

ENGN2226
Final Design Project
Greenhouse in Phuongmoche community, Nepal

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Abstract

In 2010, Engineers Without Borders (EWB) constructed a Greenhouse to assist the residents of the Phuongmoche community in Nepal, who struggle with a short growing season. On the basis of a systems analysis process, we recommend that the back wall height be increased by 10%, the transparent face of the greenhouse be oriented South rather than East, and the plastic roof be replaced with more insulative, low impact materials such as wood and straw. Collectively, these changes improve the ergonomics of the greenhouse, reduce embodied energy by 47%, initial cost by 31%, and increase the minimum daily internal air temperature. This extends the growing season of several crops: for example, tomatoes may now be grown reliably for at least three months of the year.

1 Introduction

1.1 Context

The remote community of Phuongmoche, Nepal consists of 105 students and is situated at an altitude (3000m) that limits the growing season to as brief a period as two months (FEED, 2012; Engineers Without Borders, 2013). In order to counteract the effects of the short growing season, the people (mainly subsistence farmers) need to purchase food from other sources (FEED, 2012). This undermines their food security while further reducing the scarce financial resources of the community. In addition, this can lead to malnutrition from lack of access to fresh food (Sawyer and Fuller, 2012).

In order to reduce this dependence on externally grown food, a greenhouse is to be constructed to extend the growing season. This will allow the people to increase the amount of food that can be grown throughout the year, thereby directly improving the finances of the community and indirectly the health of the population (either growing or trading for different varieties of vegetables) (Sawyer and Fuller, 2012).

1.2 Original Design

Shown in fig. 1 is the original design of the greenhouse, with key features identified.

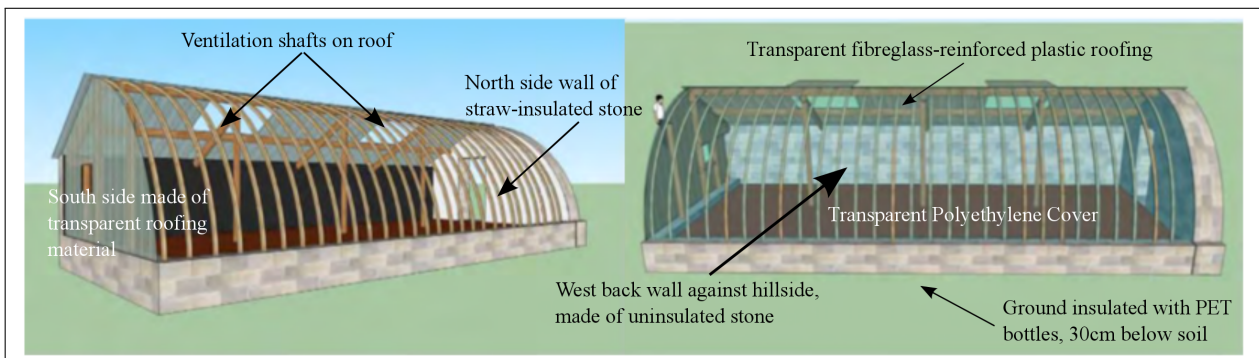


Figure 1: Overview of key design features of the original build design implemented in Phuongmoche by EWB. Note that the curved face faces East in the original design.

1.3 Summary of Changes

Systems engineering analyses were performed to improve the design of the greenhouse. The recommendations for changes to be made are shown below:

- Changed roof material from corrugated polypropylene (a.k.a. fibreglass-reinforced plastic) to hardwood with packed straw insulation
- Rotated the greenhouse 90° so that the curved transparent surface faces South
- Recommended increasing the height of the back wall of the greenhouse by 15 cm for a more ergonomic design
- Re-evaluation of cost of the greenhouse

2 Human Factors

In designing a Greenhouse for the remote community of Phuongmoche, it is necessary to tweak and optimise the design to cater to the needs of the population. The following three aspects of the design

are considered in Human Factors analysis of the greenhouse:

1. The height of the entrance and the roof of the structure.
2. The required vegetable matter to be grown in the structure.
3. The growing area at the base of the structure.

It is hoped that analysis of such data will better tailor the greenhouse to the people of Phuongmoche, Nepal and increase the success of the solution in both adoption and usage.

2.1 Structure Height

Although the height of the structure does not directly influence the vegetable yield, it has a direct bearing on the comfort with which vegetables may be grown by the people of Phuongmoche. It is expected that a substantial amount of time will be spent by workers within the structure tending to crops and so on. A height that is too low can result in poor posture for long periods, leading to a variety of symptoms including back pain, muscle aches and eventually Repetitive Strain Injuries (RSI) (Better Health Victoria, 2014; Action, RSI, 2011). Excessive height is also undesirable as the structure may become unbalanced when high winds in the region produce a large torque (proportional to the height of the structure) (ENGN2225 Group 2, 2014). An increase in height is also associated with an increase in the material consumption and hence financial cost. Thus, there is a trade-off between structure height and the issues listed above.

A reputable survey of Nepalese anthropometric data involving both men and women in a standardised measurement scheme was unable to be found and so Indian data was used for analysis. The state of Sikkim is one of the many states bordering Nepal and is closest to Phuongmoche. Hence, average heights in Sikkim have been assumed to represent the Phuongmoche population.

The mean heights were found to be 159.80 ± 1.66 cm for males (15-49 years) and 151.28 ± 1.08 cm for females (aged 15-49 years) (Perkins et al., 2011). The size of the standard deviation found is small with respect to the mean heights. According to the 68-95-99.7 rule, assuming that a normal distribution holds, nearly all values lie within three standard deviations of the mean (99.7%). Hence, upper thresholds of 164.78 cm and 154.52 cm for men and women respectively can be assumed to take the entire population into account. Hence, the greenhouse height at the top of the side wall (see fig. 1) ought to be a minimum of 165 cm. This will ensure discrepancies in Phuongmoche heights from Sikkim heights will not affect the analysis.

The minimum greenhouse roof height of 165 cm should ensure good posture for residents working at the present and in future. Although this height can be applied to the doorway itself, it may be better to have a smaller door even though it will reduce the ease of use for taller members in the community. This is because of a greater degree of heat loss, and hence reduction in the functionality of the design. Energy flows will be analysed in the next section of the report.

2.2 Vegetable Matter

In order to determine the vegetable matter to be grown in the greenhouse, cultural farming preferences of the population must be identified. The following three collections of plants have been found to be desirable based upon direct surveys of the population:

- Staple Foods: The main staples by consumption are coarse rice, wheat flour, maize and maize flour, millet and potatoes according to surveys in (Central Bureau of Statistics, 2008). Such foods form the majority of the daily calorific intake and form the basis of each meal.
- Supplemental Foods: Foods such as spinach, green onions, grapes, tomatoes, chillies, cauliflower, and lettuce have been grown in existing greenhouses by residents in the area. This information was obtained directly from interviews in the area (Dietrich, 2012). Although these foods do not

significantly contribute to raw calorific intake, they serve to balance the nutritional requirements of the population.

- **Medicinal Herbs:** There are multiple plants in Khumbu, Nepal that have high medicinal value, and they are relied upon by a significant portion of the population for medical treatment (Rawal et al., 2009). Hence, it would possibly be useful to grow these plants in the greenhouse, although the focus of the current analysis task is on growing food.

One of the original goals of the project was to improve the health and nutrition of the people, primarily through access to fresh food (Padula et al., 2010). With regards to nutrition, a wider range of foods would provide a greater range of vitamins, minerals, etc that will improve overall health. The supplemental foods do this well, and have been already incorporated into the growing cycle of existing greenhouses (Dietrich, 2012).

In addition to the supplemental foods, it may be useful to consider extending the use of the greenhouse to staples such as wheat, corn, millet and potatoes. The basis of this is that the monastery in Phungmoche in which the greenhouse is to be built must cater to approximately 105 students, and hence raw caloric intake may be preferable to ensure there is sufficient food to eat. Extra staple food can be sold or traded to obtain supplemental foods if required.

2.3 Growing Area Size

The analysis of the growing area within the greenhouse is based on growing staple crops - wheat, corn, millet and potatoes. Rice has been ignored in this analysis as it requires a large irrigated area and hence cannot be grown in a greenhouse. As mentioned earlier, staple crops can be traded for more “exotic” foods or used to supplement the core diet of the population. Residents are free to grow supplemental or medicinal foods, but basing Greenhouse growing area on caloric intake will ensure a certain portion of caloric requirements can be met. This is especially crucial during the winter season.

The required daily calorific intake of the average Nepali resident is approximately 9790 kJ (Food and Agriculture Organization, 2008). The energy content and yield of wheat, corn, millet and potatoes are outlined in table 1.

Table 1: Energy content, yield, and energy yield of crops in Nepal (USDA, 2014; FAO, 2013)

| Crop | Energy Content (KJ/100g) | Yield (g/m ²) | Energy Yield (KJ/m ²) |
|----------|-----------------------------|------------------------------|--------------------------------------|
| Wheat | 1368 | 229 | 3123 |
| Corn | 360 | 235 | 846 |
| Millet | 378 | 111 | 420 |
| Potatoes | 321 | 1364 | 4378 |

The eq. (1) below provides a way to conduct analysis with respect to particular chosen values.

$$A(cy_c + my_m + py_p + wy_w) = \mathcal{P} \times 9790 \times n \begin{cases} c + m + p + w & \in [0, 1] \\ c, m, w, p & \in [0, 1] \end{cases} \quad (1)$$

The equation above provides a relation linking the variables considered above with the dimensions of the Greenhouse. The values of c , m , p and w are the fraction of the greenhouse to be used for growing corn, millet, potatoes and wheat respectively. The variables y_w , y_c , y_m , y_p are the energy yields for wheat, corn, millet and potatoes respectively. A refers to the growing area of the greenhouse (m²), n is the number of people to be catered for, and \mathcal{P} refers to the percentage of the diet to be provided for by the greenhouse.

As an example of the analysis, a 20% daily calorific intake requirement for fifty people is chosen using equal proportions of each staple grown ($\mathcal{P} = 0.2$, $n = 50$, $c = m = w = p = 0.25$). This equates to

44.67 m² growing area size assuming equal farming of each staple crop within the greenhouse. This is similar to the existing greenhouse design (49 m²) (Padula et al., 2010). The use of parameters in the equation allows for the substitution of more accurate data as it becomes available, allowing for adaptability in the analysis.

3 Energy Analysis

3.1 Heat Transfer Model in MATLAB

To conduct an energy mass balance on this system, we must first simplify it, and only consider the most significant heat and mass transfers; convection and radiation through the thin plastic cover and roof, conduction through the back wall to the hillside, conduction through the soil and buried PET bottles to the ground, ventilation, and solar gain. Calculation of the heat capacity of the system was also conducted. Details of how each of these were calculated may be found in appendix A.1; see MATLAB functions respectively titled: *convection_R_poly*, *radiation_loss_cover*, *conv_cond_R_ground*, *air_leakage_loss*, *absolute_to_relative*, *relative_to_absolute*, *enthalpy_humid_air*, *variable_assignment_month*

The modes of usage of the greenhouse were also a factor in developing the model. The most significant of these pertain to the usage of the ventilation shafts, and to thermal mass manipulation through the use of barrels of water. Following recommendations by Viltard (2003), the ventilation shafts will be used to cool the greenhouse if it gets too hot inside (over 25°C), and to warm the greenhouse if it is too cold. See *air_leakage_loss* in appendix A.1 for details.

3.2 Thermal circuitry

The thermal circuit diagram for the greenhouse, and the derivation of the following differential expression, is given in appendix B.

$$\frac{dT_{in}}{dt} = \frac{\dot{Q}}{C} - \frac{T_{in}}{CR} \quad (2)$$

where

$$\dot{Q} = \frac{T_{out}}{R_c} + \frac{T_g}{R_g} - \dot{Q}_{Rad} + \dot{Q}_{sol}$$

$$R = R_c \parallel R_g = \frac{R_c + R_g}{R_c R_g}$$

and T = temperature (K), C = heat capacity (J/K), R_c = conductive/convective thermal resistance of cover and roof to outside air (K/W), R_g = conductive/convective thermal resistance of ground to air (K/W), \dot{Q}_{air} = air leakage loss (W), \dot{Q}_{Rad} = radiation loss through cover and roof (W), \dot{Q}_{sol} = solar gain (W).

3.3 Dynamic Internal Temperature and Sankey Diagrams in MATLAB

A function was written in MATLAB that computes the heat loss and gain from the Phuongmoche greenhouse. The internal temperature is updated hourly using the discrete form of the eq. (2). This continues for a 7-day period, by which time steady state is reached (see appendices A.2 and A.3). Thus, the total gains will equal the total losses over the final 24 hours. A balanced Sankey diagram was generated, which displayed the relative magnitudes of all major heat transfers.

3.4 Results of Analysis

We present analysis of the two most extreme conditions that the greenhouse is likely to encounter: a warm summer period in July, and a cold winter period in January.

3.4.1 Summer

For a discussion of how the external conditions were chosen, see appendix C.

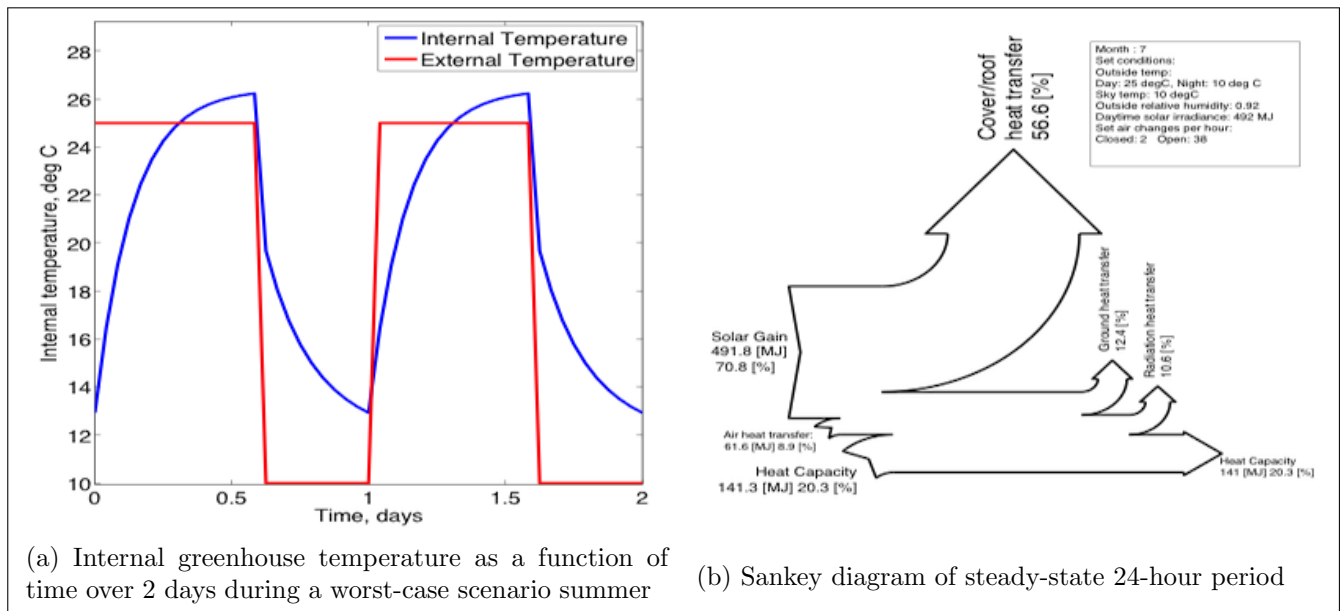


Figure 2: Internal temperature of the greenhouse and Sankey diagram for summer

Most vegetables have a relatively narrow and mild temperature range in which they grow optimally, e.g. for tomatoes it is 18-23°C (Nichols and Hilmi, 2009). We can see in fig. 2a that temperature fluctuation within the greenhouse is relatively large ($\sim 13^\circ\text{C}$), though on average the temperature is ideal for the growth of most vegetables (Viltard, 2003). We can see in fig. 2b that most of the heat loss occurs by convection/conduction through the roof/cover, and that solar gain and ventilation are the causes of rapid warming during the day, as seen in fig. 2a.

3.4.2 Winter

For a discussion of how the external conditions were chosen, see appendix C.

The greenhouse succeeds in protecting plants from frost damage by keeping the internal temperature above 0°C . We can see in fig. 3a that temperature fluctuates by only 8°C , and is significantly higher than both day and night time outside temperatures. We can see in fig. 3b that heat loss is dominated by conductive loss through the roof and cover. The ground contributes a significant amount of heat to the system, being at a higher temperature of 10°C . The greenhouse is heavily reliant on solar gain for warmth; without it, the internal temperature fluctuations would be far more similar the those of outside, which would be unsuitable for vegetable growth (Viltard, 2003).

3.5 Recommendations

3.5.1 Summer

To allow the internal air temperature to fluctuate around 20°C , we recommend to:

- Allow polyethylene cover to roll back to let more air in. This will cause the greenhouse to very rapidly track the outside temperature over the course of the day.
- The cover must be easy to replace securely, so that night time losses do not increase unduly

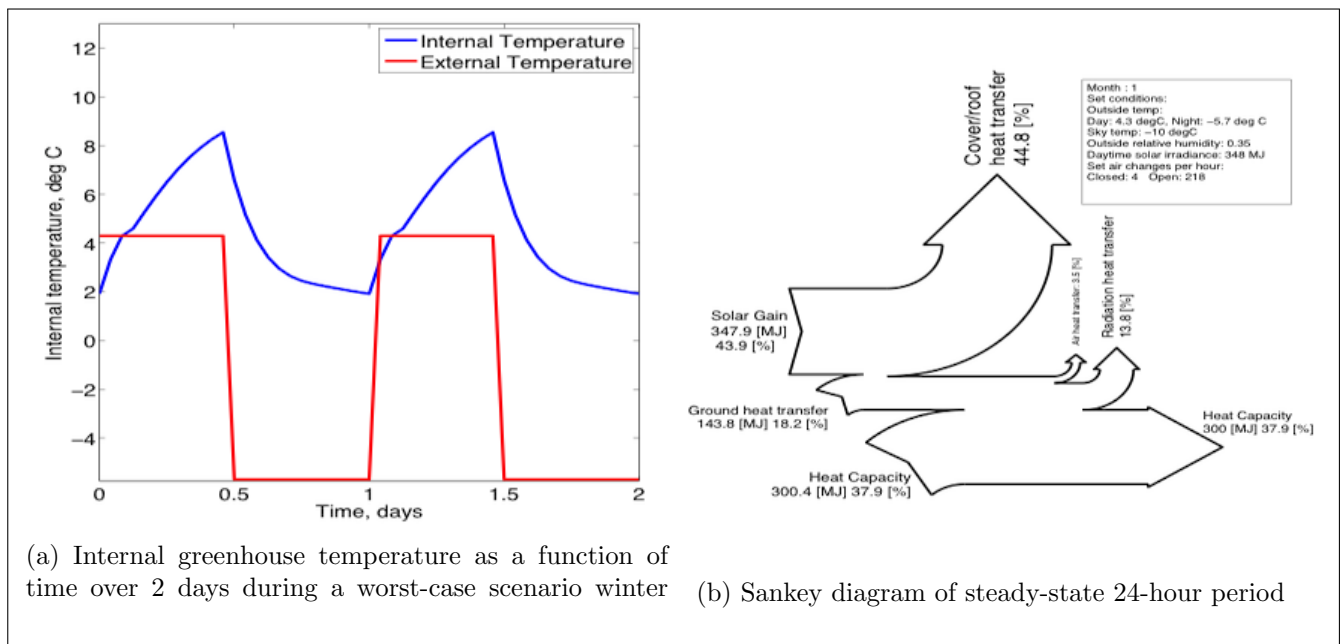


Figure 3: Internal temperature of the greenhouse and Sankey diagram for winter

- Move less temperamental crops outside in Summer, and use the extra space for water barrels; this will increase thermal mass which suppresses temperature fluctuations

3.5.2 Winter

We want to maximise internal temperature through any means possible:

- Position greenhouse due South, facing the Sun more directly (greenhouse currently faces East, which significantly lowers solar gain)
- Ensure all leakage points are minimised, e.g. gaps in the door, roof, rips in cover
- A south-facing greenhouse does not require a transparent roof, since it would be angled upwards away from the sun. Replace roof with some other material, such as wood or packed straw, increasing the roof's thermal resistance

4 Time Analysis

4.1 Construction

The construction process was set out in a PERT chart.

We can see from fig. 4 that we expect the construction of the greenhouse to take 3 weeks.

4.2 Use of the Greenhouse

From the Human Factors analysis (section 2), certain foodstuffs that can be grown in the greenhouse were identified. The crops were chosen based on interviews with members of the Phuongmoche community (Dietrich, 2012), and because they survive well in colder temperatures. For each selected crop, the minimum temperature required for thriving was found, and these are displayed in table 2. (Viltard, 2003)

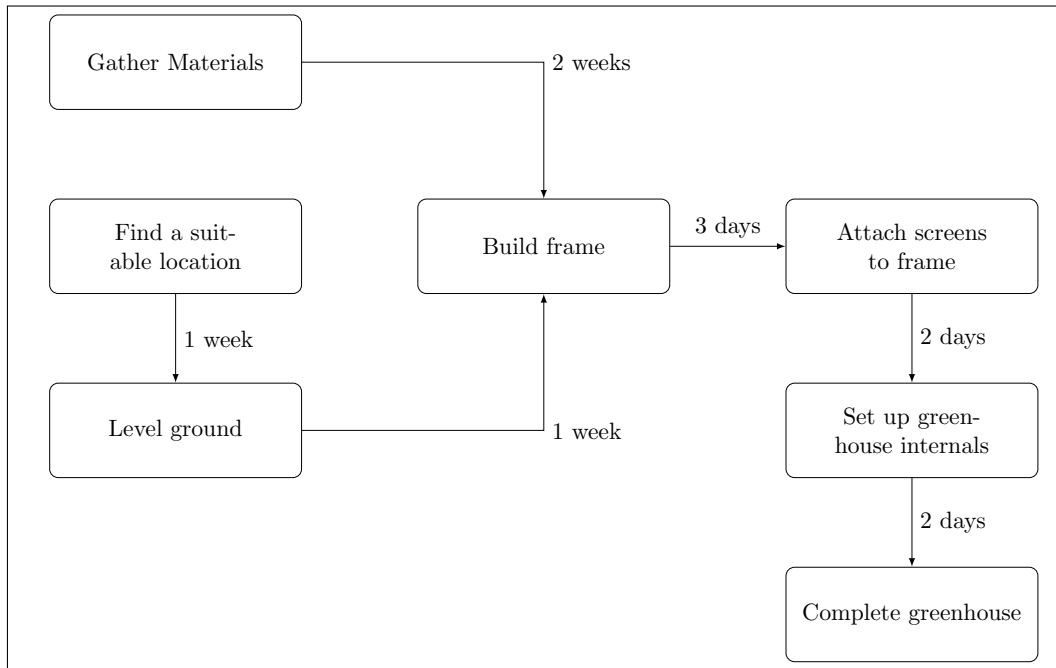


Figure 4: PERT chart showing the process for constructing the greenhouse

Table 2: A selection of crops, and the minimum temperatures required for growing

| Crop | Min. T (°C) |
|--------------|-------------|
| Spinach | 5 |
| Green Onions | 0 |
| Tomatoes | 10 |
| Beets | 5 |
| Lettuce | 0 |

The limiting factor for growing these crops is the minimum temperature, since a high internal temperature can be easily rectified by opening vents to increase the air change rate, and lower the temperature. We also assume that other requirements, e.g. water and soil nutrients, are met, and so we did not consider these for our analysis.

Using the code developed in section 3, an energy analysis was performed on the greenhouse design to find the average internal temperature fluctuations in the greenhouse for each month. The average internal temperature changes with the day-night cycle, with the temperatures decreasing through the night. Once the average and minimum temperature for each month was found, we could create a Gantt chart showing the times of the year in which each crop could be grown. This is shown in table 3. In this chart, a yellow cell indicates that the crop can be grown during that month, while a blank cell means that it cannot be grown.

It was decided that a minimum temperature within 2°C of the minimum growing temperature was acceptable, as long as the average temperature was sufficient. This was because the greenhouse would only reach its lowest temperature just before dawn, and it would not have a large effect on the crops.

Using this chart, we can plan the most efficient times to grow each crop, and how to best utilise the limited space in the greenhouse. We must also consider factors such as the time required to cultivate each crop. For example, green onions can take up to 100 days from germination until harvest (Rowell and Coolong, 2013).

Table 3: Gantt chart showing the times of the year in which crops can be grown in the original greenhouse design

| Crop | J | F | M | A | M | J | J | A | S | O | N | D |
|--------------|-----|-----|-----|------|------|------|------|------|------|------|-----|-----|
| Ave. T (°) | 4.8 | 7.3 | 7.7 | 10.6 | 14.4 | 17.3 | 16.5 | 17.1 | 15.8 | 10.5 | 6.9 | 6.0 |
| Min. T (°) | 2.0 | 2.1 | 2.5 | 3.7 | 4.8 | 6.6 | 5.6 | 6.0 | 5.8 | 3.2 | 2.4 | 2.0 |
| Spinach | | | | | | | | | | | | |
| Green Onions | | | | | | | | | | | | |
| Tomatoes | | | | | | | | | | | | |
| Beets | | | | | | | | | | | | |
| Lettuce | | | | | | | | | | | | |

4.2.1 Recommendations

The new suggested roof material will be more time-consuming to construct. We suggest that sections of the roof may need to be constructed on the ground whilst the main frame is assembled. We have also suggested a change in orientation of the greenhouse: it is understood that the current site was chosen due to the prevalence of strong southerly winds (EWB, 2010).

Deeper excavation and the construction of a berm would alleviate wind, as well as aid thermal performance. However, this would have higher time, environmental, and economic impact. Better thermal performance will also allow longer growing seasons, which will affect our Gantt chart analysis.

5 Materials Analysis

For a detailed explanation of how wood quantities and types were estimated, refer to table 9 in appendix D.1.

Shown in table 4 is the materials audit with estimated embodied energy.

The fact that Bamboo and stones have zero embodied energy suggests that naturally abundant materials are the most suitable resources for the greenhouse construction in Phuongmoche. Although no research data is available on the embodied energy of bamboo, both Cannon Design (2013) and Reiner et al. (2007) agree that the majority of the embodied energy is due to transportation, not the actual processing. Since bamboo is abundant in the region, the proportion of transport in the total embodied energy will be also minimal. As a result, the total embodied energy for bamboo is taken to be zero. Stones also have zero embodied energy as they are naturally available and thus no thermal energy input is necessary to process them for the greenhouse construction (Venkatarama Reddy and Jagadish, 2003).

5.1 Structural Recommendations

From the materials audit in table 4, it is evident that the polypropylene contributes by far the largest amount of energy, but contributions from the hardwood add up to a value comparable to that from the plastics, not because wood production is very energy intensive but rather because of the large quantity that is required. Therefore, a better design would be the one that limits both plastic and hardwood usage. A design that is worth notice is the one suggested by Nienhuys (2003) where the entire greenhouse framework was built using bundles of bamboo. As this design was implemented in a high altitude area of Nepal, this suggests bamboo can be used in more versatile ways without too much compromise in structural strength. Noting the fact that the greenhouse in Phuongmoche is much larger than the all-bamboo greenhouse from the report by Nienhuys (2003), it would not be

Table 4: Materials audit for greenhouse

| Component | Material | Quantity | Total Weight (kg) | Embodied Energy (MJ) | Cost (AUD) | Reference |
|---|---|---------------------------------|-------------------|----------------------|------------|---|
| Centre and side beams | Wood A | 112 m | 600 | 1200 | 103 | Engineering Toolbox (b); Milne and Reardon (2013) |
| Door frame, top/bottom door, sandwiching plastics, door, etc. | Wood B | 78 m | 180 | 360 | 71 | |
| Unspecified | Wood C | 25 m × 40 pieces | 815 | 1630 | 92 | |
| Curved frames for plastic covering | Bamboo | 50 pieces (no length specified) | - | 0 | 0 | Cannon Design (2013); Reiner et al. (2007) |
| Foundations and a side wall | Stones | 10.5 m | - | 0 | 0 | Venkatarama Reddy and Jagadish (2003) |
| Plastic sheet cover | Low-density Polyethylene (a.k.a. Silpaulin) | 45 m ² × 4 mm | 17 | 1518 | 229 | Dilara and Briassoulis (2000); Hammond and Jones (2011) |
| Plastic roof and wall | Corrugated plastic (polypropylene) | 35 m ² × 4 mm | 127 | 11910 | 653 | Hindle; Hammond and Jones (2011) |
| Underground layer for water collection | Polypropylene Foam | 55 m ² × 5 mm | 10 | 900 | 42 | Nienhuys (2003); Hammond and Jones (2011) |

possible to completely nullify the usage of hardwood as it may be more beneficial to have wooden central beams for the stability of the greenhouse (especially important when there is a heavy snow). Also, it would not be easy to build doors and door frames with bamboo that can effectively reduce air leakage because of the round shape bamboo takes and hence hardwood is more desirable (air leakage can quickly equalise the indoor and outdoor temperature, greatly impacting on the effectiveness of the greenhouse).

It should be noted that the calculated embodied energy for hardwood is based on kiln drying and can be overestimated if the hardwood was sourced locally and the drying process was natural. In this case, the total embodied energy of wood will be close to zero, and a heavy usage as in the Phuongmoche greenhouse construction may be justifiable. However, bamboo is still a preferred option as it grows faster than hardwood (thus more sustainable).

Because the greenhouse was not oriented such that it faced the sun, translucent corrugated plastics were used for the angled part of the roof and the side wall. This allowed solar gain to be maximised without optimal orientation. However, if the curved polyethylene side were to face South then the roof need not be translucent, allowing more thermally insulating materials to be utilised instead, as suggested in the energy analysis. This suggestion is also validated by the materials analysis as it is better to use wood (whether it is bamboo or hardwood) instead of corrugated plastics.

Therefore, it is suggested that the angled part of the roof be made from thin pieces of wooden plank and the polyethylene cover be extended over the entire roof to protect the wooden roof from rain and the damage from the sun. Hardwood is suggested instead of bamboo to minimise air leakage and give a greater structural strength especially under heavy snow. Straws or other light thermally insulating materials can be sandwiched between the top of the roof and the polyethylene cover to improve insulation. It was not possible to find an alternative material for the side wall that matched the advantages corrugated plastics have, which are translucency and sturdiness. If wood or stones are used to build this side wall then it will dim the greenhouse and will negatively impact crop growth. Polyethylene will be translucent but too weak to withstand strong wind. As a result, the polypropylene corrugated side wall is still recommended for future designs.

5.2 End-of-life Issues

After a certain time frame, the materials comprising the greenhouse will age. Partial replacement of aged materials will take place before its life time and then an entire demolition will occur at the end of its life.

The previous section suggested use of bamboo and hardwood to reduce the embodied energy. They are also good in terms of end-of-life issues as they do not have any; they simply decay without any harm to the environment and can even be turned into compost which will become nutrients for crops. However, the use of plastics could not be eliminated entirely and treatment of such materials after use is an important consideration especially for remote areas like Phuongmoche.

The the end-of-life issues of polypropylene and polyethylene are shown in appendices D.2 and D.3.

5.3 Conclusions

Two main suggestions drawn from the material analysis are:

1. Replace the corrugated plastics for the angled part of the roof to wood, and
2. Encourage more use of bamboo.

Plastics, especially polypropylene, were shown to have a much greater environmental impact than any other materials used in the greenhouse and a number of alternative options were considered to increase the sustainability of the current design. In principle, polypropylene can be completely excluded but a significant compromise has to be made in terms of the greenhouse's performance, defeating the purpose of having the greenhouse. Therefore, polypropylene is still recommended for use but with the stipulation that it be re-used for building future greenhouses. It is suggested that education programs and handbooks for greenhouse construction for locals include a recycling section specifically in order to achieve this.

6 Optimisation and Reliability

The reliability of the greenhouse can be defined as the “probability of performing without failure, its intended function under given conditions for a specific time period” (Verma et al., 2010). In this scenario, the intended function of the greenhouse is mainly the extension of the growing season in the Phuongmoche region which is limited to a short growing period (FEED, 2012). According to the recommendations made in energy analysis, the greenhouse is expected to perform under the extreme conditions of summer (July) and winter (January) (Agrawala et al., 2003).

After the identification of the defects, the failures were categorised into early failures, wear out failures and random failures for further analysis.

6.1 Early Failures

The possible early failures for the greenhouse are listed below:

- Early failure of the components used in the design due to defects in the raw materials (soft wood, bamboo, stones)
- Early manufacturing problems of the materials used for subassemblies used in the greenhouse such as plastic sheet cover (low density polyethylene), plastic roof and wall (corrugated plastic) and the underground layer for water collection (polypropylene layer) (Hammond and Jones, 2008).

- Defects due to poor workmanship can also lead to early failure and structural damage (Demirbilek et al., 1997). Even though durable and superior quality materials are used in construction, if used imperfectly, the greenhouse might not successfully serve the planned function (Pérez-Alonso et al., 2011). The general defect due to poor workmanship in the greenhouse construction is improperly fitted roofs. The main reason for poor workmanship can be identified as the employment of unskilled labour.

Identification and removal of the mentioned failures can potentially improve the performance and reliability of the greenhouse (Verma et al., 2010; Xie and Lai, 1996).

6.2 Wear Out Failures

The possible wear out failures for the greenhouse are listed below:

- The wear out failures in the greenhouse can result due to the wear out of the materials used in the construction, such as immediate end-of-life problems associated with polyethylene cover which decreases the performance of the greenhouse. The direct exposure of the polyethylene cover to the UV light decreases the durability of the greenhouse (Nienhuys, 2003).
- Due to the heavy snowfall in the Phuongmoche region in winter, the covering material used in the greenhouse should be strong enough to support the extra weight and should possess sufficient impact strength (Butler, 1987). Inability to meet these criteria makes the greenhouse less durable and unreliable.

6.3 Random Failures

The possible random failures for the greenhouse are listed below:

- Failures in the structure due to strong winds.
- Overheating of the greenhouse in summer (Avis, 2011).
- Ground freezing (currently controlled by the waste plastic underground insulation).
- Failure in the lever of the ventilation flap.
- Pest control issues which affect the crops inside the greenhouse.
- Destruction of vegetation due to frost.
- Plant diseases caused by poor management of greenhouse environment such as humidity, watering and sanitation.

6.4 Design of Experiment

The performance of the greenhouse is mainly dependent on the internal temperature of the greenhouse. As mentioned in the above sections, low temperatures in winter can result in poor crops. Since the main aim of the project is to extend the growing seasons in the Phuongmoche region, it is essential for the greenhouse to perform well during winter. The main source of heat loss from the greenhouse is due to the polyethylene cover used in the front. In this experiment we aim to analyse the effect of changing the cover area in reducing the heat loss in the system. In order to conduct the experiment, the thermal model used in the energy analysis (section 3) is used to compute the heat losses, solar gains and internal temperatures of the greenhouse in both summer and winter. The area of the cover and the stone area are considered as the independent variables in the experiment. The original value of the cover area is 39.5132 m², and the stone area is 7.315 m² (these values are calculated according to the dimensions of the greenhouse suggested in the ENGN2225 greenhouse report) and varied by

$\pm 1 \text{ m}^2$ to obtain the high and low values. In the energy analysis, the effect of the stone foundation was neglected in energy calculations due to its small area. Therefore the stone area in table 5 refers to the area of the stone wall on the side of the greenhouse. The dimensions of the existing design is given fig. 8 in appendix E.

Table 5: Setting up input parameters of the experiment

| | Low (m) | Mid (m) | High (m) |
|-------|---------|---------|----------|
| Cover | 38.5132 | 39.5132 | 40.5132 |
| Stone | 6.312 | 7.315 | 8.315 |

After setting up the parameters (stone area and cover area), the net heat loss over 24 hrs in steady state, and the solar gain were calculated for low and high independent parameter values. The experiment was conducted for 10 iterations and the average values are tabulated in table 6. In order to obtain more accurate results, the experiment was conducted for both summer and winter conditions. The following assumptions were made in the experiment:

Summer

- Temperature fluctuation: $+12.6^\circ\text{C}$ and -2.4°C
- Ventilation speed: 0.5 m/s
- Air changes per hour when ventilation shafts closed: 2

Winter

- Temperature fluctuation: $+5^\circ\text{C}$ and -5°C
- Ventilation speed: 3 m/s
- Air changes per hour when ventilation shafts closed: 4

The table 6 shows the variation of heat losses and solar gains in summer and winter for high and low cover and stone areas. From the table, we can see that the minimum heat losses in both winter and summer occurs when the area of the cover is decreased. Moreover we can see that the solar gain is maximum under two conditions: [low cover area, low stone area] and [high cover area, high stone area]. Therefore from this analysis, it can be concluded that the performance of the greenhouse can be generally optimised by decreasing the area of the polythene cover. Ideally we want the heat loss to be minimised while maintaining the solar gain at high values.

Table 6: Variation of solar gain and heat loss for summer and winter for different cover and stone area values

| Coverage Area (m^2) | Stone Area (m^2) | Summer Heat Loss (MJ) | Summer Solar Gain (MJ) | Winter Heat Loss (MJ) | Winter Solar Gain (MJ) |
|--------------------------------|-----------------------------|-----------------------|------------------------|-----------------------|------------------------|
| 39.5132 | 7.315 | 3.93×10^8 | 4.92×10^8 | 3.55×10^8 | 3.48×10^8 |
| 38.5132 | 6.315 | 3.88×10^8 | 4.87×10^8 | 3.51×10^8 | 3.45×10^8 |
| 38.5132 | 8.315 | 3.94×10^8 | 4.96×10^8 | 3.56×10^8 | 3.51×10^8 |
| 40.5132 | 6.315 | 3.93×10^8 | 4.87×10^8 | 3.54×10^8 | 3.45×10^8 |
| 40.5132 | 8.315 | 3.99×10^8 | 4.96×10^8 | 3.59×10^8 | 3.51×10^8 |
| | min/max | 3.88×10^8 | 4.96×10^8 | 3.51×10^8 | 3.51×10^8 |

In the next analysis stage, the area of the cover is decreased by replacing the bottom part of the cover by a stone wall. The height of the stone wall is varied from 0 m to 1 m and the heat losses, solar gains and temperatures are calculated for both summer and winter conditions using the previously stated assumptions. In order to ensure the reliability of the experimental results, the experiment (code) was run 100 times and the average results are plotted as shown in figs. 5 and 6.

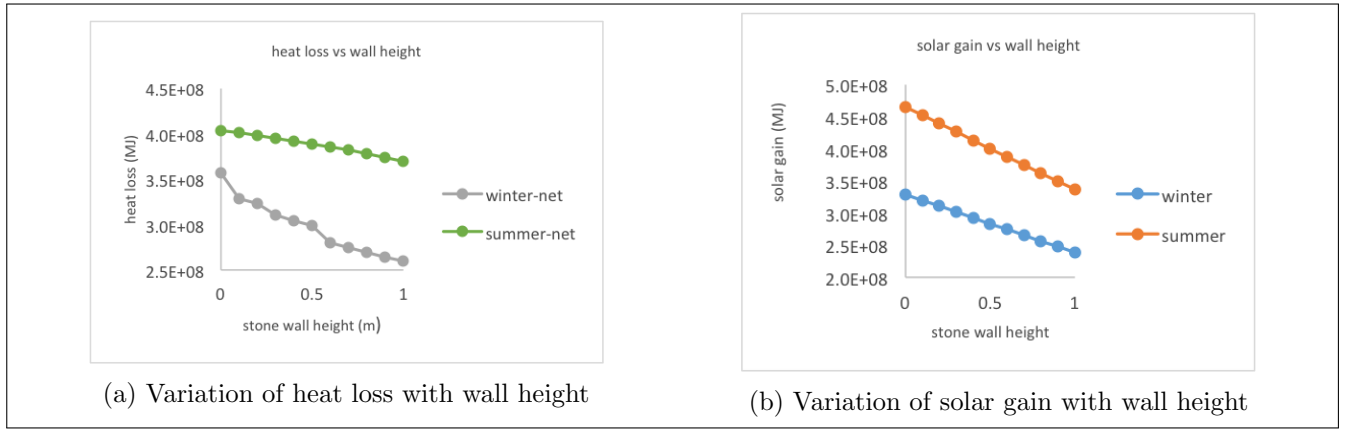


Figure 5: Variations of heat loss and solar gain with wall height

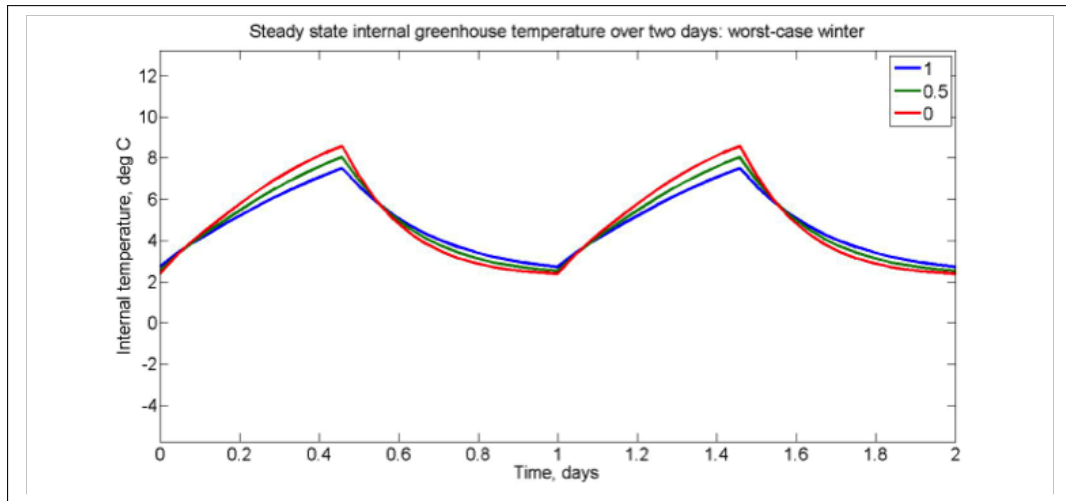


Figure 6: Steady state internal greenhouse temperature over two days, worst case winter

Figures 5 and 6 demonstrate the variation of the net heat loss over 24 hours in steady state with the height of the wall. According to fig. 5, we can see that the heat loss in winter is significantly reduced by the reduction of the cover area, while the heat loss reduction in summer is less significant. However, the increase of the stone height also decreases the solar gain (equivalent to the diurnal solar gain since the solar gain at night is 0) in both summer and winter due to the reduction of the transparent cover area which is responsible for light to pass through. So it is evident that there is a trade-off between the heat loss and solar gain with the addition of the stone wall. For further analysis, the internal temperatures of the greenhouse were calculated for daytime and night time. For summer, the average temperature of the greenhouse is within the optimum temperature range for most plants. Therefore, the analysis is focused towards the winter which is the worst case scenario. Figure 6 demonstrates the variation of steady state internal temperature with the wall height. According to the figure, we can see that the maximum temperature is attained when the wall height is zero. Even though the minimum temperature is also attained when the wall height is 0 m (day 1), the difference between the temperature at day 1 for 0 m and 1 m is insignificant. Therefore considering the cost constraints, building a stone wall might not be the optimum option to improve the performance of the greenhouse.

7 Cost Analysis

Cost Analysis is very much a matter of balancing different interests and establishing the priorities of a project (Williams, 2008). Economic techniques are used to make an informed judgement to

determine the optimum materials and dimensions to be used in the final design. Cost-Benefit analysis was conducted in order to economically optimise the greenhouse; and to ensure life-time economic feasibility, comprehensive Lifecycle Costing was conducted. The first step in the Cost-Benefit analysis and Life-Cycle Costing is to determine which factors have the greatest impact on the cost of the greenhouse, this will ensure that no analysis is wasted on insignificant costs while important factors are missed. To this end, the materials audit was appended to include the cost of the material including transportation to the site at Phuongmoche, shown in table 4 on page 9.

From the appended materials audit it is clear that the corrugated polypropylene component of the greenhouse (roof and wall) is both the most expensive, and has the highest environmental impact. Therefore it is the most important factor on which to conduct cost-benefit analysis. In the energy analysis section (section 3), it was proposed that the polypropylene roof section be reduced and partially replaced with wood to improve thermal performance, while still maintaining reliability against the strong winds in the Phuongmoche region. This agrees with the environmental analysis conducted in the materials analysis section, which indicates the vast majority of the greenhouse's embodied energy arises from the polypropylene components as can also be seen in table 4. Therefore, as all factors (performance, environmental impact, and cost) recommend a decrease in the polypropylene wall, the design will be changed accordingly. The energy analysis simulation will be reiterated for replacement of the polypropylene roof with a thermally insulating layer to determine the performance changes. It is clear that the vast majority of costs throughout the greenhouses lifecycle are incurred upfront with the construction stage, however this is expected of the lifecycle cost distribution of buildings (Vadiei and Martin, 2013).

Table 7: Lifecycle cost of Greenhouse

| Lifecycle Category | | Cost (AUD) | Source |
|--------------------|----------------------------------|-----------------|--------------------------------|
| Material Cost | | 1494 | Sherpa, Karmi and EWB (2010a) |
| Construction Cost | | 0 | Assumption of Volunteer Labour |
| Operations Cost | Seed Cost | Negligible | Katovich and Sharma (2014) |
| | Cultivation Labour and Materials | 5.12 per season | Katovich and Sharma (2014) |
| Maintenance Budget | | 12.6 per year | From table 4 |
| Disposal Cost | | Negligible | Sherpa, Karmi and EWB (2010a) |

Barring any major failure (of which the repair costs can be determined from the materials audit), the operation and maintenance costs should be fairly low. It is therefore safe to determine that external funding from EWB is only required for the upfront cost of the greenhouse. However the large disparity between categories further shows that there is room for economic improvement in the original design, and strengthens the argument for the reduction of polypropylene materials in the greenhouse.

The payback period now requires a quantitative value to be assigned to the crops grown in the greenhouse. Using a representative crop composition of 25% Tomato, 25% Cabbage, 25% Onion, 25% Chilli, the respective income for one harvest is $\$15.70 + \$9.70 + \$10.70 + \$8.60 = \$44.70$ (Katovich and Sharma, 2014). The revenue data is based on bulk prices in the rural centre of Sukhert, Nepal, which for both those reasons means that actual revenue for crops sold in Phuongmoche (particularly during winter months, where other growers will not be able to harvest crops) can be expected to be significantly higher.

7.1 Recommendations

More accurate and applicable crop sale value data must be gathered before a conclusive determination can be made with any certainty. However, based on the information available, it is vital that the community utilizes the greenhouse year round through crop rotation to grow hardy crops in winter, such that they can generate more income than that calculated.

8 Impact of Changes

Table 8: Gantt chart showing the times of the year in which crops can be grown in the improved greenhouse design

| Crop | J | F | M | A | M | J | J | A | S | O | N | D |
|--------------|-----|-----|-----|------|------|------|------|------|------|------|-----|-----|
| Ave. T (°) | 5.3 | 6.2 | 8.1 | 11.0 | 15.1 | 18.0 | 18.9 | 17.9 | 16.6 | 11.2 | 7.5 | 5.8 |
| Min. T (°) | 2.5 | 2.5 | 3.2 | 4.8 | 6.4 | 8.1 | 8.1 | 7.4 | 7.1 | 4.3 | 2.9 | 2.5 |
| Spinach | | | | | | | | | | | | |
| Green Onions | | | | | | | | | | | | |
| Tomatoes | | | | | | | | | | | | |
| Beets | | | | | | | | | | | | |
| Lettuce | | | | | | | | | | | | |

The main recommendation of this analysis is that all polypropylene components be replaced as much as possible as allowed by energy analysis and reliability considerations. This arises from the cost benefit analysis, and is backed up by the previously undertaken materials and energy analysis steps. Initial findings from the payback period calculations show that the current greenhouse design is not viable as a pure economic venture.

However, we recommend that were a new greenhouse to be constructed the back wall height be increased by 10%, the polypropylene roof material should be replaced by wood and packed straw, and the greenhouse should be constructed such that it faces due South, rather than East. Revising our analysis, we find that these changes carry significant benefit to all aspects of the design, as follows:

- Ergonomic dimensions improve user comfort, leading to higher probability of continued use
- Embodied energy reduced by 8200 MJ (47%)
- Cost reduced from \$1494 to \$1028 (savings of 466 AUD)
- Worst-case winter temperature increased from 1.9°C to 2.4°C (0.5°C)
- Crops can now reliably grow tomatoes for 3 months of the year, and the growing seasons of the other analysed crops has been extended, as in table 8

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A Code for Energy Analysis

A.1 GEA.m

```
classdef GEA
    methods (Static = true)

        function Q_leak=heat_loss_ACH(ACH,T_in,T_out,Phi_in,Phi_out)
            rho=0.8; % dry air density, kg/m^3 (DeNysschen, n.d.)
            V=10.85*4.6*0.5*(2.55+2); % volume of greenhouse, m^3
            h_in=GEA.enthalpy_humid_air(T_in,Phi_in);
            h_out=GEA.enthalpy_humid_air(T_out,Phi_out);
            Q_leak=ACH*rho*V*(h_in-h_out)/3.6; %In Watts
        end

        function Phi=absolute_to_relative(Temp,omega)
            T=5:5:35; %Temperature range in deg C
            P_sat=[0.8725,1.2281,1.7057,2.3392,3.1698,4.2469,5.6291]; % actual saturation pres
            fit=polyfit(T,P_sat,1); %find a linear fit to approximate saturation pressure at a
            P_g=fit(1).*Temp+fit(2);
            P=70;%Pressure at 3000m altitude in kPa (Cengel & Boles, 2011)
            Phi=(omega*P)/(omega*P_g+0.622*P_g); %(Cengel & Boles, 2011)
        end

        function omega=relative_to_absolute(Temp,Phi)
            T=5:5:35; %Temperature range in deg C
            P_sat=[0.8725,1.2281,1.7057,2.3392,3.1698,4.2469,5.6291]; % actual saturation pres
            fit=polyfit(T,P_sat,1); %find a linear fit to approximate saturation pressure at a
            P_g=fit(1).*Temp+fit(2);
            P=70; %Pressure at 3000m altitude in kPa (Cengel & Boles, 2011)
            omega=(0.622*Phi*P_g)./(P-Phi*P_g); %(Cengel & Boles, 2011)
        end

        function h=enthalpy_humid_air(Temp,Phi)
            omega=GEA.relative_to_absolute(Temp,Phi); %(Cengel & Boles, 2011)
            h_g=2500.9+1.82*Temp; %specific enthalpy of water vapour, kJ/kg
            h_a=1.005; %enthalpy of dry air, kJ/kg
            h=h_a+omega*h_g;
            %    figure;
            %    plot(T,P_sat,T,polyval(fit,T))
        end

        function [Q_leak,Phi_in]=air_leakage_loss(T_in,T_out,Phi_out,ACH_closed,ACH_open)
            if T_in > 25 || T_in < T_out %Open the vents
                %Using our assumption that Phi_in is greater than Phi_out by
                %half the difference between Phi_out and 100% when the
                %vents are open:
                ACH=ACH_open;
                Phi_in=Phi_out+0.25*(1-Phi_out);
            else
                %Vents will be closed, and condensation present, so:
                %Phi_in=((0.47*(T_in-T_out))/(T_in-5))-(2.3/(T_in-5))
                ACH=ACH_closed;
            end
        end
    end
end
```

```

        Phi_in=0.5*Phi_out+0.5;
    end

    Q_leak=GEA.heat_loss_ACH(ACH,T_in,T_out,Phi_in,Phi_out);
end

function cond=condensation(T_out,T_in,Phi_in)
    %Determine whether there is condensation on the inside of the
    %cover. This occurs if at Phi_in, T_out is such that Phi_cover
    %is >=100%. (Pye, 2013) Assume that the cover is at temperature T_out
    omega_in=GEA.relative_to_absolute(T_in,Phi_in);
    Phi_cover=GEA.absolute_to_relative(T_out,omega_in);

    if Phi_cover >= 1 || Phi_cover < 0
        %fprintf('\nCondensation on the cover\n')
        cond=1;
    else
        cond=0;
    end
end

function R_th=convection_R_poly(T_out,T_in,Phi_in,wind_speed,PTS)
    %Convection
    %Apply convective losses to roof as well
    conv_in=2.21*(abs(T_in-T_out))^0.33; %Inner convection heat transfer coefficient (
    U_out_cover=(PTS.A_cover*5.6*wind_speed^0.8)/(3.24^0.2); %Outer convection heat t
    U_out_roof=(PTS.A_roof*5.6*wind_speed^0.8)/(3.24^0.2);
    latent_heat=2454; %kJ/kg (Engineering Toolbox, n.d.)
    h_air=1.005; %kJ/kg (Cengel & Boles, 2011)

    if GEA.condensation(T_out,T_in,Phi_in)==1
        %There is condensation present:
        omega_in=GEA.relative_to_absolute(T_in,Phi_in);
        omega_cover=GEA.relative_to_absolute(T_out,1); %Humidity ratio at saturation (
        %Model only works under certain boundaries, so define omega as 0
        %if negative
        if omega_in < 0
            omega_in=0;
        elseif omega_cover < 0
            omega_cover=0;
        end
        U_in_roof=PTS.A_roof*conv_in*latent_heat*(omega_in-omega_cover)/h_air; % (Garz
        U_in_cover=PTS.A_cover*conv_in*latent_heat*(omega_in-omega_cover)/h_air; % (Ga
    else
        U_in_cover=conv_in*PTS.A_cover;
        U_in_roof=conv_in*PTS.A_roof;
    end

    U_in_conduction=(PTS.A_roof*PTS.k_roof)/PTS.thickness_roof; %Add conduction term f
    R_th_roof=(1/U_in_roof)+(1/U_out_roof)+(1/U_in_conduction); %Convective resistance
    R_th_cover=(1/U_in_cover)+(1/U_out_cover); %Convective resistances are in series
    R_th=1/((1/R_th_cover)+(1/R_th_roof)); %In parallel
end

```



```

function Q_rad=radiation_loss_cover(T_in,T_out,T_sky,Phi_in,time,PTS,model)
    A_cover=PTS.A_cover;
    A_ground_in=PTS.A_ground_in;
    A_roof=PTS.A_roof;
    if strcmp(time,'day')==1
        Q_rad=0;
    elseif strcmp(time,'night')==1
        if strcmp(model,'before')== 1
            area=A_cover+A_roof;
        elseif strcmp(model,'after')== 1
            area=A_cover;
        end
        %Radiation
        sigma=5.6697*10^-8; %Steffan Boltzmann constant
        tau=0.77; %Transmissivity of the cover/roof (HelloTrade, n.d.; Jaffer, 2012)
        %Emissivities:
        eps_ground=0.38; %Emissivity of a ploughed field, (Table of total emissivity,
        eps_cover=0.16; % (Garzoli & Blackwell 1981)
        eps_condensation=0.95; %(Garzoli & Blackwell 1981)
        %View factors
        F_cover_sky=0.72; %(Garzoli & Blackwell 1981)
        F_cover_ground=0.77; %(Garzoli & Blackwell 1981)
        %Assume inside ground surface temp is equal to inside air temp.
        %Assume outside ground surface temp is equal to outside air
        %temp. T_g, the characteristic ground temp is a completely
        %separate number
        if GEA.condensation(T_out,T_in,Phi_in)==1
            %There is condensation present:
            %fprintf('\nRunning Radiation loss with condensation\n')
            Q_rad=0.33*sigma*A_ground_in*tau*eps_ground*((T_out+273)^4-(T_sky+273)^4)+
                *F_cover_sky*((T_in+273)^4-(T_sky+273)^4)+sigma*(area)*eps_cover*F_cov
                ((T_in+273)^4-(T_out+273)^4)+0.67*sigma*(area)*eps_condensation*tau*F_
                ((T_in+273)^4-(T_sky+273)^4)+0.67*sigma*eps_condensation*tau*(area)*F_
                ((T_in+273)^4-(T_out+273)^4); %Adapted from (Garzoli and Blackwell,198
        else
            %fprintf('\nRunning Radiation loss without condensation\n')
            Q_rad=sigma*A_ground_in*tau*eps_ground*((T_out+273)^4-(T_sky+273)^4)+sigma
                *F_cover_sky*((T_in+273)^4-(T_sky+273)^4)+sigma*(area)*eps_cover*F_cov
                ((T_in+273)^4-(T_out+273)^4); %Adapted from (Garzoli and Blackwell,198
        end
    end
end

function R_th=conv_cond_R_ground(T_in,T_g,PTS)
    conv_ground=1.86*(abs(T_in-T_g))^0.33; %(Roy et al, 2002)
    k_soil=1.4; %(Engineering Toolbox, n.d.)
    R_cond_soil=(PTS.thickness_soil/k_soil)+(PTS.thickness_PET/PTS.k_PET); %In series
    if conv_ground==0
        R_th_ground=(R_cond_soil)/PTS.A_ground_in;
    else
        R_th_ground=(R_cond_soil+(1/conv_ground))/PTS.A_ground_in;
    end
    R_th_wall=PTS.thickness_wall/(PTS.k_wall*PTS.A_wall);

```

```

    R_th=(R_th_ground*R_th_wall)/(R_th_ground+R_th_wall);
end

function C=heat_capacity(volume_barrels,PTS)
    rho_water=1000; %kg/m^3
    c_water=4184; %J/kg K
    c_stone=840; %J/kg K %(Engineering Toolbox, n.d.)
    rho_stone=2500; %(Engineering Toolbox, n.d.)
    V_stone=PTS.A_stone*PTS.thickness_stone; %m^3 (EWB, 2010)
    %C_air=(GEA.enthalpy_humid_air(T_in,Phi_in)-GEA.enthalpy_humid_air(T_out,Phi_in))*
    C_ground=0.7*c_water*0.3*PTS.A_ground_in*rho_water;
    C_barrels=volume_barrels*rho_water*c_water;
    C_stone=rho_stone*V_stone*c_stone;
    C=C_ground+C_barrels+C_stone;
end

function ACH_open=ACH_calc(ventilation_speed,ACH_closed,PTS) %Ventilation_speed must b
    V_out=3600*PTS.A*ventilation_speed; %Volumetric rate of air leaving greenhouse,
    ACH_open=(V_out/PTS.V)+ACH_closed; %Numer of times the entire volume of air in
end

function [T_out,SG,Phi_out,T_sky,day_length,season,T_g]=variable_assignment_month(mode
    %Mean temperatures for Namche region, <30km from Phuongmoche, and similar altit
    mean_SG=[10.4,11.9,12.6,14.4,15.6,14.6,14.7,11.8,11.0,11.6,10.9,10.5]; %MJ/m^2/
    %mean_SG=[3.5,4,4,5.5,5,4,3,3,3.5,4.5,3.5,3.5]; %kWh/day
    mean_temps=[-0.7,0.6,3.5,7.2,9.2,11.4,12.4,12.1,11,7.6,4.0,0.8]; %deg C
    mean_Phi=[35,45,49,58,75,88,92,93,91,66,45,30]/100;
    day_lengths=[11,11,12,13,14,14,14,13,13,12,11,11]; %(PTAFF, 2005)
    %Ground temps (approximate)
    T_gs=[10,10,12,14,16,17,17,17,16,14,12,10]; %deg C
    %Use month_index to define our variables:
    if month_index==6 || month_index==7 || month_index==8 || month_index==9
        %Monsoon season - cloud cover (Thapa & Shakya 2008)
        T_sky=10; %deg C (Garzoli & Blackwell 1981)
    else
        T_sky=-10; %deg C (Garzoli & Blackwell 1981)
    end

    if month_index==10 || month_index==11 || month_index==12 || month_index==1 || mo
        season='winter'; %(Thapa & Shakya 2008)
    else
        season='summer';%(Thapa & Shakya 2008)
    end

    %Define length of day/night
    day_length=day_lengths(month_index); %hours/day
    %Define ground temperature
    T_g=T_gs(month_index); %Deg C

    Phi_out=mean_Phi(month_index);
    if strcmp(model,'before')

        if strcmp(time,'day')==1

```

```

        T_out=mean_temps(month_index)+fluct_plus;
        irradiance=mean_SG(month_index); %MJ/m^2/day
        %Convert irradiance in MJ/m^2/day to solar gain in W/m^2:
        SG_incident=(irradiance*10^6)/(day_length*3600); %in W/m^2
        %Transmissivity of greenhouse
        tau=0.7;
        %Angle of sun
        azimuth=27; %degrees (PTAFF, 2005)
        %Solar gain absorbed by the greenhouse
        SG=SG_incident*tau*(PTS.A_ground_in*cosd(azimuth)+PTS.A_stone*sind(azim
elseif strcmp(time,'night')==1
        T_out=mean_temps(month_index)-fluct_minus;
        SG=0;
    end
elseif strcmp(model,'after')
    if strcmp(time,'day')==1
        T_out=mean_temps(month_index)+fluct_plus;
        irradiance=mean_SG(month_index); %MJ/m^2/day
        %Convert irradiance in MJ/m^2/day to solar gain in W/m^2:
        SG_incident=(irradiance*10^6)/(3600*day_length); %in W/m^2
        %Transmissivity of greenhouse
        tau=0.8;
        %Solar gain absorbed by the greenhouse
        SG=SG_incident*tau*PTS.A_cover; %In W/m^2
    elseif strcmp(time,'night')==1
        T_out=mean_temps(month_index)-fluct_minus;
        SG=0;
    end
end
end
end
end

```

```

function drawSankey(inputs, losses, unit, labels, varargin) %(Spelling, 2010)

% drawSankey(inputs, losses, unit, labels, sep)
%
% drawSankey is a matlab function that draws single-direction Sankey
% diagrams (i.e no feedback loops), however, multiple inputs can be
% specified.
%
% inputs: a vector containing the flow inputs, the first of which will be
%         considered the main input and drawn centrally, other inputs will
%         be shown below this.
%
% losses: a vector containing all of the losses from the system, which will
%         be displayed along the top of the Sankey diagram
%
% unit:   a string indicating the unit in which the flows are expressed
%
% labels: a cell list of the labels for the different flows, starting with
%         the labels for the inputs, then the losses and finally the output
%
% sep:    an (optional) list of position for separating lines, placed after

```

```

%           the loss corresponding to the indexes provided
%
% For an example, copy and paste the lines below to the command line:
%
%   inputs = [75 32]; losses = [10 5 2.8]; unit = 'MW'; sep = [1,3];
%   labels = {'Main Input','Aux Input','Losses I','Losses II','Losses III','Output'
%
%   drawSankey(inputs, losses, unit, labels, sep);
%
% Current Version: 02.11.2009
% Developed by:    James SPELLING, KTH-EGI-EKV
%                 spelling@kth.se
%
% Distributed under Creative Commons Attribution + NonCommerical (by-nc)
% Licensees may copy, distribute, display, and perform the work and make
% derivative works based on it only for noncommercial purposes

%check parameter values%
if sum(losses) >= sum(inputs)

    %report unbalanced inputs and losses%
    error('drawSankey: losses exceed inputs, unable to draw diagram');

elseif any(losses < 0) || any(inputs < 0)

    %report negative inputs and/or losses%
    error('drawSankey: negative inputs or losses encountered');

else

    %check for the existance of separating lines%
    if nargin > 4; sep = varargin{1}; end

    %create plotting window%
    figure('color','white','tag','sankeyDiagram');

    %if possible, maximise figure%
    if exist('maximize','file')
        maximize(gcf);
    end

    %create plotting axis then hide it%
    axes('position',[0.1 0 0.8 0.85]); axis off;

    %calculate fractional losses and inputs%
    frLosses = losses/sum(inputs);
    frInputs = inputs/sum(inputs);

    if length(inputs(inputs > eps)) == 1

        %assemble first input label if only one input%
        inputLabel = sprintf('%s\n%.1f [%s]', labels{1}, inputs(1), unit);

```

```

else

    %assemble first input label if only several inputs%
    inputLabel = sprintf('%s\n%.1f [%s] %.1f [%%]', labels{1}, inputs(1), unit

end

%determine first input label font size%
fontsize = min(16, 10 + ceil((frInputs(1)-0.05)/0.025));

%draw first input label to plotting window%
text(0, frInputs(1)/2, inputLabel, 'FontSize', fontsize, 'HorizontalAlignment',

%draw back edge of first input arrow%
line([0.1 0 0.05 0 0.4], [0 0 frInputs(1)/2 frInputs(1) frInputs(1)], 'Color',

%set initial position for the top of the arrows%
limTop = frInputs(1); posTop = 0.4;

%set initial position for the bottom of the arrows%
limBot = 0; posBot = 0.1;

%draw arrows for additional inputs%
for j = 2 : length(inputs)

    %don't draw negligible inputs%
    if frInputs(j) > eps

        %determine inner and outer arrow radii%
        rI = max(0.07, abs(frInputs(j)/2));
        rE = rI + abs(frInputs(j));

        %push separation point forwards%
        newPosB = posBot + rE*sin(pi/4) + 0.01;
        line([posBot newPosB], [limBot limBot], 'Color', 'black', 'LineWidth',
        posBot = newPosB;

        %determine points on the external arc%
        arcEx = posBot - rE*sin(linspace(0,pi/4));
        arcEy = limBot - rE*(1 - cos(linspace(0,pi/4)));

        %determine points on the internal arc%
        arcIx = posBot - rI*sin(linspace(0,pi/4));
        arcIy = limBot - rE + rI*cos(linspace(0,pi/4));

        %draw internal and external arcs%
        line(arcIx, arcIy, 'Color', 'black', 'LineWidth', 2.5);
        line(arcEx, arcEy, 'Color', 'black', 'LineWidth', 2.5);

        %determine arrow point tip%
        phiTip = pi/4 - 2*min(0.05, 0.8*abs(frInputs(j)))/(rI + rE);
        xTip = posBot - (rE+rI)*sin(phiTip)/2;
        yTip = limBot - rE + (rE+rI)*cos(phiTip)/2;

```

```

%draw back edge of additional input arrows%
line([min(arcEx) xTip min(arcIx)], [min(arcEy) yTip min(arcIy)], 'Color', 'r');

%determine text edge location%
phiText = pi/2 - 2*min(0.05, 0.8*abs(frInputs(j)))/(rI + rE);
xText = posBot - (rE+rI)*sin(phiText)/2;
yText = limBot - rE + (rE+rI)*cos(phiText)/2;

%determine label size based on importance%
if frInputs(j) > 0.1

    %large inputs text size scales slower%
    fullLabel = sprintf('%s\n%.1f [%s] %.1f [%%]', labels{j}, inputs{j},
        fontsize = 12 + round((frInputs(j)-0.01)/0.05);

elseif frInputs(j) > 0.05

    %smaller but more rapidly scaling losses%
    fullLabel = sprintf('%s: %.1f [%s] %.1f [%%]', labels{j}, inputs{j},
        fontsize = 10 + ceil((frInputs(j)-0.05)/0.025);

else

    %minimum text size for input label%
    fullLabel = sprintf('%s: %.1f [%s] %.1f [%%]', labels{j}, inputs{j},
        fontsize = 10;

end

%draw input label%
text(xText, yText, fullLabel, 'FontSize', min(16, fontsize), 'HorizontalAlignment', 'center');

%save new bottom end of arrow%
limBot = limBot - frInputs(j);

end

end

%draw arrows of losses%
for i = 1 : length(losses)

    %don't draw negligible losses%
    if frLosses(i) > eps

        %determine inner and outer arrow radii%
        rI = max(0.07, abs(frLosses(i)/2));
        rE = rI + abs(frLosses(i));

        %determine points on the internal arc%
        arcIx = posTop + rI*sin(linspace(0,pi/2));
        arcIy = limTop + rI*(1 - cos(linspace(0,pi/2)));
    end
end

```

```

%determine points on the external arc%
arcEx = posTop + rE*sin(linspace(0,pi/2));
arcEy = (limTop + rI) - rE*cos(linspace(0,pi/2));

%draw internal and external arcs%
line(arcIx, arcIy, 'Color', 'black', 'LineWidth', 2.5);
line(arcEx, arcEy, 'Color', 'black', 'LineWidth', 2.5);

%determine arrow tip dimensions%
arEdge = max(0.015, rI/3);
arTop = max(0.04, 0.8*frLosses(i));

%determine points on arrow tip%
arX = posTop + rI + [0 -arEdge frLosses(i)/2 frLosses(i)+ arEdge frLos
arY = limTop + rI + [0 0 arTop 0 0];

%draw tip of losses arrow%
line(arX, arY, 'Color', 'black', 'LineWidth', 2.5);

%determine text edge location%
txtX = posTop + rI + frLosses(i)/2;
txtY = limTop + rI + arTop + 0.05;

%determine label size based on importance%
if frLosses(i) > 0.1

    %large losses have the space for a two line label%
    fullLabel = sprintf('%s\n%.1f [%%]',labels{i+length(inputs)}, 100*
    fontsize = 12 + round((frLosses(i)-0.01)/0.05);

elseif frLosses(i) > 0.05

    %single line, but still scaling label%
    fullLabel = sprintf('%s: %.1f [%%]',labels{i+length(inputs)}, 100*
    fontsize = 10 + ceil((frLosses(i)-0.05)/0.025);

else

    %minimum size single line label%
    fullLabel = sprintf('%s: %.1f [%%]',labels{i+length(inputs)}, 100*
    fontsize = 10;

end

%draw losses label%
text(txtX, txtY, fullLabel, 'Rotation', 90, 'FontSize', fontsize);

%save new position of arrow top%
limTop = limTop - frLosses(i);

%advance to new separation point%
newPos = posTop + rE + 0.01;

```

```

        %draw top line to new separation point%
        line([posTop newPos], [limTop limTop], 'Color', 'black', 'LineWidth',

        %save new advancement point%
        posTop = newPos;

    end

    %separation lines%
    if any(i == sep)

        if length(inputs) > 1 && any(inputs(2 : length(inputs)) > eps)

            %if there are additional inputs, determine approx. sep. line%
            xLeft = 0.1*posTop;

        else

            %otherwise determine exact sep. line%
            xLeft = 0.05 * (1 - 2*abs(limTop - 0.5));

        end

        %draw the line%
        line([xLeft posTop], [limTop limTop], 'Color', 'black', 'LineWidth', 2

    end

end

%push the arrow forwards a little after all side-arrows drawn%
newPos = max(posTop, posBot) + max(0.05*limTop, 0.05);

%draw lines to this new position%
line([posTop, newPos],[limTop limTop], 'Color', 'black', 'LineWidth', 2.5);
line([posBot, newPos],[limBot limBot], 'Color', 'black', 'LineWidth', 2.5);

%draw final arrowhead for the output%
line([newPos newPos newPos+max(0.04, 0.8*(limTop-limBot)) newPos newPos], [lim

%save final tip position%
newPos = newPos + 0.8*(limTop - limBot);

%determine overall ins and outs%
outputFinal = sum(inputs) - sum(losses);
inputFinal = sum(inputs);

%create the label for the overall output arrow%
endText = sprintf('%s\n%.0f [%s] %.1f [%%]', labels{length(losses)+length(input
fontSize = min(16, 10 + ceil((1-sum(frLosses)-0.1)/0.05));

%draw text for the overall output arrow%

```



```

        text(newPos + 0.05, (limTop+limBot)/2, endText, 'FontSize', fontsize);

        %set correct aspect ratio%
        axis equal;

        %set correct axis limits%
        set(gca,'YLim',[frInputs(1)-sum(frInputs)-0.4, frInputs(1)+frLosses(1)+0.4]);
        set(gca,'XLim',[-0.15, newPos + 0.1]);

    end

end

end

end

```

A.2 Main function for thermal model, fully commented

```

function [T_in,Q_air_night,Q_rad_night,SG_night,Q_cover_night,Q_ground_night,net_night,...
    Q_air_day,Q_rad_day,SG_day,Q_cover_day,Q_ground_day,net_day,...
    Q_air_tot,Q_rad_tot,SG_tot,Q_cover_tot,Q_ground_tot,net_tot,timestep,C]=...
    time_dependent_analysis_funct(PTS,model,month,fluct_plus,fluct_minus,ventilation_speed,ACH

%OVERVIEW OF FUNCTION OPERATION
%This function computes the heat loss and gain from the Phuongmoche
%greenhouse every hour over a 7 day period. Magnitudes of losses change
%over this period as a function of internal temperature. The internal
%temperature is updated every hour by the discrete form of an ODE which
%comes from thermal circuit analysis. Since the initial temperature inside
%the greenhouse is not known, the program runs for 7 days which is
%sufficient for the system to reach steady state. Thus, an energy balance
%between input and output energy over the course of 24 hours is reached.

%DEFINITION OF OUTPUT VARIABLES
%The first output, T_in, is the internal air temperature of the greenhouse.
%It is a vector containing temperatures for every hour over the 7-day
%period.

%The next outputs of this function are the total heat loss in joules over the
%course of the night, day, and 24 hour period respectively of each loss
%mechanism considered. If it happens that the "loss" mechanism actually
%provides "gain" to the system, (for example in the winter the ground will
%be warmer than inside the greenhouse, so will give energy to the
%greenhouse) then the output is negative. The exception to this is Solar
%gain, which always gives energy, and is given as a positive number.

%The second to last output is the timestep of the function, which is simply a
%vector containing the numbers corresponding to each hour for which the
%function runs

%The final output is the heat capacity of the greenhouse in J/K

%DEFINITION OF INPUT VARIABLES

```

```

%PTS: A structure containing the intrinsic physical properties and
%dimensions of the greenhouse, e.g thermal conductivity of walls,
%length of greenhouse, etc.. These properties may be changed if we decide
%to alter the greenhouse design in any way - allows us to directly see
%the thermal effect of any changes

%MODEL: This is a string; either 'before' or 'after', which designates
%whether to use the model for the existing greenhouse, or the model for
%a new greenhouse that we have made alterations to.

%MONTH: an integer between 1 and 12, corresponding to the month of the year
%for which the analysis is to be carried out. Average external temperature
%and humidity data are already defined within the function, based on
%meteorological data from close to Phuongmoche

%FLUCT_PLUS: Suggested value: 5. This is a temperature in degrees celcius,
%and should be a positive number. It represents the number of degrees by
%which the average DAILY temperature is GREATER than the average MONTHLY
%temperature (which doesn't take diurnal fluctuations into account)

%FLUCT_MINUS: Suggested value: 5. This is a temperature in degrees celcius,
%and should be a positive number. It represents the number of degrees by
%which the average NIGHTLY temperature is SMALLER than the average MONTHLY
%temperature (which doesn't take diurnal fluctuations into account)

%VENTILATION_SPEED: Suggested value: 0.5 - 5. This is a speed in m/s. It
%represents the velocity of air leaving or entering the ventilation shafts
%of the greenhouse. Changing the ventilation speed even slightly can cause
%large changes in heat transfer due to air exchange. This value is
%completely an estimate - it is far to complex to attempt to find a
%formula. As a general rule, take 0.5m/s to mean a day of low external
%wind, and 5 to be a day of relatively high external wind. If your results
%seem unreasonable, try changing this value

%ACH_closed: Suggested value: 2-5. This is the number of times the entire
%volume of air in the greenhouse is replaced every hour when the
%ventilation shafts are closed, i.e. due to air leakage through any gaps,
%such as the door, rips in the cover, gaps in the roof, etc. For an average
%house, ACH (air changes per hour) is around 1-2, but we would probably
%expect the greenhouse to be more "leaky".

%VOLUME_BARRELS: Suggested value: 1-2. This is a volume in m^3. It
%represents the volume of water users might place in the greenhouse (in
%barrels, rather than for watering, which is already taken into account as
%a constant within the model) to artificially increase thermal mass.

T_in0=10; %deg C - just a starting point: will run until steady state
ACH_open=GEA.ACH_calc(ventilation_speed,ACH_closed,PTS);
wind_speed=70/3.6; %m/s an approximation - turns out to make little difference
%Assign the following variables based on the time of day, month, and
%desired temp fluctuations
time='day';

```

```

[T_out,SG,Phi_out,T_sky,day_length,season,T_g]=GEA.variable_assignment_month(model,month,t
night_length=24-day_length;

timestep=1:24*7; %Number of hours in a week

%Preassign variables whose values will be inserted in the subsequent
%for loop
T_in=zeros(1,length(timestep));
T_in(1)=T_in0;
Q_air=zeros(1,length(timestep));
Phi_in=zeros(1,length(timestep));
Q_rad=zeros(1,length(timestep));
Q_ground=zeros(1,length(timestep));
C=zeros(1,length(timestep));
Q_cover=zeros(1,length(timestep));
%Loop over the number of hours in a week
for hours=1:(length(timestep))

    if hours==(day_length) || hours==(24) || hours==24+day_length || hours==(2*24)...
        || hours==2*24+day_length || hours==(3*24) || hours==3*24+day_length || hours=
        || hours==4*24+day_length || hours==(5*24) || hours==5*24+day_length || hours=
        || hours==6*24+day_length || hours==(7*24) || hours==7*24+day_length
        %For any hour corresponding to the transition between day and
        %night, hange from night to day, and vice versa
        if strcmp(time,'day')==1
            %Don't change day length
            time='night';
            [T_out,SG,Phi_out,T_sky,blank,season,T_g]=GEA.variable_assignment_month(model,
        elseif strcmp(time,'night')==1
            time='day';
            [T_out,SG,Phi_out,T_sky,blank,season,T_g]=GEA.variable_assignment_month(model,
        end
    end
end

%Now find heat loss for each mechanism:
%Air leakage. Use T_in of the previous time step
[Q_air(hours),Phi_in(hours)]=GEA.air_leakage_loss(T_in(hours),T_out,Phi_out,ACH_closed
%Radiation loss
Q_rad(hours)=GEA.radiation_loss_cover(T_in(hours),T_out,T_sky,Phi_in(hours),time,PTS,m
%Convection/conduction through roof/cover
R_th_cover=GEA.convection_R_poly(T_out,T_in(hours),Phi_in(hours),wind_speed,PTS);
Q_cover(hours)=(T_in(hours)-T_out)/R_th_cover;
%Convection/conduction through ground
R_th_ground=GEA.conv_cond_R_ground(T_in(hours),T_g,PTS);
Q_ground(hours)=(T_in(hours)-T_g)/R_th_ground;
%Energy stored in greenhouse
C=GEA.heat_capacity(volume_barrels,PTS);

%The remaining equations will be derived separately
R=1/((1/R_th_cover)+(1/R_th_ground)); %Equivalent R_th
Q_tot=Q_air(hours)+Q_rad(hours)-SG; %Total direct heat transfer
Q_dot=(T_out/R_th_cover)+(T_g/R_th_ground)-Q_tot; %Total heat transfer
tau=R*C; %Time constant

```

```

    if hours==length(timestep)
        continue
    else
        %Differential equation governing the thermal circuit
        T_in(hours+1)=T_in(hours)+(3600*(Q_dot/C))-(3600*(T_in(hours)/tau)); %Evaluate the
    end

end

%Steady state net nocturnal heat loss: (Summing the components of each
%heat loss vector for the hours corresponding to the final night of the
%week)
Q_air_night=3600*sum(Q_air(timestep(length(timestep))-night_length:timestep(length(timeste
Q_rad_night=3600*sum(Q_rad(timestep(length(timestep))-night_length:timestep(length(timeste
SG_night=0;
Q_cover_night=3600*sum(Q_cover(timestep(length(timestep))-night_length:timestep(length(tim
Q_ground_night=3600*sum(Q_ground(timestep(length(timestep))-night_length:timestep(length(t
net_night=Q_air_night+Q_rad_night+SG_night+Q_cover_night+Q_ground_night;

%Steady state net diurnal heat loss: (Summing the components of each
%heat loss vector for the hours corresponding to the final day of the
%week)
Q_air_day=3600*sum(Q_air(timestep(length(timestep))-24:timestep(length(timestep))-night_le
Q_rad_day=3600*sum(Q_rad(timestep(length(timestep))-24:timestep(length(timestep))-night_le
[blank,SG,blank,blank,day_length,blank,blank]=GEA.variable_assignment_month(model,month,'d
SG_day=day_length*3600*SG;
Q_cover_day=3600*sum(Q_cover(timestep(length(timestep))-24:timestep(length(timestep))-nigh
Q_ground_day=3600*sum(Q_ground(timestep(length(timestep))-24:timestep(length(timestep))-ni
net_day=Q_air_day+Q_rad_day-SG_day+Q_cover_day+Q_ground_day;

%Steady state net losses over 24 hours in MJ in steady state (Summing
%the losses from the last day and night of the week together
Q_air_tot=Q_air_day+Q_air_night;
Q_rad_tot=Q_rad_day+Q_rad_night;
SG_tot=SG_day+SG_night;
Q_cover_tot=Q_cover_day+Q_cover_night;
Q_ground_tot=Q_ground_day+Q_ground_night;
net_tot=net_day+net_night;
end

```

A.3 Script to run main function suite, and plot all relevant figures; commented and referenced

```

%To exectute each cell individually, hold command enter (or control enter for windows).
%Hold shift as well if you want the cursor to move to the next cell for
%easy execution in order.
clear all %Clear the workspace of all variables - recommended if running function multiple tim
clc %Clears the command window
%%
addpath('/Users/bennettschneider/Documents/ANU/Semester 2, 2014/Systems/Group project/Jigsaw T
import GEA.*

```

```

%Define variables. See function documentation for descriptions and
%suggested values

months=1:12; %Month of the year, integer between 1 and 12

fluct_plus=[5 6 7 8 9 10 11 11 10 9 8 7 6 5];%12.6;%5 %Temperature, deg C
fluct_minus=[5 6 7 8 9 10 11 11 10 9 8 7 6 5];%2.4;%5 %Temperature, deg C
ventilation_speed=1;%0.5; %3 %Speed, m/s
ACH_closed=3;%2; %4%Air changes per hour when ventilation shafts closed
volume_barrels=2; %Volume of water added, m^3
%%
%Properties - create structure PTS to pass all properties easily
%Following dimensions obtained from EWB (2010)
LENGTH=10.85;
slant_height=1.05;
back_height=1.5;
total_height=slant_height+back_height;
width=4.6;
slant_width=2;
cover_width=width-slant_width;
cover_slant_width=sqrt(cover_width^2+total_height^2);
ventilation_area=2;

model='after';

k_fbrplas=0.18; %fibreglass-reinforced plastic (Engineering Toolbox n.d.)
k_wdstraw=0.08; %packed straw
thickness_fbrplas=0.003; %m, fibreglass-reinforced plastic (HelloTrade n.d.)
thickness_wdstraw=0.05;%0.05;% packed straw

PTS.A_roof=LENGTH*sqrt(slant_height^2+slant_width^2); %m^2
PTS.A_cover=(LENGTH*cover_slant_width); %m^2
PTS.A_ground_in=LENGTH*width; %m^2
PTS.k_PET=0.33; %(Oumaya et al. n.d.)
PTS.thickness_soil=0.3; %m (EWB 2010)
PTS.thickness_PET=0.1; %m (EWB 2010)
PTS.A_wall=back_height*LENGTH; %m^2
PTS.thickness_wall=0.3; %m (EWB 2010)
PTS.V=LENGTH*(width*back_height+0.5*(width*slant_height)); % volume of greenhouse, m^3
PTS.A=ventilation_area; %Total area of ventilation shafts, m^2
PTS.A_stone=width*back_height+0.5*(width*slant_height)-2;
PTS.thickness_stone=0.15; %(EWB 2010)
PTS.k_wall=4.5; %(Engineering Toolbox n.d.)
if strcmp(model,'before') == 1
    PTS.k_roof=k_fbrplas;
    PTS.thickness_roof=thickness_fbrplas;
elseif strcmp(model,'after') == 1
    PTS.k_roof=k_wdstraw;
    PTS.thickness_roof=thickness_wdstraw;
end

%%

```

```

minimums = zeros(1,12);
averages = zeros(1,12);

%%
for count = 1:12
[T_in,Q_air_night,Q_rad_night,SG_night,Q_cover_night,Q_ground_night,net_night,...
    Q_air_day,Q_rad_day,SG_day,Q_cover_day,Q_ground_day,net_day,...
    Q_air_tot,Q_rad_tot,SG_tot,Q_cover_tot,Q_ground_tot,net_tot,timestep,C]=...
    time_dependent_analysis_funct(PTS,model,months(count),fluct_plus(count),...
    fluct_minus(count),ventilation_speed,ACH_closed,volume_barrels);

minimums(count) = min(T_in);
averages(count) = mean(T_in);

end

%% Plots
% %%
% %The following cells may be executed in any order. Each will create a plot
% %of some part of the output
%
% %Plot a bar graph of the total energy in MJ transferred throughout the
% %Night:
% figure;
% bar([Q_air_night,Q_rad_night,Q_cover_night,Q_ground_night,SG_night,net_night]/(10^6))
% set(gca,'XTickLabel',{'Air','Radiation','Cover/roof','Ground','Solar gain','Net loss'})
% ylabel('Approximate heat loss, MJ')
% title('Heat loss during the night')
% % %%
% % %Plot a bar graph of the total energy in MJ transferred throughout the
% % %Day
% % figure;
% % bar([Q_air_day,Q_rad_day,Q_cover_day,Q_ground_day,-SG_day,net_day]/(10^6))
% % set(gca,'XTickLabel',{'Air','Radiation','Cover/roof','Ground','Solar gain','Net loss'})
% % ylabel('Approximate heat loss, MJ')
% % title('Heat loss during the day')
% % %%
% % %Plot net losses over 24 hours in MJ in steady state
% % figure;
% % bar([Q_air_tot,Q_rad_tot,Q_cover_tot,Q_ground_tot,-SG_tot,net_tot]/(10^6))
% % set(gca,'XTickLabel',{'Air','Radiation','Cover/roof','Ground','Solar gain','Net loss'})
% % ylabel('Approximate heat loss, MJ')
% % title('Heat loss over 24 hours, steady state')
% % %%
% % %Plot the internal air temperature of the greenhouse as a function of minutes from some in
% % [T_out_day,SG_day,Phi_out,T_sky,day_length,season,T_g]=variable_assignment_month(model,mon
% % [T_out_night,SG_night,Phi_out,T_sky,day_length,season,blank]=variable_assignment_month(mod
% % night_length=24-day_length;
% % figure;
% % plot([0,timestep(1:48)]/24,T_in(length(timestep)-48:length(timestep)),'b',...
% % [0,timestep(1:48)]/24,[T_out_day,linspace(T_out_day,T_out_day,day_length),...
% % linspace(T_out_night,T_out_night,night_length),linspace(T_out_day,T_out_day,day_length)
% % linspace(T_out_night,T_out_night,night_length)],'r','LineWidth',3)

```

```

%% %timestep(length(timestep)-48:length(timestep))/24,linspace(T_out_night,T_out_night,49),'b
%% xlabel('Time, days')
%% ylabel('Internal temperature, deg C')
%% title('Steady state internal greenhouse temperature over two days')
%% annotation('textbox',[0.4,0.9,0,0],'String',{'Month : ',num2str(month)},['Set conditions:
%% num2str(T_out_day),' degC, Night: ', num2str(T_out_night),' deg C'],['Sky temp: ',num2str(rou
%% ['Outside relative humidity: ',num2str(Phi_out)],['Daytime solar irradiance: ',num2str(rou
%% 'Set air changes per hour: ',['Closed: ',num2str(ACH_closed),...
%% 'Open: ',num2str(round(ACH_calc(ventilation_speed,ACH_closed,PTS)))]},...
%% 'FontSize',12,'Interpreter','tex','FitBoxToText','on','EdgeColor',[0 0 0])
%% legend('Internal Temperature','External Temperature')
%% ylim([T_out_night-0.06,max(T_in)+3])
%% %%
%% %Plot a sankey diagram of the system over the entire day in steady state
%% if Q_air_tot > 0 && Q_ground_tot > 0
%% %Plot sankey diagram for losses: Air, cover, ground, radiation
%% %Gains: Solar, heat capacity
%% delta_T=(sum(T_in)/length(T_in))-(T_out_day+T_out_night)/2;
%% inputs=[SG_tot,delta_T*C]/10^6;
%% losses=[Q_air_tot,Q_cover_tot,Q_ground_tot,Q_rad_tot]/10^6;
%% unit='MJ';
%% labels={'Solar Gain','Heat Capacity','Air heat transfer','Cover/roof heat transfer'...
%% 'Ground heat transfer','Radiation heat transfer','Heat Capacity'};
%% sep=[0,0];
%% elseif Q_air_tot < 0 && Q_ground_tot > 0
%% %Plot sankey diagram for losses: Cover, ground, radiation
%% %Gains: Solar, air, heat capacity
%% delta_T=(sum(T_in)/length(T_in))-(T_out_day+T_out_night)/2;
%% inputs=[SG_tot,-Q_air_tot,delta_T*C]/10^6;
%% losses=[Q_cover_tot,Q_ground_tot,Q_rad_tot]/10^6;
%% unit='MJ';
%% labels={'Solar Gain','Air heat transfer','Heat Capacity','Cover/roof heat transfer'...
%% 'Ground heat transfer','Radiation heat transfer','Heat Capacity'};
%% sep=[0,0];
%% elseif Q_air_tot < 0 && Q_ground_tot < 0
%% %Plot sankey diagram for losses: Cover, ground, radiation
%% %Gains: Solar, air, heat capacity
%% delta_T=(sum(T_in)/length(T_in))-(T_out_day+T_out_night)/2;
%% inputs=[SG_tot,-Q_air_tot,-Q_ground_tot,delta_T*C]/10^6;
%% losses=[Q_cover_tot,Q_rad_tot]/10^6;
%% unit='MJ';
%% labels={'Solar Gain','Air heat transfer','Ground heat transfer','Heat Capacity','Cover
%% 'Radiation heat transfer','Heat Capacity'};
%% sep=[0,0];
%% elseif Q_air_tot > 0 && Q_ground_tot < 0
%% %Plot sankey diagram for losses: Air, cover, ground, radiation
%% %Gains: Solar, heat capacity
%% delta_T=(sum(T_in)/length(T_in))-(T_out_day+T_out_night)/2;
%% inputs=[SG_tot,-Q_ground_tot,delta_T*C]/10^6;
%% losses=[Q_cover_tot,Q_air_tot,Q_rad_tot]/10^6;
%% unit='MJ';
%% labels={'Solar Gain','Ground heat transfer','Heat Capacity','Cover/roof heat transfer'
%% 'Radiation heat transfer','Heat Capacity'};

```

```

%%      sep=[0,0];
%% end
%%
%% drawSankey(inputs, losses, unit, labels,sep); %(Spelling, 2010)
%% annotation('textbox',[0.7,0.9,0,0],'String',{'Month : ',num2str(month)},['Set conditions:
%% num2str(T_out_day),' degC, Night: ', num2str(T_out_night),' deg C'],['Sky temp: ',num2str(rou
%% ['Outside relative humidity: ',num2str(Phi_out)],['Daytime solar irradiance: ',num2str(rou
%%      'Set air changes per hour: ',['Closed: ',num2str(ACH_closed),...
%%      'Open: ',num2str(round(ACH_calc(ventilation_speed,ACH_closed,PTS)))]},...
%% 'FontSize',12,'Interpreter','tex','FitBoxToText','on','EdgeColor',[0 0 0])

```

B Derivation of differential equation for thermal circuit

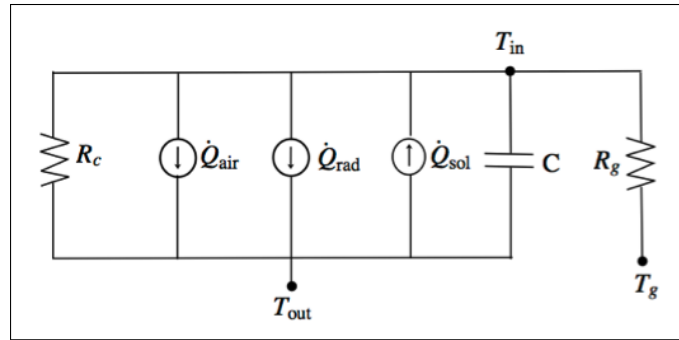


Figure 7: Thermal Circuit

Apply Kirchoff's node current law to T_{in} node:

$$\frac{T_{in} - T_{out}}{R_c} + C \frac{dT_{in}}{dt} + \frac{T_{in} - T_g}{R_g} + \dot{Q}_{tot}$$

where $\dot{Q}_{tot} = \dot{Q}_{air} + \dot{Q}_{rad} + \dot{Q}_{sol}$

$$\therefore T_{in} \left(\frac{1}{R_c} + \frac{1}{R_g} \right) + C \frac{dT_{in}}{dt} = \frac{T_{out}}{R_c} + \frac{T_g}{R_g} - \dot{Q}_{tot}$$

Let $\frac{1}{R} = \frac{1}{R_c} + \frac{1}{R_g}$

and let $\dot{Q} = \frac{T_{out}}{R_c} + \frac{T_g}{R_g} - \dot{Q}_{tot}$

$$\therefore \frac{dT_{in}}{dt} + \frac{T_{in}}{CR} - \frac{\dot{Q}}{C} = 0$$

C Discussion and justification for external temperatures chosen for simulations

Although (FEED 2012; Viltard 2003) suggest that summers can be quite hot ($> 30^\circ\text{C}$), none of the temperature data gathered from (Thapa & Shakya 2008) supports this, even from Namche observation station. The average temperature in July at Namche is only 12.4°C . This is incompatible with maximum temperatures of $> 30^\circ\text{C}$ since it is monsoon season; the air is moist and there is copious cloud cover, which would not allow significant cooling at night (Thapa & Shakya 2008). We compromise by considering an average daytime temperature of 25°C , and average night time temperature of 10°C . As a worst-case scenario, we will assume winds are low, so that the air velocity out of the ventilation shafts is 0.5m/s when they are open, and only 2 air changes per hour occur when they are closed. We

assume 2 m^3 of water is present in tanks/barrels. Data from (Thapa & Shakya 2008) does agree with (FEED 2012; Viltard 2003) for the winter months, so we will consider an average day in January, with temperature fluctuations of $\pm 5^\circ\text{C}$. As a worst-case scenario, we assume this is a windy day, with 4 air changes per hour due to leaks, and air velocities of 3 m/s if the vents are open. We assume the same amount of added heat capacity in the form of water barrels (2 m^3).

D Materials Analysis

D.1 Wood Dimensions Estimation

One major component that was not addressed in enough detail was wood, which was used extensively in the framework of the greenhouse. The list does not specify the type and size of wood, which are critical pieces of information when calculating the embodied energy. The only information given is that it is hardwood (FEED, 2012); a common hardwood type prevalent in Khumbu region of Nepal could not be found, and any wood used in construction was assumed to be birch as it is one of the common hardwoods found in the Himalayas (Schickhoff, 2005). From this, wood was categorized into three groups representing the most likely size that could have been used, as shown in table 9.

Table 9: Estimation of dimensions of wood used to construct a greenhouse. Density from Engineering Toolbox (a) and the embodied energy data from Milne and Reardon (2013)

| | Dimensions | | Density (km/m^3) | PER embodied energy (MJ/kg) |
|--------|------------|------------|------------------------------------|-----------------------------------|
| | Depth (mm) | Width (mm) | | |
| Wood A | 89 | 89 | 670 | 2.0 |
| Wood B | 38 | 89 | 670 | (for Kiln dried sawn hardwood) |
| Wood C | 19 | 64 | 670 | |

D.2 Polypropylene

Although polypropylene for the side wall and the roof can be reduced as suggested in the previous section, minimisation of the underground polypropylene layer is not really possible as it is directly related to the human factors. In many high altitude regions, watering plants is a labour-intensive task as water needs to be collected from the streams (Nienhuys, 2003). The polypropylene foam layer under the ground insulation layer can effectively reduce the amount of labour as it can collect excess water from the soil. Elimination of this layer will reduce the environmental impact but will also reduce the user satisfaction level of the greenhouse.

Since the polypropylene is highly resistant to biodegradation (Arkatkar et al., 2009), its life time is expected to be longer than that of the greenhouse, and thus can be reused as a water collecting layer for another greenhouse. As the foam will end up as waste at some point, this is in a way just delaying dealing with the waste but at least the quantity will be relatively small as a result of reuse. Reusing the polypropylene side walls are also recommended, although this can be a bit more challenging as the solar damage can be extensive.

D.3 Polyethylene

A more immediate end-of-life problem is associated with polyethylene cover because it does not last as long as polypropylene due to direct exposure to the UV light. It may be necessary to renew the cover three or more times during the lifetime of a greenhouse (Nienhuys, 2003).

One trivial option to resolve this issue is to use them as a fuel (i.e. burn them) as they have a high calorific value (Lamont, 2005, Kasirajan and Ngouajio, 2012). However, this will release toxic substances into atmosphere and thus is not viable.

A biodegradable polyethylene could be used, but the technology is still immature and problems such as incomplete or excessively rapid decomposition (around 2 or 3 months) are prevalent (Wang et al., 2004, Kasirajan and Ngouajio, 2012). Therefore, no suitable alternative to polypropylene could be found.

Hence, the only plausible option seems to be recycling: the used polyethylene sheets may be shredded to be used as a filler for the ground insulation or the wall insulation of the greenhouse. Since no adhesives were used (only nails were listed in the materials list), the greenhouse can be easily disassembled once it reaches the end of its lifespan and so recycling should be an easy process. Recycling will also reduce the total construction cost.

E Greenhouse Dimensions

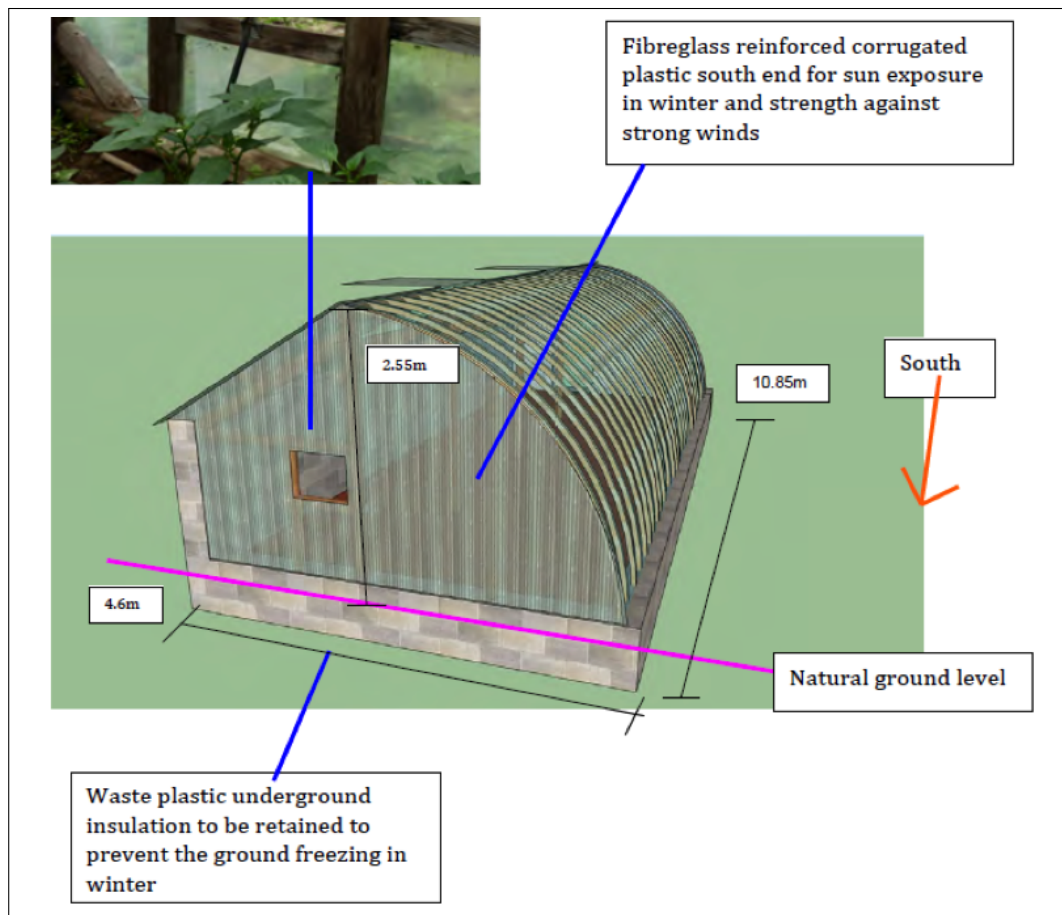


Figure 8: Dimensions of the greenhouse in Phuongmoche, Nepal