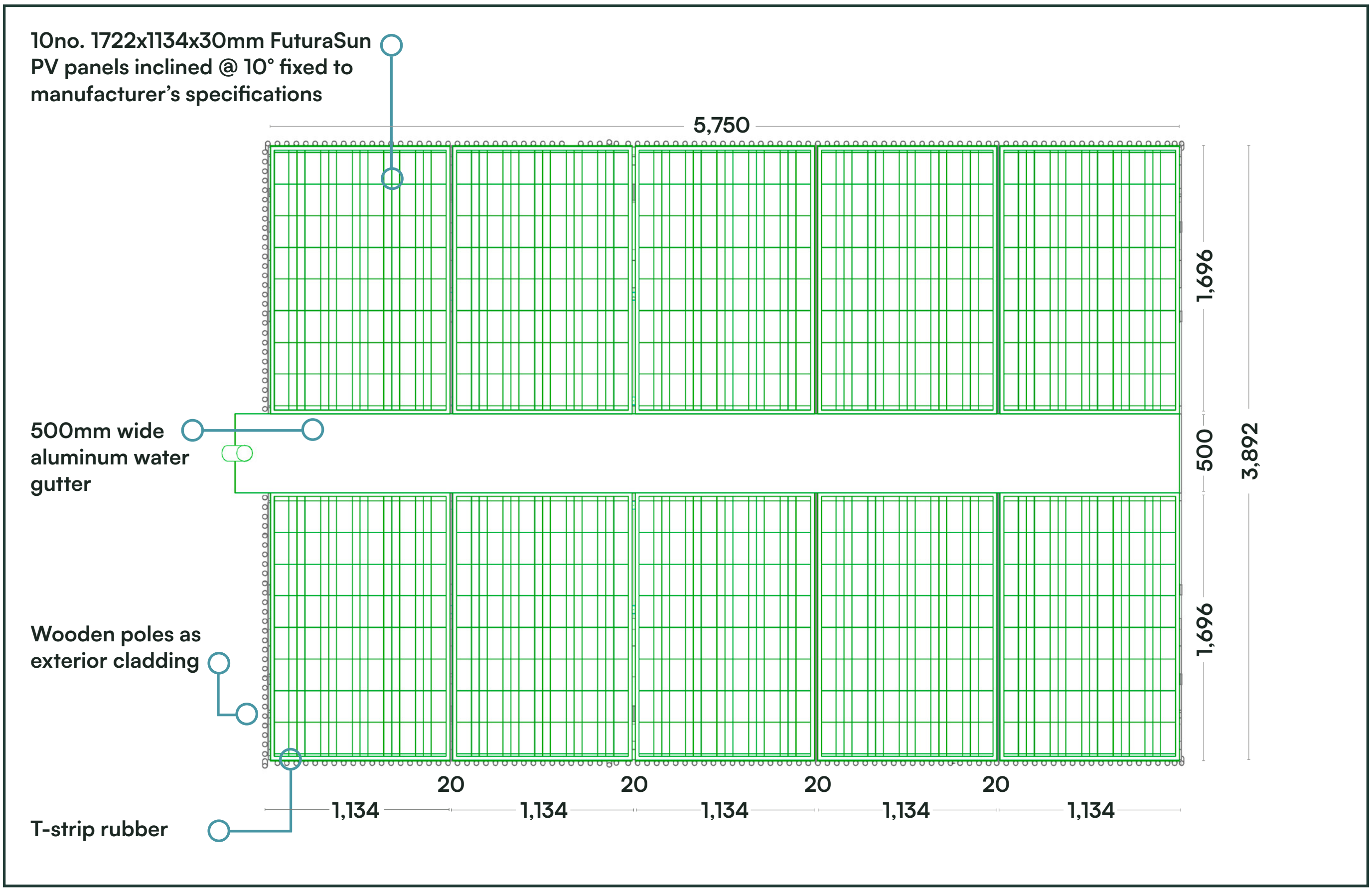


Figure 28. Roof construction details

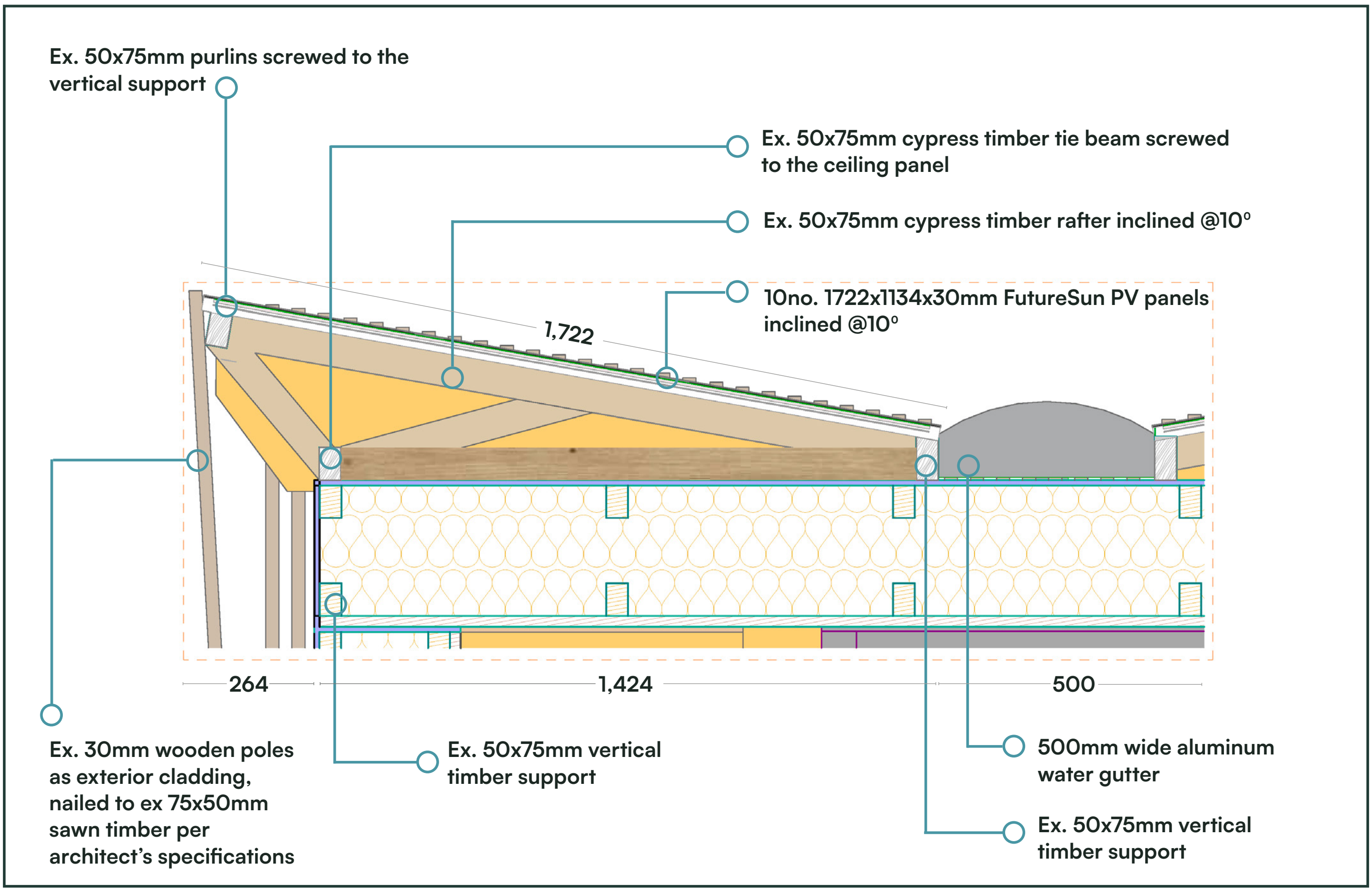


Figure 29. Rainwater collection system

DOOR CONCEPT

The door is also made from biogenic materials, complemented by a sealing rubber door gasket to ensure airtightness and prevent the infiltration of warm, humid air. The strong and durable structure is designed to avoid thermal bridges.

Biogenic insulated doors are not readily available in Kenya, necessitating their construction by local carpenters. This approach ensures that the doors are tailored to the specific requirements and built with locally sourced materials and workforce.

Figure 30. Insulated door design

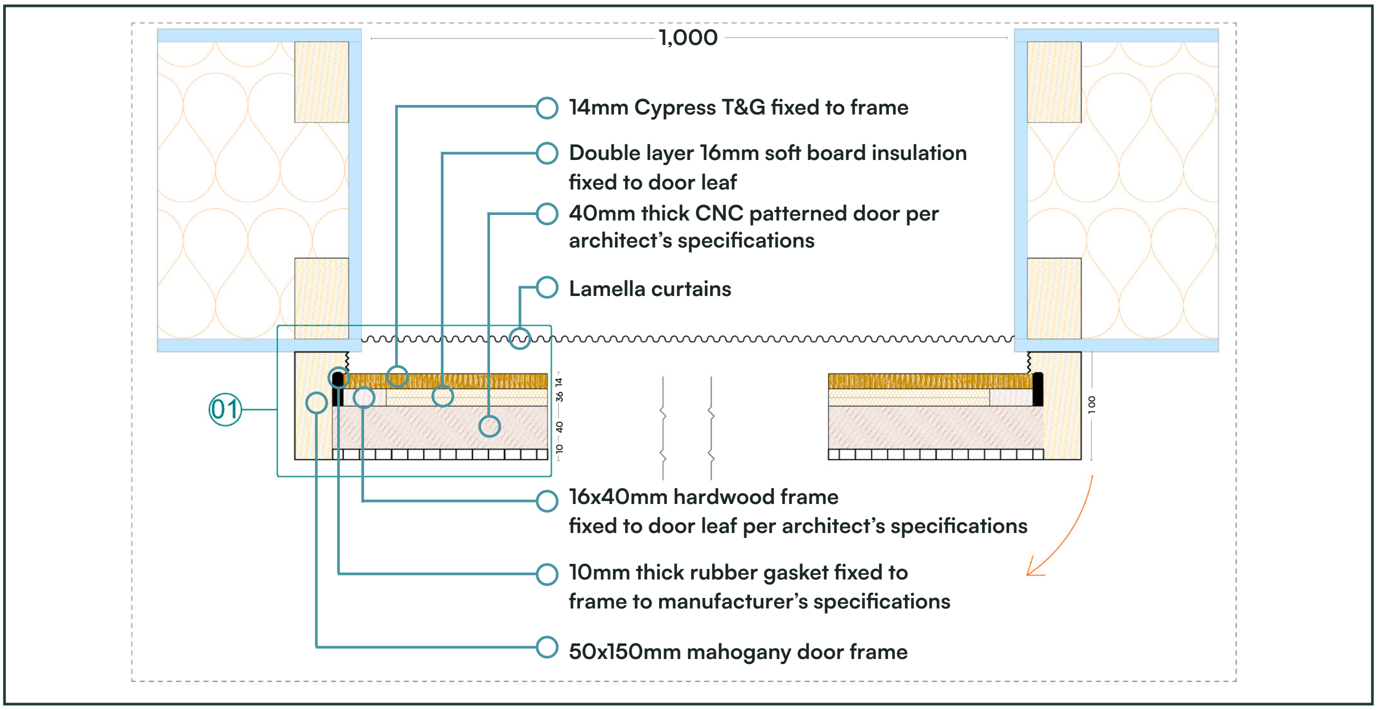
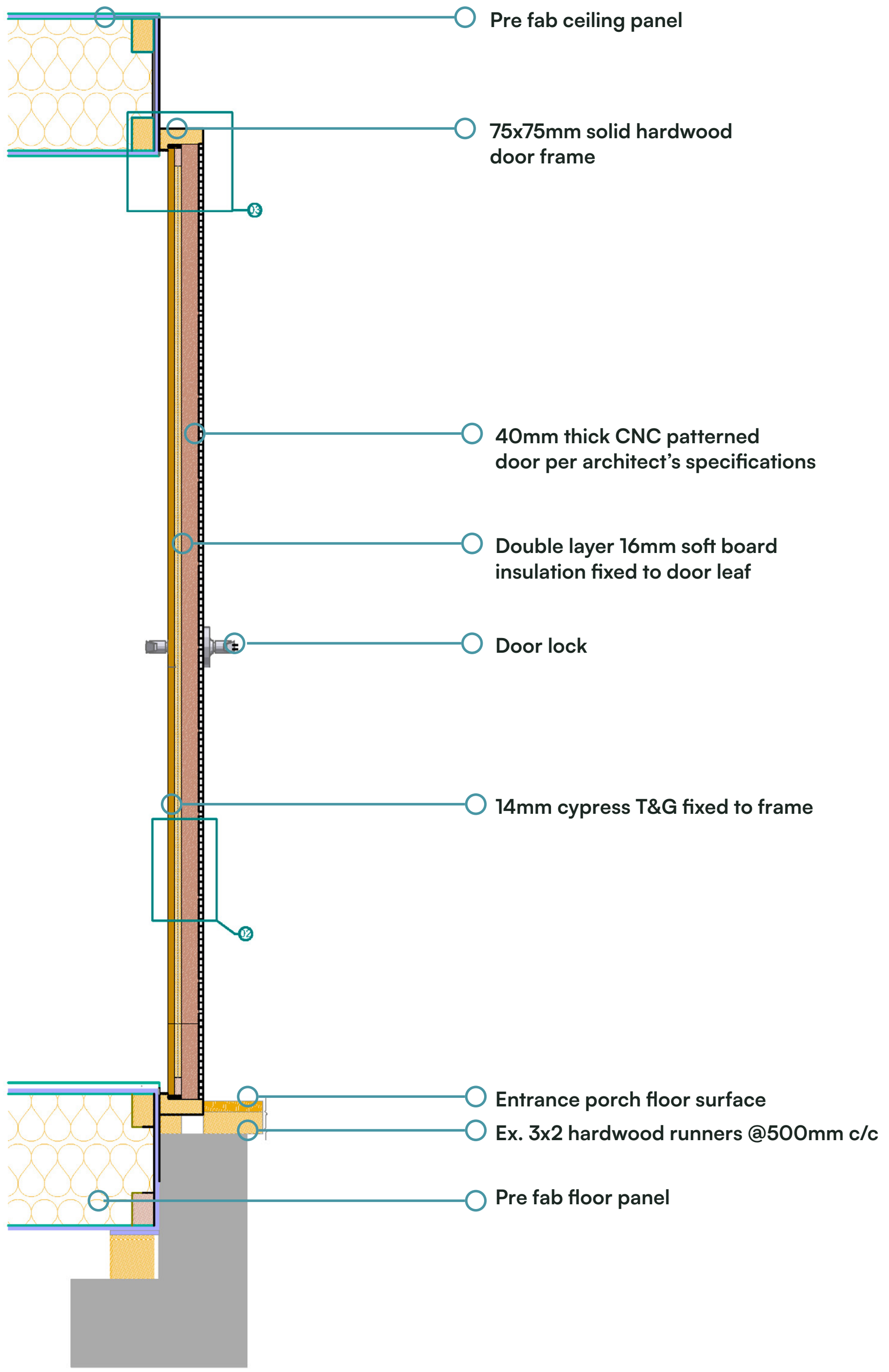
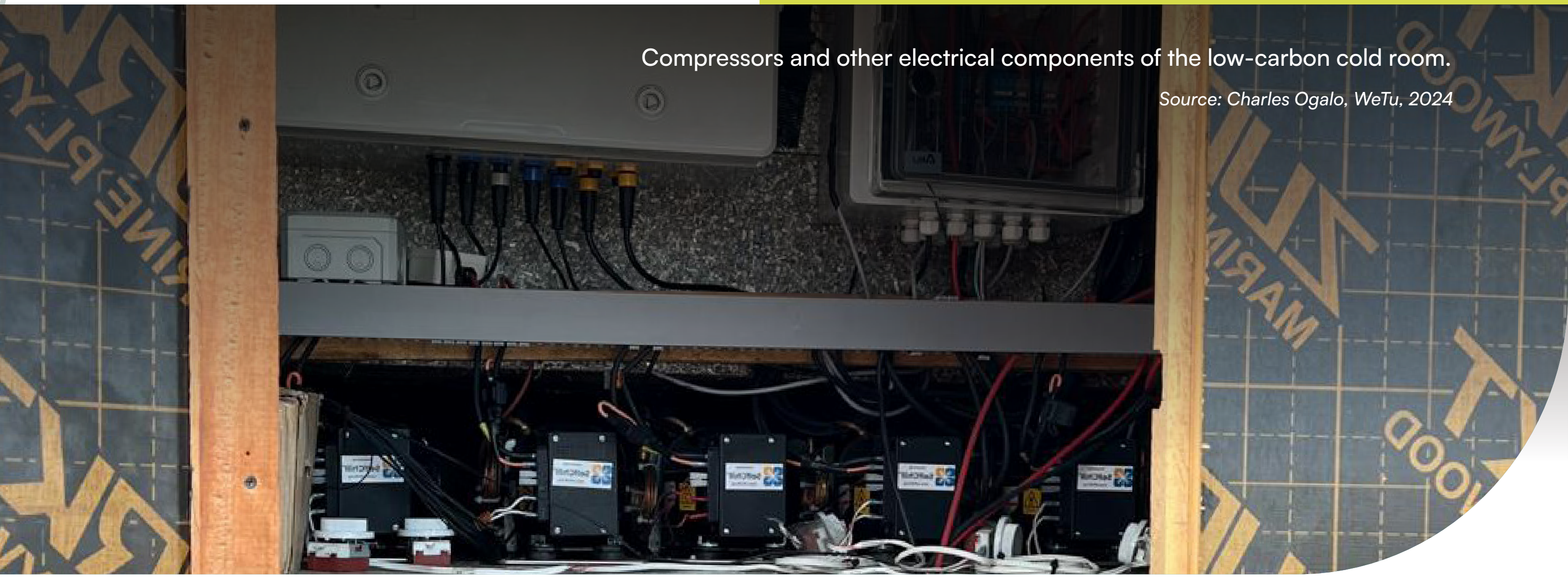


Figure 31. Side section of the insulated door design





Compressors and other electrical components of the low-carbon cold room.

Source: Charles Ogalo, WeTu, 2024

2.2. SOLAR COOLING EQUIPMENT

2.2.1. COOLING SYSTEM

Preserving perishable produce, particularly within the critical temperature range of 0-10°C and 80-95% relative humidity, is essential to ensure effective and safe food supply chains. However, limited access to reliable grid electricity in the Global South means that it is challenging to achieve these food storage conditions, affecting communities with no access to cooling solutions. To address this issue, a solar-powered vapour compression refrigeration system, referred to as a cooling unit, has emerged as a solution. This system utilises direct current (DC) electricity from photovoltaic panels coupled with electrochemical batteries to produce ice, serving as an energy storage medium for extended food preservation.

Solar cooling can be achieved through various technologies, with vapour compression being the most common option for conventional grid-connected and solar photovoltaic (PV) systems. The main difference between the "SelfChill" modular cooling unit developed by Solar Cooling Engineering and most other solar-powered cold rooms is the use of DC electricity from solar PV to power the motor directly, thereby increasing the overall system efficiency instead of converting it to alternating current (AC).

Figure 32. Methods of solar-powered cooling

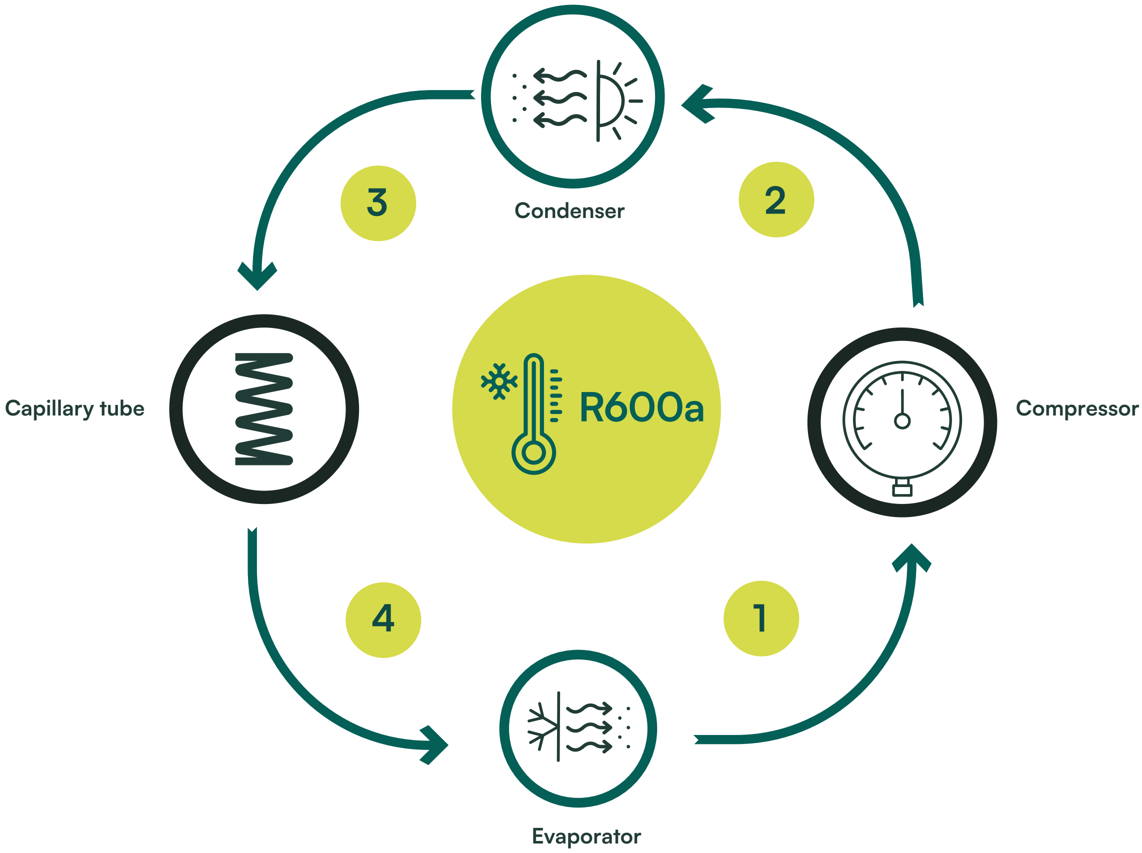
There are different methods of using solar energy to power a refrigeration system as shown in Figure 32. Thermal collectors with absorption chillers were used when solar PV panels were not yet cost-efficient. The use of conventional vapour compression AC refrigeration devices, such as monoblocs or split cooling units, is currently widely used with the help of hybrid inverters able to provide AC electricity to the cooling unit from a PV+Battery solar system. In the current case, an innovative solution integrating thermal storage and evaporative cooling has been used. Small DC driven cooling units are used without the need for inverters.

The cooling units use chilled air from an evaporative cooler to work with a higher coefficient of performance (COP) which makes the overall system efficiency considerably higher than conventional systems. In addition, thermal storage is utilised to reduce the need for electrical batteries. The system is, however, not fully battery-free due to the results of the optimised design, which showed that the combination of thermal storage and small batteries is not only considerably more cost efficient, but also has a lower carbon footprint.

A vapour compression refrigeration system, shown in Figure 33, is a one such system in which a working fluid, also referred to as a refrigerant, is used. The refrigerant absorbs heat energy from a source and releases this into a heat sink or ambient surroundings. It undergoes the processes of condensation and evaporation at temperatures and pressures near atmospheric conditions. The refrigerant remains within the system and is continually circulated throughout.

Vapour-compression refrigeration systems operate by boiling the refrigerant in the evaporator (4 → 1) at a relatively low pressure, extracting heat from a low-temperature source (such as the refrigerated space). The resulting vapour is then compressed to a higher pressure (1 → 2). It is subsequently condensed back to a liquid (2 → 3), with the heat of condensation rejected to a relatively high-temperature heat sink (ambient air for most refrigeration and air-conditioning systems). The refrigerant is then returned to the starting pressure to complete the cycle (3 → 4). The condensation and evaporation processes are ideally at constant pressure and, thus, constant temperature (for a pure fluid); the ideal compression process is at constant entropy.

Figure 33. Parts of a vapour compression cooling unit



The core component implemented in this system is the solar cooling unit shown in Figure 34 on page 48, which is a vapour compression refrigeration system with an evaporator plate that can be placed in water. It is hermetically sealed, filled with refrigerant and ready to be plugged to a PV system with or without batteries for different cooling applications. The units consist of the following parts: compressor (SECOP BD35K), condenser, evaporator plate and electronic control unit (SECOP 101N042). The selected unit uses an air forced condenser and an evaporator plate with an anti-corrosion rubber coating for applications where the evaporator plate is immersed in water. There are white evaporator plates, but the selected unit has a black coating which is corrosion resistant.

When powered by a DC electrical source (solar PV panels or batteries), a natural refrigerant R600a (Isobutane) with a very low Global Warming Potential (GWP) of 3, is circulated, absorbing heat from the surrounding water and rejecting it through the condenser. As the temperature of the water is lowered, the cold thermal energy generated is stored as frozen water in the ice storage unit.

Figure 34. Solar Cooling Unit SelfChill Liquid Indoor 45/75 A-F (Phaesun GmbH) - *See technical data in Annex 1.*

Based on the SelfChill concept, the cold room for preserving agricultural products employs DC cooling units to transform the available solar energy into cooling energy. These cooling units can be directly powered with a PV module due to their ultra-low starting current, avoiding the cost of traditional AC solutions, including power inverters and large battery banks. However, the cold room configuration selected incorporates a small battery bank to allow the cooling units to operate during low or null irradiance periods, improving their performance and enhancing system reliability.

Fully battery-free systems need larger amounts of PV panels which would make the system not only more expensive, but also have a higher carbon footprint, as demonstrated in the following sections.

Another prominent characteristic of this solution is the integration of thermal storage, which is based on the temperature reduction of a cooling medium (water) and the ice built up around the evaporator plates of the cooling units. The evaporator plates of the cooling unit are placed inside a thermally insulated water tank, also known as a water chiller, which decouples the thermal generation and demand. In this way, the water chiller provides efficient cold transfer with high discharge rates up to 2 kW cooling power even when the cooling units are not operating.

If the temperature in the cold room exceeds the desired threshold or hot agricultural products are introduced, the system will activate a heat exchanger circuit to remove excess heat. This circuit utilises an ultra-low power DC pump to circulate cold water from the water chiller through the heat exchanger, which in turn disperses cold air throughout the cold room via a blowing DC fan.

In total, six cooling units have been implemented to create the thermal (ice) storage, which in this case is placed inside the cold room to reduce thermal losses. Figure 35 shows the typical installation of the cooling units. The full integration of the cooling system with the solar system is shown in Figure 36.

Figure 35. Cooling units with evaporator plates immersed in a water chiller

Source: Charles Ogalo, WeTu, 2024

Figure 36. Parts of a vapour compression cooling unit

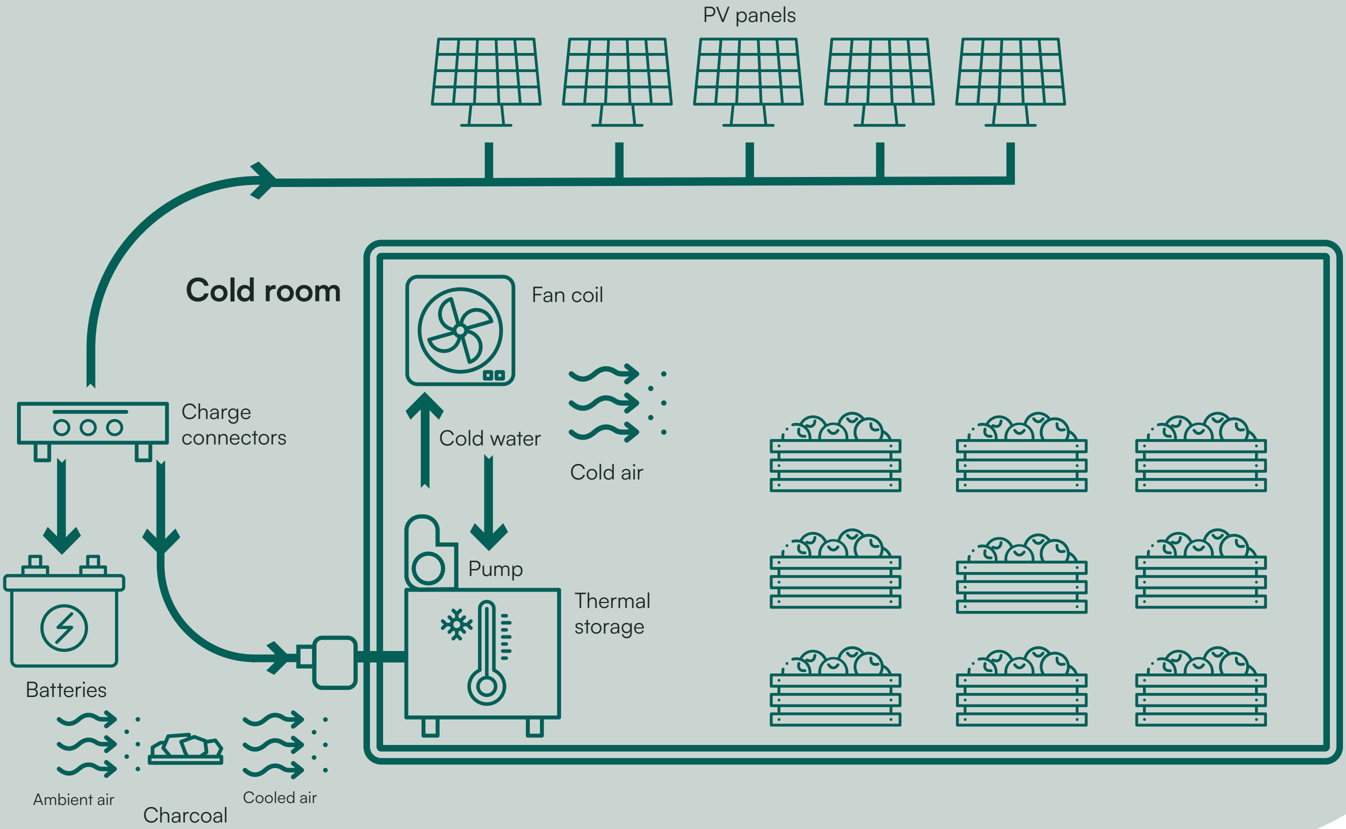


Table 3. Technical parameters of the cooling system

Technical data	
Cold room internal volume (useful volume)	21.8 m^3 (18.2 m^3)
Internal dimensions of the cold room	2.7 m x 3.8 m x 2.1 m
Maximum capacity	3 metric tonnes (50 Crates distributed in shelves and floor surface)
Maximum daily exchange of products	400 kg / day
Set-point temperature	10 °C (adjustable between 6°C and 15 °C)
P_{el} (6 cooling units)	450 W
P_{el} (pump + heat exchanger)	40 W
$P_{th,rated}$ (@ 35°C ambient temperature)	900 W
$P_{th,max}$*	2000 W
Thermal (ice) storage capacity (water/ice)	500 L / 150kg

2.2.2. TECHNICAL SECTIONS OF THE COLD ROOM

Section A of the cold room illustrated in Figure 37 represents the cold room space designated to store agricultural produce, and Section B, serves as the technical space for electrical equipment and cooling units.

Section A includes shelves stocked with product crates, an ice storage tank, and an air heat exchanger. The strategic placement of the ice storage tank within this room minimises thermal losses; for instance, the ice does not melt rapidly, thereby maintaining a stable temperature. Additionally, Section A houses the water pump and the piping that connects the ice storage tank to the fan and air heat exchanger. This configuration ensures efficient cooling and maintains the desired temperature for the stored products, thereby preserving their quality and extending their shelf life.

Section B contains all the electrical components, including batteries and the remote monitoring system. Six cooling units are installed here and need to release heat during operation. To make this process more energy efficient, an innovative solution involving charcoal and forced convection is employed. As pre-cooled air coming from the bottom of the cold room passes over the wet charcoal, it undergoes evaporative cooling, losing heat as the moisture in the charcoal evaporates. This process results in a temperature reduction of 5-10 °C. The cooled air then enters the technical room, allowing the cooling units to work with pre-cooled air that makes the coefficient of performance (COP) to be higher. In addition, batteries, and other electrical components stay protected from high ambient temperatures. This method ensures that the equipment operates within safe temperature ranges, thereby enhancing efficiency and prolonging the lifespan of the electrical and cooling system.

Figure 37. Main sections of the cold room including cooling component configuration

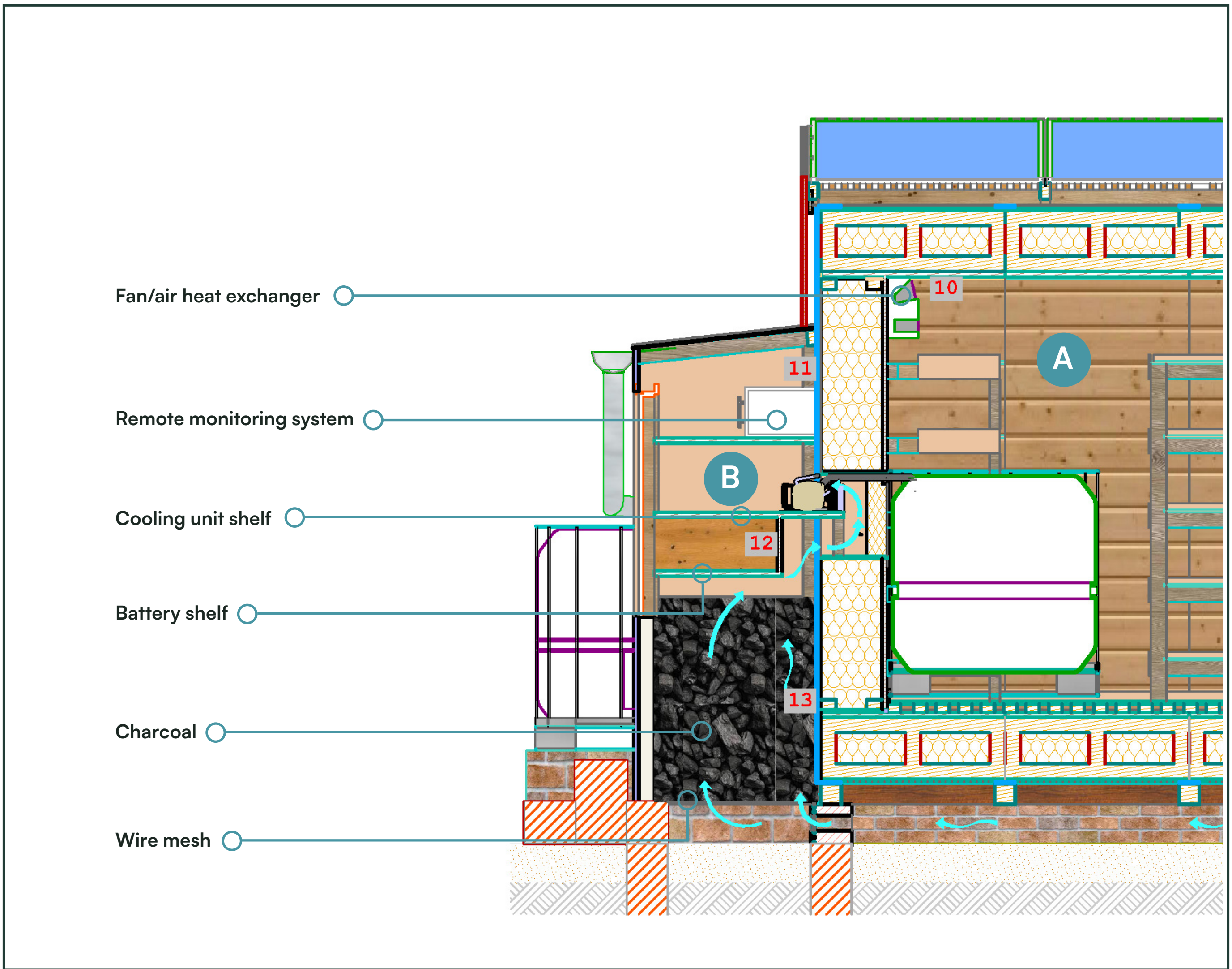


Figure 38. Installation of the charcoal inside the technical room

Source: Francis Maina, 2024.

2.2.3. THERMAL STORAGE WATER CIRCUIT

The water circuit of the thermal storage is composed of a DC water pump that transports cold water at around 1°C to the heat exchanger through insulated water pipes and a water filter. In the heat exchanger, a coil and a fan transfers the coldness of water into the air. The circuit is controlled by a digital thermostat *(see Section 2.2.7 for further details)* that turns the water pump and heat exchanger fan according to the set point temperature (10°C). *See technical data in Annex 1 and wiring diagram in Chapter 2.2.6.*

Figure 39. Heat exchanger (fan-coil) (left), direct current water pump (right)

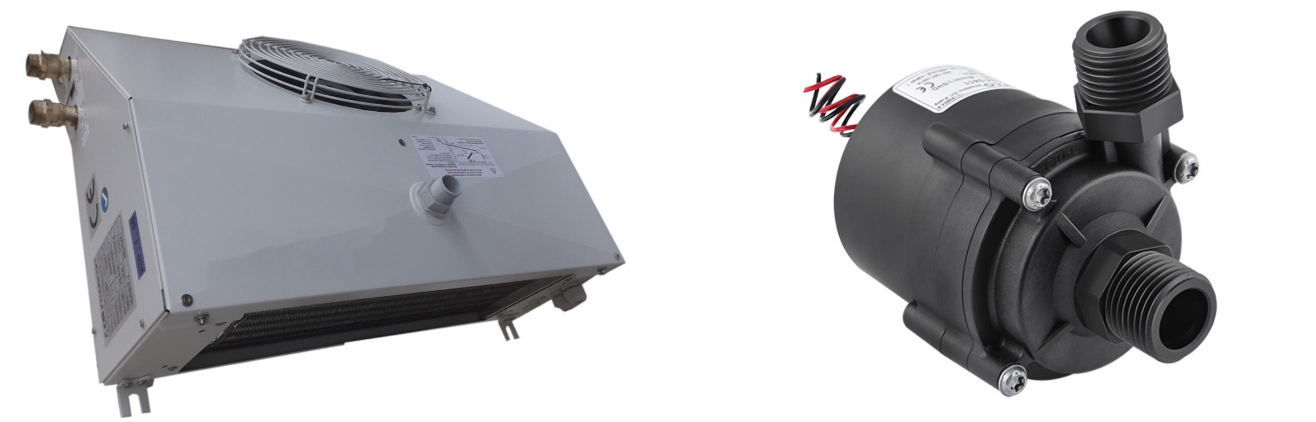


Figure 40. Water circuit including thermal storage (water chiller), pump and heat exchanger

Since the thermal storage is not insulated, condensing water is captured by a tray and transported outside of the cold room. The condensed water from the heat exchanger is transferred directly to the evaporative cooler. Since the eco-boards utilised for the floor are watertight, there is no risk to damage the biogenic elements in case of a water leakage.

2.2.4. SOLAR SYSTEM

The solar system is built similarly to a typical solar home system operating under low DC Voltage with the following components: PV panels, charge controllers and electrical batteries. Solar electrical power can be consumed directly by the cooling units or stored in the batteries. The use of a relatively small number of batteries helps to extend the operation of the cooling units after sunset with surplus energy. The solar system is divided into a primary solar system that runs the cooling units and one secondary solar system that runs the water pump, heat exchanger fan and the remote monitoring system. *Kindly find more technical data in Annex 1 and the wiring diagram in Chapter 2.2.6.*

Table 4. Solar system and battery storage parameters

Technical data for the solar system	
PV capacity (for six cooling units)	3600 W_p
PV capacity (for pump + heat exchanger)	400 W_p
Battery capacity (for six cooling units)	400Ah @24VDC LiPo
Battery capacity (for pump + heat exchanger)	200Ah @24VDC LiPo

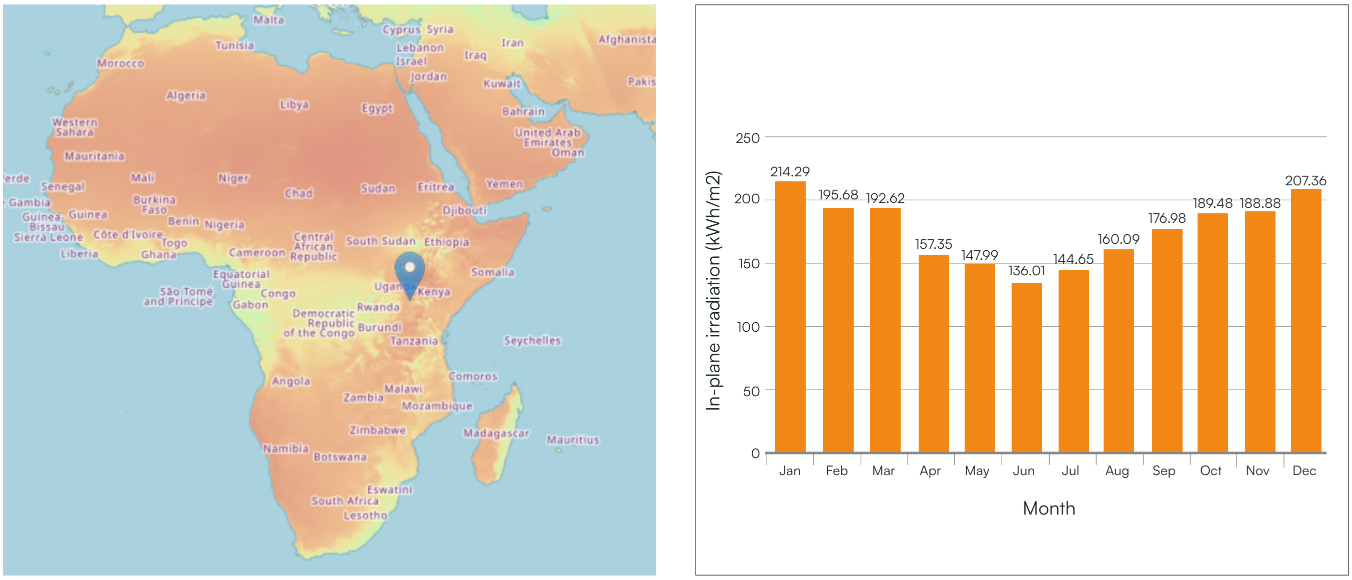
Figure 41. Monocrystalline PV panels (left), solar MPPT charge controller (middle), Lithium polymer batteries (right)

2.2.5. DESIGN AND OPTIMISATION OF COST AND EMISSIONS

The cold room was designed to minimise the embedded GHG emissions operating in Kenya at Homa Bay market at a constant temperature of 10°C (assuming a product exchange ratio of 400 kg/day).

For the design, a computational model has been implemented that considers the ambient temperature and Global Horizontal Irradiance, based on PVGIS typical weather data for Homa Bay, Kenya, as shown in Figure 42.

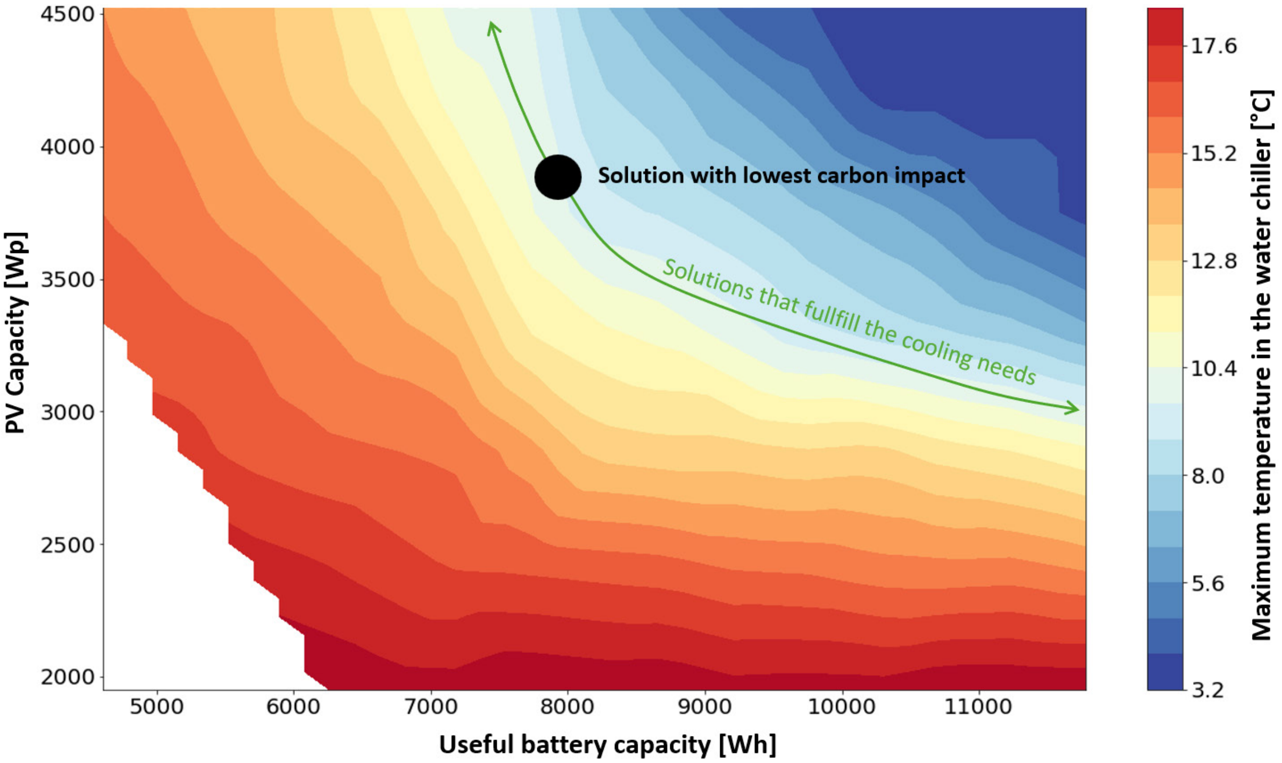
Figure 42. Location within solar maps (left) and monthly horizontal irradiation in Homa Bay, Kenya (Source: PVGIS)



Based on these weather conditions, the computational model runs specific design configurations to evaluate their capacity to maintain a set-point storage temperature of 10°C. The algorithm considers the size of the PV array (from one to seven kWp), battery capacity (from 0 up to 14 kWh of useful energy), and the number of SelfChill cooling units (from 4 to 12) as primary design variables to determine the optimal design with the lowest carbon footprint. Since the insulation material of the cold room affects energy consumption, the thickness of the insulation was also used as a variable in the design process.

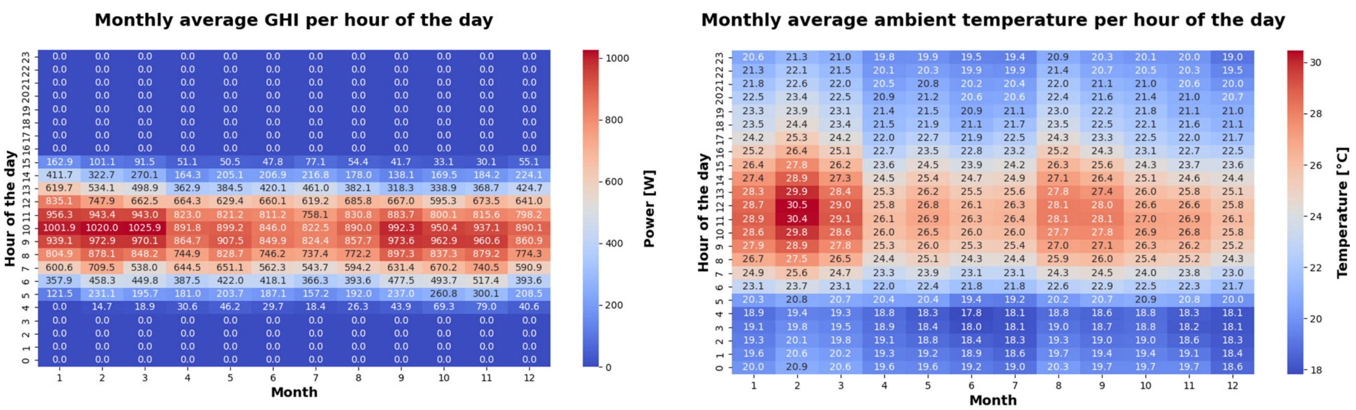
To evaluate the performance of each specific design set over a typical year, the model tracks the degree hours of deviation from the set-point temperature, measuring how long and to what extent the temperature inside the cold room exceeds the desired level. If the system reaches a specific threshold for the degree hours during the simulation process, the model stops the simulation and continues with a new configuration.

Figure 43. Results of the cooling system optimisation process for different solar PV and battery capacities



The results showed that the most critical period of the year in Homa Bay is around February and March when the ambient temperature is at its highest. The low solar radiation during the months of June and July is not critical due to the lower ambient temperatures. Low ambient temperatures not only reduce the cold room's energy demand, but also increase the COP of the cooling units.

Figure 44. Monthly average global horizontal irradiance (left) and average ambient temperature per hour of day for the location Homa Bay (Source: PVGIS)



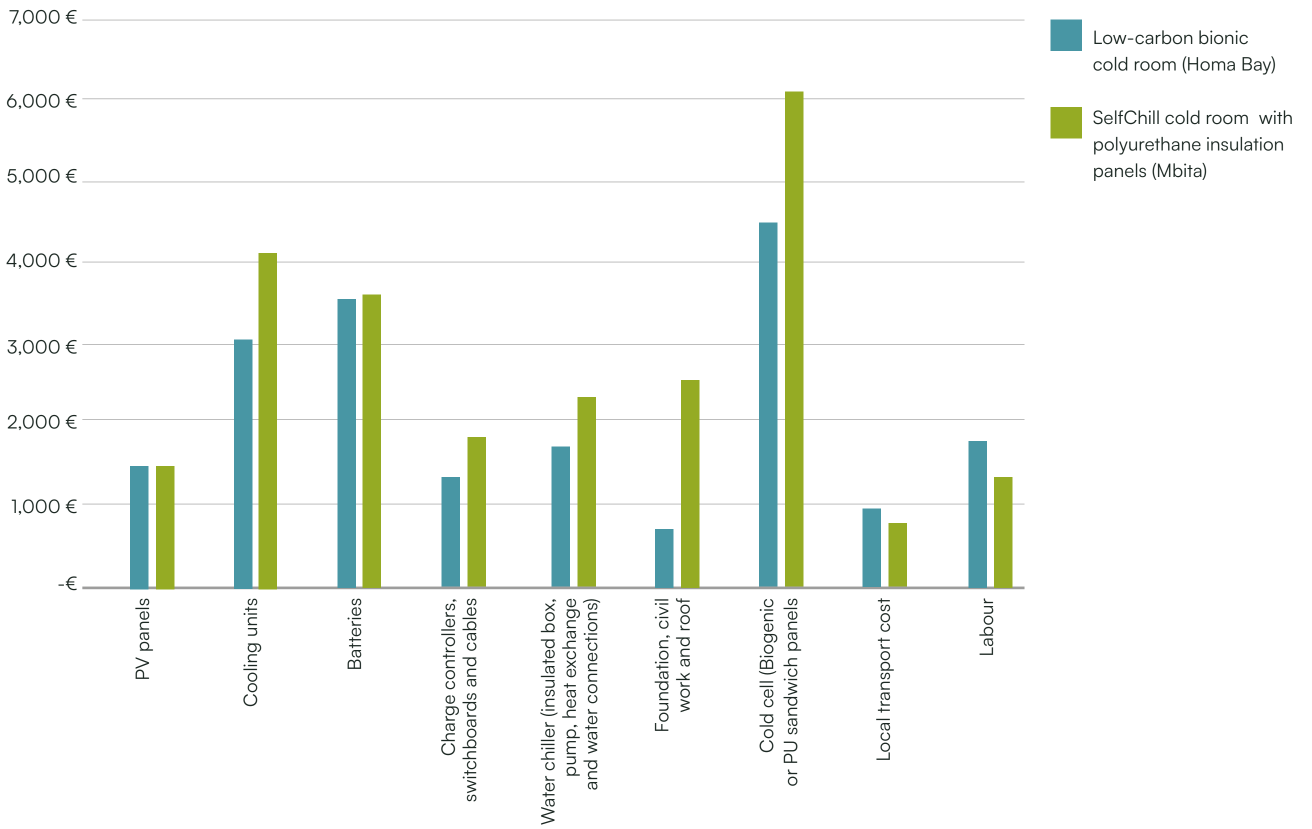
The computational model was implemented to identify the design set with the lowest carbon footprint, while meeting the necessary technical specifications for the recommended storage conditions of fruit and vegetables as shown in Table 5. The most significant design trends for achieving the lowest carbon footprint include minimising the solar PV size, selecting lithium batteries instead of lead-acid batteries, and using thermal storage in combination with evaporative cooling through the charcoal cooler to increase overall energy efficiency.

Table 5. Results from the cooling system sizing optimisation tool

Objective function of optimisation	PV capacity	Battery capacity	Cooling system	Cold cell insulation elements
Lowest carbon footprint	4.0 kWp	14.4 kWh LiPo 70 % Depth of Discharge (DOD)	Six cooling units + charcoal cooler	Biogenic 300 mm thickness

The selected solution with the lowest carbon footprint is around 20% cheaper compared to a similar sized cold room made from polyurethane insulation panels. The cost comparison between the two cold rooms is shown in Figure 45. The low-carbon cold room is more cost-effective in all areas, apart from labour and local transportation which is slightly higher for the biogenic solution. The higher energy efficiency and improved design aspects of the low-carbon cold room (including the use of charcoal cooler and placing the water chiller inside the cold room) allows it to use fewer cooling units and a smaller solar PV array which has an additional impact on the overall carbon footprint of the solution.

Figure 45. Cost comparison of a SelfChill cold room constructed with polyurethane insulation panels (such as the one recently installed by WeTu in Mbita, Western Kenya) and the low-carbon cold room made with biogenic insulation (installed in Homa Bay, Western Kenya)



The selected lowest carbon design represents a hybrid solution with PV, batteries, and thermal storage that can withstand unfavourable weather conditions. The simulation results below illustrate the system's behaviour over a typical year (left) and during the four worst-case days in March. The cold room can cool 400 kg of produce from ambient temperature to 10°C every afternoon. The average amount of ice stored (150 kg) is sufficient not only to meet the requirements during the most unfavourable days of the year but also to serve as an energy buffer for days when the amount of produce to be cooled exceeds the expected 400 kg.

Through thermal storage, the cooling capacity is around 2 kW, while the intermittent cooling energy generation by the cooling units has a maximum of around 0.95 kW. The advantages of the selected thermal storage include higher system autonomy and increase in the peak cooling power of the cold room. The energy flow for a typical day is shown below for both the electrical and thermal stages.

Figure 46. Energy flow chart for the solar cold room for a typical day at the given location

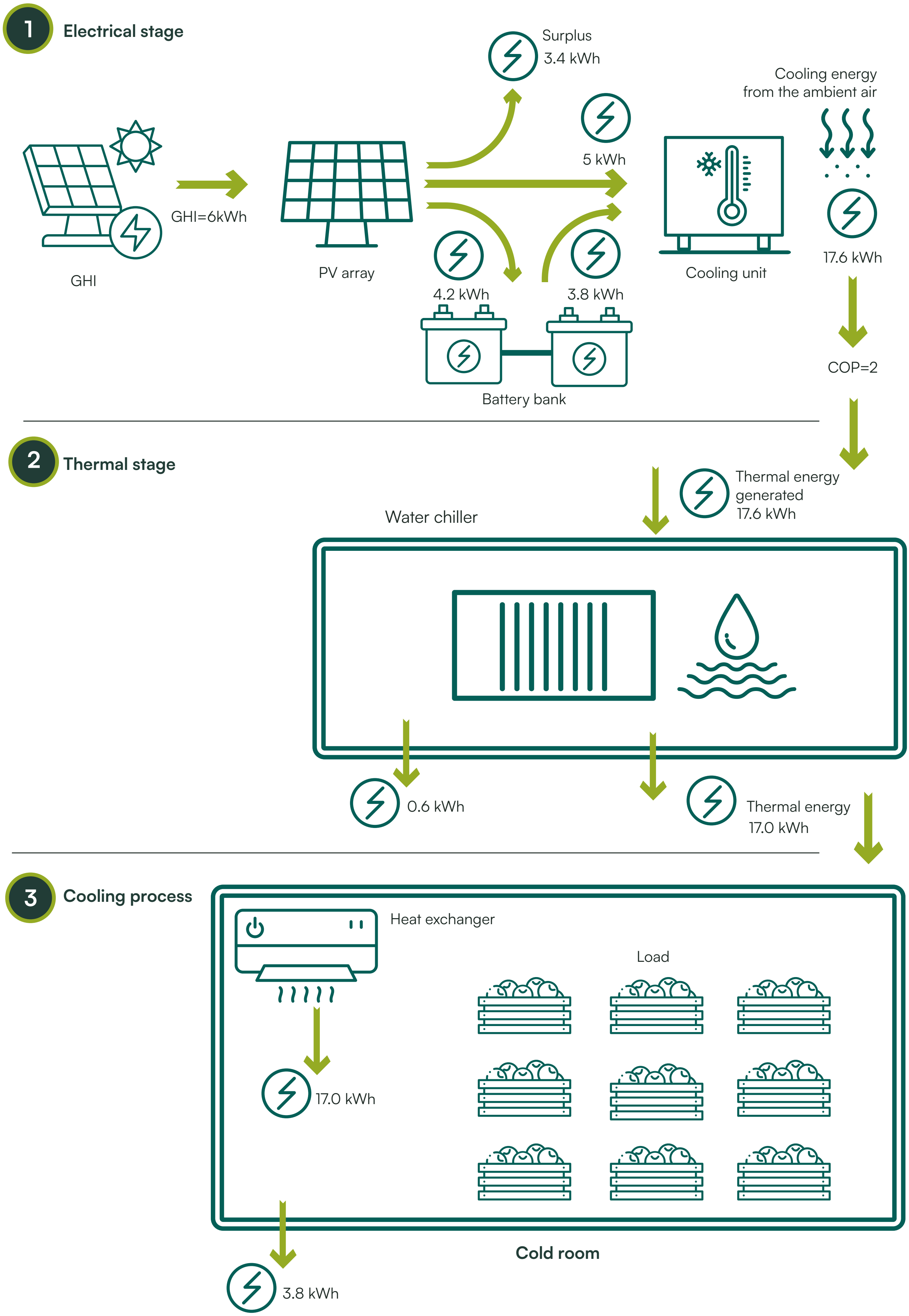


Figure 47. Temperature curves over a typical weather year in Homa Bay, Kenya

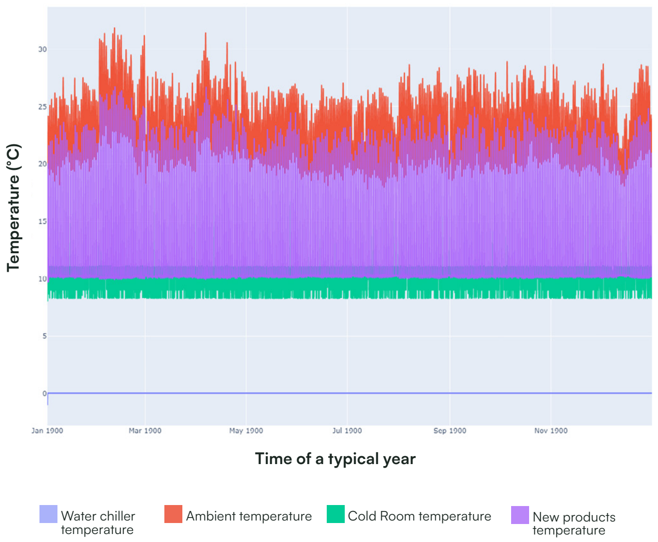


Figure 48. Temperature curves for the worst case weather conditions in Homa Bay, Kenya

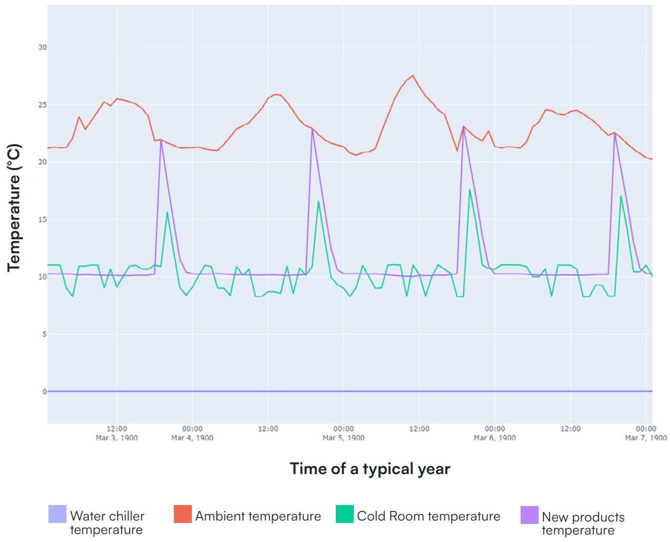


Figure 49. Electrical power flow for typical weather year

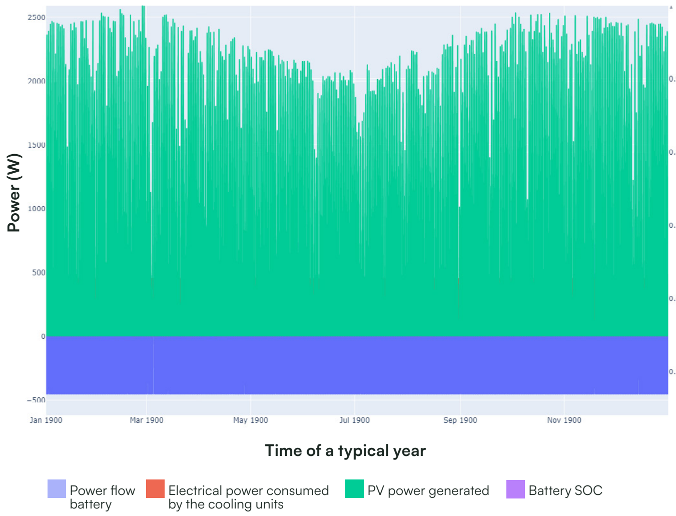


Figure 50. Electrical power flow for worst case weather conditions

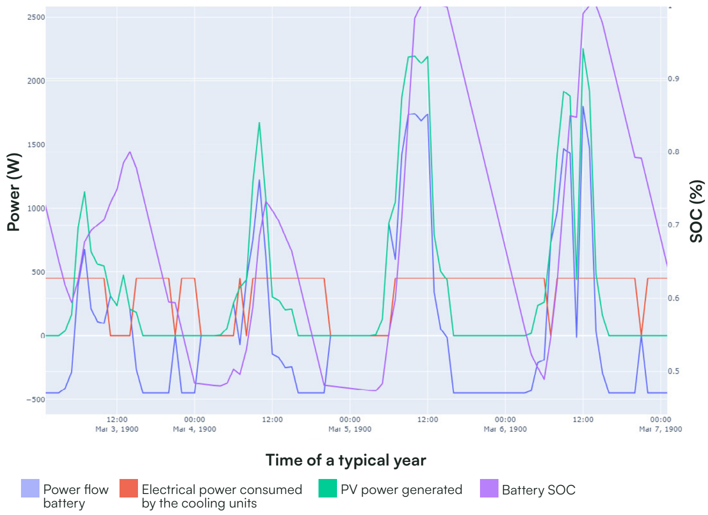


Figure 51. Thermal energy balance in the water chiller (ice-storage) for a typical weather year

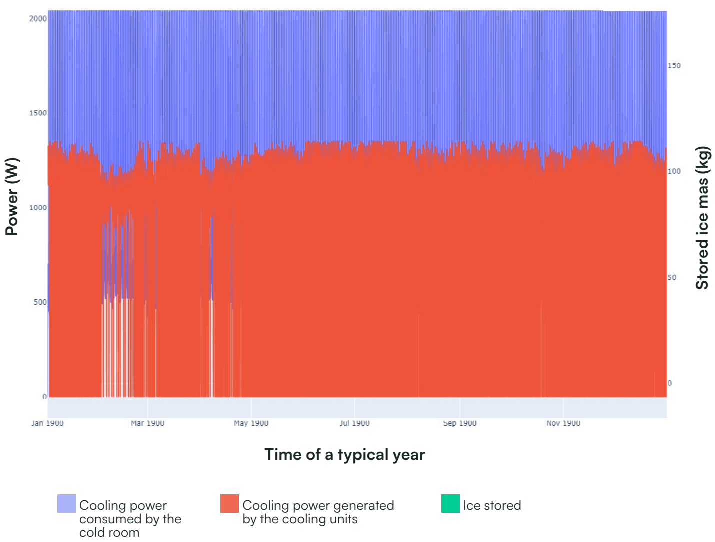
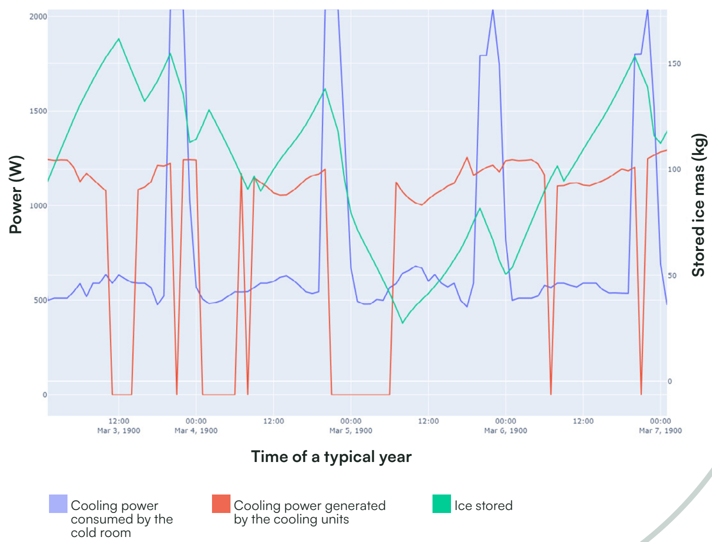


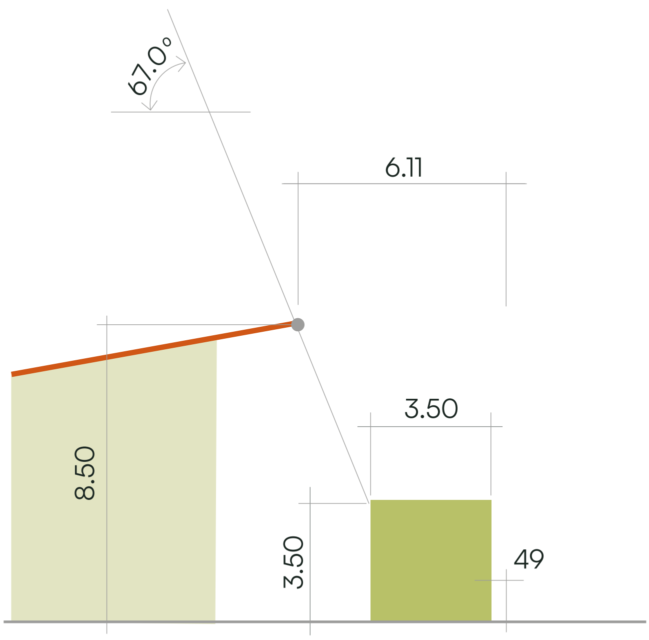
Figure 52. Thermal energy balance in the water chiller (ice-storage) for worst case weather conditions



Solar shading plays a crucial role in the efficiency and effectiveness of solar PV systems. By conducting shadow simulations, it becomes possible to identify and mitigate potential shading issues caused by adjacent structures. Such simulations ensure that solar panels are optimally positioned to receive maximum sunlight exposure throughout the day. Without this careful planning, even a small amount of shade can significantly reduce the energy output of a PV system, leading to less efficient electricity generation and higher upfront costs.

The low-carbon cold room is located in the Homabay market, which was reflected in the shadow simulations to assess the impact of nearby buildings on the PV modules. By modelling a sample building near the cold room (see Figure 53), it was possible to confirm that the panels would remain unshaded, even during the times of the year when the sun is at its lowest angle. This detailed analysis is essential in regions like Homa Bay, where ensuring continuous and optimal solar exposure can have significant implications for the performance and reliability of solar-powered systems.

Figure 53. Solar PV shading simulation

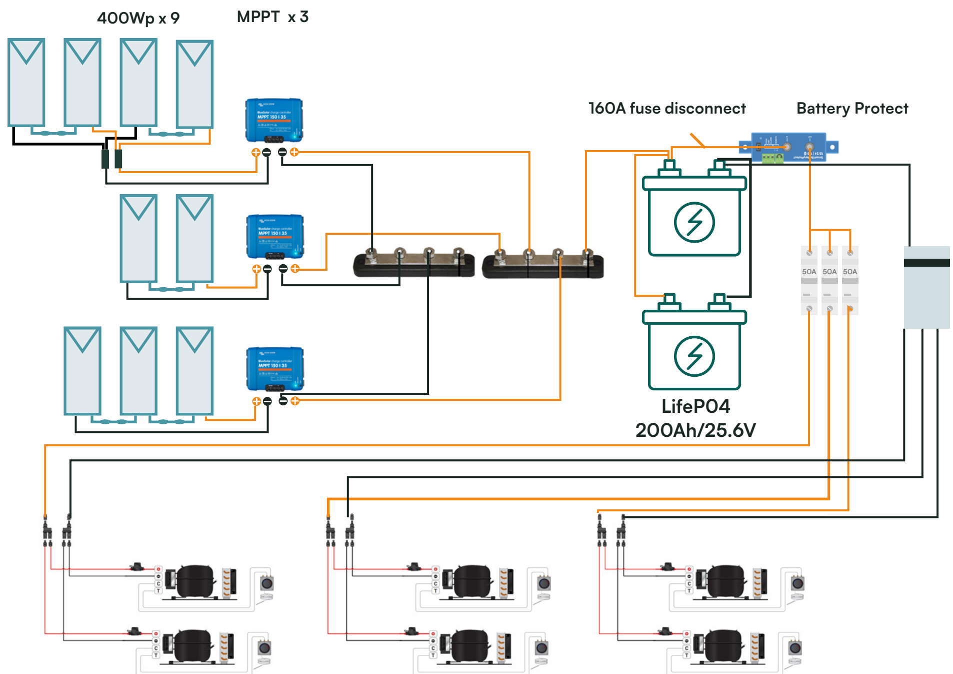


2.2.6. WIRING DIAGRAMS

The appropriate wiring in solar energy systems is critical. In the described system, which includes six cooling units, three charge controllers, nine 400 Wp PV panels, and two LifePO4 batteries, precise wiring ensures optimal performance and safety. The wiring diagram, as illustrated in Figure 54, shows a design where all PV panels charge the two batteries connected in parallel through a common bus. This configuration is crucial for maintaining a balanced and efficient flow of electricity, ensuring that each component receives the appropriate voltage and current. Proper wiring minimises energy losses, maximises the system's efficiency, and prevents potential electrical hazards.

Moreover, the wiring design incorporates a battery protect mechanism that plays a vital role in the system's overall functionality and longevity. This mechanism allows for remote control of the cooling units, providing flexibility and convenience. Additionally, it serves as an essential safeguard by limiting the battery bank's depth of discharge, protecting the batteries from being deeply discharged and therefore extending their lifespan. Correct wiring and protective measures are essential for maintaining the reliability and durability of the solar energy system, ensuring it operates smoothly and efficiently over time.

Figure 54. Primary system wiring of the power generation, storage and cooling components



The Maximum Power Point Tracking (MPPT) charge controller powers the cooling units and utilises excess solar PV power to charge the batteries. The battery bank of the primary system serves as a buffer for solar intermittency and ensures continuous operation of the cooling units during the night and on cloudy days.

The secondary system has solar PV panels and a battery bank that powers a pump to circulate cold water into the cold room via a fan coil. As the fan coil operates, cold air is generated, reducing the cold room temperature until a desired set point is reached. The primary system is significantly larger due to the need to power the cooling units, whereas the secondary system can be smaller due to its lower power demand.

The secondary system is designed to power all the auxiliary components essential for the overall functionality of the cooling system. These components include the remote monitoring and control box, pump and fan, and humidifier as shown in Figure 27. This secondary system ensures that the auxiliary components operate seamlessly, supporting the primary functions of the cooling units and PV panels. By integrating these components into the secondary system, the entire system achieves a balanced distribution of power, enhancing the efficiency and reliability.

The design allows all data to be processed by the monitoring and control system, ensuring precise management of the cold room environment. For instance, if the set temperature of the cold room is 10°C and the temperature rises to 11°C, the system automatically activates the pump and fan to circulate cold air and water, thereby lowering the temperature back to the desired level. Similarly, the system includes protective measures for the batteries; when low voltage is detected, a signal is sent to switch off the cooling units, preventing deep discharge and potential damage to the batteries. This automated control ensures optimal performance and longevity of the system components, maintaining a stable and efficient operation.

Figure 55. Secondary system wiring of the auxiliary components - overview

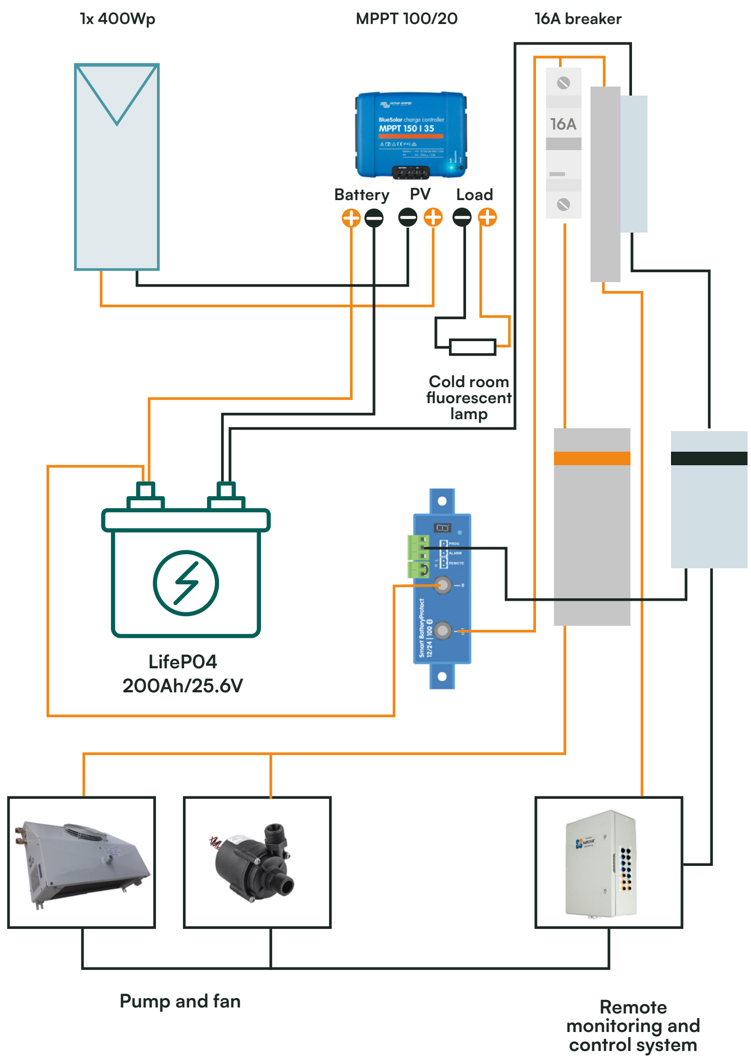
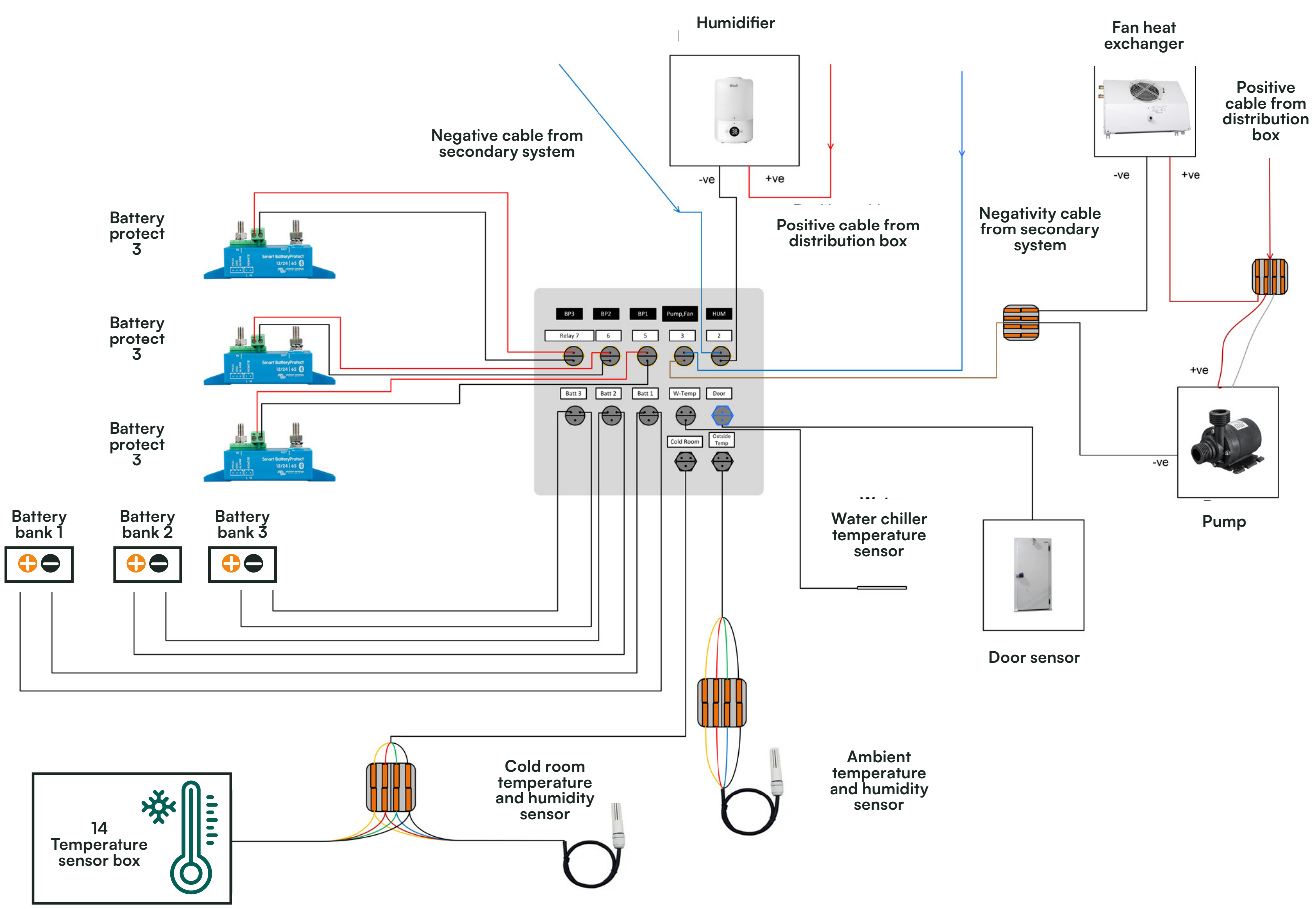


Figure 56. Secondary system wiring of the auxiliary components - sensors



2.2.7. REMOTE MONITORING

The remote monitoring and control system serves as an efficient and intelligent solution for managing the solar cooling system of the cold room. The selected system is designed to provide real-time monitoring, data acquisition, and control for various environmental parameters and equipment statuses.

The following sensors were included:

- One cold room temperature and humidity sensor
- One ambient temperature and humidity sensor
- One door sensor
- One thermal storage water temperature sensor
- One 16-fold temperature sensor array at various positions in the cold room and water circuit
- Three battery voltage sensors (positive and negative)
- One camera
- One water flow sensor

Figure 57. Remote monitoring and control system (SelfChill, Phaesun GmbH)

Figure 58. Remote monitoring sensors

The following relays were used for the system control:

- One pump negative wire
- One fan (heat exchanger) negative wire
- One humidifier negative wire
- Three anti-freezing controls for six cooling units
- One compressor speed control for six cooling units

The control algorithm manages the operations of the cold room and regulates thermal storage within the water chiller. Figure 59 on page 62 illustrates how the cold room's temperature and humidity are maintained within the desired range by controlling specific digital outputs connected to the pump, heat exchanger, and humidifier.

Thermal storage in the water chiller is managed by monitoring the state of charge of the battery bank and switching the cooling units on and off as needed as shown in Figure 59. This approach prevents excessive discharge of the batteries. The cooling units are controlled via relays. Additionally, an over-freezing protection system monitors the water temperature to limit the accumulation of excess ice around the evaporator plates.

Figure 59. Test results from the remote monitoring system for the main temperatures (ambient - outside, cold room - inside, and ice-water in the thermal storage), and the relative humidity inside the cold room

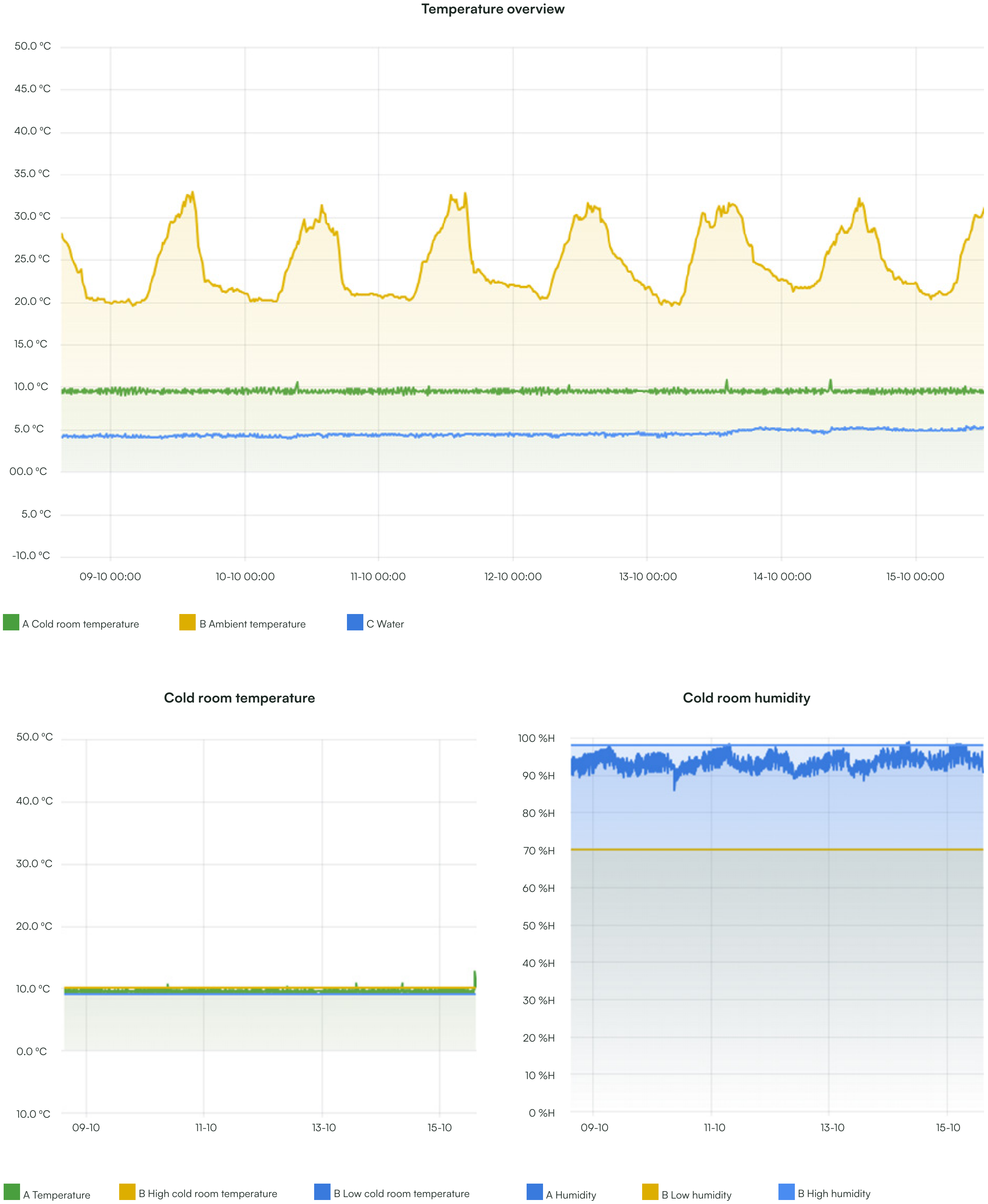
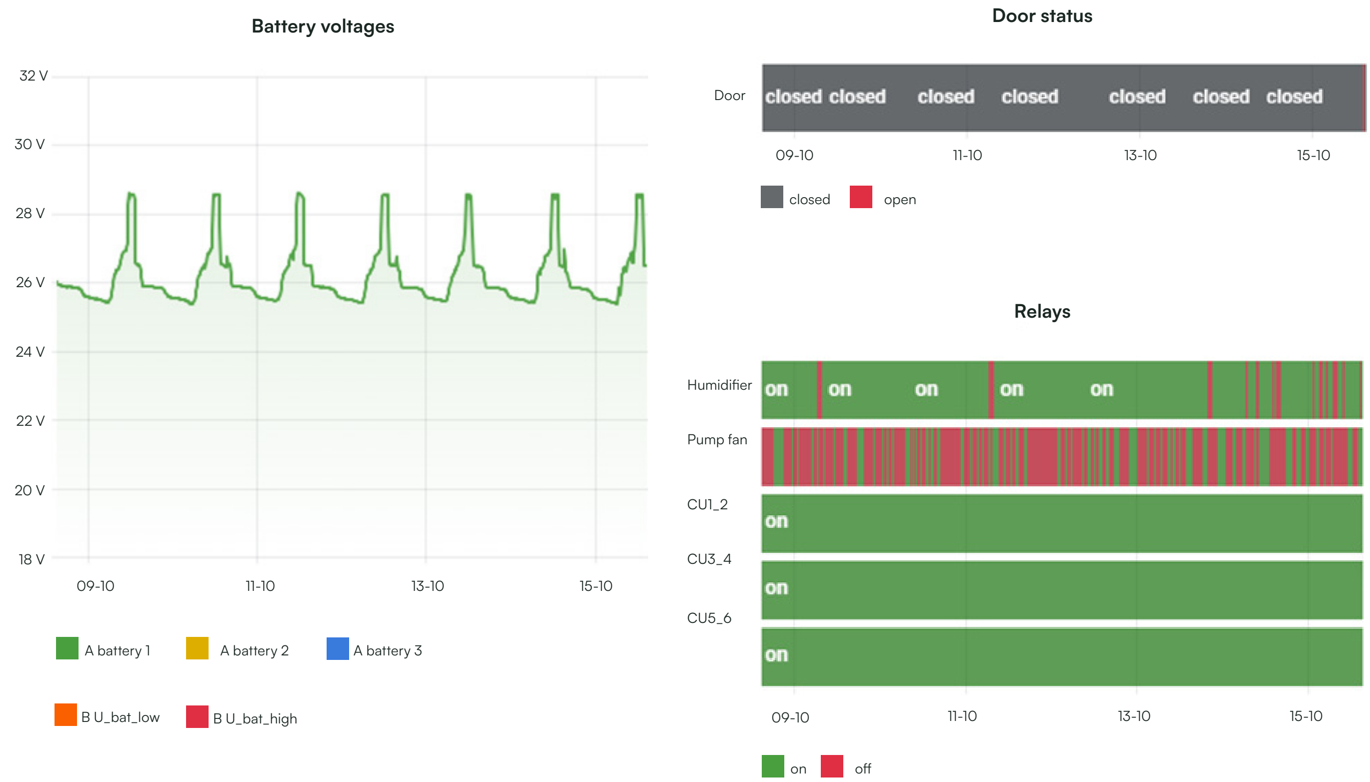


Figure 60. Test results from the remote monitoring system for the battery voltage, door status and relays



Construction of the low-carbon cold room. Homa Bay, Kenya.
Source: Humphrey Anjilla, 2024.

2.3. CONSTRUCTION AND COMMISSIONING

The construction of the cold room began in August 2024 and was completed within six weeks. Local construction workers and carpenters worked under the supervision of the Kenyan architects and WeTu who were all part of the lead design team. Their responsibilities included overseeing onsite construction, coordinating logistics, and addressing any challenges that arose during the process. This collaborative approach ensured the project remained on track and adhered to the original design intentions - *see construction photos in Figures 13-15*.

The straw bale insulation panels, a key feature of the low-carbon cold room design, were pre-assembled at the WeTu hub located close to the marketplace in Homa Bay. The pre-assembly work took approximately two weeks. These panels were then transported to the market site for installation using WeTu's small electric truck. This efficient method of pre-assembly and transport minimised disruption and allowed for a streamlined assembly process at the final deployment site.

Challenges encountered during construction included significant rainfall, which was mitigated by covering the worksite with tarpaulins. Additionally, adjustments had to be made to the wooden door to ensure that it fit the frame precisely. This was crucial to prevent heat loss while maintaining the door's functionality for regular use. Upon completion, testing of the cold room began immediately, with performance monitored through remote sensors.

Figure 61. Construction of the low-carbon cold room foundations and insulation walls

Figure 62. Assembly of the insulation walls and the solar PV panels and the water gutter on the roof

Figure 63. Installed low-carbon cold room (inside and outside) including the technical room with compressors and other electrical equipment

Source: Humphrey Anjilla, 2024.

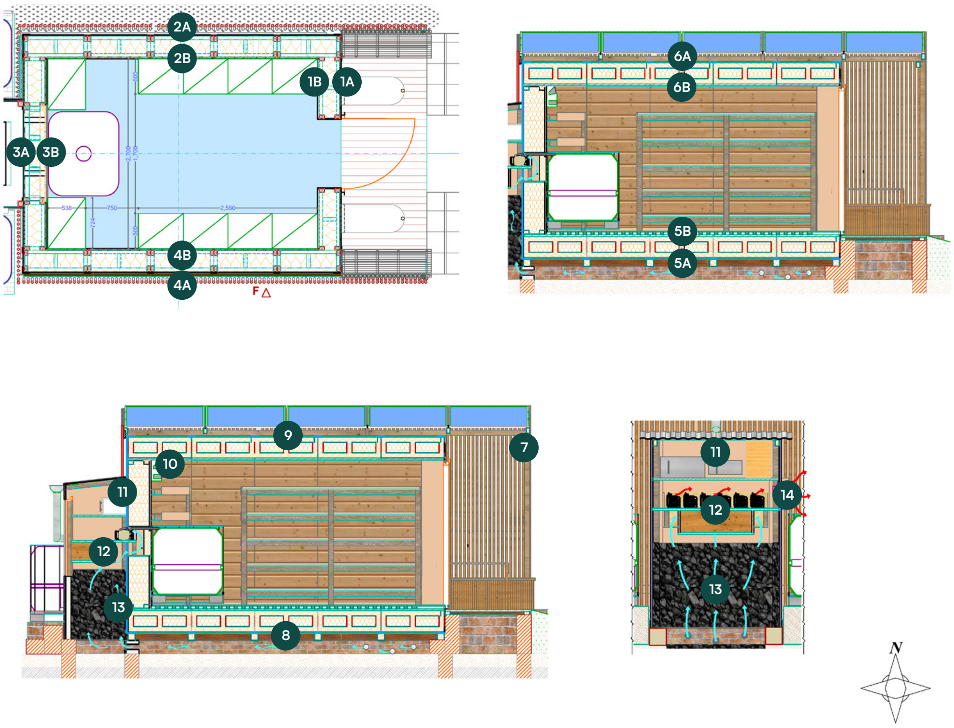
Figure 64. Final low-carbon cold room installation in the Homa Bay market, Western Kenya

2.3.1. TESTING

Sensors were strategically installed in various locations to monitor parameters deemed critical to the cold room's operations and durability. Inside the cold room, sensors tracked the temperature and relative humidity to ensure optimal conditions for preserving fresh produce. Additionally, sensors were embedded within the insulation wall elements to monitor moisture levels within the straw. This precaution was taken to prevent decay, which could occur if the moisture levels became excessively high, and compromise the structural integrity of the insulation.

In total, 14 sensors were installed to enable remote monitoring of these parameters. Their placement was carefully planned to provide comprehensive data on the cold room's performance and the condition of the insulation. The exact locations of the sensors are detailed in Figure 65.

Figure 65. Location of the remote monitoring sensors



Sensors inside pre-fabricated panels (12no.)

1a - East wall (outside) b) - East wall (inside)

2a - North wall (outside) b) - North wall (inside)

3a - West wall (outside) b) - West wall (inside)

4a - South wall (outside) b) - South wall (inside)

5a - Floor panel (outside) b) - Floor panel (inside)

6a - Ceiling panel (outside) b) - Ceiling panel (inside)

Sensors outside panels (8no.)

7 - infront @pergola

8 - Underneath floor panels

9 - Underneath PV panels

10 - @Air blower

11 - @Electronics

12 - @Batteries

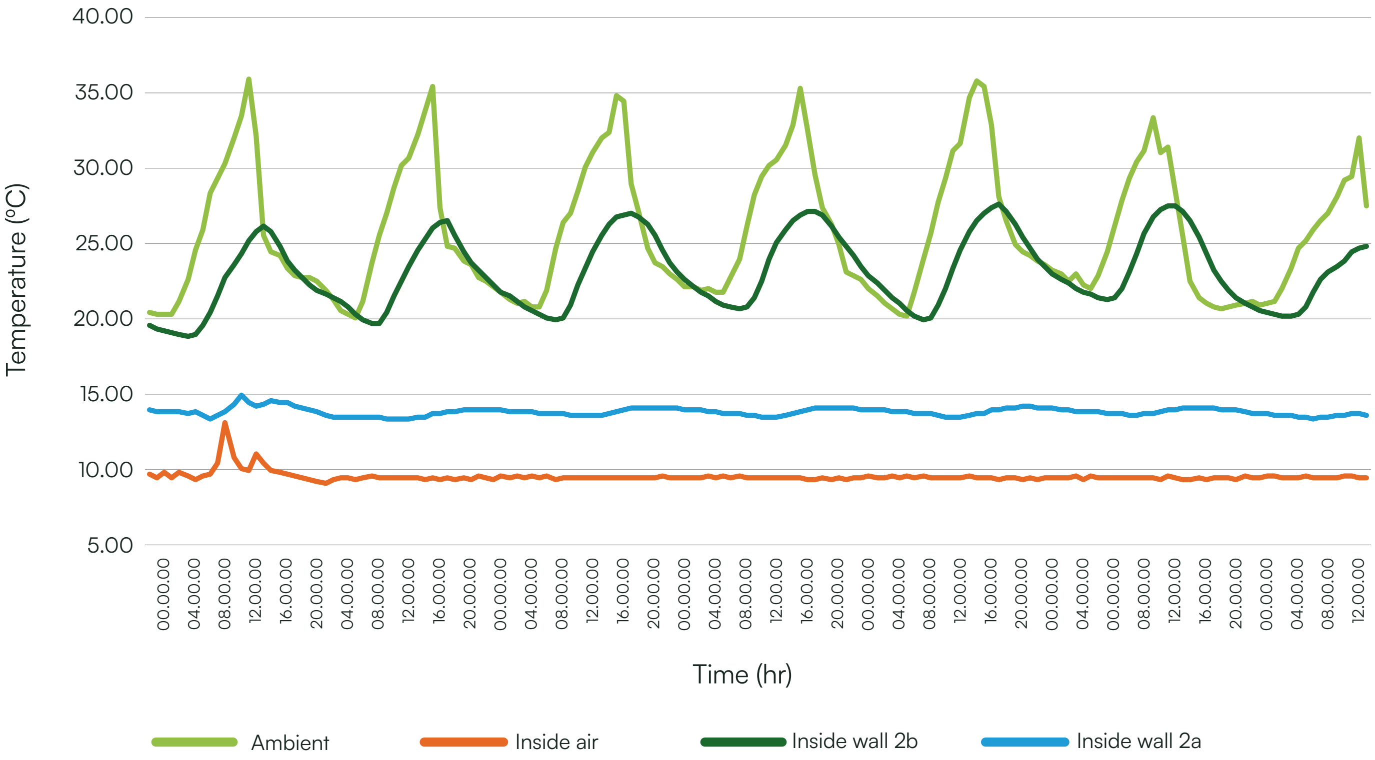
13 - @Charcoal cooler

14 - @Fan

The empty cold room was monitored for several weeks to evaluate the installation and humidity of the room's biogenic elements.

The biogenic elements have shown that they are able to provide enough insulation to keep the cold room temperature at 10°C while the ambient temperature fluctuates between 20°C and 35°C.

Figure 66. Temperature development in biogenic element 2 in comparison to the inside air of the cold room and ambient temperature (one-week monitoring period — 24 to 30 September 2024)

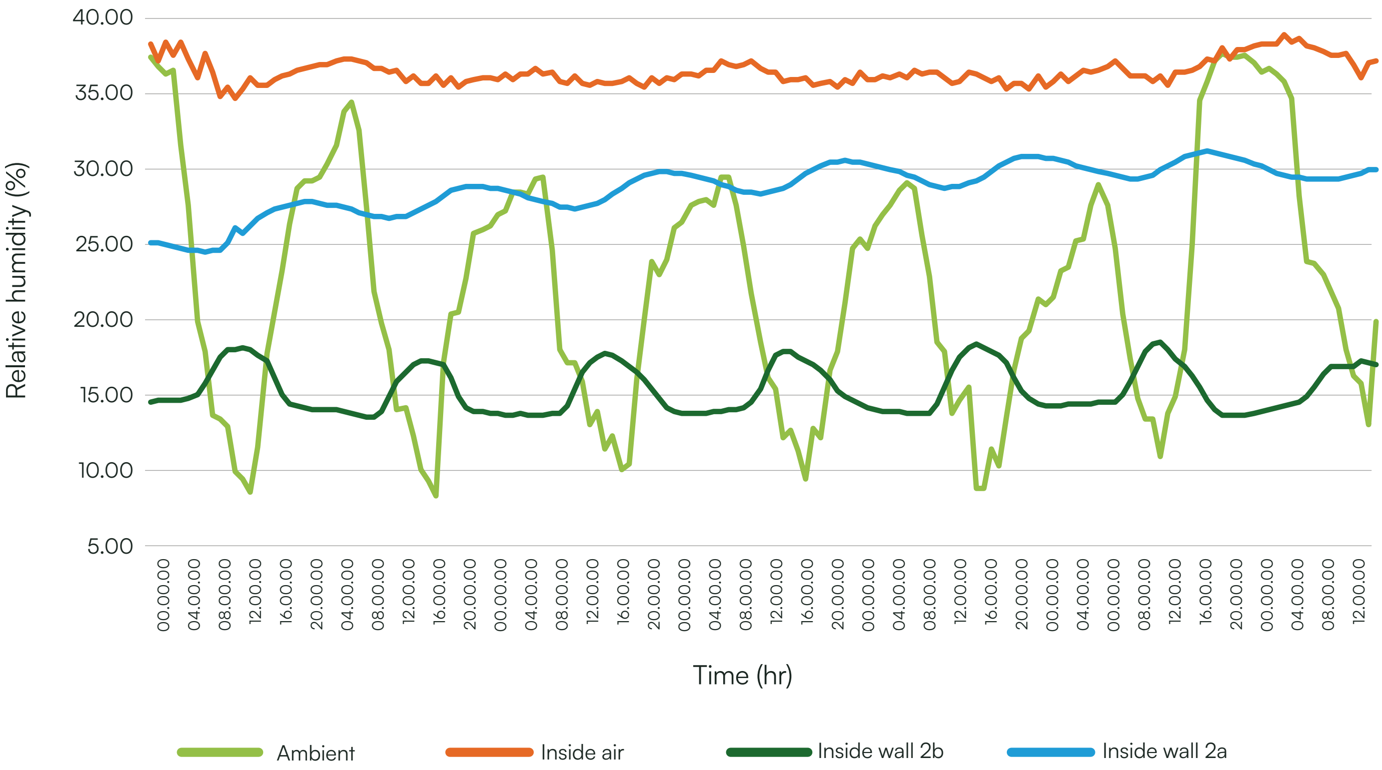


Based on the results, the average temperature difference between the ambient and the inside air was around 16°C. Based on the performance of the cooling system implemented, an average cooling power of around 310 W was provided to keep the empty room at the given set-point temperature of 10°C. Since the cold room has an internal insulating area of 47.8 m^2, the estimated thermal resistance (U) of the cold room is approximately 0.4 W/m^2 K which for the 0.3 m thickness of the biogenic elements, represents a **thermal conductivity (λ) of around 0.12 W/m·K,** slightly higher than the values determined during the mock-up testing, probably due to the lower insulation degree of the door and higher losses related to air infiltrations.

In terms of measurements taken to record the relative humidity of the biogenic elements, the maximum relative humidity (RH) of the air around straw to keep its moisture content at a safe level to prevent degradation is typically around 80% as discussed in *Section 2.1.4*. Below this RH, the straw remains stable and less susceptible to microbial growth (e.g. mould) as its moisture content remains below 15% (equilibrium moisture content).

Data from the first few weeks of operation show a maximum RH of around 80% in the layer of insulation closest to the inner wall of the cold room. The temperature in these layers is below 15°C. According to the literature, higher temperatures combined with high RH accelerate microbial activity, but both indicators appear to be below the thresholds recommended by experts to avoid degradation of the straw. A lower RH site or higher RH within the cold store would help to keep the moisture content of the straw lower, but the test was conducted to keep the RH of the cold store between 90% and 95%, which is the maximum required for agricultural produce. This, together with the fact that the ambient humidity at the location where the cold room is installed is high, makes the test successful even in a worst-case scenario for the use of the selected biogenic elements.

Figure 67. Relative humidity development in biogenic element 2 in comparison to the inside air of the cold room and ambient relative humidity (one-week monitoring period — 24—30 September 2024)



Initial observations have shown that there is a low risk of microorganisms proliferating inside the biogenic panels, but annual maintenance services will track the real deterioration rate of straw, especially in the layers close to the interior walls. Therefore, a treatment of the straw to avoid this phenomenon has not been necessary so far.

Construction of the insulation panels, Homa Bay, Kenya.
Source: Charles Ogalo, WeTu, 2024.

3. LIFE CYCLE ASSESSMENT

Construction of the sandwich panels, Homa Bay, Kenya.
Source: Charles Ogalo, WeTu, 2024.

3. LIFE CYCLE ASSESSMENT

Life Cycle Assessment (LCA) is a method to assess the environmental impacts of a product or process. The technique seeks to understand the resources and actions required over the entire life cycle of a product. This includes the materials, energy and manufacturing processes required, from raw material capture, through refinement and processing, product manufacture, packaging, storage, transport, distribution, use, maintenance or repair, and end-of-life treatment or disposal.

The potential for LCA to provide insight on environmental impacts and opportunities for improvement was demonstrated in previous work undertaken by Efficiency for Access[21]. On the present project, LCA was the key method of assessment used to determine the environmental impact of the proposed low-carbon cold room. Although LCA is useful as a standalone method, it is most beneficial when used as an iterative tool during the design process, and in combination with other assessment and development methods. This approach was achieved in this project, with design iterations undertaken following initial LCA results and the use of the method to select components.

21. Efficiency for Access. (2023). Life Cycle Greenhouse Gas Emissions Assessment of Off- and Weak-Grid Refrigeration Technologies. https://efficiencyforaccess.org/publications/lifecycle-greenhouse-gas-emissions-assessment-of-off-and-weak-grid-refrigeration-technologies/.

3.1. LIFE CYCLE ASSESSMENT METHODOLOGY

LCA encompasses a range of methods and techniques, but all should comprise four key steps:

1. **Goal and scope definition**
2. **Life cycle inventory**
3. **Life cycle impact assessment**
4. **Interpretation or improvement**

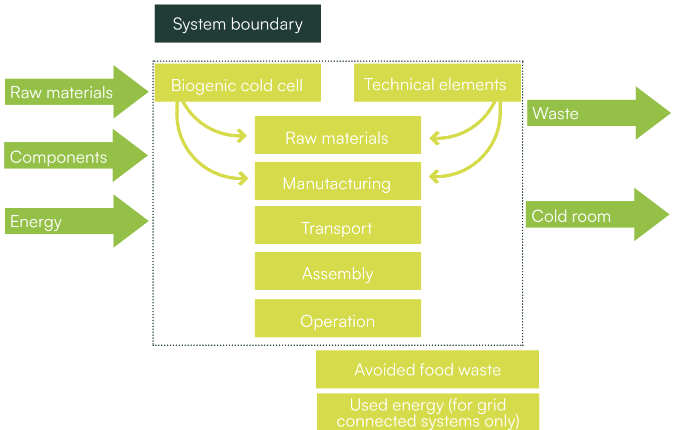
A range of standards also exist for LCA. This study was undertaken in accordance with ISO14040, though due to the necessary focus on greenhouse gas emissions not all impact category results are presented. The boundary of this assessment is shown in Figure 68. Sections included within the dashed boundary were included in the study, whereas those outside the dashed boundary were not. Arrows indicate flows into and out of the system boundary.

The operational phase of the cold room life cycle (shown in Figure 68 as "Operation") is the phase after construction. In this phase, electricity from the photovoltaic panels powers the cooling and auxiliary systems, and charges the batteries. These systems work to provide cooling and maintain a suitable temperature and relative humidity in the cold room.

The specific fresh produce stored in the cold room is not considered in this section. The presence of some produce which requires the cooling system to operate is implicit, but the fresh produce itself has not been considered in this LCA. Avoided food loss is discussed in *Section 4*. The cold room considered in this study is powered by photovoltaic panels. A comparison with grid electricity and diesel generation is also provided, in *Section 3.6*.

Goal and scope definition are key to an LCA study. The study goal defines the required outcome of the assessment, and the scope defines the boundary around the product to be assessed. A functional unit is also required to establish the unit to be assessed. In this case, the goal of the study is to assess the environmental impact of the raw material production and manufacture of a solar-powered cold room, and the functional unit is one cold room, with a capacity of 20m^3, maintained to a temperature of 10°C, over a lifetime of 20 years.

Figure 68. Life Cycle Assessment boundary diagram for cold room



The scope of this study is cradle-to-gate plus operation, meaning that the raw materials and components, manufacturing, assembly and installation, and the operation of the cold room over its lifetime are included. The subsequent end-of-life treatment of the materials and components are not included in the central LCA study due to the large number of potential options, but a separate assessment of potential end-of-life routes is given in *Section 3.5.5.*

The operational phase of the cold room has been included in this LCA but avoided food loss has not been included in the central LCA study. While the emissions avoided by the cold room's ability to prevent food losses through improved food preservation are expected to significantly outweigh the emissions generated during its life cycle stages, the goal of this study is to focus on the impact of the cold room itself, particularly the biogenic cold cell and the technical equipment.

The impact of avoided food loss has been calculated and is discussed in *Section 4*. End-of-life treatment is discussed in *Section 3.5.5*, and an assessment of the potential impact of these, as well as avoided emissions from grid and diesel electrical generation, are included in *Section 3.6*.

3.1.1. LIFE CYCLE INVENTORY AND LIFE CYCLE IMPACT ASSESSMENT

This study was undertaken using life cycle inventory data from several sources. For the photovoltaic panels and eco-boards, manufacturer environmental product declaration (EPD) data was used. For most other materials, data from the Ecoinvent 3.9.1 database was used. In some cases, for example battery refurbishment, estimates were made based on process descriptions which were modelled using the same database. GreenDelta OpenLCA software, the Allocation at Point of Substitution (APoS) and the ReCiPe 2016 impact assessment method were used. This method provides results across 18 impact categories presented in Table 6, though to present the most relevant results, in most cases only greenhouse gas emissions are presented in detail.

Table 6. Life cycle assessment impact categories (v1.03 midpoint hierarchical method)

Impact category name	Quantification method	Impact units
Acidification: terrestrial	Terrestrial acidification potential (TAP)	kg SO_2e
Climate change	Global warming potential (GWP100)	kg CO_2e
Ecotoxicity: freshwater	Freshwater ecotoxicity potential (FETP)	kg 1,4-DCB e
Ecotoxicity: marine	Marine ecotoxicity potential (METP)	kg 1,4-DCB e
Ecotoxicity: terrestrial	Terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB e
Energy resources: non-renewable	Fossil fuel potential (FFP)	kg oil e
Eutrophication: freshwater	Freshwater eutrophication potential (FEP)	kg P e
Eutrophication: marine	Marine eutrophication potential (MEP)	kg N e
Human toxicity: carcinogenic	Human toxicity potential (HTPc)	kg 1,4-DCB e
Human toxicity: non-carcinogenic	Human toxicity potential (HTPnc)	kg 1,4-DCB e
Ionising radiation	Ionising radiation potential (IRP)	kBq Co-60 e
Land use	Agricultural land occupation (LOP)	m^2a crop e
Material resources: metals/minerals	Surplus ore potential (SOP)	kg Cu e
Ozone depletion	Ozone depletion potential (ODPinfinite)	kg CFC-11 e
Particulate matter formation	Particulate matter formation potential (PMFP)	kg $PM_{2.5}$e
Photochemical oxidant formation: human health	Photochemical oxidant formation potential: humans (HOFP)	kg NO_xe
Photochemical oxidant formation: terrestrial ecosystems	Photochemical oxidant formation potential: ecosystems (EOFP)	kg NO_xe
Water use	Water consumption potential (WCP)	m^3

3.1.2. BIOGENIC STORAGE IN MATERIALS

The use of timber in the manufacture of the biogenic cold cell was a key element of the environmental design strategy for this cold room. For this reason, the treatment of biogenic materials, and particularly biogenic stored carbon, was an important part of the LCA.

Plants absorb carbon dioxide during photosynthetic growth, emit oxygen, and store carbon within their cells. When the plant is harvested, the carbon it has absorbed is trapped within the material. As a result, the raw material itself holds this stored carbon, which is referred to as biogenic carbon. This means that these materials have an inherent negative value for embodied carbon. However, to determine the net embodied carbon of a material, it is necessary to account for the greenhouse gas emissions produced during the processing of the plant into the final material. These emissions must be subtracted from the stored carbon to calculate the overall carbon impact. The treatment of these materials within Life Cycle Assessment must be considered carefully.

If the plant or timber were not harvested for use and instead left to die naturally, the carbon contained would be re-emitted to the atmosphere. If the materials were used instead of being allowed to die and re-emit this greenhouse gas, then this biogenic carbon emission would be avoided, and the biogenic carbon would be stored in the plant material. However, assuming that the material would itself eventually reach the end of its life and be disposed of, the biogenic carbon will then be released, and this storage could only be considered temporary. Since the unavoidable emission of the biogenic carbon is delayed, when considered over the cradle-to-gate scope, materials containing biogenic carbon can therefore have negative emissions. Simple illustrations of the uptake, storage and release of carbon over time in a natural case and a case where timber is used are shown in Figure 69 and Figure 70. These diagrams illustrate a compressed lifetime of plant material from left to right, and the dotted line gives an indication of the level of embodied carbon.

Figure 69. Timber emission life cycle — a natural case

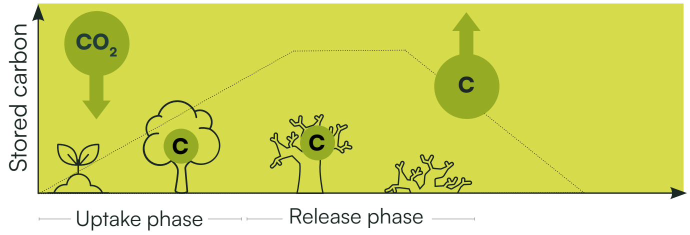
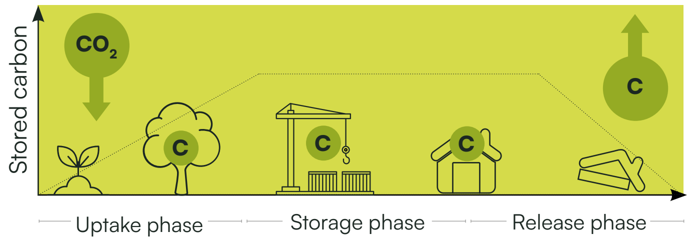


Figure 70. Timber emission life cycle — a case where timber is used



However, the direct emissions caused by harvesting, transporting, preparing and using the material must be considered, and a material can only have net negative emissions in use if these are lower than the biogenic carbon stored in the material. In simple terms, emissions of materials with biogenic storage over the cradle to gate and grave lifetimes can be summarised as:

CRADLE TO GATE EMISSIONS = DIRECT EMISSIONS - BIOGENIC STORAGE IN MATERIAL

CRADLE TO GRAVE EMISSIONS = DIRECT EMISSIONS - BIOGENIC STORAGE IN MATERIAL + RELEASE AT END-OF-LIFE

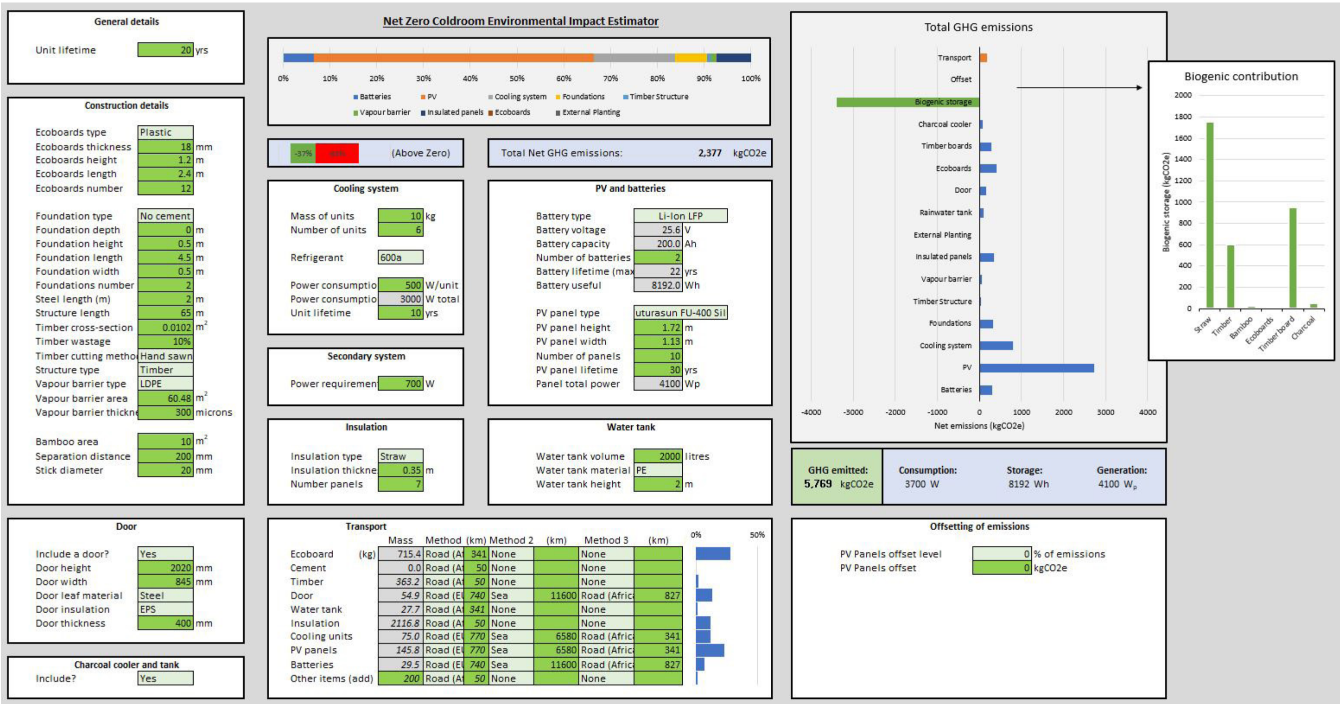
Where direct emissions are as defined above (harvesting, transporting, preparing and using the material), and release at end-of-life refers to the emissions from the chosen end-of-life treatment method, such as burning or landfill. The central LCA in this case was over the cradle to gate scope, with additional end-of-life consideration undertaken separately to allow a wider range of routes to be considered.

3.1.3. LIFE CYCLE CALCULATION TOOL

To enable the ongoing assessment of the environmental impact of the cold room during its design, an assessment tool was developed and used. This tool was created using a modular approach, effectively incorporating a series of smaller parallel assessments that could be selected and combined to provide the overall impact of the cold room. By modelling the impact of various alternative materials, options, or sizes for component parts of the cold room, this method allowed the tool to compare options and enabled the impact of design decisions to be understood in real time.

The input and output sections of the tool are illustrated in Figure 71. Light green boxes on the left indicate selectable menus (for example, material selection), dark green boxes are numerical input fields, and grey boxes are non-editable result fields. The use of the tool facilitated the easy comparison of options for many elements included in the cold room and was instrumental in understanding the contribution of each element to the total environmental impact.

Figure 71. Input and output sections of the LCA calculator tool



Construction of the roof, Homa Bay, Kenya.

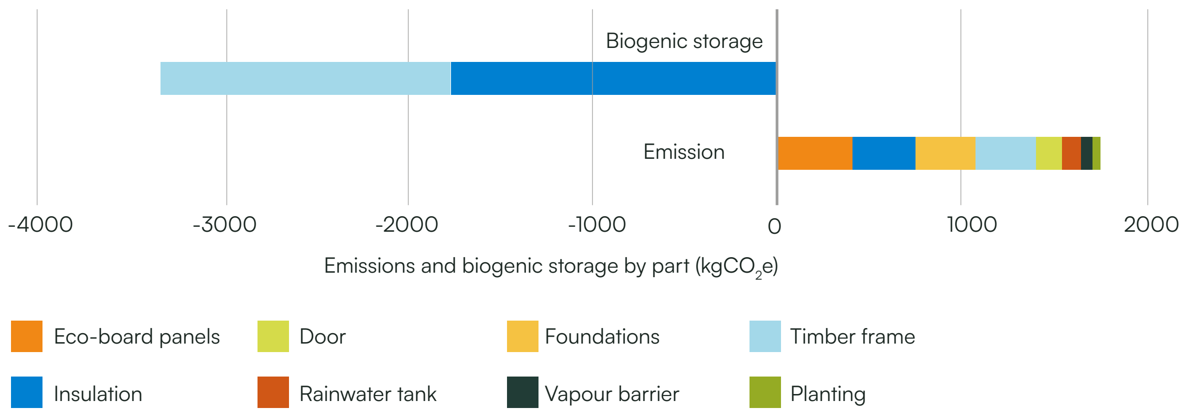
Source: Charles Ogalo, WeTu, 2024.

3.2 CONSTRUCTION ELEMENTS

Construction elements (the construction elements of the cold cell, shown in Figure 68 as “Biogenic cold cell”) include the foundations, structure and insulation of the biogenic cold cell. Raw materials were selected for performance and environmental benefit wherever possible. Three key material selections were made to minimise environmental impact: using eco-boards instead of new plastic or metal panels, straw bale insulation panels instead of expanded foam or similar materials, and timber for frame construction.

The total greenhouse gas emissions from the construction elements as designed (insulation, eco-board panels, timber frame construction, foundations including vapour barrier, door, rainwater tank and external planting) were calculated to be 1,722 kgCO_2e, with biogenic storage of 3,311 kgCO_2e over the defined functional unit as shown in Figure 71.

Figure 72. Total greenhouse gas emissions of the construction elements



3.2.1. INSULATION

Insulation is an important element in the construction of cold rooms, since sufficient insulation allows the cold room to maintain its temperature while lowering the cooling demand. Conventional cold rooms use insulation made from polymers such as expanded polystyrene (EPS). The cold room design proposed in this project used natural insulation instead of EPS, with the aim of minimising the environmental impact of the material choice. The natural material used in this project was straw bale as described in *Section 2.1.3*.

LCA modelling of straw was undertaken using a combination of primary and secondary data. Primary data was collected to measure the distance between the straw source and the location of the panel construction, and on the dimensions and mass of the straw bales. Secondary data was collected to consider the impact of the preparation of the straw bales. This data was taken from market process data from the Ecoinvent 3.9 database for straw production, including growth, harvest, transport and processing. Market process datasets represent the consumption mix of a product in each geography, connecting suppliers with consumers of the same product in the same geographical area. Markets group the producers and the imports of the product (if relevant) within the same geographical area. They also account for transport to the consumer and for the losses during that process, when relevant. Using market data reduces the effect of specific methods used by or impact caused by any one producer of a product. Each panel measured 2.4m x 2.4m and was 350mm in thickness. The straw required for each panel was calculated to have GHG emissions of around 34.5 $kgCO_2e$, and biogenic storage of straw was calculated at 129.95 $kgCO_2e/m^3$, excluding the timber frame in both cases. In total, the cold room insulation as designed has emissions of 336 $kgCO_2e$ and biogenic storage of 1,756 $kgCO_2e$.

3.2.2. ECO-BOARD PANELS

The name “eco-board” is given to several different unconnected construction materials. Most are composite boards made from waste or recycled material which has been shredded, compacted and glued to form a board. Some are timber-based, while others use plastic or general waste. In this case, as described in *Section 2.1.3*, the boards are a composite material made from a range of waste materials, primarily plastic as shown in Figure 8.

Eco-boards of 12mm thickness were used for this project. Environmental impact data for the product was taken from published Environmental Product Declaration and impact data published by the manufacturer. Both timber and plastic eco-boards were included in the LCA calculator tool to enable comparison, but plastic eco-boards were selected for the final design as described in *Section 2.1.3*.

Over a cradle-to-gate scope, timber eco-boards were found to have greenhouse gas emissions of -0.92 $kgCO_2e/kg$ of timber board including stored biogenic emissions and manufacturing emissions. Plastic eco-boards were calculated to have GHG emissions of 0.59 $kgCO_2e/kg$ based on the same cradle-to-gate scope. A total of 12 plastic eco-boards (each 18mm thick and 2.4m x 1.2m in area) were used in the cold room as designed, with total greenhouse gas emissions of 408 $kgCO_2e$ for the defined functional unit.

3.2.3. TIMBER FRAME CONSTRUCTION

Timber is used for a large part of the construction of the cold room. Various lengths and cross-sectional areas of timber are used in various parts of the cold room structure, with a total length of 65 metres of timber being required, and an average cross-sectional area of 0.01m^2. The resulting volume of timber was used to calculate biogenic storage, whereas the requirements for timber cutting and wastage (additional timber required as a raw material but not used, such as offcuts) were calculated based on actual timber lengths specified by the architects. Timber was assumed to have an average dry density of 500 kg/m^3, and an average embodied carbon value of 1.833 kgCO_2e/kg. Since CO_2 contains two oxygen molecules (molar mass 16) and one carbon molecule (molar mass 12), its molecular mass is 44. 44/12 = 3.66, meaning 3.66 kgCO_2e is equivalent to one kilogram of carbon. Dry timber is around 50% carbon, so 3.66 x 0.5 = 1.833 kgCO_2e/kg). As in other biogenic material cases, the required processing offsets a portion of this embodied carbon storage. Hand and power sawing options were included in the calculator tool. Hand-sawn timber was calculated to have an emissions burden of 43 kgCO_2e/m^3, and power-sawn timber 83 kgCO_2e/m^3. As designed, the timber elements had greenhouse gas emissions of 315 kgCO_2e and biogenic storage of 1555 kgCO_2e.

3.2.4. FOUNDATIONS

Natural stone foundations were used for the cold room. Various options were included in the calculator tool, including dimensions above and below ground, and the potential to include or exclude cement and steel elements. Quarrying of stone makes up most of the impact of the foundations if cement is not used. If cement is used, it accounts for most of the impact. Foundations in this case did not use cement. As designed, the foundations had greenhouse gas emissions of 316 kgCO_2e.

3.2.5. DOOR

The cold room door was included in the emission calculator tool, including the option to select construction materials and methods, insulation type, and dimensions. The final door used in this project was calculated to have greenhouse gas emissions of 161 kgCO_2e.

3.2.6. VAPOUR BARRIER

The vapour barrier used in the construction of the cold room was included in the emissions calculator. Low density polyethylene was included, with the thickness adjustable in the calculator tool. The 300-micron vapour barrier as designed had greenhouse gas emissions of 55 kgCO_2e.

3.2.7. WATER TANK

The environmental impact of the water storage tank was calculated based on a blow moulded polypropylene tank. The LCA tool includes a calculator which converts the entered tank volume into a material mass, and allows selection of polypropylene, polyethylene, or polyvinyl chloride material. Based on a 2000-litre polypropylene tank and resulting 24.9 kg mass, the greenhouse gas emissions of the water tank were calculated to be 102 kgCO_2e.

3.2.8. EXTERNAL PLANTING

The final aspect calculated in this section was the external bamboo planting. The planting as designed, based on the average embodied carbon as described in section 3.5.3, was found to have emissions of 0.08 kgCO_2e and biogenic storage of 29.1 kgCO_2e.

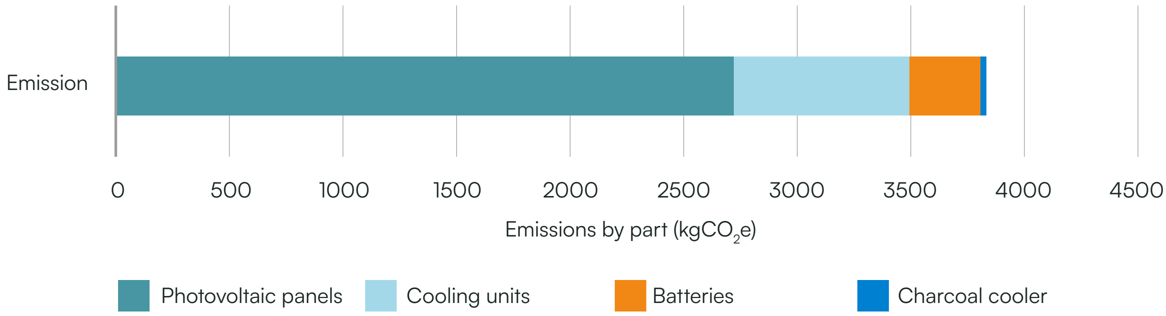
Construction of the low-carbon cold room's foundations, Homa Bay, Kenya.
Source: Charles Ogalo, WeTu, 2024.

3.3 TECHNICAL ELEMENTS

Technical elements of the cold room include the photovoltaic panels, batteries, cooling units, and the charcoal cooler and water tank. Though not technical, the external planting is also included as part of this section. The sections below summarise the data sources and LCA of key technical elements of the cold room.

The total greenhouse gas emissions from the technical elements as designed (photovoltaic panels, batteries, cooling units, charcoal cooler) were calculated to be 3,929 $kgCO_2e$, with biogenic storage of 80 $kgCO_2e$.

Figure 73. Greenhouse gas emissions from the technical elements



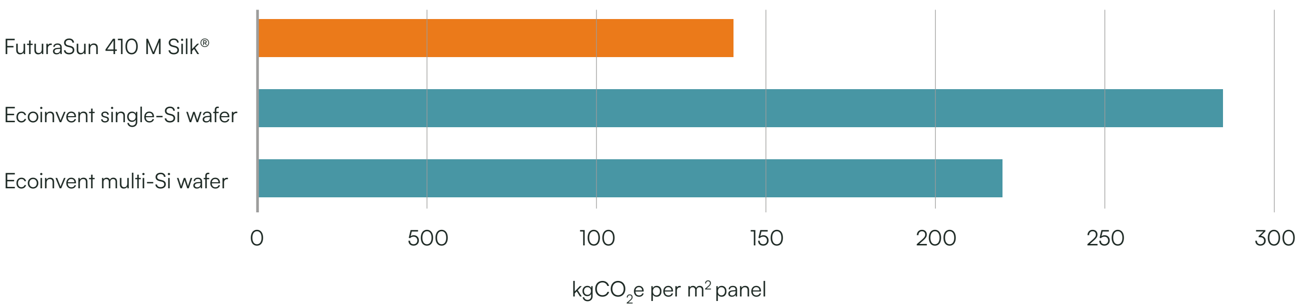
3.3.1. PHOTOVOLTAIC PANELS

Embedded GHG emissions in the manufacture of solar PV panels primarily arise from the various stages of the production process. These emissions include those from the extraction and processing of raw materials, such as silicon, which requires significant energy to purify. The production of the silicon wafers, cells, and modules involves high-temperature processes and the use of electricity, often sourced from fossil fuels. Additionally, transportation of materials and components between different manufacturing locations, and the assembly of the final product, all contribute to the carbon footprint of the panels. The aim of the project was to select solar PV panels with lower GHG emissions.

The solar PV panels selected for this project are FuturaSun 410 M Silk® Plus Carbon Neutral, manufactured by the Italian company , FuraSun srl, in Taizhou, China. The Environmental Product Declaration (EPD) for these panels provides a detailed account of their environmental impact, including the greenhouse gas emissions associated with their production. According to the EPD, the panels have emissions of 140.74 $kgCO_2e/m^2$, which was determined as reasonable when compared to data from the Ecoinvent 3.9.1 database, which is based on sector averages and panel types as shown in Figure 74.

The FuturaSun panels are marketed as "carbon neutral", which is achieved through a carbon offset scheme by removing the equivalent CO_2e emissions elsewhere. This offsetting has not been included in the emissions calculation for the cold room, with the actual embedded emissions being used instead. The total greenhouse gas emissions for the 10 panels in the final cold room design are 2,735 $kgCO_2e$.

Figure 74. Comparison of FuturaSun FU-400 panel with standard values from Ecoinvent database



Purchasing refurbished solar PV panels was not considered in detail. There are likely to be many end-of-life panels in Kenya, but the industry required to collect, refurbish and resell with necessary warranties does not currently exist at scale. However, the use of remanufactured or refurbished panels would have the potential to significantly reduce the environmental impact of this element of the cold room once the refurbished market is more mature.

3.3.2. BATTERIES

Energy storage is a crucial component of a reliable off-grid cooling system, as it ensures a consistent and dependable supply of electricity when generation from solar panels is insufficient or unavailable. This can occur during periods of low sunlight or at night, necessitating the need for stored energy to maintain uninterrupted power. This project included both, electrical and thermal storage.

Electrical storage was provided by batteries, and a comprehensive comparison of various battery chemistries was conducted using LCA. The comparison included six different types of batteries, categorised into two main groups: lead acid batteries and lithium-ion batteries. Lead acid batteries, which have been widely used for many years, are generally less expensive but have shorter lifetimes and lower power delivery capabilities. In contrast, lithium-ion batteries, commonly abbreviated as Li-Ion, require higher upfront cost but offer superior performance in terms of power delivery and longevity.

Lead acid batteries and lithium-ion batteries have fundamentally different chemistries, leading to their distinct characteristics and suitability for different applications. Lead acid batteries are often chosen for their cost-effectiveness and reliability in less demanding applications, despite their shorter lifespan. On the other hand, lithium-ion batteries, though more expensive, provide significant advantages in terms of energy density, efficiency, and cycle life. These attributes make them particularly suitable for applications requiring high power delivery and longevity, as highlighted in Table 6. The choice between these battery types depends on the specific requirements of the off-grid system, including budget constraints, performance needs, and long-term sustainability goals.

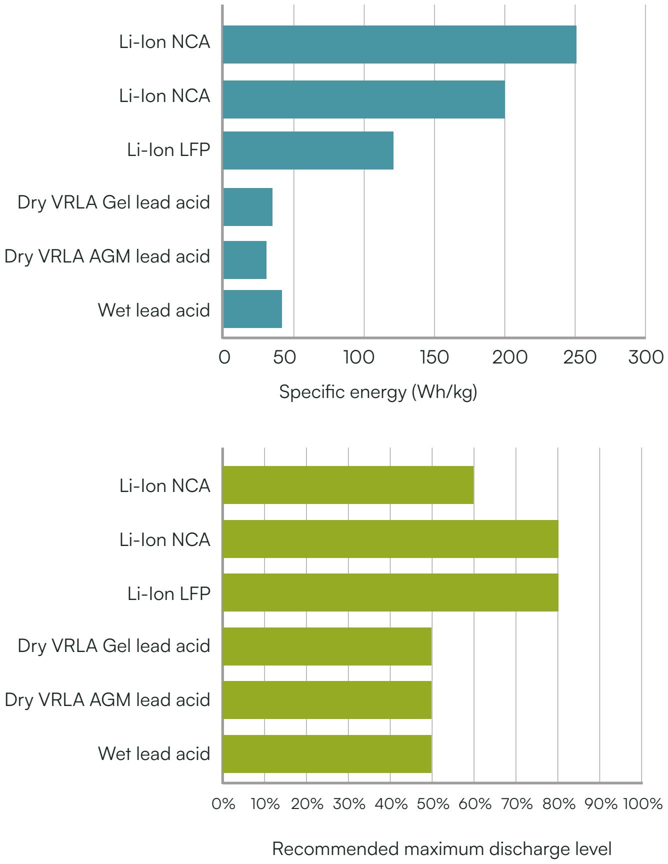
Table 7. Main battery types and their key characteristics. Sources: Manufacturer datasheets, Battery University[22], Ecoinvent 3.9 database data, and primary market research.

<table>
<tr><th>Chemistry type</th><th>Type</th><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>Wet lead acid</td><td>Conventional lead acid “car battery”</td><td>Low cost</td><td>Spill potential and low energy density</td></tr>
<tr><td>Dry valve-regulated lead-acid AGM lead acid</td><td>Lead acid type using AGM (absorbed glass mat) structure to contain liquid</td><td rowspan="2">Lower cost than Li-Ion
Lower risk of spillage than wet lead acid</td><td rowspan="2">Higher cost than wet lead acid</td></tr>
<tr><td>Dry valve-regulated lead-acid gel lead acid</td><td>Lead acid type using gel instead of liquid</td></tr>
<tr><td>Li-Ion LFP</td><td>Lithium-Ion type: lithium iron phosphate chemistry</td><td>Good energy density
100% discharge is possible
Safest Li-Ion chemistry</td><td>Higher cost than NCA</td></tr>
<tr><td>Li-Ion NMC</td><td>Lithium-Ion type: lithium nickel manganese cobalt oxide chemistry</td><td>Good energy density
100% discharge is possible</td><td>More expensive than LFP with similar characteristics and slightly less safe</td></tr>
<tr><td>Li-Ion NCA</td><td>Lithium-Ion type: lithium nickel cobalt aluminum oxide chemistry</td><td>Lowest cost Li-Ion type</td><td>Limited energy density (max 60% discharge)</td></tr>
</table>

22 Battery University. 2024. BU-205: Types of Lithium-ion. https://batteryuniversity.com/article/bu-205-types-of-lithium-ion.

A comparison of these battery types in two key measures (specific energy and maximum discharge level) is shown in Figure 75. The combination of these measures gives the total usable energy per kilogram for each battery type, which was a key factor in the decision-making process. Maximum discharge level refers to the amount of total stored energy which can be removed from the battery before recharge, without causing damage.

Figure 75. Battery type comparison in two key measures. Data from manufacturer datasheets, Battery University, Ecoinvent 3.9 database data, and primary market research.



Using these measures, environmental impact of each battery type was calculated in terms of impact per kWh of usable stored energy (allowing a fair comparison between batteries with different storage capacity and different allowable discharge levels). Using this method, Li-Ion LFP batteries were found to achieve the lowest environmental impact of all types considered, across every impact category described in this section. Li-Ion LFP batteries were calculated to have embedded emissions of 0.04 kgCO_2e/kWh, 16 times higher than wet lead acid batteries with around 0.65 kgCO_2e/kWh. All battery types were included in the calculator tool to allow comparison, but the tool also allowed other factors like cost and availability to be considered.

The final calculated emissions for the battery system planned for the cold room were 298 kgCO_2e, based on two Li-Ion LFP batteries.

REFURBISHED BATTERIES

Refurbished batteries were also considered as an alternative to new batteries. Refurbished battery LCA was undertaken based on the assumption that a refurbished battery would contain some of the impact of a new battery, plus a refurbishment impact. The former is potentially contentious, since it could be argued that the refurbished battery is based on a waste product and should not include any impact of the original battery. However, we chose to include partial impact of the original battery since the refurbished battery benefits from the raw materials and processes undertaken in the manufacture of the original battery and should therefore share the burden of the environmental impact of these.

After discussion with battery refurbishers and academic experts, it was understood that refurbishment of Li-Ion batteries commonly involves the addition of a new cell. Li-Ion batteries are made up of four cells with a nominal voltage of 3.2 V each at the start of their life, giving a battery voltage of 12.8 V. After degradation, these voltages may fall to 2.7 V, giving a total battery voltage of 10.4 V, which is insufficient. The refurbishment process involves opening the battery, testing and cleaning the existing degraded cells and adding a further fifth cell, to give a total voltage of around 13.1 V, meaning the battery can be used again. This process was represented in the LCA model using existing processes for dismantling electronic equipment, scaled to a 12 kg battery, and the addition of a small amount (0.5 kg) of Battery Management System (BMS) electronics. Though an approximation, this process is believed to give a reasonable representation of the environmental impact of battery refurbishment.

Refurbished batteries do not have the same lifetime as new batteries but offer a lower cost alternative. Refurbished batteries were found to have a cost of around USD 0.21 $/kWh over their lifetime, compared to USD 0.29 $/kWh for new batteries, but slightly higher emissions of 0.07 kgCO_2e/kWh compared to the 0.04 kgCO_2e/kWh of new batteries. The higher emissions of refurbished batteries are largely related to the short lifetime of the refurbished batteries. Consequently, the decision was taken to use new batteries in this project not only because of the LCA results but also due to the lack of suppliers of refurbished Li-Ion batteries in Kenya.

3.3.3. COOLING SYSTEM

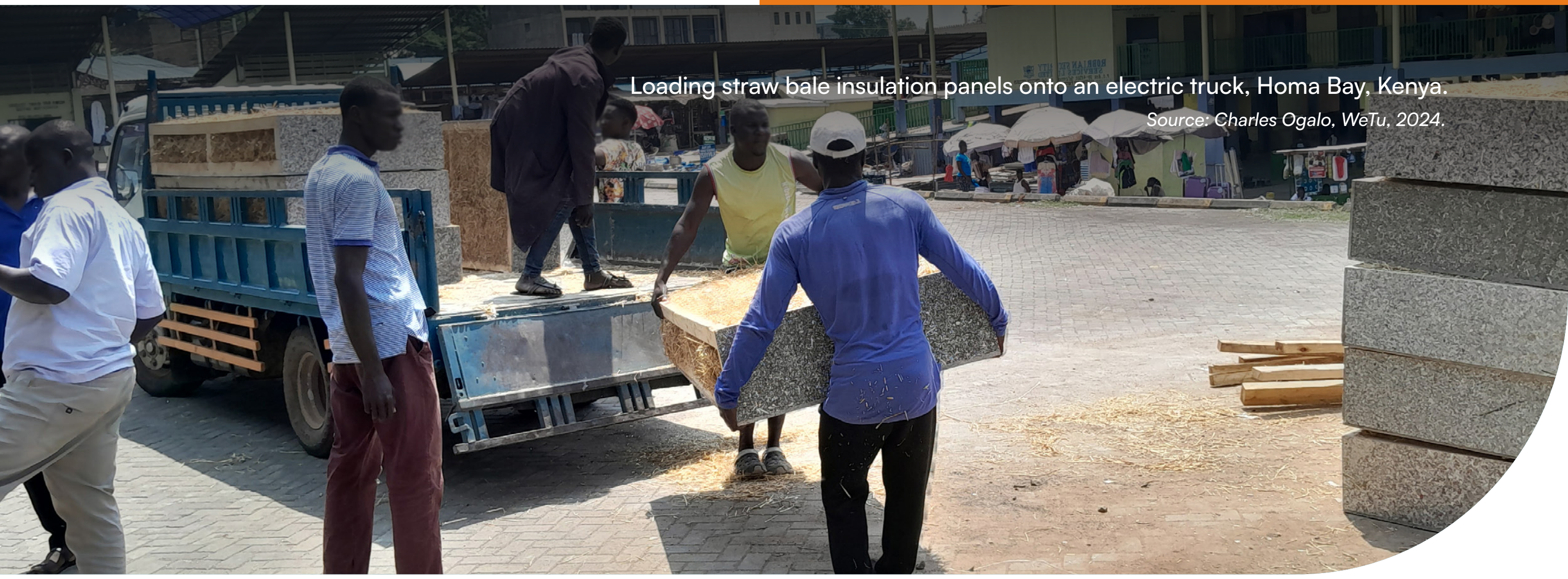
The SelfChill solar cooling units used in this project *(Section 2.2.1)* comprise a vapour compression refrigeration system with an evaporator plate that can be placed in water. In the LCA model, each cooling unit was composed of a series of parts, materials, and processes representative of those required to manufacture a cooling unit: an air compressor, an electric fan, primary copper, primary aluminium, metalworking for copper, rolling for aluminium, and metalworking for aluminium. Refrigerant was also included, with R600a (natural refrigerant isobutane) and R134a (Tetrafluoroethane) available in the calculator tool. The climate friendly refrigerant R600a (natural refrigerant isobutane) was used in the final design due to its lower Global Warming Potential in comparison to R134a and other refrigerants - see the Efficiency for Access report[23] focused on performance and environmental impact of refrigerants used within the off-grid solar refrigeration sector.

The total environmental impact of one cooling unit using R600a was 65.7 $kgCO_2e$ per cooling unit, based on a mass of around 10 kg and a lifetime of 10 years. When the cold room was set to have a lifetime of over 10 years, the tool automatically calculated the impact of new cooling units every 10 years. This section includes the entire cooling system and relevant pipework and ancillaries. The total greenhouse gas emissions of the cooling units over the design lifetime of the cold room were 789 $kgCO_2e$.

3.3.4. CHARCOAL COOLER AND WATER TANK

The charcoal cooler was represented in the LCA model as a container manufactured from timber and steel mesh, the charcoal itself, and the plastic material and manufacturing process required to manufacture the intermediate bulk container (IBC) water container.
The charcoal container was represented by timber (calculated volume of 0.01 m^3), with 1.71 kg steel drawn into wire to represent the mesh. 24 kg of charcoal was used, based on averaged global data from the Ecoinvent 3.9 database, based on European background data.
The total emissions of the manufacture of the charcoal, cooler unit, and IBC container were calculated to be 78 $kgCO_2e$. The biogenic carbon stored in the charcoal (based on timber and charcoal production values) was calculated to be equivalent to 51 $kgCO_2e$, giving net emissions of the charcoal cooler of 27 $kgCO_2e$.

23 Battery University. 2024. BU-205: Types of Lithium-ion. https://batteryuniversity.com/article/bu-205-types-of-lithium-ion.



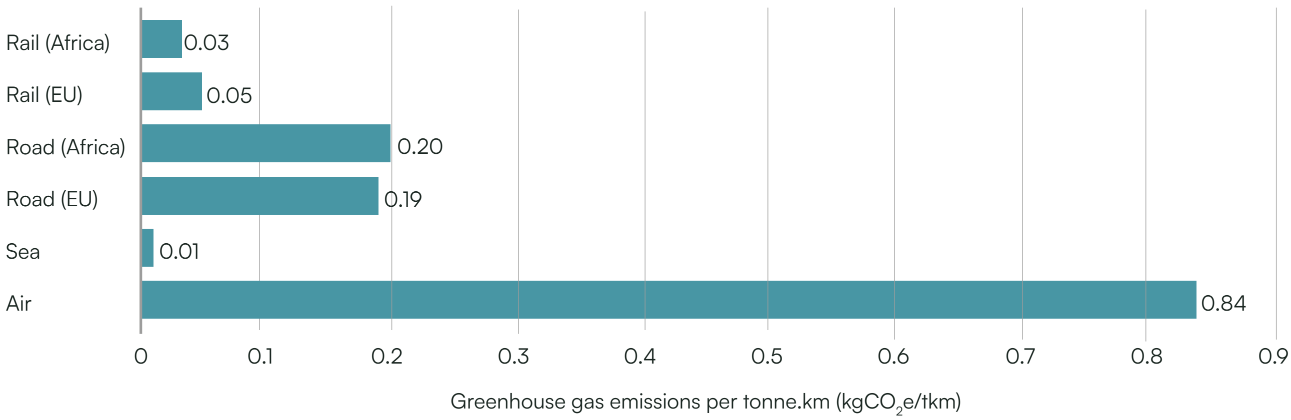
Loading straw bale insulation panels onto an electric truck, Homa Bay, Kenya.
Source: Charles Ogalo, WeTu, 2024.

3.4. TRANSPORT AND MANUFACTURING

The LCA calculator tool includes a range of transport options, allowing the relevant transport type and distance for each part to be selected. Transport by road, rail, sea and air are included. Road and rail transport within the European Union (EU) and Africa use separate emission values due to the differences in vehicle types and power sources.

All transport data are averages from the Ecoinvent 3.9 database. Transport emission values in $kgCO_2e/tkm$ (i.e. the emissions of transporting one tonne (1000 kg) of mass one kilometre in distance) are summarised in Figure 76. The figure illustrates the significance of air transport in relation to other modes of transport. To minimise the cold room's emissions, air travel was avoided wherever possible.

Figure 76. Transport emissions per tonne-km for various modes of transport



MANUFACTURING EMISSIONS IN THE CONTEXT OF THE LOW-CARBON COLD ROOM REFER TO THE EMISSIONS ARISING FROM THE ACT OF ASSEMBLING THE COLD ROOM FROM THE MATERIALS AND PRODUCTS DESCRIBED ABOVE.

For example, the manufacture of cooling units is included in the emissions, but the act of installing the units in the cold room is not. The same applies to solar PV panels and other components. Many of the manufacturing processes for the cold room were designed to have minimal impact and will be undertaken without the use of power tools.

The calculation tool includes options to select either power sawing or hand sawing, with power sawing emissions based on a two-stroke petrol power saw of around 3.1 kW power rating. Although hand tools could have a very small proportion of their manufacturing emissions attributed to each use over the lifetime of the tool, these emissions have been excluded in this case as they are assumed to be negligible in comparison to other emission sources.

23 Battery University. 2024. BU-205: Types of Lithium-ion. https://batteryuniversity.com/article/bu-205-types-of-lithium-ion.

Kevin Asika, WeTu, holding leafy greens in front of the low-carbon cold room

Source: Charles Ogalo, WeTu, 2024

3.5 LIFE CYCLE ASSESSMENT RESULTS

Environmental impact results were calculated throughout the project using the calculator tool, which allowed design features to be optimised for minimal greenhouse gas emissions. Other impacts were calculated once the final design was completed.

3.5.1. OPTIMISATION OF EMISSIONS

An initial investigation into the likely environmental impact of the low-carbon cold room revealed the significance of emissions from technical elements, particularly solar PV panels, batteries, and cooling units, which contribute 273 $kgCO_2e$, 148 $kgCO_2e$, and 66 $kgCO_2e$ respectively per element. With 10 solar PV panels, two battery packs, and six cooling units, these three elements account for 59% of the total gross GHG emissions of the cold room, with PV panels contributing the most.

Due to the substantial emissions related to these elements, it was calculated that it would be unlikely to offset these emissions sufficiently using biogenic materials without arbitrarily adding additional timber or similar materials. Keeping economic viability and commercial scalability in mind, and not opting for the emissions reduction through offsetting claimed by the solar PV panel manufacturer, a decision was made to minimise emissions as far as possible whilst maintaining the best practical design.

As a result, this design decision meant that the project did not achieve its original goal of creating a 'net-zero' cold room. However, by focusing on minimising emissions rather than relying on offsets or unnecessary biogenic materials, the project provides a more economic and scalable model to be rolled out across other off- and weak-grid areas where access to reliable cooling solutions is limited or non-existent.

The Life Cycle Calculation tool *(Section 3.1.4)* was used for further design selection and optimisation, particularly selecting foundation materials, and highlighting the importance of minimising air transport wherever possible.

3.5.2. FINAL RESULTS

Results for the proposed design of the cold room are shown in the following section.

TOTAL GROSS EMISSIONS (WITHOUT BIOGENIC STORAGE): 5,769 $KGCO_2E$

TOTAL BIOGENIC STORAGE IN BIOGENIC MATERIALS: 3,392 $KGCO_2E$

NET EMISSIONS: 2,377 $KGCO_2E$

Results per element and results for further impact categories are illustrated in the following figures. Final greenhouse gas emission results are shown in Figure 77 below. These illustrate the emissions (blue bars) and biogenic storage (green bars) of each part of the cold room. Summing these gives the total gross emissions, total biogenic storage, and net emissions of the cold room.

Figure 77. Final greenhouse gas emissions

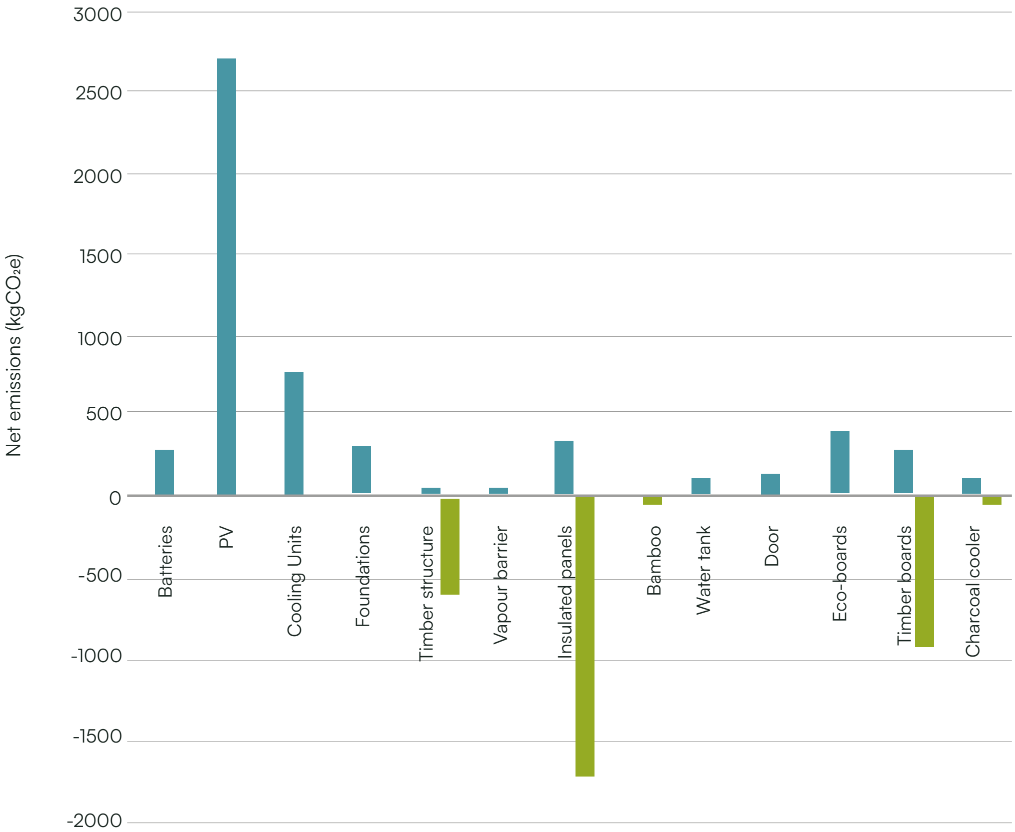


Figure 78 illustrates three additional environmental impact categories, showing the elements of the design which contribute the most to the total in each case. The key impact categories illustrated are land use, water use, and human toxicity. These indicators are related to the materials and manufacture of the cold room rather than its operation, so for example high water use does not mean the cold room will have significant water use during operation, instead that some elements (the PV panels in this case) use high levels of water in their manufacture.

Figure 78. Key additional environmental impacts per element: Land use (top), water consumption (middle), human toxicity (bottom).

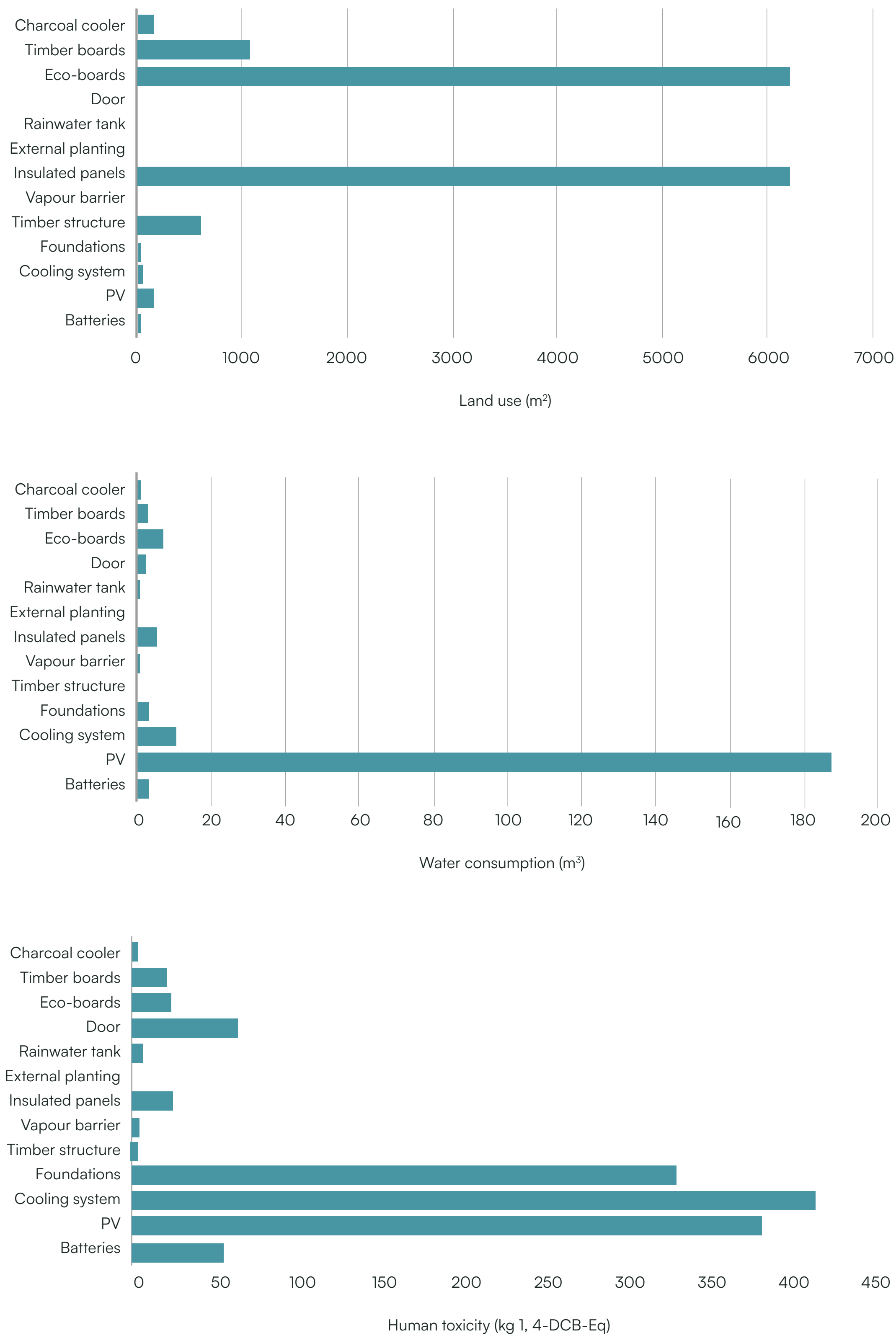


Figure 78 shows that the straw insulated panels are the largest contributor to land use. This is expected because growing the necessary material is required. However, it is important to consider that cultivating the product that produces straw can also offer additional benefits, such as enhancing soil health. If realised, these secondary benefits would be partially attributable to the straw, and partially to the grain which is also grown as part of the same plant, but they have not been considered in this study. The solar PV panels are the most significant contributor to the water use, and a significant contributor to the human toxicity indicator. This is partly due to the large number of solar panels used, meaning that they make up a large proportion of the total volume of products used in the cold room, but also due to their high specific impacts. Solar PV panels use high levels of water due to their manufacturing process, particularly the cleaning and processing of semiconductor materials. The use of water in PV panel manufacturing is small compared to other sources of electricity generation. It is important to reiterate that photovoltaic electricity generation has a much lower environmental impact than almost any other source of electricity generation.

Human toxicity indicators, as shown in the third panel of Figure 78, give a useful indication of potential sources of relatively high human health risk, but since such risks are very situation-specific, this assessment is only indicative. Though none of the numbers in this case are high, the relatively high impacts in the foundations, cooling system and photovoltaic panels are related to the use of certain materials and processes in their manufacture. In the foundations, quarrying produces dust and particulates, and in the cooling system and PV, the manufacture of electronics and components produce small amounts of potentially harmful emissions.

As in the land use case, whilst relative emissions are high, the actual emissions in these cases are low in comparison to other sources of power generation, and comparable to results for many other common pieces of equipment.

This analysis highlights the areas where the design has the greatest proportional environmental impact and can be used to inform decisions on where to focus efforts for future improvements and optimisations. By understanding these relative impacts, strategies can be developed to mitigate the most significant sources of environmental burden, enhancing the sustainability of the project.

Pre-assembly of the insulation panels, Homa Bay, 2024.

Source: StoryPro. 2024

Leafy greens stored in the low-carbon cold room, Homa Bay, Kenya.
Source: Charles Ogalo, WeTu, 2024

3.6 SENSITIVITY ANALYSIS

This section contextualises the LCA results to evaluate how different scenarios, assumptions, and data quality influence the overall outcomes. This analysis helps identify key drivers of impact and areas where further data refinement could enhance the accuracy and robustness of the assessment.

3.6.1. IMPACT OF SUSTAINABLE DESIGN DECISIONS

To understand the potential impact of the biogenic cold room[24] when used as an alternative to conventional cold room designs, an attempt was made to quantify the emissions of a series of conventional cold room designs alongside the biogenic cold room, using the same method and assumptions to enable a direct comparison. Using previously published work on cold room Life Cycle Assessment[25] , two additional cold room systems were modelled: one based on the previous SelfChill design, and one based on a commonly-used conventional system. These were respectively designated as “conventional SelfChill cold room, Mbita” and “conventional”. A further design was also modelled, based on a hypothetical but feasible design, which was developed with little consideration for the environmental impact of the cold room. This was designated “Unsustainable choices”, since the design choices made have higher environmental impact and potentially lower CAPEX but achieve the same cooling performance.

The three designs (conventional SelfChill, conventional, unsustainable choices) were modelled approximately rather than in full detail and were compared to the Biogenic cold room considered in this study using the LCA tool developed and discussed previously. All designs were based on the same functional unit of one cold room, with a capacity of 20m³, maintained to a temperature of 10°C, over a lifetime of 20 years. Data sources, methods and systems were applied consistently, as described in *Section 3.5.1.*

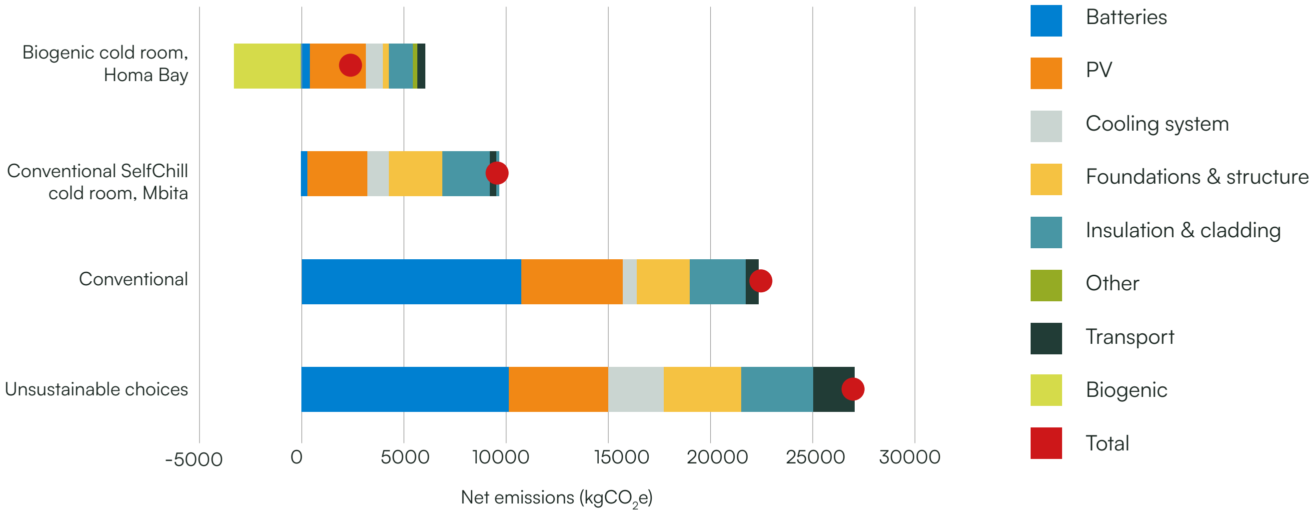
- **The conventional SelfChill design** differs from the biogenic cold room in that it uses expanded Polyurethane insulation and a metal internal structure. Lithium-Ion batteries, eleven 1.95m x 0.99m solar PV panels and eight cooling units are used. The refrigerant used was R600a. This design did not use a charcoal cooler. This design uses slightly more PV panels than the biogenic cold room so has a greater impact from this element but uses the same number and type of batteries and a greater number of cooling units, giving a higher impact contribution from this element and a higher total impact of the combined system.

- **The conventional design** used an example from the previous LCA study[26], which included 18 solar PV panels (also 1.95m x 0.99m) and 24 low voltage high-capacity batteries (2V 990Ah) - valve-regulated Lead Acid batteries were used. One large cooling unit was used. The refrigerant used was R290, and this design did not use a charcoal cooler or water chiller.

- **The unsustainable choices design** used 18 solar PV panels as in the Conventional design, but reverted to the more common 12V lead acid batteries - conventional wet lead acid batteries were used. Insulation was again provided by Polyurethane sandwich panels, and the cooling units used R134a refrigerant. No specific efforts were made to avoid air transport, so some components were transported by air freight.

A comparison of impact over a series of elements for the biogenic, conventional SelfChill, conventional and unsustainable choices designs is illustrated in Figure 79.

Figure 79. Comparison of total net emissions over 20-year lifetime for the biogenic cold room and three alternative designs



24 In this sensitivity comparison, we use ‘biogenic’ rather than ‘low carbon’ to make it clear that the type of insulation material (i.e. straw bale and eco-boards in ‘Biogenic’, and expanded polyurethane panels in ‘Conventional’) represents the main difference between the SelfChill cases. As shown in the comparison figure, they both have significantly lower embedded GHJG emissions compared to conventional cold rooms.

25, 26 Efficiency for Access. (2023). Life Cycle Greenhouse Gas Emissions Assessment of Off- and Weak-Grid Refrigeration Technologies. https://efficiencyforaccess.org/publications/life-cycle-greenhouse-gas-emissions-assessment-of-off-and-weak-grid-refrigeration-technologies/.

Though this comparison considers only speculative variation (particularly in the unsustainable choices case) in some aspects of the design, it illustrates that by making positive and informed design decisions the potential environmental impact of a cold room can be significantly reduced. Based on the calculated emissions of the biogenic cold room and estimated cases above, the impact of the unsustainable choices design is over 10 times higher than that of the biogenic cold room. Furthermore, this comparison does not consider some additional impacts, such as the potential for high impact blowing agents such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), which have historically been used to produce expanded insulation materials for cooling systems like cold rooms. Insulation materials made using these blowing agents would have much higher impact even than the results shown here, meaning that sourcing and understanding the origin of materials is a key element in impact reduction. The importance of efficient design to reduce the need for excessive PV and battery use is also clear in this comparison. Batteries with short lifetimes which require multiple replacements over the study period would lead to significant increases in emissions relative to those with longer lifetimes.

3.6.2. POWER SUPPLY COMPARISON

GRID

Using solar PV panels and energy storage means that this cold room does not require connection to a centralised electricity grid. This is useful in areas of weak or intermittent grid connection, and allows the cold room to be deployed in areas with no grid connection. Without using photovoltaic generation, operating a cold room in such off-grid areas would commonly require the use of a diesel generator. To understand the benefit of using the photovoltaic and battery system in place of grid electricity and diesel generator power, the hypothetical impact of the cold room if powered by each of these sources was calculated.

The expected energy consumption of the cold room is around 9.5 kWh/day, made up of the primary system (6 cooling units @ 75 watts x 20 hours = 9 kWh/day) and the secondary system (1 heat exchanger fan @ 27 watts x 12 hours + 1 water pump @ 15 watts x 12 hours = 0.5 kWh/day). This gives an annual power consumption of 3,469.8 kWh and based on a cold room lifetime of 20 years, a lifetime power consumption of 69,397.5 kWh[28].

In the photovoltaic panel and battery scenario, the total greenhouse gas emissions of these components amount to 3,033 kgCO_2e (2,735 kgCO_2e and 298 kgCO_2e respectively), assuming both have a lifetime of 20 years.

Around 90% of electricity supplied to the grid in Kenya is from renewable energy sources[27]. Around 41% of electricity is from geothermal sources, 30% from hydroelectricity, 16% from wind, and smaller proportions from biofuels and photovoltaic panels. Oil makes up the final 10%, but even with this small proportion of high emission, the total value is relatively low, at 274 gCO_2e/kWh .

Had the cold room been powered by the Kenyan grid, total emissions after 20 years (including the materials and manufacture of the cold room, and 20 years of operational energy) would be around 21,750 kgCO_2e. This is 3.8 times higher than (380% of) the total emissions of the system in the PV and batteries scenario.

The use of photovoltaics and batteries has another advantage in areas where grids can be unreliable or intermittent, in that the proposed system would not be affected by grid outages. Perhaps the greatest advantage of the proposed system is the ability to operate in areas without any grid connection at all, where there is unlikely to be any existing provision of refrigeration. In this case, a hypothetical scenario of using diesel generators was compared to the photovoltaic and battery system.

27 IEA. 2024. Sources of Electricity Generation: Kenya. https://www.iea.org/countries/kenya/electricity.
28 Climatiq. 2024. Emission Factor: Electricity supplied from grid: Kenya. https://www.climatiq.io/data/emission-factor/436b3bb9-c1b4-4eb5-8472-76f9317ffd04.

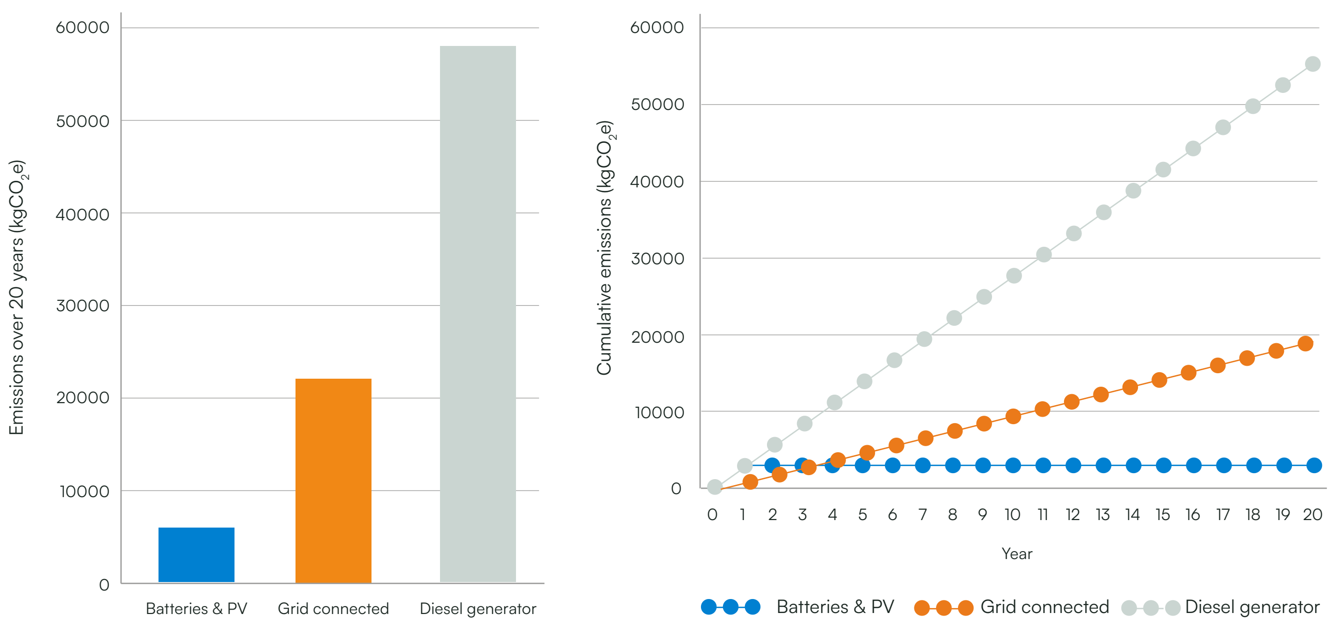
DIESEL GENERATOR

Diesel generators are commonly used around the world and offer convenient and reliable electricity generation when no other options are available or as a back-up to unreliable grid connection. However, diesel is a fossil fuel and direct combustion to generate electricity has significant greenhouse gas emissions. Most diesel generators operate with emissions of around 795 gCO_2e/kWh (data from Ecoinvent 3.9 database), considering efficiency of operations.

Had the cold room been powered by a diesel generator, total emissions after 20 years (including the materials and manufacture of the cold room, and 20 years of operational energy) would be around 57,905 $kgCO_2e$. This is approximately 10 times (1000% of) the total emissions of the system in the PV and batteries scenario. Had the diesel generator been used as a back-up to an unreliable grid, this would result in emissions somewhere between the grid and diesel generator scenarios presented in Figure 79.

Although both grid connection and diesel generator scenarios have complexities affecting their actual emissions, such as changes in the grid's energy sources and differences in fuel use or type, the proposed system is still likely to produce the least greenhouse gases compared to the other two options. Figure 80 shows the total (left) and cumulative (right) emissions of the three options. It can be seen in the right figure that the grid connected option has lower cumulative emissions than the photovoltaic and battery system until around the third year of operation. This is because the emissions related to the photovoltaic and battery system are caused by actions during the manufacture of these parts, not during their operation. Grid and diesel generator systems cause emissions continuously throughout their lifetimes but have lower emissions during the manufacture phase. However, over a likely operational lifetime of the cold room, the photovoltaic and battery system will have lower emissions, as well as offering additional benefits.

Figure 80. Greenhouse gas emissions of the cold room using the proposed photovoltaic and battery system (blue), grid connected (orange) and diesel generator powered (grey)[29]



29. The left graph shows total emissions over a 20-year lifetime, whereas the right graph shows how these emissions grow over time.

3.6.3. END-OF-LIFE TREATMENT

End-of-life treatment describes any treatment of a product or process after the end of the use for which it was primarily designed. This might mean disposal, recycling, reuse or refurbishment, among other options. Due to the range of options and the long lifetime of the cold room, which means the options available at end-of-life are unclear, end-of-life has not been included in the main LCA. However, due to the consideration of biogenic carbon in some materials, it is important to consider the end-of-life of some materials.

As discussed in *Section 3.5.2*, timber and materials with biogenic carbon storage contain stored atmospheric carbon. If these materials are burned at the end of their lives, this stored carbon is released and emitted to the atmosphere. If materials are allowed to decay, either naturally or in controlled landfill, the carbon is again released, but over a much longer timeframe. However, if these materials are reused (for example if straw used as insulation had another role after the cold room), the carbon remains in the materials and is not released. If materials are used in place of another material (for example if timber from the cold room was eventually burned to provide heat for cooking), carbon is released, but the carbon in the material which would otherwise have been used to provide heat is not released, so the net system emissions are similar. There is much discussion in the LCA world around how biogenic carbon should be treated, which materials should be awarded “credits”, and how allocation of emissions should best be undertaken. In this case, biogenic carbon results are presented separately to allow the impact to be seen both with and without biogenic carbon.

The end-of-life treatment of technical elements of the cold room is an area not considered in detail during this study. Indicative data for products and materials of similar types suggest the technical system may have end-of-life emissions of the order of 200 - 400 $kgCO_2e$, if disposed of through a combination of landfill and recycling for appropriate materials. This suggests that end-of-life treatment would not be a particularly significant contributor to total cold room emissions if these emissions were considered, but a full study would be required to confirm these values.

The potential for downcycling, reuse, refurbishment or life extension are not considered here, but all would improve circularity and allow materials or components to be used for longer. Downcycling, reuse, refurbishment or life extension would be expected to reduce overall emissions (though accounting methods may cause these to remain the same when calculated using standard methods).

3.6.4. DATA QUALITY

Various sources of data have been used in this study, which bring varying levels of quality and detail. The results must be considered in context of this quality to ensure that conclusions drawn do not exceed the accuracy of the data used to form them.

- **Data taken from the Ecoinvent database is well validated,** has undergone review before inclusion in the database, and is generally aggregated or provided by providers unlikely to have bias.
- **Data from peer reviewed academic journals is similarly expected to be of reasonable quality**, and data from multiple sources has been used wherever possible.
- **Data from Environmental Product Declarations (e.g. for eco-boards and photovoltaic panels) have been used for eco-boards and photovoltaic panels**. In both cases, studies underlying the EPD results were undertaken by consultants and have been checked for compliance. However, these results only include greenhouse gas emissions.

Temporal impacts, which refers to how impacts change overtime, have not been considered here. In most cases, time would not have a significant impact on the results of this study, since many impacts occur during the raw material or manufacturing stage, which is not very distant from the current time, and do not occur again over the duration of the project.

Some impacts which have a temporal element are included in the comparison with grid electricity. However, the significant difference in emissions between the proposed case, the grid electricity case, and the diesel generator case means that it is unlikely any temporal change in grid electricity or diesel generation emissions would change the overall result of the comparison.

Cold room worker in the low-carbon cold room, Homa Bay, Kenya.
Source: Charles Ogalo, WeTu, 2024.

4. FOOD LOSS AVOIDANCE

4. FOOD LOSS AVOIDANCE

To fulfil food demand in the market, any food loss[30] must be compensated for in additional production and supply. This implies that avoiding food loss results in reduced GHG emissions associated with food production and supply. However, this reduction is offset by the GHG emissions induced by the intervention. In this chapter, the effect of GHG emission reduction through food loss avoidance is estimated for the low-carbon cold room.

To estimate GHG emission reduction, quantitative estimates of food loss avoidance are required. In this chapter, typical loss percentages are presented for a baseline scenario (i.e. without cold storage) and for the intervention scenario (i.e. with the low-carbon cold room). Based on these assumptions, the GHG emission reduction resulting from the intervention is estimated.

It should be highlighted that reducing food loss requires interventions throughout the supply chain, both pre- and post-harvest, extending beyond technological solutions. Factors such as the timing and methods of harvesting play a critical role in minimising food loss. Similarly, post-harvest handling practices, including proper storage and crating within cold rooms, can significantly impact the amount of food loss. Attention to these operational details can lead to measurable improvements in reducing losses across various stages of the supply chain.

In market settings like the one in Homa Bay, the primary goal of deploying a cold room is to extend the storage life of produce by slowing decay and reducing spoilage over a few extra days. However, additional interventions could also be explored to further mitigate food loss, despite being beyond the immediate scope of this report. For instance, passive cooling solutions, such as shaded evaporative solutions, could be compared with traditional open-air market setups where produce, such as tomatoes, may face sun exposure. These approaches would likely require investment in consumer education and efforts to encourage behavioural changes to support their adoption.

Practitioners are therefore encouraged to adopt a holistic perspective when addressing food loss challenges. Beyond relying solely on technology, broader strategies that incorporate supply chain improvements, education, and behavioural interventions should be considered. This integrated approach has the potential to yield more sustainable and long-term solutions for reducing food losses across the agricultural and retail sectors.

4.1. VALUE CHAIN SELECTION

In a survey conducted by WeTu among vendors in a fresh market in Mbita, located in Western Kenya near Homa Bay where the low-carbon cold room is located, fish, fruit, and vegetables were identified as product categories where the intervention is considered most relevant. Since the setpoint temperature of the low-carbon cold room is higher than the recommended storage temperature for fresh fish, the analysis below focuses on fruit and vegetables.

The survey among vendors identified the following commonly traded product types: tomatoes, leafy vegetables, bell peppers, cabbage, avocados, bananas, oranges, lemons, and pawpaw. Of these, products with the shortest shelf life at the market such as leafy vegetables are most vulnerable to decay and wastage[31] and therefore will benefit most from the intervention. This is confirmed by the relatively high percentage of 'sorted out and discarded' and 'decayed' tomatoes[32] as outlined in Table 9.

4.2. FOOD LOSS OCCURRENCE WITHOUT COLD STORAGE

To estimate the average food loss percentage by vendors in the market, the previous survey provided insufficient data due to missing data points and inconsistent entries (e.g. some vendors reported higher losses than the overall amount they purchased in the first place). Due to these challenges, secondary data was used instead.

30. Food loss and waste are sometimes used interchangeably but there is an important distinction between them. Food loss occurs throughout the supply chain, from production, post-harvest, processing, storage, transport, and distribution. On the other hand, food waste typically occurs when products have reached the consumer-facing retailer and beyond. In this report, we primarily refer to food loss, as this is an area that solar-powered cold rooms can help mitigate.

31. Shuck, J., D. Nduku & R. Ekka. (2022). Pilot of Food Loss and Waste Value Chain Selection Guide in Kenya, Agribusiness Associates Inc. and Fresh Produce Consortium Kenya.

32. Kitinoja. L and Cantwell M. (2010). Identification of Appropriate Postharvest Technologies for Improving Market Access and Incomes for Small Horticultural Farmers in Sub-Saharan Africa and South Asia. WFLO Grant Final Report: Grant Number 52198. https://ucanr.edu/datastoreFiles/234-1847.pdf.

The most relevant references include:

- United Nations' Food Loss and Waste Database[33]: This presents food loss data for fruit and vegetables in the retail stage with three values from studies in Kenya. Of the provided data, only the datapoint of 9% for bananas was confirmed in the reference.
- Shuck et al. (2022): This study reports results from an extensive study of a fresh market in Kenya, indicating 5% — 10.7% of tomatoes and 5.35% of avocados are thrown away by market vendors.
- Friedman-Heiman et al. (2024): This study estimates, based on values derived from expert guesses and a set of references, an average baseline percentage of food loss for fruit and vegetables in the retail stage of the food supply chain at 6.7%.
- Porter et al. (2016) and Guo et al. (2020): These studies present substantially higher estimates for food loss at 34% in the 'distribution stage' in Sub-Saharan Africa, one reason for this higher value is that Porter's definition of the 'distribution stage' covers more activities than the retail market.

Porter's reference for the food loss percentage (Kitinoja et al., 2010) can still be used for estimating the average percentage at the retail market. Table 8 summarises percentages at retail markets for relevant fruit and vegetables as presented by Kitinoja et al.

From the products listed in Table 8, tomatoes have the highest decay and discard percentages. The average food loss ('sorted out and discarded') percentage for tomatoes is 21.4%.

Table 8. Postharvest losses at the retail market level (the percentage 'Sorted out and discarded' is actually considered food loss) (Kitinoja et al., 2010)

	Country	Sorted out and discarded	Mechanical damage	Decay
Tomato	Ghana	23%	10.5%	11.5%
Tomato	Benin	26.4%	10.5%	27.5%
Tomato	Rwanda	14.7%	12.5%	6.5%
Cabbage	Ghana	28.1%	45%	5%
Eggplant	Ghana	16.2%	9.5%	0%
Peppers	Benin	11%	10%	8%
Bananas	Rwanda	30.1%	25%	0%
Mangoes	Ghana	no data	8%	1%
Oranges	Benin	10.9%	51%	33%
Pineapples	Rwanda	15.9%	21%	2%

4.3. FOOD LOSS AVOIDANCE WITH THE COLD ROOM

Refrigerated storage is expected to significantly help reduce food loss in the Homa Bay market because it substantially decreases the chance that products spoil before sale. However, very little quantitative data on the actual effectiveness is available. As indicated by Friedman-Heiman et al. (2024), quantitative data on the effect on the percentage of food loss is very fragmented and not directly applicable for food supply chain stakeholders[34].

33. FAO. 2024. Technical Platform on the Measurement and Reduction of Food Loss and Waste. https://www.fao.org/platform-food-loss-waste/flw-data/en/.
34. Friedman-Heiman, S. A. Miller. (2024). The impact of refrigeration on food losses and associated greenhouse gas emissions throughout the supply chain. Environmental research Letters, Volume 19, Number 6. https://iopscience.iop.org/article/10.1088/1748-9326/ad4c7b.

Here, approaches for estimating food loss at the retail market, both without and with intervention, are used:

1. **ADOPTING AVERAGE EFFECTIVENESS FOR FRUIT AND VEGETABLES:**

- Friedman-Heiman et al. have estimated the average effectiveness of the intervention per stage along the food supply chain. In their view, effectiveness depends on the 'refrigeration quality': good refrigeration reflects the lowest baseline loss rate, no refrigeration reflects the highest baseline loss rate, and average and poor refrigeration reflect loss rates between the lowest and highest. For fruit and vegetables, the same study estimates that the average loss percentage in the retail stage can be reduced from 6.7% to 3.0%, 4.2%, and 5.4% through 'good', 'average', and 'poor' refrigeration, respectively[35] .

- Since the cold room is intended as a central facility, vendors will use it mainly for stocks and sell their products at ambient temperature. Here it is assumed that this practice can be described as 'average refrigeration quality'. Consequently, it is estimated that the intervention can reduce the average food loss by vendors from 6.7% to 4.2%.

2. **ESTIMATING EFFECTIVENESS FOR VULNERABLE PRODUCTS:**

- Tomatoes have the highest food loss rate due to decay in Table 8, with an average of 21.4% at retail markets. The potential effects of cold storage were not tested by Kitinoja et al. (2010). As a workaround, it is assumed that the same food loss reduction fraction as estimated by Friedman-Heiman et al. for average refrigeration quality applies. Therefore, the estimated food loss by vendors will be reduced from 21.4% to 13.4%.

Based on these assumptions, two scenarios were analysed:

Scenario 1: Based on the averages from Friedman-Heiman et al. (i.e., the intervention reduces the food loss percentage from 6.7% to 4.2%).

Scenario 2: Based on the values estimated from Kitinoja et al. for tomatoes (i.e., the intervention reduces the food loss percentage from 21.4% to 13.4%).

35. Friedman-Heiman, S. A. Miller. (2024). The impact of refrigeration on food losses and associated greenhouse gas emissions throughout the supply chain. Environmental research Letters, Volume 19, Number 6. https://iopscience.iop.org/article/10.1088/1748-9326/ad4c7b.

4.4. EMISSION REDUCTION ANALYSIS

In the GHG emission accounting, the following factors and operations are considered[36]:

GHG emissions in agricultural production:
For products in scope, the inventories of Clune et al. (2017) and Petersson et al. (2021) show GHG emission intensities for crop production varying from 0.2 to over 1 kg of CO_2e per kg of crop. Here, the average GHG emissions connected with agricultural production are assumed to be 0.40 kg of CO_2e per kg of crop (equal to the "average" proposed by Porter et al., 2016).

Losses at farm:
These are estimated at 7.0% (Friedman-Heiman et al., 2024).

Losses at wholesale market:
These are estimated at 6.0% (Friedman-Heiman et al., 2024).

Transport: The average total transport distance from the agricultural production area to the market is estimated at 300 km (from the survey: in the range of 15 to 600 km). It is also assumed that medium-sized trucks are used to transport the produce. The average GHG emission factor for this transport modality is 0.25 kg of CO_2e per tonne of produce per km.

Losses in collection transport: This is estimated at 3.2% (Friedman-Heiman et al., 2024).

Losses in transport from wholesale market to retail market: This is estimated at 5.4% (Friedman-Heiman et al., 2024).

Losses at the retail market:

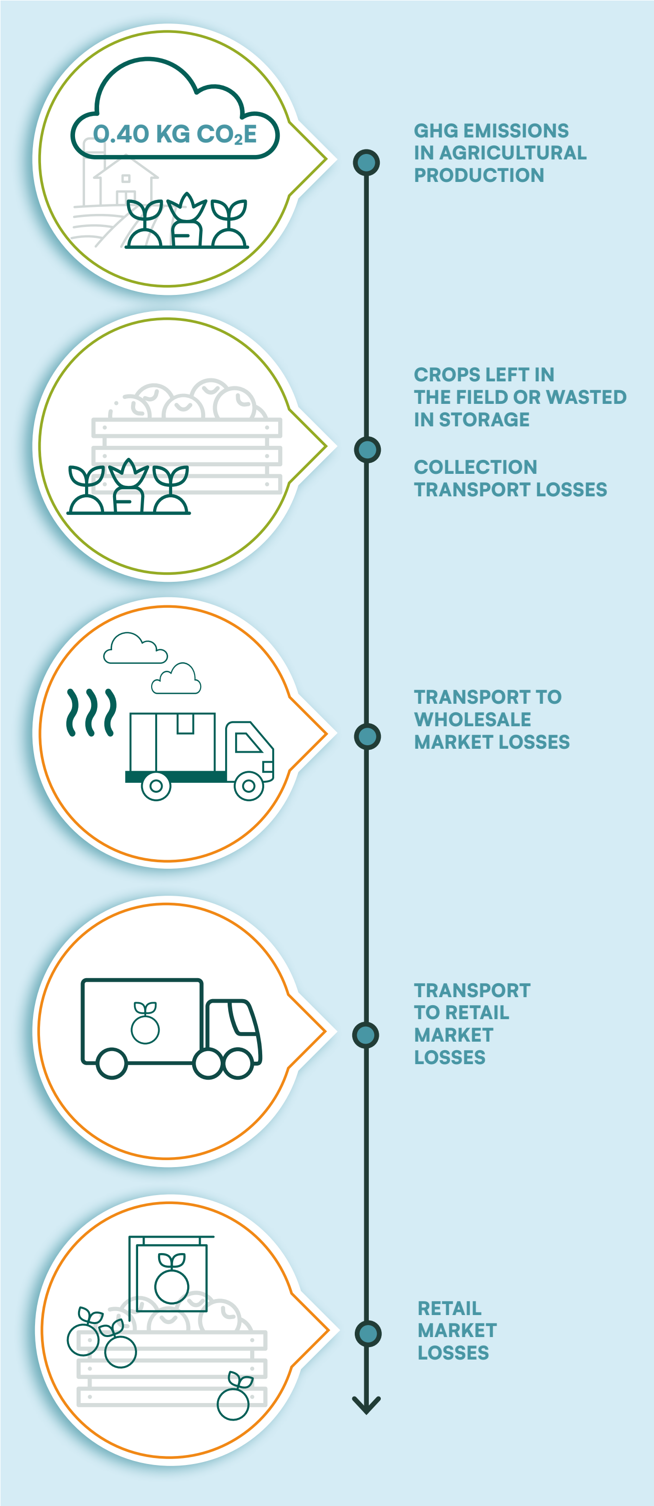
Scenarios based on food loss factors from Friedman-Heiman et al. (2024):

- Baseline scenario: 6.7%
- With intervention: 4.2%

Scenarios based on food loss factors derived from Kitinoja et al. (2010):

- Baseline scenario: 21.4%
- With intervention: 13.4%

Figure 81: Food loss emissions points from farm to the retail market



36. Operations in all stages along the supply chain except for the retail stage are the same for the baseline scenario and with intervention.

Table 9. GHG emissions associated with different activities along the supply chain (kg of CO_2e per kg of sold produce in the retail market)

	Friedman-Heiman et al.		Kitinoja et al.	
Activity	Baseline scenario	With the cold room	Baseline scenario	With the cold room
Agricultural production	0.539	0.525	0.640	0.581
Transport	0.091	0.089	0.108	0.098
TOTAL	**0.630**	**0.614**	**0.748**	**0.679**

At Mbita, most traders operate on a small scale, acquiring or harvesting only enough produce for daily sales. Fresh produce is sourced from farmers periodically, with deliveries occurring daily or every few days, particularly for green leafy vegetables. Consequently, estimating the utilisation rate (the percentage of crates being used at a given time) and daily throughput (the percentage of the cold room being filled and emptied per day) is inherently difficult. The variability of the pay-per-use business model, where the cold room operator has limited control over the stored produce, further complicates this. Consequently, we used literature sources to estimate the approximate scale of avoided food loss.

The total GHG emission reduction associated with the potential food loss avoidance are shown in Table 10. It is assumed that the cold room is used all year round without value chain seasonalities. Perishable products such as tomato and leafy vegetables are predominantly produced from May until November[37]. However, they are likely to be sold at elevated prices from local production with lower productivity or greenhouse production throughout the rest of the year.

Table 10. Effects of the intervention on GHG emission reduction of food supply

	Friedman-Heiman et al.	Kitinoja et al.
GHG emission reduction by food loss reduction (kg of CO_2e per kg of sold produce, derived from Table 9)	0.016	0.069
Amount of food sold per day (if 400 kilograms of fresh material is received by the cold room per day) (kg) (based on food loss factors presented above Table 9)	383	346
GHG emission for the volume of food sold per day (kg of CO_2e per day)	6.30	23.9
Assumed daily throughput rate (average amount of food going in and out per day compared to the maximum capacity of 400kg)	50%	50%
Total GHG emission reduction in a life span of 20 years (kg of CO_2e)	**23,000**	**87,000**

Using the cold room at a 50% throughput capacity over a period of 20 years results in a total avoidance of 23 to 87 tonnes of CO_2e. This substantial reduction in greenhouse gas emissions underscores the potential positive impact of the cold room in mitigating the environmental impact associated with food loss. The cold room itself has embedded emissions of 2,377 kg of CO_2e as outlined in *Section 3.5.2.* Therefore, the positive impact of its use is estimated to be 10 to 37 times higher than the emissions generated by its construction and operation. This positive impact 'payback' of GHG emissions is significantly improved compared to standard cold rooms with polyurethane sandwich panels with significantly higher embedded emissions[38].

37. Farm Africa. Your Seasonal Food Planner. www.farmafrica.org/downloads/food-calendar.pdf.
38. Efficiency for Access. (2023). Life Cycle Greenhouse Gas Emissions Assessment of Off- and Weak-Grid Refrigeration Technologies.

This impressive ratio highlights the efficiency of the cold room as a climate change mitigation intervention. Even when using the more conservative food loss assumptions from Friedman-Heiman et al. outlined in Table 9 and assuming a 50% daily throughput rate, the emissions payback period will be offset within two years of operation — that is three times faster than a cold room made from regulated polyurethane sandwich panels Ibid[39]. This analysis demonstrates that the environmental benefits of the cold room will be realised quickly and continue to accrue significantly over its lifespan as shown in Figure 82.

By ensuring that perishable goods such as tomatoes, leafy vegetables and other fruit and vegetables are preserved more effectively, the cold room will help maintain food quality and reduce economic losses for vendors. These comprehensive environmental and economic benefits illustrate the value of investing in such low-carbon interventions within the food supply chain.

Figure 82. Cumulative emissions over the 20-year lifetime including avoided food loss

39.Ibid.

Early stages of building the low-carbon cold room, Homa Bay, Kenya

Source: Charles Ogalo. 2024

5. LESSONS LEARNED

LESSONS LEARNED

The overarching aim of this project was to demonstrate the technical and economic feasibility of a cold room with minimal embedded GHG emissions, constructed using locally available materials, which has been successfully achieved. Throughout the project, several challenges were encountered, as would be expected given the innovative and experimental nature of the work. This chapter aims to share these experiences to inform future cold room design efforts as well as other solar-powered appliances. By openly discussing the difficulties faced and the solutions discovered, valuable insights can be provided for others undertaking similar projects in the future.

5.1. LIFE CYCLE ASSESSMENT

THERE IS LIMITED AVAILABILITY OF COUNTRY-SPECIFIC DATA ON REFURBISHED BATTERIES.

Most LCA tools assume a certain proportion of batteries are recycled, reused, or remanufactured but often fail to consider local contexts. This results in lower estimates of GHG emissions savings from secondary battery use, even though battery refurbishment in Sub-Saharan Africa is still in its early stages. Consequently, most batteries currently end up in landfill. Improving data specificity for countries in Sub-Saharan Africa, or at least identifying existing data sources that are representative of the refurbishment rates in the given country, is crucial for accurate assessments. Global averages should be avoided where possible to ensure that the LCA results are not skewed.

THE MARKET FOR REFURBISHED BATTERIES IN KENYA IS STILL NASCENT.

The original aim was to use refurbished lithium-ion batteries for the cold room, but there is a limited range of suppliers in Kenya. This shortage necessitated the use of new batteries, highlighting the need for developing a more robust supply chain for secondary batteries in the region to reduce dependency on external sources.

FINDING LOW-CARBON SOLAR PV PANELS IS CHALLENGING.

Some companies market their solar PV panels as net-zero but from an LCA perspective these are potentially misleading claims due to offsetting elsewhere. For this reason, the LCA results in this report disregarded offsets and used the actual embedded emissions of the PV panels, which were still lower compared to the industry average. This approach ensures a more accurate representation of the environmental impact.

DATA ON OTHER ENVIRONMENTAL IMPACT CATEGORIES BEYOND GHG EMISSIONS ARE OFTEN LIMITED OR NON-EXISTENT.

While LCA data is relatively comprehensive in terms of GHG emissions, information on other environmental impact categories, such as land use, water consumption or human toxicity is often limited or missing. Improving data availability to cover these additional categories is essential for a holistic understanding of the environmental impacts associated with different technologies and practices.

QUANTITATIVE, LIKE-FOR-LIKE COMPARISON WITH OTHER POWER GENERATION SOURCES IS DIFFICULT.

GHG emissions comparison between different power sources such as the electricity grid was conducted to show the benefits of the solar system, but it is also important to consider intermittency and unreliability of the grid which further strengthens the case for solar-powered systems. Additionally, the evolving power generation mix of the grid is directly linked to the emission factor, which changes on a year-by-year basis.

5.2. CONSTRUCTION

THERE IS LIMITED AVAILABILITY OF INSULATED DOORS MADE FROM BIOGENIC MATERIALS.

Door manufacturers face challenges in producing custom one-off insulated doors because they are not considered commercially viable. Therefore, purchasing a standard door and adding extra insulation was the only practical option available. Collaboration with local carpenters to retrofit the existing door enhanced the thermal efficiency, increased local content and reduced the production cost.

THE AVAILABILITY OF HIGH-POTENTIAL BIOGENIC MATERIALS FOR CONSTRUCTION DEPENDS ON THE REGION OF DEPLOYMENT.

In Western Kenya, there are locally available materials, such as straw, timber, and eco-boards, supported by the expertise of local professionals. These accessible and natural resources offered a significant opportunity to make the cold room's construction more sustainable. Engaging with local experts ensures these materials are used effectively and sustainably, fostering environmentally conscious building practices that are well-suited to the regional context. Other suitable insulation materials like seaweed were considered but not selected due to the long distance from the area of construction.

DESIGNING THE COLD ROOM TO BE FULLY NET-ZERO WOULD HAVE NEGATIVELY AFFECTED COMMERCIAL VIABILITY AND SCALABILITY.

Biogenic materials contribute to a lower overall environmental impact, yet achieving true net-zero status would require making costly decisions that might not be practical, such as significantly increasing the biogenic wall insulation.

Leafy greens in the low-carbon cold room, Homa Bay, Kenya.
Source: Humphrey Anjilla. 2024

5.3. FOOD LOSS AVOIDANCE ANALYSIS

LOCATION-SPECIFIC FOOD LOSS ASSUMPTIONS ARE LESS ROBUST COMPARED TO OTHER ANALYSES.

Using primary data for the food loss avoidance analysis would yield more robust results. However, since the cold room was yet to be constructed at the time of writing the report and primary data from the nearby site was insufficient, we used secondary data from desk-based research. This led to making assumptions which might or might not materialise once the cold room is operational.

LACK OF REAL DATA ON USAGE MAKES IT CHALLENGING TO PRODUCE ACCURATE RESULTS.

The absence of real data on throughput, unsold food returns, and utilisation rates presents significant challenges in producing accurate results. Improving data collection and sharing results with the sector to capture precise information on these variables will enhance the accuracy of future food loss assessments.

THE PAY-PER-USE BUSINESS MODEL ACCESSED BY VARIOUS VENDORS SELLING VARIOUS TYPES OF PRODUCE MAKES THE ASSESSMENT EVEN MORE CHALLENGING.

The pay-per-use business model results in less visibility of storage duration, particularly when multiple vendors store their unsold produce overnight. In addition, food crop variation of variable quantities makes it difficult to estimate overall food loss avoidance. Implementing digital solutions, such as Internet of Things (IoT) sensors and smart inventory systems, or at least keeping a basic logbook, can provide valuable data on storage conditions and durations.

Kevin Asika, WeTu and Florian Martini, Phaesun, in the low-carbon cold room, Homa Bay, Kenya.

Source: Humphrey Anjilla, 2024.

6. CONCLUSIONS

CONCLUSIONS

The vision for the low-carbon cold room was to deliver the benefits of a conventional cold room while significantly reducing the embedded GHG emissions through the use of locally available, environmentally friendly insulation materials. This approach not only reduces the number of carbon-intensive materials imported from abroad but also supports local workforce development and supports the growth of solar-powered cooling technologies in Sub-Saharan Africa.

The low-carbon cold room made from biogenic materials is not only more environmentally sustainable but also cheaper compared to conventional materials. Using straw bales for insulation reduced the cost of the low-carbon cold room by 20%, and embedded GHG emissions by 63% compared to a similar sized cold room made from regulated polyurethane sandwich panels, or more than 90% if unsustainable design choices were made. The main disadvantage of biogenic materials is their potentially shorter lifespan which is difficult to estimate without long-term testing.

The climate mitigation benefits of avoided food loss are realised quickly and continue to accrue significantly over its lifespan. Even with conservative assumptions, the GHG emissions payback is estimated to be within two years for this low-carbon cold room. However, estimating food loss avoidance remains challenging without location-specific primary data. Reliable estimates require comprehensive data over an extended period, underscoring the need for ongoing monitoring to understand total food loss avoidance.

Creation of insulation panels, Homa Bay, Kenya.

Source: Charles Ogalo, WeTu, 2024.

Constructed low-carbon cold room, Homa Bay, Kenya.

Source: Charles Ogalo, WeTu, 2024.

7. KEY RECOMMENDATIONS AND CALLS TO ACTION

1. LEVERAGE MULTIDISCIPLINARY EXPERTISE

Leveraging a multidisciplinary team of experts is a key precursor to success in sustainable cooling. In this project, the team had experience in architectural design, green building practices, construction, logistics, life cycle assessment, solar technology, refrigeration, optimal food storage requirements, and Cooling-as-a-Service business models.

Call to Action: Assemble a diverse team of experts and local stakeholders early in the project to integrate specialised knowledge and regional insights into the design and implementation phases. Hold regular design team meetings on a weekly basis to maintain momentum and enable timely, informed decisions throughout the project.

2. ENSURE HIGH LOCAL INVOLVEMENT

Ensuring local involvement in design is key to understanding feasible construction techniques, the availability of local materials and services, and cultural relevance and acceptance of design features. This engagement enhances the appropriateness and suitability of the project.

Call to Action: Engage local professionals and companies from the outset to inform the design of sustainable cooling solutions and ensure that they meet local needs and conditions.

3. OPTIMISE RELEVANT TOOLS AND TECHNIQUES

Design simplicity leads to more efficient solutions. Using design and optimisation tools streamlines the design process and enhances efficiency. The development and use of state-of-the-art optimisation tools resulted in less expensive and more sustainable cold room design.

Call to Action: Prioritise simple but effective design solutions such as using biogenic sandwich panels with moisture release features and integrate optimisation tools for the best outcomes such as the one developed for this project.

4. USE LIFE CYCLE ASSESSMENT AS A DECISION-MAKING TOOL

Using life cycle assessment as a real-time decision-making tool rather than a post-decision assessment method was this project's underlying innovation. Having an immediate understanding of environmental impacts is essential for making informed design choices quickly. The use of life cycle assessment during the design phase of this project allowed for rapid iteration and refinement of multiple design variables.

Call to Action: Integrate life cycle assessment tools into the design process from the beginning, enabling swift and informed decisions that optimise environmental impact, performance and cost.

5. BUILD A MOCK-UP TO TEST THE DESIGN AND PERFORMANCE

It is crucial to test construction methods and materials before full-scale building, especially when new features are involved. Creating mock-ups can identify potential issues and ensure the feasibility of the design, which proved to be essential to reduce moisture levels in the biogenic insulation walls to prevent degradation and potential structural failure.

Call to Action: Develop and evaluate mock-ups of key construction elements to ensure their effectiveness and address any issues before proceeding with full-scale construction.

6. CONSIDER USE CASE LIMITATIONS

Bear in mind that certain materials have specific use case limitations. For example, the project used straw bales as insulation material, which might not be suitable for meat and fish storage due to stricter food safety compliance requirements.

Call to Action: Select appropriate construction materials and assess their suitability for different types of produce, ensuring compliance with food safety requirements where necessary.

7. CONTROL HUMIDITY LEVELS DURING CONSTRUCTION AND OPERATION

Managing humidity within the insulation wall (below 80%) is critical to prolong the system's lifespan, while still achieving the required relative humidity within the cold room itself (80-95%). The moisture content of straw used in constructing biogenic elements needs to be low (properly dried) to prevent deterioration and maintain insulation quality. Biogenic sandwich panels need to be designed with one side open to release moisture, unlike polyurethane foam sandwich panels.

Call to Action: Design the system for it to withstand humidity levels recommended for the relevant produce, in this case using straw insulation placed between eco-boards to store fruit and vegetables at a relative humidity of 80-95%.

8. IDENTIFY AND MINIMISE CARBON FOOTPRINT HOTSPOTS

The number of photovoltaic panels is the main contributor to the embedded GHG emissions. Lithium-ion batteries have proven to be more sustainable compared to lead-acid batteries. Fully battery-free designs with oversized photovoltaic fields are not the most sustainable solutions due to their higher carbon footprint. Hybrid solutions that incorporate both thermal storage and lithium-ion batteries are more environmentally friendly.

Call to Action: Choose hybrid energy storage solutions that combine thermal storage with lithium-ion batteries to reduce the amount of solar PV required, maximise performance and reliability, and minimise embedded GHG emissions and cost.

9. ADOPT GREEN BUILDING TECHNIQUES

Implementing green building techniques such as reducing thermal losses around the cold room through shading and evaporative effects (i.e. utilising passive cooling) not only lowers the ambient temperature but also enhances visual appeal. It should be noted that biogenic walls made from straw have insulation properties that are approximately half as effective than typical polyurethane foam sandwich panels, necessitating insulation that is twice as thick.

Call to Action: Employ green building techniques to reduce thermal losses and improve aesthetics and compensate for the lower insulation properties of biogenic materials by increasing insulation thickness accordingly.

10. MAXIMISE COOLING EFFICIENCY

Using evaporative cooling methods, such as a charcoal pre-cooler combined with heat pumps, improves efficiency by increasing the coefficient of performance, thereby reducing the cost and carbon footprint. Locating thermal storage, in this case a water chiller, inside the cold room reduces thermal losses but results in some loss of storage space inside the cold room.

Call to Action: Implement evaporative cooling and thermal storage techniques to boost efficiency and reduce the carbon footprint, while carefully considering and managing the trade-offs related to storage space within the cold room.

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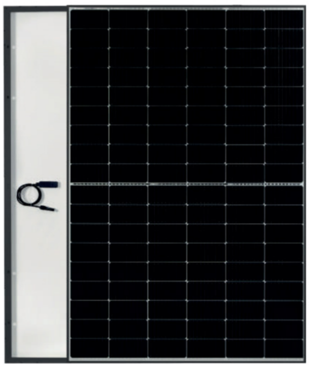
ANNEX 1 TECHNICAL DATA OF COMPONENTS

PV PANELS (FUTURASUN FU 400)

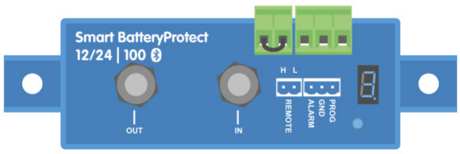


Electrical data - STC		FU 400 M
Module power (Pmax)	W	400
Open circuit voltage (Voc)	V	37.13
Short circuit current (Isc)	A	13.75
Maximum power voltage (Vmpp)	V	31.01
Maximum power current (Impp)	A	12.90
Module efficiency	&	20.48

SOLAR CHARGE CONTROLLER (VICTRON BLUE SOLAR MPPT 150/35)

	MPPT 150/35	MPPT 150/45
Battery voltage	12V / 24V / 48V Auto select, 36V: Manual select	
Maximum battery current	35A	45A
Nominal PV power, 12V 1[a,b]	500W	650W
Nominal PV power, 24V 1[a,b]	1000W	1300W
Nominal PV power, 36V 1[a,b]	1500W	1950W
Nominal PV power, 48V 1[a,b]	2000W	2600W
Max. PV open circuit current[2]	35A	45A
Maximum PV open circuit voltage	150V	
Peak efficiency	98%	
Self-consumption	12V: 20mA I 24V: 15mA / 48V: 1 0mA	
Charge voltage 'absorption'	Default setting: 14.4V / 28.V / 43.2V 57.6V (adjustable)	
Charge voltage 'float'	Default setting: 13,8V / 27,6V 14.4V / 55,2V (adjustable)	

BATTERY PROTECT (VICTRON SMART BATTERY PROTECT 65A)



Smart Battery Protect	SBP-65	SBP-100	SBP-220
Max. continuous load current	65A	100	220A
Peak current	250A	600A	600A
Operating voltage range		6 -35 V	

APPENDICES

ANNEX 1 TECHNICAL DATA OF COMPONENTS

BATTERIES (KIJO POWER KJ 25.6V 200 AH)

Lithium iron phosphate battery Electrical performance	
Nominal voltage	25.6 V
Nominal capacity	200 AH
Capacity & 8.4 A	300 min
Energy	5120 Wh
Resistance	≤50 mΩ @ 50% SOC
Self discharge	<3% /Month

SOLAR COOLING UNIT SELFCHILL LIQUID INDOOR 45/75 A-F (PHAESUN GMBH)

Technical data	
Power consumption:	45 W (at 2000 1/min) - 75 W (at 3500 1/min)
Temperature range: Evaporator: Ambient:	 -5°C to 15° 10°C to 45°C
Voltage range:	10 - 45 VDC
Refrigerant:	R-600a (Isobutane), 35g
Evaporator plate dimensions (H x W):	515,8 x 502,6 mm

COP at n = 3500 1/min

		Evaporator temperature (° C)				
		-5	0	5	10	15
Ambient temperature (°C)	15	1.94	2.38	3.03	4.11	
	25	1.46	1.70	2.02	2.47	3.14
	35	1.17	1.32	1.51	1.76	2.09
	45	0.97	1.08	1.21	1.37	1.57

Cooling power per cooling unit (W) at 3500 1/min

		Evaporator temperature (° C)				
		-5	0	5	10	15
Ambient temperature (°C)	15	97	112	131	158	
	25	79	89	101	116	136
	35	66	73	82	92	104
	45	57	63	69	76	85

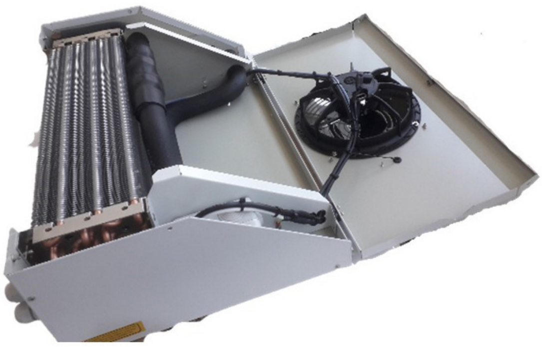
APPENDICES

ANNEX 1 TECHNICAL DATA OF COMPONENTS

WATER PUMP TOPSFLO TL-B10-B24-0905

					At max efficiency point	
Rated voltage (VDC)	Max water flow (L/min)	Max water head (M)	Rated current (A)	Rated power (W)	Rated spec. (L/min @ M)	Rated power (W)
24	9	5	0.65	15.6	5.16 @ 2.88	13.4

HEAT EXCHANGER SELFCHILL 24V DC



Technical data	
Power supply	24 VDC
Fan Input power	30 W
Fin spacing (battery)	4mm
Surface (battery)	5,2 m^2
Vol. (battery)	1,0 l
Air flow rate (fan)	475 m^3/h

Max. cooling power	
2,0 kW_{th}	6 h/d
1,70 kW_{th}	12 h/d
1,13 kW_{th}	18 h/d
0,9 kW_{th}	24 h/d

Cold room temperature				
Ambient temperature	20°C	30°C	40°C	50°C
Minimum achievable cold room temperature	4°C	6°C	8°C	10°C