The design and development of heat extraction technologies for the utilisation of compost thermal energy

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Abstract

A composting Heat Extraction Unit (HEU) was designed to utilise waste heat from decaying organic matter for a variety of heating application The aim was to construct an insulated small scale, sealed, organic matter filled container. In this vessel a process fluid within embedded pipes would absorb thermal energy from the hot compost and transport it to an external heat exchanger. Experiments were conducted on the constituent parts and the final design comprised of a 2046 litre container insulated with polyurethane foam and kingspan with two arrays of qualpex piping embedded in the compost to extract heat. The thermal energy was used in horticultural trials by heating polytunnels using a radiator system during a winter/spring period. The compost derived energy was compared with conventional and renewable energy in the form of an electric fan heater and solar panel. The compost derived energy was able to raise polytunnel temperatures to 2-3°C above the control, with the solar panel contributing no thermal energy during the winter trial and the electric heater the most efficient maintaining temperature at its preset temperature of 10°C. Plants that were cultivated as performance indicators showed no significant difference in growth rates between the heat sources. A follow on experiment conducted using special growing mats for distributing compost thermal energy directly under the plants (Radish, Cabbage, Spinach and Lettuce) displayed more successful growth patterns than those in the control. The compost HEU was also used for more traditional space heating and hot water heating applications. A test space was successfully heated over two trials with varying insulation levels. Maximum internal temperature increases of 7°C and 13°C were recorded for building U-values of 1.6 and 0.53 W/m^{2}K respectively using the HEU. The HEU successfully heated a 60 litre hot water cylinder for 32 days with maximum water temperature increases of 36.5°C recorded. Total energy recovered from the 435 Kg of compost within the HEU during the polytunnel growth trial was 76 kWh

which is 3 kWh/day for the 25 days when the HEU was activated. With a mean coefficient of performance level of 6.8 calculated for the HEU the technology is energy efficient. Therefore the compost HEU developed here could be a useful renewable energy technology particularly for small scale rural dwellers and growers with access to significant quantities of organic matter.

Chapter 1

General Introduction

1.1 General Introduction

The topic of energy availability is of critical importance to human societies in the modern globalised world. The renewed focus on energy and the security of its supply is driven by high oil prices, which increased 3 fold to a high of $150 a barrel in 2008. The threat of terrorism, instability in exporting nations, fears of a scramble for supplies, geopolitical rivalries, and countries fundamental need for energy to power their economic growth have also increased the public awareness of energy security (Yergin, 2006). Fossil fuel supplies including oil are finite and are having a damaging effect on human societies (Akella *et al.,* 2009). Many researchers believe that the peak in oil production will occur before 2020 and lead to large price increases and negative economic and social effects (de Almeida, 2009). The Intergovernmental Panel on Climate Change (IPCC) regard greenhouse gas emissions from human activity as the most likely cause of global increases in average temperature (IPCC, 2007). Predicted global temperature increases of between of 2 and 6°C could have extremely damaging effects on biodiversity, the economy and social cohesion. These concerns have led to increased use and research into renewable energy alternatives such as wind, hydro, geothermal, and biomass conversion (Jennings, 2009).

Biomass energy contributes approximately two thirds of global renewable energy (Omer 2008a). Direct combustion and anaerobic digestion account for the majority of the methods used. Aerobic digestion of organic matter is one type of biomass conversion technique that releases thermal energy. Less research has been focused on aerobic digestion when compared to the more common method of anaerobic digestion. It has been noted that aerobic digestion is potentially a more efficient technology than anaerobic digestion at dealing with organic wastes such as food (Winship, 2008). The research conducted here investigates this potential by composting bio-wastes in an enclosed vessel called a Heat Extraction Unit (HEU) designed specifically for this project. The extracted thermal energy is delivered to various applications for performance analysis. This research is purely focused on the design of the HEU and the utilisation of the compost derived heat. A separate research project investigating the most appropriate organic feed-stocks for the HEU and best organic mixes in terms of carbon, nitrogen, moisture and aeration for the generation of maximum thermal energy was conducted in conjunction and alongside this research but as a separate thesis (Fitzgerald, 2009). This thesis is formatted as a series of self contained chapters each dealing with various aspects and applications of the compost HEU. The objectives for each chapter are as follows.

Chapter 2 focuses on the design of the HEU. The aim of this section was to develop an efficient system for extracting the available heat produced by aerobic decomposition. The unit was to be low cost, be constructed using local materials and be simple to operate in order for it to be widely and easily used. The idea was to construct an insulated invessel composting container with a series of pipes embedded within. A fluid would flow through the pipes absorbing heat energy from the hot compost filling the container and deliver it to various heating applications. Experiments were conducted on the various constituent parts from which HEU was constructed. These included investigating the thermal properties of various process heating fluids and the suitability of various pipe materials. Full scale trials were conducted to assess insulation materials for the invessel composter. Design efficiency is discussed along with potential improvements in design.

In Chapter 3 the HEU was field tested and the results from these trials were discussed. The aim was to investigate the possibility of using the thermal energy from the HEU to heat polytunnels to assist the protected crop growing industry in culture enterprises. The performance of the HEU was analysed and compared to other forms of conventional and renewable energy including electrical and solar power. Plants were grown within the polytunnels to act as performance indicators of each thermal source.

Chapter 4 discusses the alternative uses of compost derived heat for space heating and hot water heating. A test area was used to carry out space heating experiments using various insulation products. A water cylinder with an internal heat exchanger was used for hot water heating experiments. Chapter 5 discusses the cost benefit analysis of the compost heating technology developed. Chapter 6 is composed of an overall discussion and conclusions.

Chapter 2

Design of compost Heat Extraction Unit

2.1 Abstract

A compost heat extraction unit (HEU) was designed to utilise waste heat from decaying organic matter for a variety of heating application. The aim was to construct an insulated small scale, sealed, organic matter filled digester capable of extracting heat energy. In this vessel a process fluid within embedded pipes would absorb thermal energy from the hot compost and transport it to an external heat exchanger. Experiments were designed and carried out to investigate the various constituent parts of the HEU in order to build the most efficient heat extraction device. Three types of process heating fluids were investigated including Water, Propylene Glycol, and Synthetic Hydrogen Oil. Various ratios of water to glycol were tested to maximise process heating fluid efficiency and to protect against frost damage. Four commonly used pipe materials copper, qualpex, PVC, and hydrodare were investigated that would transport the chosen heating fluid through the hot compost and absorb the thermal energy. Full scale trials were conducted using a 2046 litre container which held the compost. Two insulation materials for the container were tested including bubble polythene and polyurethane foam. A prototype was constructed and successfully tested using an electric heater before compost filled trials began.

2.2 Introduction

2.2.1 Traditional Heating Systems

A wide variety of heating systems have been developed over the centuries to allow humans the benefit of heated shelter in the cooler climates. Various devices have been invented usually based around the fuel type used. Combustion of timber has been the primary method used for space heating (Schroeder, 2000). The industrial revolution shifted the attention to fossil fuels such as coal, oil and natural gas with the use of chimneys in residential dwellings (Bilington, 1959). Radiator use in the late 19th century allowed the heating device to be placed outside the building and more complex gas and oil burning machines were constructed leading to widespread use of central heating.

2.2.2 Renewable Heating Systems

Of global energy used, 81% is derived from fossil fuels (Ozgur, 2008). These fuels are non renewable and their associated pollution is having a damaging effect on economic progress and the environment (Akella *et al.,* 2009). This has led to the development of alternative and renewable energy heating systems (Sørensen, 1991). Figure 2.1 shows the total global primary energy supply with renewable energies contributing 12.8%.

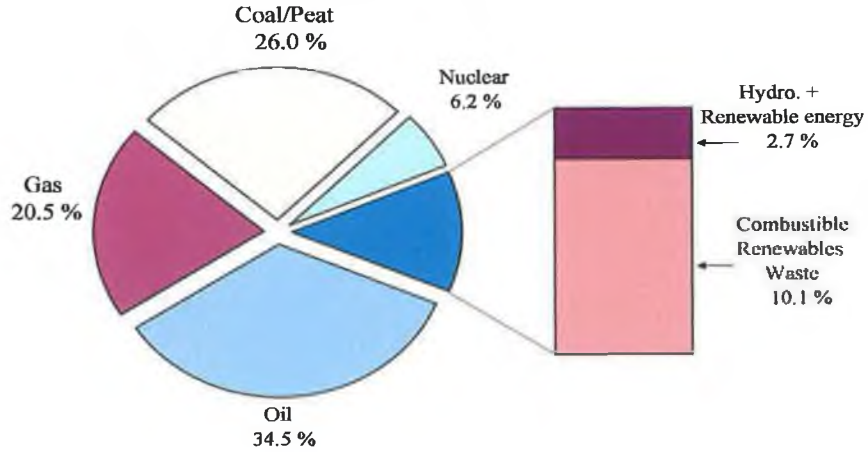

Figure 2.1: Total primary energy supply 2006. (IEA, 2008)

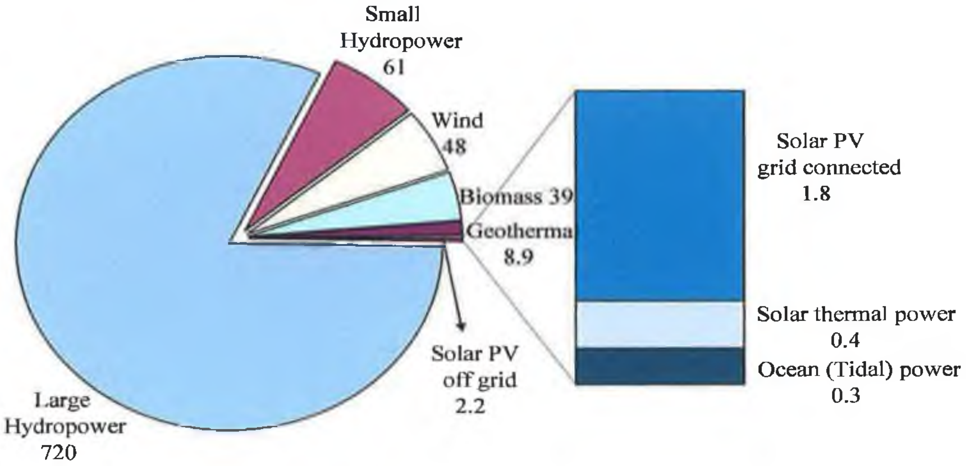

Figure 2.2: Total global renewable energy generated in gigawatts 2005. (Yüksel, 2008)

Renewable energy technologies that have been developed include geothermal, solar, biomass conversion, wind and wave energy. Figure 2.2 shows the breakdown in percentages of global renewable energy generated. Hydro power remains the largest at 88.5 % with wind second at 5.4 %. Extracting energy from biomass (4.4 %) is becoming more widespread and includes combustion, production of liquid fuels such as ethanol, thermo-chemical conversion for heat and electricity and anaerobic digestion (Omer, 2008b). Wood burning stoves and anaerobic digesters are the most common mechanical devices used to extract energy from biomass.

2.2.3 Aerobic digestion

Energy generated through the process of aerobic digestion (composting) of waste biomass can also be harnessed as a renewable energy although little research has been conducted into this method in comparison to other biomass technologies. Aerobic digestion is the biodegradation of organic matter. The decomposition is performed by micro-organism such as bacteria, yeasts and fungi alongside macro-organisms such as springtails, nematodes, fruit flies and earthworms. It has been noted that aerobic digestion is potentially a more efficient technology than anaerobic digestion at dealing with organic wastes such as food (Winship, 2008). This current study assesses a heat energy extraction system designed specifically for aerobic composting. Figure 2.3 presents a basic process diagram of what is involved in extraction of heat energy from decomposing biomass. The transport distance of the source biomass to the in-vessel composter (aerobic digestion) should be as low as possible to minimize fuel emissions. At the end use site heat energy is extracted and delivered for various heating applications such as space heating.

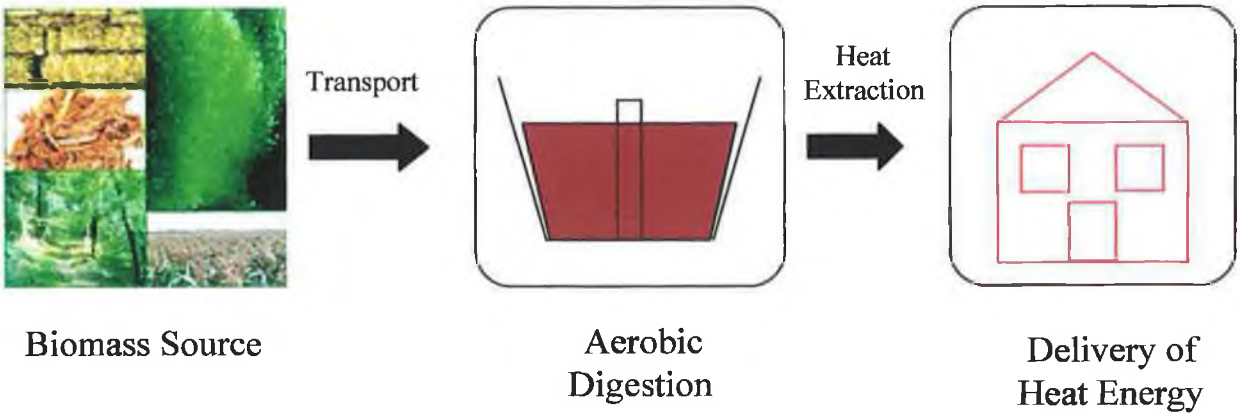

Figure 2.3: Process diagram of an aerobic decomposition and energy extraction pathway.

An overview of some of the principle designs in energy extraction from aerobic digestion that have been developed is shown in Table 2.1. The technologies involved and end uses are varied and the source biomass is also variable making direct comparison difficult. These are in chronological order and are described in more detail below. Hughes (1984) developed a heat extraction system from a 540 m^3 waste slurry lagoon on a farm. The lagoon was 26 x 10 x 2.5m deep with a heat exchanger within made from 250 m of 25mm polythene tubing wound around 4 poles. The heated fluid within is sent to a 21.6 kW water to water heat pump where it is increased to 55 °C for an adjacent radiator heating system for pig farrowing accommodation. Active aeration of the slurry is achieved with a 7 kW floating aerator on the lagoon which runs 50 % of the time. A system coefficient of performance (C.O.P) of 3.45 was achieved with a 6.5 kW average rate of instantaneous heat.

Table 2.1: Key papers involved in energy extraction from aerobic digestion of biomass.

#	Author (Year)	Type of System	Size (Tonnes/KW)	Application
1	Hughes (1984)	Slurry lagoon with heat exchanger and heat pump	540m^3, 6.5 kWh average heat extraction	Heated water at 55 °C to radiators in pig farrowing accommodation
2	Fulford (1986)	Fan driving heated air from compost to under soil.	3.8m^3 at 5 day intervals	Heat greenhouses (Horticultural production) Air temp. 13-19°C above outside ambient.
3	Svoboda and Fallowfield (1989)	Cylindrical reactor - pig slurry. Heat exchanger and heat pump used.	24 m^3 of Slurry in and out each hour. 149 kWh/day	Space heating of weaner house.
4	Seki and Komori (1995)	Reactor = chicken manure, rice bran, sawdust. Air blower + heat exchanger	0.23 m^3 0.17 kWh/day	Heat Greenhouses
5	Heinonen-Tanski *et al*, (2005)	Cattle slurry and whey or jam waste filled reactor	10 m^3	Pre heat water, washing farm machines. 50°C after plate heat exchanger used
6	Rodgers (2006)	Compost military food waste within in-vessel composter	1587 kg/day	Water + space heating. Water out at 49 °C
7	Tucker (2006)	Isobars used adjacent to compost windrows in barn	600-800 Tonnes 843 kWh/day	Heated water for farm application and heating greenhouses
8	Winship (2008)	Roll on off composting containers	150 Tonnes 1320 kWh/day	Space heating offices, leisure facilities or apartments.

extraction. Over the year total energy output from the heat pump was 75,200 kWh and electricity consumed was 21,800 kWh giving a net benefit in energy terms.

A 'bioshelter' type greenhouse was developed at the New Alchemy Institute to extract heat from composting biomass and deliver it to crops within the greenhouse (Fulford, 1986). This design comprised of a series of insulated compartments running along the side of the greenhouse which were filled with manure based compost. Within the design $3.8m^3$ of compost is used every five days. Electric blowers force air through the compost which draws off water vapour and is delivered under the soil through a duct network delivering heat and CO_2 to the plants. The heat is transferred when the water vapour condenses and releases the latent heat on to the surface where it lands. Key indicators of success in these experiments were soil and greenhouse temperature. Soil temperatures were higher than control greenhouses and averaged 25.5 °C for a soil bed above the compost chamber and 16 °C for the ground soil. Greenhouse air temperatures averaged 16 °C above the outside air temperature by using this system. Technology such as heat pumps are not employed in this system and complexity is kept to a minimum in the design. The blower rated at 8.8 m^3/min costs $40 a year to run making this a low annual cost system. The six hours a week labour that was needed to load and empty the compost chambers also makes this system a low tech / cost option.

Svoboda and Fallowfield (1989) developed an aerobic treatment plant for pig slurry enabling them to extract heat energy. The reactor 24 m^3 (3.4m diameter and 2.65m high) was constructed of glass coated steel panels on a concrete base and a plywood lid. Pumps were used to transfer slurry into and out of the unit. Active aeration was achieved with a floating aerator and foam cutters were also employed to reduce foam formation at the top of the slurry inside the device. A stainless steel tubular heat exchanger within the slurry was connected to a 12 kW heat pump. This upgraded and transfers the heat giving a maximum water temperature of 55°C to the heating circuit of the weaner house. Maximum extractable heat achieved from the system was 149 kWh/d. Seki and Komori (1995) also used a cylindrical chamber to extract heat energy from chicken manure, sawdust and rice bran based compost. It had a volume of 0.23 m^3. A stainless steel looped flexible tube set along the inside wall of the container has air passing through it which is heated by the compost. A second heat extraction method used to recover energy from the compost was achieved by placing a condenser-type heat exchanger above the compost. Sensible and latent heat from the rising evaporation off the compost was captured by the condenser. The heat (0.17 kWh/day) from both sources was to be used to heat greenhouses. Heat energy was extracted from cattle slurry that was composted with whey and jam wastes in Norway using an insulated cylindrical in-vessel composter (Heinonen-Tanski, *et al.,* 2005). A 10m^3 reactor was used with de-foaming blades at the top and an aerator at the bottom. Reactor temperatures of 70 °C were recorded and the heat energy generated was higher than electrical energy used for this technology. It was predicted that well water of 10 °C could be heated to 50 °C with a plate heat exchanger using this technology based on results from Evans *et al.,* (1982)

The military college CFB Trenton (Canada) has developed a large metal invessel composter for onsite organic waste with a 1587kg /day capacity (Rogers, 2006). A schematic of which is shown in Figure 2.4. A series of retractable rigid pipes with spikes at the end are pushed into the waste biomass. Water inside the pipes is heated to 49 °C and used as a hot water source and for space heating. Isobar technology which is a type of thermosyphon heat pipe which transfers thermal energy instantaneously along its length through an evaporation and condensing process was considered here to give the system a net positive energy balance as the prototype's input energy exceeded its output energy.

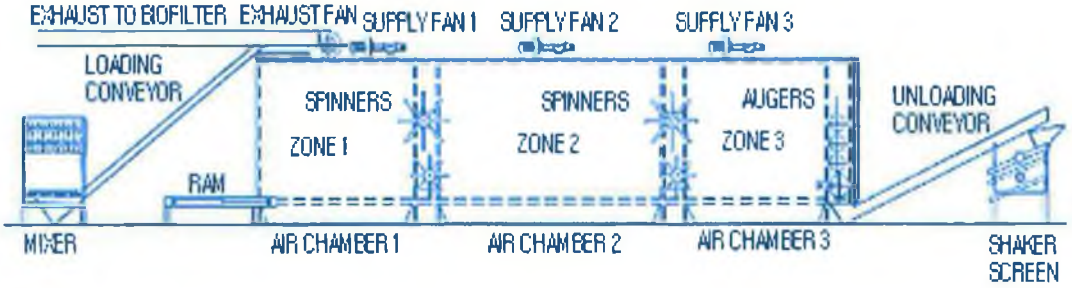

Figure 2.4: Schematic of composter system designed at CFB Trenton.

Agrilab Technologies (Canada) have also developed large scale methods of heat extraction from compost using Isobar technology to absorb and deliver thermal energy rapidly to a reservoir of water (Tucker, 2006). A special floor is constructed comprising of 'closed cell expanded foam sheets' with 200mm pipes embedded within (Figure 2.5 A). A concrete floor is poured over this and gutters in the embedded pipes are cut out to allow water vapour to be drawn through (Figure 2.5 B). Windrows (150-200 tonnes) of compost 60 feet long are created on this floor area. Air blowers draw air through the compost into the gutters allowing it to condense onto the isobars (special metal bars that transfer heat instantly over the length by using super conducting thermo-syphons) in a separate compartment (Figure 2.5 C). The heat is transferred to an insulated 3028 litre water tank. This technology produces 843 kWh of energy per day and delivers heated water for use on the farm and costs $450,000. It is suitable for very large scale operations with abundant waste biomass.

Figure 2.5 (A,B,C): Agrilab's Isobar heat extraction technology setup.

The 'Aergestor' combined heat and composting system discussed by Winship *et al.*, (2008) is the most recent attempts to extract heat through aerobic digestion. Volumes of up to 15 tonnes of organic waste are composted inside large steel containers that are rolled on and off trucks for transport from waste biomass sources and to the end use site for heat delivery (Figure 2.6). Figure 2.7 shows the schematic diagram of the process involved in extracting energy from the compost. Thermal energy is captured when the saturated process gases from aerobic decomposition are passed through an evaporator of a heat pump system by an air blower. Computers are used to control the various components such as pressure difference between supply and exhaust pipes increasing the complexity of this technology. This technology is calculated to be energy positive and generates 1320 kWh/ day when 10 aergestors are in use and the process is also carbon negative.

Figure 2.6: Aergestor system roll on roll off.

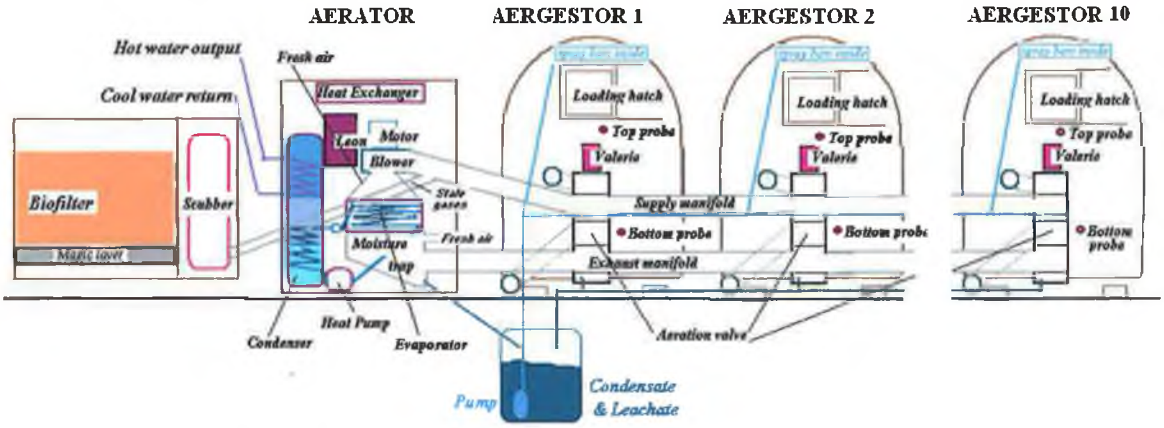

Figure 2.7: Schematic diagram of the 'Aergestor' heat extraction system.

2.2.4 Heat Extraction Unit development

The Heat Extraction Unit (HEU) developed in this section of the research project looks at the various constituent parts which make up the unit to develop the most efficient heating system. Figure 2.8 shows a basic cross section of the design envisaged. Decomposing biomass inside an in-vessel composter releases thermal energy to be captured by a process heating fluid within two layers of pipes embedded in the compost. The heat can then be used for various applications such as space heating through a radiator system or direct hot water heating. The selection and trials of the source biomass and generation of heat from composting was conducted in conjunction with these trials but as a separate study (Fitzgerald, 2009).

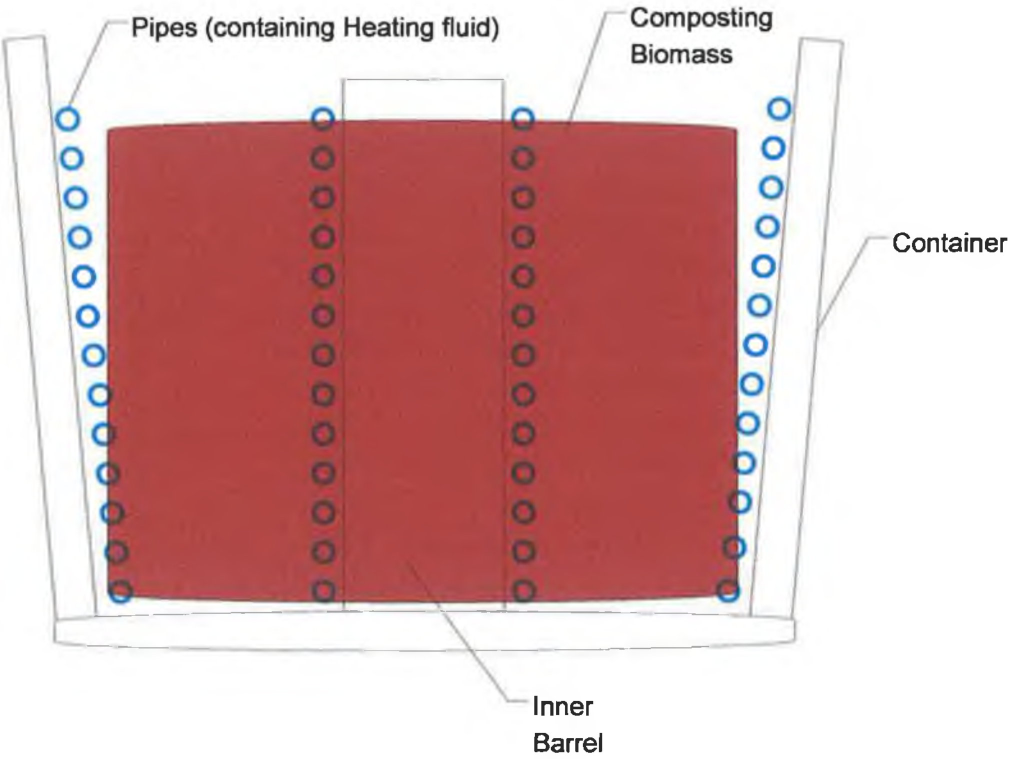

Figure 2.8: Basic diagram of the cross section of the HEU to be constructed.

Various process heating fluids were tested to investigate their thermal properties with regard to extracting the latent and sensible heat energy from decomposing organic matter within a piped system. These included water, propylene glycol and synthetic hydrogen oil. Propylene glycol was tested in our experiments due to its non toxic nature when compared to the more common antifreeze ethylene glycol (Anon. 2008a). A fluid that absorbs heat energy from the compost at the fastest rate would be advantageous. It should be resistant to freezing and have a low viscosity. The thermal properties of four commonly used pipe material were investigated that would transport the chosen heating fluid to investigate the most efficient material for heat extraction for in-vessel composting conditions. The materials commonly used in the transmission of water or heat included copper, polyethylene qualpex, PVC, and hydrodare plastic. Full scale in-vessel composting experiments were conducted using a 2046 litre water trough used for cattle (Figure 2.9). It was chosen due to its relative inexpensive cost, its light weight structure and a large enough size to conduct experiments of significant nature, although small enough to be moved by the common tractor. Two types of insulation were also tested including special UV resistant bubble polythene wrap and spray on polyurethane foam.

Figure 2.9: Example of the 2046 litre cattle trough purchased for the project trials.

2.3 Methods: Design of Heat Extraction Unit and Qualification Testing.

2.3.1 Process Fluids

In numbered beakers 0.5 litres of water, propylene glycol, and synthetic hydrocarbon oil were placed. Five replicates of each liquid were made up. They fifteen beakers were transferred to the refrigerator at random locations and allowed to cool for two hours. The fluids were transferred to the oven set at 70°C. Temperature was recorded accurate to ± 0.1 °C using a VWR submersible digital temperature probe over a 24 hour period. Temperatures of the fluids were recorded at 30 minutes intervals for the first 1.5 hours and then at 2.5, 3.5, 4.5, 6, 7.5, 10.5, 24 hours. The oven was then turned off and the 15 beakers were transferred to the bench to cool. Temperatures of the cooling fluids were recorded over a four hour period until they reached room temperature. Temperatures were taken at four 20 minute intervals and then at 2, 3, and 4 hours.

2.3.2 Water / Propylene Glycol ratios

Two litres of 10%, 20%, 30%, and 40% propylene glycol to water ratios were mixed. Four 0.5 litre replicates of each were made up in numbered beakers. The sixteen beakers were transferred to the oven (70°C) at random locations and temperature was recorded to an accuracy of ± 0.1 °C using a VWR submersible digital thermometer. Temperatures were taken at time periods 0, 0.5, 1, 2, 3.5, 4.5, 7.5, and 20 hours. After 20 hours they were taken out and left to cool at room temperature. Temperatures of the cooling fluids were recorded over a six hour period until they reached room temperature. Temperatures were taken at five 30 minute intervals and then at 4 and 6 hours. The second part of the experiment was identical except the fluids were transferred to the freezer after being heated in the oven. The temperature was recorded at time periods 0, 0.3, 0.5, 1, 1.5, 2, 3, 4, 5, 7, and 24 hours within the freezer.

2.3.3 Pipe Materials

Three different pipes including copper, PVC and Qualpex (polyethylene) were investigated for their thermal properties. Three replicates of short pipe sections were made up of dimensions 25.4 mm diameter and 300mm long. These were filled with water and sealed at both ends using expanding foam and silicone. The replicates were placed in an oven at 70°C and heated for 24 hours. Surface temperature measurements were taken to an accuracy of ± 0.1 °C using a VWR surface digital thermometer as they heated up at time periods 0, 0.25, 0.5, 1, 1.5, 2.5, 3.5, 4.5, 5.5, 24 hours and as they cooled when removed from the oven at time periods 0.25, 0.5, 0.8, 1, 1.5, 2.0, 3.0, 5.0, 7 hours. Care was taken to ensure each pipe was exposed to the identical cooling environment to ensure it did not impact on results obtained.

A second experiment investigated the rate at which water within copper, PVC and qualpex piping absorbed thermal energy. Three replicates of 25.4mm diameter, 300mm long section of the each pipe were sealed at one end using expanding foam and silicone and filled with 100ml of water. These were placed in an oven, heated for 24 hours at 70°C and the water temperatures were taken to an accuracy of ± 0.1 °C at time periods 0, 0.3, 0.7, 1.3, 2, 4, and 24 hours using a VWR submersible digital thermometer.

A third experiment in this section investigated a fourth pipe material 'Hydrodare' in comparison with copper and qualpex. Three replicates of 25.4mm diameter, 300mm long section of the each pipe were sealed at one end using expanding foam and silicone and filled with 100ml of water. These were placed in an oven, heated for 24 hours at 70°C and water temperatures were taken to an accuracy of ± 0.1 °C at time periods 0, 0.3, 0.5, 1, 1.5, 2, 3, 5, and 9 hours using a VWR submersible digital thermometer.

2.3.4 Full Scale Testing

Two 2046 litre plastic cattle troughs were purchased from JFC Plastics Ltd.. Two circular lids were constructed specifically to fit the top of these troughs (Heat Extraction Units (HEU)). Each lid was made of 18mm marine plywood and consisted of two semi-circular pieces attached with hinges onto a central piece spanning the middle of the HEU (Figure 2.10). The first experiment in this section was conducted to test which pipe material worked most efficiently for full scale trials qualpex or hydrodare. A second trial investigated if there was a significant difference in heat extraction levels between a HEU half lined with pipes and one fully lined. A third looked into the performance of various insulation types. Trials were conducted under a sheltered open barn and were replicated over time as due to the large nature of the experiments multiple replicates could not be carried out on the same day. Pseudo-replication was avoided in this case as ambient conditions on the various days were similar enough for results to be used in statistical analyses.

Figure 2.10: Example of the removable Marine Plywood Lid constructed to cover the 2046 litre trough (HEU).

2.3.4.1 Qualpex Vs Hydrodare

100 m of the 25.4mm qualpex and hydrodare piping and two 250 litre barrels were used to create 2 non pressurized circulation systems. These were set up in both HEUs to test the qualpex and hydrodare pipes. An inbuilt drainage hole along the bottom rim of the tanks allowed the pipes enter and exit the HEUs. The pipes were then looped around the inside edges of the HEUs (10 loops) and secured with plastic 25.4mm pipe clips. The pipes then lead into an inner ring of 10 loops secured onto the 250 litre barrels. Figure 2.11 shows a photograph of the looped pipe system setup inside a HEU using the qualpex piping. A series of loops can be seen around the barrel and also the inner surface of the

main 2046 litre container. An insulated plywood box was constructed to house a standard 45 litre attic header tank. The outlet and inlet pipes from the HEU were connected to the header tank. A flow pump (Groundfos UPS 15-50-130) was attached to the inlet pipe which pumped water from the tank through the piping and return it to the tank. Two electrical heaters (JMH Halogen 506) were purchased and placed inside each HEU. Figure 2.12 shows the layout of the experiment in more detail.

Figure 2.11: Qualpex piping setup inside the HEU for heat extraction experiment.

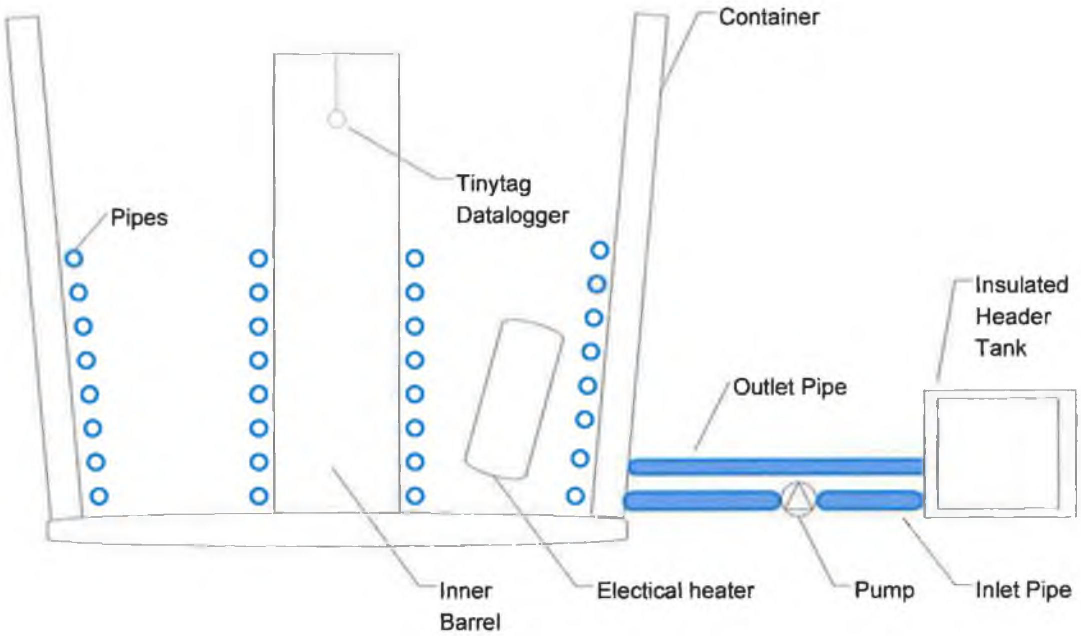

Figure 2.12: Layout of the full scale process pipe material experiment.

During the experimental test procedure the plywood lids were closed. The pumps and the electrical heaters were activated. Temperatures of the water exiting the outlet pipe into the header tanks were recorded manually at time periods 0, 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2, 2.5, 3, 3.5, 4, and 5 hours using VWR submersible digital thermometer placed under the outlet water. Temperatures inside the HEUs were recorded using 2 Tinytag Ultra 2 (TGU-4017) data loggers which are accurate to ±0.01°C. They were placed in the centre of the unit suspended on a 400mm string from the barrel centre. The experiment was conducted over five hours and repeated the next day.

2.3.4.2 Half lined qualpex versus full lined qualpex

Two HEUs were used in this experiment. The first was half lined (10 loops) with 25.4mm qualpex as in Figure 2.11 and 2.12. The second was fully lined (20 loops) with 25.4mm qualpex creating an outer ring on the inside wall of the large container and an inner ring around the barrel. During the experimental test procedure the electrical heaters were placed within the HEUs and the flow pumps were activated on both. The experiment was conducted over 7 hours and repeated over three consecutive days because the experiment was too large for it to be conducted using replicates on the same day. Temperature of the water exiting the outlet pipe into the header tanks was recorded manually at time periods 0, 0.25, 0.5, 0.75, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, and 7 hours using VWR submersible digital thermometer placed under the outlet water. Temperature inside the HEU was recorded using 2 Tinytag Ultra 2 (TGU-4017) data loggers which are accurate to ±0.01°C.

2.3.4.3 HEU External Insulation

The exterior of one HEU was covered with 50mm thick polyurethane spray-on thermal foam insulation. Insulated covers (Lids) were made using 50mm Kinspan insulation and a 7 mm Perspex plastic. Initially a 2.3 m diameter circular cover was constructed by cutting the Kinspan and Perspex to this dimension and gluing the Perspex to the Kinspan. Figure 2.13 shows the insulation described in use on the HEU. This was then cut in two semi-circles to allow the lid to be easily opened. The first experiment tested the heat retention of the spray on insulation (including the Kingspan cover) against a HEU with no insulation. This experiment was conducted over 6 hours and replicated on the following day, as due to the large nature of the experiment multiple replicates on the same day were not possible.

A second insulation experiment consisted of a HEU covered in 50mm of special insulating bubble wrap plastic. An identical insulated cover was constructed as in the first insulation experiment and was placed on top of this HEU. The experiment was replicated over 3 days to test the heat retention of bubble insulation versus the spray on insulation. During each trial the electrical heaters were placed within the tanks and the pumps were activated on both HEUs.

In each of the 5 trials water temperature within the pipes was measured at time periods 0, 0.33, 0.66, 1, 1.5, 2, 2.5, 3, 3.5, 4.5, 5.5, and 6.5 hours using a VWR submersible digital thermometer placed under the outlet water. Temperatures inside the HEUs were recorded using 2 Tinytag Ultra 2 (TGU-4017) data loggers which are accurate to ±0.01°C.

Figure 2.13: HEU showing the external polyurethane insulation and the 50mm Kinsgpan insulation lid with perspex cover.

2.4 Data analysis

A Cochran's test for equal variance was used to test for homogeneity within the experimental data. Minitab 15 was used to complete statistical analysis on the data. Fisher's Pairwise comparisons were used to investigate statistical differences in one way ANOVAs.

2.4 Results

2.4.1 Heating Fluids

Figure 2.14 shows the mean temperature of each fluid as they are heated up over a 24 hour period. Initially, all three fluids absorbed heat energy rapidly and water, glycol and Synthetic Hydrogen Oil (SHO) had risen to 50.5 °C, 55.9 °C, 56.7 °C respectively after 6 hours. The rate of increase during this period for water, glycol and SHO was 7.9, 8.9, and 9.0 °C / hour respectively. The rate of increase declined rapidly in all three fluids after six hours when it took another 18 hours for them to increase 10 °C. The rate of increase slowed to 0.37, 0.55, and 0.51 °C / hour for water, glycol and SHO respectively during this period. Glycol and SHO followed a similar rate of increase as they absorbed heat energy with the water having a lower heat absorbance rate. Water absorbed heat energy at a significantly lower rate than the glycol and the SHO (One way ANOVA, P=0.003). There was no significant difference in the rates at which Glycol and SHO absorbed heat energy (One way ANOVA, P=0.56).

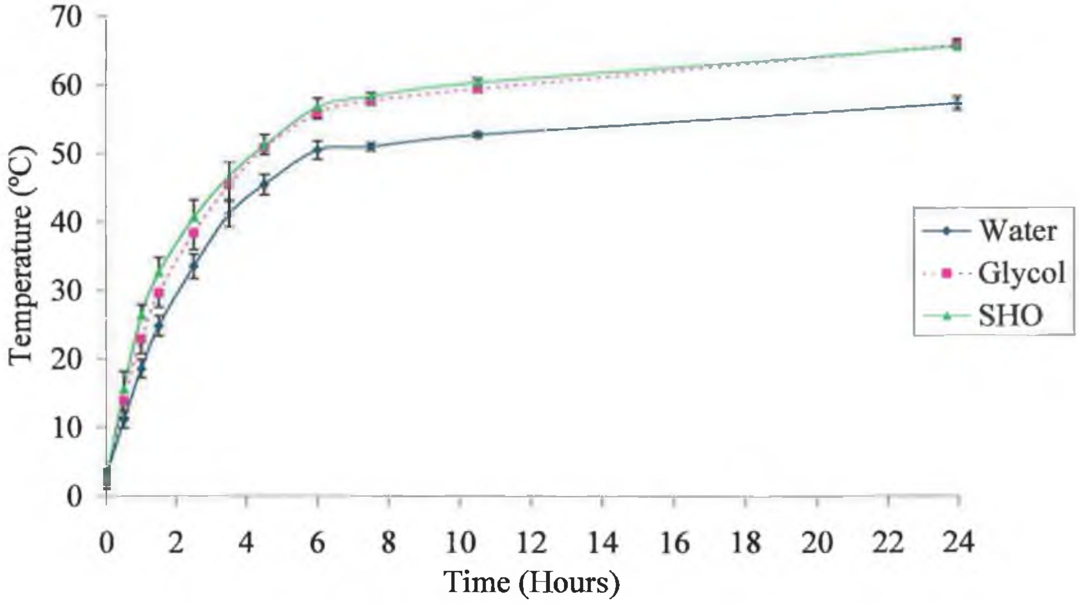

Figure 2.14: The mean (±SD) temperature of water, propylene glycol, and synthetic hydrogen oil as they are heated to 70 °C.

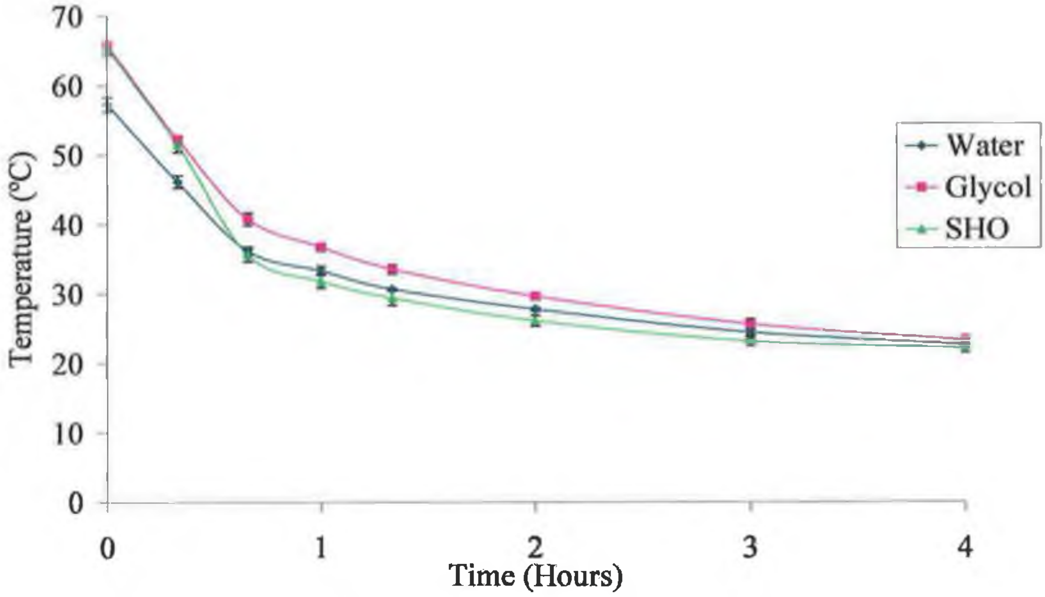

Figure 2.15: The mean (±SD) temperature of water, propylene glycol, and synthetic hydrogen oil after they are removed from the heat source.

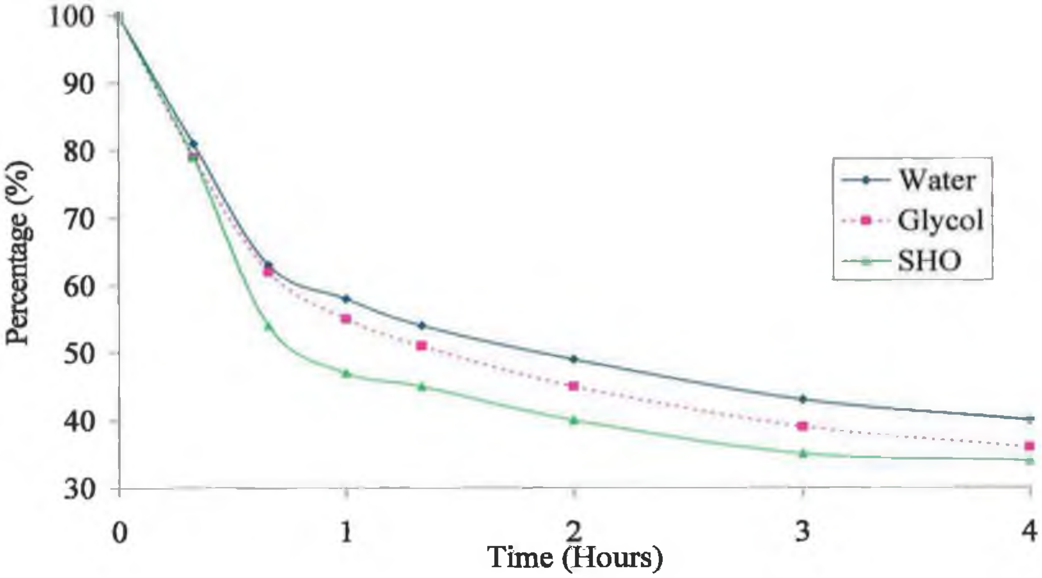

Figure 2.16: The temperature of water, propylene glycol, and synthetic hydrogen oil as a % of initial temperature after being removed from the heat source.

The temperature profiles of the three fluids after they were withdrawn from the oven are shown in Figure 2.15. There was a significant difference in the rates at which each liquid released thermal energy (One way ANOVA, P=0.005). There is a sharp decrease in temperature within water, glycol and SHO from 57.3, 65.8, 65.4 °C to 33.4, 36.8, 31.8 respectively. This decrease was over the first hour, after which the thermal energy release slowed down over the following three hours to room temperature (22 °C). The rate of decrease for water, glycol and SHO is 23.9, 29.0, and 33.6 °C / hour for the first hour respectively. This was reduced to 3.6, 4.5, 3.2 °C / hour respectively for the following three hours. Figure 2.16 shows the data as a percentage of initial temperature to allow for different initial temperatures at the end of the heating experiment. It is clear from this graph that the SHO cooled at the fastest rate decreasing to 54% of its initial temperature after one hour and water is the lowest at 42% of its initial temperature after one hour. Glycol was in between at 45% decrease of its initial temperature after one hour.

2.4.2 Water / Propylene Glycol ratios

Figure 2.17 shows the increasing temperature profile of the four Water / Glycol ratios tested as temperature rises inside the oven. All four fluids absorb heat energy quickly over the first 6 hours rising from 20 to 50 °C giving a rate of 5 °C / hour. Over the next fourteen hours an 8 ± 1 °C rise was observed in each replicate as they got closer to the oven temperature giving a reduced rate of 0.57 °C / hour. The overall trend after heat is applied, is that each fluid absorbs energy at the same rate without significant difference between them (One way ANOVA, P=0.98). Figure 2.18 shows the temperature profile of the four Water / Glycol ratios after they were removed from the oven. There is a rapid decline in temperature over the first 2.5 hours from means of 58 °C ± 1 to 26 °C ± 0.5 in each of the four fluids. Within six hours all the replicates had reached room temperature of 20 °C. There were no significant differences in the rates of cooling between the fluids (One way ANOVA, P=0.99). Figure 2.19 shows the temperature profile of the four Glycol ratios after they were placed in a freezer after a heat source was applied. There was a rapid heat loss for each fluid over the first seven hours (7.4 °C ± 0.5 / hour). Temperature dropped at a rate of 0.67 °C / hour to an average of -4.7 °C after 24 hours. Ice formed within the beaker of two of the four replicates of the 10 % Glycol solution at a temperature of -4.5 °C. There is no significant differences in cooling rates (One way

ANOVA P=0.99) during any of the time periods after they are placed in the freezer. The final design will consist of 15% propylene glycol to 75% water.

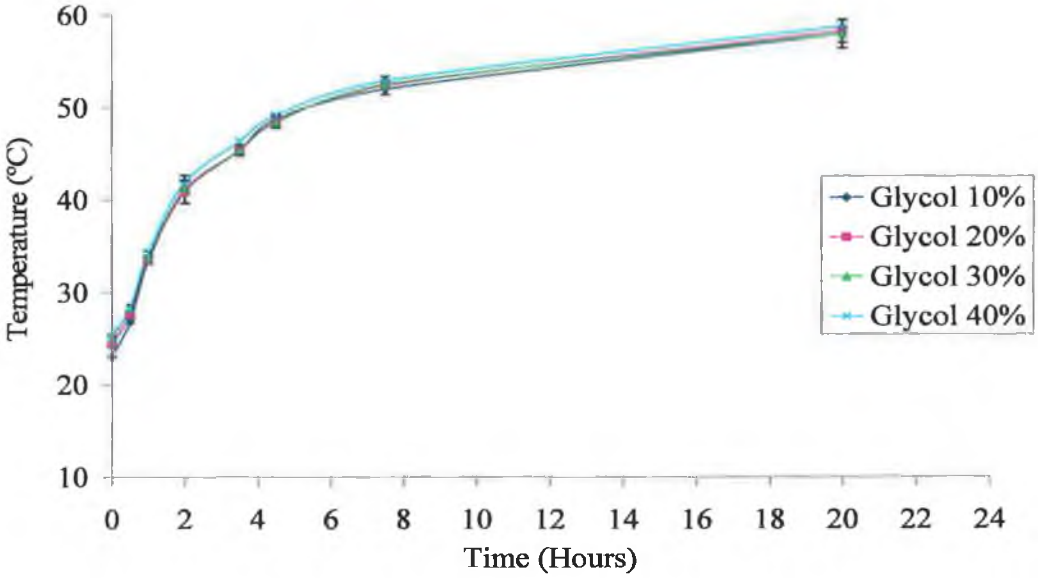

Figure 2.17: The mean (± SD) temperature of four ratios of Glycol/water as they are heated to 70 °C.

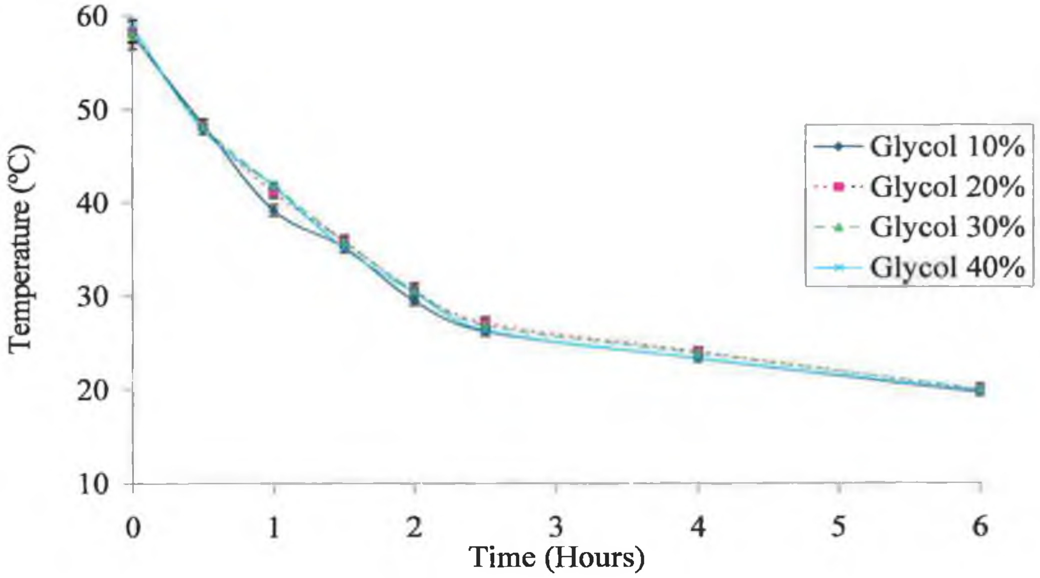

Figure 2.18: The mean (±SD) temperatures of four ratios of Glycol/water after they are removed from an oven and cooled at room temperature.

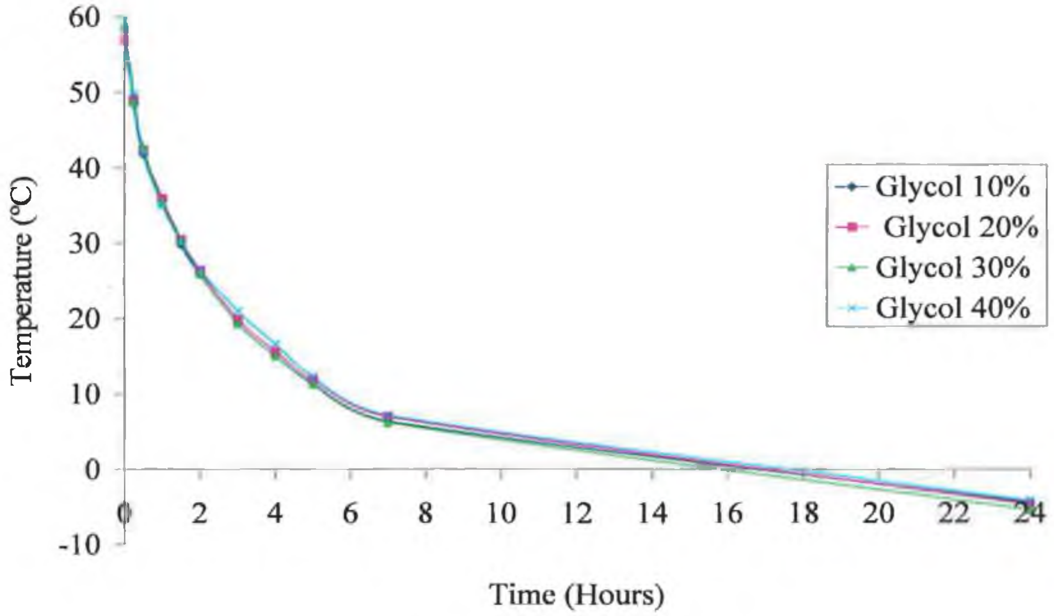

Figure 2.19: The mean (± SD) temperature of four ratios of Glycol/water after they are removed from an oven and placed in a freezer.

2.4.3 Pipe Materials

Figure 2.20 shows the mean temperature of three pipe materials as they absorb heat over a 24 hour period within a 70 °C oven. Copper absorbs heat energy at a faster rate (7.0 °C / hour) than the two plastics rising to 60 °C after 6 hours. This compares to a rise of 51 °C for qualpex (5.2 °C / hour) and 46 °C for PVC (4.7 °C / hour). The patterns remain the same after 24 hours with copper the hottest at 63.2 °C, qualpex next at 51.6 °C and PVC at 47.0 °C. There was a significant difference in the rates at which each material absorbed heat energy (One way ANOVA, P=0.01) with copper the fastest, then qualpex and the slowest was PVC. Figure 2.21 shows the rate of heat loss from the pipe materials after being removed from the oven. Each material cooled at significantly different rates (One way ANOVA, P=0.013). The majority of the heat energy was lost in the first 3 hours. Copper at the rate of 19.5 °C / hour, qualpex at 14.3 °C / hour and PVC at 12.3 °C / hour. Figure 2.22 shows the percentage of initial temperature to allow for variation in starting temperature. It can be clearly seen that copper temperature decreases at the fastest rate losing almost 100 % of its initial energy (relative to 0 °C) at 5 hours where as qualpex is at 11 % and PVC is at 15 %.

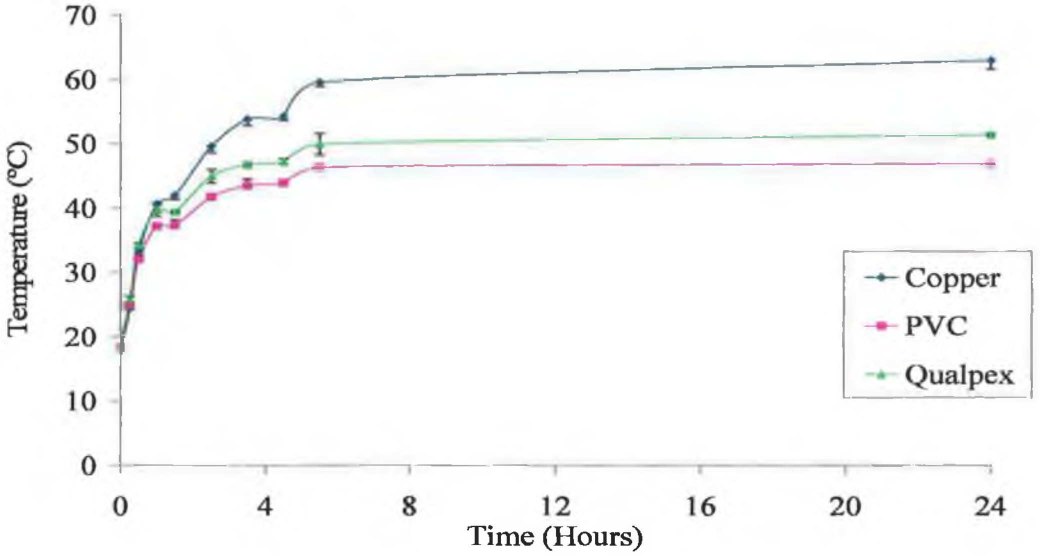

Figure 2.20: The means (± SD) surface temperatures of 25.4mm copper, PVC and qualpex pipes as they are heated to 70 °C.

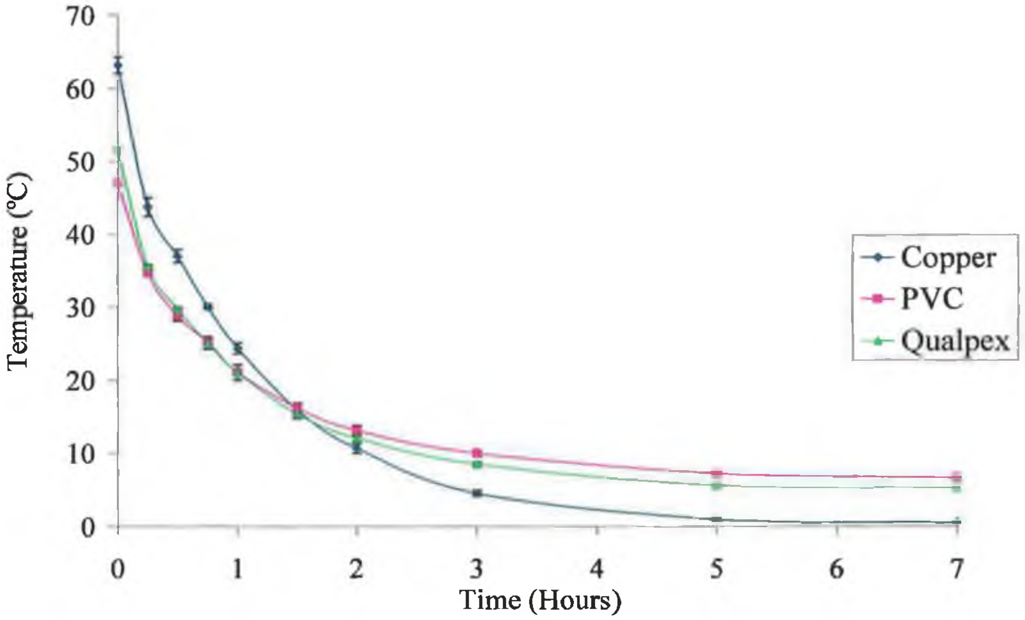

Figure 2.21: The mean (± SD) surface temperatures of 25.4mm copper, PVC and qualpex pipes once removed from the heat source.

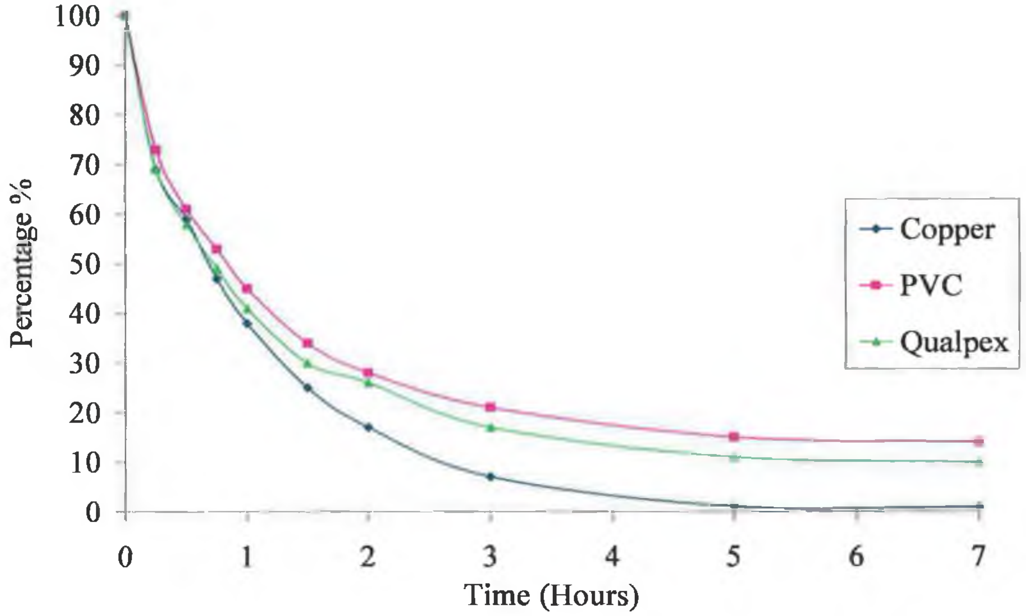

Figure 2.22: Surface temperatures of 25.4mm copper, PVC and qualpex pipes as a percentage of initial temperature once removed from the heat source.

The second experiment within this section investigated how water within these pipe materials absorbed and released heat energy. Figure 2.23 shows the increase in the mean temperature of water within the three pipe materials as it absorbs heat over a 24 hour period at 70 °C. In the first 4 hours the water temperatures increased the fastest from 20 °C to 57 ± 1.0 °C for each pipe material. The water within both plastic pipes absorbed thermal energy at a marginally faster rate than the water within the copper pipes. These rates are 8.9, 9.3, and 9.4 °C / hour for copper, PVC and qualpex respectively. There was a significant difference in the rate of heat absorption of water within each pipe material (One way ANOVA, P=0.007). A fisher's pairwise comparison showed that there was no significant difference between the qualpex and PVC but that both plastics were slightly different to copper piping in the early heating phase

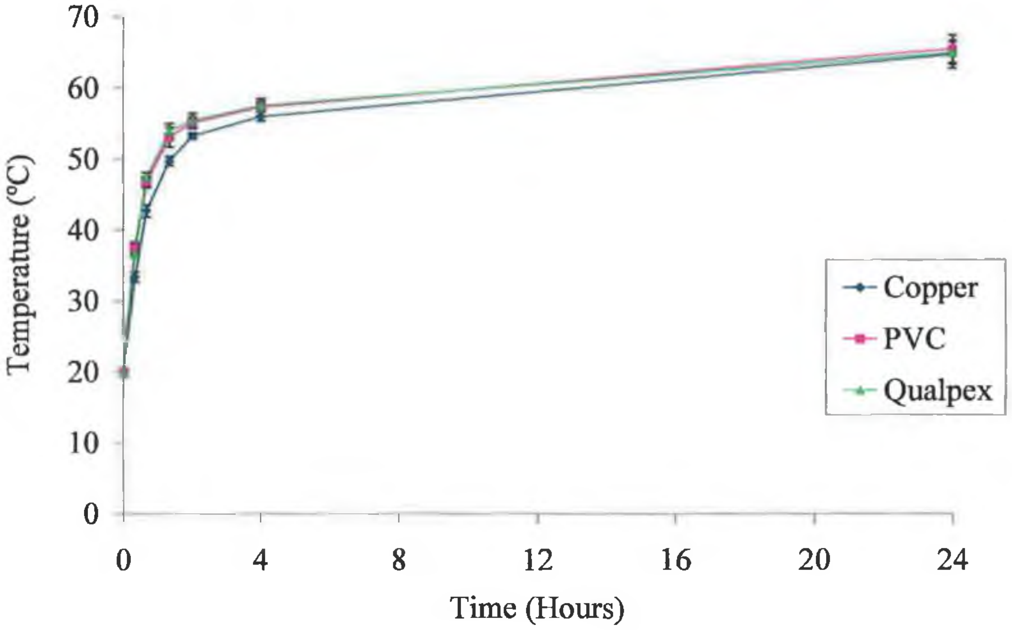

Figure 2.23: The means (± SD) temperature of water within 25.4mm copper, PVC and qualpex pipes as they are heated to 70 °C.

The third experiment within this section compared hydrodare plastic piping with copper and qualpex. Figure 2.24 shows the increase in the mean temperature of water within the three pipes as it absorbed heat over a 24 hour period at oven temperatures of 70 °C. Similar results to the previous section were observed with the greatest increase in temperature over the first 4 hours, before levelling off at 65 ± 0.5 °C. There was a significant difference in the rate of heat absorption of water between pipe materials (One way ANOVA, P=0.001). A fisher's pairwise comparison showed that there was no significant difference between the plastics but that both plastics were slightly different to copper piping in the early heating phase.

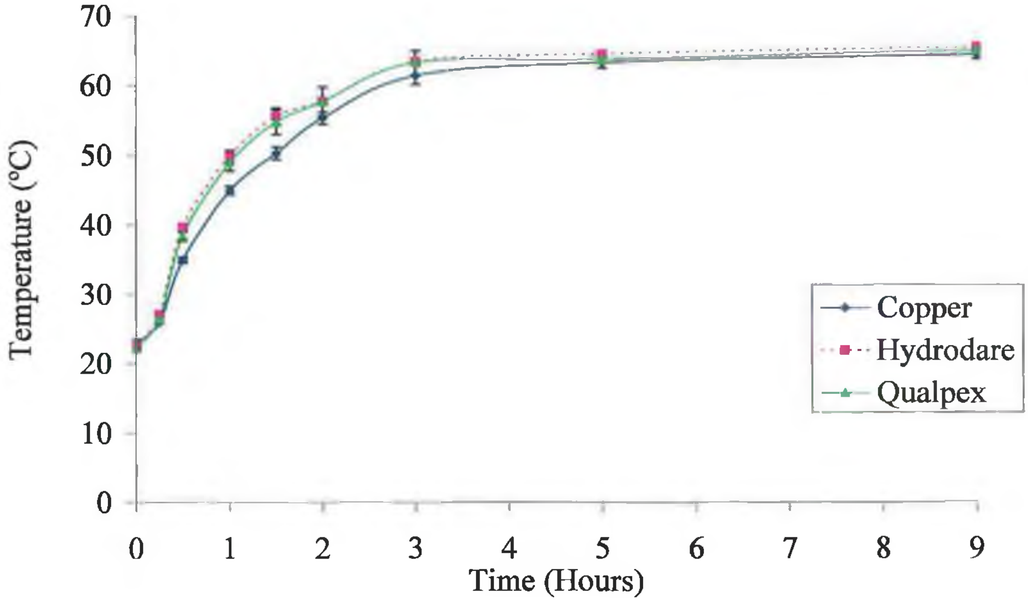

Figure 2.24: The mean (± SD) temperature of water within 25.4mm copper, hydrodare and qualpex pipes as they are heated to 70 °C.

2.4.4 Full Scale Trials.

2.4.4.1 Qualpex Vs Hydrodare

Figure 2.25 shows the increase in water temperature from the outlet pipe and the internal HEU temperature from the qualpex versus hydrodare experiment. The two HEU temperature curves overlap showing that the electrical heaters elevated the internal HEU temperatures to the same level (reaching 50 °C after 5 hours). Outlet pipe water temperature rises over 5 hours from 16.2 °C and 15.6 °C to 35.8 °C and 35.4 °C for the qualpex and hydrodare respectively. This indicated that identical conditions existed inside the HEUs during the experiment. The outlet pipe water temperatures are shown to be almost identical and no significant difference was observed between them (One way ANOVA, P=0.51).

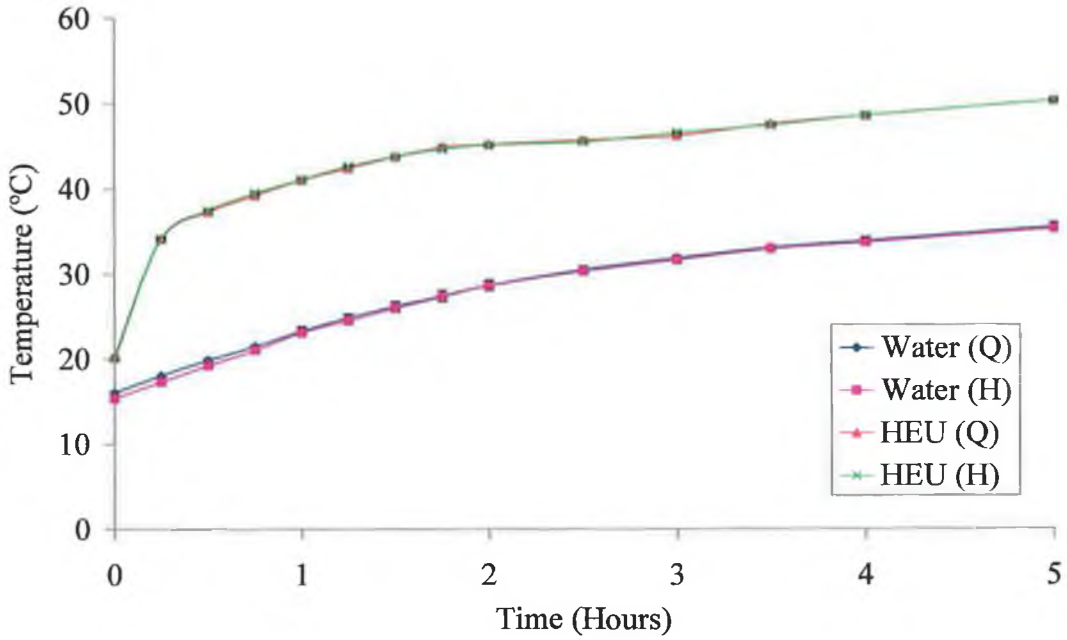

Figure 2.25: The mean (± SD) temperature of water within 25.4mm hydrodare (H) and qualpex (Q) pipes and internal HEU temperature as they are heated with an electric heater.

2.4.4.2 Half lined qualpex versus full lined qualpex

Figures 2.26 shows the mean outlet pipe temperatures recorded over three consecutive days and the internal HEU temperatures. Heat is transferred to the water in the fully lined HEU at a faster rate than the ½ lined HEU. HEU temperatures reached 51 °C during both experiments after 7 hours showing identical conditions existed. Initial water temperature is 12.6 °C in both HEUs. After 7 hours the mean water temperature in the ½ lined HEU was 35.8 °C, while the mean temperature in the fully lined HEU was 39.9 °C giving a 4.1 °C difference over 7 hours. There was a significant difference in the rate of heat absorption between the ½ and fully lined HEUs (One way ANOVA, P=0.001) with the fully lined HEU having a greater heat absorption characteristics.

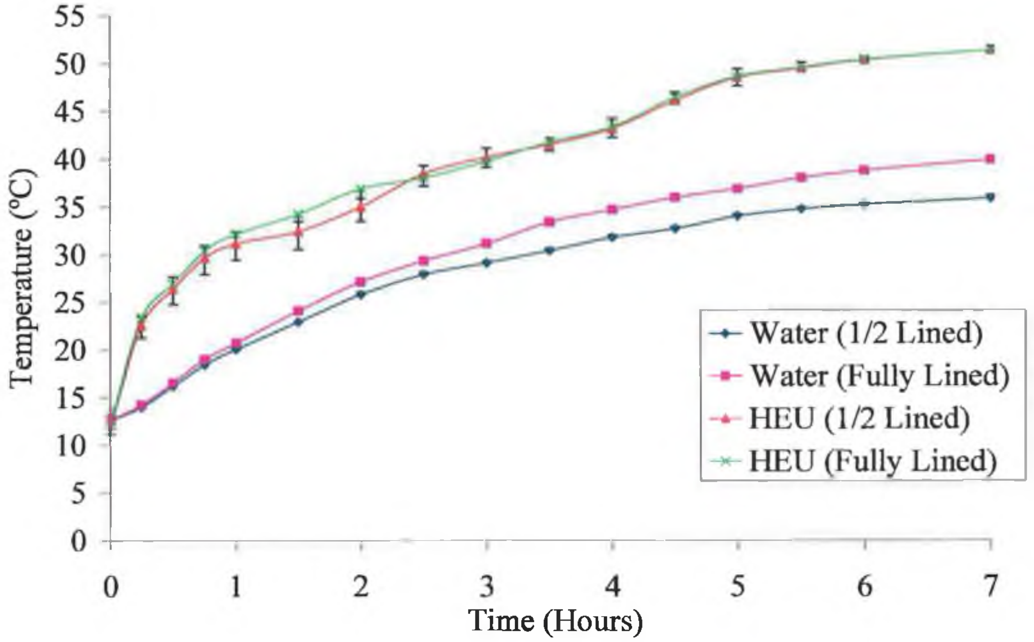

Figure 2.26: The mean ± SD temperature of water within 25.4mm qualpex piping of a ½ lined and fully lined HEU and the associated internal HEU temperatures.

2.4.4.3 HEU Insulation

Figure 2.27 shows the temperature profiles of two HEUs as they are heated. These include the piped water temperature and the internal HEU temperature from insulated and non insulated HEUs. Mean internal HEU temperature increased faster in the insulated unit and after 6 hours it was at 70.2 °C, thirty degrees above the non insulated unit. Temperature within the insulated HEU increased at a significantly faster rate than the non insulated HEU (One way ANOVA, P=0.000). Mean piped water temperature also increased faster in the insulated HEU with a 15.1 degree difference recorded after 6 hours. The mean insulated HEU water temperature rose from 13.8 to 52.9 °C during this time. The non insulated HEU saw the mean water temperature rise from 14.3 to 37.7 °C. Outlet pipe temperature increased significantly faster in the insulated HEU in comparison with the non insulated HEU (One way ANOVA, P=0.000).

Figure 2.28 shows the temperature profiles of two HEUs during the second insulation experiment. These include the outlet pipe water temperature and the internal HEU temperature from the bubble and polyurethane spray insulated HEUs. Internal HEU temperature increased faster in the polyurethane spray insulated HEU and after 6.5 hours it reached 68.2 °C, six degrees above the bubble wrap insulated HEU. The spray insulated HEU temperature increased at a significantly faster rate than the bubble insulated HEU (One way ANOVA, P=0.000). Outlet pipe water temperatures increased faster also in the polyurethane spray insulated HEU with a 5 degree difference recorded after 6.5 hours. The water temperature rose from a mean of 7.6 ± 0.46 to 51.0 ± 1.0 °C during this time. The bubble insulated unit saw the mean water temperature rise from a mean 7.9 ± 0.15 to 46.0 ± 0.15 °C over 6.5 hours. The temperature of water within spray insulated HEU outlet pipe increased at a significantly faster rate than the water within bubble insulated HEU pipe outlet (One way ANOVA, P=0.000).

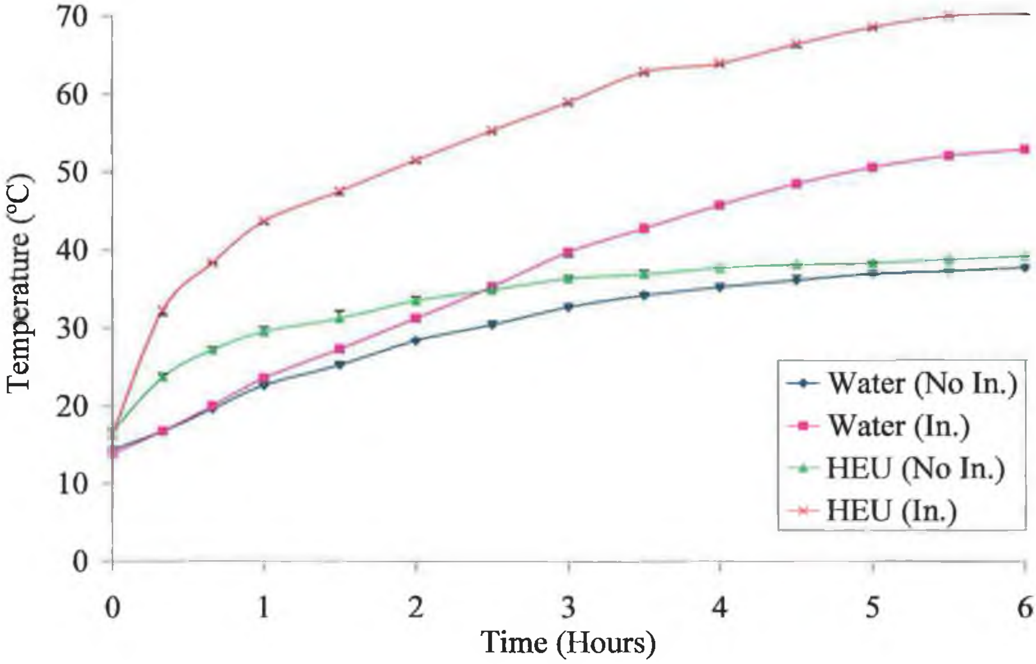

Figure 2.27: The mean (± SD) temperature of water inside the piping of an insulated (In.) and non insulated (No In.) HEU and the associated internal HEU temperatures.

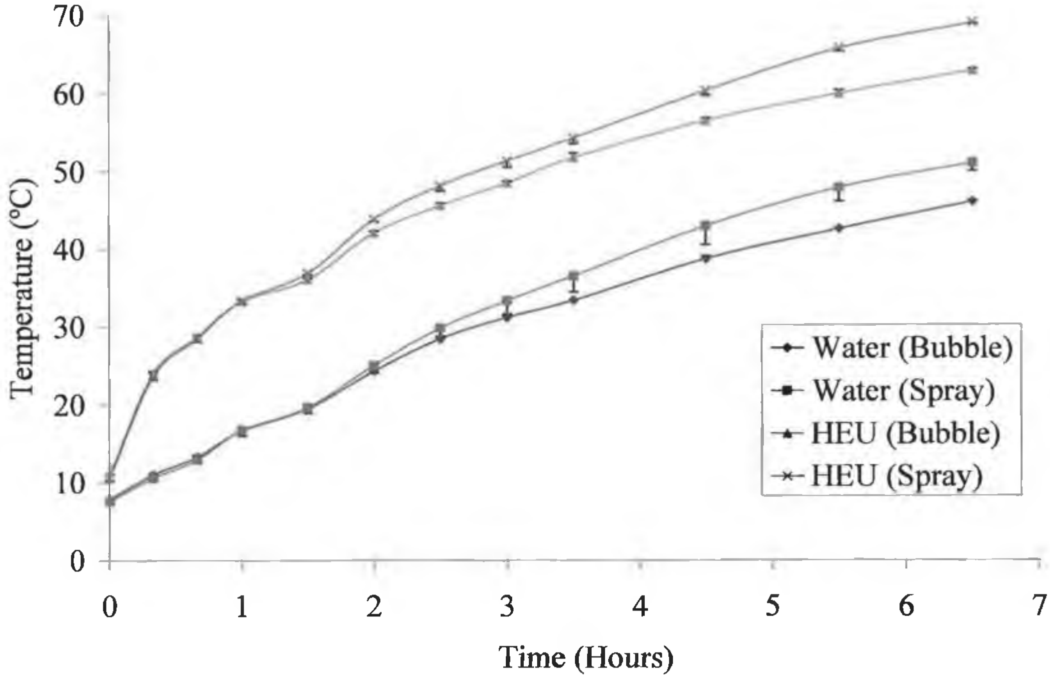

Figure 2.28: The means (± SD) temperature of water inside the piping of a bubble insulated and polyurethane spray insulated HEU and the associated internal HEU temperatures.

2.4.5 Detailed Experimental Design Specification.

Figure 2.29 shows the internal structure of the HEU before being insulated. The inner and outer looped rings of 25.4mm qualpex piping are shown. An inbuilt drainage hole along the bottom rim of the tanks allows the pipes enter and exit the HEUs. The pipes are then looped around the inside edges of the HEUs (18 loops) and secured with plastic 25.4mm pipe clips. The pipes then lead into an inner ring of 18 loops secured onto a 250 litre barrel for support. Multiple holes have been cut in the barrel to allow heat easily transfer from the decaying organic matter in the centre of the unit. The unit consists of a total 150m of pipe inside the structure. An insulated plywood box was constructed to house a standard 45 litre attic header tank. The outlet and inlet pipes from the HEU were connected to the header tank. A flow pump Groundfos (15-50 130) was attached to the inlet pipe which pumps water from the header tank through the piping of the HEU, onto a selected heat exchanger and returns it to the tank. The exterior of the HEU was covered with 50mm thick polyurethane spray-on thermal foam insulation. A 18mm marine plywood cover wass constructed with a central piece (2.06 m length by 0.3m width) spanning across the top of the unit and two side pieces which cover the area remaining hinged onto it, to allow access to the compost An insulated cover (Lid) was constructed using 50mm Kinspan insulation and a 7 mm Perspex plastic. Initially a 2.3 m diameter circular cover wass constructed by cutting the Kinspan and Perspex to this dimension and gluing the Perspex to the Kinspan. This was then cut in two semi-circles to allow the lid to be easily removed.

Figure 2.29: Photograph showing internal structure of full scale experimental design.

Figure 2.30 shows the plan view of the HEU. Figure 2.31 shows the cross section of the HEU without the polyurethane insulation. Figure 2.32 below shows the external structure of the HEU with the 50mm polyurethane insulation around the sides and base of the unit and kingspan insulating cover over the top. The unit is placed on a pallet and can be moved by means of tractor equipped with forks. Passive aeration is employed in the design of the HEU and can be seen in Figure 2.33. This allows air to flow up through the compost to aerate the heap without the need for active (energy using) aeration. It is composed of a 50.8mm vent embedded within the plywood on the top of the HEU which draws air up through the compost from two perforated 50.8mm PVC pipes that run through the HEU at the bottom, to the outside. Before the organic matter to be composted is placed in the unit a 2 inch layer of woodchips are placed over these two 50.8mm PVC pipes which lie at the bottom of the HEU (Figure 2.33) . This helps to prevent clogging of the passive aeration system and allow a continuous flow of air through the unit.

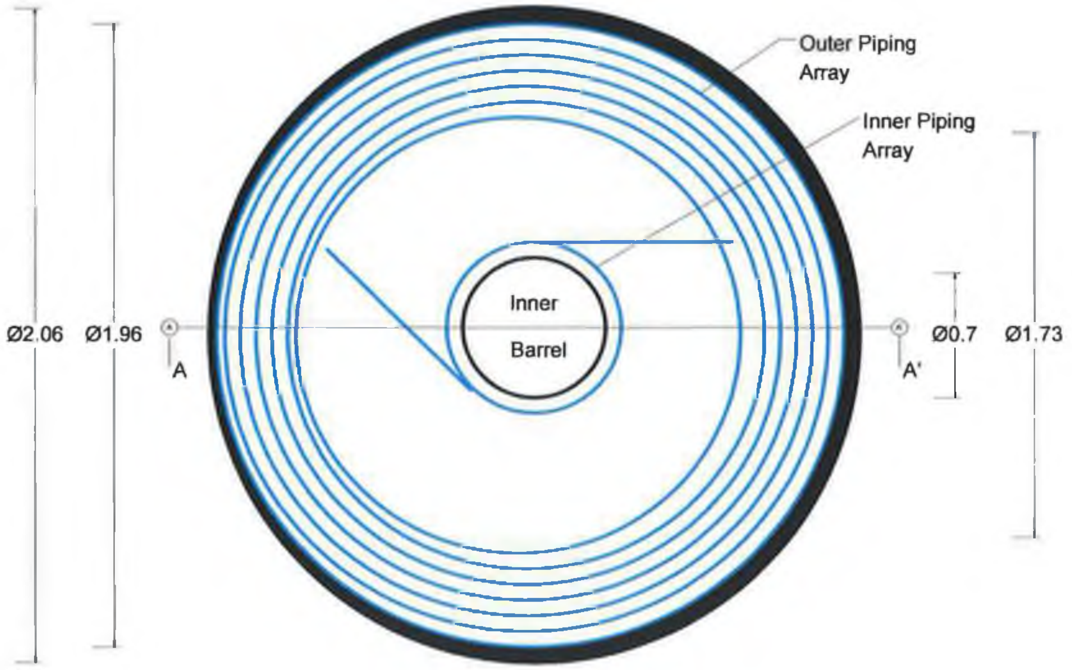

Figure 2.30: Plan view of HEU showing inner and outer pipe arrays.

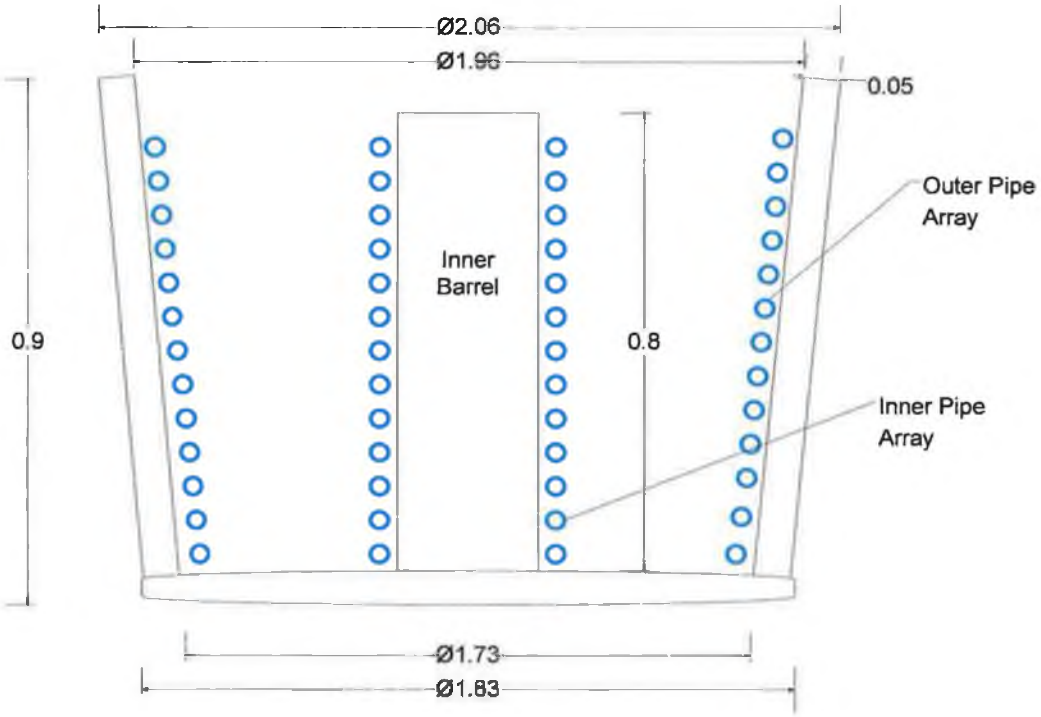

Figure 2.31: Cross-section view through section AA' in Figure 30 of the HEU showing the inner and outer pipe arrays.

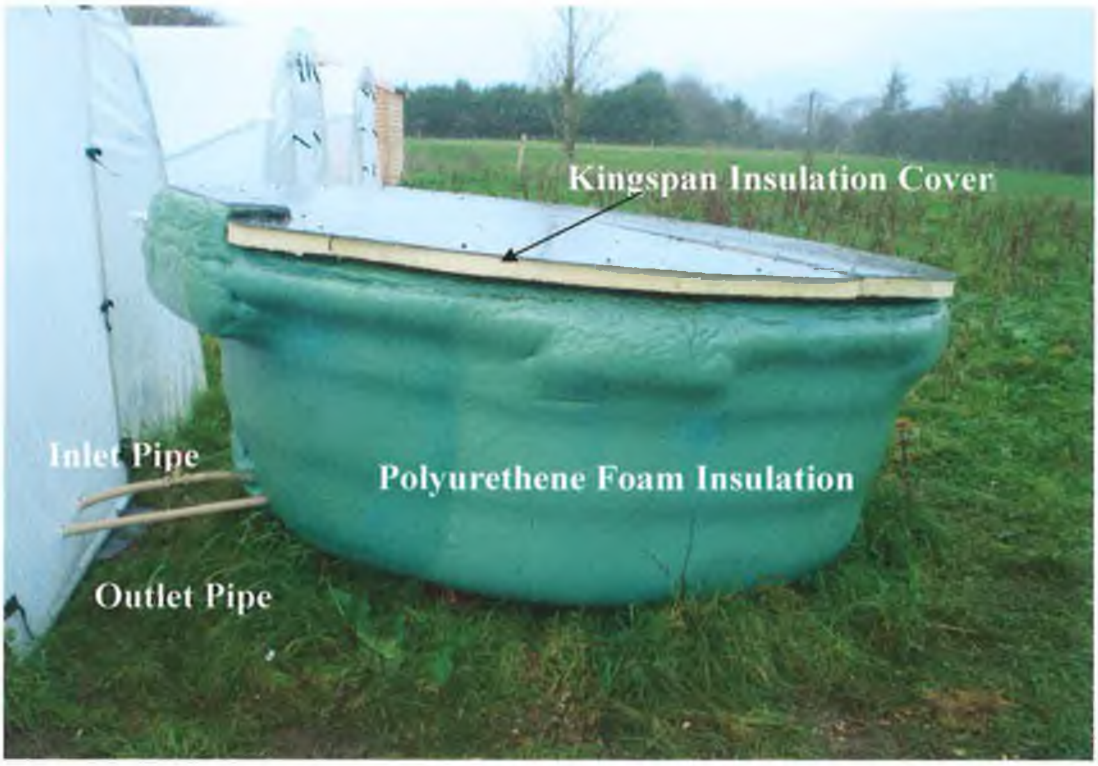

Figure 2.32: External view of full scale experimental design.

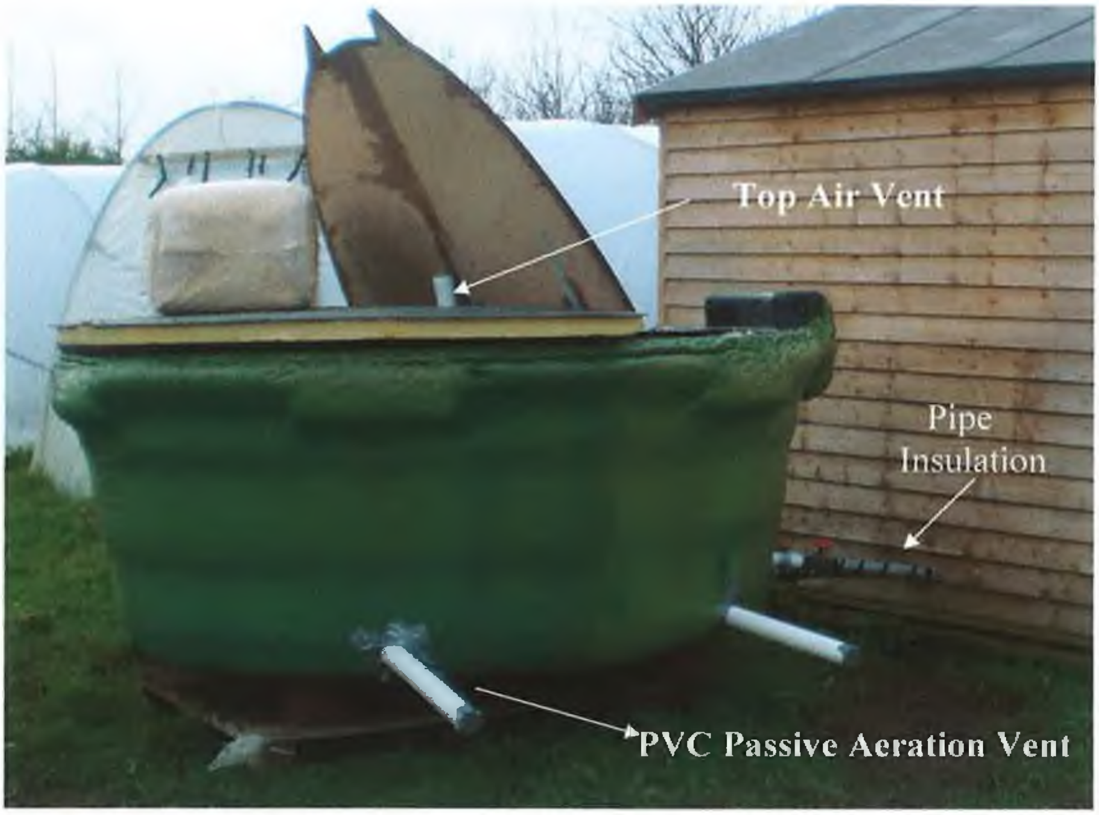

Figure 2.33: External view of full scale experimental design with passive aeration pipe work and top air vent highlighted.

2.5 Discussion

2.5.1 Composting Technology

A composting Heat Extraction Unit prototype was developed and tested and proved capable of recovering thermal energy via a piped hot water heat exchanger. This design was specifically developed to suit the invessel aerobic composting of organic waste. Designs which utilize anaerobic digestion or incineration for treatment of organic waste and energy recovery are currently the most widespread technology used. According to Winship *et al.,* (2008) aerobic digestion of organic waste through composting offers a better method of heat recovery and maintaining soil fertility with a continuous nutrient recycling loop unlike combustion methods. The composting HEU technology developed here uses aerobic digestion to deliver usable heat for various applications and produces usable compost as a by product, while providing a low cost simple alternative to anaerobic digestion.

The prototype HEU was constructed from off the shelf materials and is therefore a simple, easily accessible and cost effective technology. One of the simplest technologies developed to extract heat from compost was by Jean Pain (Pain, 1980). It consisted of composting a 50 tonne circular pile of forest brushwood thinnings that were soaked in water and had coiled pipe through out to carry heated water from the pile. No container was required as the pile was self insulating and the pump and pipes were the only technology used within the heap. The advantage with this technology is the lack of building materials required when compared even to the HEU although the need for a large forest in order to supply brushwood is not always possible.

Ersson (2005) discussed a full composting bed developed to provide domestic hot water. Local manure, food waste and woodchip were composted and a simple looped pipe design was used to extract and deliver the hot water. Fewer materials were used here when compared to the HEU although the mobility of the HEU gives it an advantage over these last two variations. Low-tech aerobic digestion technology was developed successfully at the New Alchemy Institute where thermal energy and CO_2 were distributed under the soil of a greenhouse to assist in horticultural production (Fulford, 1986). Electric blowers force air through ten insulated compost filled timber chambers on the inside wall of a greenhouse. Bacterially-generated warm vapour is blown from these chambers through ductwork to the crops. Diver (2001) discussed this method warning it produced six times the CO_2 and fifty times the Nitrogen needed for optimal plant conditions. The HEU has the advantage in this case as it is only heat that is transferred and not the gaseous emissions. Thus it can be used for domestic and horticultural heating.

Heinonen-Tanski (2005) developed a 'low-tech' approach to deal with cattle slurry wastes streams by aerobically digesting them while at the same time extracting thermal energy. A 10 m^3 insulated steel cylindrical tank was used with an aerator at the bottom giving slurry temperatures of 70 °C and a net positive thermal energy balance over electrical energy used. This research was successful in generating and extracting heat from slurry unlike experiments conducted using the HEU where no significant increase in slurry temperatures were recorded (Fitzgerald, 2009). The compost HEU (Invessel Composting) developed here uses a 'low-tech' approach also and employs a closed insulated plastic tank with a series of 25.4mm qualpex pipes looped inside. Heat is transferred through thermal conduction from the hot compost to the heating fluid within the pipes and is delivered to various applications outside using heat exchangers. The HEU developed here would be ideal for a small scale farmer, grower or any operator with the requirement to heat small to medium sized buildings and that has access to significant quantities of organic matter in particular horse manure.

Although the HEU developed here uses a 'low-tech, cost and capacity' approach it has been predominantly high-tech / high-capacity research that is being conducted recently. Current 'high-tech' (high capacity) research in the design of aerobic heat extraction systems is being carried out by Winship *et al.,* (2008). A 'combined heat and composting' system has been set up using large metallic containers (Aergestors) that can be rolled on and off trucks for transport. The Aergestor can accommodate 15 tonnes of composting matter. It captures the heat that is contained in the moisture drawn off the compost by an aerator fan and uses a heat pump to increase heat transfer efficiency. This technology can deal with up to 25 times the weight of the HEU, however the cost and complexity of this unit would exceed that of the HEU. Seki and Komori (1995) investigated sensible and latent heat energy extraction from compost using a large cylindrical steel container, with a condenser heat exchanger, aeration device and 'medium fluid machine'. Heat was recovered firstly by pipes along the inside of the unit absorbing heat energy through conduction and secondly through the condenser heat exchanger above the unit. The first heat recovery method described is similar to the piping system used in the HEU although air is the fluid medium used here. There may be potential to use a condenser heat exchanger above the HEU to capture sensible and latent energy of the compost vapours. The cylindrical shape of this technology would be more suitable for this application than the 2046 litre trough used for the HEU.

Tucker (2006) describes a large scale compost heat extraction facility in the USA. Isobar heat pipes were placed along side 20m long compost windrows and with the aid of forced aeration water vapour from the compost condenses on the heat pipes, heating them and transferring the energy to heat a reservoir of water. No container is needed for this system and 600-800 tonnes of compost can be accommodated within the barn although at $450,000 for the prototype it is an expensive option when compared to the HEU from a purely financial viewpoint. Rogers (2006) describes heat extraction using two large metal in-vessel composters with 1587 kg/day capacity. A set of pipes with spikes pushes into the composting chamber and water flows through extracting heat. The removal of these heat exchangers allows the compost to be removed more easily. The HEU developed here requires the unit to be turned on its side using a tractor and the compost to be removed by hand. This can lead to damage of the unit and a more efficient method of removing the compost is needed. It must be kept in mind that the compost which is removed must be matured under dry conditions for a lengthy period after removal for it to have a potential resale value (Fitzgerald Pers. Comm). This is most likely to be in a separate location from where the heating takes place.

The technologies discussed are all more expensive than the HEU but have proved to be efficient at extracting heat from compost apart from Rogers (2006) where more energy was consumed than produced. Further refinements of the HEU technology with these high-tech/capacity approaches in mind could lead to more efficient heat extraction from the HEU. An environmental balance needs to be maintained if using more machinery, materials and energy during the process. The design of the low-tech HEU kept these parameters to a minimum where possible unlike the high-tech approaches described. This allowed it to have reduced costs for these initial composting experiments.

2.5.2 Design Specifications

In relation to the individual components comprising the HEU, experiments were conducted on the heating fluid initially. Results here showed that water absorbed heat energy at a slower rate when compared to the propylene glycol and Synthetic Hydrogen Oil. Table 2.2 shows the various thermal and fluidic properties affecting a process heat fluid.

Table 2.2: Thermal and physical properties of the three test fluids tested.

	Specific Heat Capacity (Cp) kJ/kg K	**Thermal Conductivity (K) W/mK**	**Viscosity (μ) cp**
Water	4.19	0.58	0.89
Propylene Glycol	2.5	0.34	42
Synthetic Hydrogen Oil	1.67	0.15	140-420

It is likely that it is the higher specific heat capacity of water (Anon 2008b) of 4.19 kJ/kg K rather than the higher thermal conductivity (Anon 2008c) of 0.58 W/mK which generates the slower heating characteristics. The lower Cp value for SHO explains why it loses its heat energy at the fastest rate during the experiments. In Ireland water is ubiquitous, inexpensive, non toxic substance, with a low viscosity of 0.89 centipoises (Anon 2008d). This low viscosity will reduce pumping energy for the HEU. Therefore water will be used in the final design of the HEU. However antifreeze must also be added to prevent frost damage.

The glycol water ratio experiments showed that there was no significant difference between the various ratios in the rate at which heat energy was absorbed or released.

However with the 10% glycol:water solidifying during the freezer experiment a glycol level above this is required to prevent frost damage. The addition of the 15 % propylene glycol will prevent frost damage and does not increase costs significantly. Its lower specific heat capacity may allow the heat absorption rate to increase although its higher viscosity will increase pumping energy slightly also. It is therefore recommended that to keep costs and pumping energy low that a water glycol ratio of 85:15% is ideal for this type of heat exchange unit.

A selection of pipe materials were investigated including qualpex, copper, hydrodare, and PVC with qualpex giving favourable results for heat absorption and utility. Copper absorbed heat energy at the fastest rate, with qualpex faster than PVC. Qualpex retained heat energy for longer periods, which could be an advantage in the design by allowing heat energy release more slowly. There was also significant difference in the rates at which water within copper, PVC, hydrodare and qualpex absorbed heat energy. Water within the three plastics pipes absorbed energy at slightly faster rates. This may have been due the slightly smaller internal diameter of the plastic pipes allowing a greater surface area proportionately to the copper, touch the liquid and transfer greater energy quantities to the water. Although there was significant differences in absorption rates within the pipe materials themselves and also during experiments on the water contained within the pipes it is the strength and flexibility of the qualpex which give it the overall advantage over copper, PVC and hydrodare piping. These qualities are essential when dealing with movement of the compost and the HEU and for enduring + 70 °C compost. This extra strength gives it the advantage over hydrodare piping which is softer and cheaper by a third. For these reasons Qualpex piping was chosen for the final design mainly for its strength and flexibility over copper, PVC and hydrodare.

The first insulation experiment proved that the addition of insulation to the HEU increased thermal efficiency. There was a 75% increase in internal HEU temperature with the addition of the polyurethane insulation and a 40% improvement in temperature from the outlet pipe within the insulated trough. The second experiment showed that it was the spray on polyurethane foam which was a significantly more efficient insulator when compared to the bubble wrap. A HEU temperature of 9% higher was recorded by using the polyurethane insulation and an outlet water temperature of 11% higher than the bubble wrap insulation. The U-value of the 50mm polyurethane insulation was 0.29 W/m^2K as compared to 0.38 W/m^2K for the bubble polythene insulation allowing the polyurethane insulated HEU to retain more of the thermal energy input from the electrical heater. Consideration was given to the durability of the insulation also along with U-values. The HEU has to be moved and emptied and the spray on foam was stronger than bubble wrap. It is the improved strength and lower U–value which makes the spray on polyurethane foam the best choice for insulating the unit.

2.5.3 Design Optimisation

Central to the design of the HEU were environmental considerations. The HEU uses materials produced in Ireland for its manufacture such as the polyurethane spray on insulation, Kingspan insulation and the qualpex piping. The 2046 litre trough itself is manufactured with recycled plastic within its matrix by a local company. They are readily available with no tooling requirements to act as a basic core unit for compost heat extraction. This is an advantage in environmental and economic terms for this technology where local industry is supported and carbon emitting transport costs are kept to a minimum. The machinery used is kept to a minimum with only one small pump needed. This uses very small amounts of energy compared to some of the 'High-Tech' designs described, which use more complex machinery. Keeping technology to a minimum means maintenance costs are reduced, failures are minimised and also enables unskilled people to utilise and develop this technology. Thus it is a low maintenance easy to operate technology. Over consumption of materials such as precious metals are minimised with the reduced complexity in the design employed in the HEU.

In logistical terms the changeover of the compost and in particular the emptying presented difficulties. Turning the unit on its side with the aid of a tractor was not ideal and lead to some damage of the polyurethane insulation surrounding the unit. A cube shape may be preferable where one side could be lowered to empty the compost. This would interfere with the looped piped system employed in the design however. A retractable floor would allow the compost to be emptied without interfering with the piping system. A pulley system, hydraulic or electrical may be needed to achieve this. Damage to the insulation could be minimised if it was contained within the walls of a double layered holding tank. This could be plastic or a light gauge of metal. Any metal used would increase the weight which is undesirable as moving the unit with the tractor over soft ground such as grass leads to damage. Automation of the mixing of the compost would save time and could increase the thermal efficiency and lifespan of the compost (Fitzgerald, Pers. Comm.). Difficulties with this include increased energy demands and weight. The dense nature of the organic matter used in the HEU would mean a particularly strong device would be needed, leading to the potential use of a heavy frame to hold the device and increased energy use. Even the mixing of a liquid medium such as slurry would require such a set up to mix and aerate successfully. This would increase costs and the complexity significantly and the potential for mechanical breakdown. The larger the volume of organic matter the higher potential energy for heat extraction possible (Fitzgerald, Pers. Comm.). In fact in larger compost facilities there is need for constant mixing to keep temperatures below 70 °C. The only realistic way to increase volume and keep costs down is to have no container and some piped system that could extract energy from the hot compost but be retractable in a way that uses minimal energy.

Chapter 3

Compost heat in horticulture and a performance comparison with conventional and renewable energy sources

3.1 Abstract

A compost heat extraction unit (HEU) was designed to utilise waste heat from decaying organic matter for heating horticultural polytunnels between January and March 2008 and again in November 2008. This heat source was compared to a conventional fan driven electric heater and a renewable energy source (solar panels). Plants were cultivated within the polytunnels to act as performance indicators. Power consumption was monitored to assess the energy used and the cost associated with it. The compost HEU contributed to a 2-3°C rise above the control tunnel although the electrical heater performed better maintaining the polytunnel at the required temperature. The solar panel failed to transfer heat to the polytunnel during the test period. The costs and power consumed by the electrical unit exceeded that of the solar and compost HEU significantly however. Compost heated water was used within 'Roll n Grow' heat mats during a second heating and plant growth experiment using four crops including Radish, Cabbage, Spinach and Lettuce. The plants that were aided by the heating mats had more successful growth patterns than those in the control polytunnel.

3.2 Introduction

Energy security and adverse environmental change are two of the most important topics being discussed at present. A wider appreciation of these issues has arisen in the global community in recent years. One major contributing factor to the current global economic destabilisation was the large increase in energy prices which preceded it where oil rose to $150 a barrel. Traditional fossil fuel energy sources including oil are finite and are having a damaging effect on economic progress, the environment and human life and alternatives are required (Akella *et al.,* 2009). Peak oil is the phenomenon when half the global oil reserves have been extracted and would lead to large price increases and is likely to have a negative impact on western economies in the future (Hanlon and McCartney, 2008). The decrease in oil supply will have a dramatic impact on food production worldwide. The transportation and production of food is heavily dependent on fossil fuels and therefore volatile to changes in its availability.

Renewable energy has the potential to alleviate some of the pressure from rising energy demands. It contributes between 15 - 20% of the global energy supply with biomass accounting for two thirds (Omer, 2008a). (This figure contains data on subsistence farming biomass use unlike the IEA energy statistics which have biomass at 4.4% (IEA, 2008). The direct combustion of biomass, some of which is unsustainable is still the most common type of biomass utilisation and is particularly high in developing countries (Omer, 2008b). Recent trends in the research of energy from biomass include direct combustion, production of charcoal, production of liquid fuels such as ethanol, thermo chemical conversion for heat and electricity and anaerobic digestion (Omer, 2008b). It is of interest to note however that in this review of current biomass energy research aerobic digestion (composting) is not mentioned. It has been noted that aerobic digestion is potentially a more efficient technology than anaerobic digestion at dealing with organic wastes such as food (Winship, 2008). According to de Bertoldi (2008) the EU produces more than three billion tons of organic residues. By composting this as opposed to land filling or incineration, it is argued that CO_2 and methane emissions can be reduced and the nutrients and organic matter can be returned to soils which are being degraded through modern intensive agriculture.

Current research in the field of heat extraction from compost includes a Canadian project at the Royal Military College CFB Trenton which used two large metal in-vessel composters with 1587kg/day capacity (Rogers, 2006). Rigid pipes were pushed into the compost chamber and water flows through extracting heat. Outflow water temperatures of 49°C were recorded using the technology. An improvement in efficiency using Isobars thermosyphon technology was suggested after a low coefficient of performance (COP) resulted from trials. A large scale commercial compost thermal extraction facility has been developed recently in Vermont, USA by a Canadian company Agrilab Technologies Inc. (Tucker, 2006). On the 2000 herd cattle farm a large composting barn was built in which windrows of compost were created. Isobar heat pipes were placed adjacent to the windrows and by drawing air through the compost onto the heat pipes 843 kWh/day of thermal energy was extracted from four 150-200 tonnes windrows. The energy was used to heat a reservoir of water to 55°C. Winship *et al.,* (2008) attempt to elucidate the viability of aerobic digestion and to challenge the view that anaerobic digestion is the best available technology for managing organic waste. A 'Combined Heat and Composting' container was developed, drawing heat energy through an evaporator of a heat-pump sub system. Ten 'aergestor' containers each holding 15 tonnes of composting matter can generate 1320 kWh/day making it the most efficient of the technologies reviewed. These 3 approaches represent the more high-tech/cost end solutions to aerobic decomposition of organic waste.

Generating or using the heat of decomposition using basic low-tech techniques has been practised for over 400 hundred years in Europe. These are characterised by their low cost and maintenance, simplicity of operation and reliability. The hotbed method can be traced back to the Parisian market gardens of the 1600s (Fulford, 1983). Heat and gases were supplied from decomposing horse manure underneath the crops for winter cultivation and the extension of the growing season. The arrival of the automobile lead to the reduction of horses and therefore the fuel supply for the gardens. It was the straw bale method which then became popular. Dutch and English growers saturated the nutrient rich bales and used the heat and gaseous emissions to grow vegetables into the winter season (Loughton, 1977). The practice declined once the price of straw rose during the 1970s. It was Jean Pain who advanced the practice from his home in France during the 1960s

(Pain, 1980). Brushwood was gathered from a local forest to create a 50 tonne compost heap. Bacterial activity in the pile would produce temperatures of 60 °C in the pile and heat was extracted by running water through the heap in plastic pipes and this supplied all domestic hot water and heating needs for the household from this source. Hot water was produced at 60°C from a feed at 10 °C at a rate of four litres per minute for six months while maintaining the process. The process became anaerobic at a certain stage and methane was also extracted to power farm machinery.

Research has also been conducted on heat extraction from liquid phase organic waste streams also. Using a 21.6 kW heat pump, 6.5 kWh of heat energy was recovered from an aerated slurry lagoon by Hughes (1984). Throughout the winter and summer the slurry maintains a temperature of 35°C with a heat pump increasing this to 55°C for the radiator system. An estimate of 3-4 years payback time for the heat pump was calculated. Heat recovery has been achieved from pig slurry within an aerobic treatment system (Svoboda and Evans, 1987) while removing odour and BOD. The average metabolic heat recovery by using a heat exchanger and aerator from the system was 149 kWh/day. Svoboda and Fallowfield (1989) developed the system further using the energy for space heating of the weaner house and in algal raceway ponds. A stainless steel heat exchanger connected to a 12 kW heat pump was used to transfer heat with a maximum water temperature of 55°C.

Research into aerobic decomposition of organic waste has also been combined with renewable heating of polytunnels to assist the protected crop industry. At the New Alchemy Institute heat and CO_2 were distributed under the plants directly within polytunnels from hot compost through a fan driven ducting system (Fulford, 1986). The design comprised of a series of insulated compartments running along the side of the greenhouse which were filled with manure based compost. Of this type of organic matter $3.8m^3$ was used every five days. Soil temperatures were higher than control greenhouses and averaged 25.5 °C for a soil bed above the compost chamber and 16 °C for the ground soil. Greenhouse air temperatures averaged 16 °C above the outside air temperature by using this system. Seki and Komori (1995) attempted to extract heat from compost and use it for greenhouse heating also. This was carried out using a cylindrical compost chamber, flexible pipe and a condenser-type heat exchanger to extract heat energy. 0.17

kWh/day of heat was recovered which was 22% of heat energy within the compost. Thermal energy from aerated cattle manure and rice hull compost was used to elevate the underground temperature of soil adjacent to the composting piles within greenhouses in Korea (Hong *et al.*, 1997). Underground temperature was maintained through the release of direct heat from the compost at a range of 17.5°C to 32.5°C within the greenhouse compared to 6°C to 11.9°C for outside underground temperature.

Changes in food production and transport are not only essential but are inevitable during times when oil prices are increasing. Food imported into Ireland consumes oil during transport. Therefore the need to increase local food production is important to guard against such changes. The protected crop industry is an important element within the agricultural makeup and also the food supply and security of Ireland. It was estimated in 2005 to be worth €215 million including vegetables, mushrooms, and potted / nursery plants (Teagasc, 2005). Awareness of the 'food miles' issue is growing in parallel with a desire to increase local economic activity and improve social cohesion (Lobley *et al.*, 2008). Lifecycle analysis is becoming more important in the evaluation of the environmental effects of food and choosing more sustainable products and processes (Poritosh *et al.*, 2009). The protected growing industry would be vital to aid changes in Irish food production by allowing crops from warmer climates to be cultivated here, however it is essential that advances in protected crop growing are sustainable and environmentally sound. Having this in mind finding ways to reduce the carbon used in growing crops such as the heating of polytunnels is desirable. Biomass which is produced in large quantities within the state (Carton and Magette, 1999) could be harnessed by using the waste heat from its aerobic decomposition to heat polytunnels.

The availability of heat from agricultural or municipal sources could have the potential to improve the competitiveness of the horticultural industry by reducing costs and increasing production. The present study investigates the potential of the aerobic decomposition of compost as a heat source for horticulture. Two methods of heat distribution were used in conjunction with the Heat Extraction Unit including air heating by a radiator system and direct soil heating through heated 'Biotherm Roll and grow' mats. The radiator system was chosen as it is a common method of heat transmission which is readily available and easy to use. The second 'Roll n Grow' method was chosen as the product was specifically designed for heating within a horticultural setting and focuses that heat directly under the plant. The air heating methods will be compared to thermal energy sources including a solar panel representing an alternative renewable energy device, a conventional electrical fan heater, and a control without thermal addition. Plants were cultured within the tunnels to act as a performance indicator of each thermal source. During the air heated trials polytunnels were heated at night to prevent frost damage to the plants. Daytime heat was applied to the plants when the specialised growing mats were employed to assist in the photosynthetic phase. In these trials heat energy was directed at the root zone where studies have shown it can produce increased plant growth rates (Tyron and Chapin, 1983). A power consumption and coefficient of performance analysis was also completed to assist in the analysis of the HEU performance.

3.3 Materials and Methods

3.3.1 Site layout

The location of the experiments was in the organic section of Mountbellew Agricultural College, Co Galway. A 40 x 10m section of the field was ploughed initially and the polytunnels were setup alongside the shelterbelt of *Leylandi* trees to the south. Figure 3.1 shows the site layout of the five (numbering 1-5) specifically built 6 x 4.5m single layer polytunnels that were constructed 1m apart alongside a garden shed. (2.7 m wide, 3.7 m long, 2.7 m high at apex). The U-value of the polytunnels was 10 W/m^{2}K. The shed roof was aligned to the south for the solar panel setup.

Figure 3.1: Site layout of the testing facility including polytunnels and garden shed.

3.3.2 Temperature recording

Five Tinytag Ultra 2 (TGU-4017) temperature data loggers which are accurate to ±0.01°C were programmed to record temperatures (°C) at 5 minute intervals. A data logger was placed 1.5m above the ground in 4 of the polytunnels. A fifth was placed in an adjacent sheltered, shaded position 1.5m above ground level to record outdoor ambient temperature. Two Global Water (GL500 S-2-1) temperature data loggers which are accurate to ±0.1°C were programmed to record the water temperature (°C) within the piping of the compost Heat Extraction Unit (HEU). The first data logger was connected to the inlet pipe and the second on the outlet pipe and both were set to record at two minute intervals.

3.3.3 Heating systems setup

3.3.3.1 Polytunnel 1: Compost heated

3.3.3.1.1 Air Heating

A heat distribution system was set up inside polytunnel 1 to connect to the compost Heat Extraction Unit which was placed outside at the rear of the polytunnel (Figure 3.2). The heating system within the polytunnel comprised of a flow and return pipe, a radiator, a header tank and 2 temperature data loggers. Figure 3.3 shows an overview of the heating system in which experimental plant replicates can also be seen. A standard 45 litre plastic header tank (filling tank) was placed inside an insulated (25mm Plywood and 50mm Styrofoam) box (0.4 m high, 0.4 m wide and 0.6 m long). 25 mm qualpex piping was fitted onto the end of the tank 25mm from the bottom with a brass tank connecter and a Groundfos 'UPS 15-50 130' flow pump was connected to this pipe. Figure 3.4 shows the system where the two Global Water data loggers can be seen, alongside the pump, inlet and outlet pipes and the header tank. A 25 mm brass gate valve connected the outlet pipe of the header tank to the inlet pipe of the HEU.

A second brass gate valve connects the outlet pipe of the HEU leading to the heat exchanger. Figure 3.5 shows these gate values and the thermal insulation which is fitted onto all pipes outside the HEU. The valves can be closed to retain the heating fluid within the pipes when the HEU is being moved. The outlet pipe of the HEU was reduced to 12.7mm qualpex piping before connecting into the double panel radiator (Myson Premier HE 300 x 1600mm). The 12.7 mm qualpex return pipe from the radiator leads from the lock shield valve at the radiator end to the header tank completing the open looped system. The heating system was filled with 25 litres of water and Propylene glycol antifreeze (15 % of total) (2.4.2 Water / Propylene Glycol ratios).

Figure 3.2: The HEU setup outside the polytunnel.

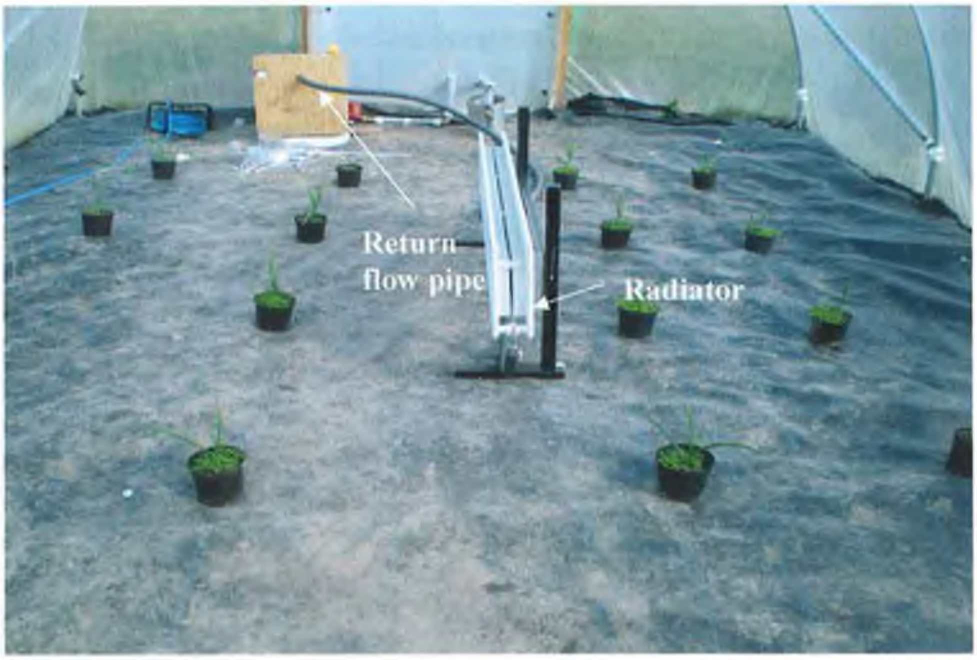

Figure 3.3: Heat distribution system within the compost heated polytunnel

Figure 3.5: Brass gate valves connecting the inlet and outlet pipes of the HEU to the heat distribution system.

Locally sourced organic matter was mixed to give a carbon nitrogen ratio of 30:1 and a moisture level of 60% (Fitzgerald, 2009) for the experiment. The main constituents of this were 300 Kgs of horse manure, 15 Kgs of sawdust and 120 Kgs of woodchip. The Heat Extraction Unit as described in section 2.4.5 was placed on a pallet, filled with the organic mix up to the capacity of the vessel and transported to the rear end of the polytunnel using a tractor. The inlet and outlet pipes of the HEU were connected to the corresponding pipes of the heat distribution system within the polytunnel (Figure 3.5) and the brass gate valves were opened fully. The pump was set on the highest flow rate and when continuous flow was observed the system was fully operational. Thermal energy was extracted by activating the system when internal compost temperature was above 60 °C in order to reduce pathogen numbers to produce saleable compost. Activation (7 pm –

8 am) of the Heat Extraction Unit at night was controlled with a 'Merlin Gerin (15720)' electrical timer.

3.3.3.1.2 Roll 'n' Grow Heating Mats

The heating system for this plant growth experiment was identical to that described in section 3.3.3.1.1 except the radiator was replaced with special EPDM rubber growing mats. 15 m^2 of this 'Biotherm Microclimate Roll n Grow Tubing' was purchased from Truleaf Technologies in California and divided into two sections of 7.5 m^2. The 5m long x 1.5 m wide mats were placed inside two polytunnels with 50mm Kinspan wall insulation underneath for frost protection (Figure 3.6). In the compost heated polytunnel the growing mat was setup to have three inlet pipes and three outlet pipes to create even heat distribution. The compost HEU outlet pipe was connected to the 3 inlet pipes of the growing mat using a 10 way manifold and the three return outlet pipes from the mat were directed to the header tank as the return flow. The control polytunnel was identical except no heating system was in place. The HEU was set to heat the 'Roll n Grow' mat for 6 hours a day from 8 a.m. to 2 p.m. over a 24 day period in November. Tinytag Ultra 2 (TGU-4017) temperature data loggers which are accurate to ±0.01°C recorded air temperature in both polytunnels during the experiment. Two Global Water (GL500 S-2-1) temperature data loggers which are accurate to ±0.1°C were programmed to record the water temperature (°C) within the piping of the compost Heat Extraction Unit (HEU).

Figure 3.6: 'Roll n Grow' heating mat setup within the polytunnel with Kingspan insulation underneath and 8 replicates of each plant.

3.3.3.2 Polytunnel 2: Electrical heated

Figure 3.7 shows the Bio Nevada 2.25 KW electric heater that was purchased from Polydome Ireland to heat polytunnel number 2. The heater was 230 V and incorporated a 2.25 kilowatt (kW) heater and a 70 watt fan. It was fitted onto a 25mm plywood backboard at 1.5m above ground level at the end of the polytunnel. The heater functioned by drawing in naturally rising warm air from the upper greenhouse. This air was heated and recirculated down towards the plant growing area through a single plastic duct system that extended along the centre of the polytunnel at ground level. It was set to regulate the temperature of the polytunnel at 10 °C during the night. Activation times (7 pm – 8 am) were set using a 'Merlin Gerin 15720' electrical timer.

Figure 3.7: Electrical heated polytunnel with Bio Nevada heater and plastic air duct

3.3.3.3 Tunnel 3: Solar Panel heated

One 20 vaccum tube solar panel (2m^2 flask type) was assembled and attached to the south facing roof of the garden shed which was adjacent to polytunnel 3 (Figure 3.8). The solar panel was connected to a 147 litre solar insulated water cylinder using 18 mm copper piping between them (Figure 3.9). The solar pump station (Wilco class F) was set up to activate the solar panel. A 'Resol Deltasol BS Plus' electronic panel within this solar station, controlled the system and gave various parameter readouts. Heating fluid (glycol antifreeze) was pumped into the system creating a pressurized loop. A pressure of two bars was set on the solar station. Four PT 1000 temperature sensors were attached to the Deltasol control panel within the solar station. The first was connected to the outlet pipe containing the heated fluid of the solar panel manifold. The second and third sensors were connected into the upper and lower parts of the hot water cylinder. The final sensor was strapped onto to pipes entering the manifold of the solar panel.

Figure 3.8: Test shed with evacuated tube solar panel attached to south facing roof.

A second non pressurized loop was assembled containing a 45 litre header tank which filled the 147 litre solar cylinder with water along with a 'Myson Premier HE 300 x 1600mm' double panel radiator in the adjacent polytunnel (Number 1). Qualpex piping (12.5mm) was used between the radiator and the cylinder with an 'UPS 15-50 130' flow pump attached. A thermostat was connected onto the top of the cylinder and was set at 30 °C so that when the internal water went above that preset temperature it would activate the pump to allow flow through the radiator in the tunnel. An expansion tank was set up alongside the cylinder to allow overflow from the heated water in the cylinder if necessary.

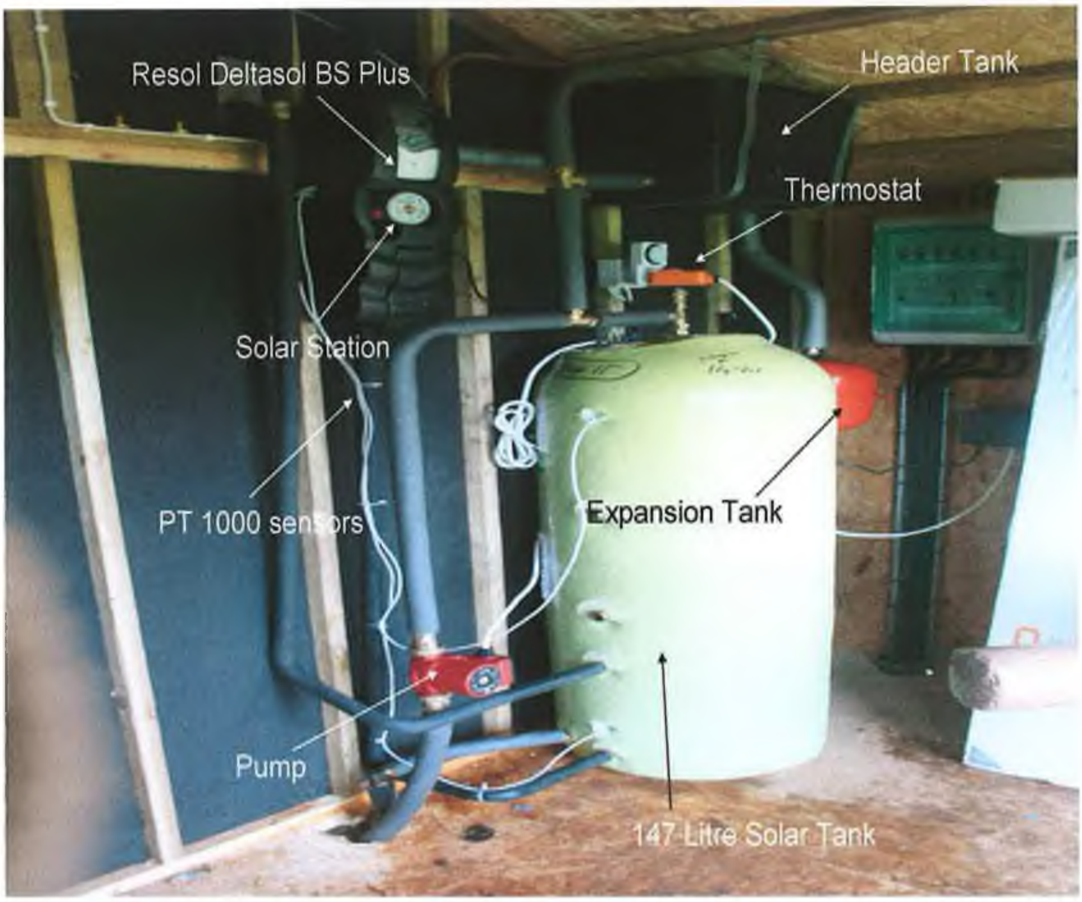

Figure 3.9: Solar Hot Water cylinder, solar station, expansion and header tanks.

3.3.3.4 Polytunnel 4: Control Polytunnel

Polytunnel number 4 was set up to be the control polytunnel and was identical to the others except no thermal heat source was applied.

3.3.4 Data recording

3.3.4.1. Power consumption analysis

Three 'Elster A100C' single phase meters with pulse output were used to collate data on energy requirements for each heat source. A meter was connected to the wall in the shed and monitored the power consumption of the solar panel which included two pumps and a 'Resol Deltasol BS Plus' monitoring panel. A second meter was connected to the 'Nevada 2.25' electrical air circulation heater within polytunnel 2. The third meter was set up to monitor the power consumption of the pump attached to the compost HEU in polytunnel 1. Meter two and three were setup with electrical timers (Merlin Gerin 15720) in specially constructed waterproof housings. Polytunnel 4 was the control polytunnel which had zero power consumption. An example of the Elster energy meters and the electrical timers is shown in Figure 3.10. The power consumption readings (kWh) were recorded 10 times over 3 weeks.

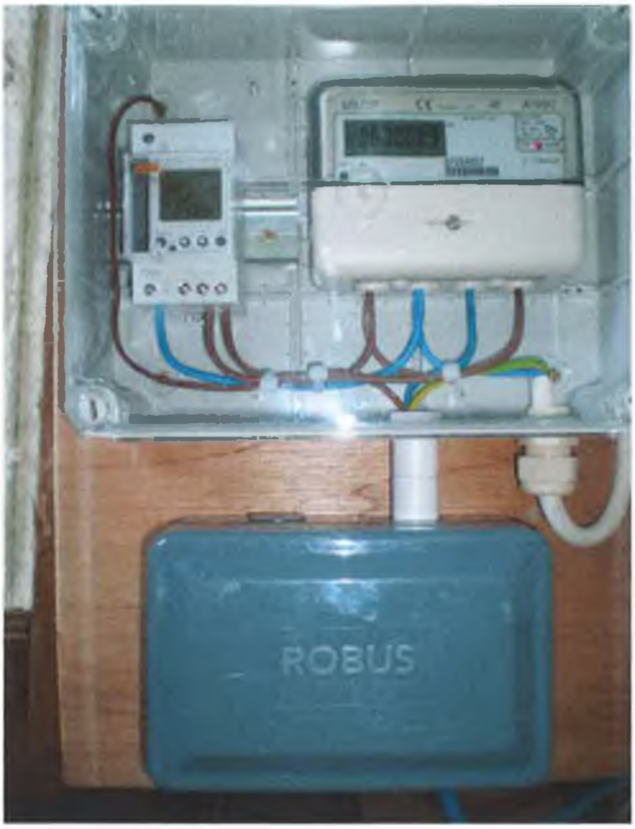

Figure 3.10: Elster A100C' single phase meter and Merlin Gerin 15720 electrical timer.

An overview of the experimental setup for the heating of polytunnels is shown in Figure 3.11. The polytunnels are numbered 1a, 1b, 2, 3, and 4. 1a is part of the air heating experiment using a radiator and polytunnel 1b is from a separate experiment when the 'Roll n Grow' mats were used to heat directly under the plants. Polytunnel 3 is the solar panel heated polytunnel, 2 is the electrical heated polytunnel and 4 is the control which had no addition of heat during either set of experiments. The data recording devices are also highlighted within the polytunnels and the compost HEU is shown placed outside the polytunnels.

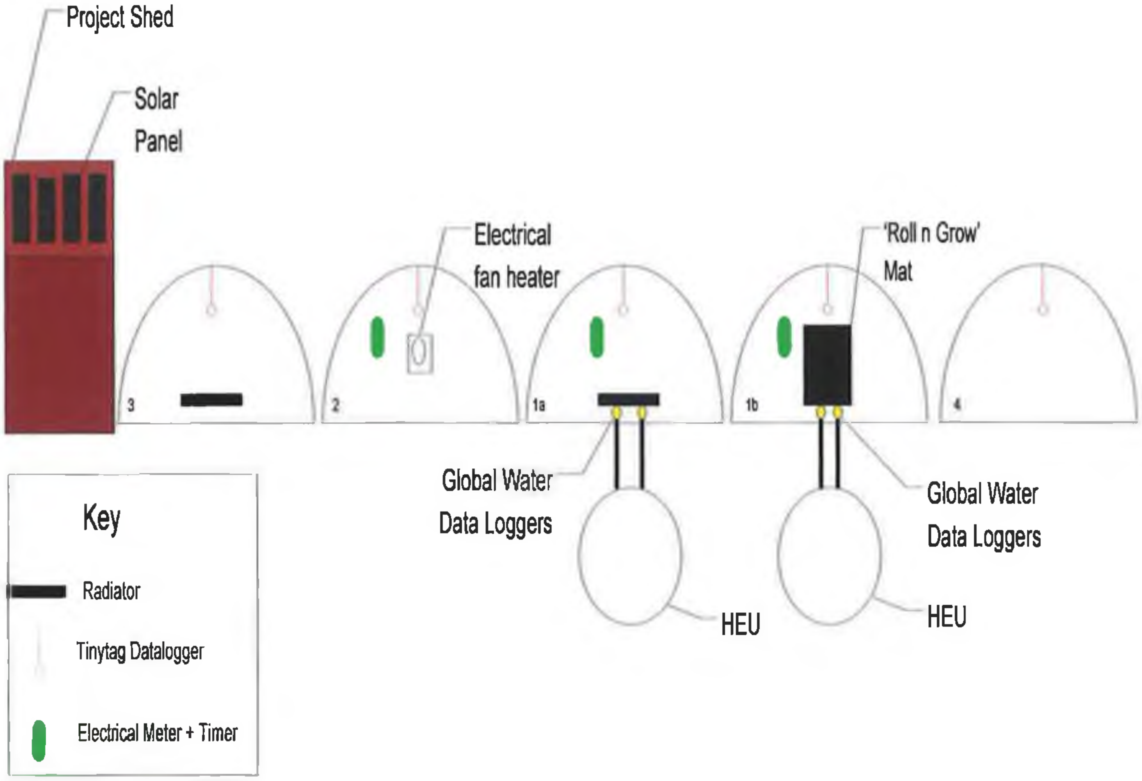

Figure 3.11: Overview of polytunnel heating experimental system including data monitors.

3.3.4.2 Plant indicator performance setup

Locally sourced winter vegetables including common garlic *(Allium sativum)* and spinach (*Spinacia oleracea* Matador variety) were used for the horticulture experiment. The plants were potted rather than sown directly in the soil to allow for movement within the polytunnel for any potential experimental adjustments and were planted on the 15th of December 2007. Organic compost and soil were used to fill 128 one litre black plastic pots in a ratio of 3:1 respectively. The garlic bulbs were divided into cloves and each clove was planted upright 25 mm into the soil mix with the upper part of the clove protruding the soil surface within 64 pots. The spinach seeds were planted 25 mm below the soil surface in 64 pots. Both sets of plants were labelled G1 to G64 (garlic) and S1 to S64 (spinach) respectively. A fully randomised block design was employed using random number tables and dividing each polytunnel into 16 squares with 2 plants, one of each in every quadrant. The position of each plant within the polytunnels was recorded. Measurements were taken of plant growth once a week. Plant height was measured from the top of each plant pot using a measuring tape. 500ml of water was added to each plant once a week throughout the experimental phase. Night time heating was employed for this experiment to help prevent frost damage to the plants.

Four plants were cultivated inside the polytunnels for the 'Roll n Grow' heating mat experiment. These included Radish (*Raphanus sativus*), Winter Cabbage (*Brassica oleracea)*, Spinach (*Spinacia oleracea)*, and Lettuce (*Latuca sativa*). Sixteen replicates of each of these plants were cultivated in 0.5 litre pots and 8 were placed in both the heated and control polytunnels. This gave a total of 32 plants in each polytunnel. Shoot length was measured from the top of the pot in each plant on a weekly basis. Soil temperature was measured using a VWR digital temperature probe on a weekly basis taking 8 pots at random. Leaf number was recorded for the Radish plant on a weekly basis. Plant mortality was also recorded and the health of the plants was monitored in terms of leaf damage and wilting using the naked eye as a measure of quality.

3.3.5 Data analysis

A Cochran's test for equal variance was used to test for homogeneity within the plant indicator and the heat performance comparison experiments. Minitab 15 was used to complete statistical analysis on the plant indicator data and the heat performance comparison data. A Moods median test was used to test temperature differences between polytunnels of the first compost heated trial versus the control. A Kruskal-Wallis Test was carried out on garlic shoot length growth rate data to test for significant difference in the medians of the plant from each polytunnel. Shoot length data from the Roll 'n' Grow heat matt 'Lettuce' plant indicator experiment was Log transformed to allow analysis of variance in Minitab.

Energy generation within the compost was calculated using compost temperature data over the month long trial. (Fitzgerald, 2009). The coefficient of performance of the HEU was also calculated during the experimental trial period. It is the ratio of the energy extracted from the compost over the pumping energy used to distribute the heated water. The energy extracted was calculated using the equation $Q = mCp(Tout-Tin)$ where Q is heat energy in Watts, m is mass flow rate, Cp is the specific heat capacity of the water glycol mix, and Tout-Tin is the difference in temperature between the inlet and outlet pipes.

3.4 Results

3.4.1 Compost HEU thermal flow performance

Results of the outlet pipe temperatures for a 20 day trial period are shown in Figure 3.12 and 3.13. These show the useful energy in terms of heated water generated by the HEU. A series of peaks and troughs were observed daily when the HEU was operational between 7 pm and 8 am for night time heating and when it was deactivated between 8am and 7pm. The shaded areas on both graphs are to highlight the nightly compost heated water temperature pattern exiting the outlet pipe before it enters the radiator. It is focused on the gradual decreasing temperature slope lasting thirteen hours when the HEU is on. The initial higher peak preceding this only lasts on average five minutes as cooler water in the header tanks mixes with it. Focusing on one 24 hour period for the outlet pipe water temperature on day 4 for example it is divided into two periods on the graph, A and B. During the initial period A the HEU was activated and peak heated water of 48 °C is detected which drops after 5 minutes to 38 °C at point C. There is a gradual decline over 13 hours until the HEU is deactivated at point D. Period B follows and water temperature drops to 5 °C (point E). There is a second peak of 25 °C following this at point F, which results from daytime natural solar radiation heating the water in the pipes. The temperature then decreases when solar radiation decreases and we return to the point where the HEU is activated again the following evening.

Figure 3.12 shows on day one a peak temperature of 60.3 °C was recorded from the HEU outlet immediately after activation when the initial temperature was 14.1 °C. The water exiting the HEU was 46.2 °C above the water in the pipes just outside the HEU at this point. This outlet water temperature was reduced to 50 °C within 10 minutes and then cooled to 40 °C within 3 hours. The HEU was deactivated after 13 hours and the water temperature had decreased to 31 °C at this point. The outlet water temperature drops to 11.1 °C upon deactivation of the system. This general pattern was repeated nightly except lower temperatures were recorded. The outlet water temperatures decreased during the first 5 days (0-120 hours) of operation but they increased slightly between days 6 to 9 (144-192 hours). During the heat extraction phase the water temperature for the majority of the time (6 – 9 hours a night) was between 40 and 30 °C for the first 10 nights. During the following 10 nights this had decreased and the water temperature was at between 25 – 30 °C (shaded area) for the majority of the night before the HEU was deactivated (Figure 3.13).

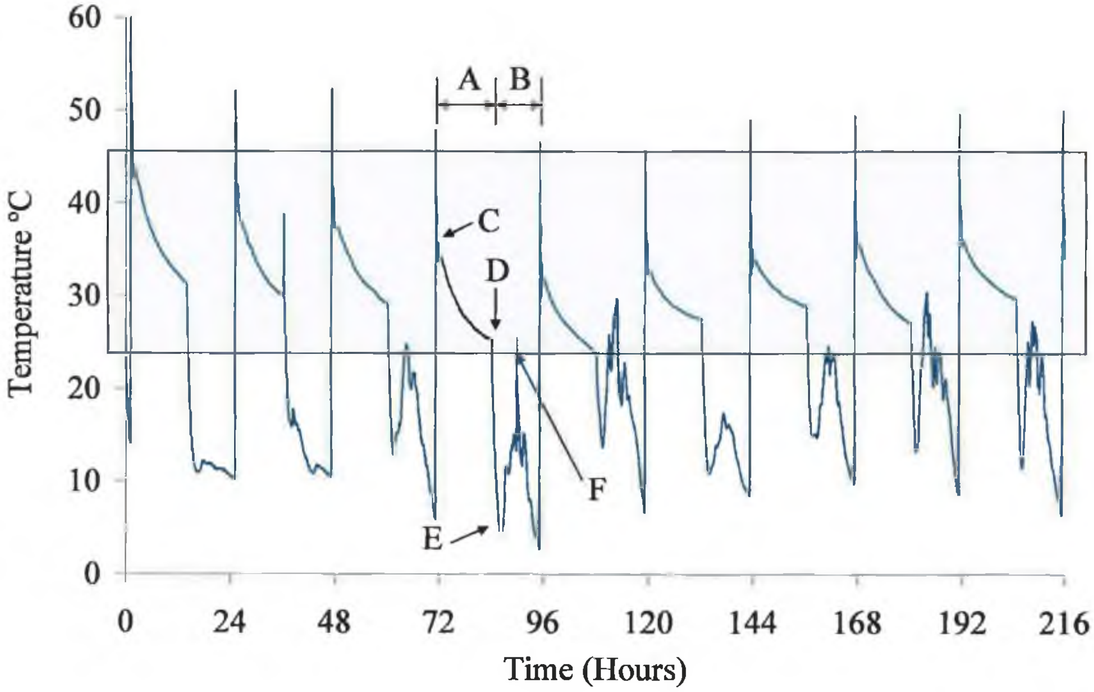

Figure 3.12: Compost HEU pipe outlet temperature profile for 10 days from 28/02/08 to 8/03/08.

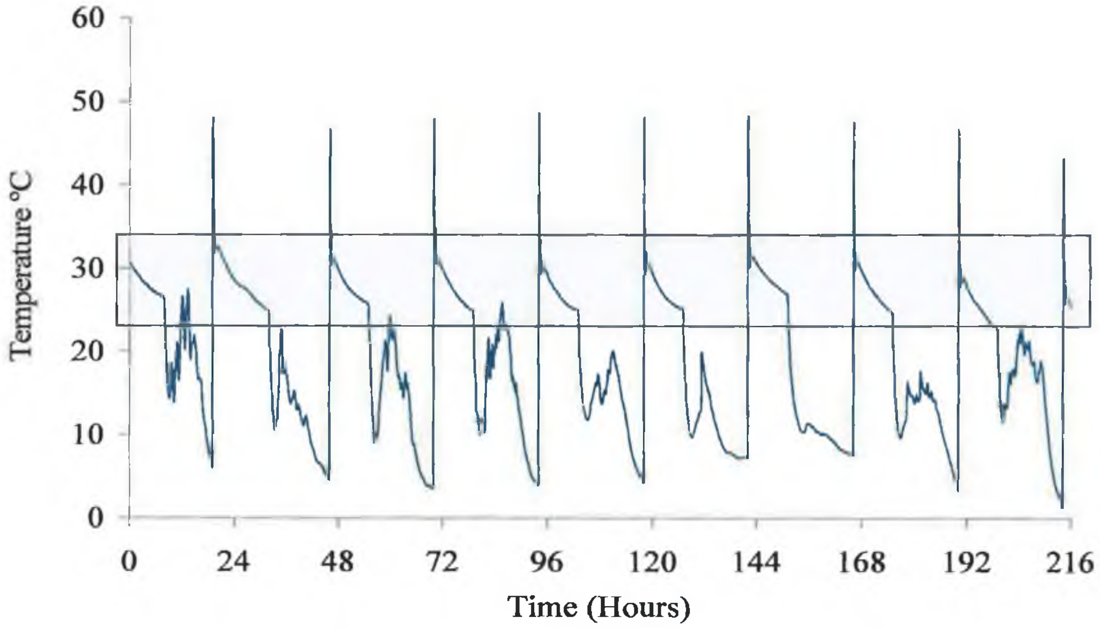

Figure 3.13: Compost HEU outlet temperature profile for 10 days from 8/02/08 to 18/03/08.

3.4.2 Energy generated, extracted and Coefficient of performance (COP) of the HEU.

Figure 3.14 shows the mean temperature of the compost over the course of the trial period, which was (Fitzgerald, 2009) (Temperatures were taken on a daily basis using a digital thermometer at 16 locations within the compost). Compost temperature increased to 65 °C after 4 days from a starting point of 15°C before decreasing gradually over the 32 days to a mean of 35°C. The energy within the compost at each time interval was calculated and is plotted in Figure 3.15 along with the cumulative heat energy extracted. The energy content of the compost heap increased from 279 MJ to a peak of 326 MJ on day 4. Heat energy is extracted on this day for the first time and the compost energy also begins to decline on this day. The compost energy decreased to a low of 298 MJ during the trial period. Cumulative energy increased to 274 MJ after 28 days of heat extraction. The coefficient of performance (COP) of the HEU during this trial period is shown on Figure 3.16. During the first four days the HEU was inactive and a COP of zero was calculated. A high COP was recorded throughout the trial period with a peak on day five of 12.5. This is reduced to a low of 3.7 on day 28.

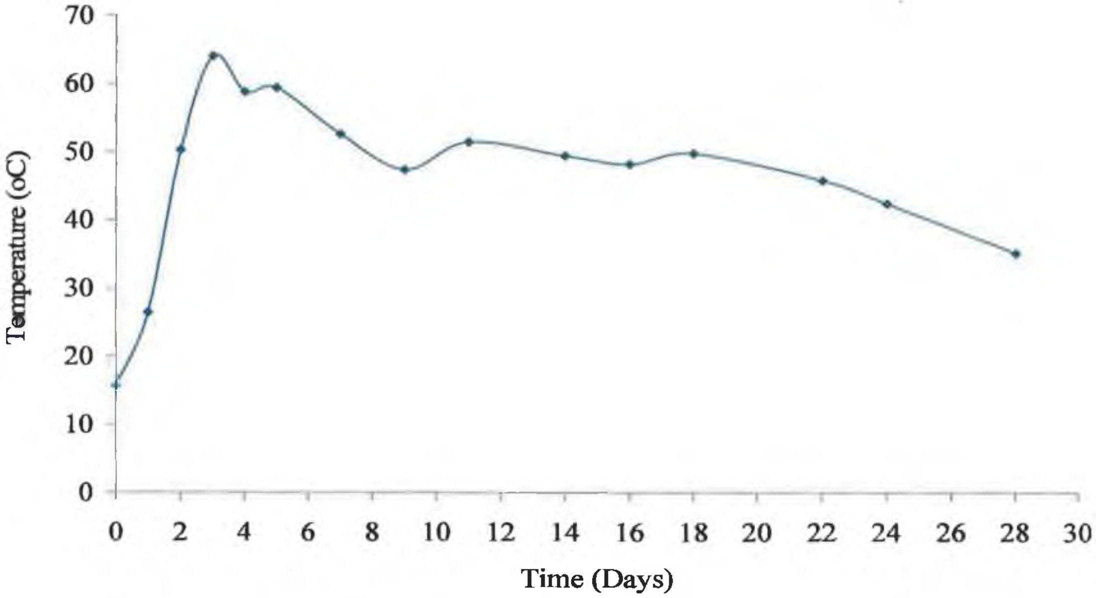

Figure 3.14: Mean compost temperature profile from 25/2/08 to 28/3/08.

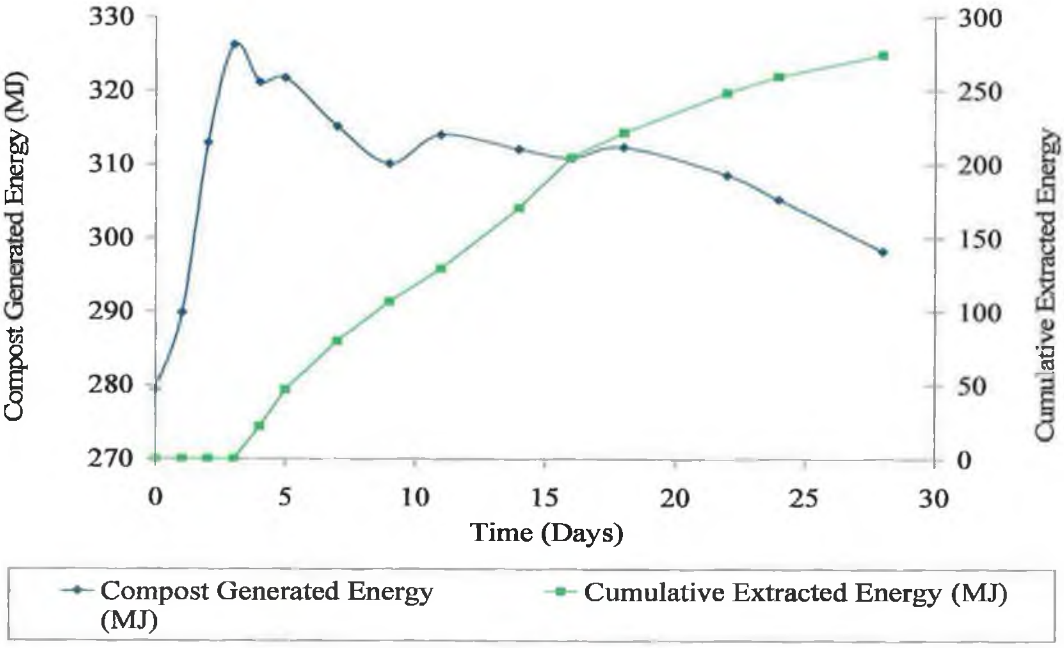

Figure 3.15: Compost generated energy and cumulative heat energy extracted during the trial period 25/2/08 to 28/3/08.

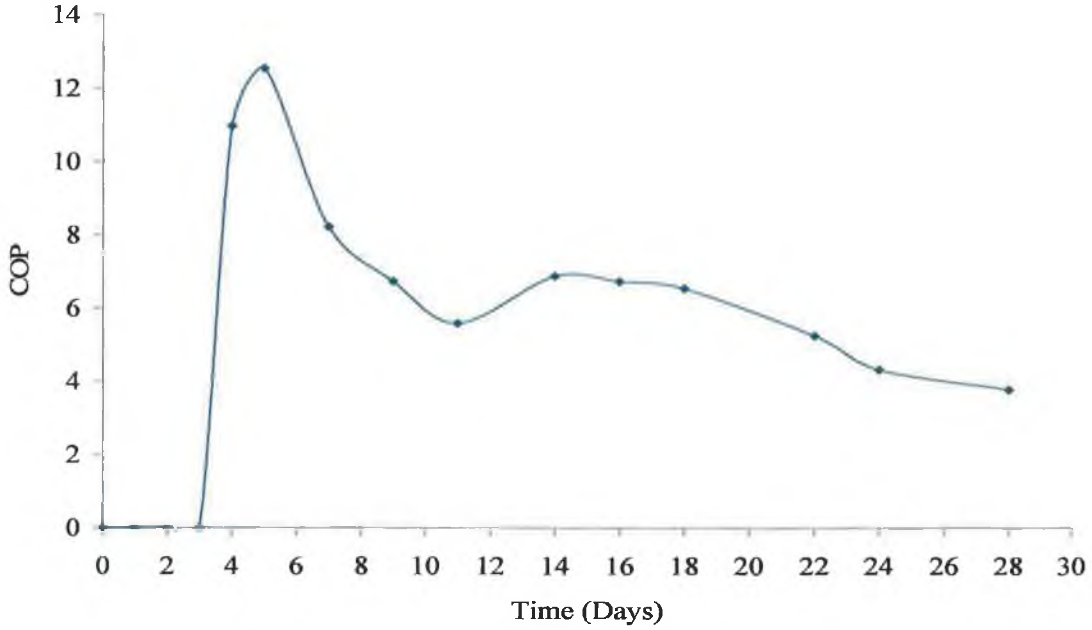

Figure 3.16: Coefficient of performance of the HEU over the 25/2/08 to 28/3/08 trial period.

3.4.2 Compost heating distribution performance analysis

Figure 3.17 shows the temperature profiles from the compost heated and control polytunnels. Results are shown for a period of eleven days only to allow ease of viewing and analysis of the data and due to diminishing heat output of the compost after this period. The majority of the useful heat available to the technology in this experiment occurs during this period so results are focused here. The compost heated polytunnel showed a temperature profile similar to the control polytunnel, however variations can be seen where the control temperatures dropped below the compost heated polytunnel during the nightly heating phases. On the night of the 29th/02 the compost heated polytunnel was 3°C above the control which was at 2.7°C. Figure 3.18 show the temperature difference between the compost heated and control polytunnels. It shows that over the ten nights following, the compost heated polytunnel was maintained at temperatures between 1.5 and 3°C above the control. Solar radiation increases temperature in the control polytunnel above (+1°C) on 4 occasions giving rise to a negative ΔT on the 28/02, 04/03, 07/03 and 08/03. Figure 3.19 shows that outdoor night temperatures dropped to 2°C on the 3rd and 4th of March. Ground level outdoor temperatures were -3°C on these nights at the closest weather station located 14 Km away in Ballygar (Met Eireann, 2008). On these nights the compost heated polytunnel was maintained above freezing conditions at 3°C when the control tunnel was at -0.5°C. There was a significant difference in temperatures between the control and compost heated polytunnels during the heating period each night (Moods Median, $P < 0.000$).

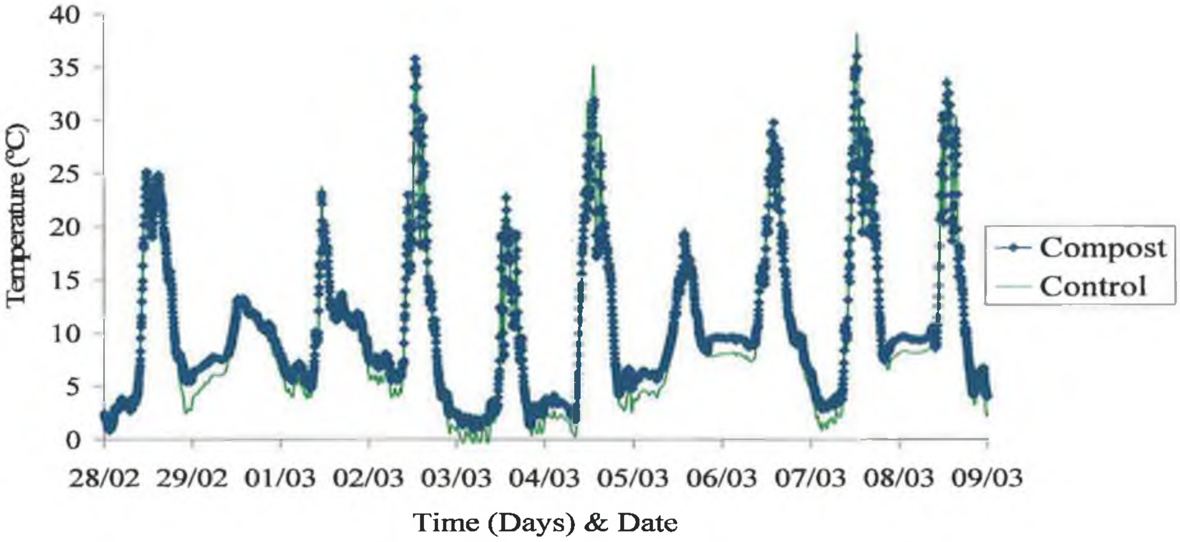

Figure 3.17: Temperature profiles of compost heated and control polytunnels over a 10 day period in February / March 2008.

Figure 3.20 shows the temperature comparison of the electrical heated and compost heated polytunnels. The electrical heater maintained night temperatures above the compost heated polytunnel at close to 10°C. This was the preset temperature at which it was set to. Figure 3.21 show the difference in temperature (ΔT) over this period between the polytunnels. The electric heated polytunnel was kept at an average of 4 degrees above the compost heated polytunnel during night heating with a high of 6.8°C recorded on the 03/08. On the 6th and 8th of March the opposite is the case when the compost heated tunnel was 1.3°C above that of the electrical polytunnel for a 9 hour duration.

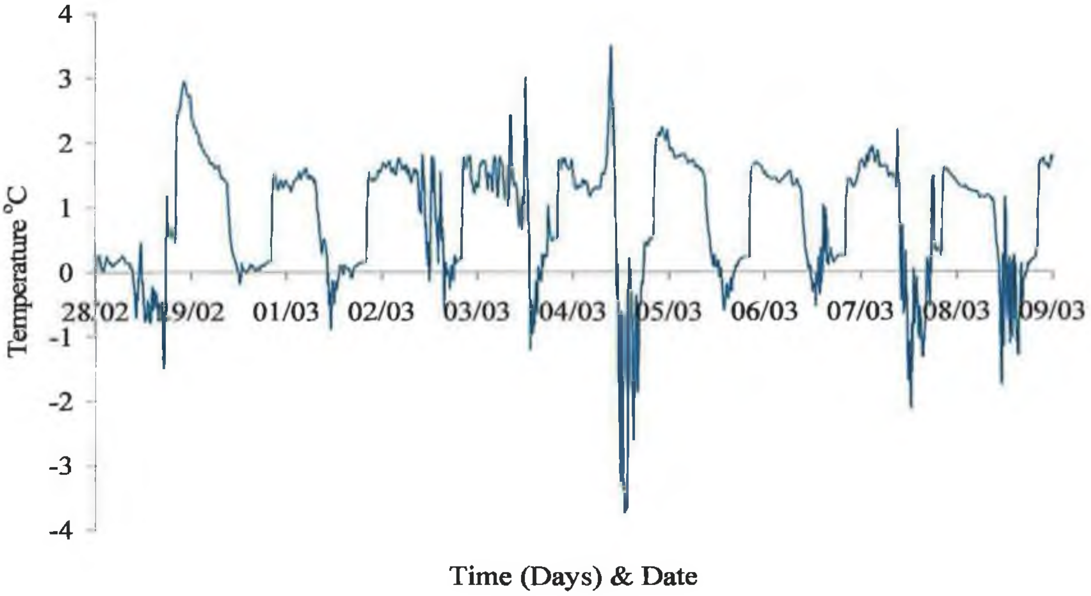

Figure 3.18: Temperature difference (ΔT) between compost heated and control polytunnels over a 10 day period in February / March 2008.

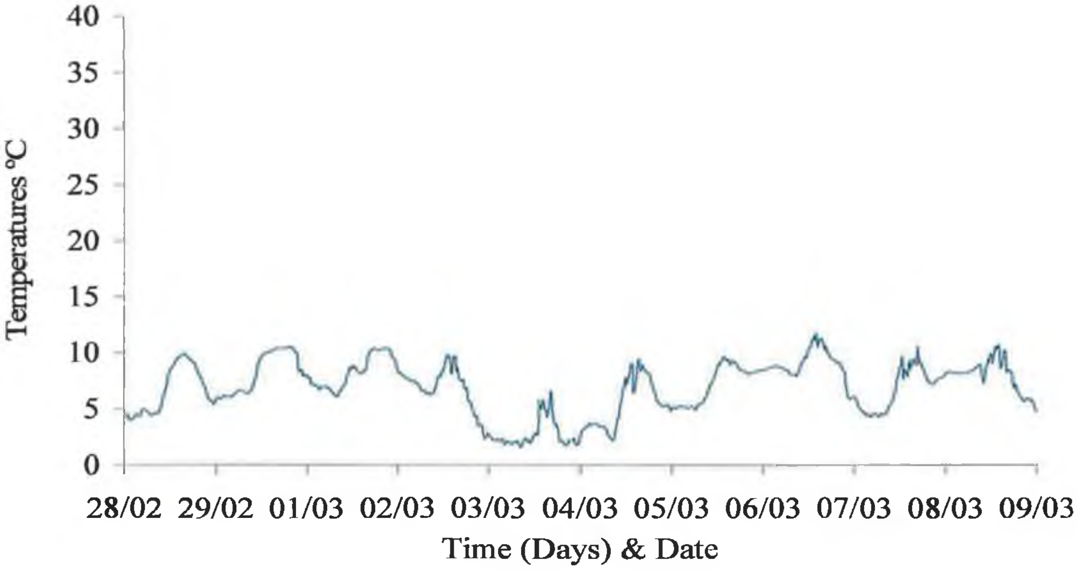

Figure 3.19: Outdoor Temperature profile over a 10 day period in February / March 2008.

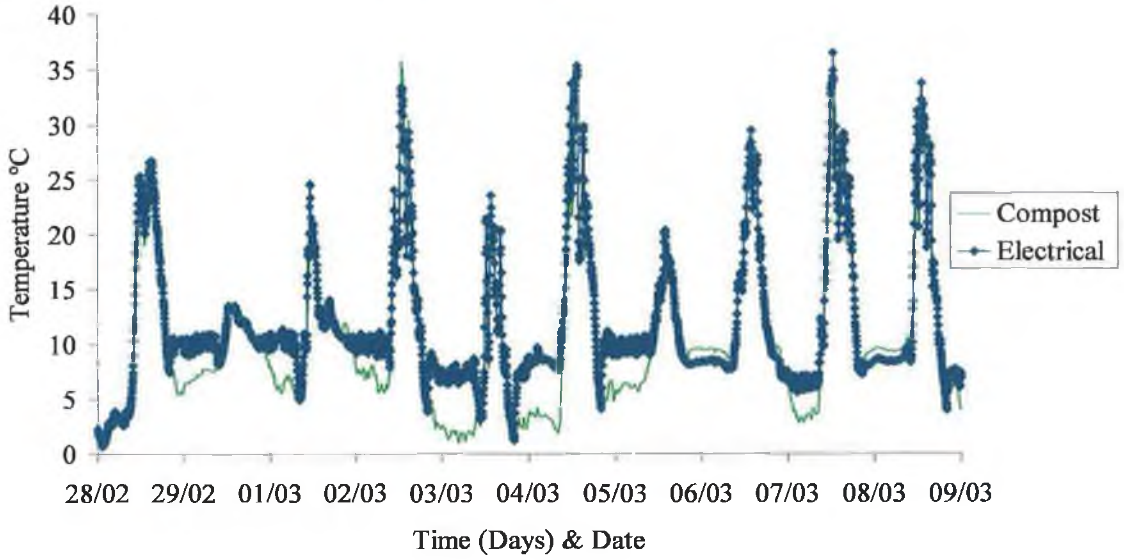

Figure 3.20: Temperature profile of the electrical heated and compost heated polytunnels over a 10 day period in February / March 2008.

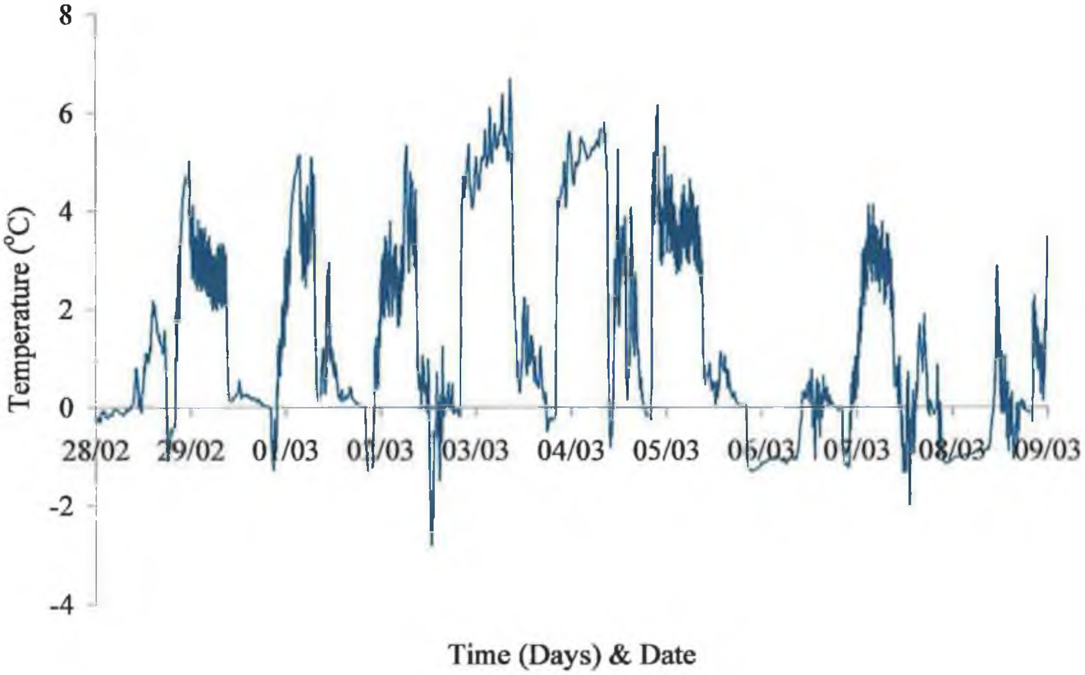

Figure 3.21: Temperature difference (ΔT) between electrical and compost heated polytunnels over a 10 day period in February / March 2008.

3.4.3 Conventional and renewable heating system performance analysis

The daily temperature results for the electrical heated and control polytunnels are shown in Figure 3.22. The electrical heater maintained the polytunnel at close to 10 °C each night while the control polytunnel varied and was similar to outdoor temperatures. The electrical heater failed to maintain night temperatures at 10°C on the 3rd and 4th of March decreasing to 8°C when outdoor temperatures dropped to 2°C and the control polytunnel was below freezing on the 3rd. On the nights of 6th and 8th very similar temperature results were recorded in both polytunnels. Figure 3.23 shows the difference in temperature (ΔT) between the electrical and control polytunnels. The heater has increased temperatures between 6-8°C above the control tunnel on most nights except on the 6th and 8th when outdoor night temperatures are at their highest of 8°C (Figure 18).

The solar heated polytunnel and control polytunnel temperatures were also compared on Figure 3.24. No additional heat was added to polytunnel 3 by the solar panel during the experimental period and therefore its temperature profile followed that of the control polytunnel. Data from the solar panel data loggers is plotted on Figure 3.25. Included are the upper and lower daily temperatures within the solar panel manifold along with mean solar hot water cylinder temperature over a 37 day period February 16th / March 25th. There were daily increases and decreases in the manifold solar high and solar low temperature data as the daily solar flux hitting the solar panel changes. A gradual rise in the mean manifold temperature from 12.95 ± 2.2 °C to 21 ± 3.1 °C was observed during this period. There was also a corresponding rise in mean solar hot water cylinder temperature during this period from 15.9 ± 2.0 °C to 20.9 ± 2.7 °C.

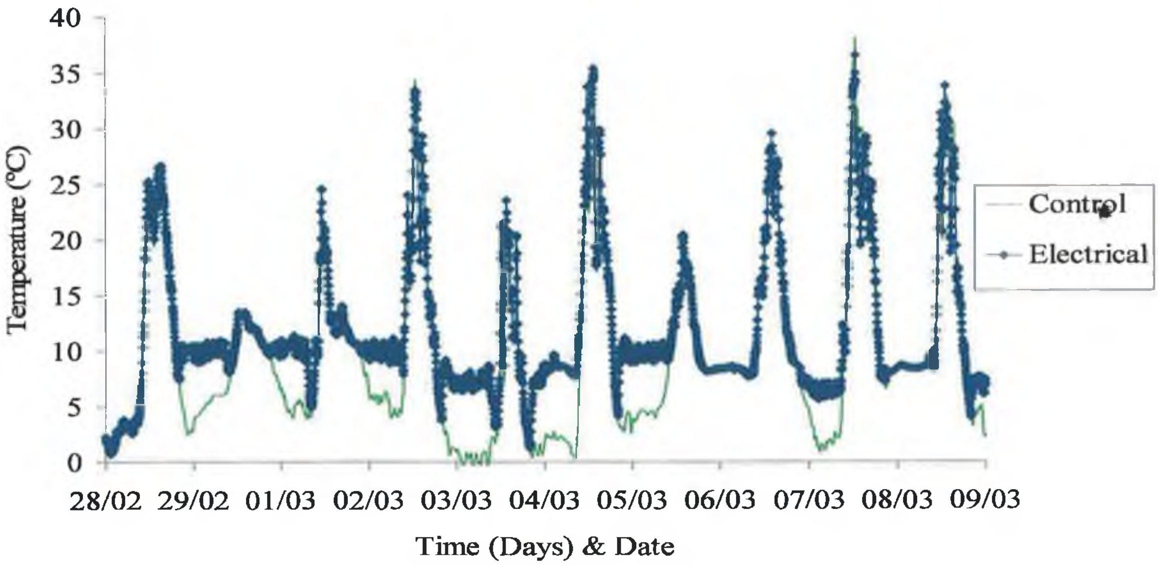

Figure 3.22: Temperature profiles of electrical heated and control polytunnels over a 10 day period in February / March

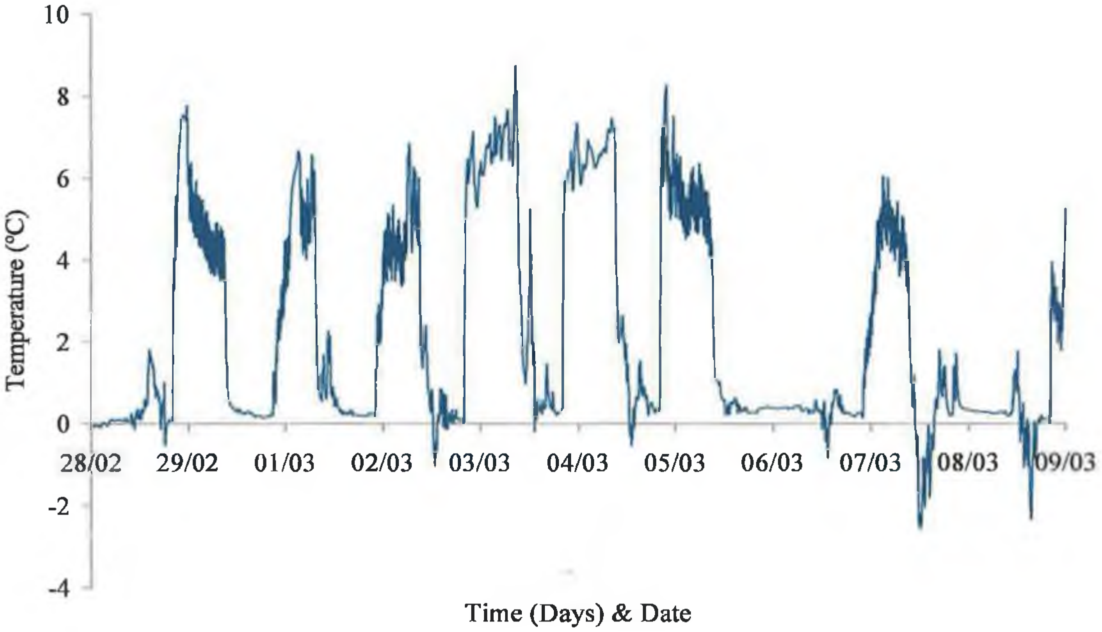

Figure 3.23: Temperature difference (ΔT) between electrical heated and control polytunnels over a 10 day period in February / March 2008.

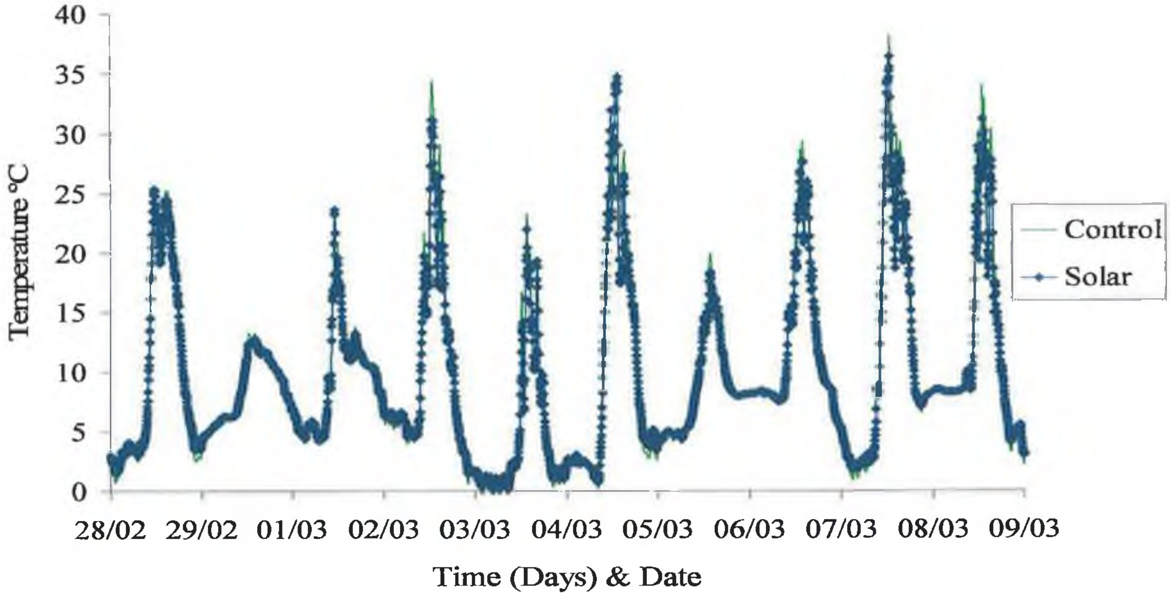

Figure 3.24: Temperature profiles of solar heated and control polytunnels over a 10 day period in February / March

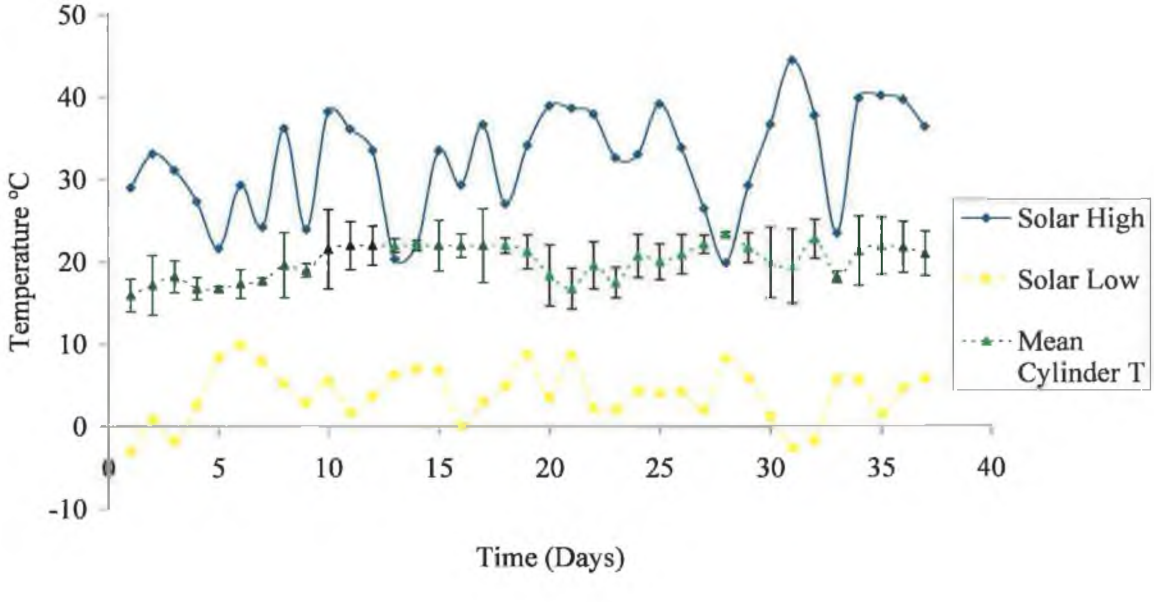

Figure 3.25: Upper and lower daily temperatures within the solar panel manifold along with mean (± SD) solar hot water cylinder temperatures over a 37 day period from February 16th / March 25th

Figure 3.26 shows an overview of the three heating technologies and their ΔT with respect to the control polytunnel. The electrical heater is clearly the most effective at increasing internal polytunnel temperature on a nightly basis with a mean of 6°C above the control. The compost HEU follows this with small temperature increases between 1.5 and 3°C with the solar technology having a ΔT of close to 0 °C on the nightly heating phases.

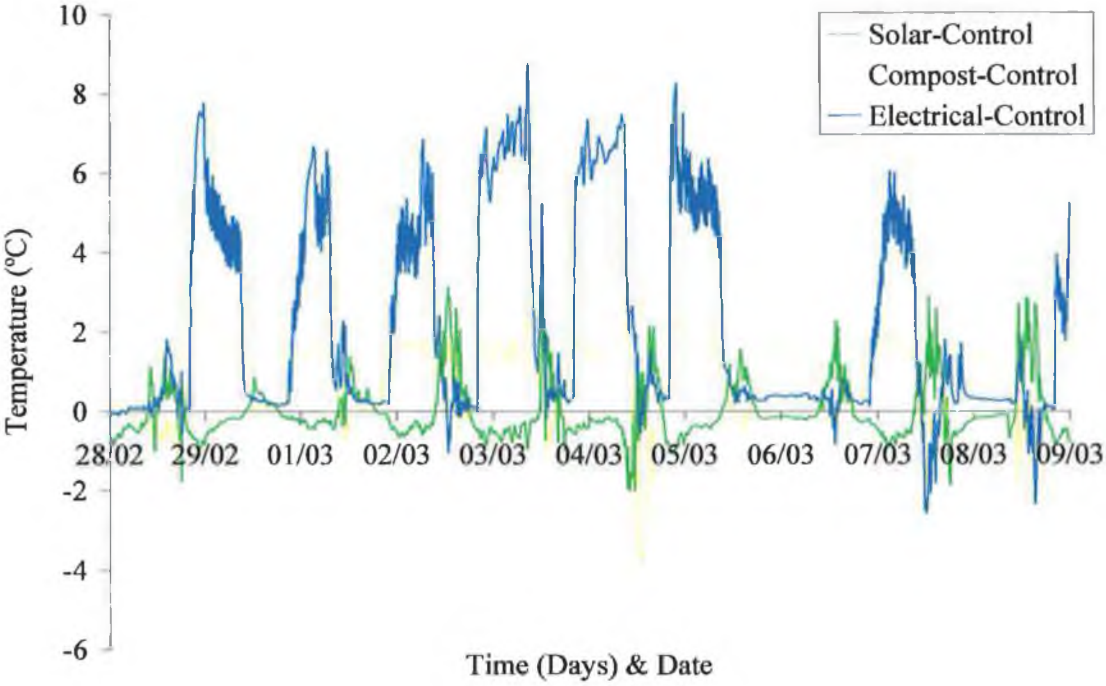

Figure 3.26: Temperature differences (ΔT) between electrical, compost and solar heated polytunnels and the control polytunnel over a 10 day period in February / March 2008.

3.4.4 Power consumption comparison

Power consumption of the three polytunnels requiring an electrical input is shown on Figure 3.27. The control tunnel had zero power usage. The Nevada 2.25 electrical air circulation heater consumed 100 kWh of electricity by day 5 of this experiment, where as the solar panel and HEU were significantly lower at 0.7 and 2.7 kWh respectively. The pattern remained the same toward the end of the experimental period with the electric heater at 331 kWh, the HEU at 9.7 kWh and the solar panel usage at 4.3 kWh. The cost of a unit of electricity at Mountbellew Agricultural College is the 'General ESB tariff' of €0.1705 per kW unit. The Electrical heated polytunnel had the highest cost at €56.43 with compost HEU heated following at €1.65 and solar panel heated at €0.73 excluding VAT. The control incurred zero electrical costs.

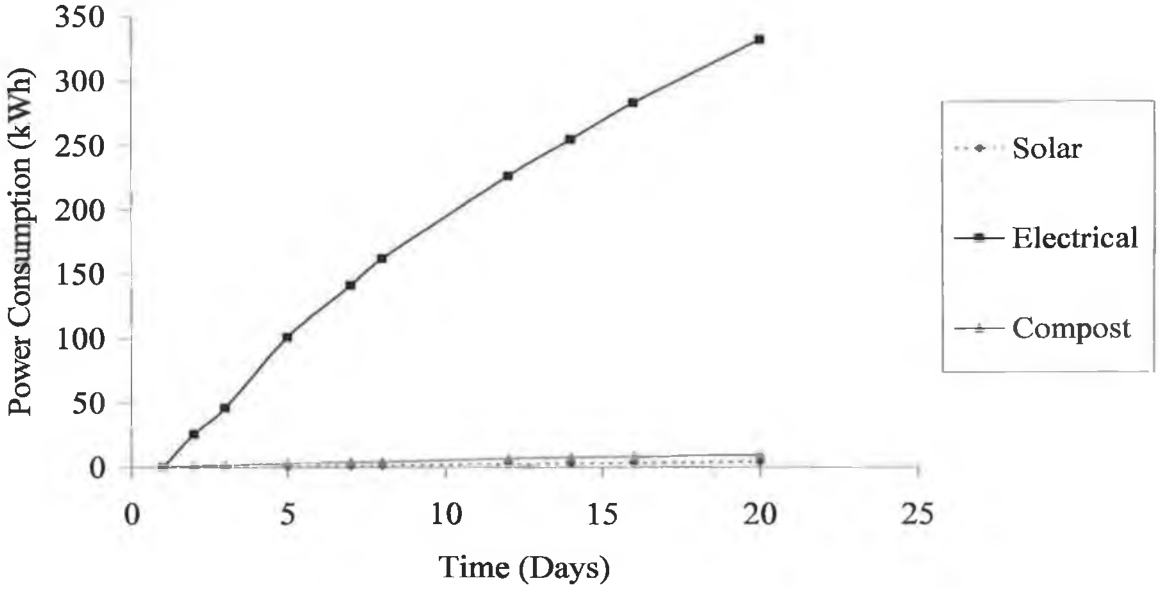

Figure 3.27: Power consumption data from Solar, Electrical, and Compost heated polytunnels from 28/2/08 to 18/3/08

3.4.5. Plant growth trials

The Garlic grew successfully with 79 out of 80 cloves developing into plants. It was in position 8 in the electric heated polytunnel where this clove failed to grow sufficiently. The Spinach seeds did not develop into plants however. The results for common garlic growth within the 4 tunnels are shown in Figure 3.28. The plant growth rates are similar in each of the four tunnels with the electrical tunnel the highest at 8.3mm/day. The solar and compost tunnels were at 7.9 and 7.5 mm/day respectively and the control tunnel the lowest at 6.5mm/day. There was no significant difference between growth rates of plants subjected to each heat treatment (Kruskal-Wallis Test, P=0.701).

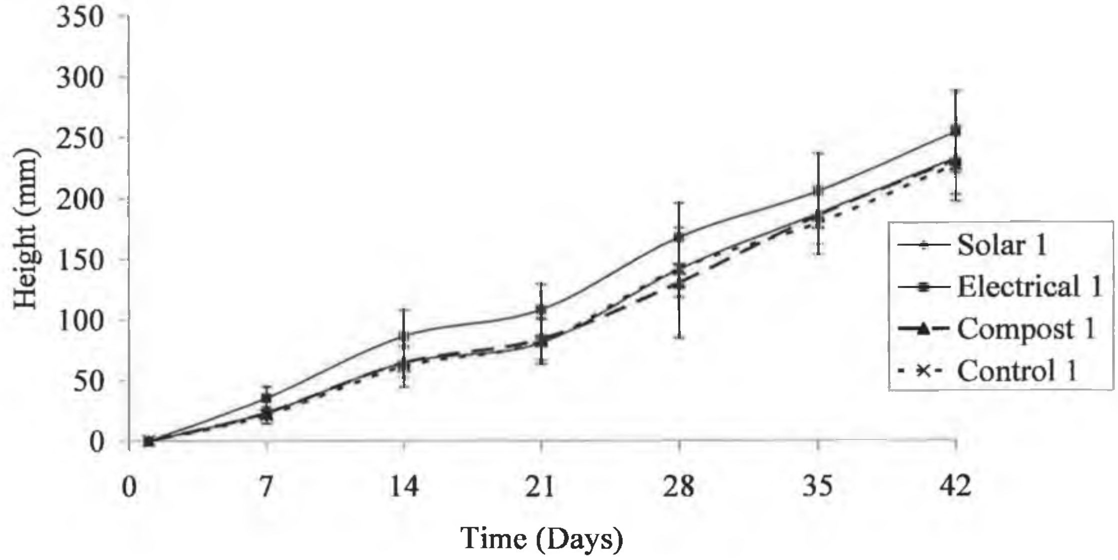

Figure 3.28: Mean ± SD of the stem heights of 16 garlic (*Allium sativum*) plants in each of the 4 polytunnels over seven weeks from 28/1/08 to 18/3/08.

Table 3.1: Compost, conventional, renewable, and control heating regime analysis in terms of efficiency, power consumed, cost and plant growth

Heating System	*Heating Efficiency*	*Power consumed (kWh)*	*Electrical Cost (€)*	*Plant Growth Rates (mm/day)*
Electrical	High	331	56.43	8.3
Solar	None	9.7	1.65	7.9
Compost	Low	4.3	0.73	7.5
Control	None	0.0	0.0	6.5

Table 3.1 shows an overview of the four-way heating system performance comparison described in the results section. The electrical heating device has the highest values in each of the categories of heating efficiency, power consumed, cost, and plant growth rates and the control has the lowest values. The extra cost and power needed for the electrical and compost heated tunnels did not create a significant difference in plant growth rates however.

3.4.6 Trueleaf Technology Roll n Grow Heating Mats.

Figure 3.29 shows the temperature profiles from the compost heated and control polytunnels. This figure shows a period of eleven days only to allow ease of viewing and analysis of the data and due to diminishing heat output of the compost after this period. The compost heated polytunnel showed a temperature profile similar to the control polytunnel, however variations can be seen during the daytime heating periods when peak temperatures during the first 9 days (192 Hours) are at a maximum 3°C above the control. During the remaining 15 days of the experiment peak temperatures in the compost heated polytunnel vary between 1-2°C above the control polytunnel. Figure 3.30 shows the difference in temperature between the compost heated and control polytunnels over the 26 day trial period where this 1-2°C difference is clearly evident each day.

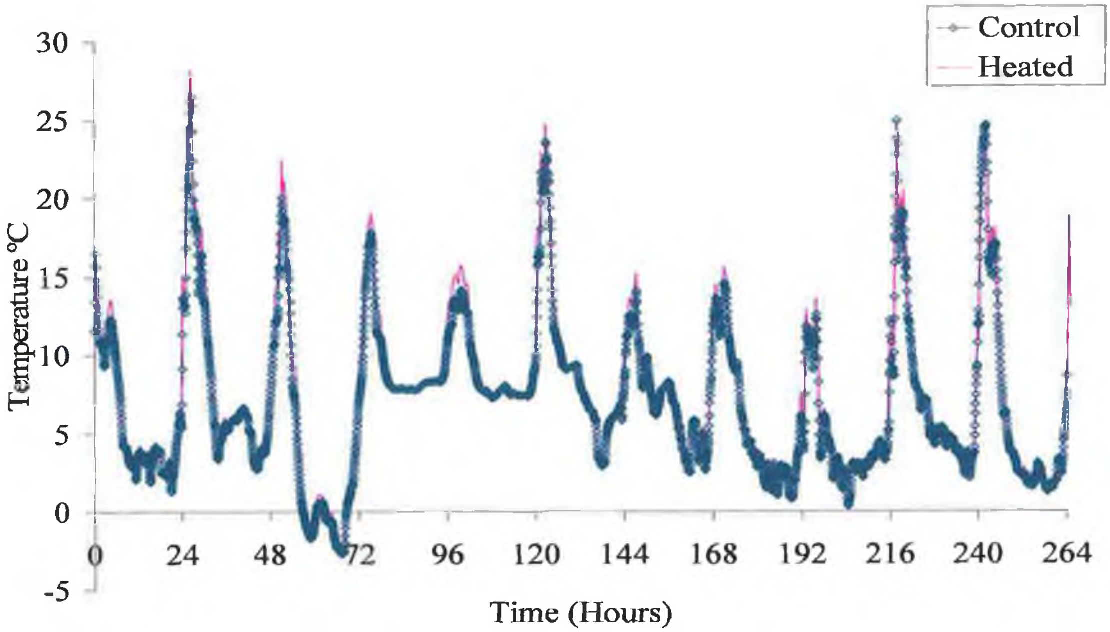

Figure 3.29: Temperature profile of the control and compost heated polytunnels over an 11 day period in November 2008

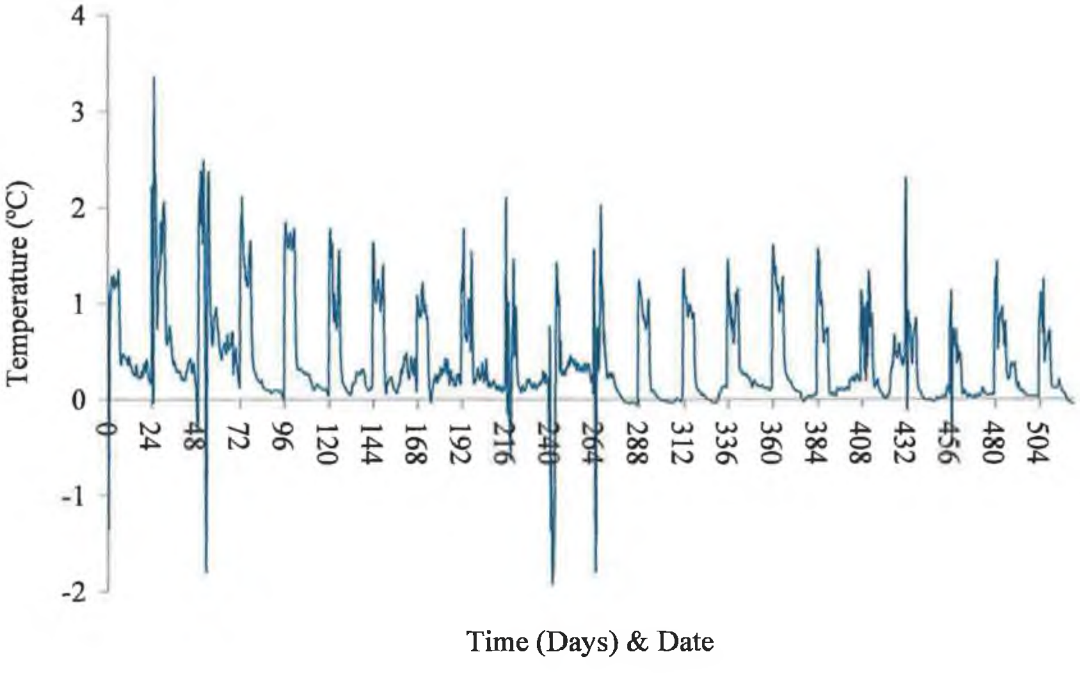

Figure 3.30: Temperature difference (ΔT) between the compost heated and control polytunnels over a 26 day period in November 2008.

Figure 3.31 shows the means ± SE of the principle shoot length of the Radish plants over a 24 day growing period in November 08. The plants in the heated tunnel had a growth rate of 1.1 mm/day which was higher than the 0.8 mm/day result for the control polytunnel. There was no statistically significant difference between growth rates of plants subjected to each heat treatment over the 24 day period (One way ANOVA, P=0.065). Figure 3.32 shows the average leaf number on the Radish plants. The heated polytunnel had higher amounts of foliage during the short growing period with a mean of 4.8 leaves compared to 3.2 for the control polytunnel.

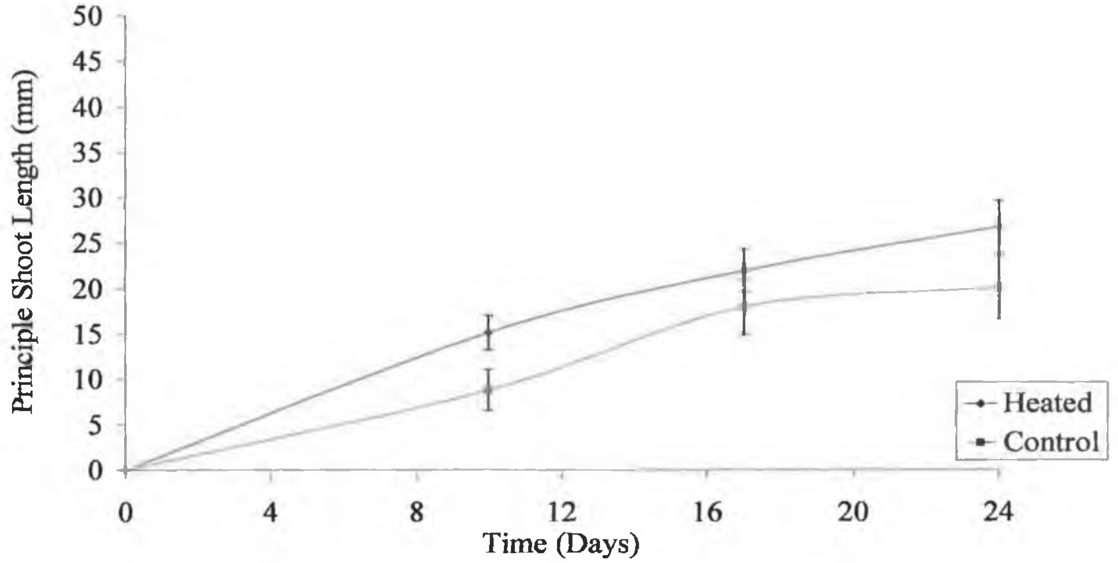

Figure 3.31: Mean ± SE of the shoot heights of the Radish (*Raphanus sativus*) plants in the compost heated and control polytunnels from 1/11/08 to 24/11/08

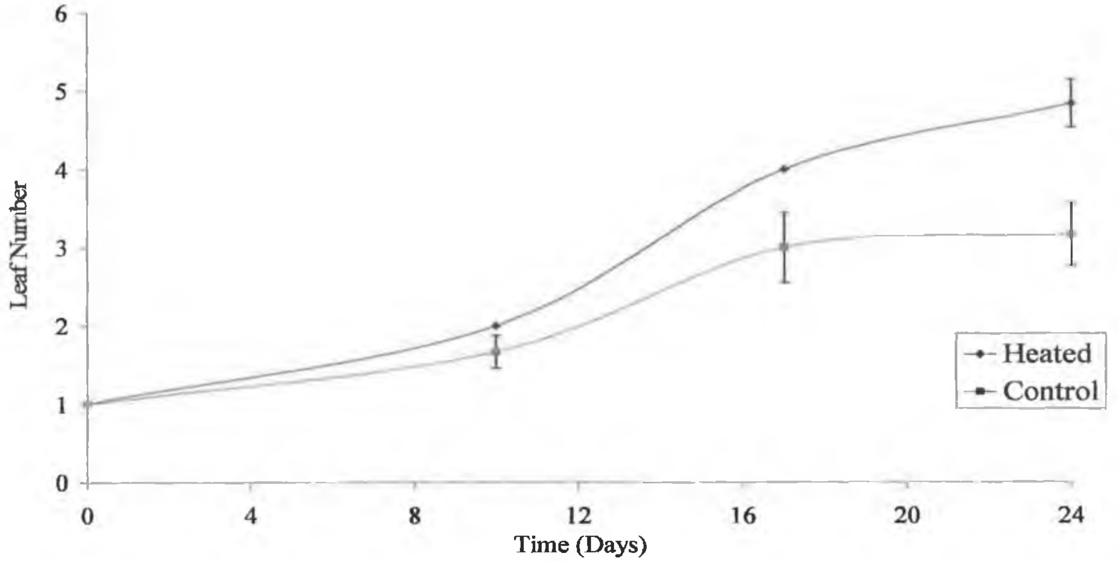

Figure 3.32: Mean ± SE of the leaf number of the Radish (*Raphanus sativus*) plants in the compost heated and control polytunnels from 1/11/08 to 24/11/08

Figure 3.33 and 3.34 show representative examples of the health of the Radish plants in the non heated and heated polytunnels respectively. It can be seen that the plant cultivated with the assistance of heat mats, appears healthier indicated by increased leaf area, higher leaf number and minimal foliage damage. In contrast the plant cultivated within the control polytunnel has a smaller leaf area, lower leaf number, is suffering from wilting and foliage damage indicated by holes within the leaves. There was a 12 % mortality rate in the heated polytunnel compared to 38 % for the control polytunnel.

Figure 3.33: A Radish plant from the non heated polytunnel.

Figure 3.34: A Radish plant from the Roll n Grow heated polytunnel.

Figure 3.35 shows the means ± SE of the principle shoot length of Cabbage plants over a 24 day growing period in November 08 in the heated and control polytunnels. Mean shoot length in the heated polytunnel was 31.7 mm compared to 17.9 for the control at the end of the trial period. The Cabbage in the heated polytunnel had a higher growth rate of 1.3 mm/day compared to 0.7 mm/day for the control. There was no significant difference between growth rates of plants subjected to each heat treatment (One way ANOVA, P=0.11). There was a 12 % mortality rate in both the heated polytunnel and the control polytunnel for cabbage.

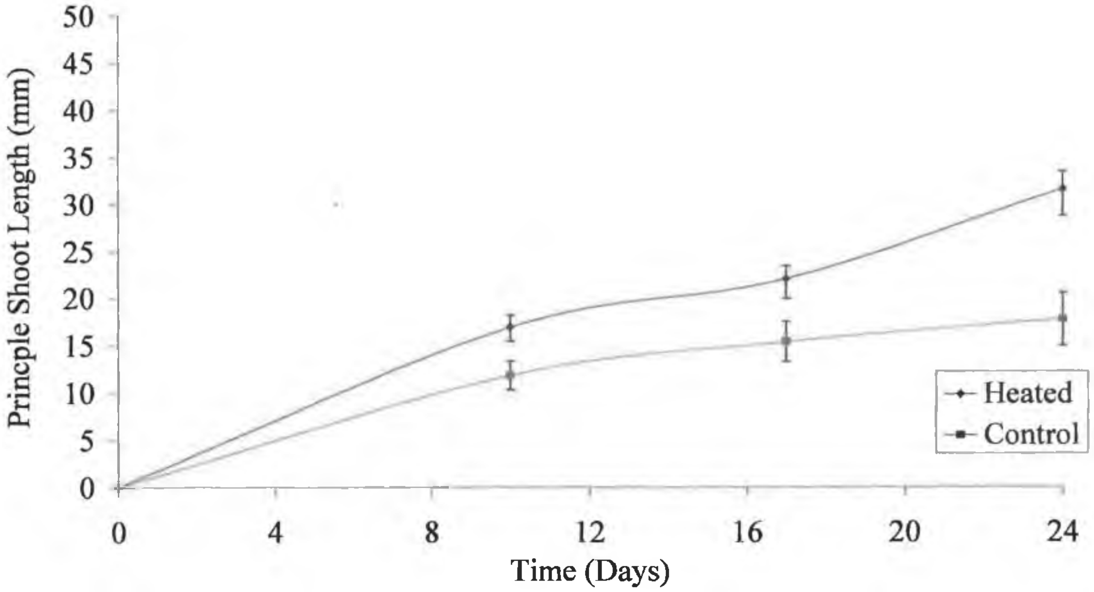

Figure 3.35: Mean ± SE of the shoot heights of the Cabbage (*Brassica oleracea)* plants in the compost heated and control polytunnels from 1/11/08 to 24/11/08

Figure 3.36 shows the means ± SE of the principle shoot length of Spinach plants over a 24 day growing period in November 08 in the heated and control polytunnels. Mean shoot length in the heated polytunnel was 43.6 mm compared to 31.3 for the control at the end of the trial period. The Spinach in the heated polytunnel had a higher growth rate of 1.8 mm/day compared to 1.3 mm/day for the control. There was no significant difference between growth rates of plants subjected to each heat treatment (One way ANOVA, P=0.107). There was a 0 % mortality rate in the heated polytunnel compared to 25 % for the control polytunnel for Spinach plants.

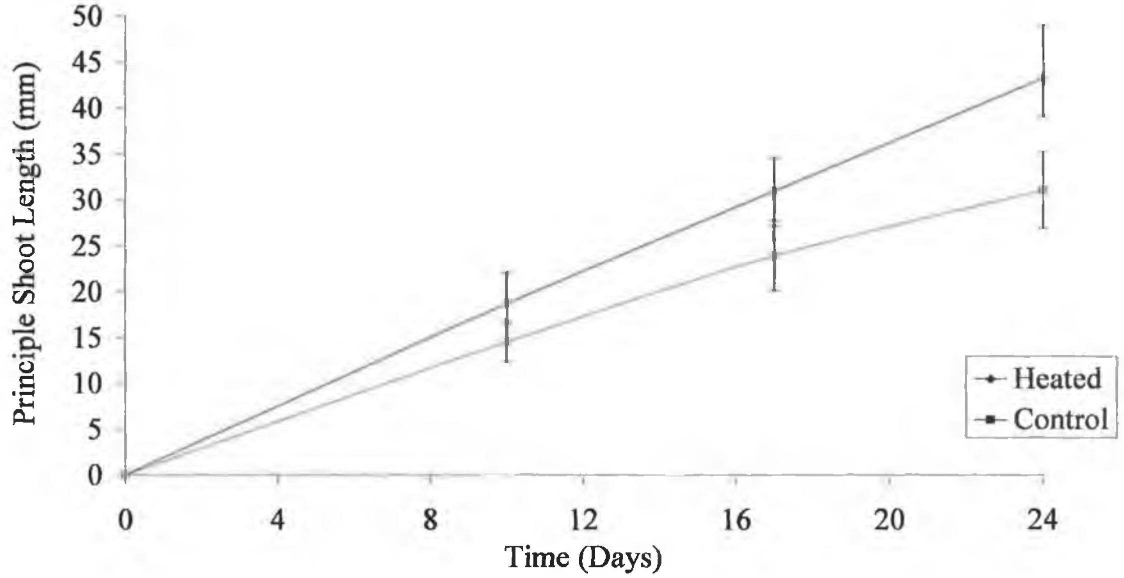

Figure 3.36: Mean ± SE of the shoot heights of the Spinach (*Spinacia oleracea*) plants in the compost heated and control polytunnels from 1/11/08 to 24/11/08

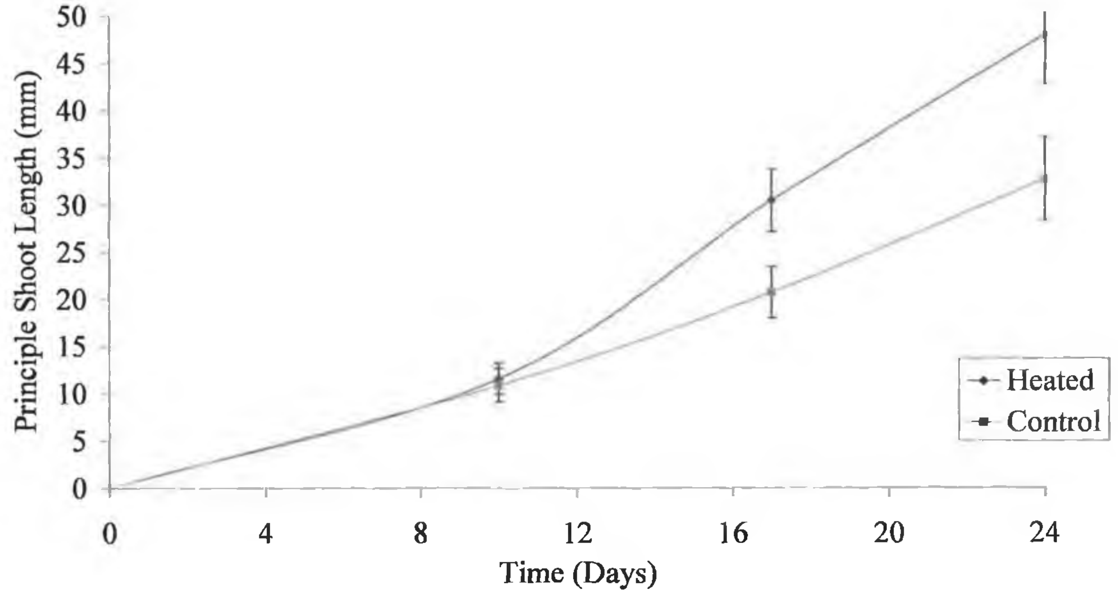

Figure 3.37: Mean ± SE of the shoot heights of the Lettuce *(Latuca sativa)* plants in the compost heated and control polytunnels from 1/11/08 to 24/11/08

Figure 3.37 shows the means ± SE of the principle shoot length of Lettuce plants over a 24 day growing period in November 08 in the heated and control polytunnels. Mean shoot length in the heated polytunnel was 48.0 mm compared to 32.7 for the control at the end of the trial period. The Lettuce in the heated polytunnel had a higher growth rate of 2.0 mm/day compared to 1.4 mm/day for the control. There was no significant difference between growth rates of plants subjected to each heat treatment (One way ANOVA, P=0.121). There was a 0 % mortality rate in the heated polytunnel compared to 25 % for the control polytunnel for Lettuce plants.

Figure 3.38 shows the mean ± SD of a random sample of eight soil temperatures taken from the potted plants in the heated and control polytunnels during the experiment. Potted soil temperatures over the heat mats were higher than those in the control tunnel throughout the experiment. There was a significant difference in soil temperatures between those subjected to each heat treatment (One way ANOVA, P=0.01). There was a 7.0°C difference initially where the compost heated soil reached 12.5°C compared to 5.8°C for the control. As the compost cooled the heated polytunnel soil temperature was reduced to 3.4°C above the control on day 24.

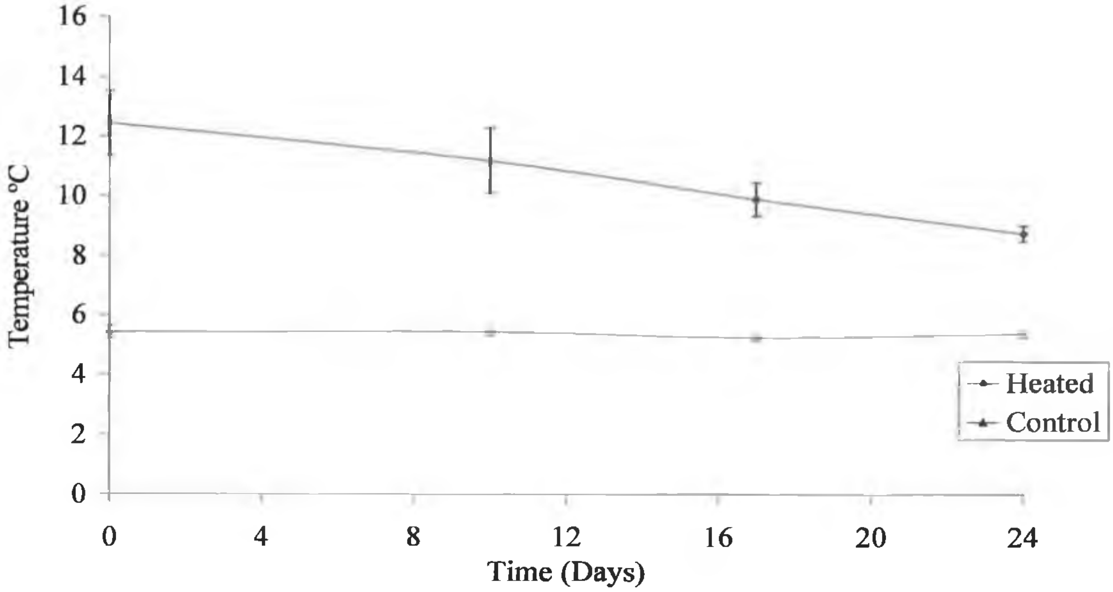

Figure 3.38: Mean ± SD of a random sample of soil temperatures from the potted plants within the compost heated and control polytunnels from 1/11/08 to 24/11/08

3.5 Discussion

3.5.1 Compost heating system performance analysis

The compost Heat Extraction Unit (HEU) was capable of heating polytunnels to an average of 2°C above control temperatures. The tunnel was kept above freezing conditions on 3 occasions during this period and depending on the plants grown within, that margin can be significant in preventing crop failure due to frost damage (Hanafi and Papasolomontos, 1999). In general it is the hot pipe or hot air heating systems which are used in the majority of greenhouse heating systems (Teitel *et al.*, 1999). These use gas or electricity generated through fossil fuels mostly which release greenhouse gases and can be expensive. The compost heat generated in this study was relatively inexpensive to produce and distribute and therefore compost may be a viable heating system for future production or utilized as a mechanism to prevent crop failure.

Similar research was carried out at the New Alchemy Institute where heat and CO_2 was distributed under the plants directly within polytunnels from hot compost through ducts (Fulford, 1986). Soil temperatures were maintained at 16°C during freezing nights. This method used 6 hours labour a week where as the compost HEU required 6 hours labour on day one and then 0.5 hours per week for mixing until it was emptied. Seki and Komori (1995) recovered 0.17 kWh/day of energy power with a trial compost heat exchanger. Total energy recovered from the 435 Kg of compost within the HEU during the current trial was 76 kWh which is 3 kWh/day for the 25 days when the HEU was activated. Energy levels within the compost began to decline after maximum temperatures were reached on day 4 of this trial which coincided with activation of the HEU. The HEU would have cooled the compost slightly but the natural compost temperature cycle (Fitzgerald, 2009) was also a major factor in the temperature and energy reduction at this time. Although energy losses were assumed to be zero (for calculations) due to the insulation, conduction losses would have occurred. The technologies discussed along with the HEU are of low / minimal technological design which could benefit the small operator with supplies of waste organic streams.

High-tech solutions have also been employed to heat greenhouses including Agrilab's patented Isobar heat transfer technology which produces up to 843 kWh/day from 600-800 tonnes of compost at a prototype cost of $450,000 (Tucker, 2006). Winship *et al.*, (2008) investigated combined heat and composting in large containers drawing latent heat energy through an evaporator of a heat-pump sub system. A net energy of 195 MJ (55kWh) per tonne of waste was achieved along with savings of 579 Kg CO_2 per tonne of compost. The need for reliable and significant organic waste volumes is vital for efficient operation in high-tech/cost solutions. European waste directives stipulate dealing with waste as locally as possible. In environmental terms the low-tech choices as developed here creates a more localised solution for bio-wastes. The waste organic matter streams are generated and composted locally. The high-tech solutions described are more reliant on transport to perform their operation decreasing their environmental efficiency and leaves them more open to market fluctuation in energy prices.

The overall COP for the HEU during the trial was 6.8. The COP had a range of 12.5 to 3.7 over the 28 days when heat was being extracted. At its peak performance 1 joule of electrical work input allowed the transfer of 12.5 joules of thermal energy from the compost to the radiator. Once COP is above 1 it remains energy efficient to use the pump to extract the thermal energy from the compost and therefore at no time was the HEU working inefficiently. A typical air-source heat pump has a COP of 3 – 4 and a geothermal heat pump 3.5 - 4.5. The HEU at 6.8 performed more efficiently than these during this trial. However heat pumps use no man power in their day to day usage unlike the HEU where the organic content must be mixed and changed at regular intervals. The heat pump has similar advantages as the electric heater evaluated here in that regard.

When discussing efficiency of an electrical appliance it is important to consider the Primary Energy Ratio (PER) which is calculated by multiplying the COP of the device by the electrical power generation efficiency. It is particularly important with regard to CO_2 emissions and the environmental consequences of the generation efficiency. The more efficiently the electricity is generated and transmitted to the end use site the less CO_2 is released. The higher the renewable energy makeup of a country's power supply the higher the generation efficiency. Ireland has a generation efficiency of 0.44 (Howley *et* *al.,* 2008). That gives the HEU a thermal performance of a 2.9 PER during this trial period. Countries such as Norway and New Zealand with very high renewable energy output due to large Hydro-electric capacity have much higher generation efficiencies. Similar electric devices used in those countries will indirectly cause the release of less climate changing gases such as CO_2. Generation efficiency increases in Ireland by 1.8% a year which makes the use of technology such as the HEU more environmentally efficient every year if connected to the national grid. By employing renewable energy to power the pump it would create a fully renewable power source.

3.5.2 Compost HEU efficiency

Research that has focused on greater efficiency of heating applications within the protected growing area has also been investigated. These included the exact position of the heat distribution elements to improve plant growth and reduce costs (Kempkes *et al.*, 2000a; Kempkes *et al.,* 2000b). The radiator used in this experiment may not be the most efficient at distributing the compost derived heat to the plants. The large volume of air (47 m^3) to be heated makes it difficult for the convective currents generated by the single radiator to create a large temperature change. There is a consistent although diminishing thermal flow to be utilised from the HEU. The pipe outlet temperatures of the HEU show a consistent profile of sharp rises and steady drops in temperature. It indicates that the compost can heat the water up to 60 °C initially when the compost is close to 70 °C. Over the course of the month long trial using the HEU there was an average 20 degree difference in the temperature of the compost and the temperature of the water flowing through the pipes. This thermal energy needs to be utilsed more effectively. However the very nature of a polytunnel, an un-insulated, un-sealed, non air tight unit with a high U-value makes it difficult to heat. Two compost HEU's working in tandem could raise the temperature further or a more large scale device could also increase the efficiency of this technology. Logistically any increase in size of an invessel composter could create problems with moving the device due the weight, particularly in an open field situation where the ground can churn up under a tractor. Improving efficiency by using heated growing mats could be of benefit as was conducted in the final experiment.

3.5.3 HEU, Electrical and solar heating performance comparison.

In overall efficiency terms the electric heater within polytunnel 2 was more successful in heating the tunnel at night than the compost HEU and maintained the 10°C night temperature presetting. The power consumption analysis showed however that the fan heater consumed more power and thus cost more to run. The consistent power and temperature control of this device was the main advantage over the compost heater although the electrical costs exceeded it. Electricity prices rise normally with fossil fuel prices making this a choice in which costs will continue to rise in the future. Electricity prices in Ireland are the highest in Europe (SEI, 2008), which makes renewable compost energy a more attractive option. The ease of use of the electrical heater over the compost heater is also an advantage. An electrical timer is all that is needed unlike the time needed to fill of the compost HEU and manual aeration of the compost by physical turning.

The solar panel was ineffective in heating the polytunnel due to the lack of sufficient solar radiation at this time year (Martin and Yogi Goswami 2005). Mean solar flux is 2.51, 4.75 and 7.48 MJ/m^2 in January, February and March respectively. This generally increases to 19.11 MJ/m^2 in June. During this period the tank was heated above the critical 30 °C on one day only and the pump activated to allow the heated water flow through the radiator. Heat could potentially be distributed at night from the stored energy of the solar panel by day but there is insufficient heat generated to do this from one panel (Fitzgerald, F. Pers. comm. 2009). The number of panels could be added to and the cylinder size increased to achieve this reservoir of heated water although the costs could exceed the benefits particularly in terms of winter heating.

The volume of air to be heated in the tunnel was 47m^3 and in order to maintain the internal polytunnel air temperature at 10 °C, which was the preset temperature for the Bio Nevada electrical heater a considerable amount of power was required. It amounted to 76 times that used to power the solar panel and 34 times that of the compost HEU. The electrical heater was more effective and reliable than the other two heat sources (solar and compost) for horticultural applications as they were unable to maintain night temperatures at desired levels. The solar panel contributed no heat and the HEU raised it

2 degrees on average above the control tunnel temperature. Although the electrical heater was more efficient the higher costs must also to be considered when evaluation these heating options. The electrical heater cost € 54.70 more than the HEU during this 20 day experiment. This equates to 34 times the electrical cost of the compost HEU. It is due to these prohibitive costs that most organic growers choose not to employ electrical or gas heating technology (Curran 2009, Pers. Comm.).

There have been other attempts to alleviate heating costs by using waste streams. Jaffrin *et al.,* (2003) investigated waste streams such as landfill biogas for heating greenhouses and improving crop growth with the excess CO_2 produced. Renewable energy in the form of geothermal heating and cooling of greenhouses has also been evaluated recently by Whillits and Gurjer, (2004). Their results showed the economic viability of heating and cooling with the result of improved crop yield. The compost HEU tested in this project combines the use of waste organic matter streams and development of a renewable energy. Thus it attempts to tackle two important current environmental issues namely waste and energy. It is a cheaper option than geothermal energy although not as efficient and does not have the cooling capability of heat pumps. It is more flexible than the landfill biogas option also in terms of possible location. Improvement in plant growth rate is the key factor in determining the efficiency of this unit however.

3.5.4. Plant growth trials and Trueleaf Technology Roll n Grow Heating Mats

The garlic plants grew consistently well in each of the tunnels and as a performance indicator of the heating variation between the tunnels no significant difference was observed. In terms of crop production for this particular plant and the extra costs of heating the tunnels with electrical heat or compost generated heat, any additional growth would not justify the expense particularly if electrical energy prices were to rise. This would not be beneficial to organic growers who generally attempt to minimize energy costs. The failure of the spinach to grow successfully may have been the result of the late planting and the sharp frosts directly after planting in late December may have damaged them also. The compost technology may be more efficiently used in the plant propagation phase within specially designed growing mats where water could flow through and the heat would be distributed directly to plant roots rather than heating a large volume of air in a polytunnel. Currently electrical heating mats are employed and are the main heating expense for organic growers. This cost will continue to rise as electricity prices rise along with fossil fuel prices.

Plants grow best when daytime temperature is about 10 to 15 degrees higher than night time temperature (Mitchell, 2009. Pers. Comm.). Photosynthesis and respiration are then optimised during the day and energy (glucose) using respiration can be minimised at night with lower temperatures. Thus the addition of extra daytime heat during the Roll n Grow experiment may be more beneficial than the night time heating of the radiator based heat trial. Although direct comparison of the two plant growth trial was not strictly comparable due to the temperature and daytime variable differences the second growth trial gave more clearly defined results. Increases in root zone temperature will lead to increased plant growth up to a limit (Malcolm *et al.,* 2007). The Roll n Grow heating experiment was successful in delivering heat directly to the plant roots. The overall 2-3°C difference in ambient polytunnel temperature between the heated and non heated polytunnels was very similar to the results of the 1st heat distribution system comprising the radiator. Thus no advantage was gained using the Roll n Grow heating mats in terms of the overall heating of the large air volume within these polytunnels.

Plant growth as a performance indicator in this experiment gave clearer results. Although a statistically significant difference in growth rates was not observed in any of the plant groups a more in depth examination of the plant growth trials indicated there was distinct variation. The Radish plant was the best example of this. When leaf number and leaf area is considered along with the overall health of the plant clear variation was observed. The addition of heat energy allowed faster growth, increased foliage, and maintained structural integrity of the plant against holes forming on the leaf surface. Total biomass at the end of the trial period would have been a better indicator than shoot height and could have given statistically significant results had it been recorded.

The plants in the non heated polytunnel also suffered from wilting more so than the compost heated plants and plant deaths were recorded. Mortality was much higher in the control polytunnel with 9 deaths as opposed to 2 in the heated polytunnel. Cabbage, Spinach and Lettuce all had higher growth rates in the heated polytunnel however high natural biological variation meant no statistically significant result was obtained. Analysing the results collectively there is a clear advantage in using the heat mats for plant cultivation.

If the experiment had been continued with a second HEU set up after the first had cooled, statistical significant differences in growth rates would most likely have been observed. Looking at figures 3.30, 3.34, 3.35, and 3.36 the shoot height curves from the control and heated polytunnel are diverging suggesting that a significant result could be achieved with a longer experimental period. Time constraints prevented this however. The results indicate that the heat mats allow a more efficient method of heat transfer from the compost to the plants when compared to the radiator system. Directing the heat to the plants roots means the entire polytunnel doesn't need to be heated. This is an advantageous when the compost cools and energy levels drop it would make it difficult to heat a large volume but can still offer useful heat through the heat mat growing system. This system could also be improved upon significantly as a lot of the heat supplied is lost to the air. The mats with a layer of insulation beneath could be embedded in a shallow layer of clay to maximise heat transfer to the soil and the plants and also to maximise heat retention in the soil. The experiment had 32 plants growing on the heat mats. The commercial grower could have at least 200 plants on the same growing area giving a potential economic advantage to this technology particularly in the early propagation phase of horticultural production.

Chapter 4

Alternative uses for the Compost Heat Extraction Unit derived thermal energy

4.1 Abstract

A compost heat extraction unit (HEU) was designed to utilise waste heat from decaying organic matter for space and hot water heating during March, May and July 2008. A test shed was used onsite for space heating experiments. Two separate insulation types were tested inside the building firstly UV resistant Polythene bubble wrap and for a second experiment 50mm Kingspan. This gave the test building U-values of 1.6 and 0.53 W/m^2K respectively. The compost HEU successfully heated the shed and contributed to a 7°C rise of internal night temperatures above ambient during the first week with the aid of the bubble wrap insulation. This was improved upon by using the Kingspan insulation where maximum internal temperatures increases of 13°C above ambient were recorded in the first week of HEU operation. The potential for hot water heating was tested using a 60 litre cylinder which was successfully heated on a daily basis by the HEU. The heated water was removed each day and fresh tap water was added. Maximum increases in water temperature of 36.5°C were recorded initially. The level of compost heat output decreased and a 22°C rise was recorded on the final day (32) of the experiment.

4.2 Introduction

Energy security and concerns about climate change have led governments to place these issues at the centre of new policy developments (Bang, 2009). The general public has become increasingly aware of these issues of late with widespread media coverage of climate change and the increase in energy costs of 2008 where oil peaked at $150 per barrel. Traditional fossil fuel energy sources including oil are finite and are having a damaging effect on economic progress, the environment and human life and alternatives are required (Akella *et al.,* 2009). Peak oil is the phenomenon when half the global oil reserves have been extracted and would lead to large price increases and is likely to have a negative impact on western economies in the future (Hanlon and McCartney, 2008). The reduction in the availability of fossil fuels and in particular oil will have a significantly negative effect on the global economy.

Renewable energy has the potential to alleviate some of the pressure from rising energy demands. In fact investing in green technology and 'greencollar' jobs have become a central part of the economic stimulus and recovery packages of many countries since the economic crises of 2008. Renewable energy contributes between 15 - 20% of the global energy supply with biomass accounting for two thirds (Omer, 2008a). The direct combustion of biomass some of which is unsustainable is still the most common type of biomass utilisation and is particularly high in developing countries (Omer, 2008b). Recent trends in the research of energy from biomass include direct combustion, production of charcoal, production of liquid fuels such as ethanol, thermo chemical conversion for heat and electricity and anaerobic digestion (Omer, 2008b). It is of interest to note however that in this review of current biomass energy research aerobic digestion (composting) is not mentioned. It has been noted that aerobic digestion is potentially a more efficient technology than anaerobic digestion at dealing with organic wastes such as food (Winship, 2008). According to de Bertoldi (2008) the EU produces more than three billion tons of organic residues. By composting this as opposed to land filling or incineration, it is argued that CO_2 and methane emissions can be reduced and the nutrients and organic matter can be returned to soils which are being degraded through modern intensive agriculture.

Current research into aerobic decomposition and heat extraction for space and hot water heating include the 'combined heat and composting method designed by Winship *et al.*, (2008). Large roll on roll off truck steal containers were used to transport and compost the organic matter while heat energy was drawn through an evaporator of a heat-pump sub system. The heat could be delivered to large urban buildings while the compost was returned to the soil creating a continuous nutrient loop. A large scale commercial compost thermal extraction facility has been developed recently in Vermont, USA by a Canadian company Agrilab Technologies Inc. for hot water heating (Tucker, 2006). On the 2000 herd cattle farm a large composting barn was built in which 150-200 tonne windrows of compost were created. Isobar heat pipes were placed adjacent to windrows and water vapour from the compost was drawn onto them to extracting 843 kWh of thermal power to heat water. A Canadian project at the Royal Military College CFB Trenton which used two large metal in-vessel composters with 1587 Kg/day capacity (Rogers, 2006). Rigid pipes were pushed into the compost chamber and water flows through extracting heat. The heated water (49°C) was delivered to adjacent buildings. An improvement in efficiency using Isobars was suggested after a low coefficient of performance (COP) resulted from trials. Compost energy for preheating water was described by Anon. (1991). Three steps were taken before the water was used to add heat a house. Mains water at 8.3°C is stored below ground where it rises to 12.7°C naturally. Secondly the water is heated within a separate solar heated tank another 11 degrees before finally entering the compost which heats it to an average of 34°C. The preheating ensures the cold mains water does not slow down the decomposition pathways of the micro-organisms within the heap.

Research has been conducted on heat extraction from liquid phase organic waste streams also. Using a 21.6 kW heat pump, 6.5 kWh heat energy was recovered from an aerated slurry lagoon by Hughes (1984). Throughout the winter and summer the slurry maintains a temperature of 35°C with a heat pump increasing this to 55°C for the radiator system. An estimate of 3-4 years payback time for the heat pump was calculated. Heat recovery has been achieved from pig slurry within an aerobic treatment system (Svoboda and Evans, 1987) while removing odour and BOD. The average metabolic heat recovery by using a heat exchanger and aerator from the system was 135 kWh/day. Svoboda and

Fallowfield, (1989) developed the system further using the energy for space heating of the weaner house and in algal raceway ponds. A stainless steel heat exchanger connected to a 12 kW heat pump was used to transfer heat (149 kWh/day) with a maximum water temperature of 55°C.

Space heating and hot water heating account for a large proportion of global energy demand. This project investigates the potential renewable compost derived energy as an alternative to fossil fuels for space and hot water heating. The onsite shed was used in this experiment to attempt to heat a building with improved energy efficiency in comparison to the heating of polytunnels. Two experiments were carried out where the rate of thermal conductivity (U-Value) of the shed was altered. Two types of insulation were used including special insulating bubble wrap and Kinspan foam. During the first experiment the bubble wrap insulated shed was heated every second night and was compared with the alternate nights without heating. A second experiment tested the HEU every night using the Kingspan insulation to investigate how long usable heat could be extracted and delivered successfully. The HEU would be activated between 3 am and 6.30 am to allow the shed to cool during the warmer months of May in order to observe a significant increase when thermal energy was applied. A third experiment investigated the heating of a specially designed hot water cylinder using the HEU. This was to examine its potential in hot water heating applications.

4.3 Methods

4.3.1 Space Heating

4.3.1.1 Bubble Wrap Insulation

A garden shed (2.7m wide, 3.7m long, and 2.7m at the apex) was used as a testing facility to conduct space heating experiments. For the first experiment it was insulated with one layer of special (1.2m wide 12mm) thick bubble polythene insulation covering the walls and ceiling using an industrial stapler. This gave the shed a U-value of 1.6 W/m^{2}K. The method for preparing the HEU and heat distribution system was identical and is outlined in the methods section 3.3.3.1 with the shed replacing the polytunnel. The data logging systems were also identical to the preparation methods are outlined in section 3.3.2. The system used is displayed in Figure 4.1. Temperatures within the compost were monitored until 60°C was recorded and the HEU was then activated. The HEU was set to activate on alternate nights for a period of 26 days. The timer (Merlin Gerin 15720) and power consumption panel (Elster A100C single phase meter) were setup on a mobile plywood board which controlled the timing of heat extraction and monitored the power consumption. It was set from 7 pm to 8 am. Internal shed temperature data was standardised by subtracting the outdoor ambient temperature from the internal shed temperature and adding 1. This eliminated outdoor temperatures affecting the analysis of internal temperature profiles.

4.3.1.2 Kingspan Insulation

A second experiment was conducted with extra insulation and the shed was heated each night during the trial. 50mm 'Kinspan' foam insulation was attached to the walls and ceiling over the bubble wrap. This gave the shed a U-value of 0.53 W/m^{2}K. The timer activated the HEU each night from 3 am to 6.30 am for a period of 27 days.

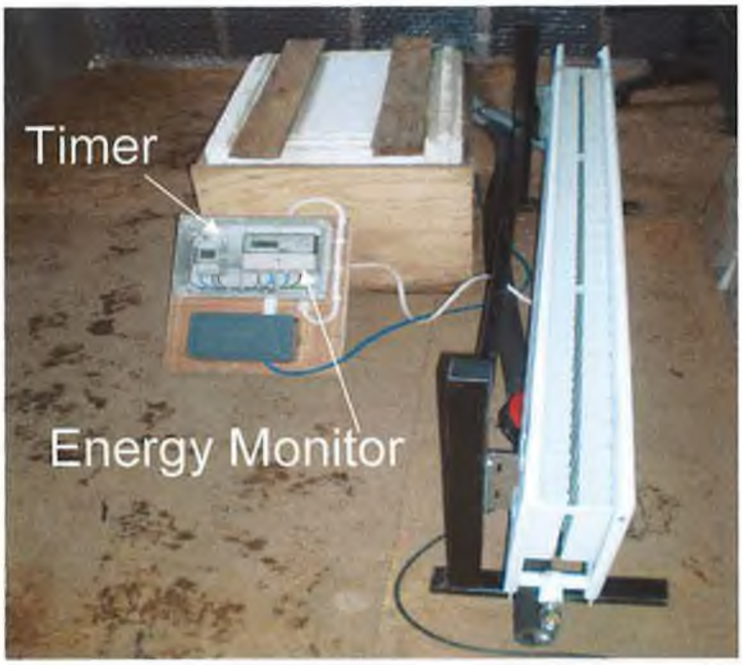

Figure 4.1: Timer, Power Consumption Meter, Insulated Header Tank and plumbing of insulated shed.

4.3.2 Water Heating

A purpose built 60 litres insulated single coil hot water cylinder complete with upper and lower entry ports for PT 1000 temperature sensors was designed and purchased locally. This was placed inside the onsite shed and attached to the outlet and inlet pipes of the HEU by feeding them through two entry ports of the shed. A 25mm brass T piece with a 12.5mm swivel valve was attached to the outlet pipe of the HEU. A closed pressurized system was created by attaching a running water hose to the swivel valve and activating the Groundfos ‘UPS 15-50 130’ flow pump for approximately 20 seconds. The excess air was bled from the system by using a 25mm siphoning valve attached to the inlet pipe of the HEU. Figure 4.2 shows the cylinder with the inlet and outlet pipes attached. The hot water cylinder was then filled with tap water through the top 25mm brass valve. The HEU was activated through a timer switch to heat the cylinder for 5 hours daily. The heated water was emptied each day and was replaced with fresh tap water manually and the timer was reset. This was repeated for 33 days.

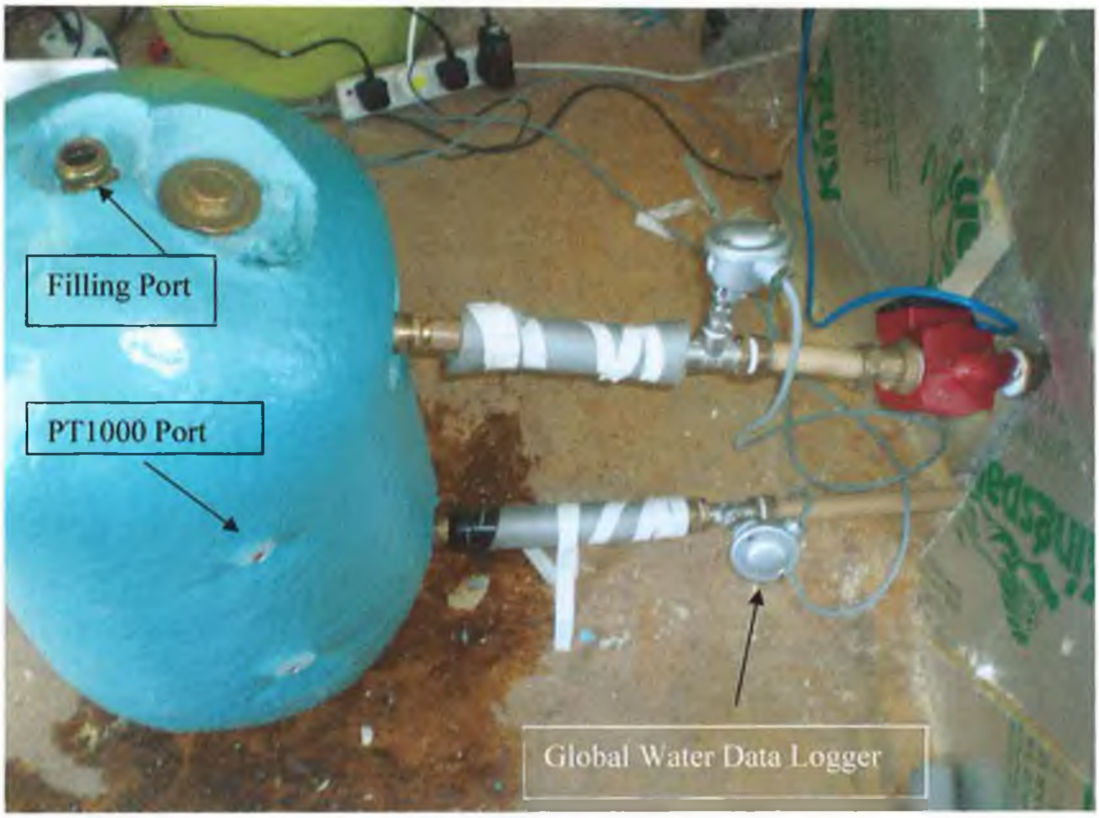

Figure 4.2: 60 litre insulated hot water cylinder inside the test shed.

4.3.3 Data Recording

Two Tinytag Ultra 2 (TGU-4017) temperature data logger which are accurate to ±0.01°C were programmed to record temperatures (°C) at 5 minute intervals for the space heating experiments. One data logger was placed 1.5m above the ground inside the garden shed. A second was placed in an adjacent sheltered, shaded position 1.5m above ground level to record outdoor ambient temperature. Two Global Water (GL500 S-2-1) temperature data loggers which are accurate to ±0.1°C were set up to record the water temperature (°C) within the piping of the compost Heat Extraction Unit (HEU). The first data logger was connected to the inlet pipe and the second on the outlet pipe and both were set to record at two minute intervals. An 'Elster A100C' single phase meters with pulse output was used to record data on pump energy used during the insulation experiments. Two PT 1000 temperature probes were inserted into specific ports on the hot water cylinder for the hot water heating experiment to measure water temperature within the cylinder. This data was logged through the solar panel 'Resol Deltasol BS Plus' data logger.

4.3.4 Data analysis

A Chochran's test for equal variance was used to test for homogeneity of the data within the experiments. Minitab 15 was used to complete statistical analysis on the data. The coefficient of performance of the HEU was calculated during the Kingspan insulation experimental trial period. It is the ratio of the energy extracted from the compost over the pumping energy used to distribute the heated water. The energy extracted was calculated using the equation $Q = m\ Cp\ (Tout-Tin)$ where Q is heat energy in Watts, m is mass flow rate, Cp is the specific heat capacity of the water glycol mix and Tout-Tin is the difference in temperature between the outlet and inlet pipes.

4.4 Results

4.4.1 Space Heating

4.4.1.1 Bubble Wrap

The insulated shed was successfully heated above the ambient internal and external temperatures over the 26 day trial period. The internal shed temperature data logger stopped recording data on the 7th of March for an unknown reason and this problem was corrected on the 12th of March. Thus no internal shed temperature data was recorded for those dates. The pipe input and output data loggers continued to record data however and this was used to extrapolate the potential heating on those dates.

Figure 4.3 shows the internal shed temperatures for the first eight days of the experiment before the fault in the data logger was discovered along with the outdoor temperatures during this period. The three periods when the HEU was activated are highlighted with a shaded box. Internal shed temperature followed the increases and decreases of outdoor temperature except when the HEU was activated. On day three (01/03) as night temperature decreased internal shed temperature increased from 11°C at 7 pm to 18.3°C within two hours of the HEU being activated. Temperatures decrease slowly after this to 13.8°C by 8am the following morning when the HEU was deactivated. A sharp decrease (point A) in temperature was then observed before the shed temperature profile again follows outdoor results. The previous night of the 29/02 without heat input the temperature declined steadily to a low of 5.4°C. The same pattern was repeated over the next 4 days. When the HEU was inactive on the 02/03 and 04/03 it was outdoor temperature affecting internal shed temperatures. When the HEU was active (shaded areas) on the nights of the 03/03 and 05/03 temperatures increased from 2.8°C to 10.9°C and 9.1°C to 16.5°C respectively. Rates of heating to peak temperature during this period were 3.65°C/hour, 1.5°C/hour, and 1.8°C/hour for the first three days of heating respectively.

A lag heating period of 1 hour was observed between the radiator heating up and the internal air temperature increasing during the second and third heating periods. For example a decrease in air temperature for the first hour was observed before an increase was recorded on the 5/03 where it is 9.6°C at 7 pm and 9.1 at 8 pm. It took 2.75 hours of heating for it reach the peak temperature of 16.5°C on this night after the initial lag phase. No lag phase was observed on the first day (01/03) of heating. On the nights were a lag phase was observed, outdoor temperatures were decreasing at a faster rate (1.7°C/hour and 0.8°C/hour) than on the night when none was observed (0.1°C/hour). Figure 4.4 shows the internal shed and outdoor temperatures after the fault in the logger was corrected on the 12/03 and to the experimental end. The heating periods are shown in the shaded areas. The increases of internal shed temperature due to thermal input of the HEU decline during this period and a 1.9°C rise was recorded on 22/03 the final day of heating. Heating rates were reduced over this period also with a mean rate of increase to peak temperatures of 1°C/hour observed. Temperature in the shed was significantly higher on the nights when heat energy was applied (One way ANOVA, P = 0.000).

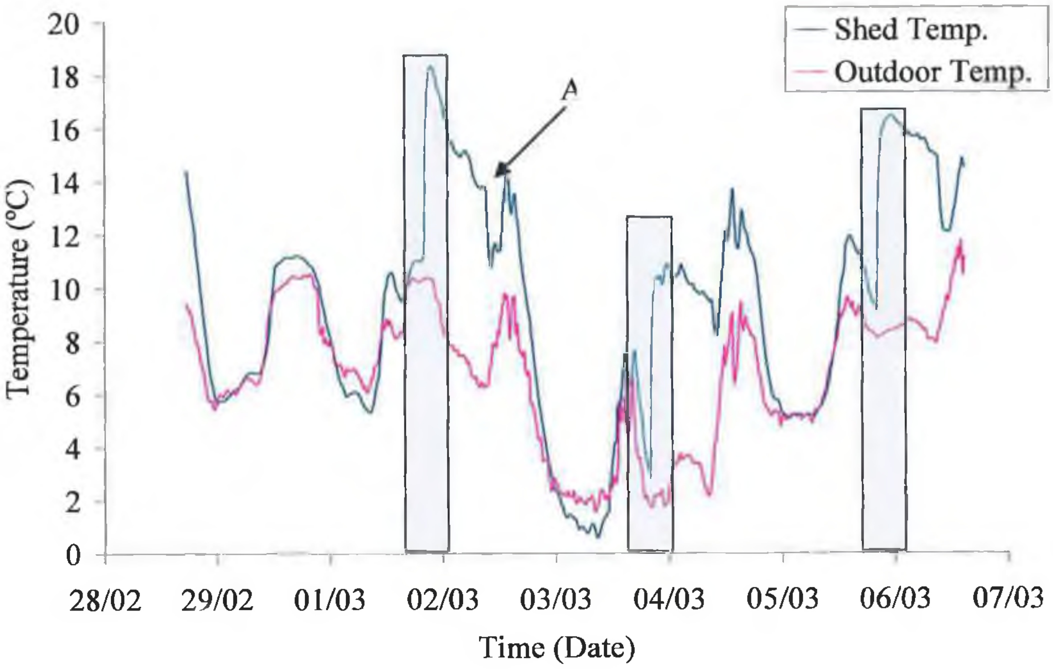

Figure 4.3: Temperature (Temp) profile inside the test space and outdoors over a period of nine days in February / March ‘08

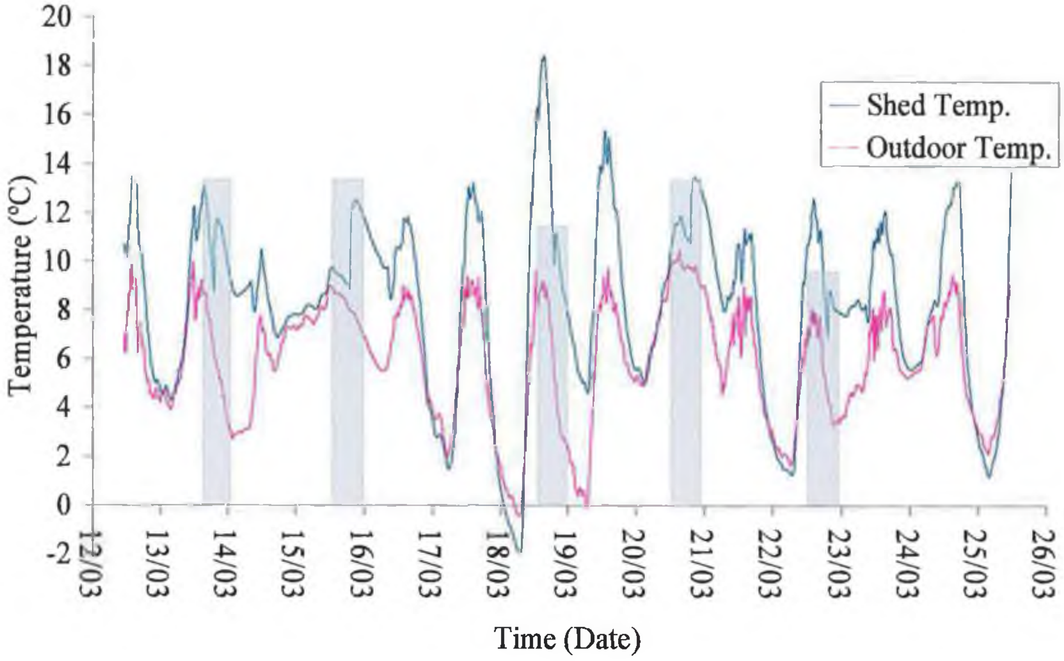

Figure 4.4: Temperature (Temp) profile inside the test Shed and outdoors over a period of fourteen days in March '08

Results of the outlet pipe temperatures for the 26 day trial period are shown in Figure 4.5. It shows the useful energy in terms of heated water generated by the HEU. A series of peaks and troughs were observed daily when the HEU was operational between 7 pm and 8 am for night time heating. The shaded areas on the graph highlight the nightly compost heated water temperature pattern exiting the outlet pipe. It is focused on the gradual decreasing temperature slope (Ponit A) lasting thirteen hours when the HEU is on. The initial higher peak (Point B) preceding this only lasts on average five minutes. Figure 4.5 shows on day one a peak temperature of 61.7°C was recorded from the HEU outlet immediately after activation when the initial temperature was 10.4°C giving an increase of 51.3°C. The water temperature was reduced to 51.3°C within 10 minutes and then cooled to 40 °C within four hours. The HEU was deactivated after 13 hours and the water temperature had decreased to 35.1°C at this point. The outlet water temperature drops to 0.5°C upon deactivation of the system after 24 hours without heat input. This general pattern was repeated nightly except lower temperatures were recorded each night. The peak temperature was reduced to 37.9°C from an initial temperature of 7.2 on the last day of heat extraction (528 Hours) giving an increase of 30.7°C. On the 18th day (432 hours) the system was off for two days and is reflected on the graph where it drops below 0°C without the addition of heat energy. This allowed the compost to transfer more heat to the water inside the pipes the following day (456 hours) where there was a higher peak of temperatures briefly. During the heat extraction phase the water temperature for the majority of the time (6 – 9 hours a night) was between 40 and 30°C for the first four heating periods. During the following seven heating periods this had decreased and the water temperature was between 20 – 30°C for the majority of the night before the HEU was deactivated. Although there was missing data from the Tinytag malfunction the temperature profiles here show heat was delivered in the radiator within the shed although at a steadily declining rate. Increases in internal shed temperature would have declined correspondingly also.

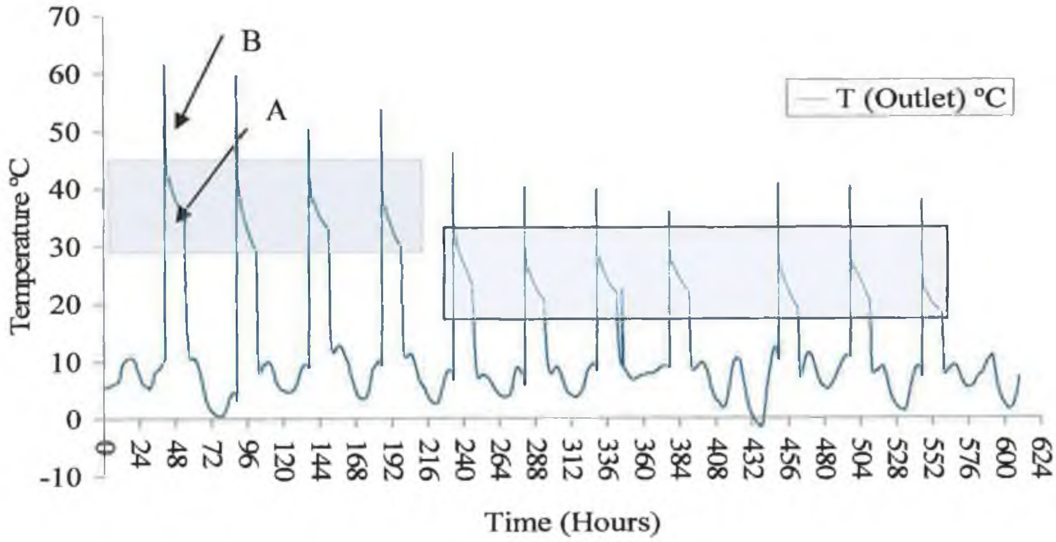

Figure 4.5: Water temperatures from the outlet pipe of the HEU recorded over 26 days from 29/02/08 to 25/03/08.

4.4.1.2 Kingspan

Figures 4.6 and 4.7 below show the temperature profile of the Kingspan insulted shed experiment over 22 days. HEU activation times are highlighted with shaded boxes. During each 24 hour period two increases in temperature were observed in the shed representing the night-time HEU heating and the ambient heating from the sun during the day. On the night of the 10/05 temperatures increased from 12.5 to 23.5°C an increase of 11 °C. This pattern was repeated the following night where there is a steady decrease in night temperature to 13.7°C on the 11/05 and then a sharp increase to a peak of 26.5°C when the HEU was activated giving a 12.8 degree overall rise. This pattern continued for the duration of the experiment, although the nightly increase in temperature was reduced with an 8 degree rise in temperature on the 21/05. The HEU was not activated on the 22/05. The general increase in temperature in Figure 4.7 was related to ambient temperature increases over this period, which is represented on Figure 4.8. It can be seen here that average outdoor temperatures are decreasing over the first half of the experimental period and rise over the second half. On the last day (31/05) of the experiment the temperature of the shed was still being increased by the addition of thermal energy from the HEU. It was elevated from 14.8 to 21.4°C, an increase of 6.6 degrees on this occasion.

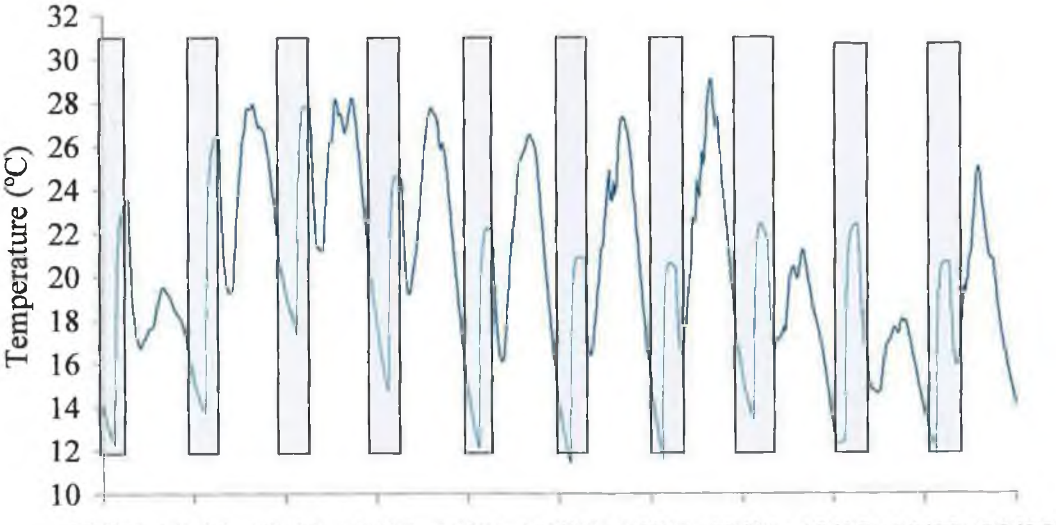

Figure 4.6: Internal shed temperature over a period of ten days in May 2008.

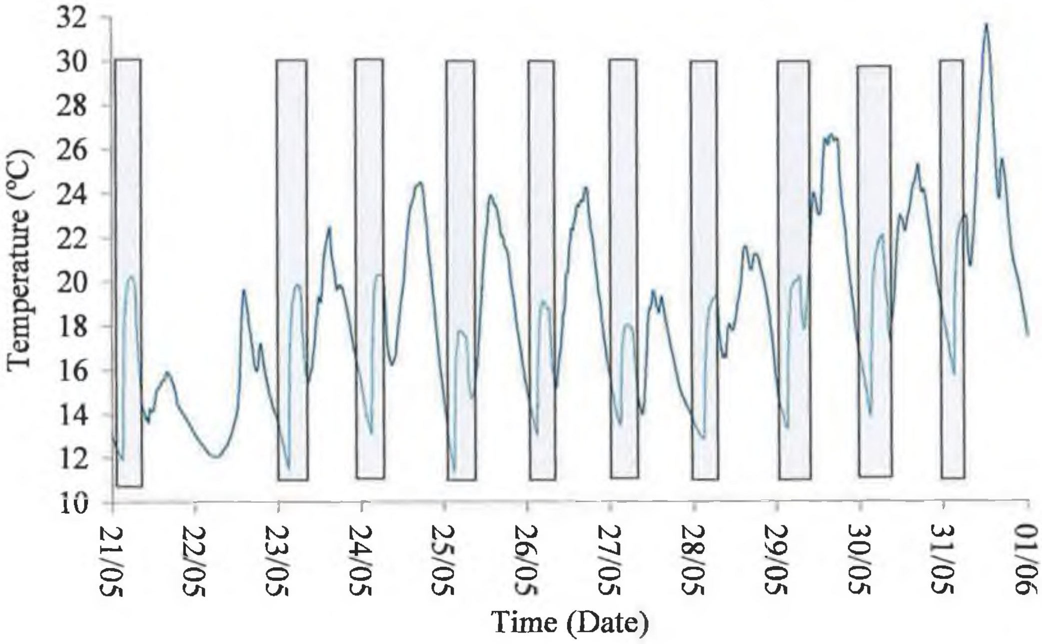

Figure 4.7: Internal shed temperature over a period of 12 days in May 2008.

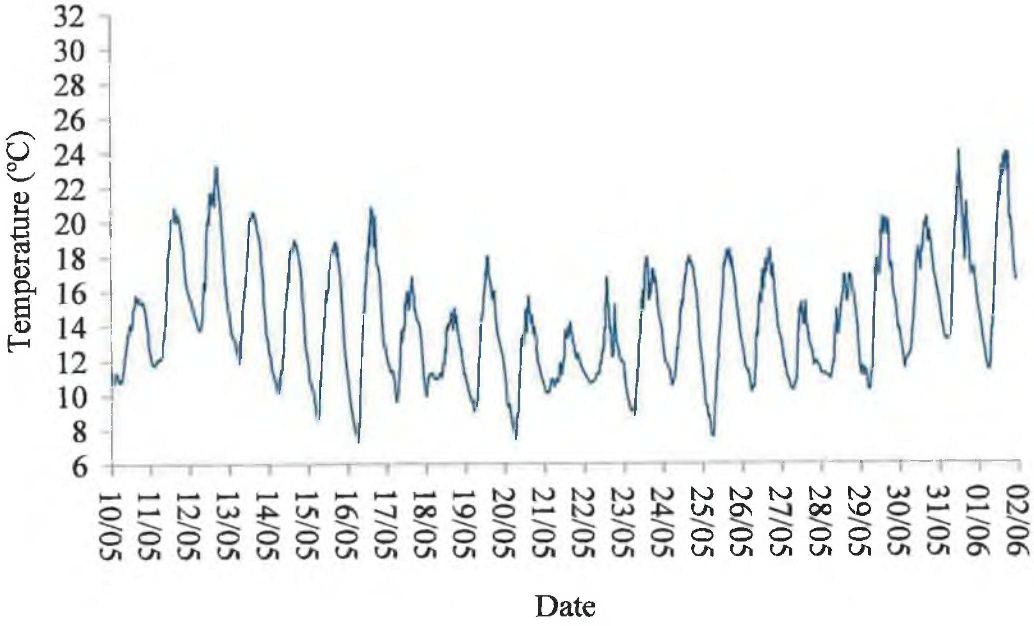

Figure 4.8: Outdoor ambient temperature for May 2008.

Figure 4.9 shows the pipe outlet temperatures from the HEU taken during the second insulated shed experiment in May 2008. Maximum temperatures of 70°C were recorded on day 2 (48 hours) and 3 (72 hours) before decreasing to a low of 50°C by day 17 (408 hours). There was an increase in thermal energy after day 17 (408 hours) and over the following 3 days before water outlet temperatures began to decrease again. These peak temperatures lasted between 5 and 10 minutes. In general, during HEU activation the water temperature exiting the unit was between 15 and 20°C below these brief upper peaks at between 30 and 50°C. A sharp daily drop was then observed in pipe outlet temperature once the unit was deactivated as can be seen on Figure 4.9 (Point A). On day 12 (288 hours) the unit was not activated.

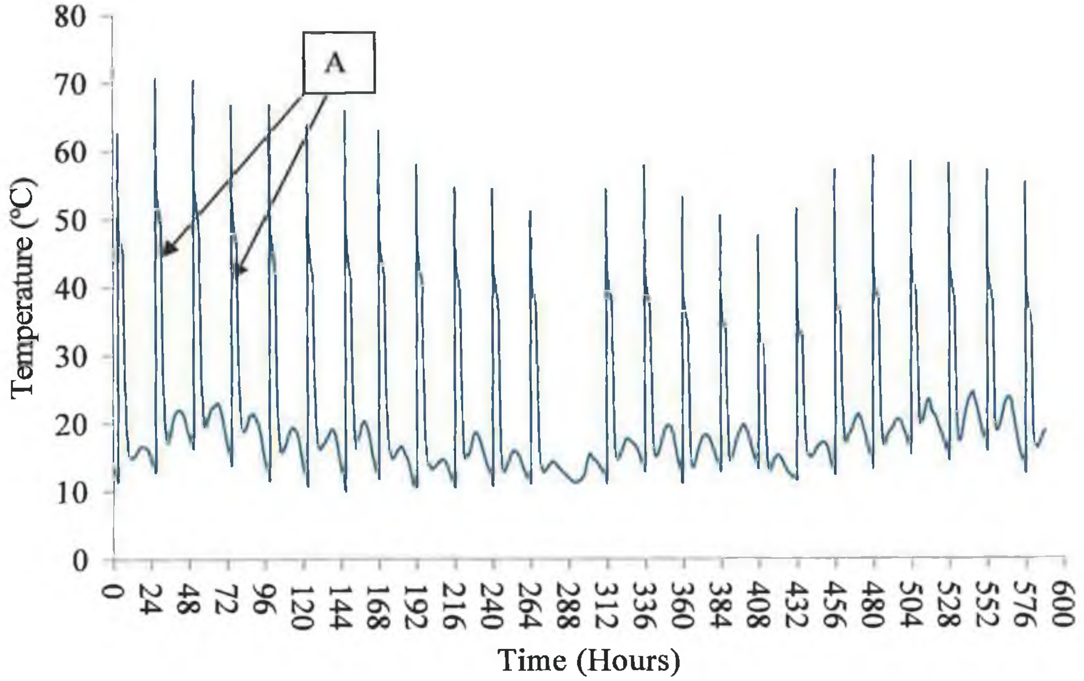

Figure 4.9: Pipe outlet temperatures of the HEU during the insulated shed experiment in May 2008.

Figure 4.10 shows the coefficient of performance (COP) of the HEU during this trial period. A high COP was recorded throughout the trial period with a peak on day two of heat extraction of 7.4. This is reduced to a low of 2.5 on day 18. There was a zero COP on the 22/05 (day 13) as the unit was not activated.

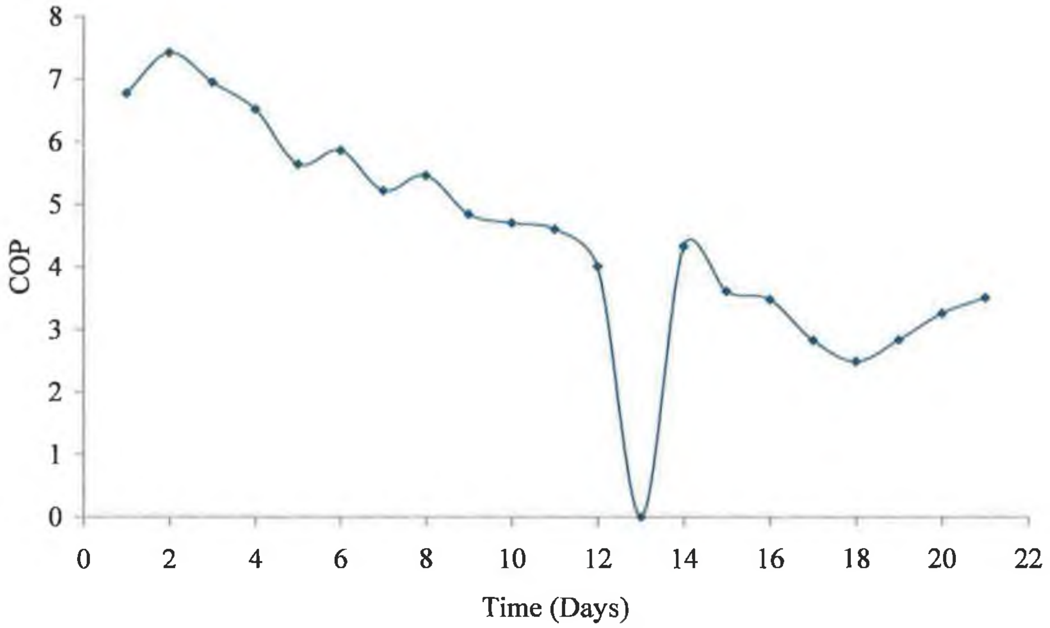

Figure 4.10: Coefficient of performance of the HEU during the Kingspan insulation trial.

4.4.2 Hot Water Heating.

The HEU successfully heated the water in the 60 litre hot water cylinder for 33 days. The data is divided into 3 graphs for ease of viewing with the shaded area representing time periods when the HEU was activated and delivering heat to the hot water cylinder. Figure 4.11 shows the temperature profile of the water inside the cylinder during the first 10 days of heating. The peaks within the shaded area are the highest temperature points the water reached during the heating phases. The troughs between them represent the temperature of colder replacement water that was used when the heated water was drained off. The water was heated from 16.2 °C to 45.1 °C on day 1 (0-24 Hours). Once the HEU was deactivated there was a slow decrease in temperature to 37.9 °C and then a sharp decrease to 19.1 °C on day 2 (24 Hours) with the removal of the heated water and addition of fresh tap water. This sharp drop can be seen in the second shaded area. Within this area also is the second peak where water temperature rises to 55.6 °C from 19.1 °C with HEU activation as compost temperature rose to above 70 °C. There is no slow decline on day two as the water was emptied immediately after the five hour heating cycle was completed and the second sharp drop in temperature was observed where it decreased to 21.1 °C. On day three (48 Hours) cylinder hot water temperature peaks at 55.0 °C from a starting point of 21.3 °C. During next 7 days (72-240 hours) this pattern was repeated whether the water was changed on the same day or the following morning a series of peaks is observed with an mean of 47 °C each day.

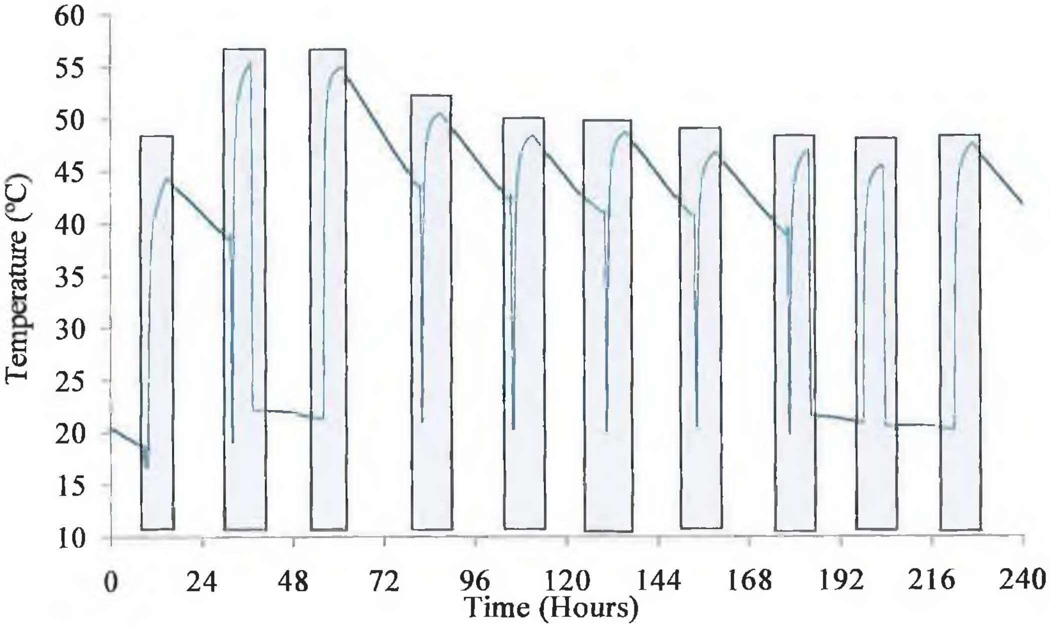

Figure 4.11: Temperature profile of the water heated in a hot water cylinder over a 15 day period in July / August 2008 (Days 1-10)

Figure 4.12 shows the temperature profile of the water inside the cylinder for the next ten days (240 – 480 Hours). The water was not emptied on day 11 (240 hours) and no sudden drop in temperature can be observed in the first shaded area. As a result the water was heated to a higher temperature of 51.8 °C on this day when compared to day 10 (47.2 °C). During the next three days the HEU was activated once (Day 12 – 288 Hours). The HEU was not activated on day 11 or 13 (264 and 312 Hours). Figure 4.13 shows the temperature profile of the water inside the cylinder for the final thirteen days (480 – 816 Hours). A steady decline in peak temperatures from Figure 4.12 on into Figure 4.13 can be seen with the final peak of 37 °C on day 32 (768 Hours). The HEU was activated every second day after day 23 (552 Hours) as is shown on Figure 13.

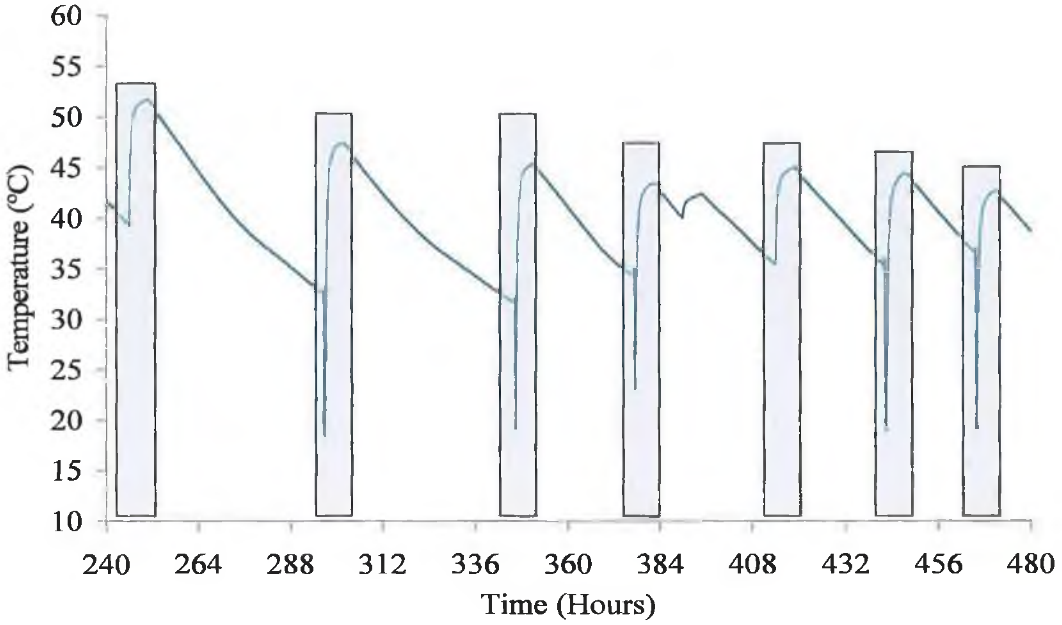

Figure 4.12: Temperature profile of the water heated in a hot water cylinder over a 10 day heating period in July / August 2008 (Days 11-20)

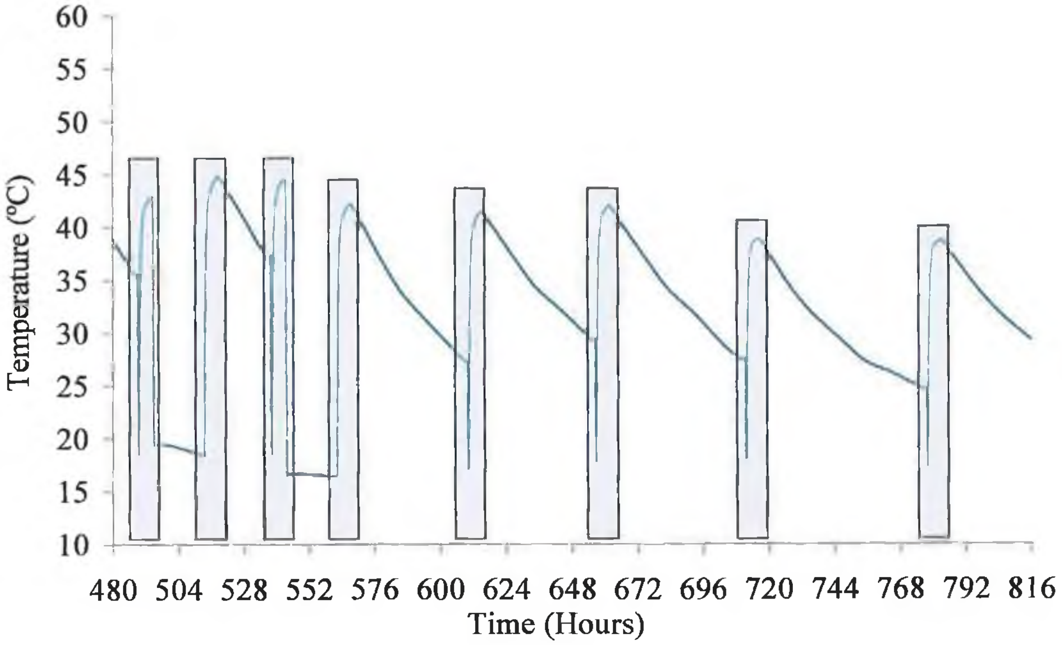

Figure 4.13: Temperature profile of the water heated in a hot water cylinder over a 9 day heating period in July / August 2008 (Days 21-33)

4.5 Discussion

4.5.1 Space Heating

The compost powered HEU was capable of heating the test shed and with the addition of extra layers of insulation internal temperature increases of up to 13 °C were recorded. In terms of energy used in residential buildings in the European Union space heating accounts for 57 % of the total (Bolattürk, 2006). A significant quantity of this energy is generated through direct burning (oil & gas) and indirect (electrical) burning of fossil fuels. Direct use of primary energy resources such as fossil fuels in conventional heating systems without any cogeneration has very low exergetic efficiency (Kilkis, 1999). Oil, gas and coal remain the primary fuels used within developed economies with combustion of biomass the predominant mode in less developed nations (Omer, 2008b). The increase in the use of renewable energy technologies for space heating is due to the finite nature of fossil fuels, increases in their price and adverse environmental effects from their pollution. Therefore renewable or alternative sources of energy will play a major role in space heating into the future.

Aerobic digestion of biomass as described in this study is a form of renewable energy and waste management. The potential for this energy to replace some of the fossil fuels used for space heating is dependent of a number of factors. The availability of organic matter to fuel the compost HEU would be a limiting factor. The quality of such organic matter is important in terms of extracting the maximum thermal energy. Horse manure based compost is more efficient at maintaining high temperatures over longer periods when compared to freshly cut grass based compost (Fitzgerald, 2009). These factors along with the need for machinery such as a tractor to move the HEU would leave the technology open mainly to rural agricultural operators and the equine sector. Compost space heating maybe more suitable for underfloor heating applications (Chapter 3, section 3.5.4) with more research required to confirm this. The relatively inexpensive low-tech compost HEU designed and used here attempts to use this form of renewable energy for space heating and therefore compost heat extraction may be a viable heating system given the correct conditions.

Although the HEU developed here uses a low-tech approach to space and hot water heating it has been predominantly high-tech research that is being conducted recently. Current 'high-tech' research in the design of aerobic heat extraction systems is being carried out by Winship *et al.*, (2008). A 'combined heat and composting' system has been set up using large metallic containers (Aergestor) that can be rolled on and off trucks for transport to where heat is required. The heat is envisaged to be ideal for large buildings such as leisure centres, office blocks and apartments. This technology has a net benefit in energy terms and deals with 25 times the volumes of the HEU but is a more expensive option and more heavily mechanised. Tucker (2006) describes a large scale compost heat extraction facility in the USA. Isobar heat pipes were placed adjacent to 60 foot windrows and with the aid of forced aeration water vapour from the compost condenses on the heat pipes, heating them and transferring the energy to heat a reservoir of water. No container is needed for this system and 600-800 tonnes of compost can be accommodated within the barn giving a continuous supply of heated water at 55°C which is increased to 68°C with the aid of oil burners. At $450,000 for the prototype it is far more expensive than the HEU developed here and very large organic matter supplies are also required to make it cost effective. Rogers (2006) describes heat extraction using two large metal in-vessel composters with 1587 kg/day capacity. A set of pipes with spikes pushes into the chamber and water flows through extracting heat. The removal of the heat exchanger spikes allows the compost to be removed more easily. The heat captured was delivered to adjacent buildings although a low COP made it a net energy loser. In environmental terms the low-tech choices as developed here creates a more localised solution for bio-wastes which is in line with EU waste directives. The high-tech solutions described use more transport to operate decreasing their environmental efficiency.

Results from both insulation experiments including maximum temperature increases 7°C and 13°C from the bubble wrap and Kingspan trials respectively have shown that when heating an insulated building the HEU has the potential to be utilised for space heating. Thermal conductivity is a critical factor when compared to previous experiments of heating of an un-insulated polytunnel. Lower U values of 1.6 W/m^2K and 0.53 W/m^2K for the bubble wrap and Kingspan insulation shed experiments respectively contrast to 10

W/m^2K for the polytunnel. The smaller volume of the shed ($22m^3$) was also a factor in the higher temperatures recorded when compared to the polytunnel ($47m^3$) where 2-3°C increases were recorded.

Compost within the HEU remained at temperatures above 60°C for a longer period during the second insulation experiment (Fitzgerald, 2009). This extended period allowed usable heat to be extracted for a longer period and therefore increased the performance. There is natural variation in the total heat output and length of heat output within compost made of similar feed-stocks and between composts of differing feed-stocks. Mixing the organic matter (horse manure for these experiments) with the correct amount of woodchip and sawdust giving a carbon nitrogen ratio of 30:1 was important in developing consistent heat output. This may have varied in the experiments as the mixing was completed by hand. Difference in aeration and moisture content of the compost with the HEU can lead to variation in compost temperatures. The rewetting of the compost increased microbial activity and thermal output during the Kingspan insulation experiment (Fitzgerald, Pers. Comm.). During this experiment the unit was activated for 3.5 hours unlike the 13 hour heating period used during the first experiment. This 3.5 hour timing period is more likely to be used in a residential heating situation which gives a more realistic evaluation of the heating behaviour that the unit could be employed in. It also allows more time for further thermal energy to be transferred to the process fluid from the compost. If ideal conditions can be achieved within the compost, the efficiency of the system would increase due to maximum heat output and reduced pumping time making the HEU viable option for small scale heating applications.

4.5.2 Coefficient of performance

The COP during the Kingspan insulation experiment was calculated and the results showed high COP values ranging from 7.4 to 2.5 over 21 days when heat was extracted. At its peak performance 1 joule of electrical work input allows the transfer of 7.4 joules of thermal energy from the compost to the radiator. Once COP is above 1 it is energy efficient to use the pump to extract the thermal energy from the compost. Thus at no time during the 21 days of heat extraction was the HEU working inefficiently. A typical air-source heat pump has a COP of 3 – 4 and a geothermal heat pump 3.5 - 4.5. The overall COP of the HEU during this trial period was 5 which shows its high efficiency in extracting thermal compost derived energy. However heat pumps use no man power in their day to day usage unlike the HEU where the organic content must be mixed and changed at regular intervals. The heat pump has similar advantages as the electric heater evaluated here in that regard.

When discussing efficiency of an electrical appliance it is important to consider the Primary Energy Ratio (PER) which is calculated by multiplying the COP of the device by the electrical power generation efficiency. It is particularly important with regard to CO_2 emissions and the environmental consequences of that generation efficiency. The more efficiently the electricity is generated and transmitted to the end use site the less CO_2 is released. The higher the renewable energy makeup of a countries power supply the higher the generation efficiency. Ireland had a generation efficiency of 0.44 (Howley *et al.*, 2008). That gives the HEU a thermal performance PER of 2.2 during this trial period. Countries such as Norway and New Zealand with very high renewable energy output due to large Hydro-electric capacity have much higher generation efficiencies. Similar electric devices used in those countries will indirectly cause the release of less climate changing gases such as CO_2. Generation efficiency increases in Ireland by 1.8% a year which makes the use of technology such as the HEU more environmentally efficient every year. By employing renewable energy to power the pump it would create a fully renewable power source.

The overall performance of the compost HEU could be improved with modifications on a number of issues. Building regulations from 2007 state U values of 0.16 W/m^2K for the roof, 0.27 W/m^2K for walls and 0.25 W/m^2K for the floor are required for new buildings. In this study the floor in the test building was unsealed and had no insulation. Experiments conducted using the HEU on a building with these U-values or lower would result in significant improvements in heating capability. Another potential method of improving the HEU efficiency would be combining it with an under-floor heat distribution system. The moderate but consistent water temperature (30-50 °C) coming from the HEU would suit an under-floor heating plan where heat is distributed more evenly across the building. This method of heat transfer uses lower temperature process fluids in comparison to the 60-70 °C water temperatures needed for effective convection from radiators. A combination of a modern sealed highly insulated building and a piped underfloor heating system could allow a significant increase in the size of the building to be heated with this technology creating more of a commercial possibility in the development of this product.

4.5.3 Hot Water Heating

The compost powered HEU increased cylinder water temperature from 25 - 35°C above ambient over a one month trial period. This experiment was conducted using a 60 litre domestic hot water cylinder. This volume of heated water has the potential to assist various daily domestic or farm yard applications. However with domestic hot water demands of between 40-60 litres a day in Ireland (Roth, Pers. Comm) the use of this technology could provide partial energy in a similar fashion to solar panels. Domestic hot water in Ireland is heated in much the same way as for space heating through the burning of fossil fuels either directly (oil) or indirectly (immersion). However the use of this form of renewable energy could alleviate some of the demand for CO_2 emitting fossil fuels and provide a buffer against sudden fuel price increases. During the warmer months space heating is not required however hot water is still in use and electricity is used to power showers and immersions. Generating heat during the warmer months is potentially easier also due to the greater availability of waste biomass (Fitzgerald, 2009). Therefore optimum use of the HEU could be achieved by utilising it for hot water heating in the summer and space heating during the winter period. Renewable compost energy as described here could potentially be utilised by small operators or rural dwellers that have access to the appropriate feed-stocks.

Chapter 5

Cost Benefit Analysis (CBA)

5.1 Abstract

A Cost Benefit Analysis was carried out on the HEU technology developed for this project. It examined the 4 way heating analysis of the polytunnels used, the 'Roll n Grow' heating mat experiment that was conducted and the insulated space heated trials. There was no benefit in terms of plant production for the polytunnel trials for any of the heating technologies. The electrical heater was more reliable and efficient at heating in comparison to the HEU and the Cost Benefit Analysis (CBA) showed that the HEU would not be suitable for heating the entire polytunnel. The Roll n Grow heat mat experiment showed that when compost derived heat is focused onto the roots of plants, production is improved. Further research is needed to show the extent of the possible monetary benefits. The insulated space heating trials were promising in that significant temperature increases were recorded using the HEU and so depending on economic conditions such as the price of oil the HEU could be considered as a viable heating device.

5.2 Introduction and Project description.

This CBA consists of a project description, a list of the alternatives methods used during the testing, identification of the cost and benefits and finally the comparison of these parameters. A compost heat extraction unit (HEU) was designed to utilise waste heat from decaying organic matter for heating horticultural polytunnels between January and March 2008 and again in November 2008. The HEU was also investigated for its space and hot water heating potential during May and July 2008. This report investigates the cost benefit analysis (CBA) of various thermal energy sources and their application in polytunnels and the HEU when applied to an insulated test space and hot water cylinder. A conventional electric fan heater was compared to renewable energy alternatives such as solar and waste heat from biomass such as compost (farm and municipal) and slurry within a polytunnel environment. Temperature inside the polytunnels was measured and plants were cultivated as an indicator of performance of the various heat treatments including a control. The technologies are compared over a three month period. A separate experiment involved using growing mats as part of a heat distribution system for cultivating various plant species.

The aim of the project was to develop an efficient system for extracting the available heat produced by aerobic decomposition. The unit was be low cost, constructed using local materials and be simple to operate to allow for the uptake of this technology. The project had a lifespan of two years between design, development, and implementation of field trials. CBA provides a means for systematically comparing the value of outcomes with the value of resources achieving the outcomes required. It is the economic efficiency of the proposed technology which is measured. A note of caution should be considered before an evaluation of CBA is carried out. Hanley (1992) and Puttaswamaiah (2002) argue that there can be intrinsic problems when applying CBA to projects involving environmental or conservation analysis. These include irreversibility of damage to ecosystems, the complex nature of ecosystems and the discounting rate often used in CBA which gives value to parameters into the future is difficult to apply.

5.3 List of alternatives scenarios

There were 4 alternative scenarios for the first set of plant cultivation and heat analysis experiments. These included 4 polytunnels heated by a) solar panel, b) electric fan heater, c) Compost heated with the HEU and radiator as the heat distribution system and d) Control, no addition of heat as described in sections 3.3.1, 3.3.2 and 3.3.3. Garlic plants were sown in each and shoot length was measured on a weekly basis. The second experiment was comprised of 2 alternative scenarios of a polytunnel heated using 'Roll n Grow' mats distributing the compost derived heat and a control without heat added. 4 plants were cultivated in each to see was there a benefit of using the growth mats. The space heating experiment involved heating an onsite test space with the compost derived heat and this was compared to the same building without heat added.

5.4 Benefits and costs identification.

5.4.1 Polytunnel Air Heating

5.4.1.1 Solar Panel

The initial cost of the solar panel including installation was € 3479.69 and Table 5.1 shows the breakdown of these costs. During the test period of heating the polytunnels from January to March the single panel system did not produce enough heat to elevate water temperature in the dual coil cylinder above 30 °C which was the predefined temperature set to activate the pump. Thus no heated water was pumped to the radiators and no net benefit was received from the solar panel within the crucial winter heating period. It was April before results allowed heated water to flow to the radiators and polytunnels temperatures were heating up significantly with natural solar energy at that stage. No addition of heat energy was required then. The electrical cost of running the solar panel during this period was €0.73 which is very low because of the lack of pumping energy required. No net benefit was gained using the solar panel with the March solar flux not strong enough to heat the water sufficiently.

Table 5.1: Solar Panel purchase and installation costs breakdown.

20 tube standard steel	1	619.83	749.99
Roof mounting kit	1	14.88	18
Tyfocor ls solar anti freeze	1	48	58.08
Anti-syphon valve	1	4.96	6
Resol controller Resol BS/3	1	161.2	195.05
Auto air vent Inc. isolator 3/8"	1	28.5	34.49
Air separator	1	45	54.45
VA32 Motorised divert valve	1	123.14	149
Ma1 HIGH TEMP MIX VALVE	1	66.75	80.77
sp1 lightning arrestor	1	15.29	18.5
135 litre dual coil copper cylinder	1	505	611.05
Pressurised system kit	1	91	110.11
Carriage	1	100	121
Installation of solar panel	1	881.06	1,000.00
1600x300 2p select rads	1	133.00	133.00
1600x300 2p select rads	1	133.00	133.00
pairs 1/2" rad valves	1		7.20

5.4.1.2 Compost Heat Extraction Unit

The compost HEU was constructed from locally produced or purchased materials at a cost of €2111.82. The breakdown of those components is shown in Table 5.2. There was approximately 8 hours of labour involved in the construction of the unit which consisted of building the heat exchange system and the insulated cover. No cost was be added for the labour as it would be part of the general cost if a unit was to be manufactured commercially.

Table 5.2: Breakdown of the construction costs (€) of one Heat Extraction Unit

Description	Number	Unit Cost	Total Cost
Construction Costs HEU			
Marine Plywood 18mm	2	58.5	141.57
Scotch Tee hinges	4	10	48.40
Glycol	2	58.94	142.63
1" nail on clips	100	100	24.2
1" talon clips	50	50	18.15
1600x300 2p select rads	1	133.00	133.00
pairs 1/2" rad valves	1		7.20
160m 1" Qualpex			464.00
1" inserts	24		11.62
3m 1/2" qualpex			2.9
1/2 inserts	6		1.45
1" 310 straight connector	10		58.08
1" 367 gate valve	2		21.78
1" 350 tank connector	1	4.2	5.08
6 x 40 screws only	20	0.06	1.45
TROUGH INSULATION 25MM	1	332	401.72
1" pump valves (pair)	1		9.66
Grundfos 15/50 circulating pump	1	180.45	218.34
450 gallon tank	1	326.27	394.66
10 gal PVC tanks	1	4.9	5.93
Total			**2111.82**

Woodchip and sawdust were used in the mix for the organic animal farm and municipal waste streams. The cost of one load of locally derived woodchip was €100 which lasted for ten fills of the HEU giving a cost of €10 per load. Recycling of this wood chip from the horse manure heaps was achieved through sieving the manure post heat extraction which reduced costs and extended the life of the woodchips. The saw dust used in the mix cost € 2.50 per bag from a local sawmill which was enough for 1 fill of the HEU. The biomass waste used in this section of the project was free locally derived horse manure and represented the organic farm waste component of the analysis. The transport cost associated with it was minimal (€7 per fill). There was an electrical cost of €1.65 for the HEU during the trial period. The benefit of using the HEU was the low cost of the fuel, and the heating of the polytunnel during the test period of between 2-3°C above the ambient.

The benefit of composting slurry in the HEU was negligible as no usable heat was derived from it and was not considered within the CBA (Fitzgerald, 2009). Grass cuttings were composted also and represented the municipal organic waste stream. The grass was free locally derived organic matter. The benefit in heat output terms was small for this waste stream and horse manure was primarily used for the experiments.

5.4.1.3 Electrical Heater

The Bio Nevada 2.25 KW electrical heater cost €400 to purchase for the trial period. There was no installation cost and electrical energy consumed during the trial period (one compost cycle of 20 days) was €56.43. The benefit of this unit is the reliability of its functioning, maintaining the polytunnel at the required preset temperature of 10 °C throughout the trial period.

5.4.2 Polytunnel 'Roll n Grow' Heating

The alternatives within this section were plants grown with compost derived heat using the Biotherm Microclimate Roll n Grow Tubing' and those grown without heat in a control polytunnel. The cost of the compost HEU was slightly cheaper when using the mats. The cost of the mat was €75 as opposed to €133 for the radiator in the air heating experiment. There was no cost to the alternative control tunnel. The benefit was improved crop production within the heated polytunnel.

5.4.3 Insulated Space Heating

The onsite shed was used for space heating trials. The cost of the HEU is identical to section 5.3.1.2 and there was no cost to the alternative of a non heated space. There was a net benefit of a rise in temperature of 7°C in internal shed temperatures when using the HEU as opposed to non heated space.

5.5 Discussion

5.5.1 Polytunnel Air Heating

Table 5.3 shows the overall costs and benefits of the various technologies tested during the polytunnel air heating experiment. The solar panel was by far the most expensive at €3336.73 due in part to the large installation cost of €1000. The potential problem with more complex technologies is the expertise needed to install and service these as opposed to the HEU developed here which uses minimal technology. Although the time/labour needed to maintain the system is minimal and electrical costs are low the single panel solar system used here is ineffective at giving any benefit to the air heating or growth of plants during the winter/spring within the polytunnel.

Table 5.3: Overall costs and benefits of the various technologies tested in the polytunnels air heating experiment during a 20 day heating cycle.

Costs (€)	Solar	Electrical	HEU	Control
Direct Cost	2479.69	400	2111.82	0
Installation Cost	1000	0	0	0
Electrical Costs	0.73	56.43	1.65	0
Fuel (Woodchip)	0	0	10	0
Fuel (Sawdust)	0	0	2.5	0
Fuel (Manure)	0	0	7	0
Total	**3480.42**	**456.53**	**2132.97**	**0**

Benefits (€)	Solar	Electrical	HEU	Control
Heating efficiency	None	High (10°C)	Low (2-3°C)	None
Maintenance	Low	Low	High	None
Plant Growth Rates (mm/day)	7.9	8.3	7.5	6.5

The HEU tested here is a slightly more effective system for the winter heating of the polytunnel. It has a lower construction cost of € 2111.82 and a maximum cost for one cycle of heating of €21.15. The fuel cost could be significantly reduced with the recycling of woodchips and the use of onsite organic matter such as horse manure if available, reducing transport costs. The cost of the electrical heater was the smallest at €400. It is a locally available product and is easily installed which reduces costs. A comparison of the electrical energy used over the 3 month growth trials shows that the electrical heater was significantly more expensive to use than the HEU. The unit cost of electricity per kWh on the farm during the experiment was €0.1705. The 'Bio Nevada' electrical heater used approximately 1492.2 kWh of electrical power over the three months giving a monetary value of €288.76 which compares to 43 kWh of power (€ 8.31) consumed by the pump driving the compost HEU.

Although the fuel costs of the electrical heater are higher than the HEU the benefit of low maintenance and high heating efficiency would outweigh these consideration for the grower who needs reliability. The electrical heater worked far more efficiently keeping the internal temperature at 10 °C unlike the HEU which only kept the temperature approximately 2-3 °C above the control tunnel. The HEU required approximately 8 hours of labour over the compost heat extraction cycles of 20 days during this trial period. That time was made up of 6 hours for the pre-mixing of the organic matter and 2 hours in aeration of the compost during the trial. The electrical heater requires no labour or daily maintenance. Organic growers predominantly don't heat their tunnels due to the prohibitive costs, thus neither of these technologies would be viewed favourably by growers in Ireland.

The common garlic (*Allium sativum)* that was successfully grown in the 4 polytunnels (Solar, electrical, compost heated and control) was sold locally for €24 (€12 per kilo). There was however no significant difference in growth rates between the tunnels so no advantage was gained by heating the polytunnels for this particular product. Thus the main potential benefit from heating of the tunnels was equal in each of the 4 heating trials. Therefore although the 2-3°C could help with the prevention of frost damage to crops the prohibitive costs of the HEU would outweigh the benefit of this low heat for the air heating method within a polytunnel environment.

Slurry sourced on the project farm represented the second type of organic agricultural waste to be tested for heat extraction potential. No increase in temperature was recorded during the test phase and thus no heat could be extracted and no cost saving accrued. Grass cut on the farm represented the municipal organic waste component of the analysis. During the trials the grass filled HEU did not perform as well as the horse manure filled HEUs. The temperatures peaked quickly and dropped at a faster rate (Fitzgerald, 2009). Thus less heat was extracted and an overall lower net benefit was achieved through this feedstock over the manure feedstock. The costs are significantly higher than the benefits when using the grass based feedstock for this type of heating.

5.5.2 Polytunnel 'Roll n Grow' Heating

The results for this experiment were more positive in terms of plant production. Although no statistically significant difference in growth rates were observed it was higher in each of the 4 plant types grown. Other indicators such as leaf area, leaf number, damage to the foliage and plant mortality were all more favourable within the compost heated polytunnel. The potential benefit of using this heat distribution method along with the HEU could be significant although a longer research period is required to confirm this. The improvements outlined in section 3.5.4 to the 'Roll n grow' mat along with a higher density of plant production could see the realisation of these benefits which could outweigh the costs of the unit.

5.5.3 Insulated Space heating

The shed was heated successfully over a period of a month in May while the pump of the HEU was activated for 3.5 hours each night. The space heating experiments were more successful when using the insulated shed (1.6 W/m^2K) as opposed to the high U-value polytunnel 9.5 W/m^2K. Although the cost of the HEU and fuel remain the same the benefits are more obviously significant. The test shed was heated to 7°C above the non heated space on alternative nights showing the minimum criteria for CBA. The improved U-value (0.53 W/m^2K) of the second insulation experiment (Kinspan) allowed the test building temperature to increase 12.8°C using the HEU. The cost of the electricity (€ 0.1705 per unit) used (3.9 kWh) during this time was €0.66. Although time and resources did not allow comparisons with other heating technologies it can be seen from the results that the real heating benefit of the HEU exists. This could be improved upon by using under-floor heating as it requires a low temperature process fluid in its operation as opposed to the 60°C water needed for most radiator heating systems. The CBA of this technology for insulated space heating is largely dependent on the price of fossil fuels. The arrival of peak oil will allow technologies such as this much higher benefits or lower costs in a CBA when compared to traditional heating methods which could become prohibitively expensive as oil price rise. Thus although the HEU may be expensive under current economic conditions a change of these parameters along with a more efficient use of the technology could allow it become a more viable technology in the future.

Chapter 6

Overall Discussion and Conclusions

6.1 Overall discussion

The aim of developing a renewable energy compost heat extraction system capable of delivering heat to various applications was achieved to varying degrees of success. Increasing interest in developing renewable energy technologies (RET) began during the oil shocks of the 1970's (Islam *et al.,* 2004). However non renewable energies such as fossil fuel combustion and nuclear power still account for 87% of global energy produced (IEA, 2008). Therefore RET have a large gap to bridge in order to supply clean energy to the world and reduce climate changing CO_2 emissions. A reduction in the amount of energy we use along with development of localised green technologies such as the compost HEU discussed here could assist in this task.

The use of biomass as a renewable energy is one of oldest forms of energy used by mankind. Today it accounts for 4.4 % of renewable energy generated with hydroelectricity at 88 %. (IEA, 2008) The majority of biomass energy is involved with the combustion of the organic matter and is being developed across the globe (Matsumura *et al.,* (2005), Filho and Badr, (2004), Tripathi, *et al.,* (1998)). Of the non combustion methods it is anaerobic digestion which is the most widespread technology used. Recent papers argue they might not be the most appropriate technologies for environmental reasons. Braungart, (2008) argues there should be no such thing as waste and a 'cradle to cradle' paradigm should be developed so that all materials biological and technological are designed for the next process rather than combustion for example. This creates a continuous cycle where waste is not avoided or minimized, there is no waste. De Bertoldi, (2008) agrees by saying that all organic wastes are valuable and by composting them and returning the nutrients to the soil, fertility is maintained and CO_2 and methane emissions are reduced. Winship *et al.,* (2008) makes the point that anaerobic digestion produces inflammable gasses and corrosive liquids and therefore the engineering systems used may be less environmentally friendly and more expensive to operate than aerobic digestion technologies.

The heat extraction unit (HEU) developed here uses the aerobic digestion pathway in its design. It is constructed of local materials and employs minimal technologies. It uses local sources of organic matter in its operation and the continuous nutrient cycle would be achieved by returning the mature compost to the local soils. This would help modern agricultural systems to create healthy soils rather than degrade them as with current practices (de Bertoldi, 2008) and reduce the energy and oil needed for artificial fertilisers (Winship *et al.,* 2008). The viability of a localised technology such as the HEU is affected by the price of fossil fuels however, which are used in the majority of space and hot water heating application in this country. Peak oil will have a major effect on the price of these fuels (Hanlon and McCartney, 2008). However it is the 'Carbon tax' or a 'Cap and Trade' system which will have a major effect on a more definite timescale. In Ireland the Programme for Government 2007–2012 states that carbon tax will be introduced in the life time of the government with details to emerge at the end of 2009 (Callan *et al.,* 2008). With the price of oil rising globally even during a deflationary economic cycle the recent drop in the price was most likely a temporary drop in the overall trend of increasing prices. Such increases may create the economic conditions where by the HEU with its high coefficient of performance could become a more viable option. The Building Energy Rating system that has been introduced to all buildings this year could help this technology into the future. The efficiency of building insulation and air tightness will increase as a result meaning a reduction in the amount of energy needed to heat buildings. The low-intensity sustainable heat extracted using the HEU could replace some of the finite fossil fuel based heating systems currently in use.

Although one of the aims of the project was to create a device that small and unskilled operators could build and operate such as the HEU, constraints to the development do exist. A ready supply of organic matter is essential to the operation of the device. In this regard the horse manure feedstock tested was far more efficient at generating heat over longer periods than the municipal grass based feedstock (Fitzgerald, 2009). This could be a constraint for operators without access to this feedstock. The recent trend of collecting organic waste from houses across the country is positive in that it keeps valuable nutrients from landfill and redistributes them back on the land. However this may be detrimental to the development of this technology if large quantities of organic matter are being centrally processed where thermal energy is wasted, rather than being locally processed for heat extraction. The current mindset of investing in large scale technological solutions to energy supply issues such as wind, wave, and anaerobic digestion plants may hinder the development of small scale devices such as the HEU. Renewable electricity generation may be the primary focus in the short to medium term in Ireland due to the large potential for wind and wave energy which could mean less research into technologies such as the HEU. Further research needs to be conducted if a path to commercialisation of the device is to be realised. Although the energy from the device is relatively small at 3 kWh/ day, with its high coefficient of performance, reasonably small amounts of organic matter could be used in a variety of heating applications particularly in the rural setting using this device. A commercially built product would cheaper to buy if mass produced than assembling one individual product. This would make the HEU a more feasible technology in the future.

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