Tampere University of Applied Sciences

Compost Heat Recovery System

Pilot-scale study for greenhouse use

Emilio Pardo

BACHELOR'S THESIS
December 2020

D.P. in Energy and Environmental Engineering
18IDEE

ABSTRACT

Tampere University of Applied Sciences
Degree Programme in Energy and Environmental Engineering

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Bachelor's thesis 44 pages, appendices 11 pages
December 2020

The purpose of this project was to build and test a pilot-scale system capable of recovering the heat from compost to be used for greenhouse ambient conditioning. The system was based on Jean Pain’s method and it was carried out at Metsärinteen Puutarha site in Karkku, Sastamala (Finland).

The pilot-scale system consisted of a 12m x 3m x 1.5m (40m^3) compost of mixed feedstock (50% woodchips and 50% horse-manure/straw bedding) with 100m of in-compost heat collector coil placed in two concentric layers, separated 40cm from each other. The coil was connected to a set of radiators inside the greenhouse and water was circulated through the system at 5 litres per minute. The test was carried out for 43 days from August to October and numerical data gathered during the test period.

The compost stayed 23 days in the thermophilic phase reaching a peak temperature of 60°C and an estimated average heat energy production of 9600 kJ/h. However, heat collection and release were inefficient, having no impact on the glasshouse conditioning. Ambient temperatures of the glasshouse were mainly influenced by the external environmental conditions.

The calculations indicate the incapacity of the compost used in this study to generate the total heat load required by the greenhouse to achieve optimal growing conditions. The conclusions are based on consideration of minimum average temperatures and solar radiation for an October – April period. Compost heat production and general system efficiency could be improved by changes in compost design, of in-compost heat collector material, and reduced water flow. To achieve better process control, improved in-compost measurements of moisture and temperature are needed.

Keywords: Composting, Heat Recovery, Greenhouse, Green Energy.

CONTENTS

1 INTRODUCTION

Composting, the microbial decomposition of organic material (Diaz L.F et al. 2007), provides new opportunities in the renewable energy sector as a heat source. Heat from composting processes can be captured, transferred and used via several methods without the need for combustion, while also providing a natural soil amendment: compost.

The process of recovering heat from compost is known as Compost Heat Recovery System (CHRS). The CHRS used in this work was based on the efforts of Jean Pain (1928-1981), a Swiss forest manager and inventor who, by the 1970's, accomplished the production of hot water from brushwood compost in Provence, southern France. (Pain I. and Pain J. 1972).

This experimental project was established with two goals. First, to test heating a small glasshouse with a 40 m3 of mixed feedstock compost pile. Second, to determine if the same system would have the capacity to heat up a polytunnel to an ambient temperature of 18 °C from October to March, in southern Finland weather conditions.

A thorough literature review from Smith, Aber and Rynk (2017) on system design, recovery rate and utilization of CHRSs aiming to standardize more than 45 CHRS's reported values as a single comparable unit of heat recovery per weight unit, proved to be an impossible task due to the great variability of results. They concluded that the main factors were system scale, type of heat exchange system, composting method, composting feedstocks, continuous versus batch loading, model versus operational data, geographic location, duration of heat recovery, and method of reporting thermal energy recovery. Thereafter, the results of this project have been estimated based on the available literature, recorded data and system features.

This project was evaluated in two ways: compost performance and heating performance. Compost performance was calculated by the compost capacity to produce the required heat energy to warm up the given spaces. Heating performance was assessed by the capacity of the system to harvest and release the heat produced without interfering with the biological processes.

The project took place in collaboration with Metsärinteen Puutarha and its owner Antti Luomala from August to October 2020 in Karkku, Sastamala (Finland).

2 THEORY

2.1 Compost principles

There is a vast literature on composting science, methods, and techniques. However, the principles remain the same. For the purpose of this work, only the basic and relevant features of composting have been presented.

Compost is the stabilized and sanitized result of the metabolic activity of different microorganisms over organic substrates in aerobic conditions (Diaz L.F. et al. 2007) regardless of the method or technique used.

The composting process is exothermic, therefore produces heat energy. For this to happen, preconditions regarding ambient temperature and a balanced ratio of moisture and air must take place (Brown G. 2014). These external conditions enhance or inhibit the decomposition to happen, thus the production of heat energy. Adequate monitoring of these factors contributes to a compost free of pathogens, undesired seed germination (Perkins R. 2019), and optimal heat production.

Moisture levels should be between 45 to 65%. A balanced water content avoids suffocation and/or dryness (Brown G. 2014). Jean Pain concluded that 1m^3 of ideal-chopped (1mm shavings) brushwood would absorb and retain about 700 L of water for 3 days. (Pain I. and Pain J. 1972).

Texture, relative to aeration, is critical. While large dense chunks may enhance aeration, microbial activity is limited to the surfaces of the material, hence, small diameter substrates allow microbes and air to get in and pass through (Brown G. 2014). Good aeration conditions can be reached by mechanically turning the pile or by passive or active aeration of static piles. The latter options provide better opportunities for heat recovery and allows beneficial (aerobic) fungal structures to develop successively. (Brown G., 2014)

Composting, influenced by external conditions, undergoes four thermal phases, beginning with a Mesophilic phase (25-40°C) takes place where primary decomposers take over consuming the energy-rich easily degradable sugars and proteins (Diaz L.F. et al. 2007) enhancing the increase in temperatures reaching up to 40°C.

This is followed by a Thermophilic phase (35-65°C) where a different set of microbes, better suited to hotter conditions, outcompete those from the previous phase. Temperatures can reach to 70°C and higher, killing human and plant pathogens as well as weed seeds while taking the decomposition even further.

The Cooling phase (or second Mesophilic phase) initiates when most of the sugars and proteins are consumed. The microbial activity of thermophilic species declines as does the heat energy released, and mesophilic microbial species outcompete the current species (Diaz L.F. et al. 2007). A similar range of temperatures, as in the first mesophilic phase, is expected now.

During maturation phase material decay is advanced and temperatures drop below 40°C. The final product can be assessed by its unrecognizable parts, earthy smell and dark-brown colour. (Lowenfels and Lewis 2014).

A well-constructed pile is likely to reach 57°C - 65°C between the first 24-72 hours. Higher temperatures than 68°C burn off the carbon content, an undesired loss, so it is recommended to ensure this temperature is not to exceed it (Lowenfels and Lewis 2014).

A critical compost volume must be met to produce and preserve heat. For northern climatic conditions, this volume needs to be above $1m^3$ (Diaz L.F. et al. 2007).

A balanced carbon and nitrogen ratio (C/N) of organic substrates should be around 25:1 to 30:1. (Lowenfels and Lewis 2014). Hence, the recommended feedstock for heat optimization and compost quality stands as: A mixture of mill shavings, or stringy shredded woodchips; sawdust; and manure in a 60, 30, and 10 per cent composition, respectively. (Brown G. 2014).

2.2 Jean-Pain Method

Jean Pain's technique to produce and capture heat consists of a series of semi-flexible polyethylene tubes placed inside a brushwood-based compost pile (Picture 1). The tubes create a circuit for water to run through while collecting the heat produced by the pile.

PICTURE1. Semiflexible tubing placed in the brushwood compost pile for heat collection via water circulation. (source: Spade 2015).

Water circulation may be achieved either by using the thermosiphon principle which requires the compost pile to be located at a lower elevation than the building intended to be heated, or by using an accelerator-circulation pump. The first option does not involve an external energy input. The latter, however, allows for higher calorific output. (Pain I. and Pain J. 1972)

Heat captors can be horizontally coiled pipes which are easier to assemble but harder to dismantle due to the compressed finished compost. Vertically oriented coiled pipes require more work and accuracy when assembled but are easier to dismantle. The latter works better with bigger piles, as 200 tons for instance (Pain I. and Pain J. 1972)

Hay bales are used as heat insulation by placing them all around the compost pile (as sidewalls) and loosely spread on top, a method first castoff by the Compost Power Network. (Brown G. 2014).

Hot water could be used directly, for vegetable production (underground the growing beds) or for ambient heat conditioning, among other uses.

2.3 Greenhouse

2.3.1 Heat load

High energy loads are needed to maintain optimal plant growing conditions in greenhouses during the winter months. Such load is determined by considering the heat losses incurred by the infrastructure and the amount of solar radiation received. (D'Arpa et al. 2014)

For this study, the heat energy needed for two types of greenhouses was developed: An A-frame glasshouse and a Quonset polyethylene polytunnel. Calculations were based on the methods used by Stefania D'Arpa (D'Arpa et al. 2014) and the American Society of Agricultural Engineers (2003)

The heat energy required by a greenhosue can be expressed with equation 1 as the difference between the heat losses and the solar radiation received. A postive result indicateds the need for heating, while a negative results indicates the need for cooling.

$$Qsys = Qk - Qs \tag{1}$$

Where $Qsys$ is the heat load required, Qk is the amount of heat losses and Qs is the specific incoming solar radiation.

There are 2 types of heat losses: through the cover area ($Qcci$) and through ventilation infiltration (Qi). Therefore, the sum of these determines Qk. The losses can be assessed by equations 2 and 3 respectively.

$$Qcci = Ac \cdot Kr \cdot \Delta T \tag{2}$$

Where Ac is the cover area, Kr is the overall heat transmission coefficient and ΔT is the temperature difference between outside and inside.

Then,

$$Qi = Nac \cdot V \cdot \rho a \cdot Cp \cdot \Delta T \tag{3}$$

Where Nac is the infiltration rate per hour, V is volume, ρa is air density, and Cp is the air specific heat capacity.

Incoming solar radiation (Qs) is calculated with equation 4.

$$Qs = \tau \cdot I \cdot Ab \tag{4}$$

Where τ is the transmissivity of the greenhouse cover, I is the solar radiation on the horizontal surface, and Ab is the greenhouse floor area.

Respective values and calculations can be seen in Appendix 2 and 3.

2.3.2 Infrastructure

In this project, the glasshouse structure was considered as 2 separate pieces; An elongated square pyramidal shape on top and a rectangular solid on the bottom (Figure 1).

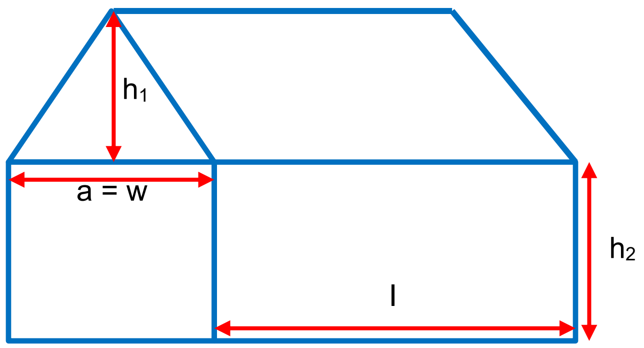

FIGURE 1. Glasshouse sketch (source: Author, 2020).

While the polytunnel was considered as a semi-cylinder on top and a rectangular solid on the bottom (Figure 2).

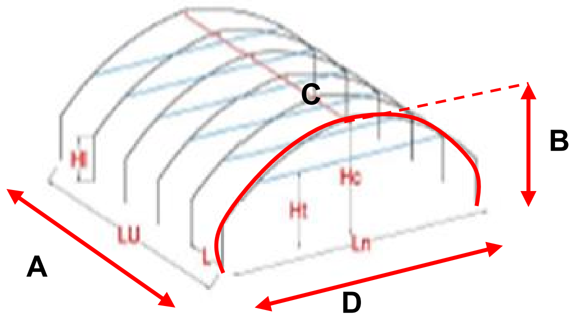

FIGURE 2. Sketch of the single layer polyethylene film polytunnel. (source: Polytunnel Quotation Request, 2020).

3 MATERIALS AND METHODS

3.1 Site description

The experimental project was carried between August the 18th and October the 3rd (2020) at Metsärinteen Puutarha site, in Karkku, Sastamala (Finland). The site has a small market garden production, planning to expand in the future.

The most relevant components of the site were the permanent beds, water well, water station, compost pile and glasshouse (Figure 3).

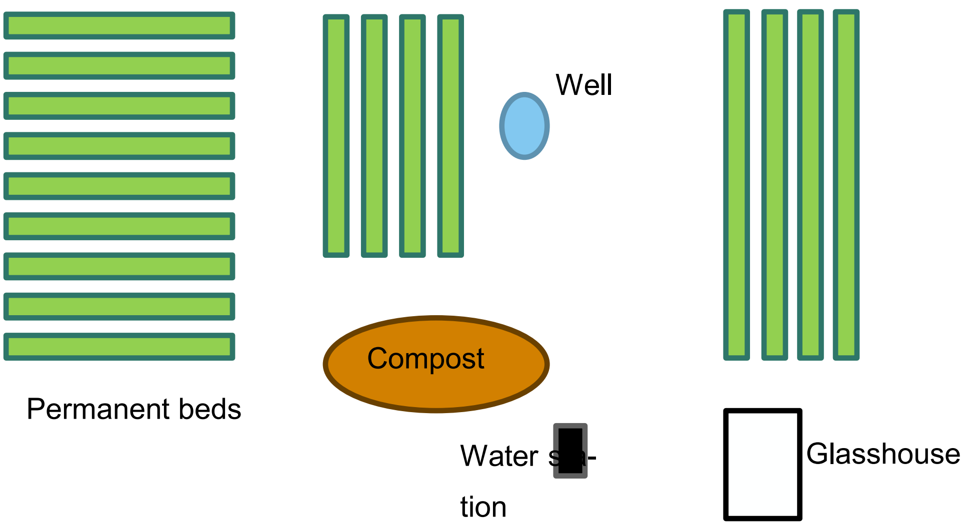

FIGURE 3. Metsärinteen Puutarha site layout.

3.2 Process overview

The general overview of the system has been described in figure 4, where arrows indicate the water flow direction, and the thermometers demonstrate the location of the devices through the system, excluding the compost thermometer that was not permanently in place. The icon with light blue edges on the top right-hand side of the figure indicated that outside temperatures were also recorded.

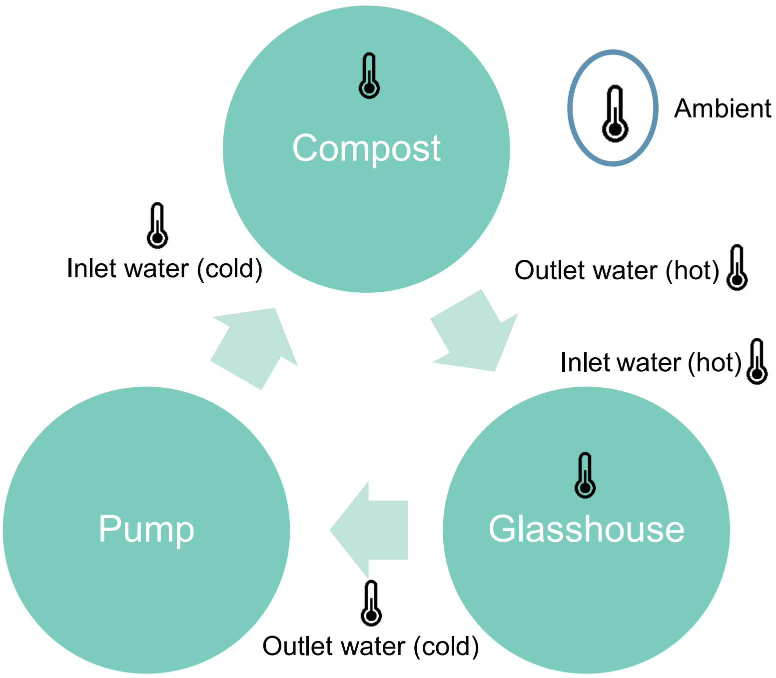

FIGURE 3. Process overview. Water flow and thermometers location.

3.3 Materials and labour

Materials used for the creation of compost and the heat recovery system have been summarized in table 1. The price of the items has been included as a reference of the start-up cost for such system, however, most of the equipment can be use further, which reduces the overall cost in the long term.

TABLE1. Materials description.

	Type	Dimensions	Units	Price (€) /unit	Transportation (€)	Total price
Feed-stock	Woodchips	20m3	1	100	100	200
	Mixed bedding	20m3	1	0	100	100
	Green manure	2kg	1	0	0	0
	Biochar	1m3	1	0	0	0
Tools	Machinery (rent)		1	273	0	273
Labour	Certified plumber		1	1733	0	1733
	Workers		3			
Insulation	Hay bales	50cm x 40cm x 90cm	30	1,5	0	45
Water hoses	Tricoflex hose pipe*	19/25mm x 50m	3			

*Note: This cost has been included in certified plumber's costs which also comprise all materials needed for the water circulation system like water pump, thermometers, etc.

Labour was carried out by the thesis author in collaboration with volunteer Dora Tkalec and Metsärinteen Puutarha General Manger, Antti Luomala. External certified plumbing work was required for the installation of the water circulation system and data collection devices.

3.4 Construction method

Approximately 20m^3 of woodchips and 20m^3 of mixed bedding (1/3 horse manure and 2/3 straw) from local sources was used, although biochar and green manure were produced on-site. The material was piled up using a rented machine (Picture 1) while mixing and spreading was done with broad forks manually.

PICTURE 1. Initiating the process. First layer of woodchips applied, and edges delineated with haybales for moisture and heat conservation. (Author 2020)

The material was piled up in 15 cm thick layers that were carefully irrigated. Biochar (Picture 2) and sawdust were added and mixed-in between the layers.

PICTURE 2. Homemade biochar. (Author 2020)

A passive aeration system was chosen for this project. A perforated swage pipe was connected to the air inlet and placed along the compost pile, over the first layer (Picture 3 and 4).

PICTURE 3. The aeration pipe connected with a T joint to the swage connection underground. (Author 2020)

PICTURE 4. The aeration pipe laying on top of the first layer of feedstock. (Author 2020)

When the pile reached a height of 50-60 cm, the first set of heat-collector hoses was placed on the top-centre forming an elongated concentric spiral (picture 5).

PICTURE 5. Assembled heat collector hoses and watering of feedstock (Author 2020)

About 15cm of hose was left hanging outside the pile to be further connected to the inlet water system (Picture 6).

PICTURE 6. Inlet (cold) water hose facing the water station. (Author 2020)

The other end of the heat collector was connected to a new heat collector hose, that was situated outside the pile, while more feedstock was added and further irrigated. The second set of heat collector hoses was put in place once the pile reached about 90cm high. Remaining feedstock was added on top leaving a compost finished pile of 1.2 meters height. The end of the second set was left hanging outside the pile facing the glasshouse (picture 7).

PICTURE 7. The end of the hose (second set) oriented towards the glasshouse. (Author 2020)

Once all feedstock was used, the top of the pile was covered with loose hay (Picture 8).

PICTURE 8. Compost pile covered with loose hay. (Author 2020)

The water circulation system was installed on the 22nd of August (3 days after the construction of the pile) by an accredited plumber. Water circulation pump was installed inside the water station while the pressure chamber (red) was outside (Picture 9). Well water was used to fill up the systems.

PICTURE 9. Water circulation system. (Author 2020)

A circulation pump was fixed inside the water station (Picture 10) to move the water through the system and to control its flow.

PICTURE 10. Grundfos Alpha 1 25-40 180. (Author 2020)

The pump was running mainly on 7 W of power while factory setting PP2 was maintained. Therefore, the water flow was determined to be approximately 0,3 m^3/h or 5 l/min based on the manufacturer's available data regarding pump setting and performance. (Grundfos Alpha1 - Installation and operating instructions. 2019)

Hot and cold hoses were connected to the glasshouse via the south facing wall (Picture 11).

PICTURE 11. Glasshouse. Grey (insulated) pipe for inlet hot water and yellow (non-insulated) for outlet cold water. (Author 2020)

A set of thermometers were used throughout the system. Compost outlet water temperature readings 5 days after the process was initiated (Picture 12).

PICTURE 12. Thermometer on insulated hose at the outer edge of the pile reading 28°C. (Author 2020)

Thermometers were connected to the inlet and outlet water hoses of the glasshouse (Picture 13). This helped to determine heat losses during the transfer from compost to glasshouse and heat released inside the glasshouse.

PICUTURE 13. Inside glasshouse thermometers. On the right inlet water, on the left outlet water. (Author 2020)

Another thermometer was installed to measure compost inlet water temperatures (Picture 14).

PICTURE 14. Thermometer for cold water coming to the compost pile reading 24°C (source: Author, 2020).

The glasshouse was located 10m from the pile. On August the 29th, 2 hydronic radiators of 60 cm x 60 cm were installed in the glasshouse to enhance heat release (Picture 15).

PICTURE 15. One 2-plate and one 3-plate radiators.

4 RESULTS and DISCUSSIONS

4.1 Heat and Energy produced

Figure 3 shows the compost temperatures during the evaluated period. The first two measurements of compost temperature were made by the “hand method” (bare hand introduced into the pile to a depth of 40 – 50 cm), and the latter two by a ReoTemp Heavy Duty compost thermometer. All readings were taken from three different locations in the pile.

An estimated average temperature curve of compost was added to the graph for better assessment of the energy produced. Energy estimation is based on the several CHRSs reports in “The compost-powered water heater: how to heat your water, greenhouse, or building with only compost” by Gaelan Brown (2014).

A 2-3 days mesophilic phase experienced an exponential increase in temperatures leading to a thermophilic phase with a peak of 60°C 3-4 days later. This phase lasted 23 days before entering the cooling phase where temperatures decreased below 40°C, which is consistent with what has been reported by Diaz L.F (2007) and Fulford (1986).

During this study, an average of 9600 kJ/h was produced between the first and last compost temperature measurements, with a peak of 11600 kJ/h on day 7 and the lowest at 7000 kJ/h on day 30. Brown (2014), Pain (1972), and other experiments from the Compost Power Network (a group of permaculture practitioners, engineers, renewable-energy experts, and compost scientists in Vermont,

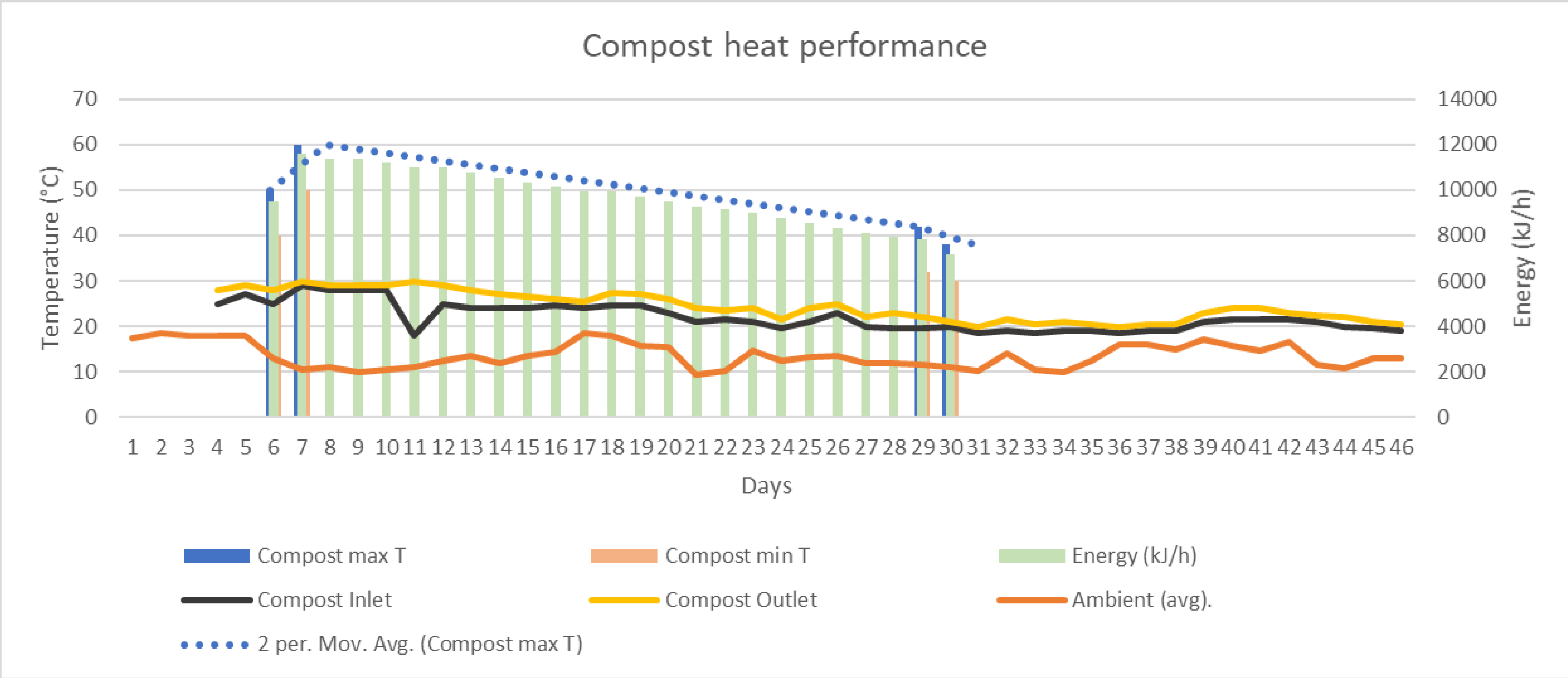

FIGURE 3. Compost temperatures and the respective estimated energy produced. Compost water and ambient temperatures were included in the analysis. (Author 2020)

US.), have reported approximately 10000 kJ/h for compost of similar feedstock, volume, and construction method. However, these estimations differ to the ones from Smith, owner of Polar Solar company, who documented 15000 – 20000 kJ/h through November and December 2010 (Brown, 2014). Smith also reported outlet water temperatures between 45-55 °C. These results are consistent with Smith, Aber and Rynk (2017) who also reported 20000 kJ/h of recovery rates.

The average difference between inlet and outlet compost water was of 2,1°C, the equivalent of 443 kJ/h. However, the circulating water was able to maintain an average of 5000 kJ/h due to the initial temperature of the water, the heat energy gained from the compost, and the inefficient release in the glasshouse.

A maximum of 6300 kJ/h (at 30°C) and a minimum of 4200kJ/h (at 20°C) were recorded for outlet water, representing a 50% and 36% less than the 60°C and the 55°C reported for outlet water by Pain (Pain, 1972) and Smith (Brown, 2014), respectively. This issue could be related to the in-compost heat collector material and the speed of water flow, as well as compost features like low moisture content or inconsistent aeration.

The Tricoflex hose pipe, with a 6mm thickness, was counterproductive in heat collection and release but had good insulation capacity. In a project planning guide for small-scale Jean Pain system Agrilab Technologies and Compost Power (Brown 2014) suggested the use of PEX or polyethylene tubing for in-compost heat exchange loops and insulated supply/return lines.

On the same report, they recommended a circulation rate of 3,8 litres/minute for inlet water at 9°C, and 11 litres/minute for inlet water above 35°C. These suggestions were made for a 275 meters loop of in-compost heat exchange PEX tubing laid out over seven layers along the compost height.

The biggest difference recorded between inlet and outlet water took place on day 11 with a noticeable drop in the inlet water temperature. It was observed that, on the same day, the water system was interrupted to install the radiators. Hence, it is reasonable to assume that the newly installed and cold radiators temporarily affected the circulating water temperature. Nevertheless, this effect was observed to have lasted less than 24 hours.

4.2 Heat released

Figure 4 combines the temperatures from inlet and outlet glasshouse water with glasshouse and outside ambient temperature recordings. The Glasshouse max and Outside max curves present a similar pattern. Therefore, it is reasonable to assume that the inlet water did not release sufficient heat energy to affect the glasshouse ambient temperatures, and that the glasshouse temperature was dependent on environmental conditions.

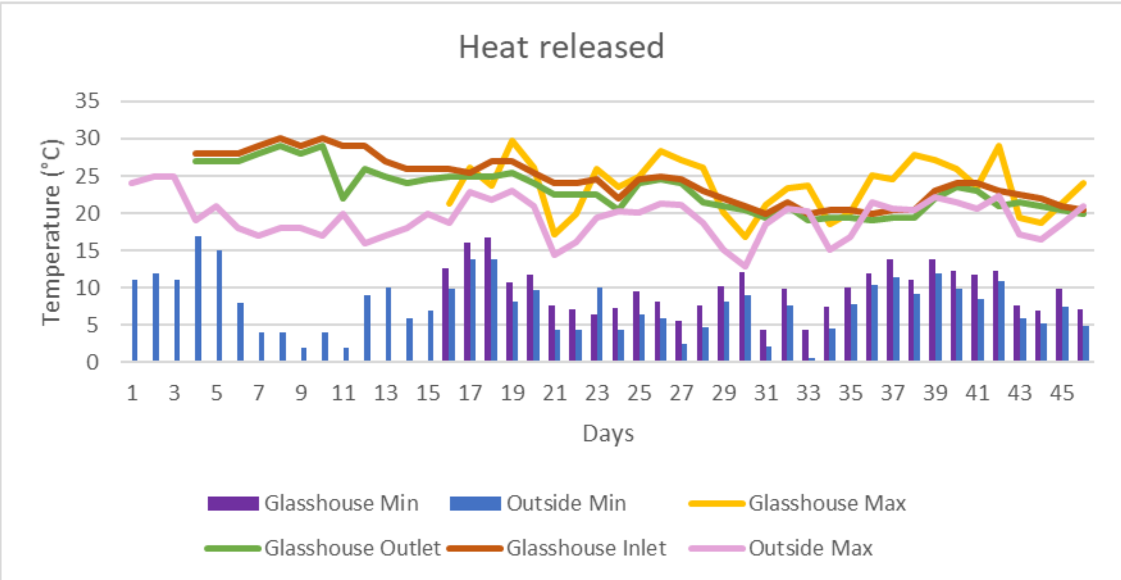

FIGURE 4. Temperature correlations between glasshouse water, glasshouse ambient and external conditions.

The mean average difference between inlet and outlet glasshouse water, in the 42 days analysed period, was 1,1°C. This represents 232 kJ/h of heat energy released, out of the 443 kJ/h the water was able to absorb from the compost. This result highlights the inefficacy of the heat releasing system and the consequent minimal impact on glasshouse ambient temperature.

D'Arpa (D'Arpa et al. 2016) reported that 73% of heat transferred to the water from the theoretical value of heat energy in composting windrows when polyethylene pipes were used. In this project, the water was carrying about 50% of the theoretical heat energy.

PEX polytube water hoses for heat collection and release is a sound alternative to overcome the above-mentioned issues. Additional suggestions may include a decrease of water flow. A site-specific proposal comprises the inclusion of a 1 – 1,5 m^3 water tank to act as a heat bank as well as a radiator, as documented by Karl Hammer, founder of Vermont Compost (Brown G. 2014). Further recommendations include an in-compost vertically oriented heating tower to seize the heat from the warm exhaust air to the water (D'Arpa et al. 2016)

4.3 Greenhouse heat requirements

An estimation of the required heat energy needed for the analysed greenhouses was calculated. The results were based on the minimum average monthly temperatures and their specific incoming solar radiation. Figure 5 is representative of the obtained values.

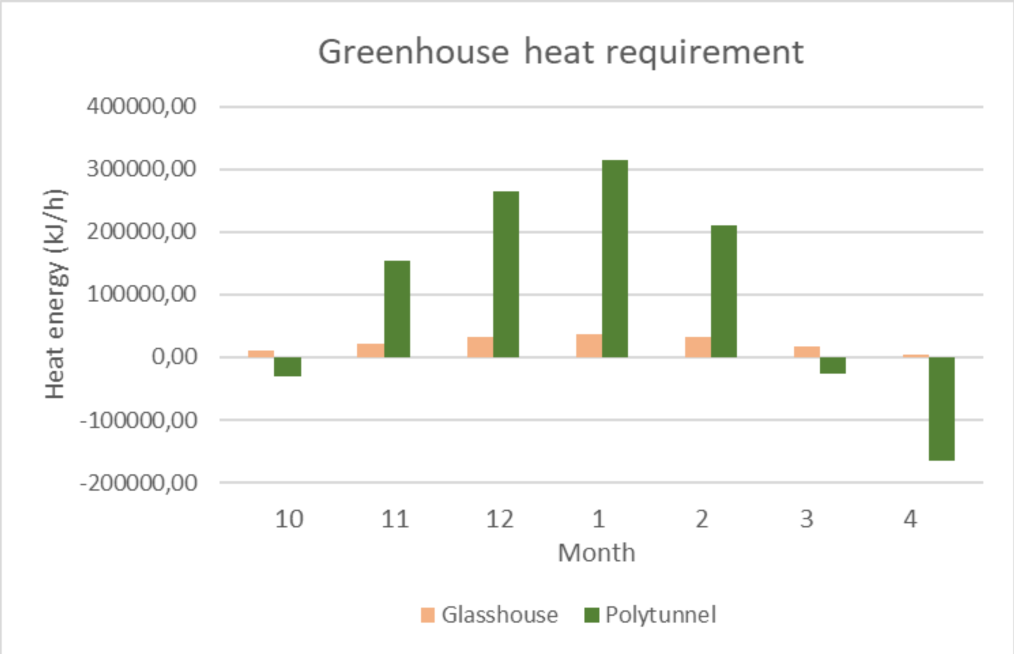

FIGURE 5. Average heat energy in kJ/h per month for each infrastructure.

The glasshouse maximum energy need has been estimated at 37600 kJ/h in January, and about 314000 kJ/h for the polytunnel in the same month. The average of the 7 months studied has been determined at 2.8 kWh/m2 when assessing both infrastructures together. This is slightly above the 2,3 kWh/m2 value reported by Jaakkonen A. K. (2019), regarding Finnish greenhouses in 2017.

4.3.1 Glasshouse analysis

Figure 6 illustrates the analysis between the heat energy required by the glasshouse from October to April, and the highest values of heat produced by the compost during the thermophilic phase. Besides, the figure also shows the scenario where the compost heat energy produced would be doubled, which has been demonstrated possible by Smith from Polar Solar, in 2010 (Brown, 2014).

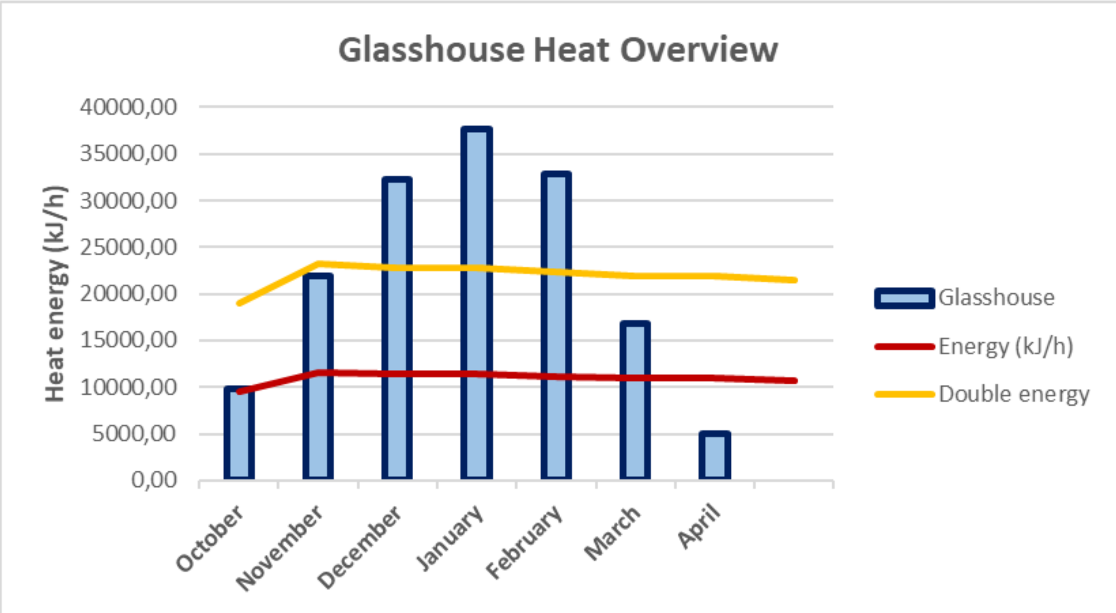

FIGURE 6. Glasshouse heat requirements, highest compost values in a 10 days period and the scenario when twice the amount of energy is produced.

It can be determined that the compost is not capable of producing enough heat to satisfy the demand of the glasshouse for the coldest months in southern Finland, and that other energy sources are required to fulfil this need.

Improvements in compost design (size, shape, and feedstock) are suggested to increase the heat output. Changes in heat collectors, water flow as well as better aeration and moisture management could further improve the system.

All gathered data can be found in Appendix 1.

5 CONCLUSION

From the outcomes of the experimental project, it has been demonstrated that compost heat can be used as an extra, cheap, and clean energy source for greenhouse ambient conditioning. However, it is not sensible to rely completely on compost.

Besides the high energy needs from greenhouses to achieve ideal growing conditions during the winter months, it is sensible to say that CHRS's can provide the energy needed to reach the mentioned conditions only during October and March. This can also be interpreted as an advantage for growers, by allowing them to extend the season by 2 months.

Although the compost behaved in an expected manner, later observations demonstrated inconsistencies in the final compost product: a dry and not ideally decomposed bottom layer. Therefore, changes in design are required to improve heat production, collection, release and decomposition patterns.

The project highlighted a lack of in-compost temperature data. Improving in this area could help with moisture management, a critical factor of heat production. Although this project experienced several weak points, it also identified a need for more in-depth research and accurate trials that may help to develop the system as an environmentally friendly energy source.

It is relevant to emphasise that more time should have been invested in the project planning phase.

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APPENDICES

Appendix 1. Data collection sheet

Date	Time	Person	Compost In-let	Compost Out-let	Glasshouse In-let	Glasshouse Out-let
18/08/2020						
19/08/2020						
20/08/2020						
21/08/2020						
22/08/2020	9.00	Antti	25	28	28	27
23/08/2020	10.00	Antti	27	29	28	27
24/08/2020	10.00	Emilio	25	28	28	27
25/08/2020	11.00	Emilio	29	30	29	28
26/08/2020	21.00	Antti	28	29	30	29
27/08/2020	21.00	Antti	28	29	29	28
28/08/2020	21.00	Antti	28	29	30	29
29/08/2020	21.00	Antti	18	30	29	22
30/08/2020	21.00	Antti	25	29	29	26
31/08/2020	21.00	Antti	24	28	27	25
01/09/2020	21.00	Antti	24	27	26	24
02/09/2020	21.00	Antti	24	26,5	26	24,5
03/09/2020	20.15	Antti	24,5	26	26	25
04/09/2020	21.30	Antti	24	25,5	25,5	25
05/09/2020	17.30	Antti	24,5	27,5	27	25
06/09/2020	18.00	Antti	24,5	27	27	25,5
07/09/2020	20.15	Antti	23	26	25,5	24
08/09/2020	21.20	Antti	21	24	24	22,5
09/09/2020	20.00	Antti	21,5	23,5	24	22,5
10/09/2020	21.00	Antti	21	24	24,5	22,5
11/09/2020	22.15	Antti	19,5	21,5	22	20,5
12/09/2020	21.00	Antti	21	24	24,5	24
13/09/2020	16.00	Päivi	23	25	25	24,5
14/09/2020	20.00	Päivi	20	22	24,5	24
15/09/2020	19.15	Antti	19,5	23	23	21,5
16/09/2020	21.00	Antti	19,5	22	22	21
17/09/2020	21.15	Antti	20	21	21	20,5
18/09/2020	20.15	Antti	18,5	20	20	19,5
19/09/2020	20.30	Antti	19	21,5	21,5	21
20/09/2020	19.40	Antti	18,5	20,5	20	19
21/09/2020	20.30	Antti	19	21	20,5	19,5
22/09/2020	20.00	Antti	19	20,5	20,5	19,5
23/09/2020	21.15	Antti	18,5	20	20	19
24/09/2020	20.30	Antti	19	20,5	20,5	19,5
25/09/2020	20.30	Antti	19	20,5	20,5	19,5
26/09/2020	20.00	Antti	21	23	23	22

27/09/2020	20.30	Antti	21,5	24	24	23,5
28/09/2020	19.45	Antti	21,5	24	24	23
29/09/2020	20.15	Antti	21,5	23	23	21
30/09/2020	19.00	Antti	21	22,5	22,5	21,5
01/10/2020	20.00	Antti	20	22	22	21
02/10/2020	20.05	Antti	19,5	21	21	20,5
03/10/2020	20.00	Antti	19	20,5	20,5	20

Outside T min (C)	**Outside T max (C)**	**Glasshouse max (C)**	**Glasshouse min (C)**
5	23		
11	24		
12	25		
11	25		
17	19		
15	21		
8	18		
4	17		
4	18		
2	18		
4	17		
2	20		
9	16		
10	17		
6	18		
7	20		
9,9	18,7	21,3	12,7
13,9	22,9	26,1	16,0
13,8	21,9	23,8	16,8
8,2	23,1	29,7	10,8
9,7	21,0	26,2	11,8
4,3	14,4	17,1	7,6
4,3	16,1	20,0	7,2
10,0	19,5	26,0	6,5
4,4	20,3	23,5	7,3
6,5	20,1	25,0	9,5
6,0	21,3	28,3	8,2
2,5	21,2	27,2	5,6
4,8	18,7	26,1	7,7
8,1	15,2	20,1	10,3
9,0	12,9	16,9	12,1
2,2	18,5	21,2	4,3
7,6	20,7	23,3	9,8
0,6	20,2	23,7	4,3
4,6	15,2	18,6	7,5
7,9	16,9	20,1	10,1
10,4	21,5	25,1	12,0
11,5	20,7	24,6	13,8

9,2	20,4	27,8	11,1
12,0	22,1	27,1	13,8
9,8	21,5	25,9	12,3
8,5	20,7	23,6	11,7
10,9	22,4	29,1	12,3
6,0	17,1	19,4	7,7
5,2	16,5	18,7	7,0
7,4	18,5	21,3	9,8
4,9	20,9	24,0	7,2

Appendix 2. Parameters for heat load calculations

Greenhouse data table

	Glass-house	Poly-tunnel	Sources
Ac-Cover area (m2)	61,80	345,20	Own calculations
Kr-Overall heat transfer coefficient (W/m2 °C)	6,00	9,30	Building Integrated Photovoltaics. 2013 and D'Arpa, Colangelo, Starace, Petrosillo, Bruno, Uricchio & Zurlini. 2016
Nac-Air change per hour (1/h)	0,80	0,80	D'Arpa, Colangelo, Starace, Petrosillo, Bruno, Uricchio & Zurlini. 2016
V-volume (m3)	21,40	817,00	Own calculations
ρa-Air density (kg/m3)	1,29	1,29	D'Arpa, Colangelo, Starace, Petrosillo, Bruno, Uricchio & Zurlini. 2016
Ca-Air specific heat capacity (kJ/kg °C)	1,01	1,01	D'Arpa, Colangelo, Starace, Petrosillo, Bruno, Uricchio & Zurlini. 2016
τ-Transmissivity of the cover	0,88	0,92	Bello and Dillip. 2011
Ab-Area of the floor (m2)	9,68	176,00	own calculations
Ti-Internal temperature (°C)	18,00	18,00	D'Arpa, Colangelo, Starace, Petrosillo, Bruno, Uricchio & Zurlini. 2016

External temperatures and incoming solar radiation by month in southern Finland.

Te-External temperature (°C)	**October**	**November**	**December**	**January**	**February**	**March**	**April**	**Source**
Minimum average	1,7	-1,5	-8	-12	-13	-8	-1,5	Weather & Climate. 2020
I-Solar radiation intensity (W/m2)	400,00	150	100	100	300	600	700	Pihlakivi, E. 2015

Appendix 3. Calculations

- <u>Glasshouse volume</u>

The volume was calculated as follows:

$$V = Vsp + Vrs_G$$

Where:
V is the Total Volume, Vsp is the volume of the square pyramid and Vrs_G is the volume of the rectangular solid.

Vsp was calculated with equation 5:

$$Vsp = a^2 * \frac{h1}{3} \quad (5)$$

where a is the base edge, and h_1 is the height, therefore:

$$Vsp = (4{,}2m)^2 * \frac{0{,}5m}{3}$$
$$Vsc = 2{,}94\ m^3$$

Then, Vrs_G was calculated with equation 6, as follows:

$$Vrs_G = length\ (l) * width\ (w) * height\ (h_2) \quad (6)$$
$$Vrs_G = 4{,}2m * 2{,}2m * 2m$$
$$Vrs_G = 18{,}48\ m^3$$

Thus, the Total Volume (V) of the glasshouse remains:

$$V = Vsp + Vrs_G = 2{,}94\ m^3 + 18{,}48\ m^3 = 21{,}42\ m^3 \approx 21{,}4m^3$$

- Glasshouse cover area

The area was calculated using equation 7:

$$Asp_G = a^2 + 2a\sqrt{\frac{a^2}{4} + h^2} \quad (7)$$

By replacing with the respective values:

$$Asp_G = 4{,}2m^2 + 2 * 4{,}2m\sqrt{\frac{4{,}2m^2}{4} + 0{,}5m^2}$$

$$Asp_G = 26{,}5m^2$$

And the area of Ars_G:

$$Ars_G = 2(wh + hl) + wl$$

Where: w is width, h is height and l is length, and all values are expressed in meters (m).

Thus,

$$Ars_G = 2(2{,}2m * 2m + 2m * 4{,}2m) + (2{,}2m * 4{,}2m)$$

$$Ars_G = 35{,}28m^2$$

Hence, by replacing with the obtained values, the total area of the glasshouse is:

$$A = 26{,}5m^2 + 35{,}28m^2$$

$$Ac = 61{,}78m^2 \approx 61{,}8m^2$$

- Polytunnel Volume

The volume of the polytunnel was calculated with equation 8:

$$Total\ Volume(V) = semi - cylinder\ (Vsc) + rectangular\ solid\ (Vrs_P) \tag{8}$$

Vsc was determined with equation 9:

$$Vsc = \frac{1}{2} * \pi * r^2 * h \tag{9}$$

where r is half the value of the Bay width (Ln), and h is the $Total\ lenght(LU)$, therefore:

$$Vsc = \frac{1}{2} * \pi * (4\ m)^2 * 22\ m$$

$$Vsc = 552{,}9 \approx 553\ m^3$$

Vrs is calculated with equation 10:

$$Vrs = Total\ lenght\ (LU) * Bay\ width\ (Ln) * Pillar\ height\ (HI) \tag{10}$$

$$Vrs = 22\ m * 8\ m * 1{,}5\ m$$

$$Vrs = 264\ m^3$$

Thus, by replacing the values obtained for Vsc and Vrs into equation 8, the Total Volume (V) of the polytunnel remains:

$$V = Vsc + Vrs = 553\ m^3 + 264\ m^3 = 817\ m^3$$

- <u>Polytunnel Cover Area</u>

Polytunnel area was assessed with equation 11:

$$Ac = (A * C) + (2 * (B * D) \qquad (11)$$

where

A = 22m, B = 3.7m, C = 13m, and D = 8m

Thus, by replacing with the respective values:

$$Ac = (22m * 13m) + (2 * (3{,}7m * 8m)$$

$$Ac = 286m^2 + 59{,}2m^2$$

$$Ac = 345{,}2m^2$$

- <u>Heat requirements</u>

Glasshouse							
	October	**November**	**December**	**January**	**February**	**March**	**April**
Cover losses (Qcci) in watts Ac*Kr*(Te-Ti)	6044,04	7230,6	9640,8	11124	11494,8	9640,8	7230,6
Infiltration losses (Qi) in kJ/h Nac*V*ρa*Ca*(Te-Ti)	361,78	432,81	577,08	665,86	688,05	577,08	432,81
in watts	100,5	120,2	160,3	185,0	191,1	160,3	120,2
Total Heat Losses (Qk) in watts Qcci+Qi	6144,5	7350,8	9801,1	11309,0	11685,9	9801,1	7350,8
Solar radiation (Qs) in watts τ*/*Ab	3407,36	1277,76	851,84	851,84	2555,52	5111,04	5962,88
Required Heat in watts Qk-Qs	2737,2	6073,1	8949,3	10457,1	9130,4	4690,1	1387,9

Polytunnel							
	Octo-ber	November	December	January	February	March	April
Cover Losses (Qcci) in watts Ac*Kr*(Te-Ti)	52328,9	62602,0	83469,4	96310,8	99521,2	83469,4	62602,0
Infiltration losses (Qi) in kJ/h Nac*V*ρa*Ca*(Te-Ti)	13812,0	16523,5	22031,4	25420,8	26268,2	22031,4	16523,5
in watts	3836,7	4589,9	6119,8	7061,3	7296,7	6119,8	4589,9
Total Heat Losses (Qk) in watts Qcci+Qi	56165,5	67191,9	89589,2	103372,1	106817,9	89589,2	67191,9
Solar radiation (Qs) in watts τ*/*Ab	64768	24288	16192	16192	48576	97152	113344
Required Heat in watts Qk-Qs	-8602,5	42903,9	73397,2	87180,1	58241,9	-7562,8	-46152,1

	Heat required per structure (Watts)						
	October	**November**	**December**	**January**	**February**	**March**	**April**
Glasshouse	2737,2	6073,1	8949,3	10457,1	9130,4	4690,1	1387,9
Polytunnel	-8602,48	42903,89	73397,18	87180,13	58241,87	-7562,82	-46152,11

	Heat required per structure (kJ/h)						
Glasshouse	9853,83	21863,03	32217,33	37645,63	32869,46	16884,21	4996,60
Polytunnel	-30968,91	154453,99	264229,85	313848,47	209670,73	-27226,15	-166147,61

	Heat required per structure (kWh/m2)						
	October	**November**	**December**	**January**	**February**	**March**	**April**
Glasshouse	0,3	0,6	0,9	1,1	0,9	0,5	0,1
Polytunnel	-0,05	0,24	0,42	0,50	0,33	-0,04	-0,26

	in kWh/m2		
	total	**average**	**reference**
G	4,5	2,8	2,3
P	1,13		