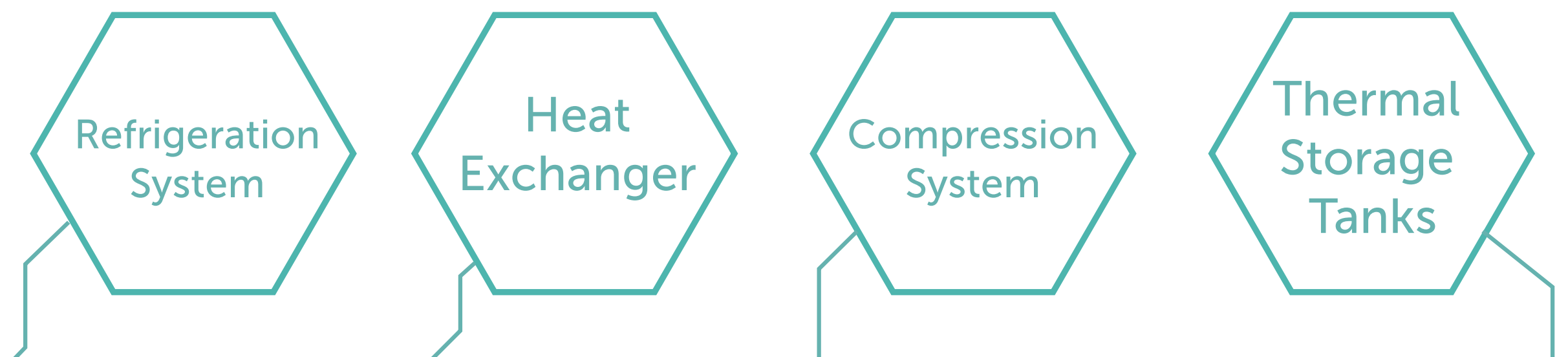
eCOOL : Pumped Thermal Energy Storage (PTES)

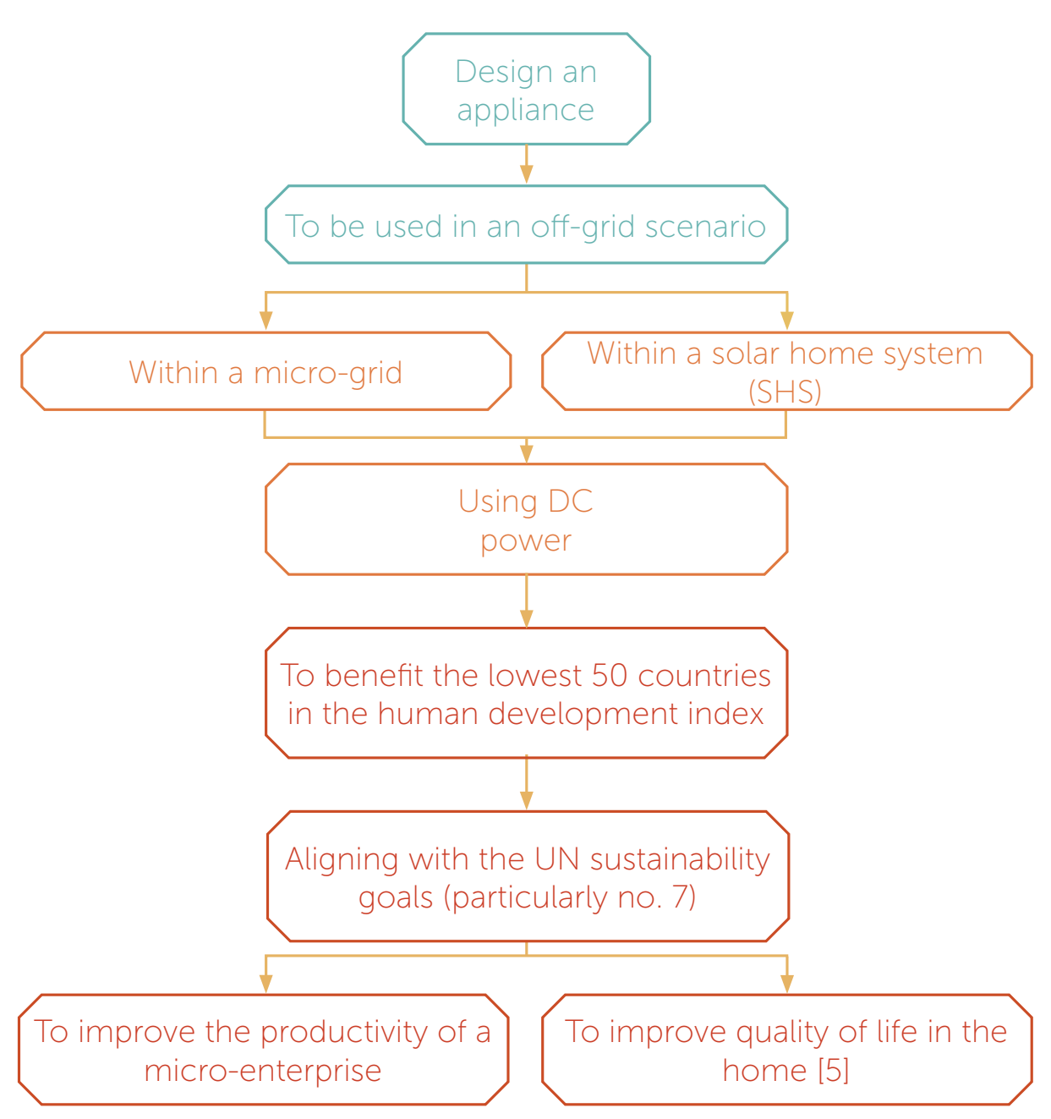


Project Background

The Problem

- There are currently 800 million people in the world without access to electricity [1]
- Electricity is a basic human requirement. It improves multiple areas of life by improving people's wealth, health and education.
- The United Nations (UN) have set 17 Goals to be achieved by 2030. These goals covered a vast range of issues, such as climate change. For this project, however, particular focus was paid to number 7, which aims to achieve universal access to electricity, taking that figure of 800 million down to 0. [2]
- Engineers Without Borders (EWB), however, have estimated that this goal will be missed by 650 million people. Therefore, it is a problem which still needs significant investment and development
- EWB also researched and found that this lack of electricity disproportionately affects those in the lowest countries in the Human Development Index (HDI) [1]

Project Brief



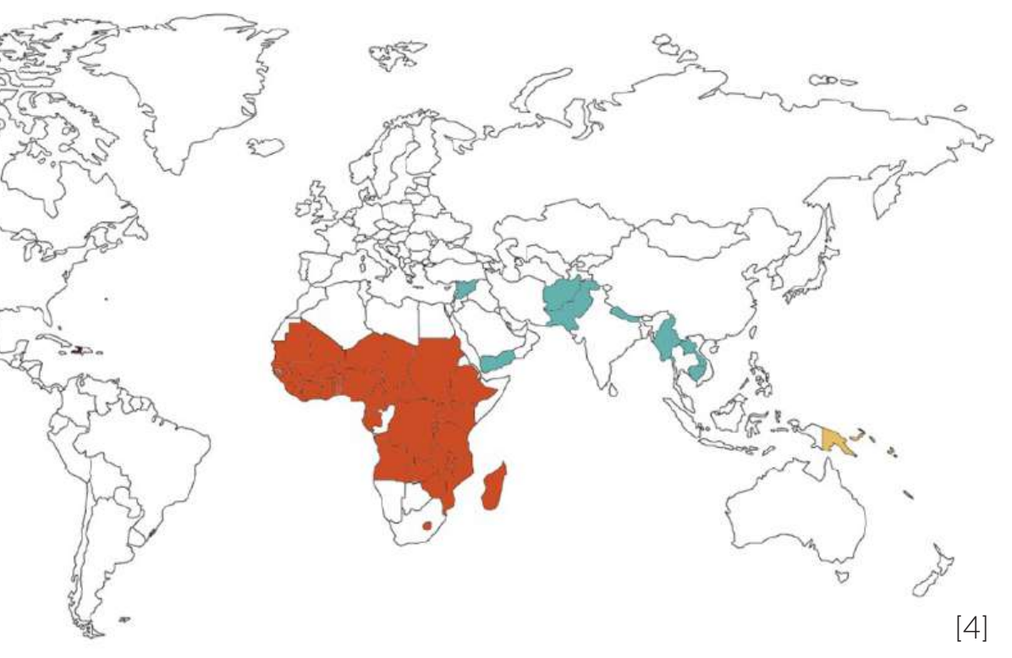
Solution

Strategy

- Design of affordable, super-efficient products
- Leads to mass uptake of quality appliance and electricity

Additional Benefits

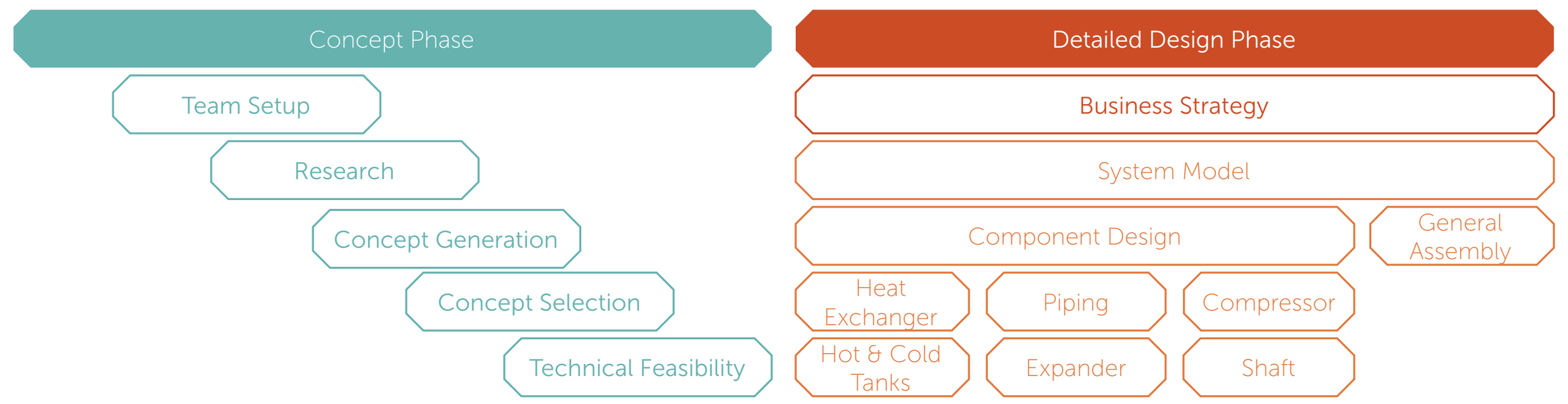
- Stronger markets and company sales
- Increased public and private investment
- Reduced greenhouse emissions
- Improved well-being:
  - Health
  - Education
  - Equality
  - Wealth
  - Food Storage [3, 4]


[4]

- The countries are mainly in Sub-Saharan Africa
- 87% of people live in rural areas

Project Plan

The Gantt chart below summarises the plan followed throughout the project. It is divided into two main phases: the concept, and the detail design phase. Within the detail design phase, a system model was developed throughout on MATLAB, in parallel to the design of the physical components. Once all the individual parts were designed, they were brought together within the general assembly.

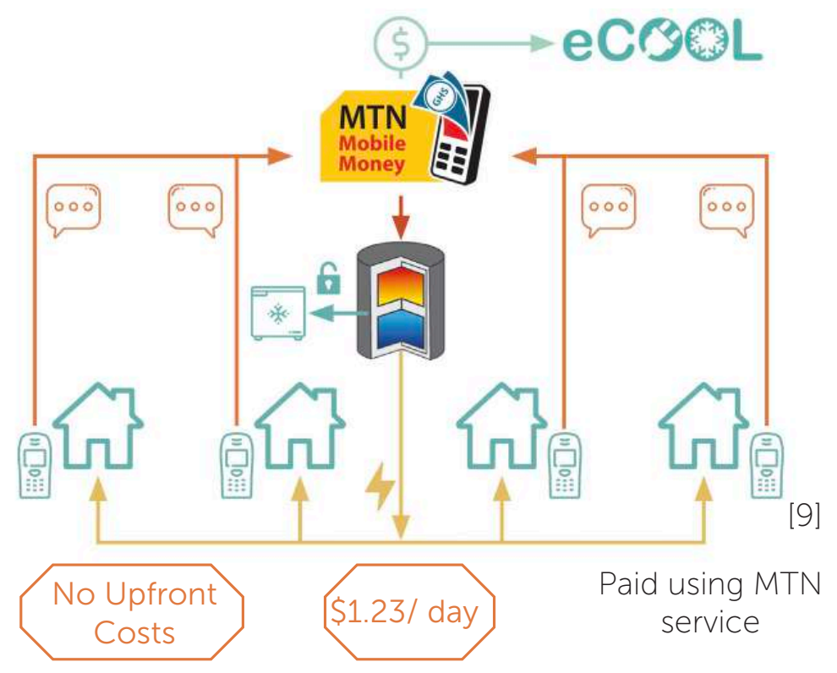


---

[1] Engineers Without Borders, "Efficiency for Access Design Challenge Challenge Brief," 2020
[2] United Nations, "Energy – United Nations Sustainable Development." [Online]. Available: https://www.un.org/sustainabledevelopment/energy/. [Accessed: 19-May-2020]
[3] Engineers Without Borders, "Why Efficiency for Access?," 2020. [Online]. Available: https://efficiencyforaccess.org/why-efficiency-for-access. [Accessed: 19-May-2020]
[5] GBDP Group 17, Rosie Knight SG7 Project Manager Report [4] GBDP Group 17, SG3 Report

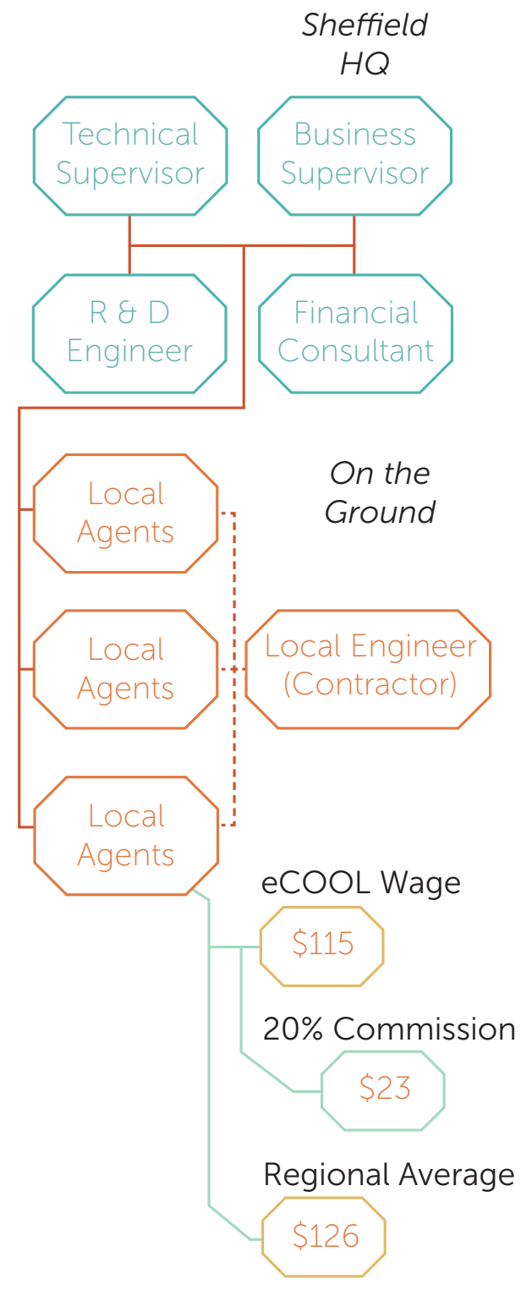
Business Model

The eCOOL business plan was devised based on studies and research conducted into potential markets within the bottom 50 of the Human Development Index. Liberia was selected as the start-up location based on a feasibility study looking into factors such as Global Peace Rating, electricity access rate and mobile network coverage. The eCOOL headquarters will be set up in Sheffield, UK to oversee all operations and financial management. Manufacturing facilities will be established in South Africa, taking advantage of its relatively stable economy and material sourcing potential. eCOOL systems will be shipped to Liberia to be installed by local agents. Local agents will also be responsible for marketing and sales within target areas. To achieve eCOOLs core value of sustainability, systems will be collected at the end of its life-cycle. Components will be reused or remanufactured.



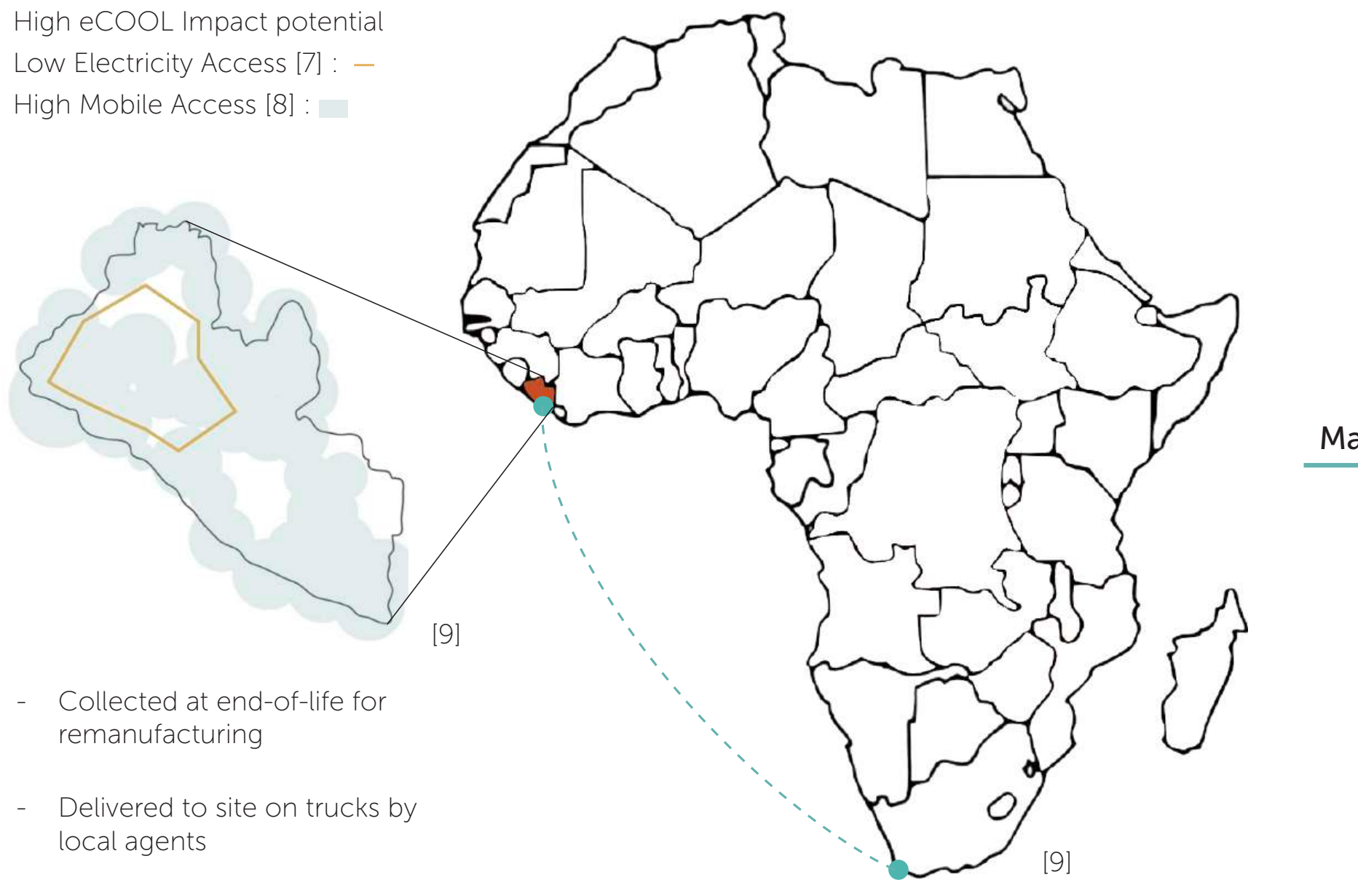
[9]

Company Structure



Target Country: Liberia

- High Global Peace Rating [6]
- High eCOOL Impact potential
- Low Electricity Access [7] : —
- High Mobile Access [8] : ▨


[9]
[9]

- Collected at end-of-life for remanufacturing
- Delivered to site on trucks by local agents
- Manufacturing in South Africa

Market Comparison

Finances

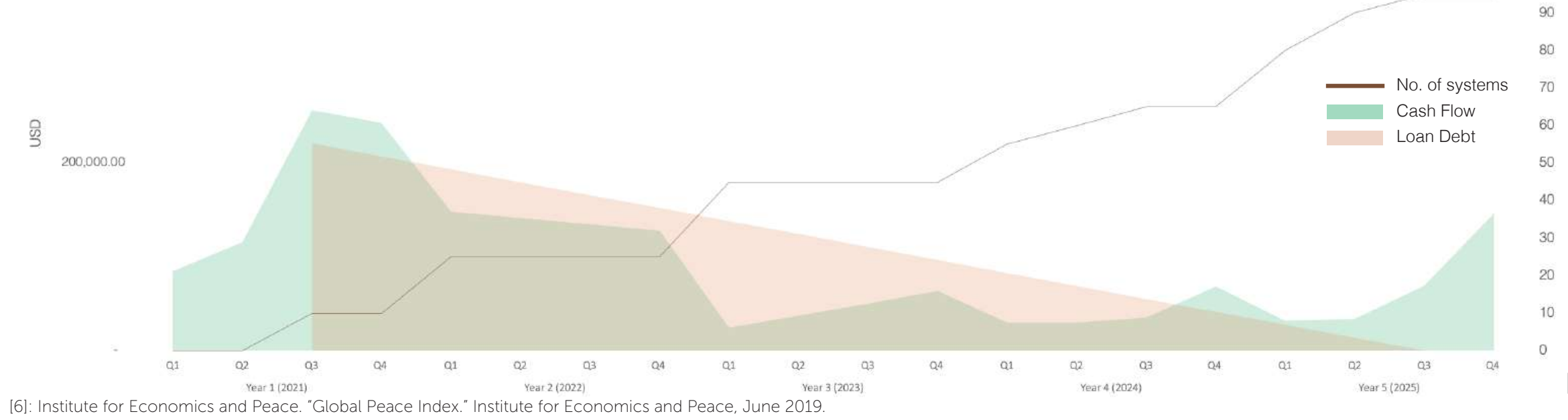
Funding

SETsquared Investment : $25,000
GOV Innovation Fund (Phase 1) : $60,000
GOV Innovation Fund (Phase 2) : $60,000
Business Loan (5% interest) : $200,000

After Five Years

Systems Installed : 95
All Loans Repaid
Cash Reserves : $146,000

Manufacturing Cost
Per System: $4800



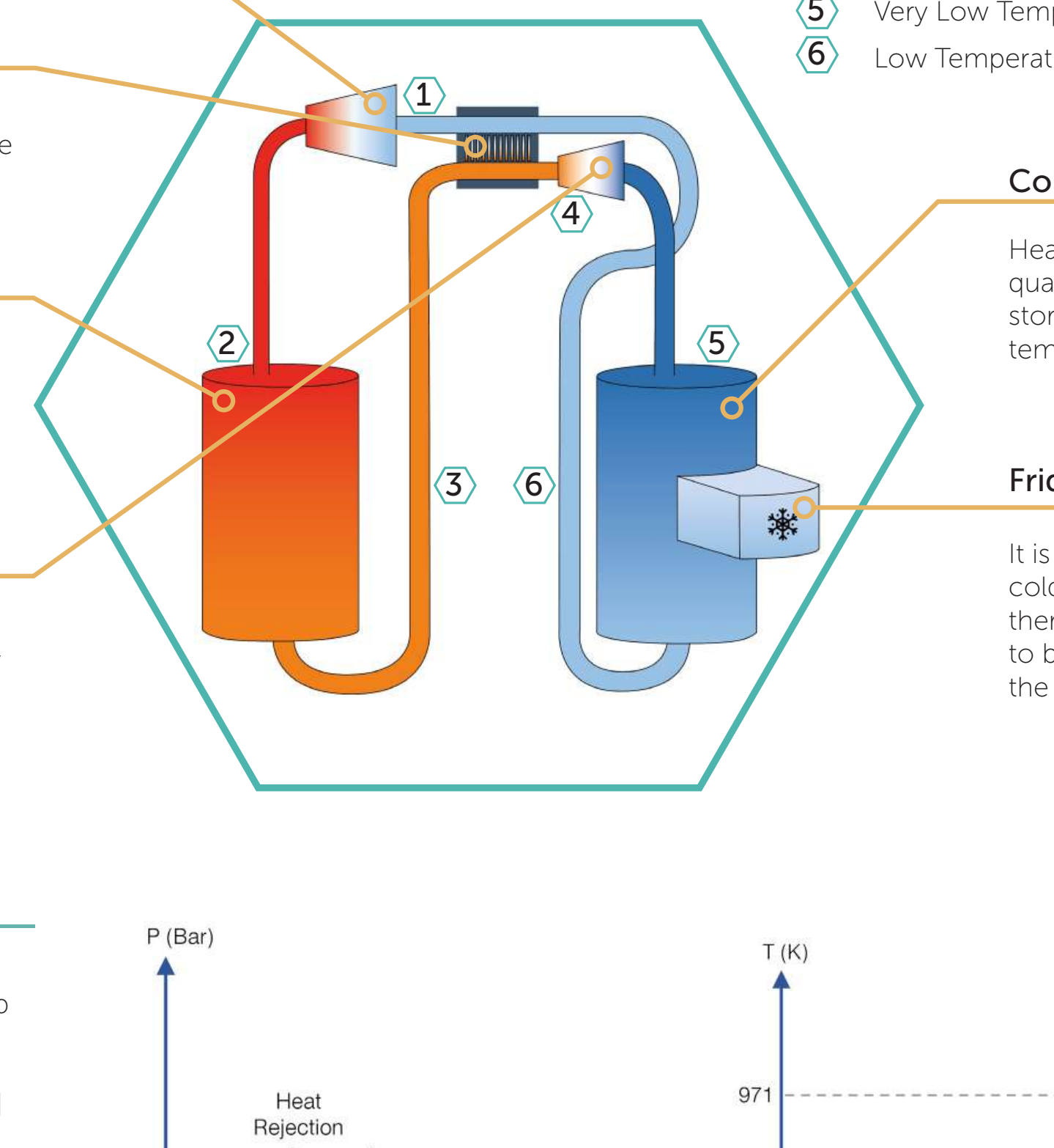
[9]

---

[6]: Institute for Economics and Peace. "Global Peace Index." Institute for Economics and Peace, June 2019.
[7]: US Aid. "Power Africa in Liberia: Power Africa." U.S. Agency for International Development, 16 Apr. 2020, www.usaid.gov/powerafrica/liberia.
[8]: GSMA. "Network Coverage Maps." Coverage Maps, 2020, www.gsma.com/coverage/#3950.
[9]: GBDP Group 17, SG5 Business Report

Pumped Thermal Energy Storage

The Pumped Thermal Energy Storage (PTES) system is an energy storage solution, installed with an intermittent off-grid energy solution such as solar panels, to enable uninterrupted power. It is installed into existing mini grids to increase power security as an alternative to batteries. The energy is stored as a temperature differential which can be directly utilised in different applications.



Compressor

The argon is compressed, increasing the pressure and temperature of the gas.

Heat Exchanger

Heat is transferred between the pipes, equalising the temperature of.

Hot Reservoir

Heat is transferred from the argon to the quartz gravel to store thermal energy at high temperature.

Expander

The argon is allowed to expand and work is extracted to partially power the compressor. The temperature drops significantly and the pressure returns to ambient.

① Ambient Temperature & Pressure
② Very High Temperature & High Pressure
③ High Temperature & High Pressure
④ Ambient Temperature & High Pressure
⑤ Very Low Temperature & Ambient Pressure
⑥ Low Temperature & Ambient Pressure

Cold Reservoir

Heat is transferred from the quartz gravel to the argon to store thermal energy at low temperature.

Fridge/Freezer

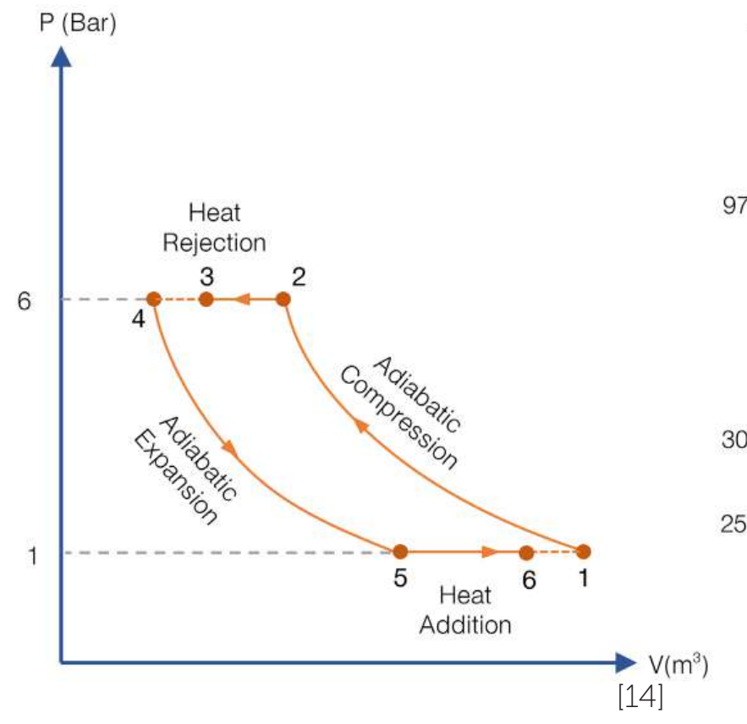
It is connected to the cold reservoir with a thermosyphon to allow heat to be drawn away, freezing the stored ice-packs.

Thermodynamics

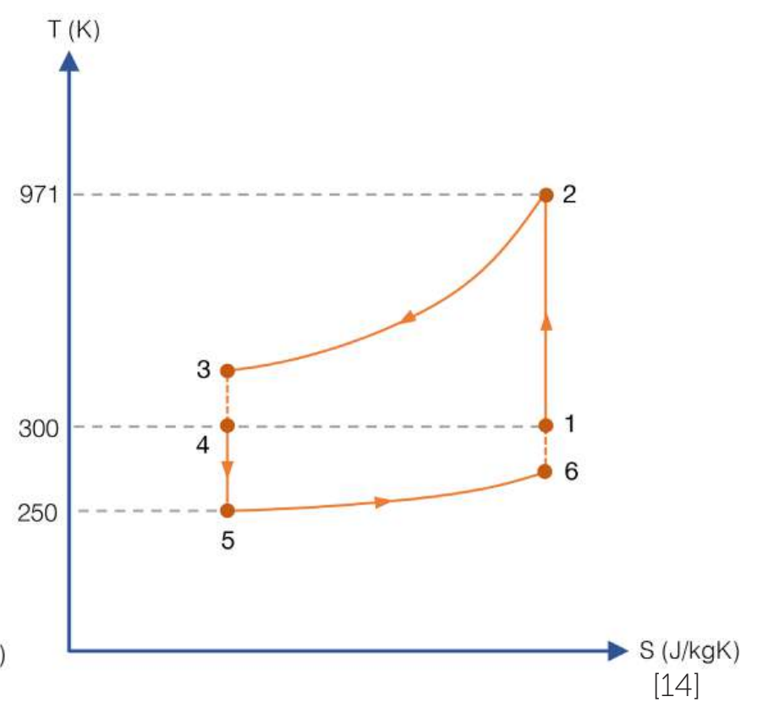
Argon (working fluid) is ideally pumped around the closed loop Joule-Brayton cycle [10].

1-2: Isentropic Compression [11]
2-4: Isobaric Heat Rejection
4-5: Isentropic Expansion
5-1: Isobaric Heat Addition

In reality, the compression and expansion processes are adiabatic with friction losses leading to an irreversible cycle. Heat exchangers (3-4 and 6-1) ensure reversibility at the cost of lower efficiency [10].



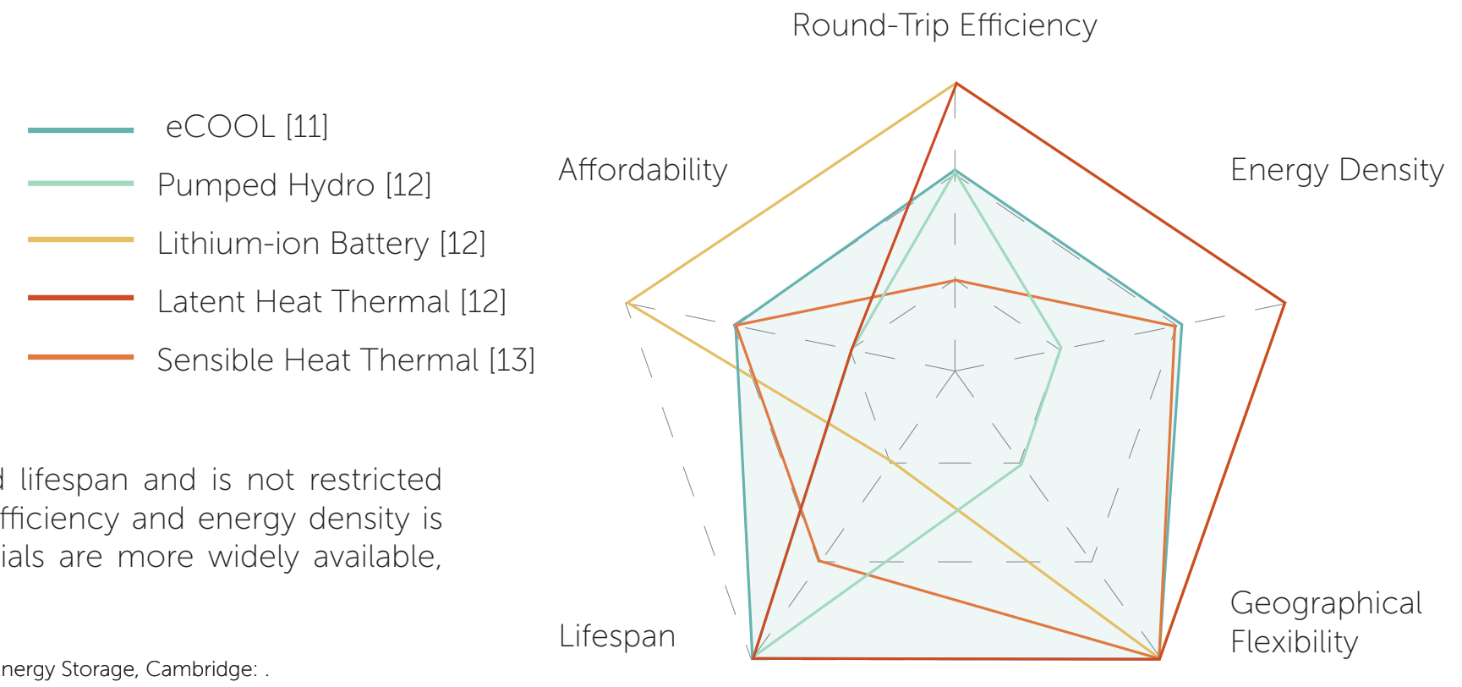
[14]



[14]

Comparison of Energy Storage

Existing micro-grids and solar home systems use lithium-ion batteries due to their high efficiency and energy density. However, lithium-ion batteries have a relatively short lifespan, which is only shortened further by the climate in Sub-Saharan Africa.



PTES negates the issues with shortened lifespan and is not restricted geographically. Although its round-trip efficiency and energy density is lower than other alternatives, the materials are more widely available, making it cheaper.

---

[10] McTigue, J (2016) Analysis and Optimisation of Thermal Energy Storage, Cambridge: .
[11] European Association for Storage of Energy (EASE) (2016) Pumped Heat Electrical Storage, : .
[12] EESI (2019) Fact Sheet: Energy Storage (2019), Available at: https://www.eesi.org/papers/view/energy-storage-2019 (Accessed: 10/06/2020).
[13] ETSAP (2013) Thermal Energy Storage, : IRENA., [14] GBDP Group 17, Donny Wong SG7 eCOOL System Integration and Overview Report.

Refrigeration System

In addition to the energy crisis, Sub-Saharan Africa faces a severe lack of affordable refrigeration solutions; 50% of fruit and vegetables are lost in SSA annually, largely due to a lack of refrigerated storage [15]. As initial system models predicted eCOOL's cold thermal store could potentially reach temperatures of -20°C [Ref_Fridge 2], use of this sub-zero thermal mass for food refrigeration was proposed. The results is a 3-component refrigeration system; a phase change material (PCM) "eCOOL Pack", charged within the "eCOOL Charging Station" which users replace every 24 hours to refrigerate their "eCOOL Fridge" at home.

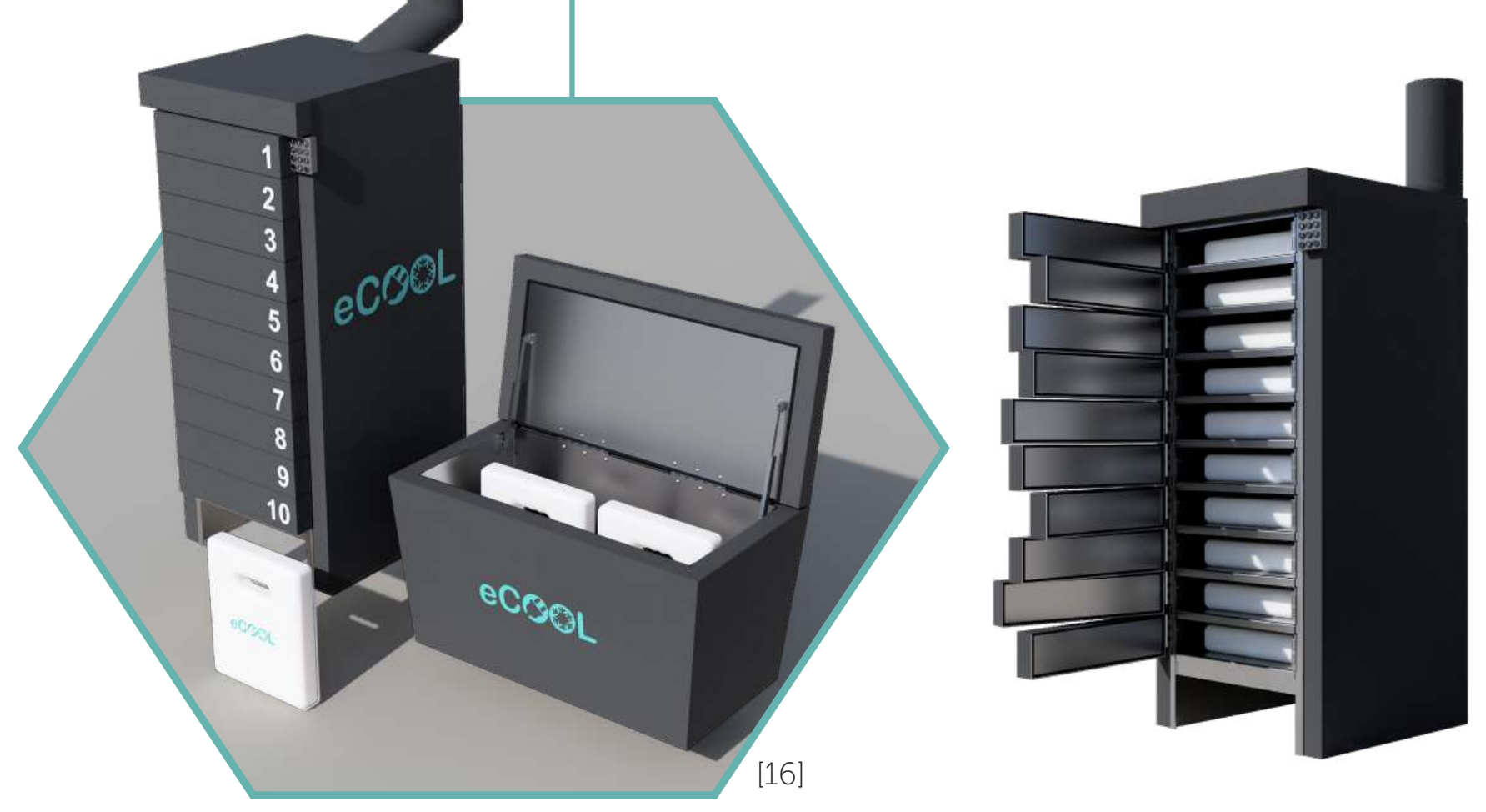
eCOOL Cool Box


[16]

- Telescopic sprung hinges ensure slow closing and easy lifting of potentially heavy lid
- Chest-style design with lid instead of door minimises heat influx when fridge is opened
- Stainless steel allows easy cleaning and no corrosion and creates divided storage areas within Fridge
- Vertical and central placement of eCOOL packs promotes natural convection, allows easy replacing every 24 hours and creates divided storage areas within eCOOL cool box.

eCOOL Pack

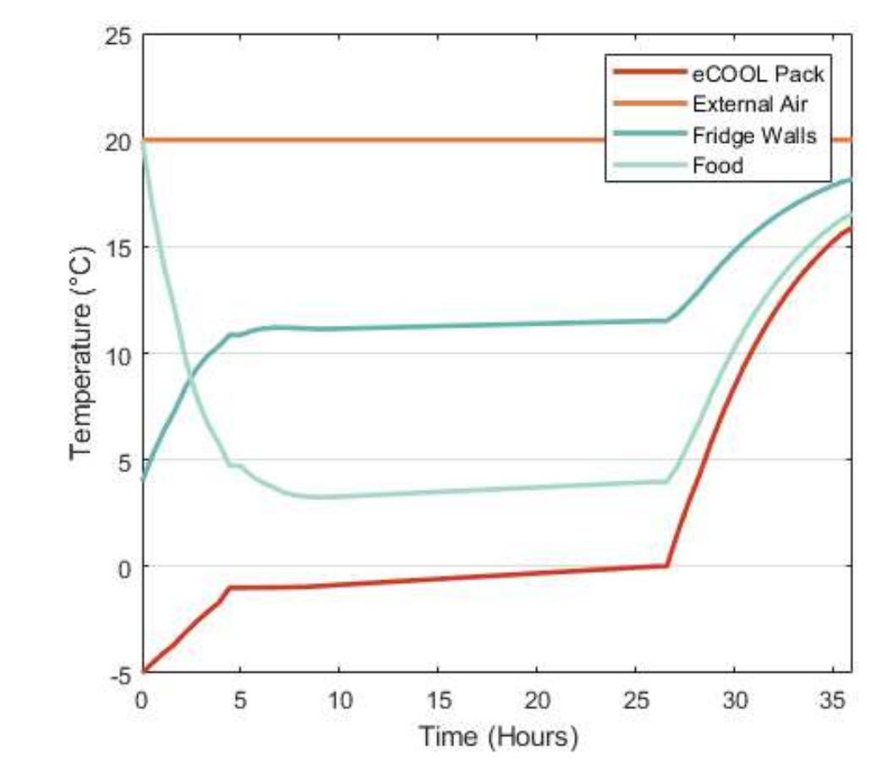
eCOOL Charging Station


[16]

- Water selected as phase change material (PCM) due to easy sourcing, low cost and melting temperature below ideal food storage conditions (-4°C) [17]
- 10kg of PCM needed per refrigerator split into two 5kg packs for ergonomic reasons

- Users are text a pin-code after completing mobile payment which they enter at the locker
- Electromagnetic latch controls locked or open state of lockers
- Users collect 2 x 5kg eCOOL Packs for at 24 hours of at-home refrigeration

Thermal Modelling




[16]

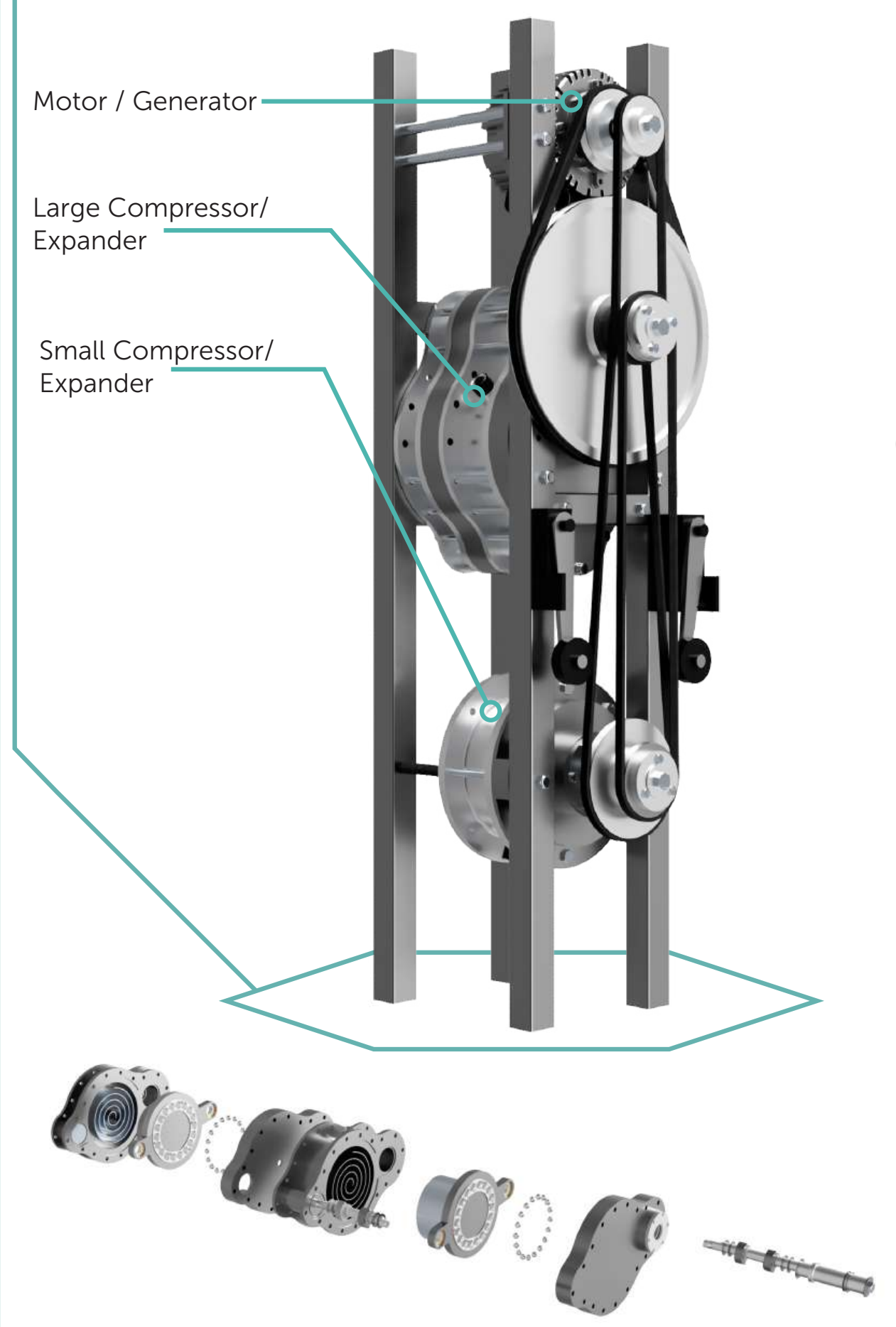
- Folded 2.5mm sheet steel construction, riveted means low cost, low volume manufacture & easy mounting of hinges and to eCOOL main frame

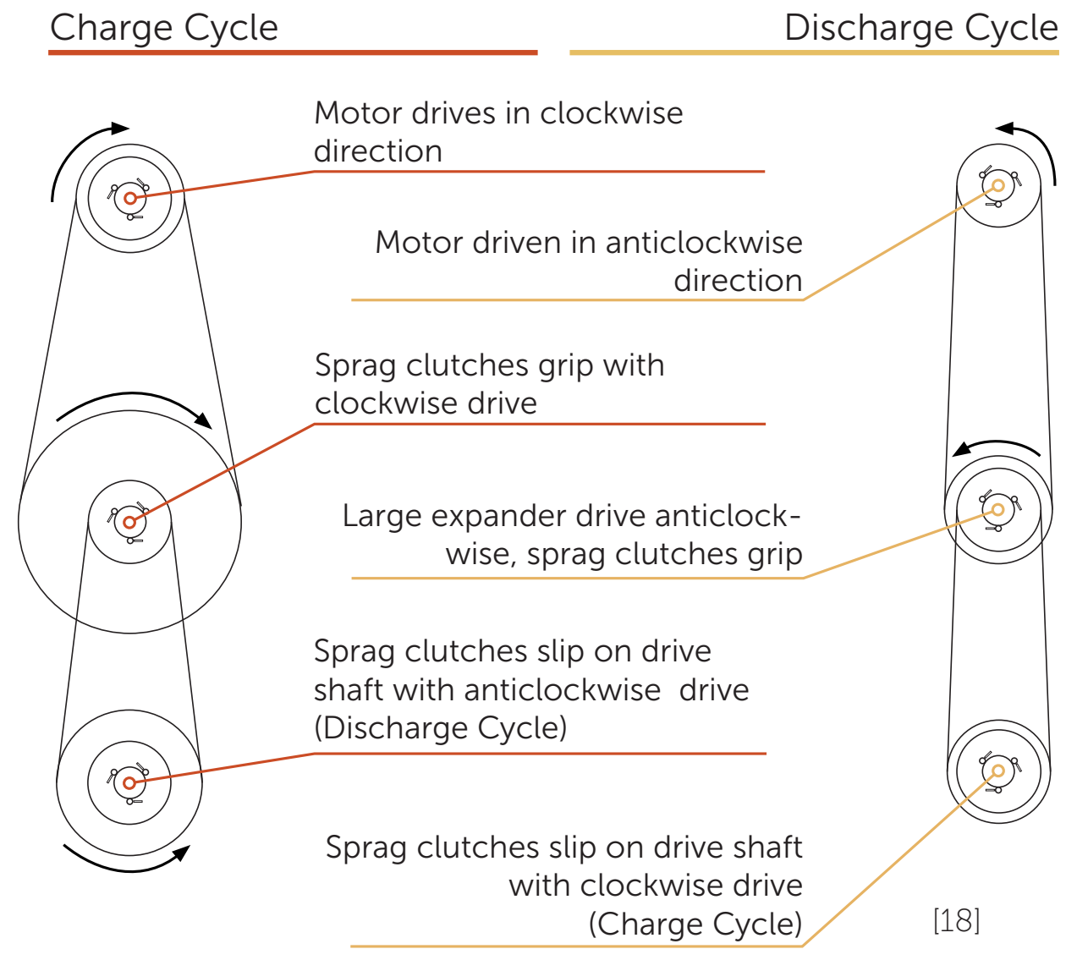
- Thermal model was created using Simscape (MATLAB Simulink plug-in) to determine scale of eCOOL pack [16]
- Convection was the primary heat transfer mode considered between 5 thermal masses

---

[15] P. For & A. L. L. Fact, Decentralized Renewables : Boosting Agriculture and Improving Nutrition. (2017) 9–10.
[16] GBDP Group 17, Jerome De Saulles SG7 Refrigeration Technical Report
[17] Are You Storing Food Safely? | FDA. https://www.fda.gov/consumers/consumerupdates/are-you-storing-food-safely (accessed May 26, 2020).

Motor/ Compressor Assembly





[18]

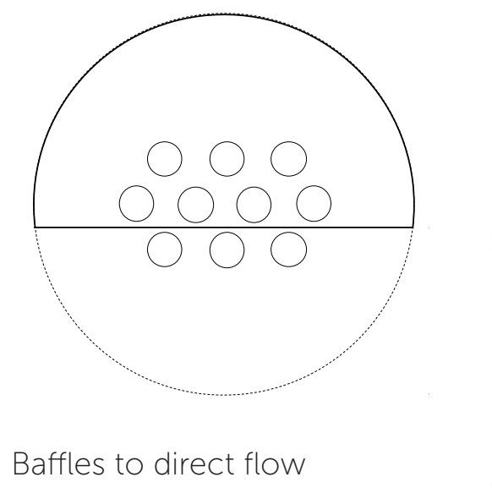

[18]

The reversible compressor/ expander assembly uses scroll units as they are easily reversible. The system consists of a two stage scroll, compression ratio = 8 and a single stage scroll, compression ratio = 4. These units are connected to a motor/ generator by the double pulley system that automatically adjusts the gearing of the system dependant on direction, using sprag clutches.

Heat Exchanger

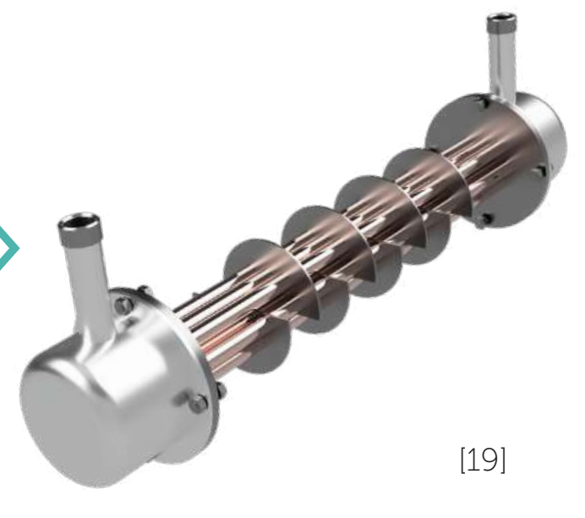
The eCOOL heat exchanger increases overall system efficiency by bringing argon exiting the cold and hot tanks down to ambient temperature (20°C). This is crucial to the overall running of the system as it ensures the appropriate temperature differential can be created between the tanks for energy storage. This is achieved using a counter-flow shell and tube heat exchanger where the hot and cold argon undergo thermal exchange across the tube walls. The heat exchanger attaches to the eCOOL frame body and has 4 connections into the hot and cold tanks, as well as the compressor and expander.

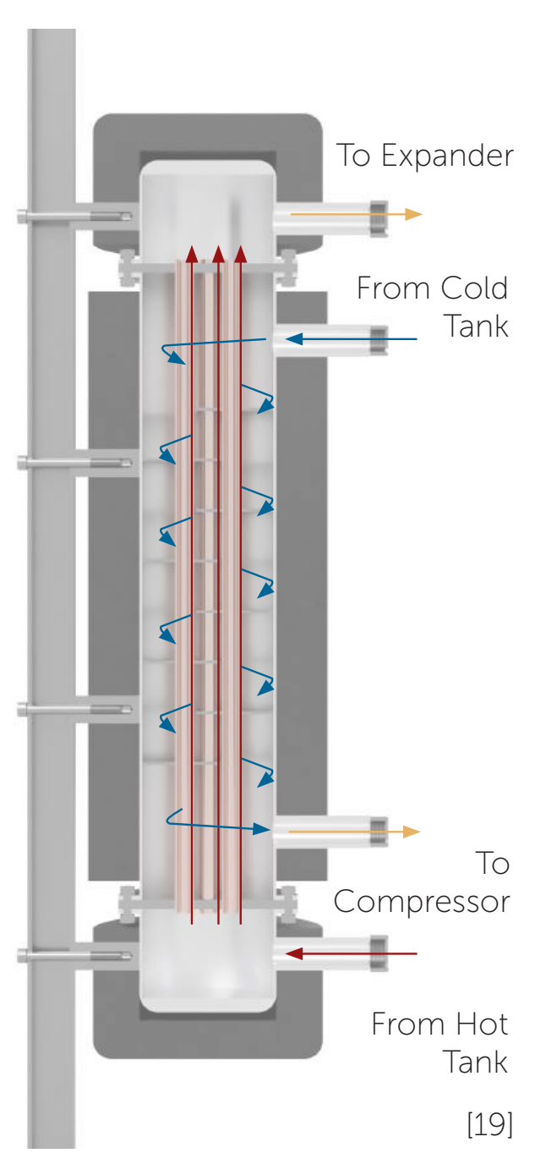
Counter-flow shell and tube heat exchanger
Increases system efficiency by bringing fluid temperature to ambient before compression/expansion
Designed following Kern's method



8 Baffles to direct flow
700mm Tube Length
Triangular array
10 Tubes [19]

Insulation Material:
FOAMGLAS ONETM


[19]



[19]

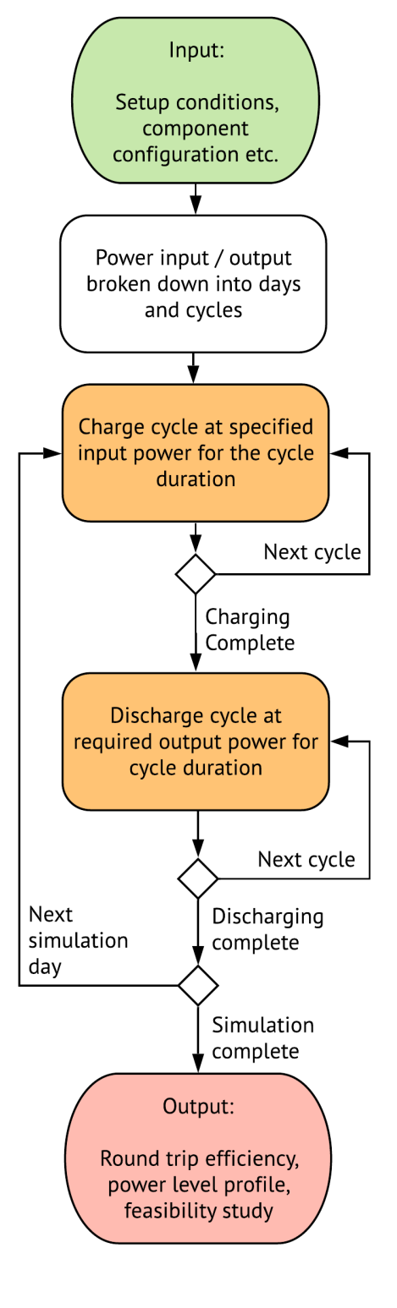
---

[18]: GBDP Group 17, Sam Riddell-Webster SG7 Compressor Report
[19]: GBDP Group 17, Jerry Chung SG7 Heat Exchanger Report

System Optimisation Modelling

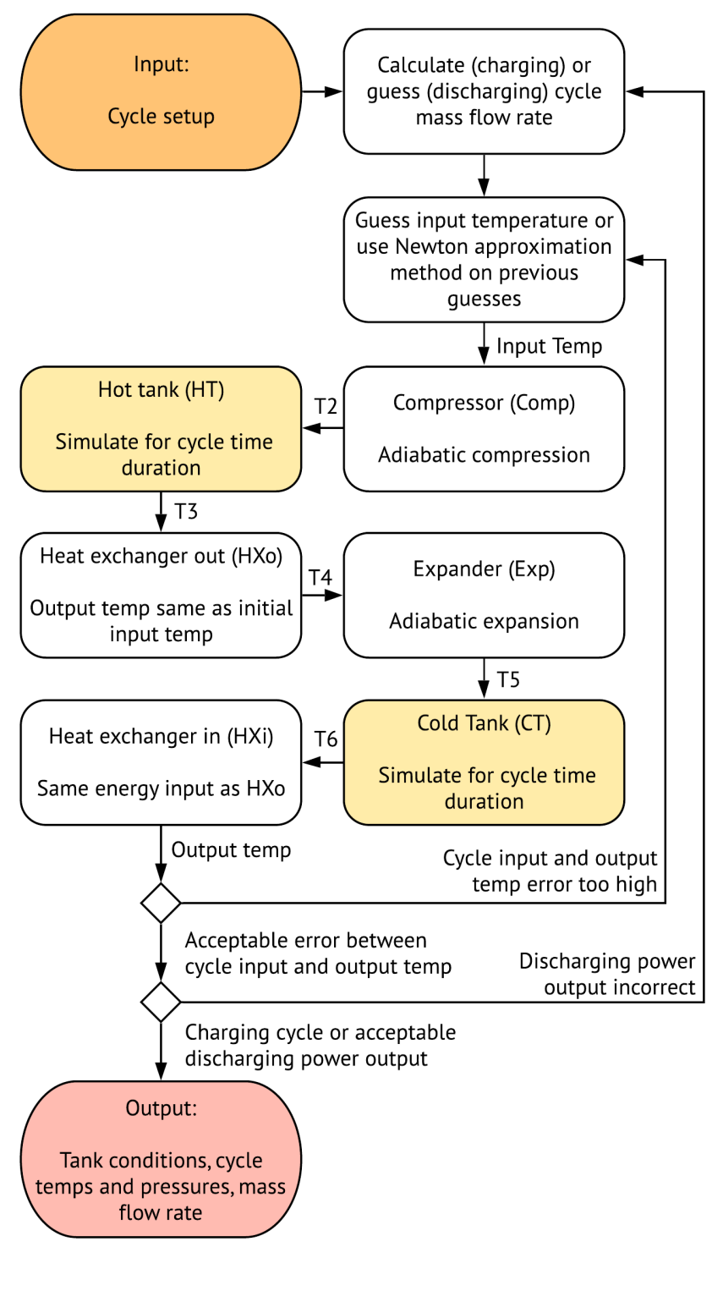
To understand the system, a numerical simulation model of its operation was required. The MATLAB model allows for a deeper understanding of the interactions between components and provides feedback on less obvious design choices.

Simulation Overview



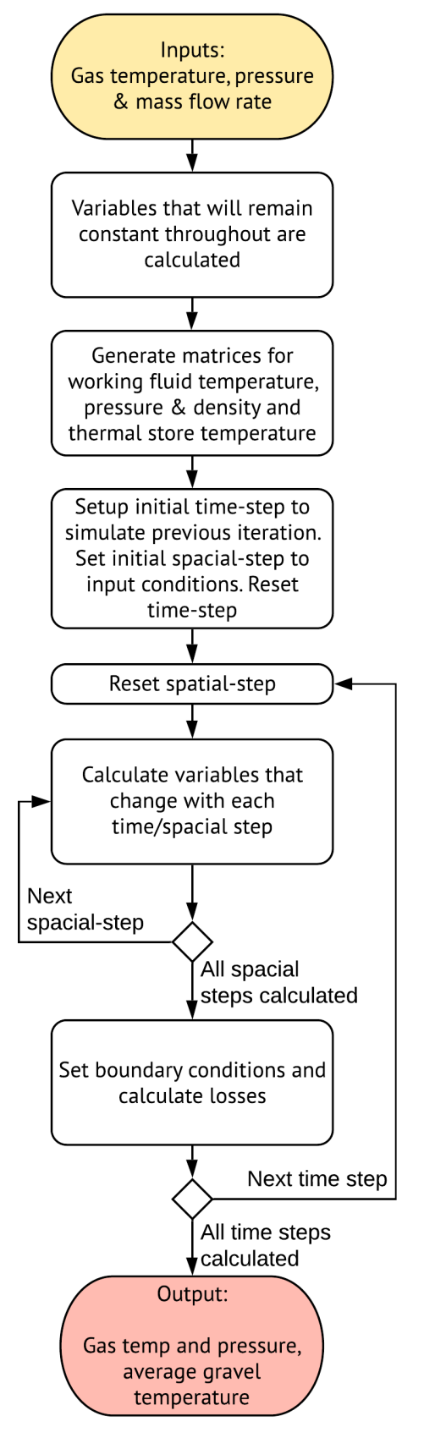
Breakdown of the top-level program which breaks simulation down to simulation cycles. [13]

Charge & Discharge Cycle



Runs through each component and ensures each cycle is quasi-static. [13]

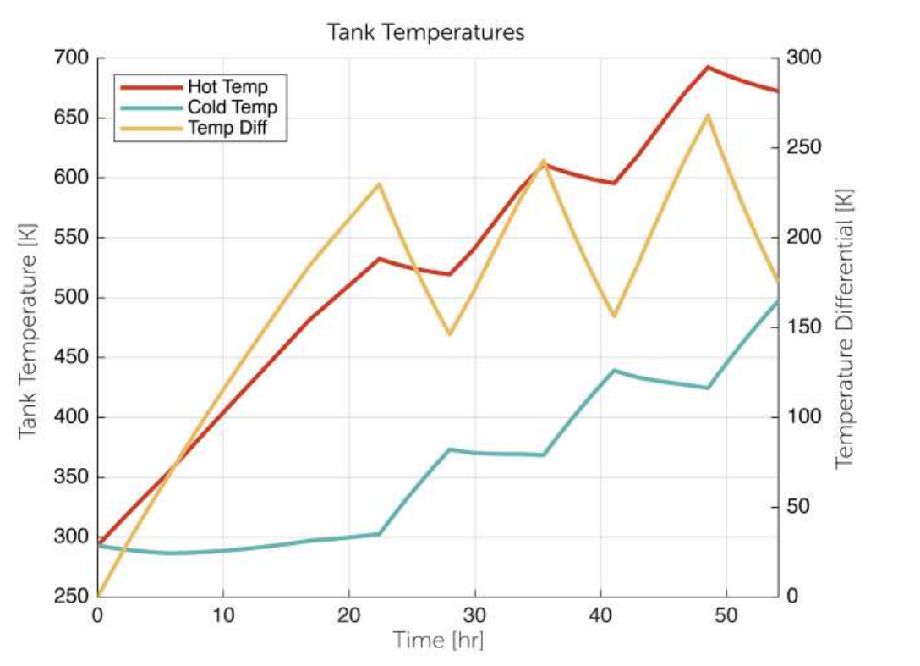
Hot/Cold Reservoir



Simulation of heat transfer in the thermal tanks for input cycle. [20]

System Performance Profiles

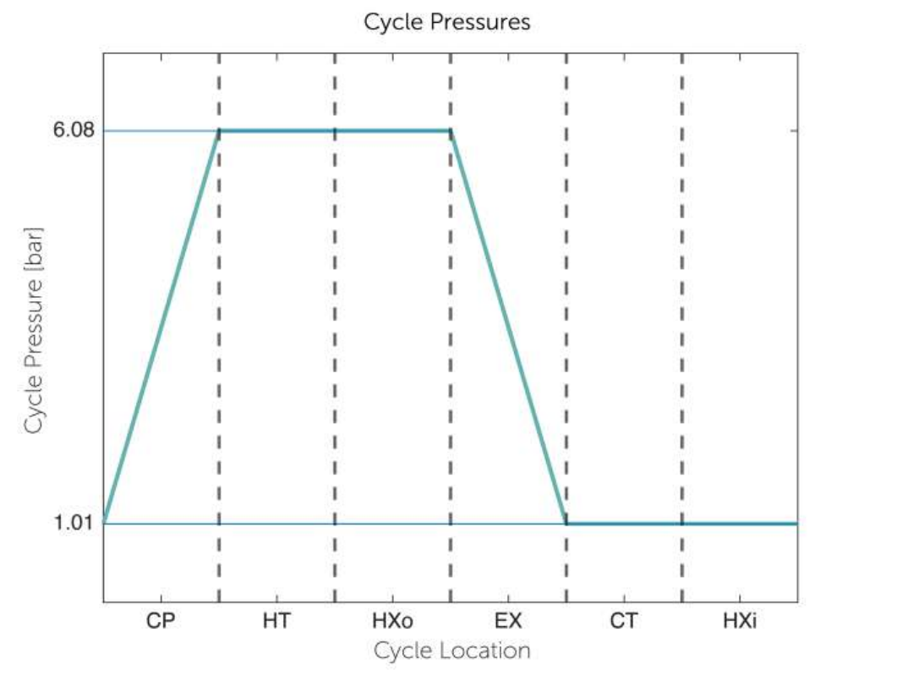
Over 30 iterations of different system configurations were simulated. The performance profiles of the latest and best iteration are shown here. The graphs presents three days of charging, followed by individual days of discharging and charging. Further work is required to refine the configuration to optimise the tank temperatures.



Tank Temperature Profile [13]

- Steady profile of storage capacity over time.
- The rise and fall are charge and discharge cycles.

The temperature differential is required to drive the flow of the PTES on discharge and hence a direct indicator of energy capacity stored.



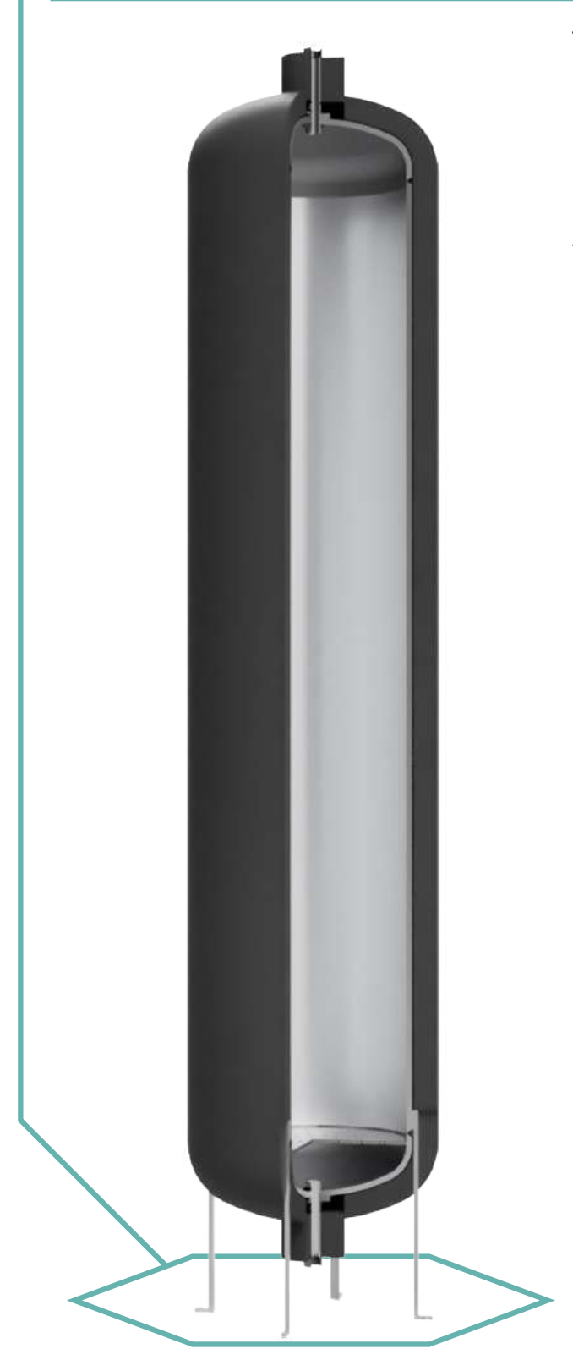
Cycle Pressure Profile [13]

Breakdown of cycle pressures throughout the cycle. The pressures are ambient on the cold side of the system and at 6 bar on the hot side (average of the compression ratios).
Pressure is assumed to be constant on either side of the compressor/ expander with isobaric components.

---

[13] ETSAP (2013) Thermal Energy Storage, : IRENA., [14] GBDP Group 17, Donny Wong SG7 eCOOL System Integration and Overview Report.
[20] GBDP Group 17, Jack Martin SG8 eCOOL Thermal Tank Optimisation Report.

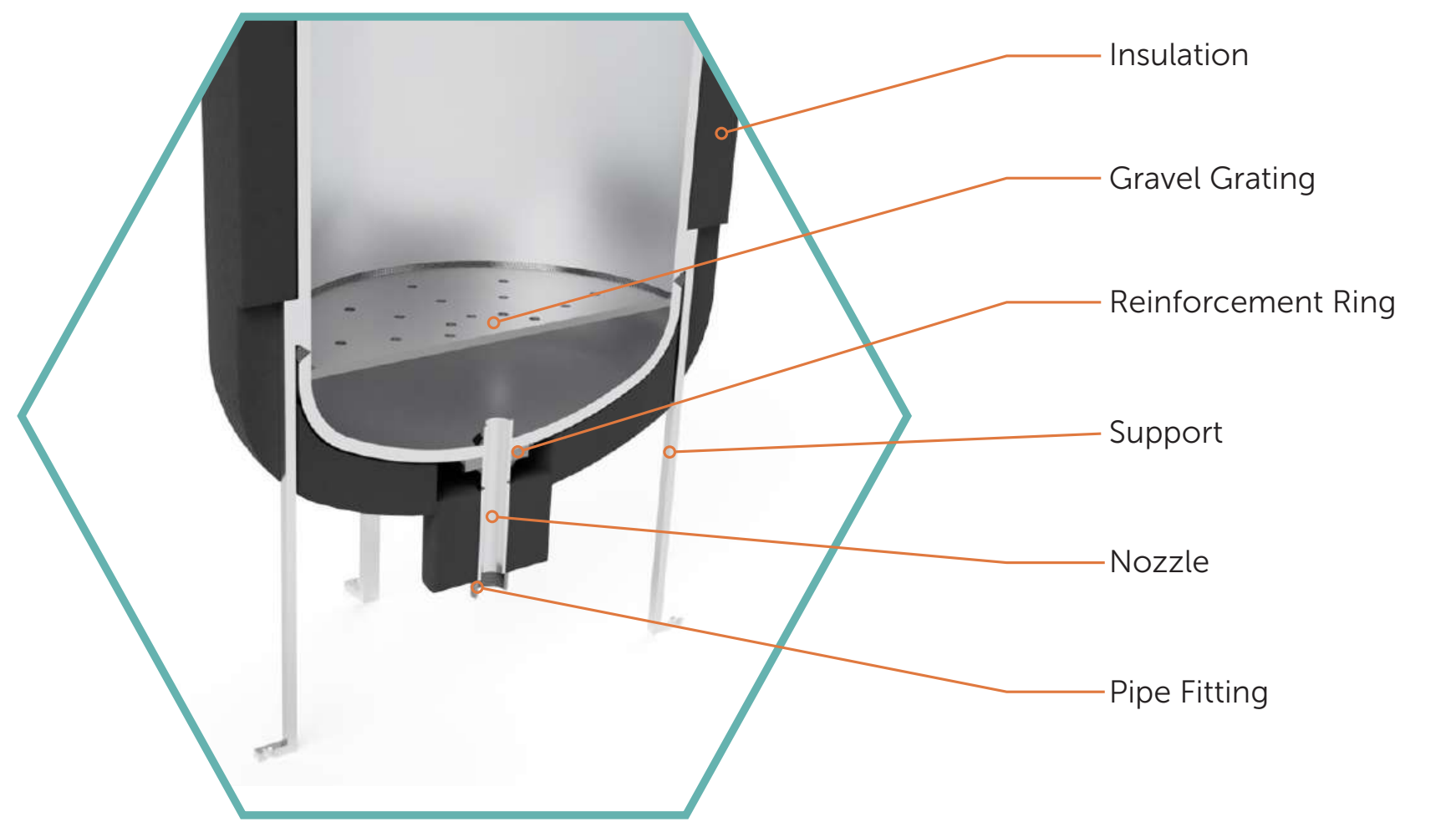
Tanks



The tanks were both designed to adhere to the regulatory standards laid out in the American Society of Mechanical Engineers (ASME) pressure vessel legislation. This meant the tanks were able to withstand the internal pressures and loads from the argon and gravel at the limiting temperatures, ensuring safe operation.

An internal gravel grating was designed to stop the gravel entering the piping, whilst allowing for the flow of the working fluid, argon.

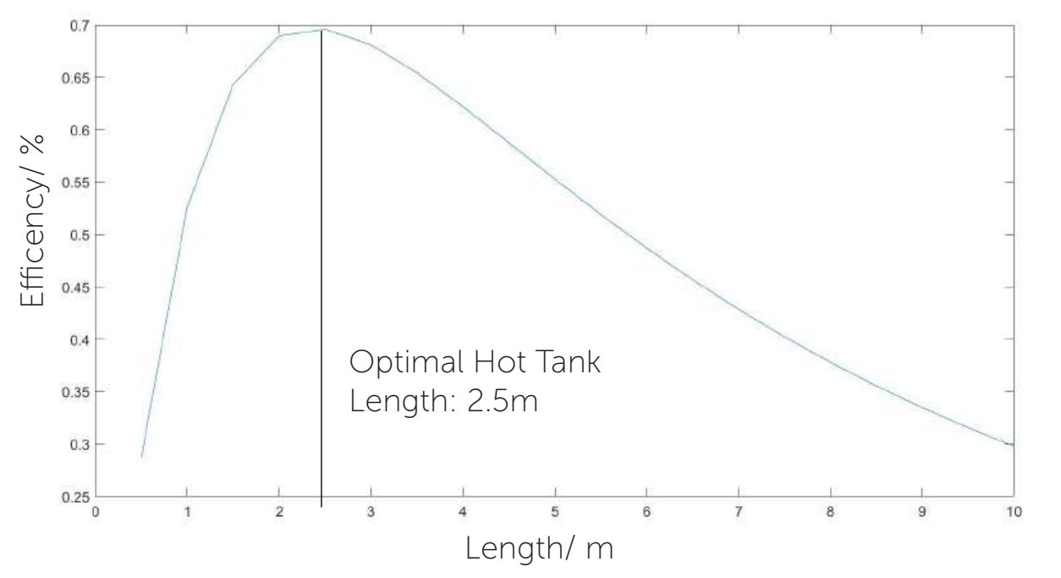
Semi-elliptical heads were used to form the ends of the vessels, leading to nozzles which required reinforcement pads to cope with the stress concentrations at these points.



Packed-Bed Thermal Reservoir Optimisation

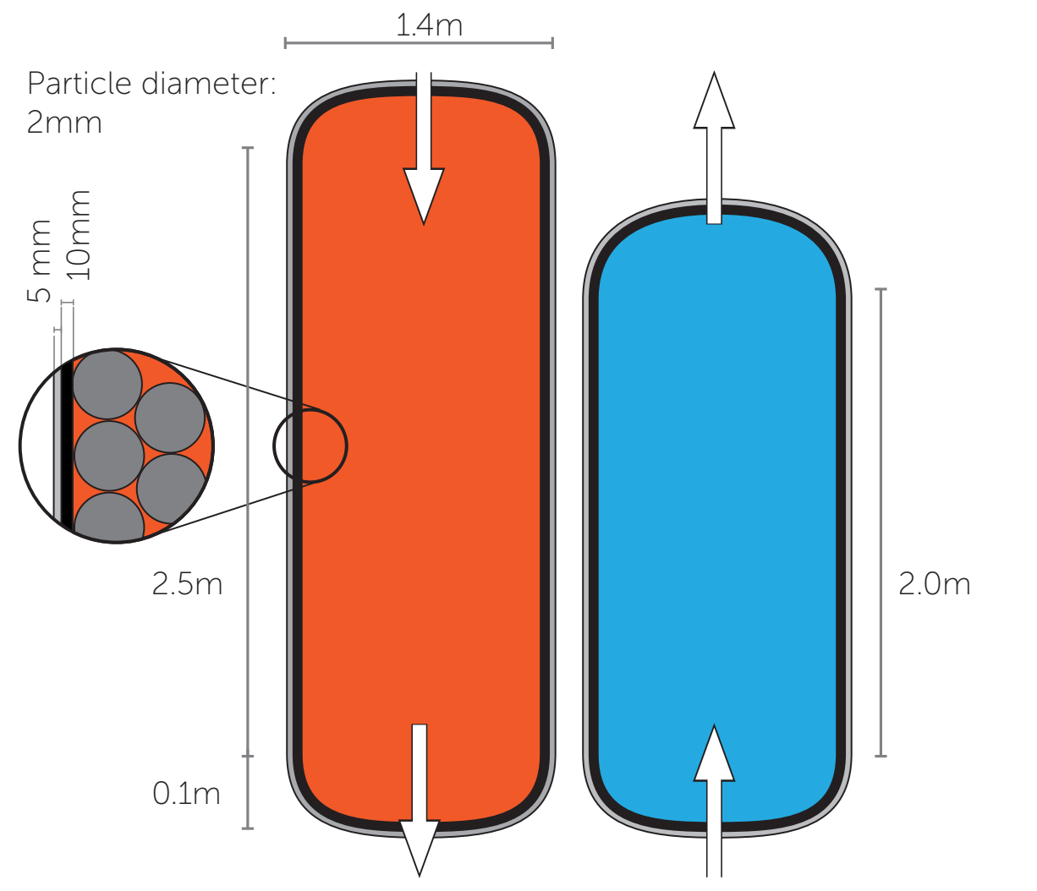
The Packed-Bed Thermal Reservoir (PBTR) stores thermal energy. The energy is stored as a temperature differential between the hot and cold reservoirs. To optimise the storage capacity, efficiency and charging time for the reservoirs; simulations were run with differing variables to find the optimal values for:

- Reservoir Length
- Reservoir Diameter
- Thermal Storage Material's Particle Diameter
- Insulation Thickness
- Steel Casing Thickness
- Mass Flow Rate
- Number of Reservoirs in Series

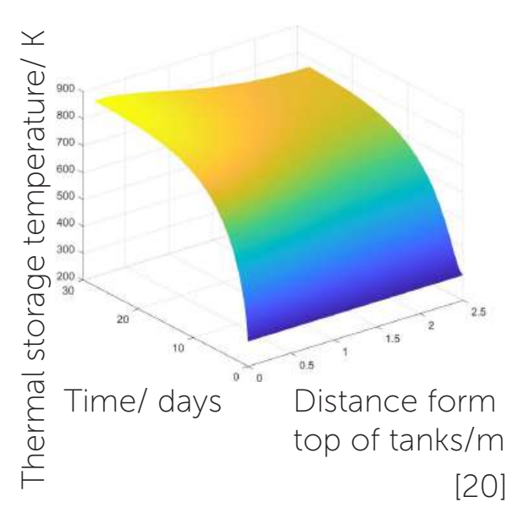


A graph showing the round-trip storage efficiency of the reservoir for a varying length, whilst all other parameters and inputs are kept constant

Optimal Tank Dimensions

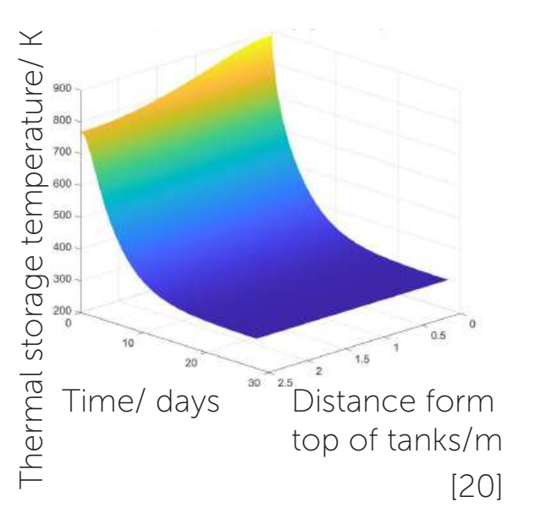


Optimal Hot Tank Charging



[20]

Optimal Hot Tank Discharge



[20]

---

[20] GBDP Group 17, Jack Martin SG8 eCOOL Thermal Tank Optimisation Report.