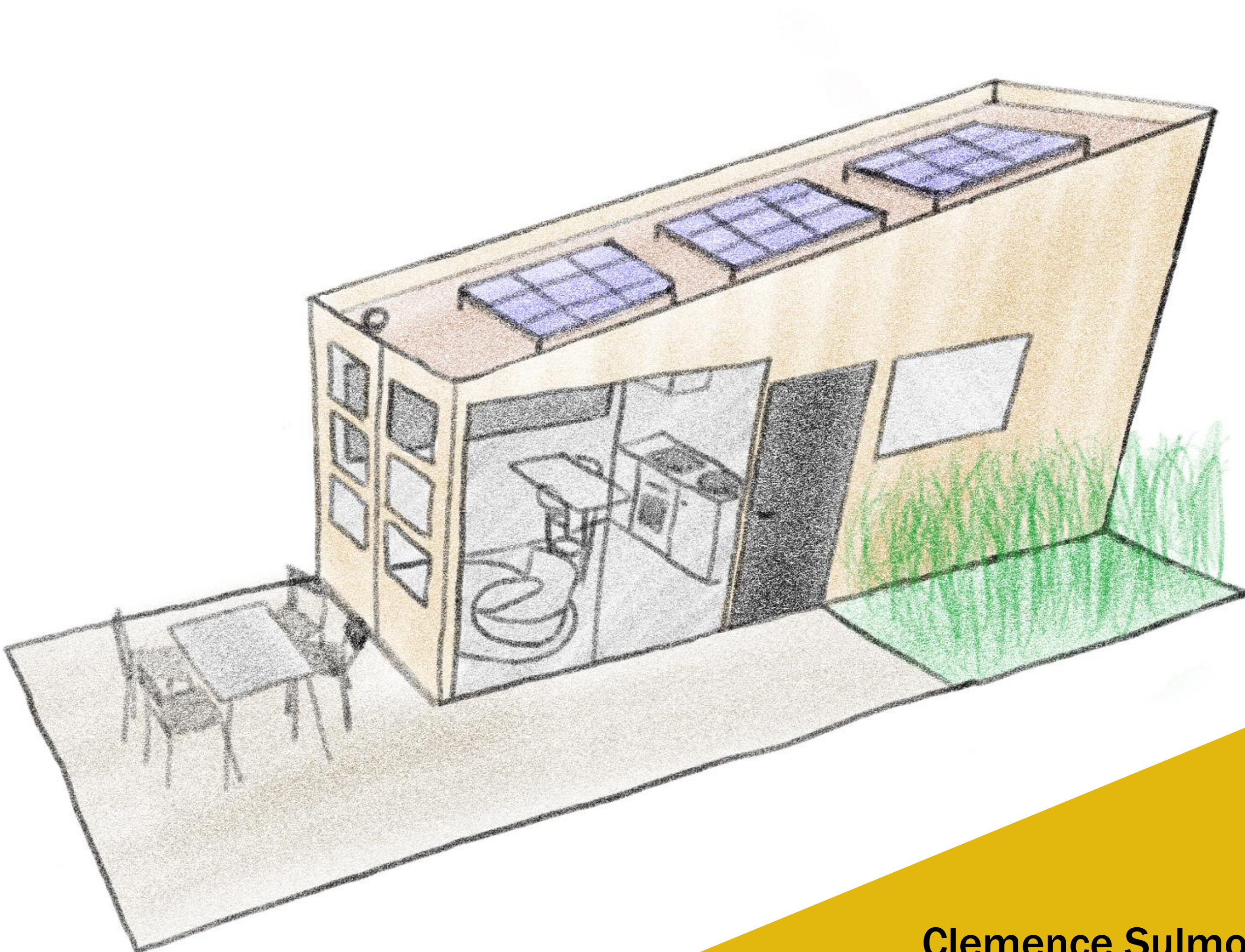
Carbon Neutral Tiny House



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Summary of Proposal

Although most houses are built from scratch which allows more freedom in decisions, the process is quite long and expensive. Therefore some people have started to use pre-existing structures to renovate into their homes, such as shipping containers. Made of metal, these require quite a few arrangements to transform the steel box into a comfortable home. Another trend that has been growing in house building is the creation of tiny homes, with all equipment packed in a small space. These are often built for one or two people, and are cheaper due to the smaller surfaces.

To test how both these trends could co-exist in a sustainable way, the tiny container house was analysed and designed to be carbon neutral. Implementation of isolation for all surfaces to avoid heat transfer energy loss and 20 mm diameter piping for optimum pressure loss helped reduce the energy demand of the house. A rain water collection system on the roof, suppling the grey water usage of the shower and toilets, and eight solar panels covering all the power demand of the house were also installed to meet the needs of the user. With these features, the tiny container house was found to be carbon neutral. Only the kitchen and bathroom tap couldn't be integrated to this closed energy loop as norms are in place, regulating the potable water circuits. However future technology could ameliorate water filtration and allow this house to become completely self sufficient.

Sketch views of tiny container house

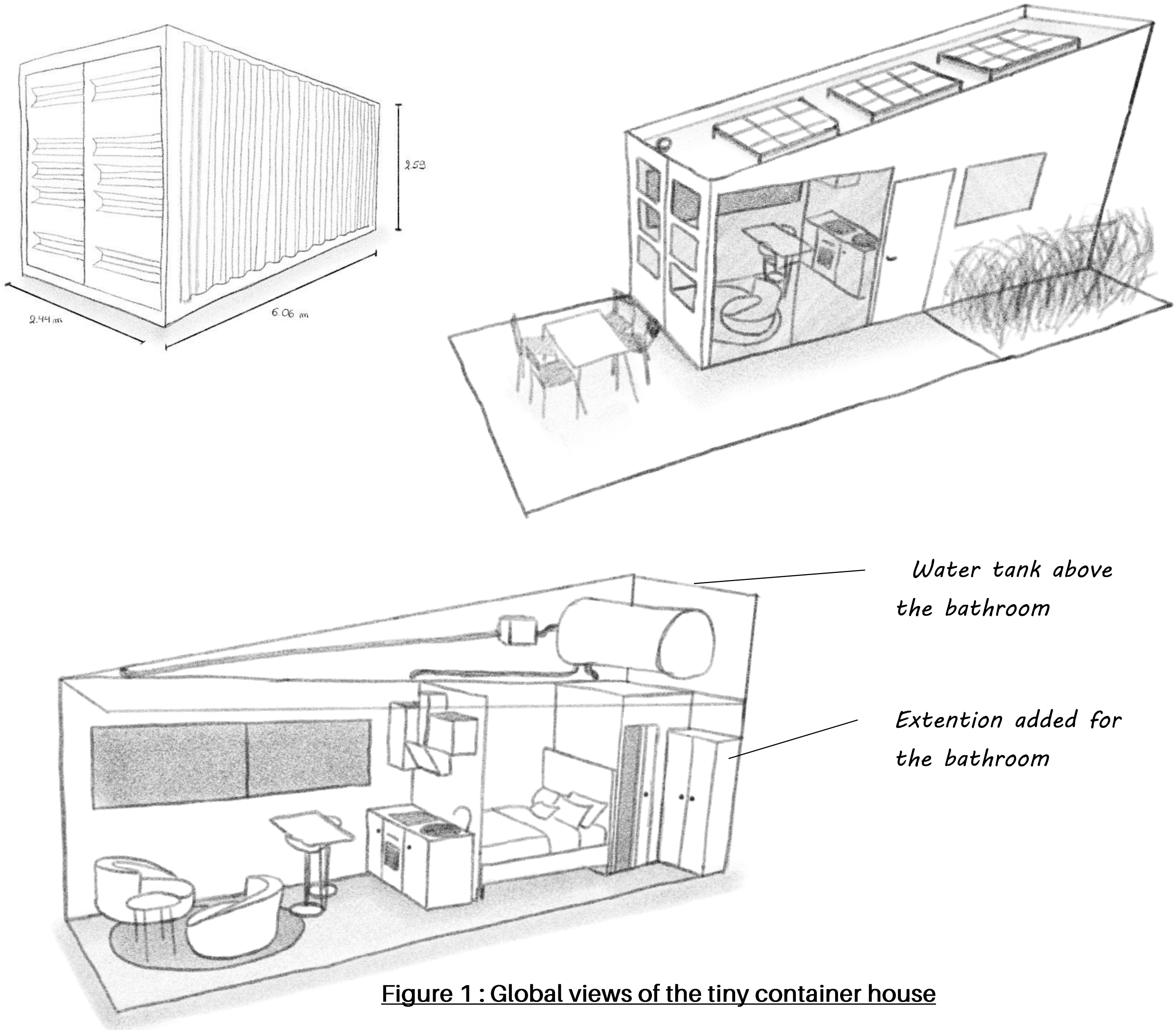


Figure 1 : Global views of the tiny container house

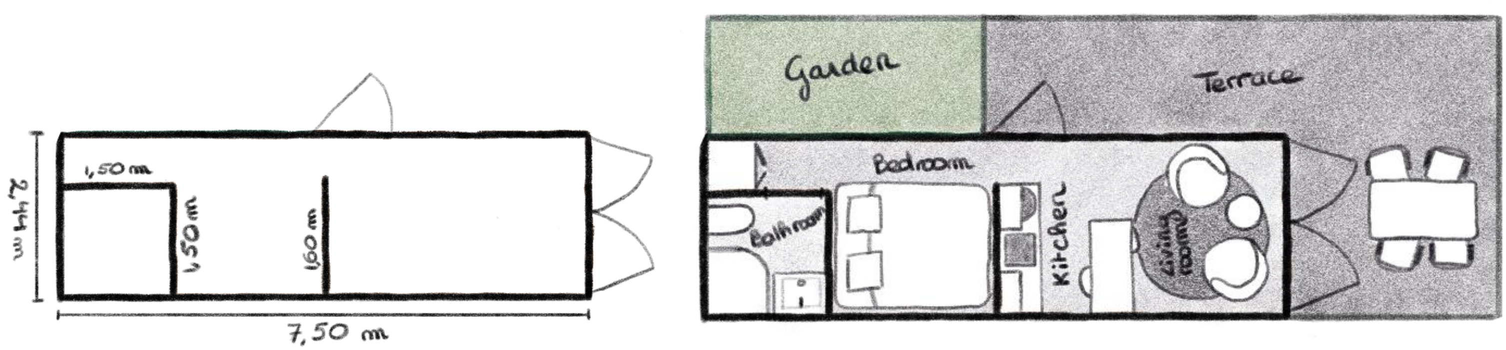


Figure 2 : 2D plans of the house

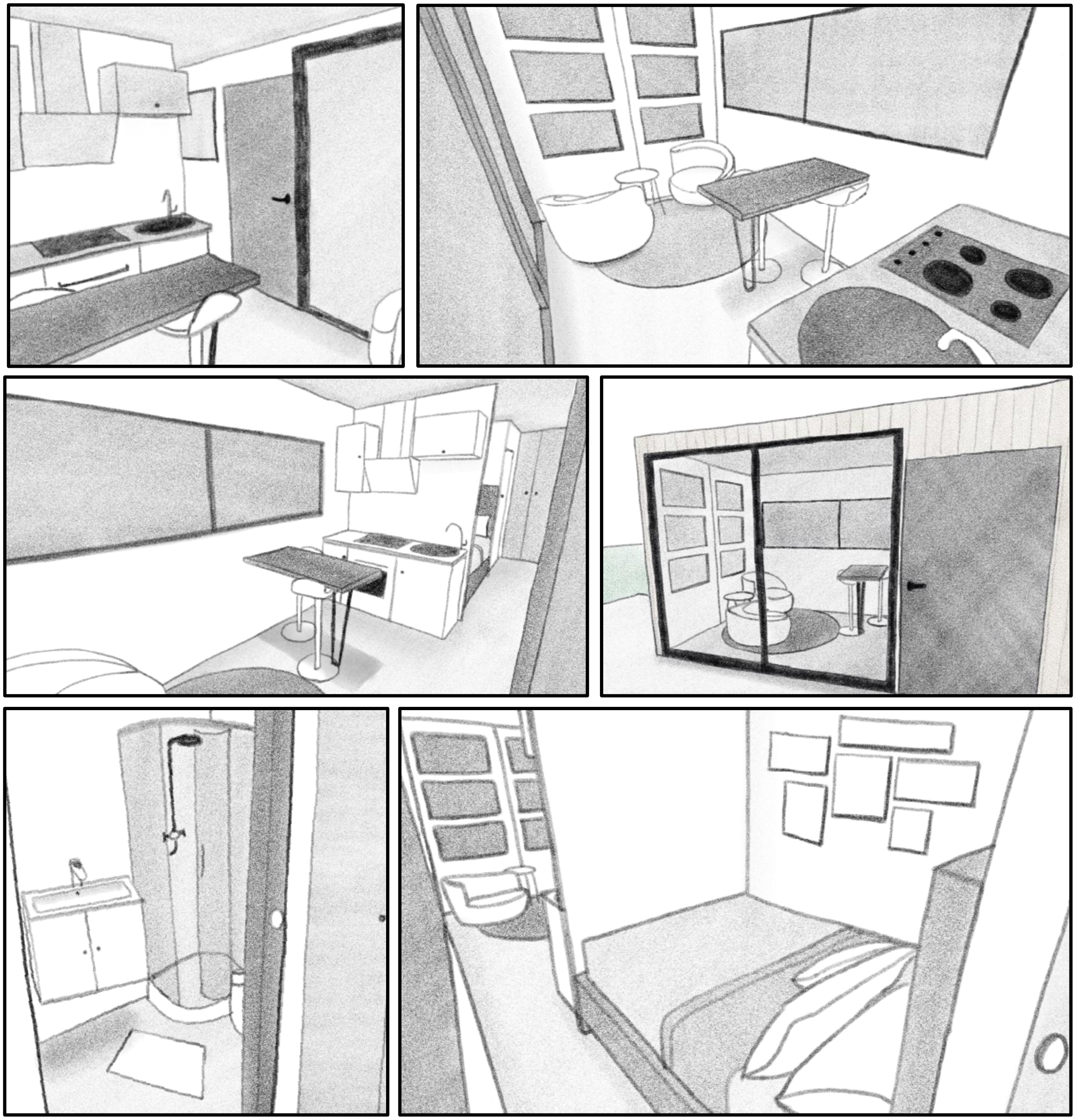


Figure 3 : Inside views of the house

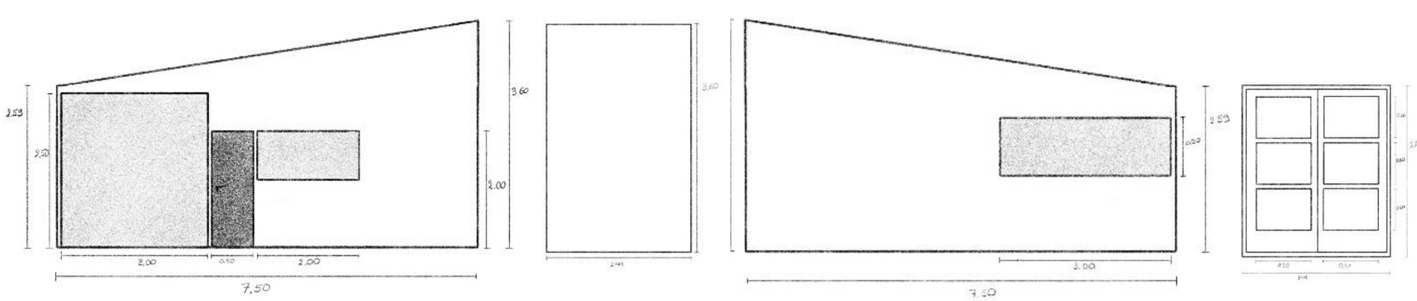


Figure 4 : Dimensions of the house

Intervention 1 – Heat loss reduction

Heat transfer Is the cause of the biggest energy loss in the house. Originally containers are completely made of corten steel which has a high thermal conductivity therefore isolation is essential. Using the following equations the heat loss reduction was observed.

$$q = \frac{T_i - T_o}{\frac{1}{h_i} + \frac{L_a}{k_a} + \frac{L_b}{k_b} + \frac{L_c}{k_c} + \frac{1}{h_o}}$$

$$Q = q * A$$

q – heat flux (W/m^2)
T_i – inside temperature (°C)
T_o – outside temperature (°C)
L – Thickness (m)
h – heat transfer coefficient (W/m^2)
A – Area (m^2)
Q – Heat loss

It was assumed that :
- Thermal conductivities were taken from CES Edupack and online[XX].
- Thicknesses were estimated from online sellers.
- Inside temperature (T_i) is of **22°C** and the outside temperature (T_o) is of **10°C**.
- Heat transfer coefficient inside (h_i) is **10 W/m²k** and outside (h_o) of **30 W/m²k**.
- A 1D steady rate radial conduction.
- Heat transfer radiation is neglected.
- There is perfect thermal contact between layers.

Thermal conductivity values

Cedar wood = 0.15 W/mk
Plywood = 0.13 W/mk
Chipwood = 0.13 W/mk
Glass wool = 0.04 W/mk
Corten steel = 25 W/mk
Plaster = 0.2 W/mk
Glass = 0.96 W/mk
Argon Gas = 0.016 W/mk
Slate tiles = 2.01 W/mk
Concrete = 0.8 W/mk

- Walls

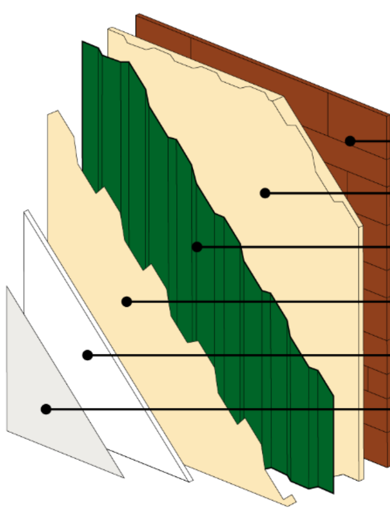
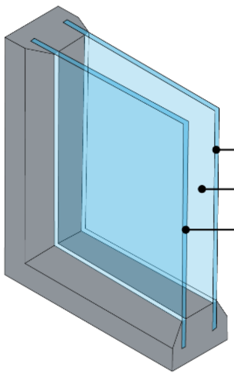


Figure 5 : Layer diagram of the wall

insulation	Area (m^2)	q / Heat flux (W/m2)	Q / Heat loss (W)	Energy saved (kW / h)	Cost economy (£ / h)
without	19.87	104.93	2085.54	1882.21	323.74
with		10.23	203.33		

- Windows

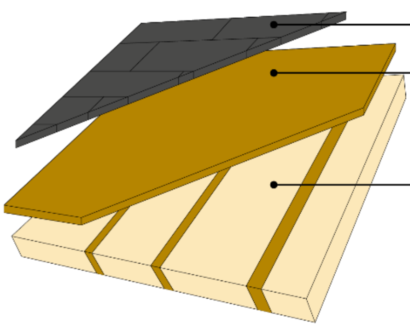


insulation	A Area (m^2)	q Heat flux (W/m2)	Q Heat loss (W)	Energy saved (kW / h)	Cost economy (£ / h)
without	14.14	101.05	1428.88	1171.37	201.47
With		18.21	257.51		

The heat loss was also computed with air instead of argon, but the results were found to be less conclusive with a heat loss of 376.76 W.

Figure 5 : Layer diagram of the double glazed windows

- Roof

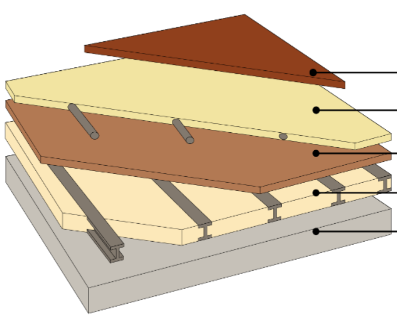


The roof is the only element which does not contain any structure from the container as it was been elevated and inclined.

insulation	A Area (m^2)	q Heat flux (W/m2)	Q Heat loss (W)	Energy saved (kW / h)	Cost economy (£ / h)
without	18.46	65.96	1217.64	1040.9	179.03
With		9.57	176.74		

Figure 5 : Layer diagram of the roof

- Floor



As the oak wood is in the opposite direction to the heat loss due to the heating mat, and should let heat pass, it has been ignored in the loss of energy.

insulation	A Area (m^2)	q Heat flux (W/m2)	Q Heat loss (W)	Energy saved (kW / h)	Cost economy (£ / h)
without	18.3	66.58	1218.51	1154.82	198.63
With		3.48	63.69		

Figure 5 : Layer diagram of the floor

We find that the total energy lost in heat transfer despite the isolation installed is of 701.27 W per hour, so 16.83 kW lost per day. This energy loss, which lowers the temperature of the home, will be supplied by the underfloor heating mat.

Intervention 2 – Pipe flow

Due to regulations around potable water, tap water must be from an external resource. However, the pump driving this circuit must be accounted for.

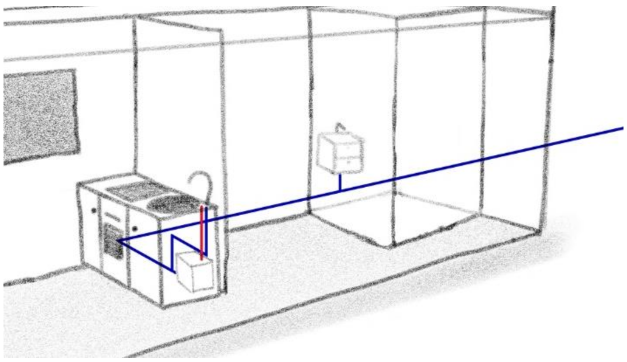
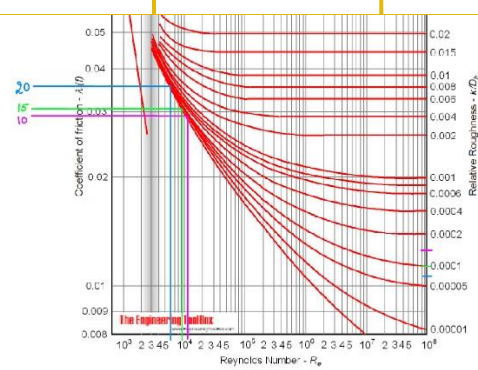


Figure 5 : Tap water piping

Ideal tap flow rate = 6 L/m
Q =6 / (60 * 1000) = 0.0001 m^3/s
Water density (p) = 1000 kg/m^3
Hot water pipe length (L_h) = 0.65 m
Cold water pipe length (L_c) = 7.12 m
Water viscosity at ambient temperature (μ) = 0.00046 kg/m^3
Copper roughness (e) = 0.0015 mm

- Identification of ideal pipe diameter

Calculations were done with 3 different values of pipe diameters to find which would give the lowest friction pressure loss.

Pipe diameter (d)	10 mm	15 mm	20 mm
area (A) = $\frac{\pi * d^2}{4}$	$7.85 * 10^{-5}$ m^2	$1.77 * 10^{-4}$ m^2	$3.14 * 10^{-4}$ m^2
velocity (u) = $\frac{Q}{A}$	1.27 m/s	0.56 m/s	0.32 m/s
Reynolds number (R_{ed}) = $\frac{p * u * d}{\mu}$	$1.27 * 10^4$	$8.49 * 10^3$	$6.37 * 10^3$
Turbulent or laminar?	Turbulent	Turbulent	Turbulent
Relative roughness (R) = $\frac{e}{d}$	0.00015 mm	0.0001 mm	0.000075 mm
Friction coefficient (Cf) using Moody chart Cf =	 0.029	0.031	0.037
Friction factor (f) = Cf * 4	0.116	0.124	0.148
Friction pressure loss (ΔP_f) using Daicy's equation : $\Delta P_f = f * \frac{L * p * u^2}{2 * d}$	66946.55 Pa	9424.01 Pa	2669.21 Pa

66946.55 > 9424.01 > 2669.21
Therefore the lowest friction pressure loss occurs with 20 mm diameter piping.

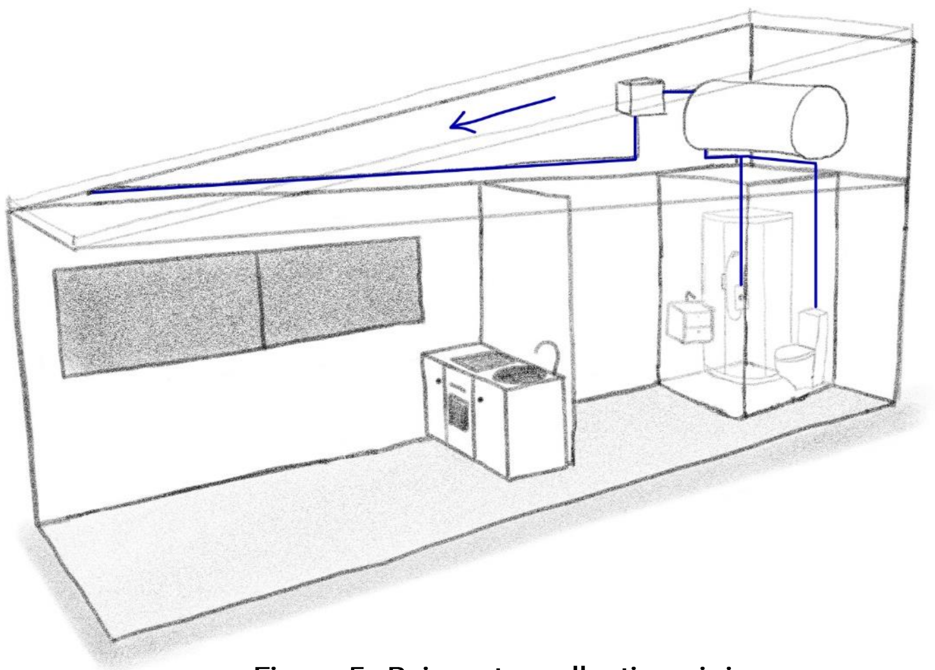
- Other pressure losses

Pressure loss due to elevation	$\Delta P_{el} = p * g * h$	ΔP_{el} – pressure loss (Pa) p – density (1000 kg/m^3) g – gravity (9.81 m/s) h - vertical pipe length (h_c = 1.9 m, h_h = 0.65 m) $\Delta P_{el,\,c} = 1000 * 9.81 * 1.9$ $\Delta P_{el,\,c} = 18639$ Pa $\Delta P_{el,\,h} = 1000 * 9.81 * 0.65$ $\Delta P_{el,\,h} = 6376.5$ Pa
Pressure loss due to fittings	$\Delta P_{ex} = 0.1 * \frac{p * u^2}{2}$ $\Delta P_c = 0.5 * \frac{p * u^2}{2}$	ΔP_{ex} – sudden expansion pressure loss (Pa) ΔP_c – sudden contraction pressure loss (Pa) p – density (1000 kg/m^3) u – velocity (0.32 m/s) $\Delta P_{ex} = 0.1 * \frac{1000 * 0.32^2}{2}$ $\Delta P_{ex} = 50.66$ Pa $\Delta P_c = 0.5 * \frac{1000 * 0.32^2}{2}$ $\Delta P_c = 25.33$ Pa Therefore the total pressure lost due to fittings is : $\Delta P_{fit} = \Delta P_{ex} + \Delta P_c$ $\Delta P_{fit} = 75.99$ Pa
Pressure loss due to bendings	$\Delta P_b = c * \frac{p * u^2}{2}$	ΔP_b – sudden expansion pressure loss (Pa) p – density (1000 kg/m^3) u – velocity (0.32 m/s) c – loss coefficient ($c_{t\text{-}joint}$ = 1.8, $c_{90°\,elbow}$ = 0.4) $\Delta P_{t\text{-}joint} = 1.8 * \frac{1000 * 0.32^2}{2}$ $\Delta P_{t\text{-}joint} = 91.19$ Pa $\Delta P_{90°\,elbow} = 0.4 * \frac{1000 * 1.27^2}{2}$ $\Delta P_{90°\,elbow} = 45.59$ Pa Therefore, $\Delta P_b = \Delta P_{t\text{-}joint} + 4 * \Delta P_{90°\,elbow}$ $\Delta P_b = 91.19 + 4 * 45.59$ $\Delta P_b = 273.57$ Pa

We find that the total pressure lost in piping is of $2.60 * 10^4$ Pa.
With a 40% efficient pump, it would require 6.51 W of power to drive the circuit.

Intervention 3 – Rainwater collection

Another piping circuit was designed to collect and use rain water. This can only be compatible with grey water appliances, such as the shower or toilets. An electric shower was chosen to heat the water immediately as the user needs it.



1
Rain flows down the roof thanks to its slope

2
Water is pumped into the tank, ready to be used.

3
Water is taken when the toilet or shower is used.

Figure 5 : Rain water collection piping

Feasability

Amount of grey water needed In the house	Amount of rain fall collected in a year in the UK
Toilets : 4 flushes per person per day 4 L of water used per flush Total : 4 ⁎ 4 = 16 L per person per day Electric shower : Water flow of 5 L/min 6 min long showers Total : 6 ⁎ 5 = 30 L per person per day Total grey water needed (w_{demand}) : 16 + 30 = 46 L per day 46 ⁎ 365 = 16 790 L per year	1308 L of precipitation in the UK in 2020 Drainage coefficient of 0.9 Filter efficiency of 0.95 Roof area of the house : 18.46 m^2 Total grey water collected (w_{supply}) : 1308 ⁎ 0.9 ⁎ 0.95 ⁎ 18.46 = 20 644 L per year
	16 790 < 20 644 So the rainwater collected should cover all the grey water needs of the house.

- Tank Size

Rain isn't a continuous resource supply, therefore storage is required to fit the needs of the user every day.

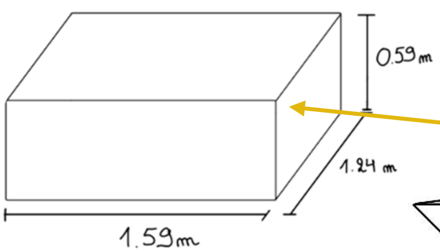
In the UK there is an average of 21 days of droughts, therefore :

$$\text{Tank size} = \frac{W_{supply} + W_{demand}}{2} * \frac{\text{Drought}}{365}$$

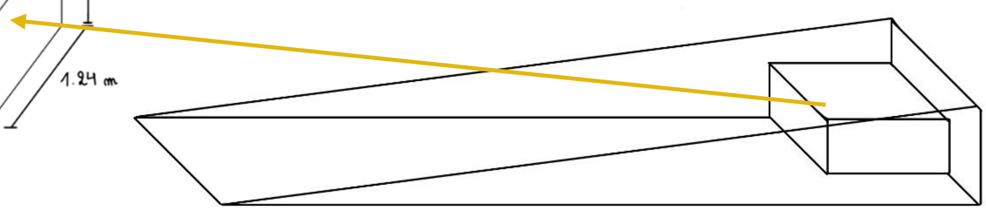
$$\text{Tank size} = \frac{20\,644 + 16\,790}{2} * \frac{21}{365}$$

$$\text{Tank size} = 1\,076.88 \text{ L}$$

$$\text{Tank size} = 1.08 \text{ m}^3$$



For ease of visualisation, the following standard rectangular 1000 L tank was considered to verify it would fit in the loft above the house as shown below.



The tank has been placed above the elements which it supplies (toilet / shower), so gravity will allow the water to reach them. Pressure will be added by the electric shower.

- Pump power

Pressure loss due to fittings

Smooth bell mouth at the edge of the roof, therefore there is no pressure lost due to fittings in this pipe circuit.

Pressure loss due to elevation

$\Delta P_{el} = \rho * g * h = 1000 * 9.81 * 0.5 = 4905$ Pa

Pressure loss due to bendings

The circuit only presents one 90° elbow and from above we know : $\Delta P_{90° \, elbow} = 45.59$ Pa

Pressure loss due to friction

Using pipe of 20 mm diameter over 7 m and the above method, we obtain the following results :
Reynolds number $R_{ed} = 6.37 * 10^3$
Relative roughness R = 0.000075 mm
Friction factor f = 0.037
Using Daicy's equation, $\Delta P_f = 656.05$ Pa

Overall, this circuit losses 5606.54 Pa from it's design. With a pump efficiency of 0.4, it would require 1.40 W to operate.

Intervention 4 – Solar Panels for carbon neutrality

Solar panels are more and more sought out to produce greener energy and become carbon neutral. The container house is no exception. To validate the house's carbon neutrality feasibility, the power demand and power supply was compared.

- Power demand

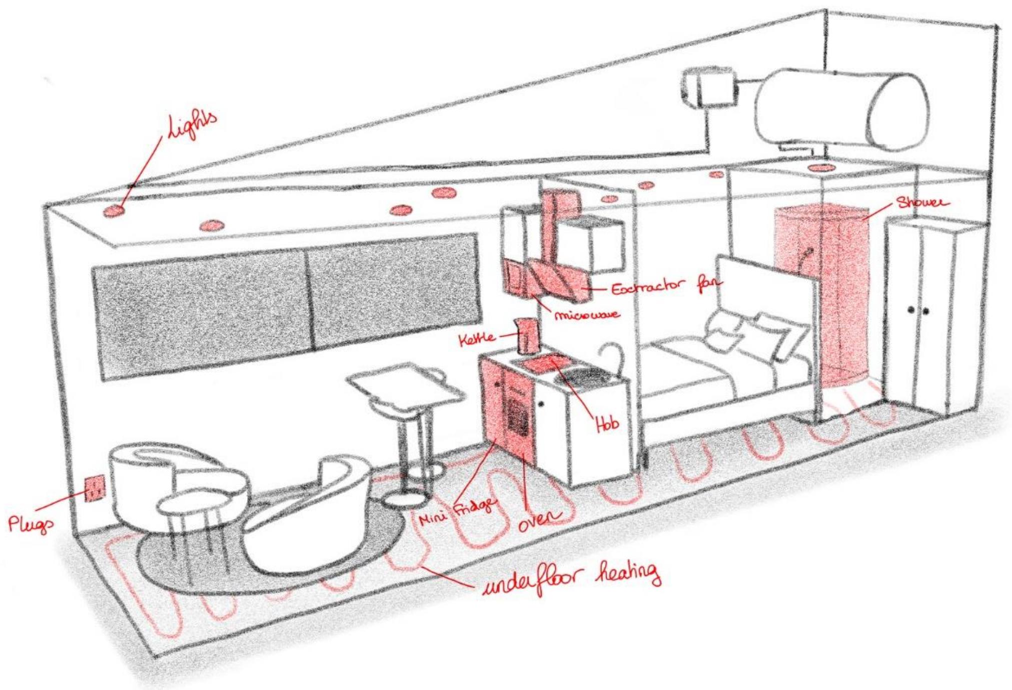


Figure XX: Diagram of all household appliances in the house

Appliance	Power (W)	Daily usage (h)	Energy used daily (W)
Lights	80	12	960
Plugs	5	4	20
Electric shower	7500	0.1	750
Mini fridge	50	24	1200
Oven & Hob	2150	0.5	1075
Microwave	600	0.08	50
Extractor fan	200	0.5	100
Kettle	900	0.17	150

Table of all energy requirement for household appliances

From previous calculation we know the following additional power is needed.

- Pump for the taps = 6.51 W
- Pump for rain collection = 1.40 W
- Underfloor heating = power needed ⋆ floor area ⋆ daily usage = 70 ⋆ 18.3 ⋆ 10 = 8610 W

Therefore the total power with the house needs to be operative is of 12.92 kW per day.

- Power supply

Daily energy production of solar panels
Nowadays, solar panels product 400 W of power per hour. To validate the compatibility of rainwater collection feasibility and solar energy production, the sunshine data was taken from 2020, in which the UK registered an average of 4.6 hours of sunlight per day.

Hence the total power produced by a solar panel in a day is of 1.84 kW.

Number of solar panels needed to be carbon neutral

= daily power need / daily power production
= 12.92 / 1.84
= 7.02 so 7 solar panels

Number of solar panels that would fit on the roof
Solar panels are 2 m^2 large.
The house roof size is of 18.46 m^2.
18.46 / 2 = 9.23 solar panels could fit on the roof of the house.

7.02 < 9.23 therefore enough solar panels can be installed on the house to fit it's needs.

With all power demand covered by solar panels, the container house is now carbon neutral.

References

Calculation values :
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https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/482120/gbs-taps-automatic-sprays-showers-urinal-2015.pdf

Intervention information :
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Information on containers :
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https://www.containerhuis.eu/
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