**DISSERTATION**

By:

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For the fulfilment of the requirements for the degree D Tech (Mech. Eng.)

# The development and characterization of a cost-effective, renewable energy greenhouse for production of crops in atypical climatic conditions.

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# PREFACE (DECLARATION)

I, **FC AGGENBACHT,**

hereby declare that all the work included in this **Dissertation** is my own work; that none of the work included in the dissertation is a copy of the work of any other author; and that all sources (literature or otherwise) that were eventually consulted and used for completing this dissertation have been properly and completely acknowledged according to generally accepted principles of referencing.

Signed: ______________

F.C. Aggenbacht

Date: ______________

1 Jul 2017

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# ABSTRACT

The aim of this investigation is to determine if it would be financially viable to use alternative energy technologies in the heating and cooling of greenhouses that are used to grow temperature-sensitive crops all year round in the central region of South Africa. For the purpose of this study "alternative energy sources/technologies" will refer to technologies that can be used to collect energy directly from the primary source (like the sun, for example). A greenhouse was constructed and equipped with a natural ventilation system as well as a solar heating system that consisted of a flat plate solar water heater, a water storage system and a regulated heat exchange system inside the greenhouse. Cut-roses were grown in raised beds with a heat exchange system installed underneath the enclosed beds. An automatic weather station was used to read and log the climatic variables inside as well as outside the greenhouse. Data loggers were placed underneath the enclosed raised beds and inside the water storage to log the variations in temperatures. Data was collected over two growing seasons with the required alterations being made to the system for the second growing season. Extreme weather conditions were experienced during the experimental growing seasons and were very helpful in determining the applicability of the system. Data obtained from the experiment was plotted on Excel sheets, while theoretical steady-state as well as a transient temperature model were developed to determine the heating requirements during cold winter nights and cooling requirements during hot summer days. From these models the required sizes and efficiencies of the heating and cooling systems could be determined and were ultimately used to develop a financial model that could be used to determine the financial viability of applying these technologies. Results showed that naturally ventilated greenhouses could not be cooled below an internal temperature that exceeded the external temperature by at least 5 $^{o}$C. The efficiency of the constructed solar water heating system was approximately 40 %, while the required collector area was approximately 2.5 to 3 times the area of the greenhouse, making it very difficult to ensure the financial viability for the application of the solar water heating system in particular. During moderate climatic conditions a naturally ventilated cooling system can, however, be used effectively to obtained the required climatic growing requirements.

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## LIST OF ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| µm | Micrometer |
| $^{o}C$ | Degrees Celsius |
| A | Width of pressure coefficient zone |
| A | Area |
| $A_l$ | Area of the emitting leaves' surface |
| $A_{req}$ | Required area |
| $A_s$ | Surface area |
| $A_t$ | Tributary area for determination of wind loads on components and glazing |
| b | Horizontal dimension of greenhouse normal to wind direction (m) |
| CER | Carbon dioxide exchange rate |
| BM | Bending moment |
| C | Basic wind speed |
| CER | Carbon Dioxide Exchange Rate |
| cm | Centimetre |
| $CO_2$ | Carbon dioxide |
| COP | Coefficient of performance |
| $C_p$ | External pressure coefficient |
| $c_p$ | Specific heat storage capacity of water |
| $C_{pi}$ | Internal pressure coefficient |
| D | Dead load |
| d | Horizontal dimension of greenhouse parallel to wind direction ridge line |
| DC/dc | Direct current |
| dia | Diameter |
| F | Rise to span ratio for an arched roof |
| FEA | Finite Element Analysis |
| G | Gust response factor |
| h | Convection heat transfer coefficient |
| HAF | Horizontal air flow |
| $h_1$ | Height 1 |
| $h_{roof}$ | Mean roof height of greenhouse |

| | |
|---|---|
| I | Importance coefficient |
| $I_A$ | Second moment of area |
| $I_S$ | Solar radiation |
| IDPM | Integrated disease and pest management |
| IPM | Integrated pest management |
| IR | Infra-red |
| J | Joule |
| k | Thermal conductivity |
| K | Degrees kelvin |
| kg/m$^3$ | Kilogram per cubic metre |
| km/h | Kilometres per hour |
| kWh/day | Kilowatt hour per day |
| kWh/m$^2$/day | Kilowatt hour per square metre per day |
| $K_Z$ | Velocity exposure coefficient at height z |
| L | Live load |
| ℓ | Litre |
| L/L | Lower limit |
| LDPE | Low density polyethylene film |
| m | Metre |
| M | Mass |
| m/s | Metres per second |
| m$^2$ | Square metre |
| MJ | Megajoule |
| MJ/day | Megajoule per day |
| MJ/m$^2$/day | Megajoule per square metre per day |
| Mph | Miles per hour |
| N | Change in wind velocity exponent |
| N/m$^2$ | Newton’s per square metre |
| $\eta_{collector}$ | Efficiency of solar collector |
| NGMA | National Greenhouse Manufacturers Association |
| Nm | Newton metre |
| Ø | Angle of plane |
| P | Design pressure |

| | |
|---|---|
| PC | Polycarbonate |
| $P_{comb}$ | Combined/Actual load |
| PE | Polyethylene |
| $P_h$ | Design pressure at height z = h |
| PLC | Process logic control |
| ppm | Particles per million |
| $P_{wind}$ | Design wind load |
| $P_z$ | Design pressure at height z |
| q | Velocity pressure |
| $\dot{Q}$ | Rate of heat transfer |
| $\dot{Q}_{absorbed}$ | Thermal radiation absorbed |
| $\dot{Q}_{cond}$ | Rate of heat transfer through conduction |
| $\dot{Q}_{cond\_canopy}$ | Rate of heat conducted by canopy |
| $\dot{Q}_{conv}$ | Rate of heat transfer through convection |
| $\dot{Q}_{encl}$ | Rate of thermal radiation absorbed by enclosure |
| $\dot{Q}_{floor}$ | Rate of energy lost by the floor through conduction |
| $\dot{Q}_{incident}$ | Rate of incident radiation |
| $\dot{Q}_{infl}$ | Rate of heat transfer through infiltration |
| $\dot{Q}_{leaves}$ | Rate of thermal radiation emitted by leaves |
| $\dot{Q}_{rad}$ | Rate of thermal radiation |
| $\dot{Q}_{suppl}$ | Rate of energy supplied by the heating system |
| $Q_{absorbed}$ | Thermal radiation absorbed |
| $Q_{available}$ | Available heat |
| $q_h$ | Velocity pressure at height z = h |
| $q_z$ | Velocity pressure at height z |
| r | Rise to span ratio for arched roofs |
| R | Thermal resistance |
| r/min | Revolutions per minute |
| RH | Relative humidity |
| S | Snow load |
| T | Temperature |
| $T_\infty$ | The temperature of the fluid/gas sufficiently far from the surface |
| Ti | Inside temperature |

| | |
|---|---|
| $T_l$ | Absolute temperature of the emitting surface |
| $T_o$ | Outside temperature |
| $T_s$ | Surface temperature |
| $T_{surr}$ | Absolute temperature of the surroundings |
| U/L | Upper limit |
| UV | Ultraviolet |
| V | Volume |
| *V* | Volt |
| $v_1$ | Wind speed at height one |
| $v_2$ | Wind speed at height two |
| $vp_{air}$ | Partial pressure of water vapour in air (Pa) |
| $vp_{canopy\ sat}$ | Saturation pressure inside greenhouse canopy (Pa) |
| VPD | Vapour pressure deficit |
| $vp_{sat}$ | Saturation pressure (Pa) |
| W | Watt |
| Y | Distance to outer surface |
| Z | Height above ground level (m) |
| Α | Absorptivity of a surface |
| $\alpha_{encl}$ | Absorptivity of enclosure |
| $\Delta T$ | Change in temperature |
| $\Delta x$ | Wall thickness |
| ε | Emissivity of a surface |
| ρ | Reflectivity of a surface |
| σ | Stefan-Boltzman constant |
| $\tau$ | Transmissivity of a surface |

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# 1. INTRODUCTION

## 1.1 Background

The purpose of a greenhouse is to create an area where the environment can be controlled for the cultivation of plants that require specific climatic conditions for optimum growth and for the production of fruit/flowers. Before a growing system can be developed, the climatic requirements of the various temperature-sensitive crops need to be investigated so that this can be used for setting the initial climatic requirements as set-point for the growing system. With all the relevant information available, a growing system can be designed for the specific purpose of this research project. The growing system will consist of a super structure that will be cladded with a suitable cladding material, a ventilation system that can supply fresh air and cool down the greenhouse during hot summer days, a solar water heating system that will be able to collect solar energy during daytime, store it and release it to the internal environment of the greenhouse during cold winter nights, as well a control system. As the investigation progresses and more information become available, additional sub-problems may arise and will need to be dealt with.

Greenhouses can have different types of structural frames and can be used in a single or multi-span configuration, depending on the area required for cultivation and the climatic requirements of the plants. Each type of structure has its advantages and disadvantages and will be investigated. Apart from the type of structure that is used, the orientation of the structure also plays a significant role in the functioning of the greenhouse and needs to be investigated.

All greenhouses are actually solar collectors but the term solar greenhouse is used for greenhouses that are orientated in such a way that they collect the maximum amount of sunlight during winter [3]. Solar greenhouses in the Southern Hemisphere will be constructed with a huge northern wall and a flat roof [4]. The northern wall and flat roof form a plane at a right angle to the sun’s rays at midday to collect the maximum possible amount of heat. These types of greenhouses are often built in countries in the Northern Hemisphere that are relatively far from the equator.

In the following sections, the optimum levels for all the known factors that influence plant growth, such as the maximum day-time temperature, the minimum night-time temperature, required day-time light intensity, required day-length, vapour pressure deficit (VPD), relative humidity (RH) and required levels of $CO_2$ will be determined through the research of existing knowledge to determine their respective influences on optimum plant growth [1] [2].

## 1.2 Problem statement

The application of external sources of energy for heating and cooling purposes has become problematic lately due to the sharp increases in the costs thereof. Alternative sources for heating and cooling need to be investigated and their applicability in the greenhouse industry needs to be determined.

## 1.3 Hypothetical resolution

Various natural and/or renewable sources/methods for the heating and cooling of spaces have been identified/developed which can be used in the greenhouse industry. A natural ventilation system may, for example, be a viable alternative to a forced draft ventilation system, while a solar water heating system may be used to replace a conventional gas, electrical or coal fired heating system.

## 1.4 Purpose of the study

The purpose of this study is to investigate the possibility of using an energy efficient and economical viable growing system to grow temperature-sensitive crops year-round in the central region of South Africa. The viability of applying a natural ventilation system to regulate the internal temperature of the greenhouse for example as well as a solar water heating system to enable the system to collect, store and exchange heat when needed may be some of the most important issues that needs to be addressed.

## 1.5 Importance of the study

The cost of food has increased dramatically lately and needs to be addressed urgently. More economical and secure food-producing systems need to be developed to enable the supply of the required volumes of food for the ever increasing world population.

## 1.6 Methodology

The following methodology was used:

a) Gather information regarding the latest developments in alternative greenhouse technologies.
b) Determine the climatic requirements for the relevant temperature-sensitive plants.
c) Perform a literature review on the relevant mechanisms of heat transfer and determine how to apply the theory in the determination of the heat losses and gains as experienced by a greenhouse.
d) Perform a theoretical analysis on the available technologies to determine the most suitable.
e) Design a basic setup including all the chosen technologies.
f) Construct a basic setup and run the production for one to two growing seasons in order to capture all relevant data.
g) Use the captured data to develop a numerical heating and cooling (ventilation) model that can be used to evaluate the chosen technologies.
h) Present a final heating and cooling model that can be used to construct a financial model to evaluate the viability of applying the chosen technologies in the greenhouse industry.

# 2. LITERATURE REVIEW

## 2.1 Introduction

The purpose of this chapter is to review existing literature to determine the basic requirements of a growing system and what technologies are currently available that can assist the grower in obtaining the basic requirements.

## 2.2 General climatic requirements for temperature-sensitive crops

The purpose of a greenhouse is to create an area where the environment can be controlled for the cultivation of plants that require specific climatic conditions for optimum growth and for the production of fruit/flowers. A greenhouse normally consists of a lightweight structure, made from steel or wood, that is clad with a transparent material such as glass, polyethylene sheeting, polycarbonate sheeting, etc. The purpose of the cladding is to allow the rays of the sun to penetrate the structure, to trap the heat and to protect the plants inside from the external environment (rain, wind, hail etc.). Inside this space, the environmental factors that influence plant growth, such as temperature, relative humidity (RH), level of radiation and light intensity can be controlled to promote growth and combat insects and fungal diseases [1]. The maximum temperature and level of radiation during the mid-summer months inside greenhouses, in the central region of South Africa, normally exceeds the levels that the plants require for optimum growth and the minimum temperatures inside the greenhouses may fall below the allowable minimum temperatures that temperature-sensitive plants are able to tolerate during night-time in winter.

A greenhouse must always have some type of ventilation system for the purpose of cooling, to supply fresh air to the plants and to lower the RH inside the greenhouse. A ventilation system can either be of the forced draft type or a natural ventilation system [4] [5]. The required rate of ventilation for a greenhouse, according to the National Greenhouse Manufacturers Association of the U.S.A. (NGMA), is based on the floor area, because the solar heat in the greenhouse is related to the floor area. The application of fan-and-pad systems has become problematic lately, due to sharp increases in the cost of energy. Manufacturers of greenhouses are trying to incorporate passive ventilation systems that enhance natural ventilation, as they require almost no external energy during operation.

Natural ventilation systems rely on a draft that may be created by the wind or the cooling effect of convection when hot air moves through the roof vent and sucks cooler air into the greenhouse through the side vents. The required rate of ventilation needs to be determined and modelled so that the applicability of a natural ventilation system can be determined for greenhouses in the central region of South Africa [6] [7]. In this study, an experimental setup will be used to collect the required environmental data for the evaluation of the system.

In general, temperature-sensitive crops are defined as those types of crops that stop producing fruit and flowers as soon as the minimum temperatures, especially in winter, drop below a certain point. Below this temperature, fruit development is terminated and no new fruit or flowers are formed. The plant will also stop feeding and developing existing fruit and flowers [1]. The ideal climate for most plants does, however, depend on more than just the minimum temperatures. The ideal in this situation would mean a climate that would stimulate optimum production of high-quality fruit and flowers. The ideal climate is normally defined as a range within which a specific parameter may vary and that will enable the plants to develop fruit and flowers of reasonable quality and a reasonable volume [8] [9]. The upper and lower limits of these parameters are normally defined while the actual parameter may vary during the course of a normal day to allow plants to receive their required periods of exposure to various combinations of parameters. Plants need the difference in day/night temperatures to set flowers and fruit, while the 24-hour average temperature is necessary to ensure proper fruit development. Table 1 below provides a compiled summary of the ideal climatic requirements of some temperature-sensitive greenhouse crops [1] [8] [10].

**Table 1 - Ideal climatic conditions for various greenhouse crops**

| Crop | Min night-time temperature ($^{0}$C) | Max day-time temperature ($^{0}$C) | Light intensity required µmol.m$^{-2}$s$^{-1}$ | Day length (h) | Ideal relative humidity % | VPD (g/cm$^{3}$) | $CO_2$ level (PPM) |
|---|---|---|---|---|---|---|---|
| Cut-roses | 15 | 28 | ≥300 | 12 | 60 – 70 | 4 – 5 | 1000 |
| Tomatoes | 15 | 35 | ≥300 | 12 | 60 – 70 | 3 – 5 | 1000 |
| Cucumbers | 15 | 25 | ≥300 | 12 | 70 – 80 | 3 – 5 | 1000 |
| Green Peppers | 16 – 17 | 20 – 21 | ≥300 | 12 | 75 – 80 | 3 – 5 | 1000 |

The ideal conditions to grow cut-roses would be a climate where the night-time temperature drops to 15 $^{o}$C and remains constant at 15 $^{o}$C, and where the day-time temperature rises to 28 $^{o}$C and remains constant for the duration of the day. The day length should be 12 hours, the RH fixed at 60-70 %, with a light intensity of more than 300 µmol.m$^{-2}$s$^{-1}$ [1]. The ambient values for these parameters do however fluctuate gradually between the minimum and the maximum values and the function of the greenhouse would be to try and create this optimum climate for the plants to grow in. At present, growers use these predetermined values as set-point in the greenhouse's climate control system, if any are available.

Currently, most of the greenhouses in the central region of South Africa are still manually operated. Most have roof vents only, which are manually opened and closed depending on the internal temperature. In the absence of a proper control system, huge fluctuations in the internal temperature due to the greenhouse effect can sometimes occur. The existing natural ventilation systems are often unable to obtain a reasonable maximum day-time temperature, especially during the hotter summer months. This causes greenhouses to overheat which has a detrimental effect on the fruit and flower quality. The required quantity of fruit and flowers are often obtained, but at the expense of quality.

### 2.2.1 Minimum night-time temperature

The minimum temperature to which the internal greenhouse climate may cool down is one of the most critical factors that influences a greenhouse's ability to provide an ideal climate for the production of temperature-sensitive crops. If the plants are exposed to a night-time temperature which is lower than the minimum required, as indicated in Table 1, fruit set is terminated and no new fruit or flowers will be formed. On the other hand, plants need a lower night-time temperature than the maximum day-time temperature, to be able to develop fruit and flowers. Cut-roses, for example, need a certain number of maximum day-time temperatures and a certain number of minimum night-time temperatures to enable them to form rose buds with a length of at least 5 cm, as required for the export market. The required temperature is sometimes called the et-mol temperature. Apart from the damage that could be done to the crop as a result of too low minimum night-time temperatures, the required growing time is also increased, as stated in section 2.1 [1] [2] .

Various heating systems are available for greenhouses, the most common being stationary coal-fired air heaters, coal-fired steam kettles with a water circulation system that is connected to heat exchanger/s inside the greenhouse and mobile or hanging gas-, diesel- and paraffin-fired or even electric heaters [11] [12] [13] [14] .

Solar heating systems are characterized into three types: The first type consists of solar ponds (e.g. phase-change materials and heat pumps); the second type of air-heat exchange systems consists of rock bed solar systems and earth-air heat exchange systems; and the third type consists of systems such as the passive solar systems and water spraying on the greenhouse. Passive water heating systems normally consist of different types of water storage containers inside the greenhouse and heated with the greenhouse's captured heat during daytime. The biggest problem with the passive solar heating systems is the total lack of control that is associated with these types of systems.

The problem that growers face with the commonly used heating systems is the increase in fuel prices, making it financially nonviable to produce temperature-sensitive crops year-round, resulting in an inability for growers to obtain fixed contracts [13].

In this study, the application of solar heating systems will be investigated to determine their applicability in the commercial greenhouse industry. As in the case of the evaluation of the natural ventilation system, an experimental solar heating system needs to be constructed and the appropriate data collected and analysed to ultimately determine the financial viability of using such a system. The solar heating system may not be able to supply all the required heat during mid-winter but may be applied economically to extend the growing season. The term "solar savings fraction" or "solar fraction" is defined as the amount of energy provided by the solar technology divided by the total amount of energy required [15]. This study will also aim to develop a tool that can enable a grower to determine what solar fraction can be economically applied. Cut-roses will be grown as a crop and the capability of the proposed growing system will be evaluated against the climatic requirements of the plants [16] [17] .

### 2.2.2 Maximum day-time temperature

The ideal maximum day-time temperature for cut-roses, as indicated in Table 1, is 28 $^{o}$C. In general, a greenhouse acts as a solar collector, due to the heat transfer from the external to the internal climate through radiation. This effect enables a climate-controlled greenhouse to easily reach the required maximum day-time temperature during periods of lower external temperatures, if ample levels of sunlight are available. It may, however, become problematic during periods of elevated external temperatures, as the greenhouse will need to find ways to get rid of the excess heat it collects.

In industry, two ventilation techniques, namely natural ventilation (through ventilation openings) and forced draft ventilation (through a fan or a fan-and-pad system) are used to remove the excess heat from the greenhouse [4]. Various methods of blocking the excess rays from the sun, through a system of fixed or retractable internal or external curtains, are also used and are called shading and reflecting techniques depending on the physical characteristics of the curtain material [1].

The recent sharp increases in the cost of energy made the application of the forced draft technique financially nonviable and greenhouse manufacturers and researchers are more and more looking into the application of natural ventilation through a combination of side wall and roof openings, since this technique is very energy efficient.

As far as this project is concerned, natural ventilation is the preferred choice of ventilation technique and it will be obtained through the application of side and roof vents. The exact type of vents to be used will be determined in the concept design phase. The external temperature, in the central region of South Africa may often rise above 36 $^{o}$C, while the application of natural ventilation is not able to lower the internal temperature below 36 $^{o}$C, which means that additional cooling and shading techniques may be needed to obtain the ideal internal maximum day-time temperature of 28 $^{o}$C [18].

The required rate of ventilation for greenhouses in summer is in the order of 60 air exchanges per hour [4]. This can be obtained with two side vents and a roof vent that creates an opening equal to at least 25% of the floor area. This will allow the internal temperature to exceed the external temperature by approximately 5 – 6 $^{o}$C. This will also ensure that the levels of $CO_2$ do not drop significantly below the atmospheric levels.

When roses are grown for cut-flowers, the flowers' size and stem length are two important factors that have a huge influence on the flower quality [1] . If the growing temperature increases, the number of days from bud break to flowering is reduced, but only up to a certain limit. The optimum upper limit of the day-time temperatures, has been determined as 28 $^{o}$C. At lower growing temperatures, the stem length and bud size will increase but more development time will be required from bud break to flowering. This means that the grower has to create a balance between the required stem length plus bud size versus the number of days required for development. There is no financial reward for stem lengths and bud sizes in excess of what the market requires. During experimental analysis, the size of the buds ~~are~~ normally weighed both as fresh and dry flowers. The data obtained can then be plotted against the growing temperature and used to determine the optimum as shown in the figure below [1]. If greenhouses need to be heated, a grower would like to use the least amount of energy required, meaning that the lowest possible set-point at which the required quality at the optimum growing time can be obtained. If the growing temperature is reduced from 30 $^{o}$C to 15 $^{o}$C, for example, the number of days required from bud break to flowering, increases from 21.6 to 63 days [1].

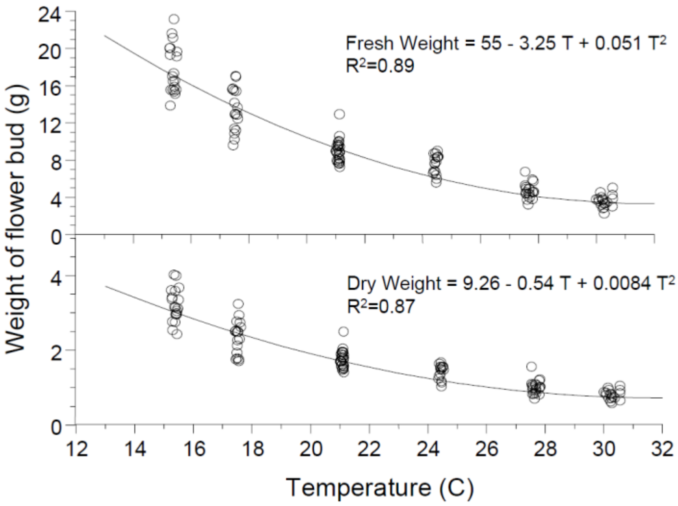


**Figure 1 - Effect of growing temperature on fresh and dry bud weight** [1]**.**

### 2.2.3 Light intensity

For the production of high quality cut-roses, a light intensity of at least 300 $\mu mol.m^{-2}s^{-1}$ during daytime is required [1] [9] [19] [20]. The light intensity which the plants receive will depend on the percentage of light that the cladding material transmits. Plants need light with a wavelength of 400 to 700 µm, known as photo synthetically active radiation (PAR). Polyethylene (PE) film will typically transmit 77 to 92 % of the received light, depending on the various additives. These additives are used to stabilize the film against UV degradation, to diffuse the light inside the greenhouse, to block UV light from entering the greenhouse, to block IR light from leaving the greenhouse at night and to control condensation inside the greenhouse [21].

### 2.2.4 Day length

Greenhouse-grown cut-roses do not need a specific day-length before they begin to flower. The initiation of flowers may rather depend on obtaining a certain stage or age of development. During the shortest day in winter, 21 June, the Free State still receives almost ten-and-a-half hours of sunlight. The effect of the actual length of daylight will therefore be ignored in this study. Extending daylight is an energy consuming activity, while the focus of this project is on the development of a sustainable greenhouse [1]. Daylight extension is not often used for normal plant production. Roses, in general, need approximately six hours of direct sunlight per day to function properly.

### 2.2.5 Vapour pressure deficit

The vapour pressure deficit (VPD) is the difference between the amount of moisture in the air and how much moisture the air can hold when it is saturated. The SI units for VPD is kPa and the ideal range is between 0.45 and 1.25 kPa, with an optimum at 0.85 kPa [22]. If the air becomes saturated with water, the water will start to condense and form a film of water on the leaves of the plant. This is critical in greenhouses since this film of water will make the plants more susceptible to the development of fungi on the leaves. The temperature at which condensation occurs at a specific RH is called the dew point. If the VPD becomes too high, plants need to draw more water through their roots to prevent dehydration.

To calculate the actual VPD one must determine the air temperature (internal and external) and the relative humidity. The saturation pressure ($vp_{sat}$) must be determined for both the canopy and the external environment from a psychometric chart. The partial pressure ($vp_{air}$) of the water vapour in the air is determined as follows:

$$vp_{air} = vp_{sat} * RH/100 \tag{2.1}$$

And then the VPD as follows:

$$VPD = vp_{sat} - vp_{air} \text{ or } VPD = vp_{canopy\ sat} - vp_{air} \tag{2.2}$$

The VPD thus determines the water-holding capacity of the air by taking its temperature and RH into account, thereby allowing the grower to identify healthy air moisture conditions for crop production. Earlier research determined that a higher VPD, in other words dryer air, during the growing period of cut-roses, has a positive effect on the vase life on all the tested varieties and creates less favourable conditions for the development of fungi on the leaves [23].

### 2.2.6 Relative humidity

The relative humidity (RH) is the ratio of the partial pressure ($vp_{air}$) of water in an air-water mixture to the saturated vapour pressure ($vp_{sat}$) of water at a given temperature [23] [24]. The relative humidity of air in a closed system is dependent on both the temperature (determining $vp_{sat}$) and the total pressure (influencing changes in $vp_{air}$ ). The RH of an air-water mixture is calculated as follows:

$$RH=(vp_{air} / vp_{sat})*100\ \% \tag{2.3}$$

The relative humidity of the air inside the greenhouse influences the rate of transpiration of the plants, which in turn influences the rate of water uptake through the root system. The optimum RH inside the greenhouse, for cut-rose production, must be between 60 and 70 %. A combination of dry and warm days with cool and humid nights will enhance the development of fungal diseases such as powdery mildew, while a constantly low RH enhances the development of pests like red-spider mites. If the RH rises above 90 % for extended periods of time, it negatively influences the shelf life of the product and may cause the development of bacterial and fungal diseases such as black spot [4] [22]. Because the RH of air is dependent on temperature, the VPD or air is a more accurate way of determining the rate of transpiration from the leaves. At a specific temperature, the RH of the air may be 90 % while the VPD is 1.0 kPa. The value of the VPD is independent of temperature and a high value of VPD, e.g. 1.0 kPa, means that the air can still hold a large amount of water. Therefore, a large gradient exists between the plants that are nearly saturated with water and the air. At a VPD of 1.0 kPa, the plants can still transpire and dry out although the RH reading may be 90 % at the specific temperature. A VPD of zero would mean that the air is completely saturated and it will therefore not be possible for the plants to transpire.

### 2.2.7 Levels of $CO_2$

The ambient level of $CO_2$ is approximately 340 ppm by volume. In an enclosed environment, the level of $CO_2$ can drop significantly if not properly ventilated due to the process of photosynthesis. Most plants will grow quite well at the ambient levels of $CO_2$ although an increase to 1000 ppm may increase the rate of photosynthesis by approximately 50 % [25]. A proper ventilation system is therefore required to ensure that the levels of $CO_2$ do not drop significantly below 340 ppm, and $CO_2$ supplementation is sometimes required should it prove to be economically feasible. In this project, a natural ventilation system will be incorporated, which should be able to obtain the required levels of $CO_2$ in the air without any supplementation. $CO_2$ supplementation can be performed chemically if needed, but is normally not necessary if a natural ventilation system is used because normally there is a sufficient rate of air exchanges obtained with such a system (30 to 60 air exchanges per hour) [4].

## 2.3 Current status of greenhouse technology

The previous section focussed on the climatic requirements of the various crops. To obtain the required levels for these climatic requirements, various technologies are used and will be described in the sections to follow. With the technologies that are currently available, it is possible to create the ideal climate but at a cost, especially as far as the required temperatures for optimum growth is concerned. Growers have to ensure that the growing operation is financially viable otherwise the sustainability of the operation will be jeopardised.

The cost of electricity and fossil fuels has increased dramatically in recent years and alternatives need to be found to ensure sustainability in the sector. A great deal of research is done regarding the known climatic requirements of the crops in order to determine what influence alternative set-points for the different climatic parameters will have on the volume and quality of the produce [1] [26]. On the other hand, much research is also undertaken to evaluate the possibility of applying alternative technologies to obtain the required climatic requirements [11].

In the sections that follow, the current status regarding the applied technologies in South Africa and the rest of the world will be discussed as well as possible alternatives that need to be investigated.

## 2.4 Current status of greenhouse technologies used.

In this section, the different technologies that are currently used in South Africa will be discussed and compared with what is being used in the rest of the world.

### 2.4.1 Managing minimum temperatures

To prevent the internal temperatures from dropping below the point where fruit and flower formation is terminated, various heating technologies such as gas- or diesel-fired burners, electric heater/fan combinations as well as water heat exchange systems, where the heat is normally generated with coal-fired boilers, are generally applied [27]. The running costs of these conventional technologies are dependent on the costs of fossil-fuels and have increased dramatically in recent years. Many growers were forced to terminate the year-round production of temperature-sensitive crops and to focus on the time of the year where temperatures are more suitable. Greenhouse systems that were developed for year-round production are now being used only to extend the growing season. The value of temperature-sensitive crops is normally higher during the off-season due to the lower volumes that can be supplied to the market.

Similar technologies used for the heating of greenhouses in South Africa are used in Europe and the U.S., and similar problems regarding the cost of fuels are being experienced. Energy conservation strategies and the application of alternative energies are being investigated in an effort to reduce the cost of heating greenhouses [13]. An energy conservation strategy may include any combination of the following factors:

- Paying more attention to the insulation of the greenhouse structure;
- Installing double layers of polyethylene film;
- The application of thermal blankets;
- Optimizing the heating systems efficiency (fuels, clean radiation surfaces, etc.);
- The installation of horizontal air flow fans; and
- Testing different set-points for environmental control [60].

An alternative to traditional greenhouses, that is growing rapidly in the U.S., is the application of high tunnels [29]. High tunnels are defined as greenhouses without any electrical connections, meaning that no energy can be used for heating or cooling purposes. High tunnels can be used in a single-span or multiple span application and normally have both ends open. High tunnels are much simpler in construction, if compared to conventional greenhouses, and are used to extend the growing season of temperature-sensitive crops. An example of a high tunnel is presented in Figure 2.

**Figure 2 – High tunnels at Haygrove** [28]

The application of heat pumps to heat the water in water-circulation greenhouse heating systems has increased lately [12] [29]. Heat pumps extract heat from the outside air and can be up to 75 % more efficient than a conventional boiler heating system. In experiments conducted by the Graduate School of Horticulture in Chiba, Japan, an average coefficient of performance (COP) of 4 was obtained when a heat pump was used for the heating of a greenhouse [30]. The value of the COP does however depend on the temperature of the source, which can be either air or ground-water, and may sometimes drop to 1, which makes heat pumps less efficient than boilers.

The application of biomass for greenhouse heating has also received attention. Biomass can be used in a number of ways with the most favourable being the application of biomass as fuel in direct combustion or gasification systems [17]. The amount of heat that can be generated by burning a certain mass of biomass is lower than that generated by burning the same mass of fossil-fuels, but biomass in the form of field crop residues are normally less expensive than fossil-fuels. Another concept that is being explored in the U.S. is cogeneration, where the heat that is generated by electricity generation equipment, e.g. an internal combustion engine, is used for heating purposes. Heating greenhouses with stored solar energy is a concept that is not applied in the greenhouse industry and needs to be investigated.

### 2.4.2 Managing maximum day-time temperatures

The maximum day-time temperatures that can be reached inside a greenhouse are normally lowered through the application of a fan-and-pad system for evaporative cooling, or the application of a natural ventilation system, sometimes in combination with an energy screen, or the application of a misting system in combination with either a fan-and-pad system or a natural ventilation system. These technologies are commonly used in South Africa as well as in the rest of the world. A fan-and-pad system can be much more effective than a natural ventilation system if the RH of the outside air is not too high, which reduces that rate of evaporation that can be obtained by the fan-and-pad system [5] [31]. It also has the added advantage of increasing the internal humidity and creating the required air flow across the plants. The typical required rate of ventilation for a fan-and-pad system is in the order of one air exchange per minute [4]. The biggest disadvantage of the fan-and-pad system is the electricity and water that it consumes and for this reason, natural ventilation systems have become the preferred choice of most growers. It is, however, important to mention that a natural ventilation system is not able to reduce the internal temperature to a level that is below the ambient temperature. In fact, at best it is normally able to obtain an internal temperature of 3 to 5 degrees higher than the ambient, depending on the efficiency of the system. If a natural ventilation system is however used in combination with an energy screen, it can lower the levels of solar radiation that the plants receive and thereby enable them to tolerate the higher-than-ambient temperatures. The problem here is, however, that the ambient temperatures in South Africa may often exceed temperatures that the plants can tolerate (as listed in Table 1) during midday and this does pose as a threat to the quality of the produce. Misting systems are very effective in reducing the internal temperatures and simultaneously increasing the humidity of the air inside the greenhouse, but at the expense of the water that is consumed. The latest systems, called “Dry Misting Systems”, produce very small droplets (small nozzle orifice with a high fluid pressure) in an effort to reduce the water consumption [12].

### 2.4.3 Obtaining the required light intensity

Various types of cladding, ranging from glass to PC sheeting to PE film, are used as cladding material throughout the world. In Europe, many greenhouses are covered with glass but in South Africa, PE film is mostly used due to the high cost of glass. Various types of PE film, consisting of up to five layers, each with its specific purpose, is used in South Africa and the rest of the world. A specific film, called IR Rose, is normally used as greenhouse film for roses in South Africa. This specific film possesses all of the abovementioned additives and transmits 77 – 88 % of the light [21] [32] .
Experiments performed on a cut-rose cultivar named ‘Mercedes’ showed that the rate of flowering from the uppermost shoot decreased from 89 to 6% when the light intensity decreased from 270 $\mu mol.m^{-2}s^{-1}$ to 6 $\mu mol.m^{-2}s^{-1}$ during a 12-hour growing period [19].
One of the most important functions of a greenhouse is to provide enough light for the plants and although the plants will be able to function at lower-than-required light intensities, the production will be severely influenced by the lower levels of light [1]. Most greenhouses in the central region of South Africa are covered with a single layer of PE film that does allow adequate levels of light to reach the plants. Shade screens are sometimes used to reduce the level of radiation on the plant leaves with the disadvantage that it also reduces the light intensity inside the greenhouse. A trade-off has to be made between the level of radiation on the plant leaves and the light intensity inside the greenhouse. Most shade screens are constructed from different grades of shade cloth with strips of Aluminium wound through the cloth [33]. The purpose of the

strips is to reflect the radiation from the greenhouse. Shade screens can fulfil a dual purpose by also blocking some of the radiation from the plant leaves at night, the effectiveness of which is also dependent on the grade of shade cloth that is used.

### 2.4.4 Altering the day-length

The length of a day, the period during which adequate light is available for photosynthesis during a 24-hour period, is called the photoperiod [1] [9]. Plants respond to an increase or decrease of the photoperiod. Scientists have realised that the length of the uninterrupted dark period (night-length) is a critical factor in plant development. The so-called length of the “critical night” must be exceeded to induce a short-day response or decreased to induce a long-day response. The interruption of the dark period by brief intervals of lighting will trigger a long-day response. The interaction of lower temperatures and longer dark periods creates what is called the “autumn effect”. For a plant to be able to survive it needs to be in synchrony with the environment within which it grows.

Plant responses to changing photoperiod maintain the plant in synchrony with its environment and prolong its survival. For example, moving in latitude away from the equator toward one of the poles, the short days of autumn that precede winter's low temperatures induce bud dormancy and condition the plant to survive low temperatures. In the central region of South Africa, the buds normally start to go dormant by May and become active in August. The average day-lengths and temperatures for Bloemfontein are presented in Figures 3 and 4 below [18]. From Figure 3 it can be seen that the average day-length is approximately 10.5 hours with an average maximum temperature of 23 $^{o}$C and an average minimum temperature of 1 $^{o}$C. During August, the average day-length has increased again to approximately 10.5 hours with practically the same average maximum and minimum temperatures as in May. For the period of dormancy, the night-time period will decrease from 13.5 hours to a low of approximately 14 hours in June/July.

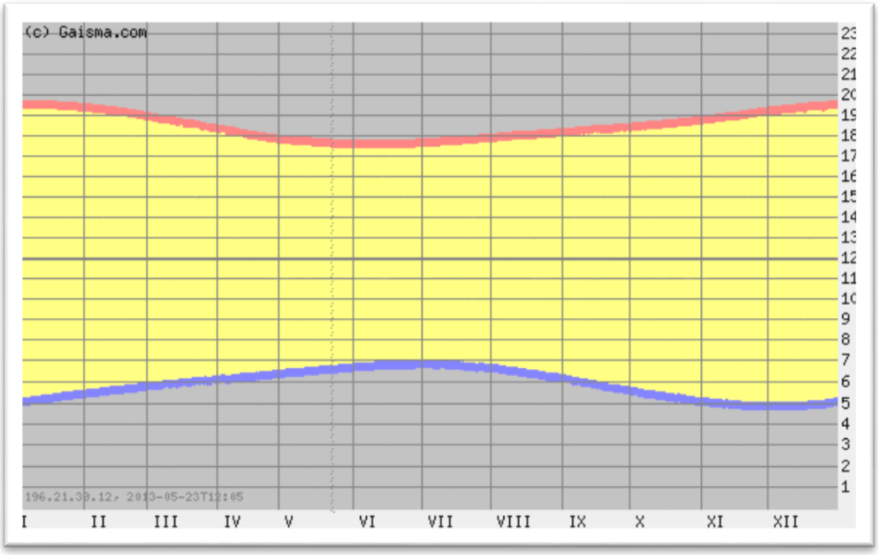


**Figure 3 - Annual variation in day-length for Bloemfontein** [18]**.**

Towards June/July, the average maximum day-time temperatures as well as the average minimum night-time temperatures drops by approximately 2 ºC, although some much colder spells can be experienced during this phase, which tend to move rose plants into dormancy relatively quickly. Although the day-length follows the graphs as presented in Figure 3, it is known that the actual temperatures may fluctuate a lot from what is presented in Figure 4.

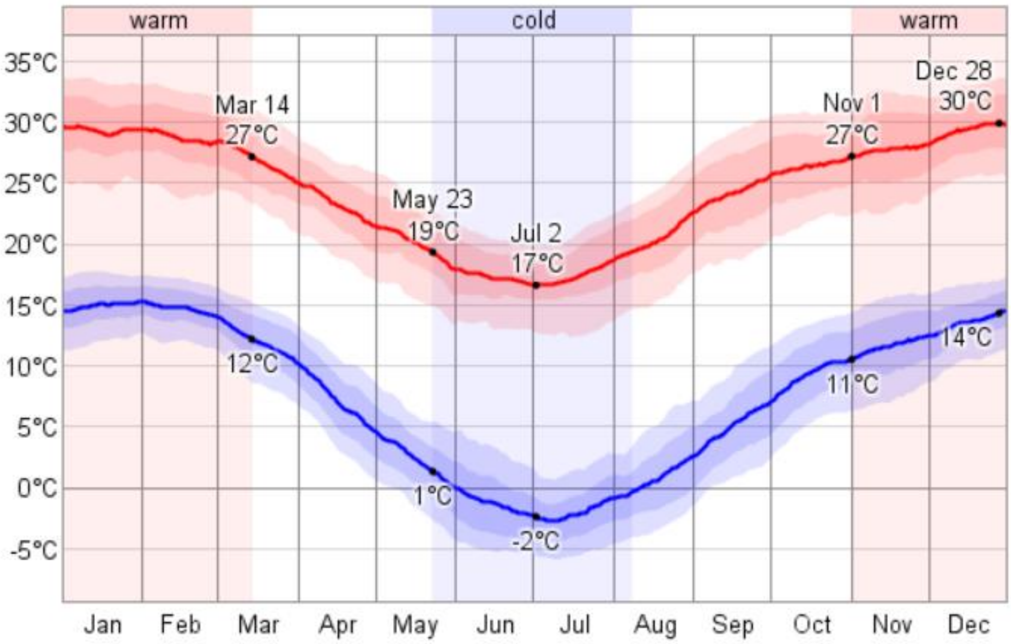


**Figure 4 - Average temperatures for Bloemfontein** [18]**.**

The night-time period increases by approximately half-an-hour and experience has shown that this increase in the night-time period does not have a notable effect on plant growth because the plants continue to produce if the temperature does not change dramatically during that period. For this reason, the extension of the photoperiod will be ignored as far as this study is concerned. The extension of the photoperiod is a concept that is not applied in the central region of South Africa. In Europe, where the day-length can become relatively short, it becomes a necessity.

### 2.4.5 Controlling the vapour pressure deficit

The VPD can be used to evaluate the disease threat, determine the possibility for condensation and determine the irrigation needs of a greenhouse crop. To prevent condensation inside a greenhouse is very important because pathogens require a water film on the plant for them to develop and infect [22]. In monitoring the VPD, the grower will be able to determine when condensation will occur and take the necessary steps to prevent it. In greenhouses, the VPD is lowered by the removal of moisture from the air through a process called dehumidification. The dehumidification process can form part of the ventilation process, should the ventilation process prove to be sufficient in the removal of moisture from the air inside the greenhouse [4] [5]. The efficiency of the dehumidification process, through ventilation, will however also depend on the RH of the ambient air.

Studies have shown that fungal pathogens have a better survival rate when the VPD is below 0.43 kPa, while disease infection can be most damaging when the VPD is below 0.02 kPa . The VPD of the greenhouse climate should therefore be kept above 0.02 kPa to prevent disease and damage to crops [22]. When biological control agents are however used inside the greenhouse, the required VPD should be re-evaluated because these organisms require specific VPD conditions for growth and distribution.

Most growers in South Africa, as well as the rest of the world, follow an Integrated Disease and Pest Management (IDPM) strategy, meaning that the control of diseases and pests are not done through the application of chemicals only, but by taking all the factors (e.g. climate) into account that can create conditions that are suitable for pathogens and pests to develop. To control the VPD, the following techniques can be applied:

- Use a bottom heating or between-row heating system. If the bottom heating system is installed below the roots of the plants it is also called a root zone heating system. These systems will assist in keeping the plant surface temperatures above the dew point through the temperature gradient that will be developed inside the greenhouse, which in turn will also stimulate air circulation.
- Use a thermal screen to keep the plants warm. Thermal screens, used just above the crop level, not only reduces the volume of air the needs to be heated inside the greenhouse but also reduces the heat loss through radiation and conduction.
- Improve the air circulation inside the greenhouse by installing horizontal air flow (HAF) fans. The circulation of the air will distribute the warmer air and that will encourage the evaporation of the condensate into the air.

These techniques should be kept in mind, especially during the design of the heating system [10] [34]. Should condensation still appear, HAF fans can be installed to alleviate the problem.

### 2.4.6 Controlling the RH

To control the humidity inside a greenhouse can be quite challenging, even for automated humidity control systems. This is due to the inflow of air, caused by the ventilation system, the fluctuating values of the ambient RH, as well as the water that the plants continually add to the air through transpiration. The RH inside the greenhouse will have a huge influence on the crop quality because non-optimum levels of the RH can cause plant stress, lost yields, disease outbreaks as well as the wasting of energy through the limitations of equipment and the wrong climate control set-points. The main aim in controlling the humidity in high humidity conditions is to avoid humidity levels near the dew-point because the condensation of free water onto the plant surfaces can promote fungal growth. Under saturated conditions, the plants will also not be able to evaporate water from their leaves, which will in turn limit the uptake of nutrients which are normally deposited during this evaporation process.
Not all the surfaces in a greenhouse will necessarily be at the same temperature, which would mean that at high levels of humidity, water vapour may start condensing from cooler surfaces which causes dripping. Dripping is to be avoided inside a greenhouse because it assists in spreading diseases through the greenhouse. The average daily

high (indicated in blue) and daily low (indicated in brown) variation for Bloemfontein is shown in Figure 5 (inner bands from 25th to 75th percentile, outer bands from 10th to 90th percentile).

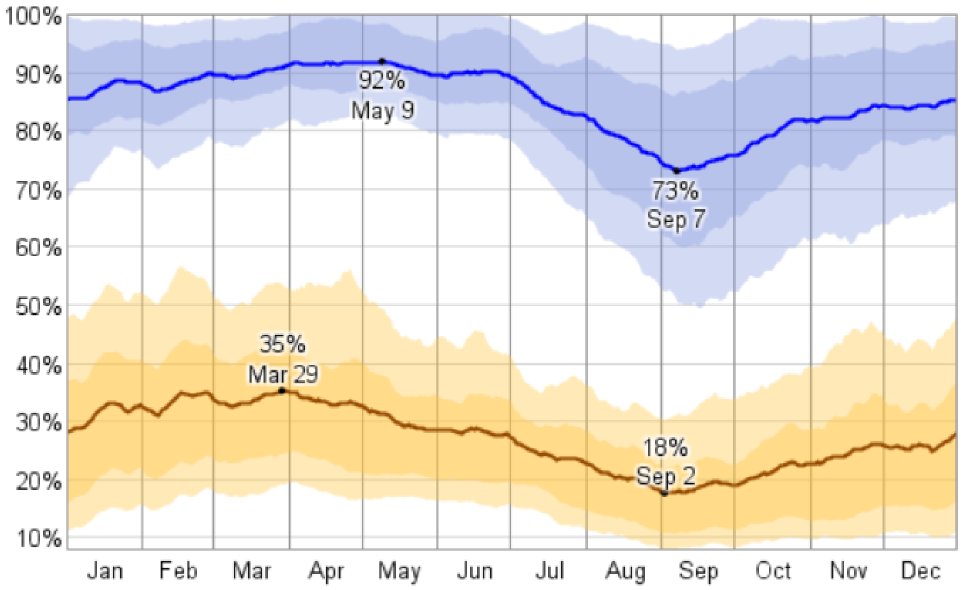


**Figure 5 - Variation in average RH for Bloemfontein** [18]**.**

The problem with the RH is that it varies daily between these values and that the maximum values are normally obtained during early morning, when the ventilation system is not operational because the ambient temperatures have dropped. To alleviate this problem, a combination of heating and venting is used to exchange moist air with drier outside air and heating to reduce the RH levels [4]. When a control system is available, this temperature rise and humidification process at sunrise is incorporated into the daily program.

### 2.4.7 $CO_2$ supplementation.

Carbon dioxide is an important component in photosynthesis, a process where light is used to convert $CO_2$ and water into sugars in green plants. The sugars are used for plant growth through respiration. If the rate of photosynthesis exceeds the rate of respiration, dry-matter is accumulated which is called growth. Growers, therefore try to increase the rate of photosynthesis by increasing the levels of $CO_2$, which improves plant vigour and growth and ultimately increases yields. For most crops, net photosynthesis increases as the levels of $CO_2$ increases from 340 – 1000 ppm. If the levels of $CO_2$ are increased above 1000 ppm, no increase in plant growth is expected, as indicated in Figure 6 [25].

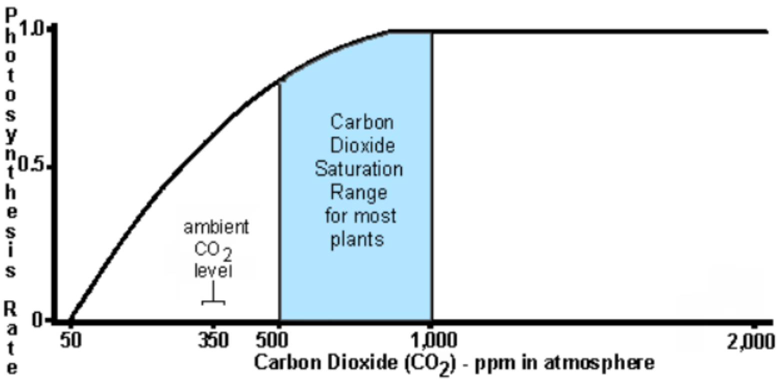


**Figure 6 - Effect of carbon dioxide on plant growth** [25]**.**

The levels of $CO_2$ can be increased by burning carbon-based fuels such as natural gas, propane and kerosene or by chemical injection from $CO_2$ tanks. Burning carbon-based fuels has the added advantage that heat is also generated that can supplement the heating system. Incomplete combustion or contaminated fuels may however cause damage to the plants. The sulphur levels of the fuels should also not exceed 0.02 % by weight. The natural gas, propane and liquid fuels are normally burnt through specialized $CO_2$ generators that are located throughout the greenhouse. The number of units required is determined by their heating capacity and the degree of horizontal airflow that they create. A potential disadvantage of these types of systems is that the heat that is created may be quite localized whereby it may cause a disease incident. Water vapour is also created when natural gas and propane is burnt, which will increase the humidity inside the greenhouse. Another method that is being used is to direct a portion of the flue from the natural gas burners, which are connected to the heating system, to the greenhouse. These types of burners must then be equipped with a flue gas condenser. Liquid $CO_2$ has become very popular in recent years because of its purity as it eliminates concerns regarding crop damage, no heat or moisture is produced and the $CO_2$ levels can be better controlled [25]. Experiments conducted on miniature roses showed that the $CO_2$ exchange rate varied during a 24-hour period daily cycle, as shown in Figure 7. The Carbon Dioxide Exchange Rate (CER) also showed a significant increase when the available levels of $CO_2$ in the air were increased from 370 µmol mol$^{-1}$ $CO_2$ to 800 µmol mol$^{-1}$ $CO_2$ [25].

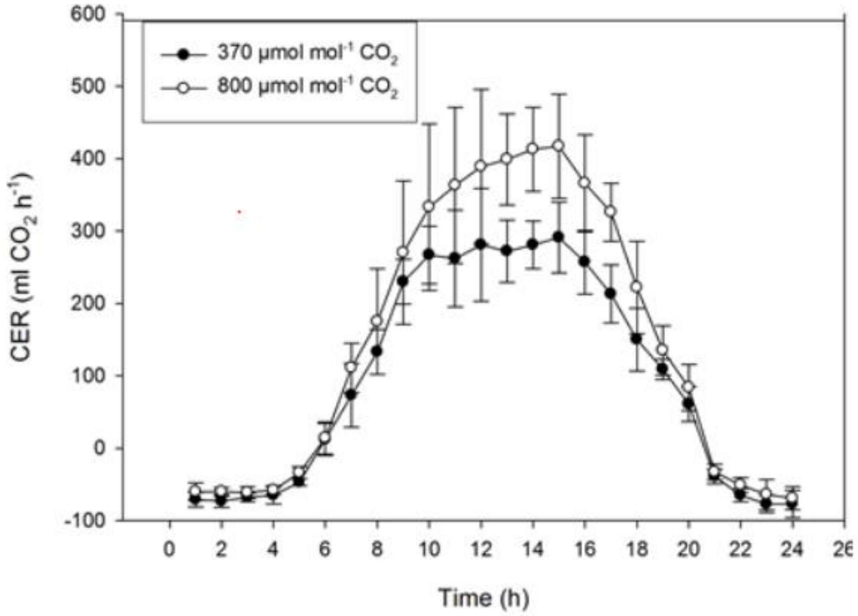


**Figure 7 - Variations in $CO_2$ requirements during the day** [25].

What is also clear from Figure 7 is that the plants do not require additional $CO_2$ during the night-time period, when the ventilation system is not operational, meaning that no additional $CO_2$ or ventilation is required during the night-time which may place an additional load on the heating system.

### 2.4.8 Questions to be addressed in this research

As stated earlier, the ideal growing conditions for growing cut-roses, as far as the temperature is concerned, would be a climate where the night-time temperature drops to 15 $^{o}$C and remains constant at 15 $^{o}$C and where the day-time temperature rises to 28 $^{o}$C and remains constant for the duration of the day. Controlling the internal temperature is currently the single biggest problem that growers are faced with due to the recent increases in the cost of energy. Some research still needs to be done regarding the application of alternative heating and cooling systems to alleviate the burden that the increasing cost of energy is placing on growers. The heating of the greenhouse remains the most expensive operational cost and therefore the biggest factor that limits the economical year-round production of temperature-sensitive crops. To be able to design a heating system for a greenhouse, it is necessary to fully understand the relative importance of each phenomenon involved. A mathematical model can provide a good tool to quantify the importance of each phenomenon. To be able to design any type of heating system for a greenhouse it will be important to develop an accurate model for determining the possible heat losses.

## 2.5 Conclusion

The basic climatic requirements for the optimum growing system was determined and the technologies that are currently being used was investigated. The cooling and heating of a greenhouse is normally the most difficult and costly to control and alternative methods of doing this needs to be investigated.

## 2.6 Greenhouse Thermal Design

## 2.7 Introduction

In this chapter all possible methods for a greenhouse to either gain or lose heat will be investigated, expressed numerically, and combined to create a total heat loss/gain model for both the steady state as well as transient scenarios.

### 2.7.1 Energy balance

For a complete energy balance, the following heat losses and gains need to be considered:

- Heat gains and losses through radiation,
- Heat losses through ventilation and infiltration (convection),
- Heat losses through conduction,
- Heat losses through ground interchange (conduction),
- Heat gains from people and equipment,
- Plant biological activity interchange (e.g. transpiration),
- Heat losses through condensation,
- Heat losses through reflection, and
- Heat gains from the heating system.

This energy balance can be schematically presented, as shown in Figure 8. The control volume consists of the internal volume of the greenhouse.

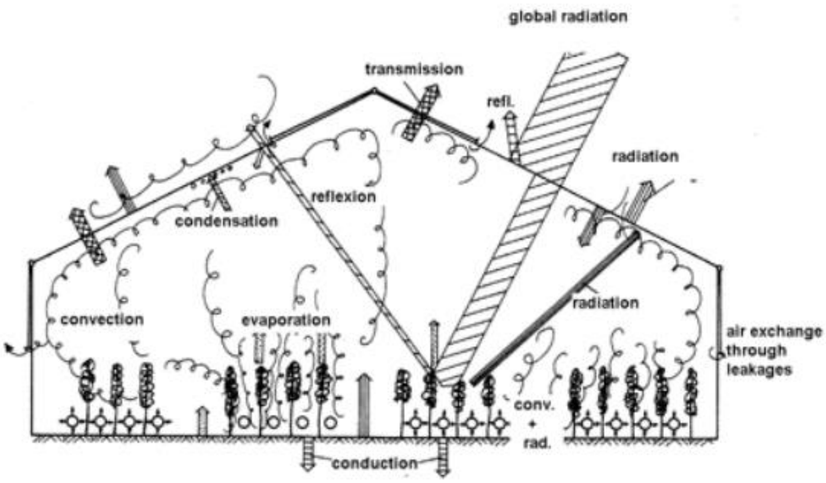


**Figure 8 - Greenhouse energy balance** [35]

Some of these heat transfer processes (or paths) will occur independently of one another (in parallel) and others will be dependent on the previous process (in series). For the typical heat loss scenario during a cooler winter's night, the following paths of heat transfer will be established:

- Heat will be transferred from the warmer surface of the leaves to the surrounding air inside the greenhouse through convection, due to the movement of this air, as created by infiltration,
- Some of this heat will then be transported by the moving air to the cladding and structure,
- From the warmer greenhouse cladding, some heat will be conducted to the colder outside air, some reflected back to the surface of the leaves and some absorbed by the greenhouse structure and cladding,
- The greenhouse floor which was heated during the day will convect some of this heat to the internal air through the movement of this air, as created by infiltration,
- The heated greenhouse floor will also radiate some of its collected heat to the plants and open sky, if a direct path is available,
- The surface of the leaves will radiate heat directly to the outside air,
- The cladding and structure will radiate some of this heat back to the plants,
- Water vapour that condenses against the inside of the greenhouse cladding during the early morning will remove some heat from the internal air, and
- Heat will be added to the greenhouse's internal environment by the heating system.

From the above-mentioned it is clear that the heat transfer/transport system can be quite complex and that certain assumptions need to be made to make theoretical calculations possible. In making the assumptions, a conservative approach needs to be followed to ensure that the actual rate of heat transfer is not underestimated. Values obtained can also be benchmarked against industry standards [35] [36].

The heat loss situation was presented to a local company, Munters, specializing in greenhouse heating and cooling, and based on their experience in this field they proposed a 30 kW heating system for this specific greenhouse operating under the specified climatic conditions .

As far as the heat loss mechanisms are concerned, the following initial assumptions were made and can be verified at a later stage:

- The moving air will transport a portion of the heat that was collected from the surface of the leaves to the canopy from where a certain portion will be absorbed, some reflected and the rest conducted to the outside air [35].
- The greenhouse floor was covered with a single layer of 500 µm thick black PE film, which would mean that it would be able to collect a reasonable amount of heat during the day directly from the sun through radiation, should it be fully exposed. This is however only the case when the plants are young, but for plants in full production, the portion of the floor that is still directly exposed normally decreases to almost zero. For that reason, we can safely assume that the floor will receive little radiation from the sun and because of this covering, the sub-soil will not be able to radiate large amounts of heat to the greenhouse. Should this however be possible, it can be seen as a net heat gain that can be disregarded for the purpose of determining the maximum rate of heat loss [35].
- Anti-drip greenhouse films, that eliminate the condensation of water vapour on the inside of the cladding during the night because of certain additives, can be used, and should this prove to be effective, the loss of heat due to condensation can be disregarded. Should the physical experiments however prove that condensation still takes place, the effect of it on the total rate of heat loss can be included [22].

On clear sunny days, a net gain is normally experienced inside greenhouses in the central region of South Africa and the ventilation system is used to balance the energy gains and losses in order to obtain the optimal internal temperature. The exception here is on warm sunny summer days when the heat gain through radiation may exceed the capability of the ventilation system to remove enough heat from the greenhouse. The biggest problem does however occur during night-time in the colder season when the heat losses exceed the gains by far and a heating system is required to supply the energy needed to obtain the required internal temperature for optimal plant production. An equation for the energy balance during that period can be created as follows:

$$\dot{Q}_{suppl} = \dot{Q}_{rad} + \dot{Q}_{conv} + \dot{Q}_{cond} + \dot{Q}_{floor}, \text{[Watt]} \qquad (2.4)$$

Where: $\dot{Q}_{suppl}$ = Energy supplied by the heating system

$\dot{Q}_{rad}$ = Energy lost through radiation

$\dot{Q}_{conv}$ = Energy lost through convection (air infiltration)

$\dot{Q}_{cond}$ = Energy lost by the side walls and roof through conduction

$\dot{Q}_{floor}$ = Energy lost by the floor through conduction

In order to calculate the amount of energy required to heat the greenhouse, the total energy loss needs to be determined [37] .

### 2.7.2 Mechanisms of heat transfer

Heat can be transferred through three basic mechanisms, namely conduction, convection and radiation. The maximum rate at which the heat is transferred is a very important issue because it provides the designer with a direct indication of what the capacity of the heating system needs in order to be able to tolerate the maximum possible rate of heat loss. All three mechanisms need to be considered when the rate of heat transfer from a greenhouse is determined. The following sections provide an overview of the three mechanisms and how the rate of heat loss through each mechanism can be determined [38] [39].

### 2.7.3 Conduction

If the temperature of a substance is raised, the particles it consists of are energised. As a result of the interaction between the particles, the more energetic particles will transfer some of their energy to the adjacent less energetic particles and this process of heat transfer is called conduction. Conduction can take place in solids, liquids and gasses. In gasses such as air, heat is conducted through the collisions and diffusion of the molecules during their random motion [39].

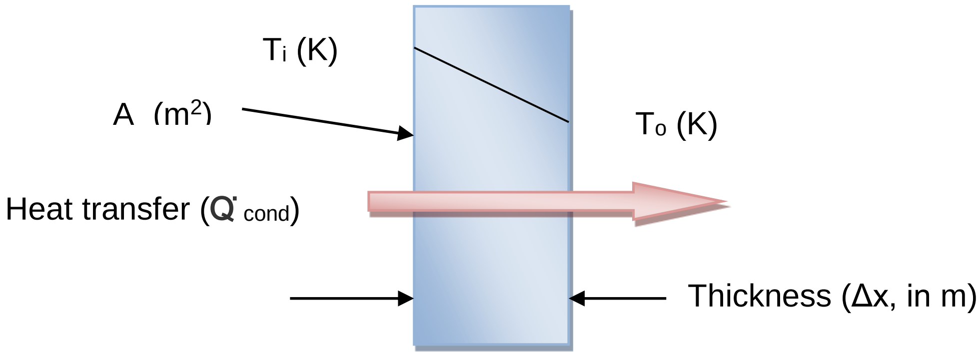


**Figure 9 - Heat transfer through conduction**

In solids, heat is conducted through the vibrations of the molecules in their lattice structure while the energy is transported by free electrons. The rate which the heat is conducted through a material will depend on the characteristics of the material, such as its composition, thickness and the temperature difference from the one surface to the other, as shown in Figure 9. For steady-state heat transfer, the rate of heat transfer is in direct relation to the area of the surface (A) and the temperature difference across the surface ($\Delta T = T_i - T_o$) and in indirect relation to the wall thickness ($\Delta x$). It can therefore be determined as follows:

Rate of Conduction = (Area)(Temperature difference)/(Thickness)

or,

$$\dot{Q}_{cond} = kA(T_i - T_o)/(\Delta x) \text{ [W]} \qquad (2.5)$$

Where: $k$ = A constant of proportionality in W/mK;

A = the surface area in $m^2$;

$T_i$ = the temperature of the warmer surface in K,

$T_o$ = the temperature of the cooler surface of the material in K, and

$\Delta x$ = the wall thickness in m.

The *constant of proportionality k* is the thermal conductivity of the material and is a measure of the ability of the material to conduct heat. When $\Delta x \rightarrow 0$, the differential is reduced to:

$$\dot{Q}_{cond} = kA(dT)/(dx) \text{ [W]} \qquad (2.6)$$

which is called **Fourier's law** of heat conduction.

Greenhouse film is normally supplied with a consistent thickness, eg. 200 µm, and in such cases the thermal conductivity of the material is specified in $W/m^2K$. Therefore, eq. 2.6 can be written as follows:

$$\dot{Q}_{cond} = UA(T_i - T_o) \text{ [W]} \qquad (2.7)$$

Where: U = The thermal conductivity in $W/m^2K$.

In greenhouses, heat is conducted through the cladding at night, from the warmer internal surface to the cooler external one. When calculating the heat loss through conduction, the inner surface of the cladding is assumed to be at the same temperature as the internal environment, and the outer surface at the same temperature as the external environment. Heat loss through conduction occurs through the canopy to the surroundings as well as through the floor covering to the cooler soil below. Various cladding and floor covering materials are available for greenhouses and the selection of a specific material will be dealt with in the design phase.

The thermal conductivity of each material is a very important characteristic that needs to be considered during the selection process. Unfortunately, the thermal conductivity of the available cladding materials decreases with an increase in the cost of these materials. It is also common practise to specify the *Thermal Resistance* of a material; in other words, the ability of a material to resists heat flow through conduction. The thermal resistance (or insulating value) of a material is the inverse of its thermal conductivity and is designated by the symbol R and expressed in $m^2K/W$. The thermal conductivity of some typical greenhouse covering materials were summarised and presented in Table 2 [32] [40] [41].

**Table 2 - Thermal conductivity of some typical cladding materials**

| **Type of cladding material** | **Thermal conductivity "k"** [W/mK] |
|---|---|
| Single polyethylene film | 6,0 – 8,0 |
| Double polyethylene film | 4,2 – 6,0 |
| Single glass | 6,0 – 8,8 |
| Double glass, 9mm air space | 4,2 – 5,2 |
| 10mm Twin wall polycarbonate | 4,7 – 4,8 |
| 16mm Triple wall polycarbonate | 4,2 – 5,0 |

The thermal conductivity of materials varies with temperature and that may cause complexity in evaluation. In calculations, the thermal conductivity of the material at average temperatures is normally used, and kept constant. The material is also assumed to be isotropic, meaning it has uniform properties in all directions, which is realistic for the type of materials that are used as greenhouse coverings.

### 2.7.4 Convection

Heat is transferred through convection by a fluid or a gas when it moves adjacent to a surface and is performed through the combined effect of conduction and fluid motion. The rate of heat transfer through convection is in direct relation to the fluid- or gas's velocity. If no moving fluid or gas is available, the heat will be transferred from a surface to the surroundings through conduction only [39]. In greenhouses, heat is transferred from the plants to the surrounding air and as this air is exchanged through leaks and/or ventilation systems, it transports the heat out of the greenhouse when the air outside is cooler then the air inside the greenhouse. The rate of heat transfer through convection can be increased if the rate of air movement through the greenhouse is increased through a *forced draft* or *natural ventilation system*. The convection can be called forced convection if the air is forced to flow through external means such as a fan, or natural convection if the air moves due to the buoyancy effect that is created due the different densities of the air at different temperatures at different heights. This is called the stack effect and the vertical height of the greenhouse will play a significant role in creating the stack effect. The two different types of ventilation are shown in Figure 10.

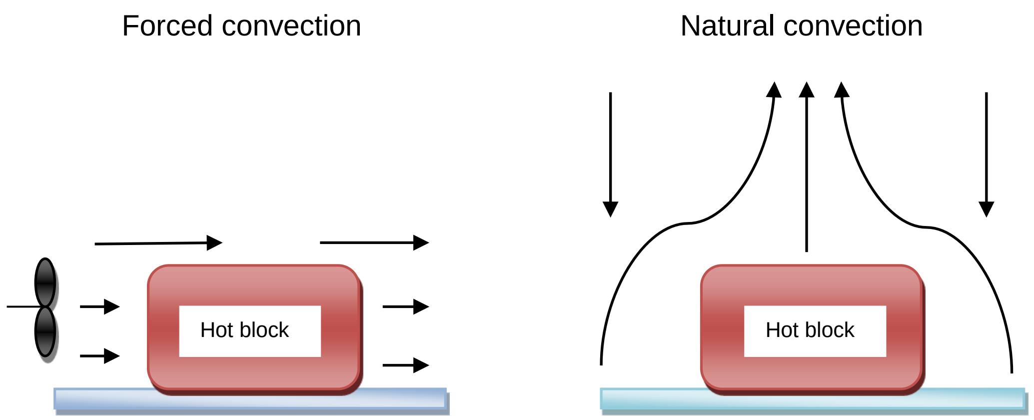


**Figure 10 - Forced convection with fan and natural convection**

On the surface of the leaves, the heat will be transferred through conduction to the layer of air adjacent to the leaves and be moved away through convection to finally reach the open sky. The rate of heat transfer through convection can be calculated by using **Newton's law** of cooling as:

$$\dot{Q}_{conv} = hA_s(T_s - T_\infty) \text{ [W]} \tag{2.8}$$

Where: h = Convection heat transfer coefficient of the fluid/gas in $W/m^2K$;

$A_s$ = The surface area through which convection takes place;

$T_s$ = The temperature of the surface in K, and

$T_\infty$ = The temperature of the fluid/gas sufficiently far from the surface.

It is important to note that the coefficient h is not a property of the fluid or gas here, but an experimentally determined parameter which value depends on all the factors that influence convection in the specific situation, such as surface geometry, the nature of the fluid/gas motion, the properties of the fluid/gas and the bulk fluid/gas velocity.

Typical values for the coefficient h is presented in Table 3.

**Table 3 - Typical values for heat transfer coefficient** [39]

| Type of convection | h [$W/m^2K$] |
|---|---|
| Free convection of gases | 2-2,5 |
| Free convection of liquids | 10-1000 |
| Forced convection of gases | 25-250 |
| Forced convection of liquids | 50-20 000 |
| Boiling and condensation | 2500-100 000 |

The rate at which heat is lost through convection is directly related to the rate of infiltration, because the heat is transported to the outside when warm air moves out and cooler air infiltrates the greenhouse. The rate of heat loss due to infiltration can therefore be determined by the following equation [39]:

$$\dot{Q}_{infl} = 0{,}5VN(T_i - T_o) \text{ [W]} \tag{2.9}$$

Where: $\dot{Q}_{infl}$ = Rate of heat transfer through infiltration,

V = the internal volume of the greenhouse in $m^3$,

N = the number of expected air exchanges per hour,

$T_i$ = the instantaneous air temperature inside the greenhouse in K and

$T_o$ = the instantaneous air temperature outside the greenhouse in K.

A constant value varying from 0.018 to 0.5 is added to equation 2.9 so that the number of expected air exchanges per hour, N, can be specified as a whole number [35]. The magnitude of this value will depend upon the ability of the greenhouse to exchange air through infiltration and will increase as the condition of the greenhouse covering material deteriorates with age. For the purpose of calculations, it was decided to use the maximum recommended value of 0.5 in order to determine the maximum possible rate of heat loss from the greenhouse.

If the infiltration of air is limited, the loss of heat through convection will therefore also be limited. This would mean that all the doors and vents need to seal properly to limit the loss of heat from the greenhouse through convection.

### 2.7.5 Radiation (Thermal)

Energy is transferred through radiation from a body, in the form of electromagnetic waves, that does not require a medium and can be transferred through a vacuum as well. The energy transfer through a vacuum is in fact the fastest, occurring at the speed of light - a typical example here is the transfer of energy from the sun to the earth. As far as heat transfer is concerned, the focus is on thermal radiation, a transfer of heat from bodies because of their temperature. All solids, liquids and gases can emit, absorb and transmit radiation to various degrees. Radiation is a *volumetric phenomenon* but is usually considered as a *surface phenomenon* for solids that are opaque to radiation, such as metals, wood and rocks, because the radiation emitted by the interior regions of such bodies can never reach the surface, while the radiation that such a body receives is normally absorbed near the surface. If a body has a temperature above absolute zero it will emit thermal radiation. The ideal surface that can emit the maximum amount of thermal radiation is called a *black body* while the radiation emitted by a black body is called *black body radiation*. The maximum rate at which the heat can be emitted from the surface of a black body, an absolute temperature, can be determined with the **Stefan-Boltzman law** as follows [39]:

$$\dot{Q}_{rad} = \sigma A_s T^4 \text{ [W]} \tag{2.10}$$

Where: $\sigma = 5.67 * 10^{-8}$ W/m$^2$ · K$^4$ – the Stefan-Boltzman constant,

$A_s$ = The area of the emitting surface, and

T = the absolute temperature of the emitting surface in K.

All other surfaces will be able to emit only a fraction of a black body's radiation and that fraction is characterised as a surface's *emissivity* ($\varepsilon$, where $0 \leq \varepsilon \leq 1$). The thermal radiation that can be emitted by a surface, other than a black body, can therefore be calculated as follows:

$$\dot{Q}_{rad} = \varepsilon \sigma A_s T^4 \text{ [W]} \qquad (2.11)$$

Where: $\varepsilon$ = The emissivity of the radiating surface.

Another important factor to consider is the *absorptivity* of a surface ($\alpha$, where $0 \leq \alpha \leq 1$). A black body is also the ideal absorbing surface, meaning it will absorb all the thermal radiation incident on it while all other surfaces will absorb only a fraction of the incident radiation. Both $\varepsilon$ and $\alpha$ depend on the surface's temperature and the wavelength of radiation. According to **Kirchoff's law**, the emissivity and the absorptivity of a surface, at a given temperature and wavelength, are equal. The rate at which a surface can absorb thermal radiation can be determined as follows [39]:

$$\dot{Q}_{absorbed} = \alpha \dot{Q}_{incident} \qquad (2.12)$$

Where $\dot{Q}_{incident}$ is the rate of incident thermal radiation and $\alpha$ the absorptivity of a surface.

If a surface is non-transparent (opaque), the portion of incident radiation that is not absorbed by the surface, is reflected back. The net heat transfer of a surface is therefore the difference between the radiation emitted and the radiation absorbed. If the emissivity of the leaves is approximately that of the covering material and the absorptivity of the surface of the leaves is taken as equal to its emissivity, the rate of energy transfer due to thermal radiation between the surface of the leaves and the enclosure can be determined as follows:

$$\dot{Q}_{rad} = \varepsilon \sigma A_s (T_1^4 - T_2^4) \text{ [W]} \qquad (4.13)$$

Where: $T_1$ = The temperature of the leaves' surface taken as equal to the internal temperature and

$T_2$ = The temperature of the enclosure taken as equal to the external temperature.

In greenhouses, heat is emitted from the surface of the leaves in all directions, in the form of thermal radiation. A very important aspect to consider during thermal radiation is the *view factor*, referring to the orientation of the surfaces relative to each other. The view factor determines the fraction of thermal radiation that will leave a surface and hit the adjacent surface. Since the plants are completely enclosed by the greenhouse canopy and separated only by a gas, the air inside the greenhouse, the view factor in this case, can be taken as 1. The greenhouse cover will transmit, absorb and reflect the heat radiated from the leaves surface in various proportions according to the properties of the covering material, as indicated in Figure 11.

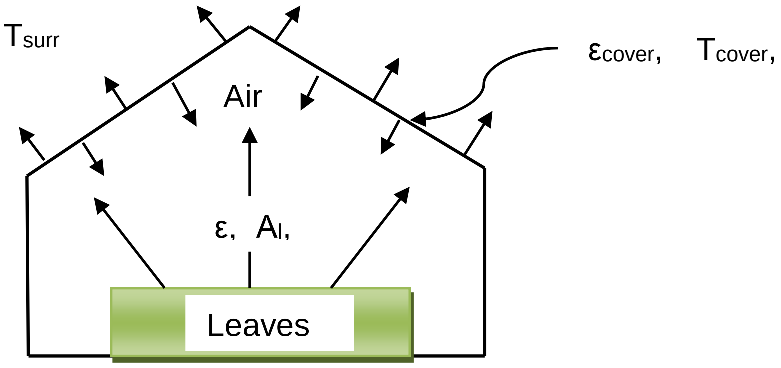


**Figure 11 - Radiation heat transfer between the crop and the canopy**

The following factors also need to be considered in determining the heat loss through thermal radiation from the leaves to the enclosure [7] [42]:

- The surface of the leaves is assumed to be a diffused radiating surface, meaning that the radiating properties of the surface of the leaves is independent of direction. Heat is assumed to be radiated from the surface of the leaves in all directions with equal intensity.
- In what wavelengths the most heat is to be transmitted from the plants. The radiation emitted from bodies at room temperature normally falls into the infrared region of the spectrum, with wavelengths from 0.76 to 100 µm. If an infrared film is used in the construction of a greenhouse, the heat loss due to re-radiation is slowed down due to additives in the plastic film (added to the plastic to diffuse incoming light) that absorbs the heat loss. This property of the film creates an additional thermal value for heat loss due to re-radiation. For the purpose of theoretical calculations, the heat loss due to re-radiation will be calculated across

all wavelengths and the ability of the greenhouse film to block some of this re-radiation, will be ignored.

- The characteristics of the glazing material, such as:
    - Its *Absorptivity* – the fraction of radiant flux that it will absorb (designated by α, where $0 \leq \alpha \leq 1$);
    - Its *Reflectivity* – the fraction of radiant flux that it will reflect back inwards (designated by ρ, where $0 \leq \rho \leq 1$); and
    - Its *Transmissivity* – the fraction of radiant flux that will transmit to the open sky (designated by $\tau$, where $0 \leq \tau \leq 1$).

- The emissivity of the surface of the leaves – the ratio of radiation that will be emitted by the surface of the leaves, at a given temperature, in relation to the radiation that will be emitted by a black body at the same temperature (ε, where $0 \leq \varepsilon \leq 1$). For the purpose of this study, the emissivity of the surface of the leaves is assumed to be constant with directional, wavelength and temperature variation.

The amount of heat that the greenhouse will be able to collect during day-time from solar radiation can be calculated as follows [36] [43]:

$$\dot{Q}_{rad/sun} = I_s * A_s \qquad (2.14)$$

Where: $I_s$ = Solar radiation in W/m$^2$, and

$A_s$ = The surface area with direct sunlight in m$^2$.

### 2.7.6 Heat loss calculations

For the purpose of this study, a greenhouse of 8 * 30 m was constructed and six raised rose beds, each with a width of 400 mm and an in-between row spacing of 1000 mm, was placed inside the greenhouse. The relevant dimensions of the raised beds are indicated in Figure 12.

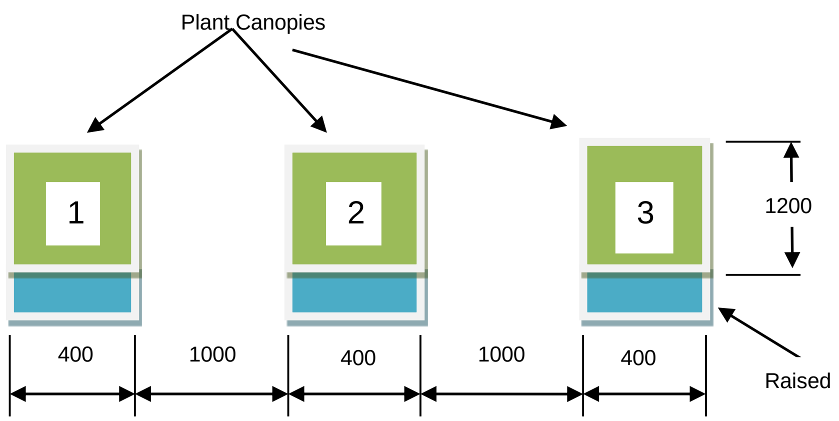


**Figure 12 - Typical layout of rose beds.**

When the plants were in full production, the spaces between the raised beds were almost completely filled with plant material, but the plant canopy is not a solid area, but very porous. For the purpose of theoretical calculations, the assumption was made that the plant canopy consisted of a single rectangular three-dimensional shape, as shown in Figure 13, with an actual radiating surface area of approximately 25 % of the total surface area.

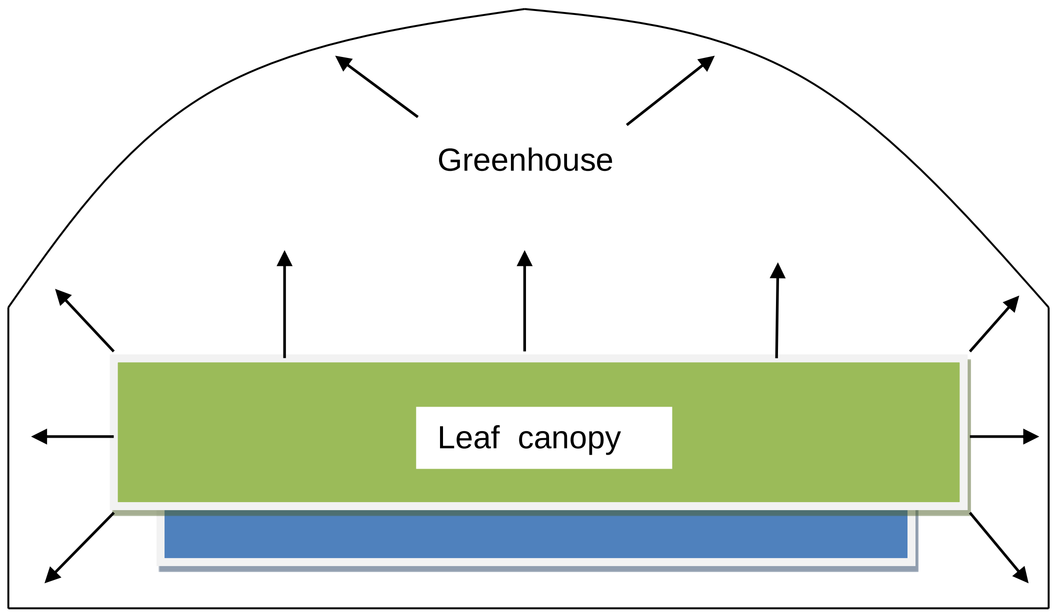


**Figure 13 - Plant canopy for theoretical calculations.**

The length of the raised beds is 28 m, which can be taken as the length of the rectangular shape, while the width can be taken as 7.5 m, with a height of 1.2 m. This will give an estimated total surface area of 295.2 $m^2$, as shown in Figure 14. As stated before, the radiating surface is not completely covered with the surfaces of the leaves and therefore for the purpose of theoretical calculations, the actual radiating surface of the leaves was taken as 50 % of the total external surface of the leaves. The actual radiating surface can therefore be determined as follows:

$$A_s = (50\ \%)*295.2$$
$$= 147.6\ m^2$$

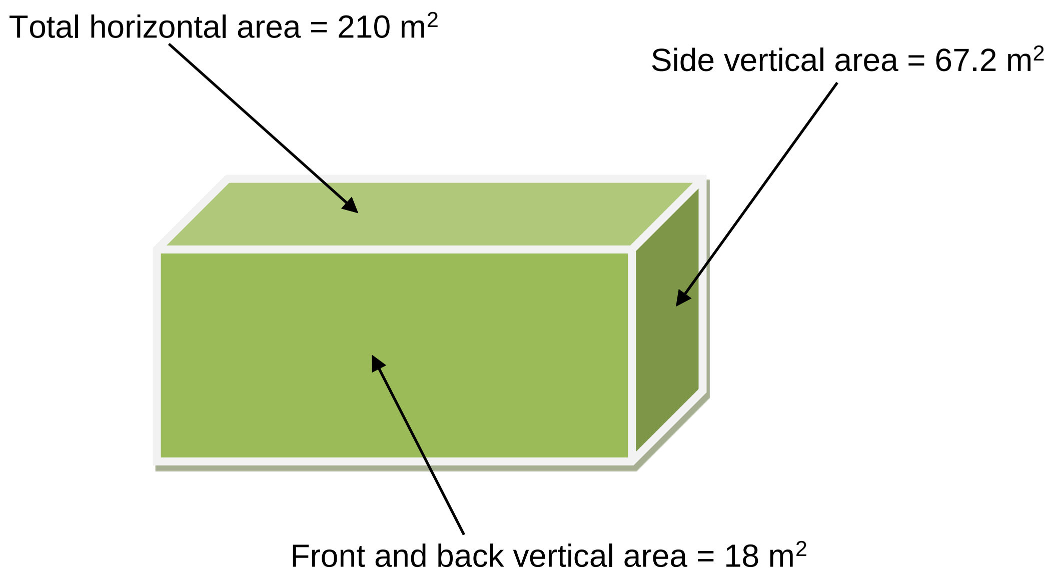


**Figure 14 - Assumed rectangular shape for theoretical calculations.**

## 2.7.7 Heat loss through radiation

The plant canopy is fully enclosed by the greenhouse structure, as shown in Figure 13, and the assumption can be made that all the heat that will be *radiated* from the plant canopy will either be absorbed, reflected or transmitted by the greenhouse structure or glazing [36]. The plant canopy will be heated by the sun's radiation to the required daytime temperature and the excess heat needs to be removed by the ventilation system.

As night falls, the plant canopy's temperature will drop due to the loss of heat through convection (infiltration), conduction and radiation until the minimum required internal temperature is reached. At this point the heating system will need to replace any additional energy that is lost to ensure that the leaf temperature does not drop below the required minimum. For the purpose of determining the maximum rate of heat loss, the internal temperature is not to drop below 15 $^oC$. The surface of the leaves is assumed to be at the same temperature as the internal air.

In an enclosed system, such as a greenhouse, the enclosure will absorb a certain percentage of this heat and reflect it back to the plants. For a typical three-layer greenhouse film, the average values for α, ρ and $\tau$ across the band of wavelength from 400 to 1100 nm were determined as 0.06, 0.08 and 0.86 respectively [7] [21] [32]. That would mean that the greenhouse film would absorb 6 %, reflect 8 % and transmit 86 % of the received heat flux. The total amount of heat that will be lost by thermal radiation from the surface of the leaves can be calculated by using equation 2.13 and incorporating an emissivity of 0.9 for the surface of the leaves and the PE film:

Radiation from leaf canopy is:

$\dot{Q}_{leave} = \sigma A_{leave}\, \varepsilon\, [(T_{leave})^4 - (T_{canopy})^4]$

$= (5.67 * 10^{-8})(147.6)(0.9)[(288)^4 - (273)^4]$

$= 9.980$ kW

It is clear that the PE greenhouse canopy does very little to retain the radiation heat inside the greenhouse during night-time. To improve the heat retention capability, tinted or coated glass is often used as cladding material, especially in European greenhouses, with its disadvantage being its cost.

## 2.7.8 Heat loss through convection

The heat loss through convection is caused by the movement of air across the greenhouse glazing. The number of air exchanges per hour may vary from 0,5 to 1,5 the total internal volume of the greenhouse and depending on the type and the condition of the greenhouse glazing, structure and openings [7] [42] [44]. For an average number of air exchanges of one volume per hour, the heat loss through infiltration, for an internal volume of 864 $m^3$, can be calculated as follows:

$\dot{Q}_{infl}$ = 0,5*1*864*(288 – 273)

= 6,48 kW

### 2.7.9 Heat loss through conduction

The heat loss through conduction is facilitated by the greenhouse glazing and floor covering material. The total area of the glazing is 472,4 m$^2$ with a heat transfer coefficient of 0,83 (if a single layer of 200 µm PE film is used) while the total floor area is 240 m$^2$ with a heat transfer coefficient of 0,83 (for the same type of material) as well [21]. For an estimated soil temperature of 6 $^{o}$C, the total heat loss through conduction by the glazing and floor can therefore be determined as:

$\dot{Q}_{cond\_canopy}$ = 0,83*472,4*(288 – 273)

= 5,881 kW

And the heat loss by conduction through the floor:

$\dot{Q}_{floor}$ = 0,83*240*(288 – 279)

= 1,793 kW

### 2.7.10 Total Heat Loss

The total heat loss for the greenhouse can therefore be determined as:

$\dot{Q}$ = 9.980 + 6,48 + 5,881 + 1,793

= 24.134 kW

The contributing factor for each means of heat loss can be summarized as shown in Table 4.

**Table 4 - The influence of the various mechanisms of heat transfer.**

| Means of Heat Loss | kW | Percentage of total |
|---|---|---|
| Radiation | 9.980 | 41.35 % |
| Infiltration | 6.480 | 26.85 % |
| Conduction – glazing | 5.881 | 24.37 % |
| Conduction – floor | 1.793 | 7.43 % |
| Total | 24.134 | |

## 2.7.11 Developing a steady-state heat-loss calculator

Developing a tool that can be used in determining the heat loss from the greenhouse and ultimately the required heating capacity of the solar heating system will be necessary especially if different scenarios need to be investigated. Different set-points for the minimum temperature inside the greenhouse may, for example, be investigated to determine the heating capacity needed for each. The different mechanisms for heat loss can be combined and compared with the ability of the solar heating system to collect heat. The formulas used in determining the heat loss through each mechanism can be summarized as follows:

- Conduction, from equation 2.1.

  $\dot{Q}_{cond} = kA(T_1 - T_2)/(\Delta x)$ [W]

  In equation 2.4, the area A designates all the different areas of covering material that can lose heat through conduction. The external dimensions of the greenhouse are used to calculate these different areas as shown in Table 5 below. Different materials can be used for different purposes meaning that the different k values of the different materials need to be considered in the calculation as shown in Table 5.

- Convection (infiltration), from eq. 2.7.

  $\dot{Q}_{infl} = 0{,}5VN(T_1 - T_2)$ [W]

  In determining the heat loss through convection, the internal volume of the greenhouse needs to be calculated and the number of air exchanges that will occur per hour, be assumed. By using the calculator, the values for the internal ($T_1$) and external temperature ($T_2$) can also be altered to determine the heat loss for the specific temperature differences. The number of heat exchanges per hour (N) can be varied to account for the heat losses of different greenhouse designs, especially as far as the doors and ventilation systems are concerned.

- Radiation, from eq. 2.10.

  $\dot{Q}_{leaves} = \varepsilon \sigma A_l (T^4_l - T^4_2)$ [W]

  The temperatures $T_1$ and $T_2$ can be taken as the leaves' surface temperature and the enclosure surface temperature respectively, with the emissivity of the leaves' surface equal to the emissivity of the enclosure material at 0.9.

**Table 5 - Example of greenhouse heat loss calculator.**

| Steady-State Greenhouse Heat Loss Calculation | |
|---|---|
| **Heat Loss Through Conduction** | **Value** |
| Greenhouse Length (m) | 30.000 |
| Greenhouse width(m) | 8.000 |
| Side Wall Height (m) | 2.400 |
| Roof Height (m) | 2.500 |
| Roof Slope Length (m) | 9.000 |
| Roof Area | 270.000 |
| East Wall Area (m^2) | 72.000 |
| West Wall Area (m^2) | 72.000 |
| South Wall Area (m^2) | 29.200 |
| North Wall Area (m^2) | 29.200 |
| Total Side Wall Area (m^2) | 202.400 |
| Floor Area (m^2) | 240.000 |
| Total Wall Area (m^2) | 472.400 |
| k Value side walls (W/m^2K) | 0.830 |
| k Value for floor (W/m^2K) | 0.830 |
| k Value for roof (W/m^2K) | 0.830 |
| Inside Temperature (K) | 288 |
| Outside Temperature (K) | 273 |
| Soil Temperature (K) - assumed | 279 |
| Heat Conducted through roof (kW) | 3.362 |
| Heat Conducted through side wall (kW) | 2.520 |
| Heat conducted through floor (kW) | 1.793 |
| **Tot Heat Loss through Conduction (kW)** | **7.674** |
| **Heat Loss Through Convection** | **Value** |
| Internal Volume ($m^3$) | 864.000 |
| Number of Air Changes per hour | 1 |
| **Total Heat Loss through Cenvection (kW)** | **6.480** |
| **Heat Loss Through Radiation** | **Value** |
| Emmisivity of leaves and enclosure (ε) | 0.9 |
| Temperature of surface 1 (K) | 288 |
| Temperature of surface 2 (K) | 273 |
| Stefan-boltzman constant | 5.670E-08 |
| Plant canopy area (m2) | 147.600 |
| **Total Heat Loss through Radiation (kW)** | **9.981** |
| **Total Heat Loss (kW)** | **24.135** |

A further expansion of the tool would be to include the heating requirements and capacity of the solar water heating system. To determine this, the required time of operation of the heating system must first be determined, e.g. from 17:00 in the evening till 08:00 the next morning would require a heating time of 15 hours. With the required heating capacity and heating time, the amount of heat needed, in Joules, can then be determined. When the amount of heat required is known, the required capacity of the solar heating system can be determined by taking the heat storing capacity of the water, or any other working fluid, into account. The heat storing capacity of water can be determined as follows:

$Q = mc_p\Delta T$ [J] (2.15)

Where: m = the mass of the water,

$c_p$, = specific heat storage capacity of water (4,183 J/kgK) and

$\Delta T$ = the change in temperature of the water.

The tool becomes very handy in determining the characteristics of the solar water heating system. Once the efficiency of the solar collector, the water storage and heat exchange system is known, the tool can be expanded to size these components as well.

**Table 6 - Heat loss calculator combined with thermal storage calculator**

**Thermal Storage Calculator**

| Heat Loss Through Conduction | Value |
|---|---|
| Greenhouse Length (m) | 30.000 |
| Greenhouse width(m) | 8.000 |
| Side Wall Height (m) | 2.400 |
| Roof Height (m) | 2.500 |
| Roof Slope Length (m) | 9.000 |
| Roof Area | 270.000 |
| East Wall Area (m^2) | 72.000 |
| West Wall Area (m^2) | 72.000 |
| South Wall Area (m^2) | 29.200 |
| North Wall Area (m^2) | 29.200 |
| Total Side Wall Area (m^2) | 202.400 |
| Floor Area (m^2) | 240.000 |
| Total Wall Area (m^2) | 472.400 |
| k Value side walls (W/m^2K) | 0.830 |
| k Value for floor (W/m^2K) | 0.830 |
| k Value for roof (W/m^2K) | 0.830 |
| Inside Temperature (K) | 288.000 |
| Outside Temperature (K) | 273.000 |
| Soil Temperature (K) | 279.000 |
| Heat Conducted through roof (kW) | 3.362 |
| Heat Conducted through side wall (kW) | 2.520 |
| Heat conducted through floor (kW) | 1.793 |
| **Tot Heat Loss through Conduction (kW)** | **7.674** |
| **Heat Loss Through Convection** | **Value** |
| Internal Volume ($m^3$) | 864.000 |
| Number of Air Changes per hour | 1 |
| **Total Heat Loss through Cenvection (kW)** | **6.480** |
| **Heat Loss Through Radiation** | **Value** |
| Emmisivity of leaves and enclosure (ε) | 0.9 |
| Temperature of surface 1 (K) | 288 |
| Temperature of surface 2 (K) | 273 |
| Stefan-boltzman constant | 5.670E-08 |
| Plant canopy area (m2) | 147.600 |
| **Total Heat Loss through Radiation (kW)** | **9.981** |
| **Total Heat Loss (kW)** | **24.135** |
| **Solar Water Heating** | |
| Heating time (h) | 15 |
| Heating Capacity needed (kW) | 24.135 |
| Amount of heat needed (J) | 1303297352 |
| Initial Temperature of Storage Water (°C) | 80 |
| Final Temperature of Storage Water (°C) | 25 |
| **Amount of water needed (ℓ)** | 5665 |

### 2.7.12 Developing a numerical transient heat transfer model for predicting the required rate of ventilation for the greenhouse during the day-time period.

The heat transfer tool, as developed in section 2.4.11, was based on steady-state heat transfer, meaning that the variations in temperature were taken as independent of time. This tool can be useful to determine the maximum heating requirements but sometimes a tool is needed to be able to determine entities such as the required rate of ventilation needed for a ventilated greenhouse so as to sustain the desirable internal temperatures. To be able to develop this model, the total mass of the internal air of the greenhouse is considered and its temperature is numerically determined based on the influence the various heat transfer mechanisms has on it. The model will be developed by incorporating the following general assumptions [7] [31] [42] [45]:

- No temperature gradient existed in each layer of the internal air and the temperature was measured at mid-height.
- The density of the internal air remained constant in the range of operating temperatures of the greenhouse.
- The heat transfer coefficients of the covering materials remained constant with a variation in temperature.
- The floor was not heated by direct solar radiation during the day because the crop completely covered the total floor area.
- The levels of solar radiation experienced were based on the averages for Bloemfontein on a clear day with no solar radiation after sunset.
- Ventilation openings were opened from sunrise till sunset during summer and from 09:00 till 16:00 during winter.

For the day-time model, the following mechanisms of heat transfer were considered:

- Heat gains through radiation from the sun [43] [46] [47],
- Heat losses through natural ventilation [7] [48],
- Heat losses through conduction by the enclosure, and [32]
- Latent heat losses [23] [49] [50].

The energy balance equation from which the transient heat transfer model for the prediction of the required rate of ventilation was determined, could be presented as follows [31] [42] [44] [51] :

$$\dot{Q}_{rad} = \dot{Q}_{vent} + \dot{Q}_{cond} + \dot{Q}_{L} \quad (2.16)$$

Solar radiation

The heat gain through solar radiation can be determined as follows [7] [8] [21]:

$$Q_{rad} = \tau_{encl} Q_{GR} \quad (2.17)$$

Where: $\tau_{encl}$ = the solar radiance transmittance of the glazing material,

$Q_{GR}$ = the outside horizontal global solar radiation in W/m$^2$.

To be able to determine the heat generated inside the greenhouse due to solar radiation, the global horizontal irradiance, as it varies with time during the day for the specific site, had to be calculated. An Excel spreadsheet containing the relevant data was compiled from internet-based tools as shown in Figure 15 [16] [43] [46] [47] [52].

| | 2016-01-21 | 2016-02-21 | 2016-03-21 | 2016-04-21 | 2016-05-21 | 2016-06-21 | 2016-07-21 | 2016-08-21 | 2016-09-21 | 2016-10-21 | 2016-11-21 | 2016-12-21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 05:00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 05:30 | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 28 | 87 |
| 06:00 | 318 | 105 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 28 | 325 | 387 |
| 06:30 | 560 | 419 | 173 | 0 | 0 | 0 | 0 | 0 | 168 | 429 | 564 | 601 |
| 07:00:00 | 715 | 630 | 473 | 194 | 7 | 0 | 5 | 189 | 469 | 636 | 718 | 740 |
| 07:30:00 | 819 | 764 | 662 | 474 | 262 | 163 | 254 | 471 | 659 | 768 | 820 | 834 |
| 08:00:00 | 890 | 852 | 782 | 652 | 502 | 424 | 495 | 649 | 780 | 855 | 891 | 901 |
| 08:30:00 | 941 | 914 | 862 | 765 | 655 | 597 | 650 | 763 | 860 | 916 | 942 | 949 |
| 09:00:00 | 979 | 958 | 917 | 841 | 754 | 709 | 750 | 840 | 916 | 960 | 980 | 984 |
| 09:30:00 | 1007 | 990 | 957 | 893 | 821 | 785 | 818 | 892 | 956 | 992 | 1007 | 1011 |
| 10:00:00 | 1027 | 1014 | 985 | 930 | 868 | 836 | 865 | 929 | 984 | 1015 | 1028 | 1030 |
| 10:30:00 | 1042 | 1030 | 1004 | 955 | 899 | 871 | 897 | 954 | 1004 | 1031 | 1042 | 1044 |
| 11:00:00 | 1052 | 1041 | 1017 | 972 | 920 | 893 | 917 | 971 | 1017 | 1042 | 1052 | 1054 |
| 11:30:00 | 1057 | 1048 | 1025 | 981 | 931 | 906 | 929 | 980 | 1024 | 1048 | 1058 | 1059 |
| 12:00:00 | 1059 | 1050 | 1027 | 984 | 935 | 910 | 933 | 983 | 1027 | 1050 | 1060 | 1061 |
| 12:30:00 | 1057 | 1048 | 1025 | 981 | 931 | 906 | 929 | 980 | 1024 | 1048 | 1058 | 1059 |
| 13:00:00 | 1052 | 1041 | 1017 | 972 | 920 | 893 | 917 | 971 | 1017 | 1042 | 1052 | 1054 |
| 13:30:00 | 1042 | 1030 | 1004 | 955 | 899 | 871 | 897 | 954 | 1004 | 1031 | 1042 | 1044 |
| 14:00:00 | 1027 | 1014 | 985 | 930 | 868 | 836 | 865 | 929 | 984 | 1015 | 1028 | 1030 |
| 14:30:00 | 1007 | 990 | 957 | 893 | 821 | 785 | 818 | 892 | 956 | 992 | 1007 | 1011 |
| 15:00:00 | 979 | 958 | 917 | 841 | 754 | 709 | 750 | 840 | 916 | 960 | 980 | 984 |
| 15:30:00 | 941 | 914 | 862 | 765 | 655 | 597 | 650 | 763 | 860 | 916 | 942 | 949 |
| 16:00:00 | 890 | 852 | 782 | 652 | 502 | 424 | 495 | 649 | 780 | 855 | 891 | 901 |
| 16:30:00 | 819 | 764 | 662 | 474 | 262 | 163 | 254 | 471 | 659 | 768 | 820 | 834 |
| 17:00:00 | 715 | 630 | 473 | 194 | 7 | 0 | 5 | 189 | 469 | 636 | 718 | 740 |
| 17:30:00 | 560 | 419 | 173 | 0 | 0 | 0 | 0 | 0 | 168 | 429 | 564 | 601 |
| 18:00:00 | 318 | 105 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 117 | 325 | 387 |
| 18:30:00 | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 28 | 87 |
| 19:00:00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Figure 15 - Global horizontal irradiance for each month.**

This data could then be used to plot the curves for the expected global solar irradiance as shown in Figure 16.

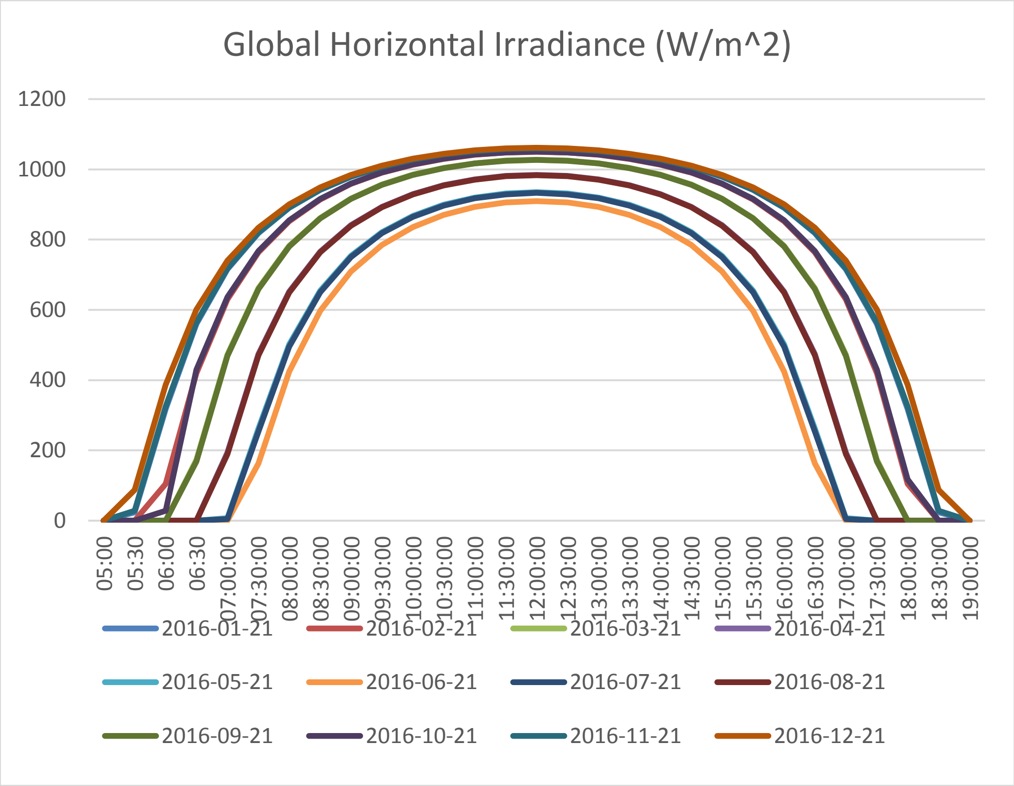


**Figure 16 - Global horizontal radiation for each month - graphically.**

From this, a transient heat gain model was developed in Excel, as shown in Figure 17, by using equation 2.17.

| Time | Timestep | Temperature | | | Radiation | |
|---|---|---|---|---|---|---|
| | | To | Ti act | Tideal | Qgr | Qgr in |
| | | (deg C) | (deg C) | (deg C) | (W/m^2) | (kW) |
| 07:00:00 | 0.00 | -4.0 | -1.9 | 12.0 | 5 | 0.9 |
| 07:30:00 | 0.50 | -2.1 | -1.6 | 12.0 | 254 | 48.7 |
| 08:00:00 | 1.00 | 0.9 | 2.7 | 12.3 | 495 | 95.1 |
| 08:30:00 | 1.50 | 3.4 | 8.2 | 13.4 | 650 | 124.8 |
| 09:00:00 | 2.00 | 6.6 | 13.1 | 15.1 | 750 | 144.1 |
| 09:30:00 | 2.50 | 8.3 | 16.8 | 17.3 | 818 | 157.1 |
| 10:00:00 | 3.00 | 11.9 | 20.3 | 19.7 | 865 | 166.1 |
| 10:30:00 | 3.50 | 14.0 | 23.7 | 22.2 | 897 | 172.2 |
| 11:00:00 | 4.00 | 14.9 | 26.2 | 24.5 | 917 | 176.1 |
| 11:30:00 | 4.50 | 15.9 | 28.2 | 26.3 | 929 | 178.4 |
| 12:00:00 | 5.00 | 16.7 | 29.7 | 27.5 | 933 | 179.1 |
| 12:30:00 | 5.50 | 17.1 | 30.5 | 28.0 | 929 | 178.4 |
| 13:00:00 | 6.00 | 17.6 | 30.9 | 27.7 | 917 | 176.1 |
| 13:30:00 | 6.50 | 18.1 | 30.8 | 26.7 | 897 | 172.2 |
| 14:00:00 | 7.00 | 18.1 | 29.9 | 25.0 | 865 | 166.1 |
| 14:30:00 | 7.50 | 17.7 | 28.7 | 22.8 | 818 | 157.1 |
| 15:00:00 | 8.00 | 17.7 | 27.3 | 20.4 | 750 | 144.1 |
| 15:30:00 | 8.50 | 18.2 | 25.3 | 17.9 | 650 | 124.8 |
| 16:00:00 | 9.00 | 18.1 | 23.3 | 15.6 | 495 | 95.1 |
| 16:30:00 | 9.50 | 17.7 | 21.3 | 13.8 | 254 | 48.7 |
| 17:00:00 | 10.00 | 17.6 | 19.3 | 12.5 | 5 | 0.9 |
| 17:30:00 | 10.50 | 15.4 | 16.6 | 12.0 | 0 | 0.0 |
| 18:00:00 | 11.00 | 12.7 | 12.7 | 12.0 | 0 | 0.0 |
| 18:30:00 | 11.50 | 9.7 | 10.0 | 12.0 | 0 | 0.0 |
| 19:00:00 | 12.00 | 7.5 | 8.1 | 12.0 | 0 | 0.0 |

**Figure 17 - Transient heat gain model.**

Natural ventilation

The energy exchange through natural ventilation can be determined as follows :

$$Q_{vent} = Q_L + q_v c_p \rho (T_i - T_o) \qquad (2.18)$$

Where: $Q_L$ = the latent heat loss due to evaporation,

$q_v$ = the rate of ventilation in $m^3/s$,

$c_p$ = the specific heat storage capacity of air,

$\rho$ = the density of the air,

$T_i$ = the instantaneous air temperature inside the greenhouse in K and

$T_o$ = the instantaneous air temperature outside the greenhouse in K.

The temperatures inside and outside the greenhouse was measured on a half-an-hour basis, with the help of the automatic weather station. Raw data from the weather station is exported into Excel and from that the required information is summarized as shown in Figure 18.

**Day Time Data (Summarized)**

| Date | Time | Temp Out (deg) | Hi Temp (deg) | Low Temp (deg) | Out Hum (%) | Dew Pt. (deg) | Wind Speed (km/h) | Wind Chill (deg) | Heat Index | Pressure (mBar) | In Temp (deg) | In Hum (%) | In Dew (deg) | In Heat | In EMC | In Air Density (kg/m^3) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2014-07-14 | 07:00 AM | -4 | -3.8 | -4.3 | 70 | -8.7 | 0 | -4 | -4.2 | 1055.90 | -1.9 | 80 | -4.9 | -2.1 | -2.1 | 1.3513 |
| 2014-07-14 | 07:30 AM | -2.1 | -2.1 | -4.1 | 67 | -7.4 | 0 | -2.1 | -2.3 | 1056.10 | -1.6 | 81 | -4.4 | -1.7 | -1.7 | 1.3497 |
| 2014-07-14 | 08:00 AM | 0.9 | 0.9 | -2 | 57 | -6.6 | 0 | 0.9 | 0.5 | 1055.70 | 2.7 | 83 | 0.1 | 2.6 | 17.65 | 1.326 |
| 2014-07-14 | 08:30 AM | 3.4 | 3.4 | 1 | 53 | -5.3 | 0 | 3.4 | 2.9 | 1055.00 | 8.2 | 83 | 5.5 | 8.1 | 17.62 | 1.296 |
| 2014-07-14 | 09:00 AM | 6.6 | 6.6 | 3.4 | 43 | -5.1 | 0 | 6.6 | 5.9 | 1054.70 | 13.1 | 78 | 9.3 | 12.8 | 15.74 | 1.2702 |
| 2014-07-14 | 09:30 AM | 8.3 | 8.3 | 6.6 | 39 | -4.9 | 0 | 8.3 | 7.4 | 1054.20 | 16.8 | 72 | 11.8 | 16.7 | 13.75 | 1.2505 |
| 2014-07-14 | 10:00 AM | 11.9 | 11.9 | 8.3 | 33 | -3.9 | 0 | 11.9 | 10.5 | 1053.70 | 20.3 | 65 | 13.5 | 20.3 | 11.88 | 1.233 |
| 2014-07-14 | 10:30 AM | 14 | 14.2 | 11.9 | 28 | -4.3 | 1.6 | 14 | 12.1 | 1053.20 | 23.7 | 59 | 15.2 | 24.1 | 10.77 | 1.2165 |
| 2014-07-14 | 11:00 AM | 14.9 | 15.1 | 14 | 25 | -4.9 | 1.6 | 14.9 | 12.7 | 1053.40 | 26.2 | 53 | 15.9 | 26.4 | 9.65 | 1.2054 |
| 2014-07-14 | 11:30 AM | 15.9 | 16.2 | 14.9 | 22 | -5.8 | 1.6 | 15.9 | 13.4 | 1053.00 | 28.2 | 49 | 16.5 | 28.7 | 8.89 | 1.1961 |
| 2014-07-14 | 12:00 PM | 16.7 | 16.9 | 15.9 | 20 | -6.4 | 1.6 | 16.7 | 14.1 | 1052.60 | 29.7 | 45 | 16.5 | 30.3 | 8.24 | 1.1897 |
| 2014-07-14 | 12:30 PM | 17.1 | 17.2 | 16.7 | 19 | -6.7 | 1.6 | 17.1 | 14.3 | 1052.00 | 30.5 | 42 | 16.1 | 30.9 | 7.81 | 1.1866 |
| 2014-07-14 | 01:00 PM | 17.6 | 17.6 | 16.7 | 17 | -7.8 | 1.6 | 17.6 | 14.7 | 1051.50 | 30.9 | 38 | 14.9 | 30.7 | 7.2 | 1.186 |
| 2014-07-14 | 01:30 PM | 18.1 | 18.3 | 17.5 | 16 | -8.1 | 1.6 | 18.1 | 15.2 | 1050.80 | 30.8 | 38 | 14.8 | 30.7 | 7.2 | 1.1858 |
| 2014-07-14 | 02:00 PM | 18.1 | 18.1 | 17.6 | 15 | -9 | 1.6 | 18.1 | 15.1 | 1050.70 | 29.9 | 39 | 14.5 | 29.9 | 7.33 | 1.1893 |
| 2014-07-14 | 02:30 PM | 17.7 | 18.1 | 17.4 | 15 | -9.3 | 3.2 | 17.7 | 14.7 | 1050.70 | 28.7 | 41 | 14.2 | 28.9 | 7.68 | 1.1946 |
| 2014-07-14 | 03:00 PM | 17.7 | 18.2 | 17.7 | 14 | -10.2 | 1.6 | 17.7 | 14.7 | 1050.60 | 27.3 | 37 | 11.4 | 26.6 | 7.13 | 1.2031 |
| 2014-07-14 | 03:30 PM | 18.2 | 18.4 | 17.7 | 13 | -10.7 | 1.6 | 18.2 | 15.1 | 1050.40 | 25.3 | 42 | 11.5 | 24.9 | 7.9 | 1.2107 |
| 2014-07-14 | 04:00 PM | 18.1 | 18.6 | 18.1 | 13 | -10.8 | 1.6 | 18.1 | 15.1 | 1050.50 | 23.3 | 45 | 10.7 | 23 | 8.45 | 1.2199 |
| 2014-07-14 | 04:30 PM | 17.7 | 18.1 | 17.6 | 14 | -10.2 | 1.6 | 17.7 | 14.7 | 1050.60 | 21.3 | 54 | 11.6 | 20.6 | 9.94 | 1.2273 |
| 2014-07-14 | 05:00 PM | 17.6 | 17.7 | 17.4 | 14 | -10.3 | 0 | 17.6 | 14.6 | 1050.70 | 19.3 | 63 | 12.1 | 19.2 | 11.61 | 1.2353 |
| 2014-07-14 | 05:30 PM | 15.4 | 17.6 | 15.4 | 17 | -9.6 | 0 | 15.4 | 12.8 | 1051.00 | 16.6 | 66 | 10.2 | 16.2 | 12.28 | 1.2495 |
| 2014-07-14 | 06:00 PM | 12.7 | 15.4 | 12.7 | 20 | -9.8 | 0 | 12.7 | 10.7 | 1051.40 | 12.7 | 68 | 7 | 12.2 | 12.95 | 1.2698 |
| 2014-07-14 | 06:30 PM | 9.7 | 12.7 | 9.7 | 25 | -9.4 | 0 | 9.7 | 8.6 | 1052.00 | 10 | 70 | 4.8 | 9.8 | 13.35 | 1.2843 |
| 2014-07-14 | 07:00 PM | 7.5 | 9.8 | 7.5 | 28 | -9.9 | 0 | 7.5 | 6.5 | 1052.30 | 8.1 | 71 | 3.1 | 7.8 | 13.58 | 1.2949 |

**Figure 18 - Summarized climate data.**

This summarized data is then fed directly into the ventilation model to perform the relevant calculations, as shown in Figure 19.

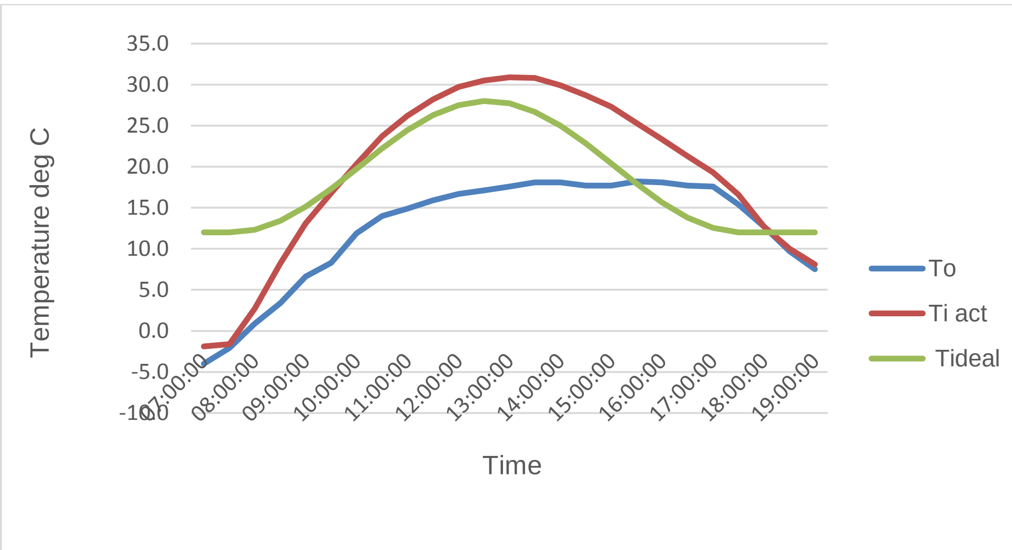


**Figure 19 - Typical variation in daily temperatures.**

The latent heat loss due to evaporation is determined as follows [24]:

$Q_L = \dot{m}_{air}(\omega_2 – \omega_1)(h_{g\ at\ t2})$ (2.19)

Where: $\dot{m}_{air}$ = the mass flow rate of the ventilated air in $m^3/s$,

$\omega_2$ = the moisture content of the internal air in $kg_{moist}/kg_{dry\ air}$,

$\omega_2$ = the moisture content of the external air in $kg_{moist}/kg_{dry\ air}$,

$h_{g\ at\ t2}$ = the evaporation enthalpy of moist air at a specific temperature.

The automatic weather station that was installed during the experiential phase measured the RH inside as well as outside the greenhouse at half-an-hour intervals. The RH expresses the ratio between the available water vapour pressure ($P_w$) and the saturation pressure at a specific temperature ($P_{sd}$) on a percentage basis and is calculated as follows [23] :

$RH = P_w/P_{sd}$ (2.20)

Where: $P_w$ = the current water vapour pressure in $N/m^2$, and

$P_{sd}$ = the saturation water vapour pressure at a specific temperature in $N/m^2$.

The saturation water vapour can be determined as follows:

$P_{sd} = 610,6\exp(17,27t_d/(237,3 + t_d))$ (2.21)

Where: $t_d$ = dry bulb temperature in $^oC$.

With the saturation pressure known, the RH can be used to determine the water vapour pressure at the specific temperature and from that the moisture content (specific humidity) can be calculated as follows:

$\omega = 0,622(P_w/(P – P_w)$ (2.22)

Where: P = The measured air mixture pressure.

The evaporation enthalpy of moist air at a specific temperature can be determined using the following equation:

$h_g = h_a + \omega h_w$ (2.23)

Where: $h_a$ = the specific enthalpy of dry air at a specific temperature in kJ/kg, and

$h_w$ = the specific enthalpy of water vapour at a specific temperature in kJ/kg.

The specific enthalpy of dry air can be determined as follows:

$h_a = c_pt$ (4.21)

Where: $c_p$ = the specific heat of air at constant pressure in $kJ/kg^oC$, and

t = the air temperature in $^oC$.

For the purpose of these calculations, the value of $c_p$ was taken as 1005,7 $J/kg^oC$. The temperature t used was taken as $t_d$.

The specific enthalpy of water vapour can be expressed as:

$$hw = c_{pw}t + h_e \tag{2.25}$$

Where: $c_{pw}$ = the specific heat of water vapour at constant temperature, and

$h_e$ = the evaporation heat of water at 0 $^oC$.

For the purpose of these calculations the value of $c_{pw}$ was taken as 1840 J/kg$^o$C and $h_e$ as 2501 kJ/kg. If combined, $h_g$ can be determined as follows:

$h_g = (1{,}0057 kJ/kg^oC)t + [(1{,}84 kJ/kg^oC)t =(2501\ kJ/kg)]$

Conduction

The energy lost through conduction can be expressed as :

$$Q_{cond} = kA(T_i - T_o) \tag{2.26}$$

Where: k = the heat transfer coefficient of the glazing in W/m$^2$, and

A = the surface area of the glazing in m$^2$.

To determine the ideal growing temperature for cultivating plants, the ideal rate of ventilation had to be determined. Not much is known about the ideal temperature except the minimum and maximum required temperatures and that plants require periods of time at the different temperatures. The actual temperatures follow a typical sinus curve which means that the ideal temperatures can be modelled as a sinus curve with the maximum not exceeding 28 $^o$C and the minimum not dropping below 12 $^o$C as specified in Table 1. An example of the actual and modelled temperatures is presented in the figure below. The basic formula for a sinus curve can be expressed as:

$$y(t) = A\ \mathrm{Sin}(wt + \alpha) \tag{2.27}$$

Where: A = the amplitude,

$w = 2\pi f$ and $f$ is the frequency, and

$\alpha$ = the phase.

With the specified minimum and maximum temperatures, the sinus curve can be expressed as:

$$t(time) = 7{,}5*\mathrm{Sin}(15*time) \tag{2.28}$$

Where: t = temperature in $^o$C.

To be able to calculate the actual and required rates of ventilation, the energy balance was rewritten as follows:

$$\dot{Q}_{GR} = \dot{Q}_{cond} + \dot{m}(Q_L + Q_v) \quad [kW] \tag{2.29}$$

Where: $Q_v$ = The heat loss due to ventilation (change in air temperature).

Equation 2.29 could then be used to determine the actual and required mass flow rate of ventilation in kg/s.

### 2.7.13 Developing a numerical transient heat transfer model for predicting the heating requirements during the night-time period.

The transient heat transfer model, as developed in section 2.4.12 can now also be used to determine the heating requirements of the greenhouse during the colder winter nights by considering the following mechanisms of heat transfer [7] [42] [50] [53] [54]:

- Heat gained from the heating system,
- Heat lost through radiation from the leaves surface,
- Heat lost due to convection (infiltration),
- Heat lost through conduction, and
- Heat lost through evaporation inside the greenhouse.

Through the consideration of all the mechanisms of heat losses, the night-time transient heat transfer model can be constructed by considering the following heat balance equation .

$$\dot{Q}_{suppl} = \dot{Q}_{rad} + \dot{Q}_{conv} + \dot{Q}_{cond} + \dot{Q}_{evap} \text{ [Watt]} \qquad (2.30)$$

The heat supplied to the greenhouse from the water storage system was determined by using the measured drop in temperature that was read every hour. An Excel spreadsheet was compiled to determine the heat released by the heating system as shown in Figures 20 and 21.

**Actual Water Heating System Capacity**

| | | |
|---|---|---|
| Vol water (l) | | 2000 |
| Cpwater (J/kgK) | | 4183 |
| Time Inteval (s) | | 3600 |
| Efficiency (%) | | 40 |
| Date | | 14 July 2014 |

| Time | Hour nr. | T1 (deg C) | T1 (deg C) | ΔT (deg C) | Time Step | Qheater (J) | Time Value | Qheater (kW) | Qheater calc (kW) |
|---|---|---|---|---|---|---|---|---|---|
| 18:30:00 | 0.00 | 23.257 °C | 23.257 | | 1 | | 0.771 | | |
| 19:30:00 | 1.00 | 23.170 °C | 23.170 | -0.087 | 2 | 291338 | 0.813 | 0.081 | 1.176 |
| 20:30:00 | 2.00 | 21.926 °C | 21.926 | -1.244 | 3 | 4163959 | 0.854 | 1.157 | 1.176 |
| 21:30:00 | 3.00 | 20.739 °C | 20.739 | -1.186 | 4 | 3969332 | 0.896 | 1.103 | 1.116 |
| 22:30:00 | 4.00 | 19.611 °C | 19.611 | -1.128 | 5 | 3776044 | 0.938 | 1.049 | 1.056 |
| 23:30:00 | 5.00 | 18.521 °C | 18.521 | -1.090 | 6 | 3647576 | 0.979 | 1.013 | 0.996 |
| 00:30:00 | 6.00 | 17.493 °C | 17.493 | -1.028 | 7 | 3438459 | 0.021 | 0.955 | 0.936 |
| 01:30:00 | 7.00 | 16.542 °C | 16.542 | -0.951 | 8 | 3182460 | 0.063 | 0.884 | 0.876 |
| 02:30:00 | 8.00 | 15.663 °C | 15.663 | -0.879 | 9 | 2943025 | 0.104 | 0.818 | 0.815 |
| 03:30:00 | 9.00 | 14.846 °C | 14.846 | -0.817 | 10 | 2734343 | 0.146 | 0.760 | 0.755 |
| 04:30:00 | 10.00 | 14.093 °C | 14.093 | -0.753 | 11 | 2520810 | 0.188 | 0.700 | 0.695 |
| 05:30:00 | 11.00 | 13.405 °C | 13.405 | -0.688 | 12 | 2301788 | 0.229 | 0.639 | 0.635 |
| 06:30:00 | 12.00 | 12.760 °C | 12.760 | -0.645 | 13 | 2157591 | 0.271 | 0.599 | 0.575 |
| 07:30:00 | 13.00 | 12.257 °C | 12.257 | -0.503 | 14 | 1683641 | 0.313 | 0.468 | 0.515 |
| | | | | | | | Average | 0.787 | 0.871 |

**Figure 20 – Calculating the heat released from heating system.**

The measured values were then plotted and a numerical model developed from that could be used in the transient heating model as shown in Figure 20 below.

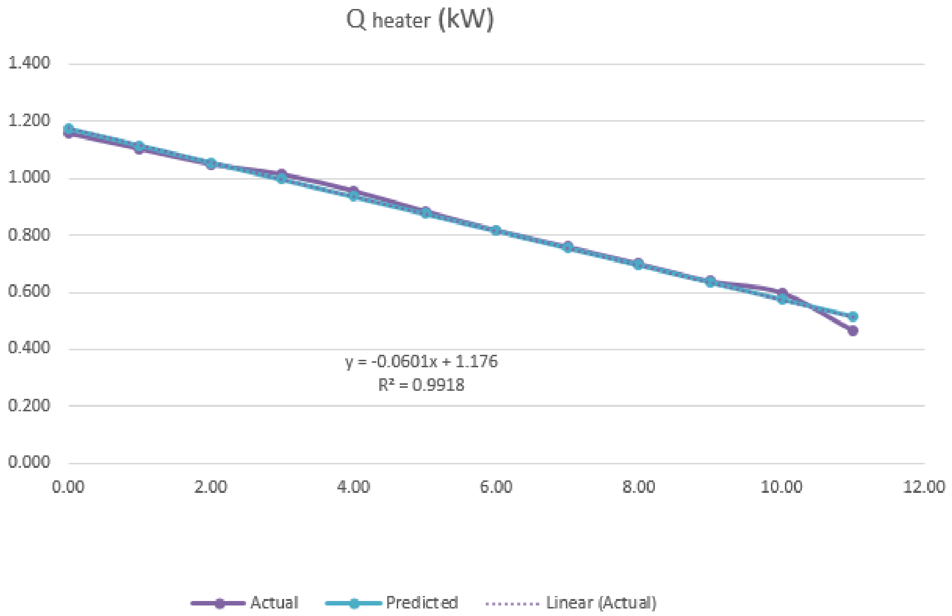


**Figure 21 - Development of numerical heat release model.**

The heat lost through conduction by the floor is once again considered to be relatively small, because the floor was completely covered by the plant canopy, and therefore did not receive much heat through radiation during the day.

The various mechanisms through which heat was lost can be expressed mathematically as follows:

**Radiation:**

$$\dot{Q}_{rad} = \varepsilon\sigma A_s(T_1^4 - T_2^4)\ [W] \quad (2.13)$$

With equation 2.13, a transient heat loss model was then developed in Excel, as shown in Figure 22. The temperature of the surface of the leaves, $T_1$, was assumed to be similar to the internal temperature of the greenhouse. The predicted radiation was based on the ideal temperature - the temperature that would be ideal for optimum plant growth.

| Time | Timestep | Temperature | | | Pressure | Radiation | Radiation |
|---|---|---|---|---|---|---|---|
| | | To | Ti | Tideal | | Qrad act | Qrad predict |
| | | (deg C) | (deg C) | (deg C) | kPa | (kW) | (kW) |
| 19:00:00 | 0.00 | 7.5 | 8.1 | 15.0 | 89.1 | 0.376 | 4.879 |
| 19:30:00 | 0.50 | 4.8 | 6.6 | 15.0 | 89.2 | 1.104 | 6.542 |
| 20:00:00 | 1.00 | 3.3 | 5.4 | 15.0 | 89.2 | 1.269 | 7.446 |
| 20:30:00 | 1.50 | 3.2 | 4.5 | 15.0 | 89.2 | 0.781 | 7.506 |
| 21:00:00 | 2.00 | 1.6 | 3.9 | 15.0 | 89.2 | 1.366 | 8.452 |
| 21:30:00 | 2.50 | 0.7 | 3.3 | 15.0 | 89.2 | 1.531 | 8.977 |
| 22:00:00 | 3.00 | 1.2 | 2.7 | 15.0 | 89.2 | 0.883 | 8.686 |
| 22:30:00 | 3.50 | 0.6 | 2.3 | 15.0 | 89.2 | 0.995 | 9.035 |
| 23:00:00 | 4.00 | 1.3 | 1.9 | 15.0 | 89.3 | 0.352 | 8.628 |
| 23:30:00 | 4.50 | 0.5 | 1.6 | 15.0 | 89.3 | 0.641 | 9.093 |
| 00:00:00 | 5.00 | -1.0 | 1.3 | 15.0 | 89.3 | 1.328 | 9.955 |
| 00:30:00 | 5.50 | -2.2 | 0.1 | 15.0 | 89.4 | 1.310 | 10.635 |
| 01:00:00 | 6.00 | -1.3 | -0.1 | 15.0 | 89.4 | 0.686 | 10.126 |
| 01:30:00 | 6.50 | -1.7 | -0.2 | 15.0 | 89.4 | 0.855 | 10.353 |
| 02:00:00 | 7.00 | -1.9 | -0.4 | 15.0 | 89.4 | 0.853 | 10.466 |
| 02:30:00 | 7.50 | -3.1 | -0.4 | 15.0 | 89.4 | 1.526 | 11.138 |
| 03:00:00 | 8.00 | -3.1 | -0.7 | 15.0 | 89.4 | 1.354 | 11.138 |
| 03:30:00 | 8.50 | -3.2 | -0.9 | 15.0 | 89.4 | 1.296 | 11.194 |
| 04:00:00 | 9.00 | -3.1 | -1.1 | 15.0 | 89.4 | 1.126 | 11.138 |
| 04:30:00 | 9.50 | -2.6 | -1.2 | 15.0 | 89.3 | 0.790 | 10.859 |
| 05:00:00 | 10.00 | -3.5 | -1.3 | 15.0 | 89.3 | 1.235 | 11.360 |
| 05:30:00 | 10.50 | -4.1 | -1.4 | 15.0 | 89.3 | 1.509 | 11.692 |
| 06:00:00 | 11.00 | -4.4 | -1.6 | 15.0 | 89.4 | 1.561 | 11.857 |
| 06:30:00 | 11.50 | -4.2 | -1.7 | 15.0 | 89.4 | 1.394 | 11.747 |

**Figure 22 - Transient radiation heat loss model.**

**Infiltration/Ventilation:**

$\dot{Q}_{conv} = q_v c_p \rho (T_i - T_o)$ (2.15)

In similar fashion, a heat loss model was developed to determine the heat lost through ventilation based on the actual internal temperatures as well as on the ideal internal temperatures and is shown in Figure 23.

| Time | Timestep | Temperature | | | Convection | Convection |
|---|---|---|---|---|---|---|
| | | To | Ti | Tideal | Qconv | Qconv predict |
| | | (deg C) | (deg C) | (deg C) | (kW) | (kW) |
| 19:00:00 | 0.00 | 7.5 | 8.1 | 15.0 | 0.001 | 0.018 |
| 19:30:00 | 0.50 | 4.8 | 6.6 | 15.0 | 0.004 | 0.025 |
| 20:00:00 | 1.00 | 3.3 | 5.4 | 15.0 | 0.005 | 0.029 |
| 20:30:00 | 1.50 | 3.2 | 4.5 | 15.0 | 0.003 | 0.029 |
| 21:00:00 | 2.00 | 1.6 | 3.9 | 15.0 | 0.006 | 0.033 |
| 21:30:00 | 2.50 | 0.7 | 3.3 | 15.0 | 0.006 | 0.035 |
| 22:00:00 | 3.00 | 1.2 | 2.7 | 15.0 | 0.004 | 0.034 |
| 22:30:00 | 3.50 | 0.6 | 2.3 | 15.0 | 0.004 | 0.035 |
| 23:00:00 | 4.00 | 1.3 | 1.9 | 15.0 | 0.001 | 0.034 |
| 23:30:00 | 4.50 | 0.5 | 1.6 | 15.0 | 0.003 | 0.036 |
| 00:00:00 | 5.00 | -1.0 | 1.3 | 15.0 | 0.006 | 0.039 |
| 00:30:00 | 5.50 | -2.2 | 0.1 | 15.0 | 0.006 | 0.042 |
| 01:00:00 | 6.00 | -1.3 | -0.1 | 15.0 | 0.003 | 0.040 |
| 01:30:00 | 6.50 | -1.7 | -0.2 | 15.0 | 0.004 | 0.041 |
| 02:00:00 | 7.00 | -1.9 | -0.4 | 15.0 | 0.004 | 0.042 |
| 02:30:00 | 7.50 | -3.1 | -0.4 | 15.0 | 0.007 | 0.045 |
| 03:00:00 | 8.00 | -3.1 | -0.7 | 15.0 | 0.006 | 0.045 |
| 03:30:00 | 8.50 | -3.2 | -0.9 | 15.0 | 0.006 | 0.045 |
| 04:00:00 | 9.00 | -3.1 | -1.1 | 15.0 | 0.005 | 0.045 |
| 04:30:00 | 9.50 | -2.6 | -1.2 | 15.0 | 0.003 | 0.043 |
| 05:00:00 | 10.00 | -3.5 | -1.3 | 15.0 | 0.005 | 0.046 |
| 05:30:00 | 10.50 | -4.1 | -1.4 | 15.0 | 0.007 | 0.047 |
| 06:00:00 | 11.00 | -4.4 | -1.6 | 15.0 | 0.007 | 0.048 |
| 06:30:00 | 11.50 | -4.2 | -1.7 | 15.0 | 0.006 | 0.047 |

**Figure 23 - Transient Ventilation Heat Loss Model.**

**Conduction:**

$\dot{Q}_{cond} = UA(T_i - T_o)$ [W] (2.7)

By applying equation 2.4, a model was developed to determine the heat loss through conduction as shown in Figure 24 below.

| Time | Timestep | Temperature | | | Tot Loss | Tot Loss |
|---|---|---|---|---|---|---|
| | | To | Ti | Tideal | Qlost | Qlost predict |
| | | (deg C) | (deg C) | (deg C) | (kW) | (kW) |
| 19:00:00 | 0.00 | 7.5 | 8.1 | 15.0 | 2.191 | 27.563 |
| 19:30:00 | 0.50 | 4.8 | 6.6 | 15.0 | 6.920 | 37.136 |
| 20:00:00 | 1.00 | 3.3 | 5.4 | 15.0 | 7.953 | 42.707 |
| 20:30:00 | 1.50 | 3.2 | 4.5 | 15.0 | 4.934 | 43.066 |
| 21:00:00 | 2.00 | 1.6 | 3.9 | 15.0 | 8.441 | 48.846 |
| 21:30:00 | 2.50 | 0.7 | 3.3 | 15.0 | 9.516 | 52.099 |
| 22:00:00 | 3.00 | 1.2 | 2.7 | 15.0 | 5.601 | 50.428 |
| 22:30:00 | 3.50 | 0.6 | 2.3 | 15.0 | 6.194 | 52.460 |
| 23:00:00 | 4.00 | 1.3 | 1.9 | 15.0 | 2.286 | 50.073 |
| 23:30:00 | 4.50 | 0.5 | 1.6 | 15.0 | 3.996 | 52.819 |
| 00:00:00 | 5.00 | -1.0 | 1.3 | 15.0 | 8.367 | 58.345 |
| 00:30:00 | 5.50 | -2.2 | 0.1 | 15.0 | 8.594 | 62.666 |
| 01:00:00 | 6.00 | -1.3 | -0.1 | 15.0 | 4.316 | 59.296 |
| 01:30:00 | 6.50 | -1.7 | -0.2 | 15.0 | 5.418 | 60.862 |
| 02:00:00 | 7.00 | -1.9 | -0.4 | 15.0 | 5.392 | 61.450 |
| 02:30:00 | 7.50 | -3.1 | -0.4 | 15.0 | 9.743 | 66.013 |
| 03:00:00 | 8.00 | -3.1 | -0.7 | 15.0 | 8.689 | 65.881 |
| 03:30:00 | 8.50 | -3.2 | -0.9 | 15.0 | 8.301 | 66.239 |
| 04:00:00 | 9.00 | -3.1 | -1.1 | 15.0 | 7.225 | 65.882 |
| 04:30:00 | 9.50 | -2.6 | -1.2 | 15.0 | 5.048 | 64.088 |
| 05:00:00 | 10.00 | -3.5 | -1.3 | 15.0 | 7.865 | 67.183 |
| 05:30:00 | 10.50 | -4.1 | -1.4 | 15.0 | 9.700 | 69.461 |
| 06:00:00 | 11.00 | -4.4 | -1.6 | 15.0 | 10.126 | 70.667 |
| 06:30:00 | 11.50 | -4.2 | -1.7 | 15.0 | 8.981 | 69.822 |

**Figure 24 - Heat loss model for conduction.**

**Evaporation:**

$$\dot{Q}_{evap} = \dot{m}_{air}(\omega_2 - \omega_1)(h_{g\ at\ t2}) \qquad (2.16)$$

And similarly for evaporation, as shown in Figure 25.

| Time | Timestep | Temperature | | | Pressure | Evaporation (Actual) | | | | | | Evaporation (Predicted) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | To | Ti | Tideal | | RHin | Psd | Pw | ω | hg | Q evap | Psd | Pw | ω | hg | Q evap pred |
| | | (deg C) | (deg C) | (deg C) | kPa | (%) | kPa | kPa | (kg/kga) | (kJ/kg) | (kW) | kPa | kPa | (kg/kga) | (kJ/kg) | (kW) |
| 19:00:00 | 0.00 | 7.5 | 8.1 | 15.0 | 89.1 | 71.0 | 1003.8 | 712.7 | 0.005 | 2515.802 | 0.000 | 1499.6 | 1064.7 | 0.008 | 2528.325 | 0.000 |
| 19:30:00 | 0.50 | 4.8 | 6.6 | 15.0 | 89.2 | 73.0 | 917.5 | 669.8 | 0.005 | 2513.079 | 0.372 | 1499.6 | 1094.7 | 0.008 | 2528.325 | -0.257 |
| 20:00:00 | 1.00 | 3.3 | 5.4 | 15.0 | 89.2 | 74.0 | 853.3 | 631.4 | 0.004 | 2510.901 | 0.332 | 1499.6 | 1109.7 | 0.008 | 2528.325 | -0.126 |
| 20:30:00 | 1.50 | 3.2 | 4.5 | 15.0 | 89.2 | 75.0 | 807.7 | 605.8 | 0.004 | 2509.268 | 0.221 | 1499.6 | 1124.7 | 0.008 | 2528.325 | -0.129 |
| 21:00:00 | 2.00 | 1.6 | 3.9 | 15.0 | 89.2 | 76.0 | 778.5 | 591.7 | 0.004 | 2508.179 | 0.119 | 1499.6 | 1139.7 | 0.008 | 2528.325 | -0.135 |
| 21:30:00 | 2.50 | 0.7 | 3.3 | 15.0 | 89.2 | 77.0 | 750.3 | 577.7 | 0.004 | 2507.090 | 0.120 | 1499.6 | 1154.7 | 0.008 | 2528.325 | -0.129 |
| 22:00:00 | 3.00 | 1.2 | 2.7 | 15.0 | 89.2 | 77.0 | 723.0 | 556.7 | 0.004 | 2506.001 | 0.181 | 1499.6 | 1154.7 | 0.008 | 2528.325 | 0.003 |
| 22:30:00 | 3.50 | 0.6 | 2.3 | 15.0 | 89.2 | 78.0 | 705.3 | 550.1 | 0.004 | 2505.275 | 0.057 | 1499.6 | 1169.7 | 0.008 | 2528.325 | -0.129 |
| 23:00:00 | 4.00 | 1.3 | 1.9 | 15.0 | 89.3 | 78.0 | 687.9 | 536.6 | 0.004 | 2504.549 | 0.119 | 1499.6 | 1169.7 | 0.008 | 2528.325 | 0.009 |
| 23:30:00 | 4.50 | 0.5 | 1.6 | 15.0 | 89.3 | 79.0 | 675.2 | 533.4 | 0.004 | 2504.004 | 0.028 | 1499.6 | 1184.7 | 0.008 | 2528.325 | -0.130 |
| 00:00:00 | 5.00 | -1.0 | 1.3 | 15.0 | 89.3 | 79.0 | 662.6 | 523.5 | 0.004 | 2503.460 | 0.083 | 1499.6 | 1184.7 | 0.008 | 2528.325 | -0.003 |
| 00:30:00 | 5.50 | -2.2 | 0.1 | 15.0 | 89.4 | 79.0 | 614.5 | 485.4 | 0.003 | 2501.282 | 0.328 | 1499.6 | 1184.7 | 0.008 | 2528.325 | 0.010 |
| 01:00:00 | 6.00 | -1.3 | -0.1 | 15.0 | 89.4 | 80.0 | 606.8 | 485.4 | 0.003 | 2500.919 | 0.001 | 1499.6 | 1199.7 | 0.008 | 2528.325 | -0.130 |
| 01:30:00 | 6.50 | -1.7 | -0.2 | 15.0 | 89.4 | 80.0 | 602.9 | 482.3 | 0.003 | 2500.737 | 0.026 | 1499.6 | 1199.7 | 0.008 | 2528.325 | 0.000 |
| 02:00:00 | 7.00 | -1.9 | -0.4 | 15.0 | 89.4 | 81.0 | 595.3 | 482.2 | 0.003 | 2500.374 | 0.001 | 1499.6 | 1214.7 | 0.009 | 2528.325 | -0.130 |
| 02:30:00 | 7.50 | -3.1 | -0.4 | 15.0 | 89.4 | 80.0 | 595.3 | 476.3 | 0.003 | 2500.374 | 0.051 | 1499.6 | 1199.7 | 0.008 | 2528.325 | 0.131 |
| 03:00:00 | 8.00 | -3.1 | -0.7 | 15.0 | 89.4 | 80.0 | 584.1 | 467.3 | 0.003 | 2499.830 | 0.076 | 1499.6 | 1199.7 | 0.008 | 2528.325 | -0.001 |
| 03:30:00 | 8.50 | -3.2 | -0.9 | 15.0 | 89.4 | 80.0 | 576.7 | 461.4 | 0.003 | 2499.467 | 0.049 | 1499.6 | 1199.7 | 0.008 | 2528.325 | -0.002 |
| 04:00:00 | 9.00 | -3.1 | -1.1 | 15.0 | 89.4 | 80.0 | 569.4 | 455.6 | 0.003 | 2499.104 | 0.050 | 1499.6 | 1199.7 | 0.008 | 2528.325 | 0.000 |
| 04:30:00 | 9.50 | -2.6 | -1.2 | 15.0 | 89.3 | 80.0 | 565.8 | 452.7 | 0.003 | 2498.922 | 0.023 | 1499.6 | 1199.7 | 0.008 | 2528.325 | -0.003 |
| 05:00:00 | 10.00 | -3.5 | -1.3 | 15.0 | 89.3 | 81.0 | 562.2 | 455.4 | 0.003 | 2498.741 | -0.024 | 1499.6 | 1214.7 | 0.009 | 2528.325 | -0.132 |
| 05:30:00 | 10.50 | -4.1 | -1.4 | 15.0 | 89.3 | 81.0 | 558.6 | 452.5 | 0.003 | 2498.559 | 0.025 | 1499.6 | 1214.7 | 0.009 | 2528.325 | 0.000 |
| 06:00:00 | 11.00 | -4.4 | -1.6 | 15.0 | 89.4 | 80.0 | 551.6 | 441.2 | 0.003 | 2498.196 | 0.097 | 1499.6 | 1199.7 | 0.008 | 2528.325 | 0.134 |
| 06:30:00 | 11.50 | -4.2 | -1.7 | 15.0 | 89.4 | 80.0 | 548.0 | 438.4 | 0.003 | 2498.015 | 0.025 | 1499.6 | 1199.7 | 0.008 | 2528.325 | 0.004 |

**Figure 25 - Model for determining the heat lost through evaporation.**

## 2.8 Conclusion

The numerical heat loss/gain models that was developed in this chapter can now be used to evaluate the applicability of applying alternative energy technologies in obtaining the ideal climatic requirements.

# 3. RESEARCH METHODOLOGY

## 3.1 Introduction

This chapter outlines the methodology the will be used for this research problem.

## 3.2 Greenhouse Design – Problem statement

The title of this dissertation was given as “The development and characterization of a cost-effective, renewable energy greenhouse for production of crops in atypical climatic conditions.” The following sub-problems were identified and will be dealt with during the design phase:

1. Choosing the correct covering material,
2. An energy and cost effective structure that will be able to withstand the elements of nature,
3. The orientation of the structure,
4. Vents to enhance natural ventilation and ensuring effective sealing in order to eliminate the filtration of cold air into the greenhouse during periods of low external temperatures,
5. The design of a cost effective solar heating system,
6. The design of an effective heat exchange system, and
7. A control system.

## 3.3 Specifications

A complete set of specifications for the greenhouse is needed to ensure that the outcome reflects the initial requirements, although some of the initial set specifications may be opportunistic. Table 7, outlines the required specifications as well as possible test conditions that can be used to determine if the required specification has been obtained or not [55] [56].

## Table 7 - Product design specifications for greenhouse

| Aspect | Objective | Criteria | Test condition |
|---|---|---|---|
| Size | Construct a greenhouse with similar area to that which is used commercially. | The smallest commercial-size greenhouse that is used in industry is 8*30m.<br>Vertical wall height of 2,4 m.<br>Span between braces of 3 m.<br>Apex height of 5 m. | Measure |
| Load-bearing capacity | Design a structure that can handle the set requirements. | Structure must be able to handle a wind speed of 100 km/h.<br>Structure must be able to handle a crop load of 30 kg/m$^2$. | Stress analysis<br>Stress analysis |
| Door | Create a large enough opening for spraying equipment, etc. at entrance with effective sealing. | Construct a door system that can create an opening of at least 4 m wide and 2 m high with flange-type seals. | Measure |
| Infiltration | Minimize infiltration at night to not more than one air exchange per hour. | Create effective seals at all possible points of infiltration. | Test |
| Materials | Cost effective | Construct frame from Grade 300 Mild Steel. | |
| Material finishing | Prevent rust and overheating of steel structure that can damage PE film on contact. | Finish frame with one layer steel primer and two layers white paint. | |
| Cost | Limit the total expenditure for the project to R 300 000. | The greenhouse must be able to deliver a reasonable return on investment during its expected lifetime. | Determine return on investment at the end of experimental phase. |
| Life | Maximize | Greenhouse film is guaranteed for 3 years only but the structure must be designed for a life of at least 20 years. | Test the actual greenhouse film life during experimental phase. |
| Maintenance | Easy | Provide easy access to most components and use as many standard components as possible. | Determine the ease of maintenance during the experimental phase. |
| Performance | Energy efficient | The greenhouse must rely on as little as possible external energy for cooling, heating and ventilation purposes. | Determine energy efficiency during experimental phase. |

| | | | |
|---|---|---|---|
| | Provide ideal climatic conditions as specified in table 1. | The greenhouse must be able to provide an internal climate that is as close as possible to the climatic requirements of the plants. | Log and compare internal climate with ideal during experimental phase. |
| | Low maintenance costs | The maintenance costs of the greenhouse during its expected lifetime must be as low as possible. | Determine actual maintenance during experimental phase. |
| Manufacture | Ease of manufacture | Limit the usage of complex parts.<br>Keep design as simple as possible. | Determine ease of manufacturing of final product. |
| Patents | Avoid | Do not infringe on existing patents. | Patent search |
| Safety | High | Must comply with existing legislation. | Check national and international standards and relevant legislation. |

## 3.4 Concept design phase

Various possible solutions exist for each of the sub-problems, as listed in section 2.1. The following sections will look at the advantages and disadvantages of each possible solution and evaluate them against the required specifications, where necessary, to determine the best possible solutions for each sub-problem.

### 3.4.1 Sub-problem 1 – Greenhouse covering material

Various materials are used in industry to cover greenhouse structures in industry, each with its own properties, advantages and disadvantages, and will be described in the sections below. The different types of covering materials that are available for greenhouses are listed in the Table 8 [32] [21] [53] .

Table 8 - Summary of available greenhouse covering materials

| Type of covering material | Advantages | Disadvantages | Light transmission t | Insulating value "R" | Est. life | Est. cost (R/m2) |
|---|---|---|---|---|---|---|
| Single | Inexpensive | Short life | **85%** | **0.83** | 1 to 4 years | R 14.62 |
| Polyethylene film | Easy to install | | | | | |
| | | | | | | |
| Double | Inexpensive | Short life | **77%** | **1.43** | 1 to 4 years | R 29.23 |
| Polyethylene film | Saves on heating costs | | | | | |
| | Easy to install | | | | | |
| | | | | | | |
| Corrugated | High transmittance | Scratches easily | **91%** | **0.83** | 15 plus years | R 228.27 |
| Polycarbonate | High impact resistance | | | | 10 year warranty | |
| | | | | | | |
| Glass | High transmittance | High cost | **88%** | **0.91** | 25 plus years | R 150.00 |
| Double strength | High UV resistance | Difficult installation | | | | |
| | Resists scratching | Low impact resistance | | | | |
| | | High maintenance | | | | |
| | | | | | | |
| Glass | High transmittance | Very high cost | **78%** | **1.43** | 25 plus years | R 300.00 |
| Insulated | High UV resistance | Difficult installation | | | | |
| | Resists scratching | Low impact resistance | | | | |
| | | | | | | |
| 8 mm | High impact resistance | Requires glazing system to install | **80%** | **1.64** | 15 plus years | R 219.00 |
| Twin-wall polycarbonate | Saves on heating costs | Scratches easily | | | 10 year warranty | |
| | | | | | | |
| 10 mm | High impact resistance | Requires glazing system to install | **80%** | **1.79** | 15 plus years | R 295.00 |
| Twin-wall polycarbonate | Saves on heating costs | Scratches easily | | | 10 year warranty | |
| | | | | | | |
| 16 mm | High impact resistance | Requires glazing system to install | **78%** | **2.38** | 15 plus years | R 472.00 |
| Triple-wall polycarbonate | Saves on heating costs | Scratches easily | | | 10 year warranty | |

### 3.4.1.1 Option 1 - PE Film

PE film is the most common plastic that is used to cover greenhouses in industry. The film is normally guaranteed for 36 months by its manufacturers, while the actual lifetime is in the region of 60 months, depending on the extreme climatic conditions it may experience during its life. The average cost of this film is R 14.62/m$^2$ depending on the properties of the material. Various additives and layers are added to the plastic film to create certain properties, e.g. light diffusion, to prevent dripping from condensation, to prevent UV and IR light from penetrating the greenhouse, to make the film sulphur resistant, and to prevent the spread of viruses. The normal thickness of the film is 200 µm and is readily available [32].

#### 3.4.1.2 Option 2 - Glass

The application of glass as covering material has become limited to very high value crops, and where certain light transmission requirements, which can only be achieved with glass, are required. The average cost of glass-covered greenhouses is in the order of R 1800/m$^2$ of which the glass alone is R 150/m$^2$, while PE-covered greenhouses cost approximately R 300/m$^2$. Due to the weight of glass, a much heavier structure needs to be designed to support glass as glazing material [21].

#### 3.4.1.3 Option 3 - Polycarbonate sheets

Polycarbonate (PC) sheeting is certainly one of the best covering materials available on the market, but the cost of the material, approximately R 228.27/m$^2$, limits its application to mostly hobby-type greenhouses. PC sheets are available in different colours, as single layers or double-layered sheets with an air gap in between which can provide excellent insulation properties to a greenhouse [21].

#### 3.4.1.4 Decision – Covering material

Taking the advantages and disadvantages of the three above-mentioned glazing materials into account, it becomes clear that PE film is the material best suited for this application and therefore supports the reasoning behind its preferred choice of material for application in the local greenhouse industry.

### 3.4.2 Sub-problem 2 – Greenhouse structure

The structure that needs to be designed will therefore be covered with one or two layers of greenhouse film. It was decided to focus the study on a commercial size single-span greenhouse of 8 * 30 m, because the control of the environment inside a hobby-type greenhouse is challenging due to the low internal volume of the greenhouse which allows for rapid changes in the internal climate. What happens inside hobby-type greenhouses can therefore not easily be extrapolated to the expected environmental fluctuations inside a commercial size greenhouse. If the envisaged system will be able to control the internal climate of this single-span greenhouse, it should be possible to apply the same techniques to a multi-span greenhouse. When a structure is designed that needs to be covered with greenhouse film, the roof trusses must be designed with an outer curved profile to ensure constant contact between the film and the structure. If the film is able to separate from the structure, it can be damaged during periods of high wind speeds. The following types of structures with curved trusses are used quite commonly in the greenhouse industry [57] [58] .

#### 3.4.2.1 Option 1 – Quonset greenhouse

Figure 19 shows the design of a typical Quonset greenhouse with vertical walls. The roof is arched and sometimes this arch may stretch to ground level and sometimes side walls are included, as in Figure 26. The arch allows the structure to transfer the stresses to the ground effectively.

**Figure 26 - Quonset greenhouse** [59]**.**

A Quonset greenhouse is relatively easy and cost effective to construct but tends to overheat especially during midday in summer, when the rays of the sun are almost orthogonal to the centre of the roof.

#### 3.4.2.2 Option 2 – Gothic-arch greenhouse

In gothic-arch greenhouses, the truss consists of two arches, which are joined in the middle, to create an elevated centre, as indicated in Figure 27. The main advantage of a gothic-arch greenhouse is lower internal temperatures because the sun's rays cannot be orthogonal to the roof for most of the day and especially at midday. A truss can be designed for a specific area according to the path the sun will follow on 21 Dec, the longest day of the year.

**Figure 27 - Gothic-arch greenhouse** [60]**.**

Another advantage of a gothic-arch greenhouse is that condensation which forms on the inside of the roof during night-time is directed towards the side-walls, due to the higher pitch of the roof, which eliminates the spreading of bacteria and viruses.

#### 3.4.2.3 Option 3 – Solar greenhouses

Solar greenhouses are commonly used in the colder areas of the Northern Hemisphere and a typical layout of such a greenhouse is shown in Figure 28. Although all greenhouses are basically solar collectors, solar greenhouses are constructed in such a way that the wall which faces the sun's path, acts as a solar collector, while the wall/s which will receive no or little sunlight, are normally non-translucent and well-insulated walls which create a thermal mass to store the solar energy during day-time and transmit during night-time.

**Figure 28 - Solar greenhouse** [61]**.**

Solar greenhouses are not common to the Southern Hemisphere, because they will completely overheat during summer time.

#### 3.4.2.4 Decision – Sub-Problem 3

From the paragraphs above it is clear that a gothic-arch type of greenhouse would be more advantageous.

### 3.4.3 Sub-Problem 3 – Orientation of the greenhouse

A typical sun path for the Southern Hemisphere is shown in Figure 29. If a solar greenhouse was to be constructed, the greenhouse would have an East-West orientation as shown in Figure 29. The southern wall would be isolated and would create a thermal mass to enable the greenhouse to store heat for the cooler periods. For a normal greenhouse, a North-South orientation is more beneficial, especially for a gothic-arch greenhouse. The minimum day-length for Bloemfontein (21 June) is just more than 10 hours, as indicated in Figure 3, which is adequate for plant production under protection, e.g. a well-designed greenhouse, if the low night-time temperatures can be eliminated. During the longer summer days, the greenhouse will be cooler inside with a North-South orientation, because the sun's rays will be orthogonal to the roof for shorter periods of the day and not during mid-day.

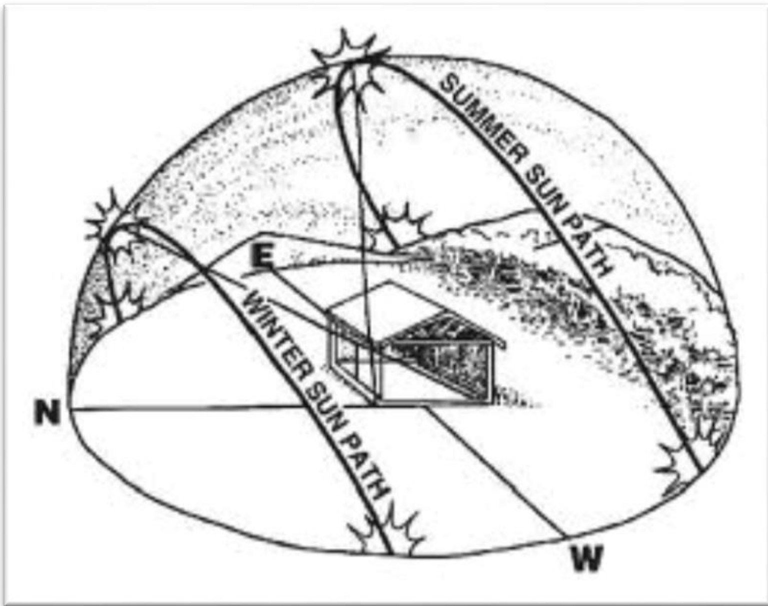


**Figure 29 - Typical sun path for Southern Hemisphere** [62]**.**

### 3.4.4 Sub-Problem 4 – Ventilation System

The ventilation system of a greenhouse is needed to remove excess heat from the greenhouse, supply the plants with fresh air and to prevent build-up of high levels of humidity inside the greenhouse. The average humidity in the Free State is relative low, eliminating the need for the ventilation system to remove humidity from the greenhouse. For the purpose of this research project, the ventilation system will be designed to remove excess heat and to supply the plants with fresh air. Due to the nature of the project, only natural ventilation systems will be investigated.

#### 3.4.4.1 Option 1 – Roll-up curtains

Roll-up curtains, as shown in Figure 30, are used quite commonly in the greenhouse industry; in fact, most side vents are normally roll-up curtains. They are easy to construct and can create fairly large ventilation openings. A roll-up curtain can be used as a side or a roof vent.

**Figure 30 - Roll-up side vent** [63]**.**

#### 3.4.4.2 Option 2 – Rack and Pinion Vents

Rack and pinion vents, as shown in Figure 31, are also used quite commonly in the greenhouse industry, especially for roof vents, possibly due to the lower gradients that are often available on the roofs of greenhouses for the effective closing of roll-up curtains. They can also create fairly large ventilation openings but are much more difficult to construct and much more expensive than roll-up curtains.

**Figure 31 - Rack and pinion vents** [64]**.**

### 3.4.4.3 Option 3 – Solar operated window vents

Solar operated window vents are fairly common in hobby-style greenhouses, due to the fairly small ventilation openings they create, as shown in Figure 32. A gas-filled cylinder which operates by the expansion and contraction of the gas inside the cylinder, due to variations in ambient temperature, is used to open and close a window. The cylinders are however limited in operating force and cannot respond to higher wind speeds.

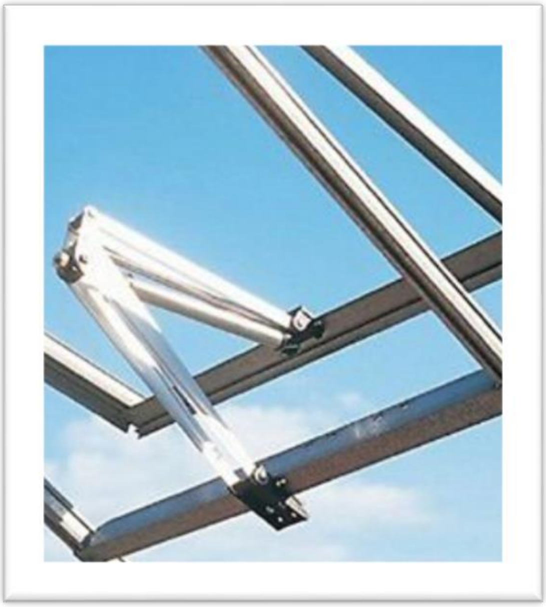

**Figure 32 - Solar operated window vent** [65]**.**

#### 3.4.4.4 Decision – Sub-Problem 4

Roll-up curtains as ventilation system, for the side and roof vents, were chosen for the project due to their cost effectiveness, simplicity and because they allow for the possible installation of an external roof curtain.

### 3.4.5 Sub-Problem 5 – Solar heating system

In choosing the correct method of solar heating, the total life cycle of the various technologies must be taken into account. For this reason, the application of photovoltaic panels were excluded as a possible option. If solar energy is to be used for heating purposes at night, some kind of thermal mass is needed to store the heat, as it is collected during the day, and make it available to be exchanged into the greenhouse internal environment at night [11] [66].

The thermal mass can be stored inside the greenhouse to create a passive heating system that will exchange heat through natural convection, conduction and radiation at night. The main problem with these kinds of heating systems is the total lack of control over the heating system and ultimately over the internal environment of the greenhouse [67].

Most temperature-sensitive crops need a certain amount of low temperature hours to assist in fruit and flower development and with a completely passive heating system, the greenhouse can become too warm during warmer nights in winter, therefore eliminating the possibility of applying a completely passive system. The answer to this problem would be to store the thermal mass outside the greenhouse and to move the thermal mass in and out of the greenhouse to enable it to exchange the captured heat into the internal environment of the greenhouse when needed, meaning that some kind of direct system would be needed [40].

Water was chosen as an applicable thermal mass, because it is readily available, can be moved relatively easily and it possesses good thermal properties. Solar water heating systems are divided into two main categories, namely direct and indirect systems. In direct systems, the heated water acts as the heat transfer fluid as well. The water is normally pumped through a collector, where it collects heat through solar radiation, and is stored in a tank [47] [66] [68].

Possible problems that may arise through the application of a direct system are the possibility of the heat transfer fluid freezing in the collector pipes during cold winter nights, and the build-up of scaling on the inside walls of the pipes creating some insulation between the water and the pipe walls. In indirect systems, a different fluid or gas than the heated water is used to collect the heat in the collector and exchange that heat to the water through an exchanger in the hot water tank [68].

In this project, the heated water will not be exchanged, eliminating the possibility of scaling because the water can be treated, while the problem of freezing can be eliminated through the application of a flexible PE piping system in the collector, or by draining the collector at night.

Direct heating systems have some financial advantages over indirect systems, due to the simplicity of the system, and are always the preferred solution if applicable to the specific problem. It was, therefore, decided to focus on the development of a suitable direct system for this application.

Solar heat collectors are classified in two main types, namely flat plate collectors and concentrating collectors. Flat plate collectors are the preferred choice for low temperature applications (typically below 90 $^{o}$C), whereas concentrating collectors (e.g. parabolic troughs, parabolic dish and central receiver collectors) are used for high temperature applications [47]. The construction of flat plate collectors is also much simpler than that of concentrating collectors, making it the most logical option. The cost of the collector is a very important issue, since it will reflect on the return of investment of the greenhouse.

The heated water must be stored in tanks to accumulate heat for exchange during night time. These tanks must be insulated to limit the heat loss to the surroundings [51] [52].

### 3.4.6 Sub-Problem 6 – Heat exchange system

Various types of heat exchange systems are used in the greenhouse industry, as discussed in the sections that follow.

#### 3.4.6.1 Option 1 – Space heaters

In space heaters, heated water is circulated through a coiled tube while the heat transfer and the distribution of the heat inside the greenhouse is assisted with the application of a fan. Figure 33 shows the typical application of a unit heater to heat a greenhouse.

**Figure 33 - Unit heater** [69]**.**

### 3.4.6.2 Option 2 – Central heating system

In a central heating system, a water heating system supplies hot water to more than one smaller heaters, typically to space heaters which are located throughout the greenhouse.

### 3.4.6.3 Option 3 – Pipe or rail heating systems

In pipe or rail heating systems, hot water is circulated through a network of pipes or rails. The length of the exchanger piping system creates enough area to allow for the required rate of heat transfer. A typical application of a pipe or rail heating system is shown in Figure 34.

**Figure 34 - Pipe/rail heating system** [70]**.**

### 3.4.6.4 Option 4 – Under-bed heating system.

An under-bed heating system, as shown in Figure 35, is very similar to a pipe heating system, except that the heating pipes are installed underneath the benches. This is an ideal position for the installation of the heating pipes since they create more heat at the root zone but this can only be done if the growing beds allow for the piping system to be installed underneath.

**Figure 35 – Under-bench heating system** [71]**.**

### 3.4.6.5 Option 5 – Underfloor heating system

In an underfloor heating system, a network of underfloor pipes is installed before the floor is laid. Heated water is then circulated through these pipes which heat the floor and ultimately the internal environment of the greenhouse. The loss of heat to the soil below the floor is an issue of concern and must be limited through the application of a suitable insulation material. A typical underfloor heating system for a small greenhouse is shown in Figure 36.

**Figure 36 - Underfloor heating system** [72]**.**

### 3.4.6.6 Option 6 – Overhead heating system

Overhead heating systems also consist of a system of finned or bare pipe that is installed overhead, as indicated in the Figure 37 below, with the function of providing additional heat to the greenhouse in colder winter months.

**Figure 37 - Overhead heating tubes inside a greenhouse** [73]**.**

### 3.4.6.7 Option 7 – Perimeter heating system

A perimeter heating system, as shown in Figure 38, is as in the case with an overhead heating pipe system, an additional set of heating pipes that are installed on the perimeter of the greenhouse, to provide additional heat in situations where the pipe/rail, or under-bench or underfloor heating system cannot provide enough heat to heat the greenhouse during the colder winter months.

**Figure 38 - Perimeter heating system** [74]**.**

#### 3.4.6.8 Decision – Sub-Problem 6

From the previous paragraphs it is thus clear that a space heater, or a central heating system will require additional energy in terms of the distribution fans which are required, and the purpose of this project is to eliminate the application of external energy as far as possible. The installation of an underfloor heating system is a relatively expensive exercise due to the concrete floor that is needed to house the heating pipes and the insulation that is needed below this floor. Roses were chosen as the temperature-sensitive crop to be grown in the greenhouse and it therefore makes sense to grow the roses in raised benches with an under-bench heat exchange system. Should this exchange system prove to exchange too little heat during the colder winter nights, additional overhead or perimeter heat exchange system can be installed to assist the under-bench system.

### 3.4.7 Sub-Problem 7 – Control system

The specific type of control system that can be used will depend on the type of components it needs to control. In this problem, the control system will need to control the roll-up curtains which will be used as vents. The roll-up curtains can be motorized, as shown in Figure 39.

**Figure 39 - Motorised roll-up curtain** [75]**.**

Motorised roll-up curtains will allow the greenhouse to control the internal temperature by opening and closing the vents. In the event of high wind speed, the vents can be closed to eliminate damage to the crop and the greenhouse. This will, however, mean that the control system will need to close the vents in high wind speeds when the internal temperature of the greenhouse may be above the set-point. During these periods of elevated internal temperatures, the rate of transpiration of the plants may increase to such a level the plants may begin to stress if the irrigation system does not allow for additional irrigation, or the greenhouse is cooled internally, or the internal humidity of the greenhouse is raised.

Additional irrigation can be allowed for by measuring the levels of moisture in the plants' leaves or the growing medium. Plants are able to tolerate higher temperatures if it is combined with a higher RH. The elevated RH will help to keep the rate of transpiration under control, but only to a certain point. Increasing the internal RH can be obtained by wetting the greenhouse floor or by using mist nozzles. The evaporation of moisture from the floor will increase the internal RH and provide some cooling effect as well as will the mist nozzles. Whether this would be sufficient remains to be determined through practical experiments. Other types of internal cooling may be difficult to achieve during periods of high wind speed, due to the additional energy that it may require.

Allowing for a limited amount of ventilation by limiting the distance to which the roll-up curtains open, or creating limited vent openings in the downwind direction, are some practical considerations that can only be determined through practical experimentation. To allow for these possible changes to the control system during the experimental phase, it was decided to use a programmable logic control (PLC) unit as a control system. This PLC can be replaced with a more cost effective micro controller once the parameters for a satisfactory control program have been determined.

The control of the solar heating system will be performed with the same PLC, since it will also require the internal temperature as input. The control of the irrigation system will, however, be separated from the climate controller and will be handled by a commercial-type time-clock irrigation controller. If no control system is available, an irrigation controller can also be used to operate the heating system because it is controlled through the operation of two solenoid valves and a pump only. The one valve is used to direct the flow of the working fluid through the solar collector during day-time and the other to direct the flow through the heating system during night-time.

## 3.5 Detailed design phase

### 3.5.1 The greenhouse structure

The structure of the greenhouse was designed according to the AGMA standards and is presented in Addendum A [53]. A general layout of the structure is presented in Figure 40. Most of the structural components were based on standard hollow tubular steel sections that are commercially available. The structure was also designed to be constructed on site with bolted connections between all major components.

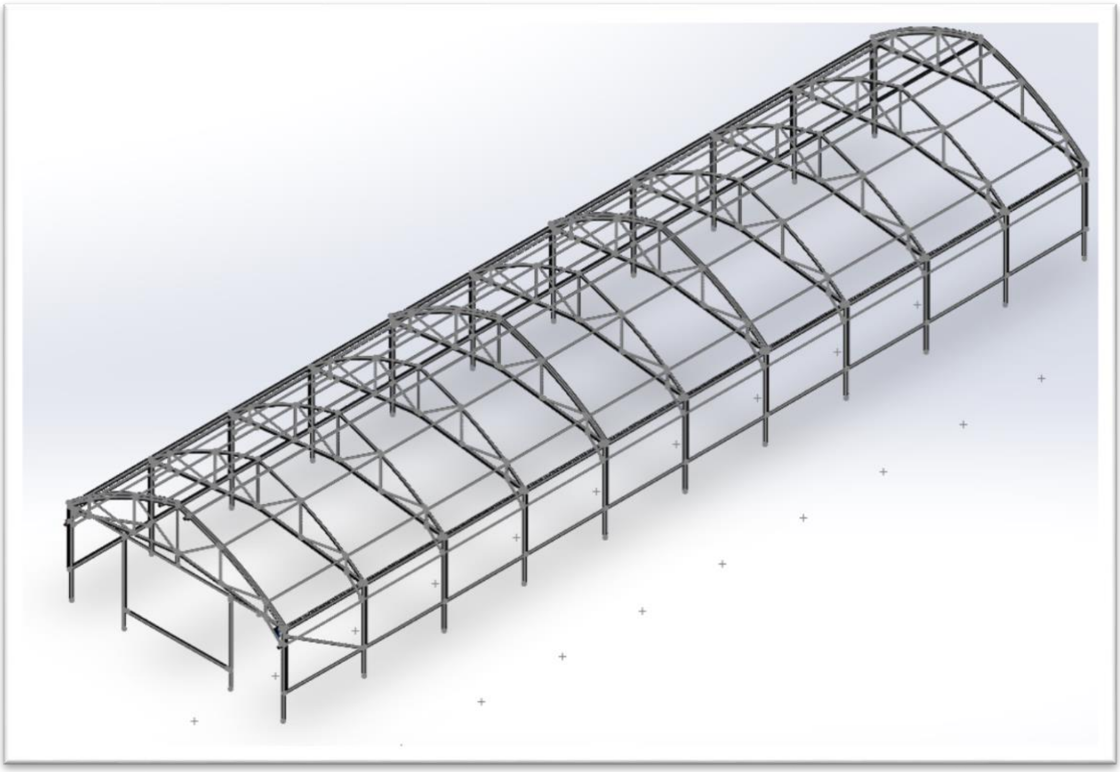

**Figure 40 - Greenhouse structure**

### 3.5.2 Roll-up vents

Roll-up vents were chosen as ventilation system due to their simplicity and the fairly large openings they can create to enhance natural ventilation. The greenhouse covering material is normally used as the curtain material, which is in this case 200 µm thick PE film. The curtains will be opened and closed with a geared electric motor that is controlled by a PLC to ensure a stable internal environment. The roll-up vents need to be closed when the wind speed exceeds a certain velocity, typically around 40 km/h, to protect the greenhouse.

The geared motors that open the vertical side vents, must be able to deliver more torque than the motors for the roof vent, and are therefore used as a guideline in the determination of the required output. Due to the long distance which the curtain needs to cover, it is not possible to roll the curtain down from a top hanging roller. Instead, a roller must be used at the bottom of the curtain. The curtain is fixed to the structure at the top and to a pipe at the bottom over which the curtain can roll up, as indicated in Figure 39.

A standard 38,2 * 2 mm fence and gate tube, with a mass per metre length of 1,78 kg, was selected for this project. The circumference of this pipe is 120 mm and the thickness of the film is 200 µm. For each revolution, the vent will thus be opened by approximately 120 mm. The opening speed can be very slow to eliminate the possibility of large fluctuations on the internal climate of the greenhouse. For control and safety reasons, geared DC motors are commonly used to drive the roll vent.

The PLC can be programmed in such a way that the motor is powered for a specific time and then waits for a set period to determine the change in the internal climate. The advantage of using a PLC is that these on/off periods can be altered according to the graphs as plotted by an automatic weather station which is placed inside the greenhouse. The greenhouse film is made from low density polyethylene (LDPE) film with a density from 910 to 940 kg/m$^3$. The maximum required opening for the side vents can be taken as 1.5 m, which means that the weight of the pipe with film wound around it can be taken as 61.86 kg over a length of 30 m. If a service factor of 1.2 is used, the required torque can be calculated as:

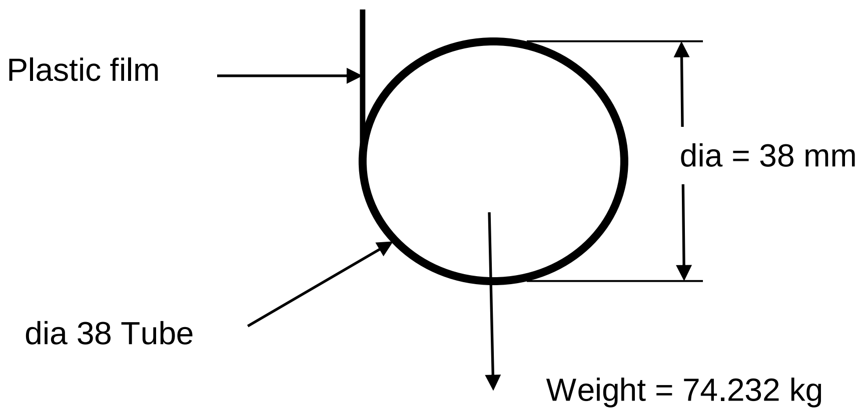


**Figure 41 - Torque calculation for roll vent.**

T = (74.232)*(9.81)*(0.038/2) = 13.836 Nm, as shown in Figure 41. A Parvalux geared 12V DC motor with an output of 17 Nm of torque at 6 r/min, as shown in Figure 42, was selected.

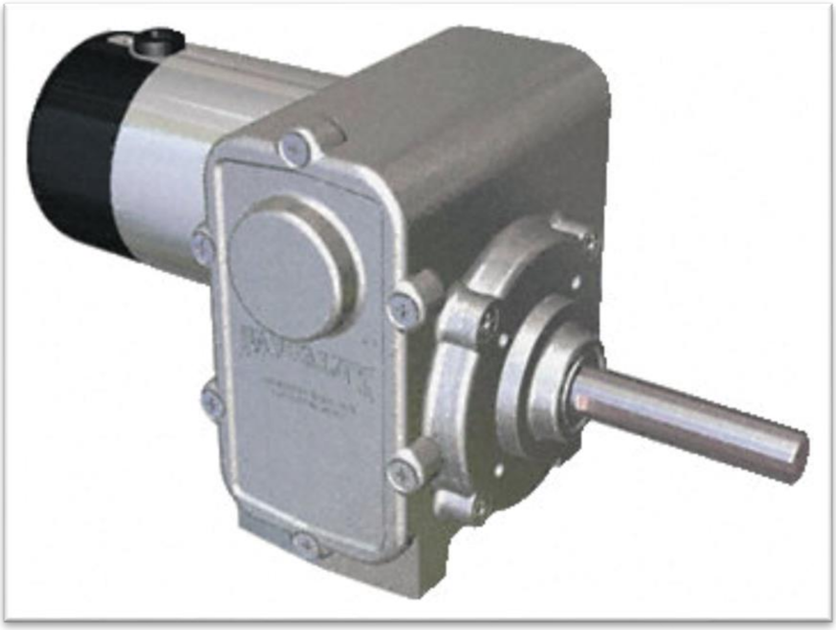

**Figure 42 - Selected geared motor.**

The construction of the geared motor makes it possible to mount the output shaft directly into a bush that can be fitted to the pipe, as shown in Figure 43.

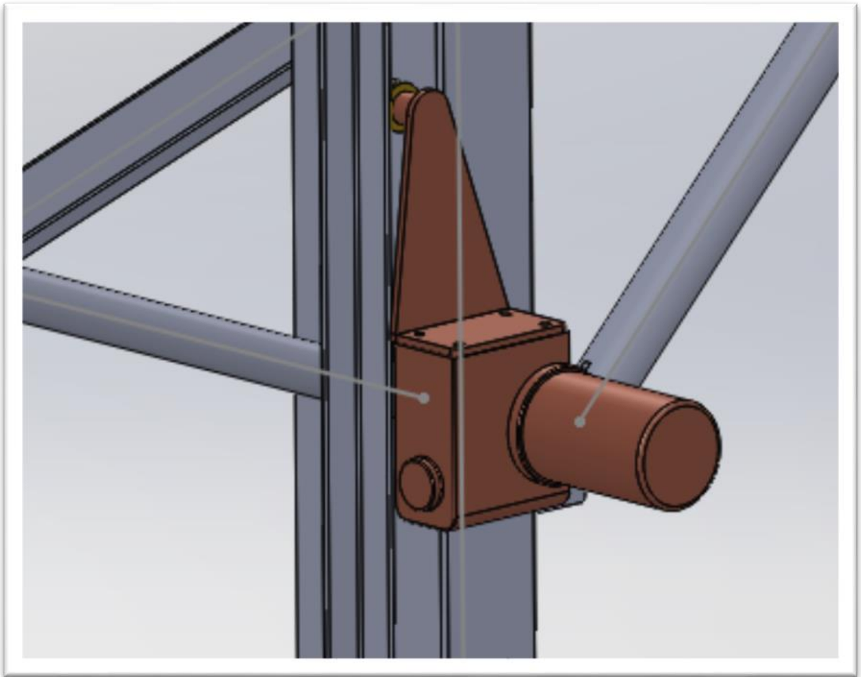

**Figure 43 - Geared motor fitted to roll vent tube.**

### 3.5.3 The solar heating system

The solar heating system consists of three basic systems, namely the solar collector, the heat storage system and the heat exchange system. During the concept design phase, if a flat plate solar water heater was chosen to heat the water, that will then be stored in tanks and pumped through a network of under-bench PE pipes, to exchange the heat to the internal environment of the greenhouse. The dimensions of the flat plate collector will depend on the amount of energy that would be required to keep the greenhouse at the desired temperature.

The total heat loss for the greenhouse is calculated as 1.039 MJ, as shown in the Table 9 below. From this value, the amount of water needed, and the temperature it needs to be heated to can be calculated. At this stage, the calculations show that 4498 litres of water need to be heated from 25 to 80$^{0}$C, which is considered a large amount of water in this context. Additional losses will also occur in the water storage and heat exchange system, meaning that even more heat will be needed.

A decision was made to construct a solar water heating system with a capacity of 3000 litres of water and then determine what percentage of the required heat the system will be able to deliver. Once this is known, the heating system can be scaled up to determine the actual size needed. Through the construction of the system, the actual efficiency of the system as well as actual losses can be determined and considered in future designs.

**Table 9 - Heat loss and water storage calculator.**

| **Thermal Storage Calculator** | |
|---|---|
| **Heat Loss Through Conduction** | **Value** |
| Greenhouse Length (m) | 30.000 |
| Greenhouse width(m) | 8.000 |
| Side Wall Height (m) | 2.400 |
| Roof Height (m) | 2.500 |
| Roof Slope Length (m) | 9.000 |
| Roof Area | 270.000 |
| East Wall Area (m^2) | 72.000 |
| West Wall Area (m^2) | 72.000 |
| South Wall Area (m^2) | 29.200 |
| North Wall Area (m^2) | 29.200 |
| Total Side Wall Area (m^2) | 202.400 |
| Floor Area (m^2) | 240.000 |
| Total Wall Area (m^2) | 472.400 |
| k Value side walls (W/m^2K) | 0.830 |
| k Value for floor (W/m^2K) | 0.830 |
| k Value for roof (W/m^2K) | 0.830 |
| Inside Temperature (K) | 288.000 |
| Outside Temperature (K) | 273.000 |
| Soil Temperature (K) | 279.000 |
| Heat Conducted through roof (kW) | 3.362 |
| Heat Conducted through side wall (kW) | 2.520 |
| Heat conducted through floor (kW) | 1.793 |
| **Tot Heat Loss through Conduction (kW)** | **7.674** |
| **Heat Loss Through Convection** | **Value** |
| Internal Volume ($m^3$) | 864.000 |
| Number of Air Changes per hour | 1 |
| **Total Heat Loss through Cenvection (kW)** | **6.480** |
| **Heat Loss Through Radiation** | **Value** |
| Emmisivity of leaves and enclosure (ε) | 0.9 |
| Temperature of surface 1 (K) | 288 |
| Temperature of surface 2 (K) | 273 |
| Stefan-boltzman constant | 5.670E-08 |
| Plant canopy area (m2) | 147.600 |
| **Total Heat Loss through Radiation (kW)** | **9.981** |
| **Total Heat Loss (kW)** | **24.135** |
| **Solar Water Heating** | |
| Heating time (h) | 15 |
| Heating Capacity needed (kW) | 24.135 |
| Amount of heat needed (J) | 1303297352 |
| Initial Temperature of Storage Water (°C) | 80 |
| Final Temperature of Storage Water (°C) | 25 |
| **Amount of water needed (ℓ)** | 5665 |

The design philosophy requires that commonly available agricultural materials and components be used in the design of the whole heating system. The water will be heated to 80 $^{0}$C, which is well below the 90 $^{0}$C that common PE agricultural plastic tubing can withstand. The amount of water in the solar heating system will also need to ensure that the heating system does not overheat. In this case, the system has room to move from 80 $^{0}$C to 90 $^{0}$C, which will require an additional 255.227 MJ, which is 143 % additional energy. Flat plate solar collectors are normally installed facing north at an angle to the horizontal equal to the latitude at their specific position, which in this case is $29^{0}$. This will ensure that the efficiency of the solar collector is decreased in summer, when it is not in use, and increased during the winter months with an optimum efficiency on 21 June, when the sun's rays will be normal to the collector surface around midday.

The solar collector may be shifted by as much as $15^{0}$ from north, with no significant influence on the amount of solar heat that is collected, depending on when the maximum demand is required. For this specific design, most heat will be needed late in the afternoon as it will limit the amount of heat that can be lost from thermal storage, due to the limitation that is placed on the time in thermal storage. The solar collector was therefore rotated by $15^{0}$ west of north. The available insolation for Bloemfontein, as indicated in Table 10, is 3.32 kWh/m$^2$/day.

**Table 10 - Available insolation for Bloemfontein** [76]**.**

| Variable | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Insolation, kWh/m²/day | 7.02 | 6.19 | 5.28 | 4.44 | 3.74 | 3.32 | 3.54 | 4.36 | 5.29 | 5.97 | 6.71 | 7.07 |
| Clearness, 0 - 1 | 0.59 | 0.56 | 0.56 | 0.58 | 0.61 | 0.61 | 0.62 | 0.63 | 0.62 | 0.58 | 0.58 | 0.59 |
| Temperature, °C | 21.91 | 21.15 | 19.63 | 16.48 | 11.92 | 7.60 | 7.61 | 10.97 | 15.34 | 17.98 | 19.71 | 20.73 |
| Wind speed, m/s | 4.84 | 4.49 | 4.44 | 4.49 | 4.58 | 4.89 | 5.06 | 5.54 | 5.77 | 5.56 | 5.20 | 5.04 |
| Precipitation, mm | 84 | 97 | 77 | 52 | 18 | 10 | 9 | 14 | 22 | 49 | 64 | 64 |
| Wet days, d | 10.7 | 10.8 | 10.9 | 8.2 | 3.8 | 2.7 | 2.0 | 2.5 | 3.7 | 7.0 | 8.4 | 9.4 |

The solar collector will be constructed from black PE irrigation pipe that lies on a black-coated corrugated plate surface. Polycarbonate plates will be used for the cover, with a layer of Durafoil as insulation material below the corrugated plates. Professionally constructed solar water heaters can normally transfer 60 – 70 % of the energy that they receive from the sun to the working fluid [78]. The expected efficiency of a solar water heater, which is constructed from basic materials, can therefore be assumed to be in the region of 30 – 40 %. For an efficiency of 40 %, the required area for the collector to collect 233.7 MJ/day would be :

Efficiency of collector ($\eta_{collector}$) = Energy collected/Available energy for area

For $\eta_{collector}$ = 40 %

Energy to be collected = Available energy for area * $\eta_{collector}$

= 3.32 kWh/m$^2$/day * 0.4

= 1.328 kWh/m$^2$/day

= 4.781 MJ/m$^2$/day

For 2,337 MJ

Area required = 233,7 MJ/day/4,781 MJ/m$^2$/day

= 48,88 m$^2$

This is about 21 % of the floor area of the greenhouse while the efficiency of the thermal storage and the heat exchange system is still excluded. At this stage it can be seen that for a solar collector to be able to heat the greenhouse to the desired set-points during the coldest winter months, the size thereof (and cost) would be immense. A solar heating system, of reasonable scale and cost, can therefore only be used to either extend the growing season of the plants or to try to prevent frost damage to plants during winter months.

The cost of constructing such a solar heater is prohibitive and it was decided to construct a smaller solar water heating system and to extrapolate its capacity to that required. To ensure applicability to multi-span greenhouses, a solar heating system that does not exceed the width of the greenhouse will be designed. The length of the solar collector will be designed in such a way that it correlates with standard corrugated plate lengths, e.g. a 2.2 m plate. The available heat from this solar collector can be fed back into the heat loss and water storage calculations to try and determine what internal temperature can be obtained with this heating system.

The area of the solar collector now becomes:

Area = 8 * 2.2 = 17.6 m$^2$, and

Available energy = 17.6 * 3,32 kWh/m$^2$/day * 0.4

= 23.373 kWh/day

= 84.143 MJ/day

This will only be a fraction of the heat that is required but once this fraction is known, the actual applicability of this type of solar water heating system for this type of application can be determined.

Having lower than required amounts of energy available, a decision was made to direct the available heat to where it is needed most, the root zone [77]. The plants will be grown in raised beds with under-bench heating. The side walls of these beds can be closed with PE sheets to ensure that the available heat is concentrated at the root zone. The width of the beds is 400 mm, their length 28 m, their elevation from ground level is 400 mm and there are six of them.

### 3.5.4 Heat exchange system

During the concept design phase, a decision was made to use an under-bed heat exchange system. These types of heat exchange systems normally consist of a simple closed loop of PE pipes that are installed underneath the raised beds. To increase the efficiency of the heat exchange system, PE pipes with an outer diameter of 32 mm will be installed. This will create an outer exchange surface of 34 $m^2$ for the 338,4 m length of heat exchanger pipe. The side walls of the beds will be closed with a single layer of PE film to ensure that the heat is trapped underneath the growing bed.

To ensure that the heat is evenly distributed throughout the greenhouse, strainers with an orifice of 8 mm will be installed at the entrance to each closed loop. The diameter of this orifice can be altered should the heat not be exchanged evenly throughout the greenhouse. In ideal situations, the temperature of the working fluid should have a temperature gradient of 10 $^0$C above that of the environment that needs to be heated [77].

### 3.5.5 Control System

A decision was made to use a PLC to control the internal climate of the greenhouse because of the and/if-functions that are needed to control the internal climate of the greenhouse. To limit the possibility that the greenhouse climate control may jeopardize the functioning of the heating system when not functioning properly, the control of the heating system was separated from that of the greenhouse climate. Control of the heating system can be obtained by the application of a simple irrigation controller. Once the operational problems have been sorted out, the systems can be integrated into one single control system, if needed.

Limit switches will be placed above and below each roll vent and the position of the upper limit switch will be made adjustable to control the maximum vent size. The following inputs and outputs needs to be considered in compiling a program for the PLC [13] [36].

**Inputs (13)**

1. Inside temperature
2. Outside temperature
3. Wind speed (0 – 40 km/h)
4. Outside relative humidity (open/close all vents)
5. Inside relative humidity (open/close floor wetting sprinklers)
6. Western side vent upper limit (U/L)
7. Western side vent lower limit (L/L)
8. Western roof vent U/L
9. Western roof vent L/L
10. Eastern side vent U/L
11. Eastern side vent L/L
12. Eastern roof vent U/L
13. Eastern roof vent L/L

**Outputs (4)**

1. Open/Close western side vent (60 Watt 12 *V* dc motor) – 2 outputs
2. Open/Close western roof vent (60 Watt 12 *V* dc motor) – 2 outputs
3. Open/Close eastern side vent (60 Watt 12 *V* dc motor) – 2 outputs
4. Open/Close eastern roof vent (60 Watt 12 *V* dc motor) – 2 outputs

A Siemens PLC, which is programmed in LOGO ! Soft Comfort version 7.0, was selected and the program to control the vents is shown schematically in Figure 44.

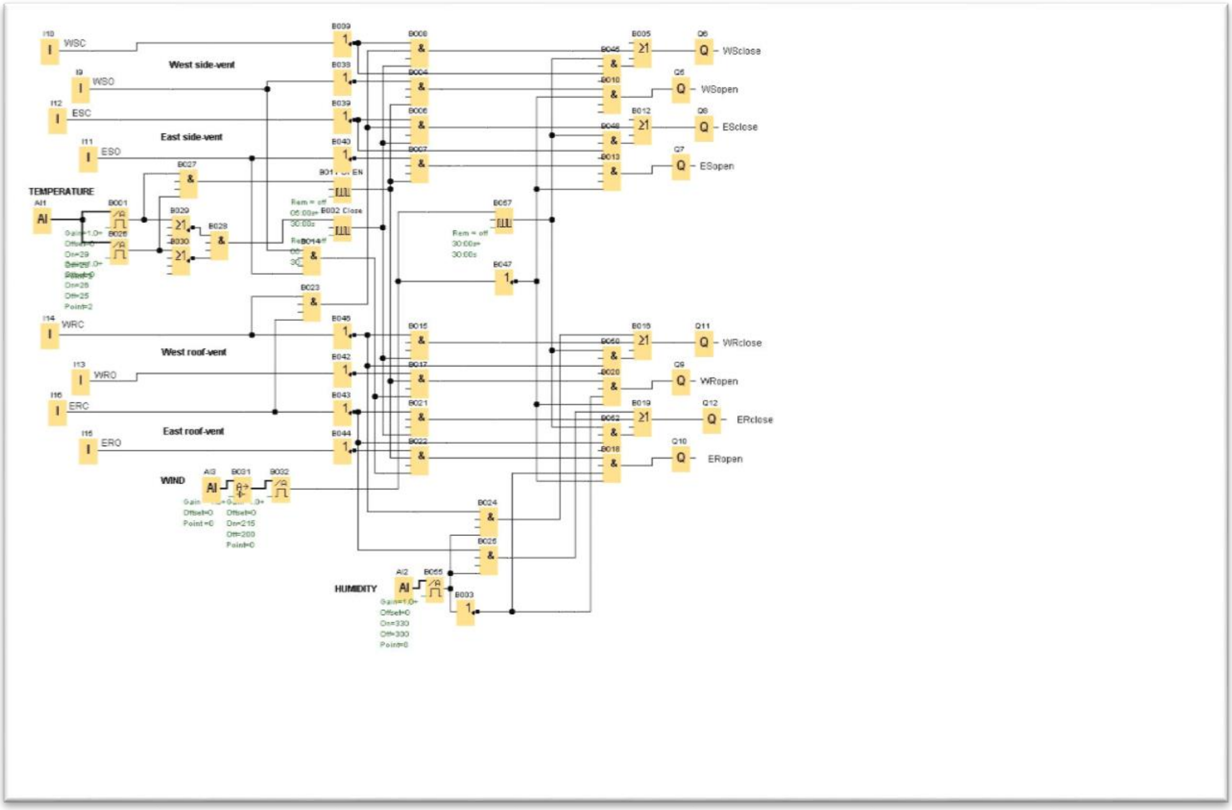


**Figure 44 - Schematic representation of Logo Soft program**

The roll vents on the side walls will open first and once they are fully opened, the roof vents will start to open. A running time of 5 seconds was allowed during the opening and closing phase with a waiting period of 5 minutes in between. This will ensure that the internal climate does not fluctuate too rapidly. These initial time settings were however made adjustable should they prove to be problematic. Sensors were placed inside the greenhouse to measure the internal temperature and humidity, while a wind speed sensor was placed on the roof of the greenhouse to measure the wind speed. The vents function primarily on internal temperature but can be overridden should the wind speed exceed a certain limit or if the humidity reaches the point of maximum saturation, hence the need for the and/if functions. In conditions of high wind speed, all vents will be closed, to protect the greenhouse structure. The roof vents are closed in conditions of high RH humidity to protect the flowers from rain damage and to prevent fungal growth, should the leaves of the plants be wetted by rain and remain wet for too long. The required internal humidity is 60 to 70 % and this will be obtained by a set of sprinklers that are placed underneath the raised beds to wet the floor during periods of low RH, from where this water can be evaporated to create the required internal RH. The plants will be irrigated by a set of micro sprayers that are controlled by an irrigation controller. This controller will also be separate from the greenhouse climate control and the heating system control.

## 3.6 Conclusion

An outlined research and design methodology enabled the researcher to look at appropriate technologies and to determine how these technologies can possible be applied to reach the envisaged end goal.

## 3.7 Commissioning phase

## 3.8 Introduction

In this chapter some insight will be provided on how the experimental setup was constructed and operated.

### 3.8.1.1 Final experimental setup

The experimental final setup consisted of a single-span, 8 * 30 m greenhouse, with vertical side walls of 2.4 m. The greenhouse structure was covered with a single layer of 200 µm, IR Rose, greenhouse film, while the floor was covered with a single layer of 250 µm thick PE sheeting. Six raised rose beds of 0.4 * 28 m were used to grow 1500 rose plants comprising the following varieties from Bartell's Roses:

1. 750 plants of Tinto (dark velvet red),
2. 250 plants of Tara (bright yellow rose), and
3. 500 plants of Purity (white rose).

The plants were planted in potting soil, that mainly consisted of composted bark, which formed a very light and well-aerated medium. In-line micro irrigators were installed on the raised beds and fertilizer was injected into the irrigation water on a continual basis through the application of an in-line venturi. To simplify the fertigation, water soluble chemical fertilizer that contained the macro- as well as all the required micro elements, for rose production was used. The irrigation system functioned well and no operational problems were experienced during the three growing seasons. The first season was used to gain experience in flower production and with the system functioning, the remaining two seasons were used to experiment with the natural ventilation and solar heating system. The solar collector system, as shown in Figure 45, consisted of a flat plate collector of 2.2 * 8 m that was covered by corrugated PC plates.

**Figure 45 - Solar heating system.**

A network of 20 mm black PE pipes was used to heat the water on a black-coated corrugated steel plate background.

The greenhouse was erected in a south to north orientation, with the solar heating system on the northern side of the greenhouse.

The storage facility consisted of three 1000 litre, horizontal insulated plastic tanks, as shown in Figure 46. A set of valves was installed to either integrate or isolate each tank from the water storage facility so that the maximum storage capacity could be varied between 1000, 2000 or 3000 litres.

**Figure 46 - Hot water storage.**

The heat exchange system consisted of a ring system of 40 mm black PE pipe that was installed underneath each bed, as shown in Figure 47.

**Figure 47 - Heat exchange system installed underneath raised beds.**

A single layer of clear 200 µm PE greenhouse film was used to enclose the raised beds so that heat could be trapped underneath the root zone to ensure effective root zone heating, as shown in Figure 48.

**Figure 48 - Enclosed raised beds**

### 3.8.2 The greenhouse environment control

The commissioning of the environment control system proved to be very challenging. The limit switches on the roll vents created serious problems by not functioning properly. The internal- as well as the external environment seemed not to be compatible with the type of limit switches that was used, despite having an IP 63 standard for isolation.

During periods of high levels of RH, the oxidation on the contact points formed a nonconductive layer between the contact points of the limit switches, leading to the malfunctioning of the limit switches. This created very serious problems and the roll vents were damaged on various occasions. Further research indicated that the control systems for greenhouses are problematic and that most growers remove the greenhouse control after one or two seasons of growing.

The temperature set-point for the greenhouse was set at 28 $^{0}$C, which would mean that the internal temperature of the greenhouse would have to rise to 28 $^{0}$C before the vents would start opening. This was also problematic due to the high heat load that was induced initially on the greenhouse, during periods of elevated external midday temperatures, because the naturally ventilated greenhouse would then struggle to maintain the internal temperature at an acceptable level. To counter the effect of elevated midday temperatures, a single layer of 40 % shade cloth was placed on the roof of the greenhouse to help maintain the internal temperature at reasonable levels without compromising the levels of light intensity inside the greenhouse.

High wind speeds created serious problems as well. The roll vents were not able to handle high wind speeds due to the lack of tensioning in the vent glazing, especially on the roof of the greenhouse where the angle of inclination is much lower than that of the side walls. High wind speeds tend to lift the roll vent from the lower limit, causing the control system to keep driving the vent downwards whereby the tension inside the roll vent glazing is reduced even further until the vent provides no barrier for incoming air and the glazing is torn from the vent structure. Gusts of up to 62.5 km/h were experienced at the site.

An automatic weather station was installed inside the greenhouse to monitor the following internal and external climatic conditions:

1. Internal temperature
2. Internal humidity
3. External temperature
4. External humidity
5. Wind speed

The data received from this weather station could then be used to make possible alterations to the climate control system or the greenhouse components, e.g. the size of ventilation openings could be limited to a point where a further increase in the size would have no influence on the internal temperature as a result of increased rates of ventilation.

### 3.8.3 Problems experienced during the commissioning phase

The control system created many operational problems due to the movement of the roll vents during periods of high wind speeds and moisture between the contacts of the limit switches. Failures in operation led to continual breakdowns and the roof and side walls of the greenhouse were ripped off twice during the commissioning phase. Various sets of limit switches were used on the roll vents and limit switches with an IP63 classification for isolation functioned relatively well with breakdowns occurring less frequently.

The fairly large openings created by the roll-vents created opportunities for the wind to damage the greenhouse structure, should the operating system not function timeously and properly. Another problem created by roll vents was the lack of tension in the greenhouse film when the vents were closed, especially on the roof with the lower gradient. The relative movement between the film and structure, as created by the wind, creates tears in the film, where the film runs adjacent to the greenhouse structure. The seal, as created by a closed roll-vent, is also not very effective and a lot of heat may be lost due to the ineffective sealing capacity of roll-vents.

The solar collector was not able to increase the temperature of the 3000 litres of water in the storage tanks significantly and a decision was made to reduce the amount of water to 2000 litres. The layout of the water storage was arranged as indicated in Figure 49. Three horizontal plastic tanks, with a capacity of 1000 litres each were connected in parallel. Manually operated gate valves were installed on both the inlet as well as the outlet of each tank to allow tanks to be isolated from the system.

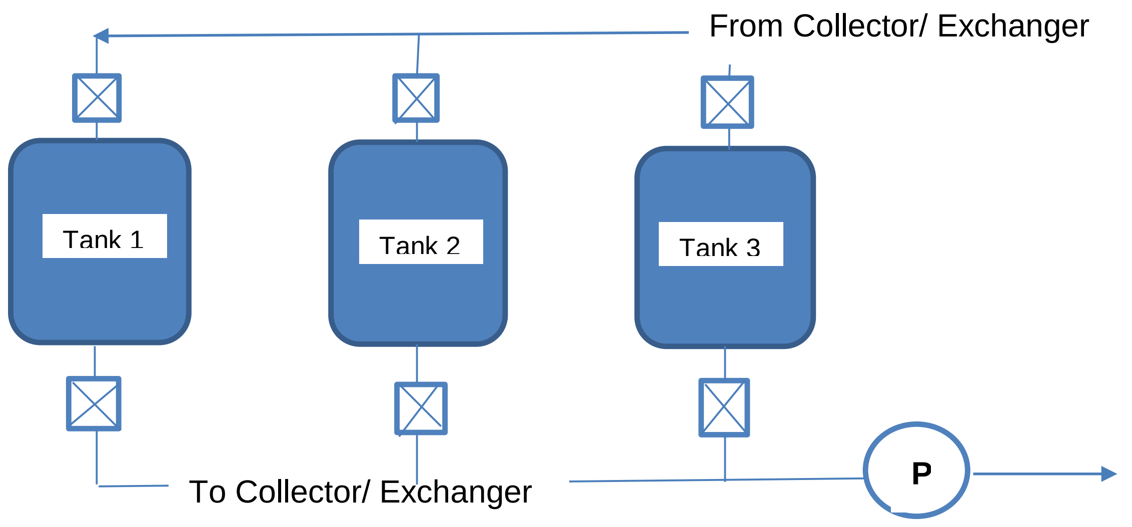


**Figure 49 - Layout of water storage system.**

Water was extracted from the bottom outlet of each tank and once it passed through the solar collector it was added through an inlet at the top of each tank. The data logger that measured the water temperature was placed at mid-height in tank 3. Two solenoid valves that were controlled with an irrigation controller directed the flow through the collector during the day and through the heat exchange system at night.

## 3.9 Conclusion

This chapter highlights how the setup was operated and what shortcomings were experienced during the experimental phase.

# 4. PRESENTATION AND DISCUSSION OF RESULTS

## 4.1 External environment

The temperatures and wind speeds measured during the experimental stage were really extreme for the location. The hottest and driest November in 120 years was experienced during 2013 accompanied by the coldest July in 50 years during 2014. This was really good for the experimental phase because the ability of the greenhouse to provide a suitable internal environment for optimal plant growth was put to the test. The challenge with developing an effective growing environment is to change the internal environment into an environment that is more suitable for optimum plant growth. This was normally done with heating systems that were driven by electricity or fossil fuels, but lately this has become too expensive. During the hot summer months, the external temperatures can fluctuate from a minimum of around 5 $^{0}$C to a maximum of approximately 37 $^{0}$C, as shown in Figure 50.

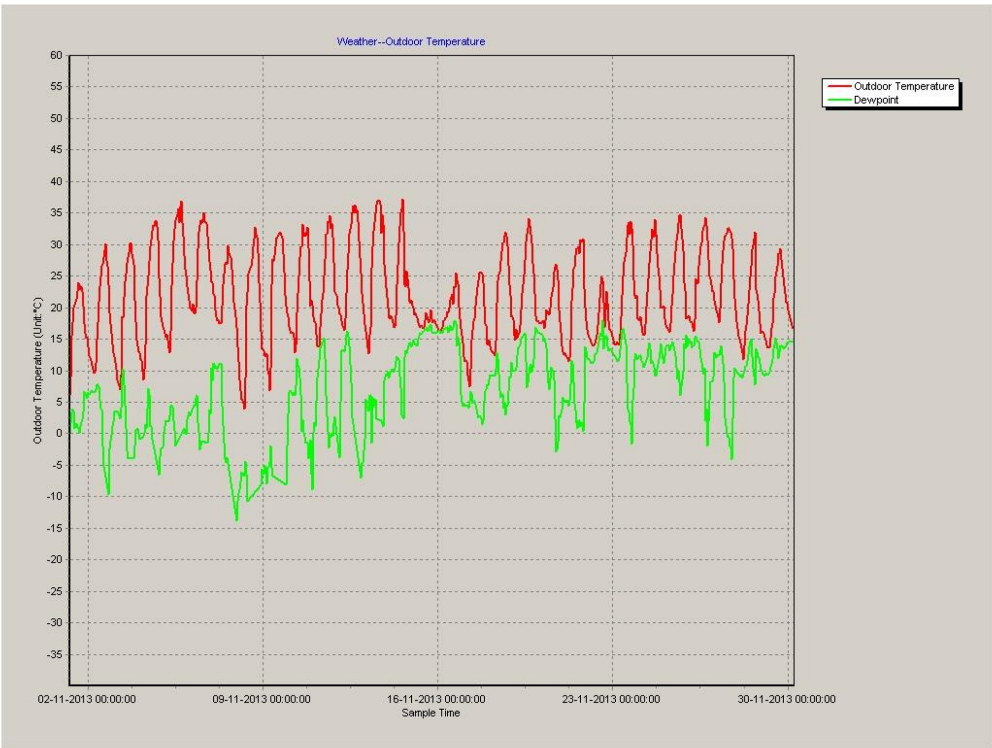


**Figure 50 - Fluctuation in external temperatures during a hot summer's day.**

Apart from the high temperatures that may be experienced during the hot summer months, the environmental RH may also vary significantly between day and night-time, from a maximum value of 95 % to a minimum value of 10 %, as can be seen from Figure 51.

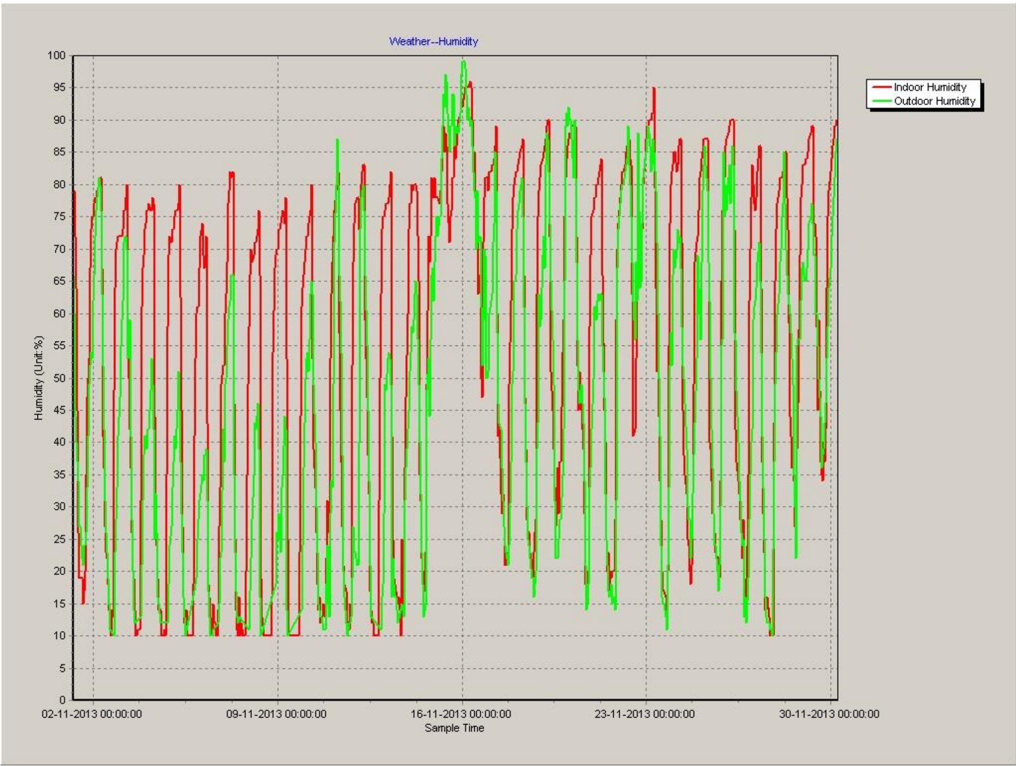


**Figure 51 - Variation in RH between day and night-time.**

The coldest winter months are also a difficult period for a grower because a sharp decrease in night-time temperatures does not only slow down plant growth but can also damage the plants. If the temperature does not drop significantly enough to damage a plant, it will still be able to produce should it be exposed to the right temperatures for certain required periods of time. Part of this research problem was also to determine what the required periods and temperatures should be. Figure 52 shows how the external temperatures typically varied from 25 $^{0}$C to -5 $^{0}$C, as experienced during the colder winter months at the location.

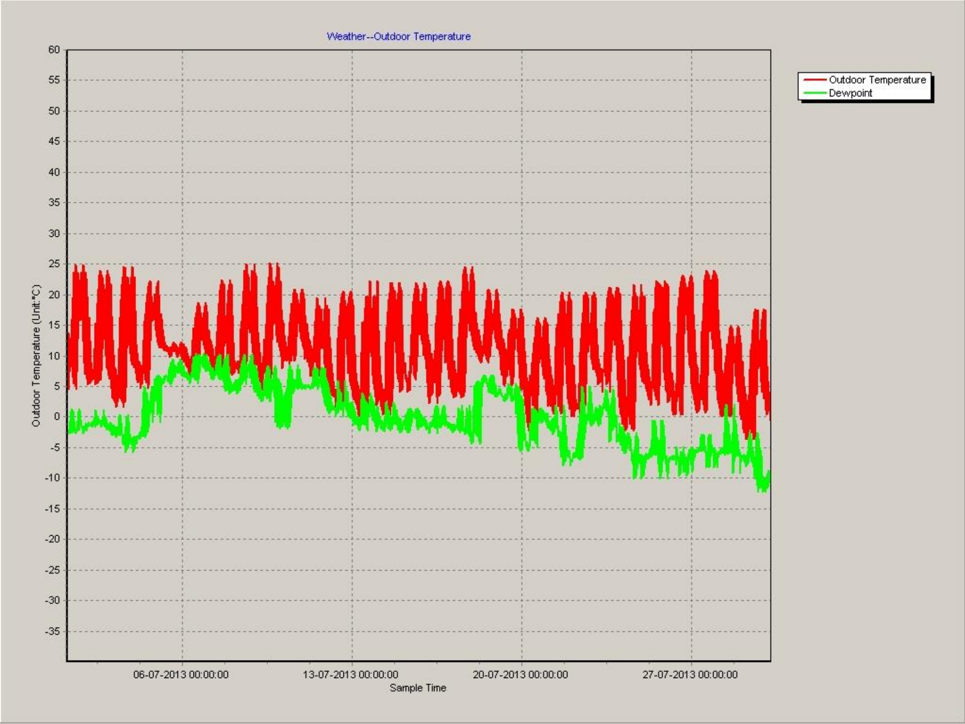


**Figure 52 - Variation in outdoor temperatures during July 2013.**

## 4.2 Solar collector and hot water storage

The lowest external temperatures of the growing season are normally experienced during July. Minimums can drop to -4 $^0$C and sometimes even as low as -9 $^0$C. The minimum temperature the plants should be exposed to is normally taken as 6 $^0$C, while some growers do not go below 12 $^0$C. A considerable amount of heat is then needed to keep the internal environment at the required lower set point.

The purpose of the solar collector would be to collect heat from the sun during day-time and to store that heat for exchange to the internal environment during night-time. A temperature data logger was placed at mid-height inside one of the three 1000 litre tanks to determine the variation in temperature of the working fluid and ultimately the amount of heat that is collected during the day, the amount that is lost by the tanks as well as the amount that is available for exchange to the internal heating system at night. A typical variation in the water temperature is shown in Figure 53.

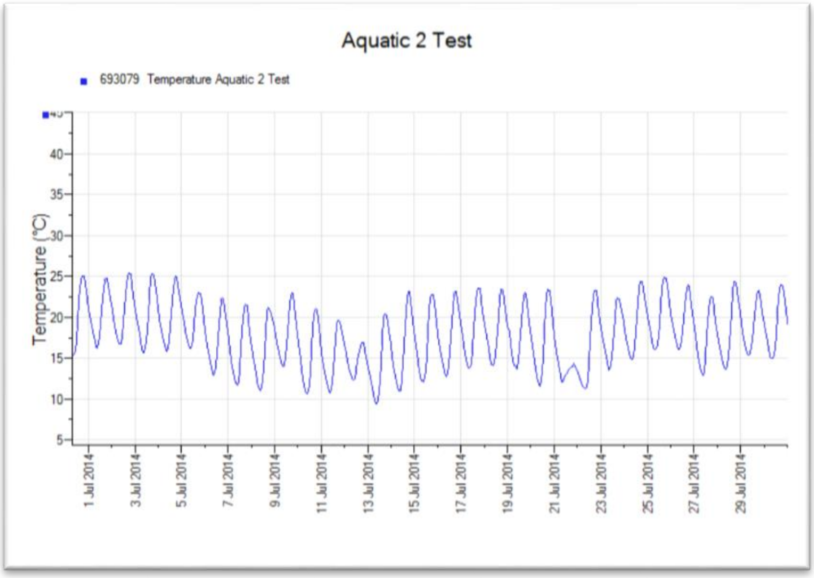


**Figure 53 - Variation in working fluid temperature for during July 2014.**

## 4.3 Greenhouse internal environment

Data regarding the internal environment of the greenhouse was retrieved directly from the automatic weather station. Figure 54 shows the variation in internal temperature for July 2013 while Figure 55 shows the variation in internal temperature for November 2014.

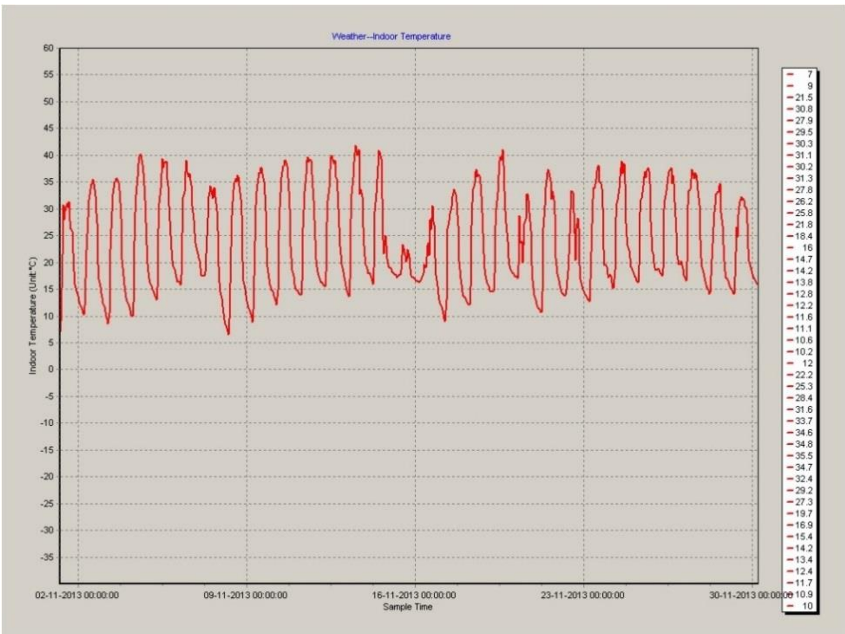


**Figure 54 - Variation in internal temperatures for July 2013.**

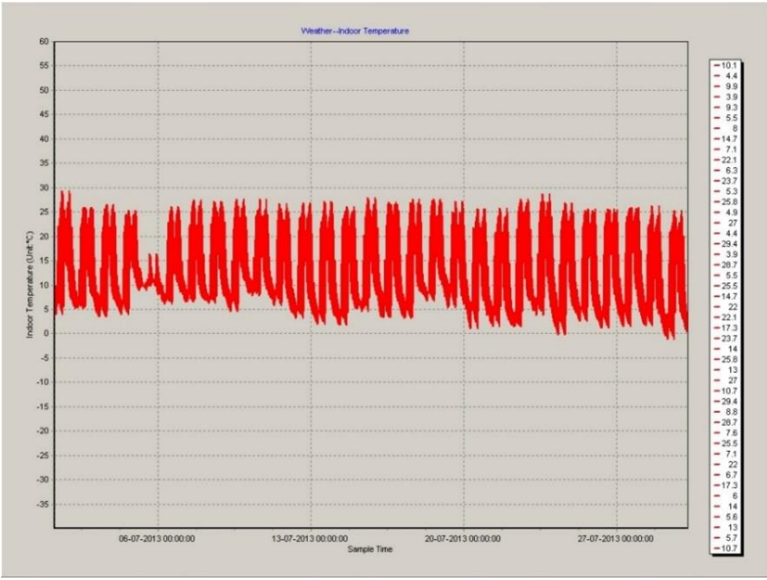


**Figure 55 - Variation in internal temperatures for July 2013.**

## 4.4 Under-bed heating system and internal environment

A temperature data collector was also placed underneath the enclosed growing beds to log the variation in temperature during the winter months when the heating system is in operation. The data received from this logger could then be used to determine the actual amount of heat the system exchanged to the under-bench region. An example of such data is shown in Figure 56.

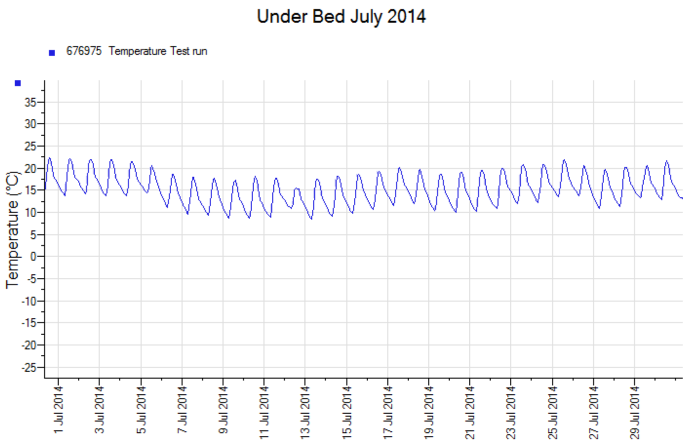


**Figure 56 - Variation in under-bench water temperature - July 2014.**

## 4.5 Greenhouse external environment (winter)

For the purpose of determining the actual heat required in the greenhouse, the temperatures of a typical day, in this case 14 July 2014, was used. During that day the external temperatures varied, as shown in Figure 57.

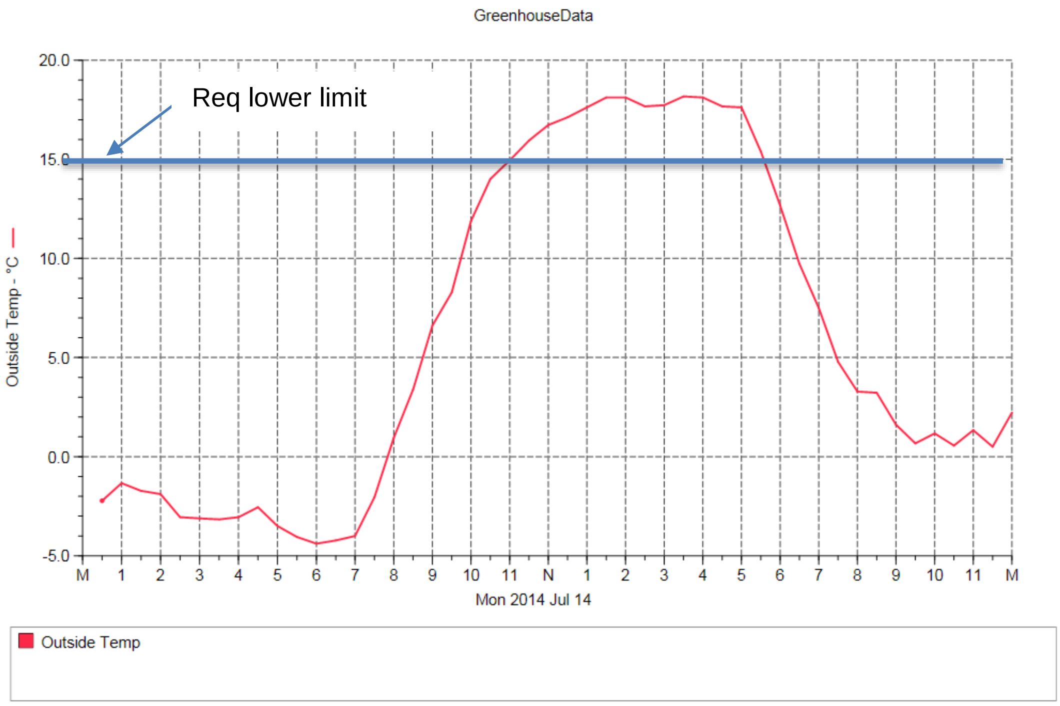


**Figure 57 - Variation in external temperature - 14 July 2014.**

The maximum temperature reached approximately 18 $^0$C while the minimum plummeted to – 4,5 $^0$C. The different periods during which the plants were exposed to the different temperatures can also be seen from the plot. The photoperiod will be the period above the 15 $^0$C line and the dormant period, the period below. It is clear that the plants were exposed to lower than required temperatures for relative long periods and that the periods that the plants were exposed to more desirable temperatures (the photoperiod) were shorter – not the optimum environment for plant growth. Apart from the lack of exposure to the required temperatures, it is also clear that the minimum temperatures dropped below freezing point which means that the plant tissue may be damaged by freezing, thus no production of any kind would be possible.

The external humidity remained fairly good for optimum plant production except for a few short periods from 03:00 till 06:00 in the early morning. These are, however, not critical because the temperatures were fairly low during these periods. The variation in external humidity for 14 July 2014 is shown in Figure 58.

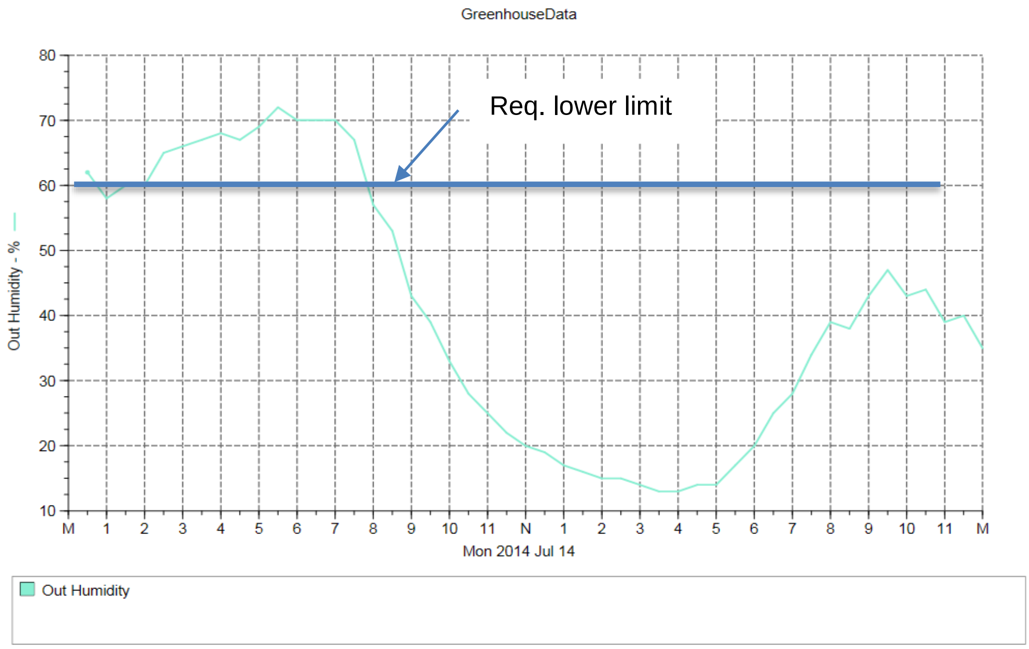


**Figure 58 - Variation in external RH - 14 July 2014.**

## 4.6 Greenhouse external environment (summer)

The variation in the external temperature of a typical hot summer's day is shown in Figure 59 below. The external temperature rose to approximately 32 $^0$C which is about 7 $^0$C above the optimum of 25 $^0$C. The minimum temperature dropped not lower than 14 $^0$C which is very good. The main concern during these periods is the maximum temperatures and the low levels of humidity that were experienced. If one compares Figure 59 with Figure 60, it can be seen that the humidity drops to its lowest level when the temperature is at its highest. With the temperature peaking at 33 $^0$C, the humidity dropped to approximately 15 % between 12:00 and 15:00 in the afternoon. These conditions make optimum plant growth difficult, and with cut-roses, the bud length starts to decrease to approximately 3 cm from the expected 5 cm.

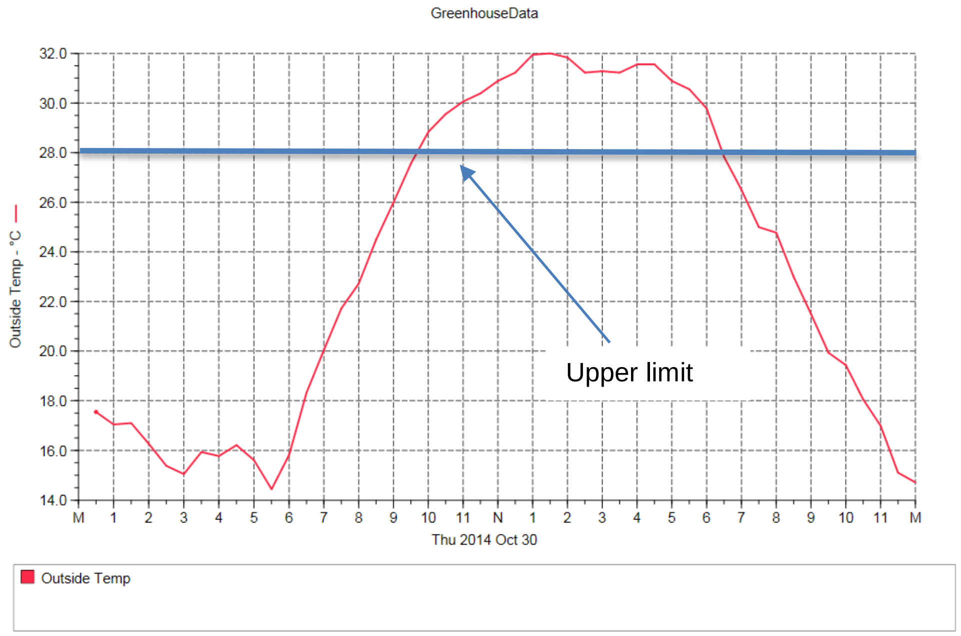


**Figure 59 - Variation in external temperatures - 31 Oct 2014.**

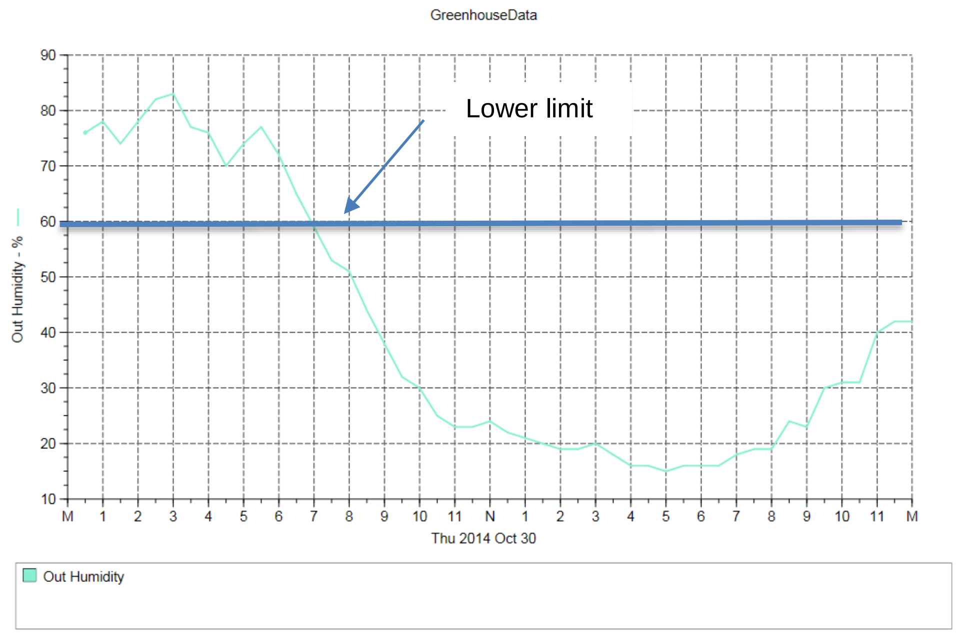


**Figure 60 - Variation in external RH - 30 Oct 2014.**

## 4.7 Solar collector performance

The actual maximum and minimum temperatures of the working fluid (water), measured in the storage tanks of the solar heater can be used to determine the actual amount of heat that the solar collector can collect and from that the efficiency of the solar collector can be calculated. Figure 61 shows how the temperature of the working fluid varied over the course of a few days during July 2014.

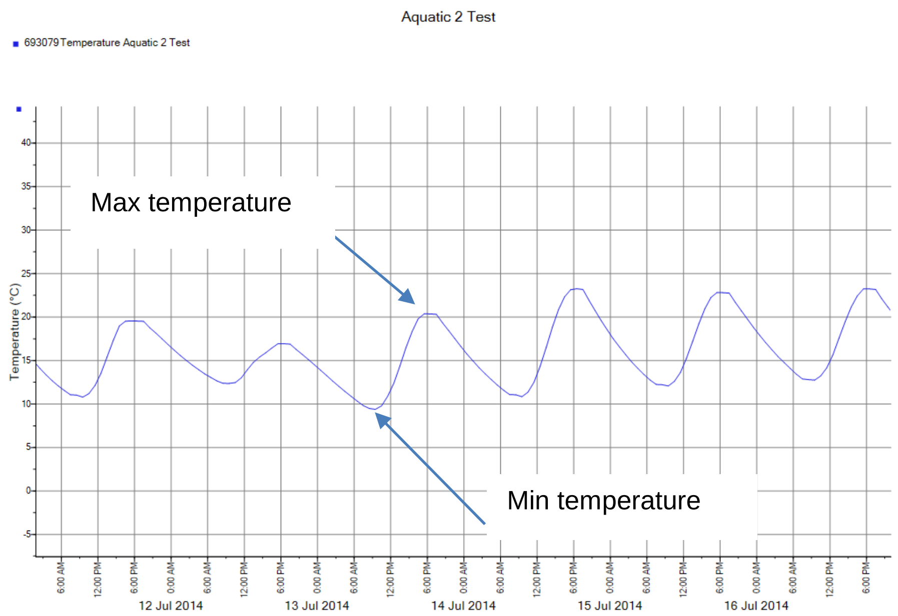


**Figure 61 - Typical variation in working fluid temperature during July 2014.**

On 14 July 2014, the temperature rose to 23 $^{0}$C during the day, and dropped to 12 $^{0}$C during the night. The actual amount of heat that the solar collector was able to add to the water can now be calculated by using equation 2.15.

$Q = mc_p\Delta T$ [J]

$= (2000)*(4183)*(296 – 285)$

$= 92.026$ MJ

The available solar insolation was taken as 3.32 kWh/m$^2$/day in section 2.4.3. This would mean that the total amount of solar insolation that is available to the solar collector can be taken as :

Area (solar collector) = 8 * 2.2 = 17.6 m$^2$, and

Available energy = 17.6 * 3.32 kWh/m$^2$/day

= 58,432 kWh/day

And that will amount to 210.355 MJ/day

The efficiency of the solar collector can then be calculated as follows:

$\eta_{collector}$ = $Q_{absorbed}/Q_{available}$

= (92.026/210.355) * 100

= 43.75 %

It was determined through the application of the heat loss calculation tool, presented in Table 9, that the greenhouse would require 1787 MJ of heat for a typical winter's night. This would mean that the current solar heating system would be able to supply (92,026MJ/1787MJ) or 5,15 % of the required heat, for the night of 14 July 2014. The area needed for the solar collector to supply all of the required heat can now be calculated as follows:

$A_{req}$ = Current Area/(5.15%)

= 341.75 $m^2$

The floor area of the greenhouse was 240 $m^2$, which means that the required area for the solar collector is (341.75/240)*100 or 143 % of the greenhouse floor area.

## 4.8 Greenhouse internal environment (winter)

The variation in internal and external temperatures for 14 July 2014 are presented in Figure 62.

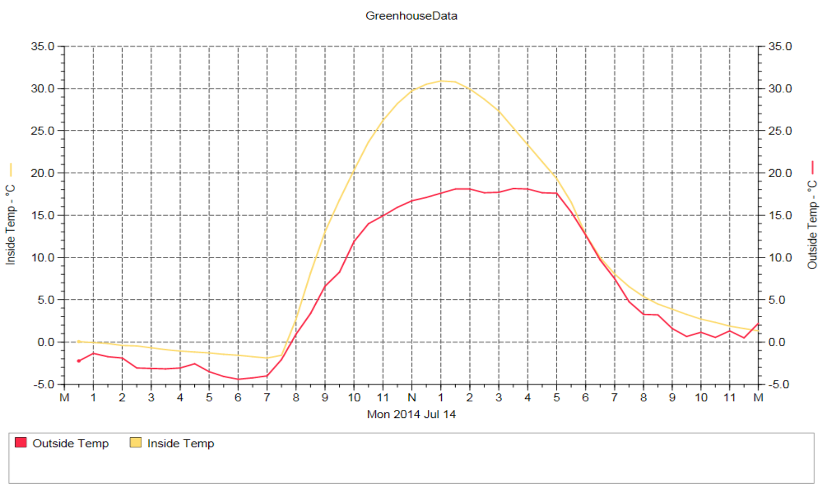


**Figure 62 - Internal and external temperatures – 14 July 2014.**

It is clear that the heating system did not have much of an influence on the internal temperature of the greenhouse because the minimum that was obtained was very close to the minimum of the external temperature. This supports the calculation, as performed in section 7.4, which determined that the solar heating system was able to supply only 5,5 % of the required heat. This means that both the efficiency and the collector area needed to be increased dramatically to obtain the required amount of heat necessary. The heat was supplied to the enclosed root zone. For effective root zone heating, the root zone needs to be heated to at least 20 $^0$C, while the canopy needs to be heated to at least 12 $^0$C. The idea in root zone heating is that a higher temperature is obtained at the root zone which in turn will create a heating effect of the canopy, to a temperature that may be a bit lower than what is required when a conventional heating system is used. The actual root zone temperatures varied, as shown in Figure 63. On 14 July it reached a maximum temperature of 18 $^0$C and dropped to a minimum of 9 $^0$C at night.

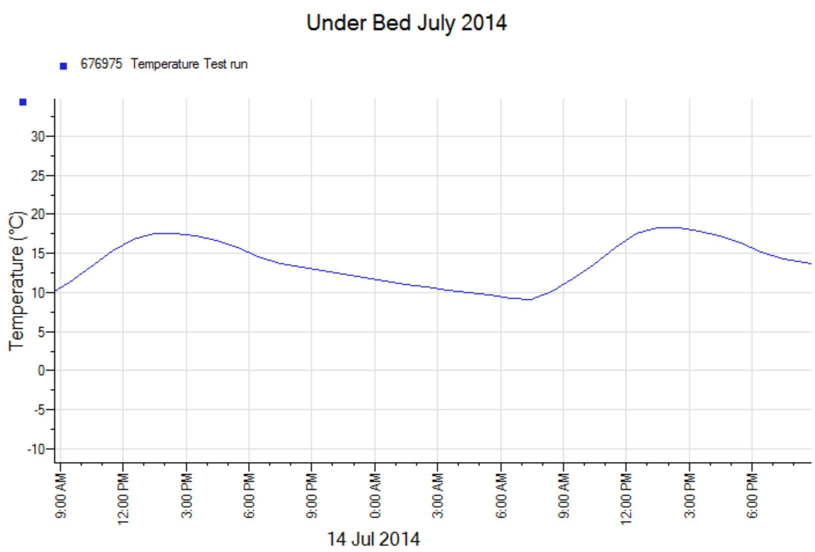


**Figure 63 - Variation in root zone temperature - 14 July 2014.**

## 4.9 Greenhouse internal environment (summer)

The internal temperature of a greenhouse that is ventilated through natural ventilation, can never be lower than the external temperature and the differences that were experienced in this project, is shown in Figure 64. The maximum day-time internal temperatures sometimes exceeded the external temperatures by more than 10 $^0$C. This is very problematic since the maximum day-time temperatures already exceed the maximum day-time temperature of 28 $^{0}$C, as required for optimum plant growth.

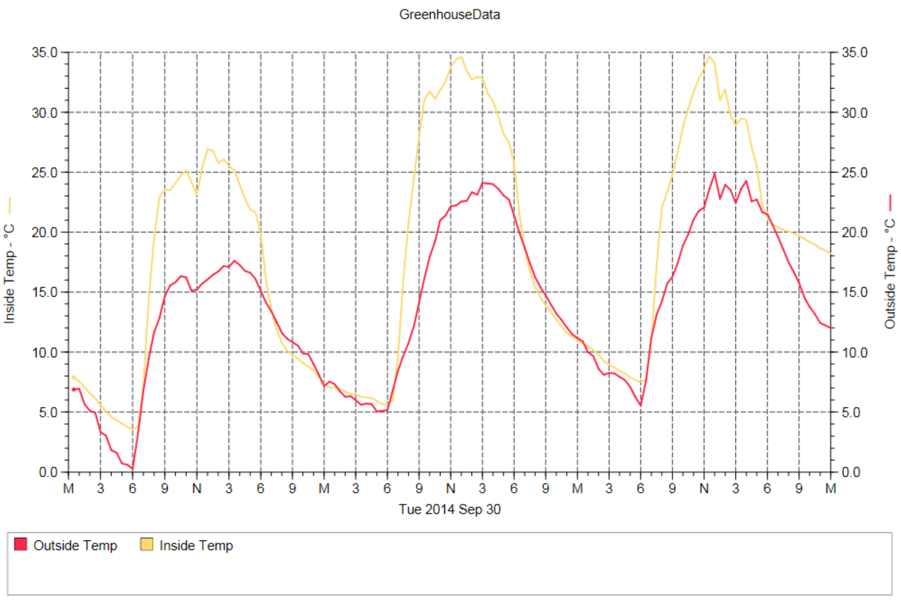


**Figure 64 - Internal and external temperatures - 30 Sept 2014.**

The vertical side wall height of the greenhouse and the opening size of the vents have a direct influence on the rate of natural ventilation occurring during periods of elevated temperatures. With the maximum internal temperatures reached, as shown in Figure 64, it becomes clear that the vertical side wall height of the greenhouse was too low and/or that the size of the ventilation openings on the greenhouse were too small. This is especially true for the lower-than-required single-span greenhouses that are so common in the horticultural industry.

## 4.10 Under-bed heating system

In an effort to increase the efficiency of the under-bed heat exchange system, the side walls were enclosed with a single layer of PE film during the second growing season. The idea was to concentrate more heat at the root zone and in doing that the greenhouse would not lose the added heat through the common mechanisms of heat transfer so easily. Earlier experiments have shown that a root zone temperature of 20 $^{0}$C combined with an internal temperature of 6 $^{0}$C can still sustain growth for greenhouse cut-roses [26]. The temperature at the root zone dropped to 10 $^{0}$C which means that the heating system could not supply enough heat to keep the root zone at the required 20 $^{0}$C.

## 4.11 Determining the solar fraction based on steady-state heat transfer

Once the amount of heat required by the greenhouse and the amount of heat that can be delivered by the solar heating system is known, the solar fraction can be determined. The solar fraction was earlier defined as the amount of energy provided by the solar technology divided by the total amount of energy required. The required amount of heat will vary from month to month as the minimum temperatures varies, and so will the amount of heat that can be collected vary through the year as the levels of solar insolation varies, as indicated in Table 10. With this information available, the heat loss and water storage calculator can be expanded to determine the solar fraction for the various months, as presented in Table 11 below. The solar fraction, as calculated here, was based on the steady-state heat calculations and is presented as an initial result only.

Central University of Technology, Free State

**Table 11- Solar fraction available from solar collector**

Greenhouse Heat Loss Calculation

| Heat Loss Through Conduction | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Greenhouse Length (m) | 30.000 | 30.000 | 30.000 | 30.000 | 30.000 | 30.000 | 30.000 | 30.000 | 30.000 | 30.000 | 30.000 | 30.000 |
| Greenhouse width(m) | 8.000 | 8.000 | 8.000 | 8.000 | 8.000 | 8.000 | 8.000 | 8.000 | 8.000 | 8.000 | 8.000 | 8.000 |
| Side Wall Height (m) | 2.400 | 2.400 | 2.400 | 2.400 | 2.400 | 2.400 | 2.400 | 2.400 | 2.400 | 2.400 | 2.400 | 2.400 |
| Roof Height (m) | 2.500 | 2.500 | 2.500 | 2.500 | 2.500 | 2.500 | 2.500 | 2.500 | 2.500 | 2.500 | 2.500 | 2.500 |
| Roof Slope Length (m) | 9.000 | 9.000 | 9.000 | 9.000 | 9.000 | 9.000 | 9.000 | 9.000 | 9.000 | 9.000 | 9.000 | 9.000 |
| Roof Area | 270.000 | 270.000 | 270.000 | 270.000 | 270.000 | 270.000 | 270.000 | 270.000 | 270.000 | 270.000 | 270.000 | 270.000 |
| East Wall Area (m^2) | 72.000 | 72.000 | 72.000 | 72.000 | 72.000 | 72.000 | 72.000 | 72.000 | 72.000 | 72.000 | 72.000 | 72.000 |
| West Wall Area (m^2) | 72.000 | 72.000 | 72.000 | 72.000 | 72.000 | 72.000 | 72.000 | 72.000 | 72.000 | 72.000 | 72.000 | 72.000 |
| South Wall Area (m^2) | 29.200 | 29.200 | 29.200 | 29.200 | 29.200 | 29.200 | 29.200 | 29.200 | 29.200 | 29.200 | 29.200 | 29.200 |
| North Wall Area (m^2) | 29.200 | 29.200 | 29.200 | 29.200 | 29.200 | 29.200 | 29.200 | 29.200 | 29.200 | 29.200 | 29.200 | 29.200 |
| Total Side Wall Area (m^2) | 202.400 | 202.400 | 202.400 | 202.400 | 202.400 | 202.400 | 202.400 | 202.400 | 202.400 | 202.400 | 202.400 | 202.400 |
| Floor Area (m^2) | 240.000 | 240.000 | 240.000 | 240.000 | 240.000 | 240.000 | 240.000 | 240.000 | 240.000 | 240.000 | 240.000 | 240.000 |
| Total Wall Area (m^2) | 472.400 | 472.400 | 472.400 | 472.400 | 472.400 | 472.400 | 472.400 | 472.400 | 472.400 | 472.400 | 472.400 | 472.400 |
| k Value side walls (W/m^2K) | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 |
| k Value for floor (W/m^2K) | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 |
| k Value for roof (W/m^2K) | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 | 0.830 |
| Inside Temperature (K) | 288.000 | 288.000 | 288.000 | 288.000 | 288.000 | 288.000 | 288.000 | 288.000 | 288.000 | 288.000 | 288.000 | 288.000 |
| Outside Temperature (K) | 287.000 | 287.000 | 285.000 | 280.000 | 276.000 | 272.000 | 272.000 | 274.000 | 277.000 | 282.000 | 285.000 | 286.000 |
| Soil Temperature (K) | 287.000 | 287.000 | 285.000 | 280.000 | 276.000 | 272.000 | 272.000 | 274.000 | 277.000 | 282.000 | 285.000 | 286.000 |
| Heat Conducted through roof (kW) | 0.224 | 0.224 | 0.672 | 1.793 | 2.689 | 3.586 | 3.586 | 3.137 | 2.465 | 1.345 | 0.672 | 0.448 |
| Heat Conducted through side wall (kW) | 0.168 | 0.168 | 0.504 | 1.344 | 2.016 | 2.688 | 2.688 | 2.352 | 1.848 | 1.008 | 0.504 | 0.336 |
| Heat conducted through floor (kW) | 0.199 | 0.199 | 0.598 | 1.594 | 2.390 | 3.187 | 3.187 | 2.789 | 2.191 | 1.195 | 0.598 | 0.398 |
| **Tot Heat Loss through Conduction (kW)** | **0.591** | **0.591** | **1.774** | **4.730** | **7.096** | **9.461** | **9.461** | **8.278** | **6.504** | **3.548** | **1.774** | **1.183** |
| **Heat Loss Through Convection** | **Value** | **Value** | **Value** | **Value** | **Value** | **Value** | **Value** | **Value** | **Value** | **Value** | **Value** | **Value** |
| Internal Volume ($m^3$) | 864.000 | 864.000 | 864.000 | 864.000 | 864.000 | 864.000 | 864.000 | 864.000 | 864.000 | 864.000 | 864.000 | 864.000 |
| Number of Air Changes per hour | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Total Heat Loss through Cenvection (kW** | **0.432** | **0.432** | **1.296** | **3.456** | **5.184** | **6.912** | **6.912** | **6.048** | **4.752** | **2.592** | **1.296** | **0.864** |
| **Heat Loss Through Radiation** | **Value** | **Value** | **Value** | **Value** | **Value** | **Value** | **Value** | **Value** | **Value** | **Value** | **Value** | **Value** |
| Emmisivity of leaves and enclosure (ε) | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 |
| Temperature of surface 1 (K) | 288 | 288 | 288 | 288 | 288 | 288 | 288 | 288 | 288 | 288 | 288 | 288 |
| Temperature of surface 2 (K) | 287 | 287 | 285 | 280 | 276 | 272 | 272 | 274 | 277 | 282 | 285 | 286 |
| Stefan-boltzman constant | 5.670E-08 | 5.670E-08 | 5.670E-08 | 5.670E-08 | 5.670E-08 | 5.670E-08 | 5.670E-08 | 5.670E-08 | 5.670E-08 | 5.670E-08 | 5.670E-08 | 5.670E-08 |
| Plant canopy area (m2) | 147.600 | 147.600 | 147.600 | 147.600 | 147.600 | 147.600 | 147.600 | 147.600 | 147.600 | 147.600 | 147.600 | 147.600 |
| **Total Heat Loss through Radiation (kW)** | 4.851 | 4.851 | 14.401 | 37.412 | 54.955 | 71.752 | 71.752 | 63.446 | 50.641 | 28.354 | 14.401 | 9.651 |
| **Total Heat Loss (kW)** | **5.874** | **5.874** | **17.471** | **45.599** | **67.235** | **88.125** | **88.125** | **77.772** | **61.897** | **34.494** | **17.471** | **11.697** |
| **Solar Water Heating** | | | | | | | | | | | | |
| Estimated hours of sun shine | 11 | 11 | 11 | 10 | 9 | 9 | 10 | 10 | 11 | 11 | 12 | 12 |
| Heating time (h) | 13 | 13 | 13 | 14 | 15 | 15 | 14 | 14 | 13 | 13 | 12 | 12 |
| Heating Capacity needed (kW) | 5.874 | 5.874 | 17.471 | 45.599 | 67.235 | 88.125 | 88.125 | 77.772 | 61.897 | 34.494 | 17.471 | 11.697 |
| Amount of heat needed (MJ) | 275 | 275 | 818 | 2298 | 3631 | 4759 | 4441 | 3920 | 2897 | 1614 | 755 | 505 |
| Solar Insolation Available (kWh/m²/day) | 7.02 | 6.19 | 5.28 | 4.44 | 3.74 | 3.32 | 3.54 | 4.36 | 5.29 | 5.97 | 6.71 | 7.07 |
| Solar Heat Collected (MJ) | 200.154 | 176.489 | 150.543 | 126.593 | 106.635 | 94.660 | 100.932 | 124.312 | 150.828 | 170.217 | 191.316 | 201.580 |
| **Solar Fraction** | **73%** | **64%** | **18%** | **6%** | **3%** | **2%** | **2%** | **3%** | **5%** | **11%** | **25%** | **40%** |

It is clear from Table 11 that the solar heating system, of the size as constructed for this experiment, will not be able to deliver all the heat that is required for the year-round production of temperature-sensitive crops as initially planned. A solar heating system, depending on its capacity, can however assist in extending the growing season, enabling growers to start production earlier in spring and continuing later into autumn. The solar heating system can also assist growers in handling cold spells that may occur during the growing season, if the working fluid is kept at the maximum operating temperature during spring and autumn. The solar heating system should be assisted by a conventional heating system during periods when the demand exceeds the capacity of the solar heating system. The price of fresh produce is normally better when there is a scarcity, e.g. during the off-season, and the cost of constructing a solar water heating system should be evaluated against the possible increase in the annual revenue from the growing system. Fruit and flower development will only start once the growing environmental conditions are suitable and with the amount of heat that a grower will have available from the solar water heating system, the grower should be able to predict the expected start and end date of the growing season.

## 4.12 Transient ventilation model

A transient day-time ventilation model was developed to determine the actual required day-time rates of ventilation that will ensure that the maximum growing temperature is not exceeded. A transient model is very helpful in the sense that it allows the designer to determine the required rate of ventilation during certain times of the day. Figure 65 below shows the actual versus the required rate of ventilation for 14 July 2014. It tends to over-ventilate in the morning when the vents open and cold air streams into the greenhouse from outside. Conversely, it tends to under-ventilate as the day progresses and the external temperature increases. This is quite common for naturally ventilated greenhouses and highlights the shortcomings of a natural ventilation system. At best, a naturally ventilated greenhouse will be able to reach a maximum internal day-time temperature that is approximately 5 $^{0}$C above the external temperature [53]. An additional cooling system is required for regions like the Free State, where the maximum ambient temperature often exceeds the maximum temperature required for optimum plant growth. The experiment showed that summer production became very difficult as the maximum ambient temperatures rose in excess of 25 $^{0}$C.

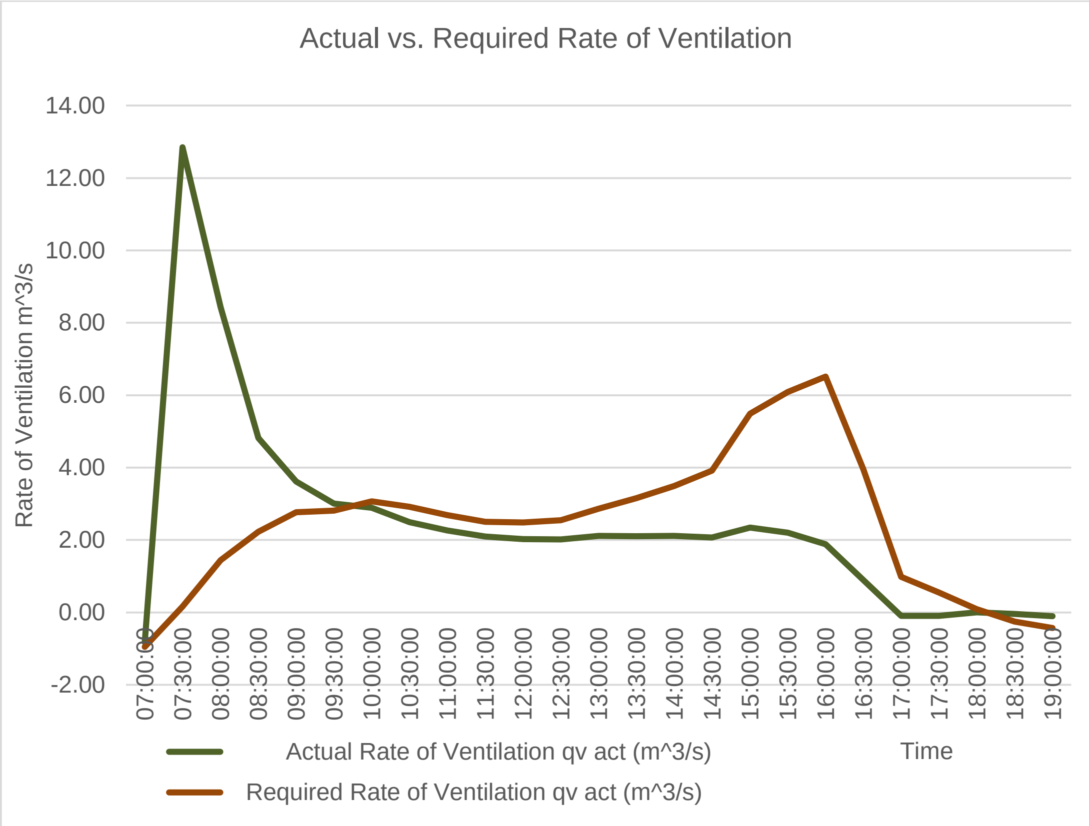


**Figure 65 - Day-time ventilation model- 14 July 2014.**

## 4.13 Transient Heating Model

A transient heating model was also developed to determine the heating requirements at specified time-steps during winter nights as shown in Figure 66. With the initial solar water heating system being used for the experiments, the dimensions and capacity of the required solar water heating system could be determined through this heating model.

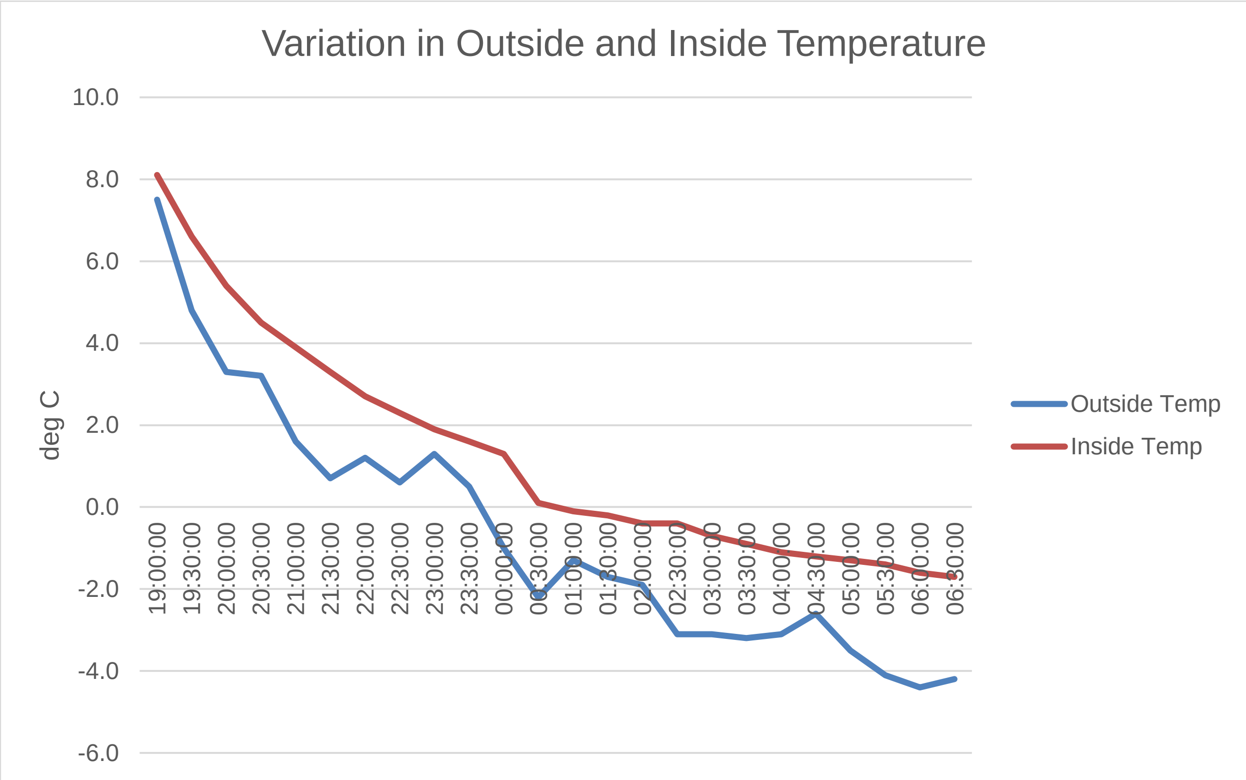


**Figure 66 - Variation in inner and outer night-time temperature.**

The inner temperature follows the outer temperature relatively closely as the night progresses and heat is lost through the various mechanisms, as indicated in figure 66, above. Greenhouses have fairly large outer surfaces that are exposed to the elements and heat losses through infiltration tend to increase as the greenhouse film ages with time. With an optimum internal temperature specified, the heating requirements at the various time-steps could then be determined with the heating model and were calculated as shown in Figure 67.

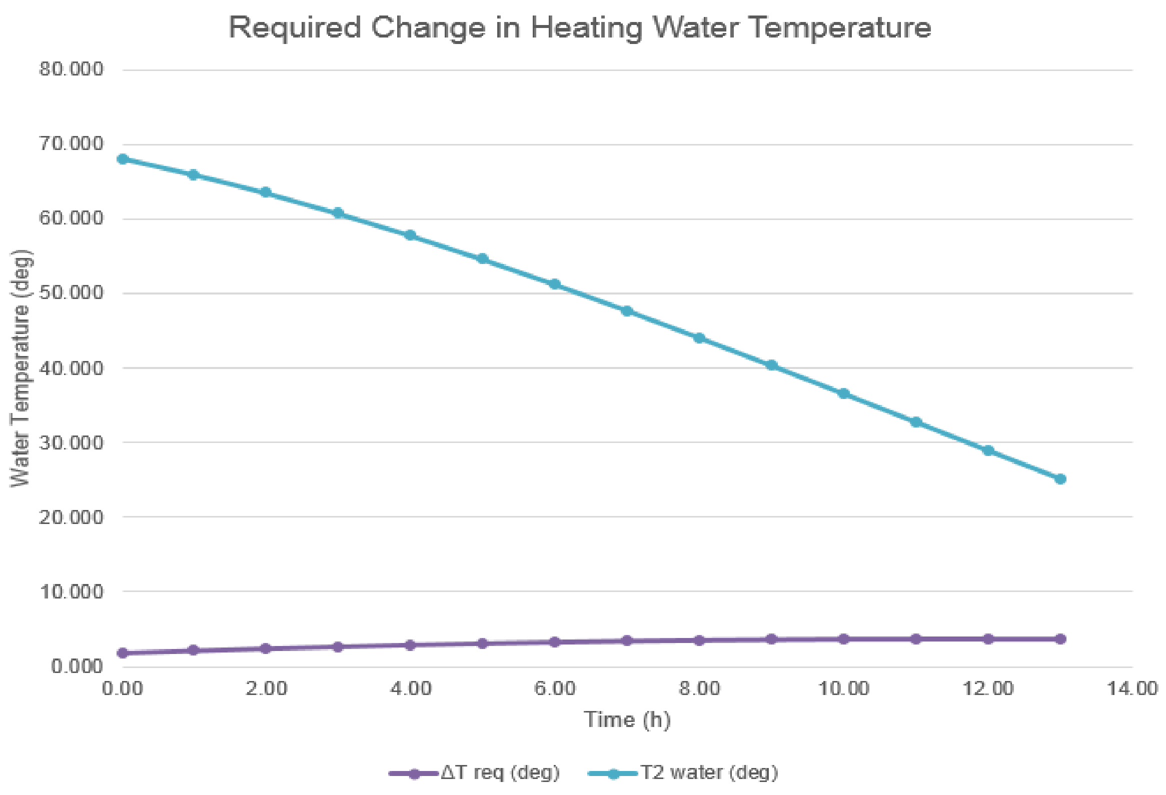


**Figure 67 - Actual vs. required heating capacity.**

The heating model showed that the required heating capacity was much higher than the actual. Once the required heating capacity was determined, a numerical equation could be written for it, which could be used to determine the required characteristics of the solar water heating system, such as collector area, storage capacity, required efficiency and required rise in temperature of the working fluid during the heating cycle. In Figure 67, the heating requirements of the greenhouse, was plotted in time-steps of 30 minutes that started at 19:00. Figure 68 also shows a typical calculation used to determine the heating system characteristics and the required change in temperature for such a system. From figure 68 it can be seen that 40 000 litres of stored water needs to be heated by a flat plate collector of similar design, with an area of 613 m$^2$ from a temperature of 26 $^0$C to a temperature of approximately 70 $^0$C. The required size of the solar collector would then be 2.554 times the area of the greenhouse. Should this not be possible, the solar water heating system can be scaled down to extend the growing season to where it may still be economically viable. In the last section of this chapter that deals with the financial model, this possibility will be investigated further.

**Required Water Heating System Capacity**

| | |
|---|---|
| Vol water (l) | 40000 |
| Cpwater (J/kgK) | 4183 |
| Time Inteval (s) | 3600 |
| Efficiency | 40.00% |
| T initial | 70 |
| Date | 14 July 2014 |
| Ins (kWh/day/m | 3.32 |
| Area Req (m^2) | 613 |

| Time | Time Step | Q req (kW) | Q req (kJ) | ΔT req (deg) | T2 water (deg) | Temp Grad (deg) |
|---|---|---|---|---|---|---|
| 18:30:00 | 1 | 29.839 | 1.074.E+05 | 1.605 | 68.395 | 53.395 |
| 19:30:00 | 2 | 40.742 | 1.467.E+05 | 2.191 | 66.203 | 51.203 |
| 20:30:00 | 3 | 47.120 | 1.696.E+05 | 2.535 | 63.669 | 48.669 |
| 21:30:00 | 4 | 51.645 | 1.859.E+05 | 2.778 | 60.891 | 45.891 |
| 22:30:00 | 5 | 55.155 | 1.986.E+05 | 2.967 | 57.924 | 42.924 |
| 23:30:00 | 6 | 58.023 | 2.089.E+05 | 3.121 | 54.803 | 39.803 |
| 00:30:00 | 7 | 60.448 | 2.176.E+05 | 3.251 | 51.552 | 36.552 |
| 01:30:00 | 8 | 62.549 | 2.252.E+05 | 3.364 | 48.187 | 33.187 |
| 02:30:00 | 9 | 64.401 | 2.318.E+05 | 3.464 | 44.723 | 29.723 |
| 03:30:00 | 10 | 66.059 | 2.378.E+05 | 3.553 | 41.170 | 26.170 |
| 04:30:00 | 11 | 67.558 | 2.432.E+05 | 3.634 | 37.536 | 22.536 |
| 05:30:00 | 12 | 68.927 | 2.481.E+05 | 3.708 | 33.829 | 18.829 |
| 06:30:00 | 13 | 70.186 | 2.527.E+05 | 3.775 | 30.053 | 15.053 |
| 07:30:00 | 14 | 71.351 | 2.569.E+05 | 3.838 | 26.215 | 11.215 |
| Total Amount of Heat Required | | | 2.930.E+06 | | | |

**Figure 68 - Numerical model to determine the required characteristics of the solar heating system.**

In the heating requirement calculator, as shown in Figure 68, the final temperature of the water can be altered to such a value that creates a useful temperature gradient to allow heat to be transferred from the heating system to its surrounding environment. The efficiency of the solar heating system can also be altered to reflect the characteristics of the specific heating system, should another system be used.

## 4.14 Financial viability

As stated above, the solar water heating system could possibly be used to extend the growing season. Cut-roses is a typical summer crop and higher than average prices can normally be obtained during the off-season. A financial model was developed that can assist in determining the financial viability of a typical solar water heating system. For the rose plants which were used, the average annual production volume (in stems per plant) was indicated by the breeder as approximately 22 for a normal growing season over a production period of 42 months.

With all the costs known, at this stage a financial model was developed where the required capital investment was discounted over the life expectancy of each item and added to the expected annual running cost. This was then subtracted from the expected annual income to determine the rate of return of the project. An example of such a return on investment calculator is shown in Figure 69, with the distribution of costs for the initial investment presented in Figure 70 and that of the annual costs presented in Figure 71. This financial model can now be used to scale the size of the solar water heating and with an expected escalation in the annual number of stems to be harvested per plant, the expected rate of return can be calculated. This model can be altered to incorporate the costs of alternative solar heating systems as well. With the initial model, as presented in Figure 69, it becomes obvious that it would be very difficult to obtain an acceptable rate of return with the solar water heating system, at least as far as the current design is concerned [78] [79].

## Financial Model for Cut-Rose Production (Single Span, 17.6 m^2 Heater)

| | |
|---|---|
| Current Interest Rate (%) | 10.00% |
| Rate of Insurance | 2.00% |
| Number of plants | 1600 |
| Average annual nr of stems per plant | 22 |

| Item | Description | Qty | Unit Cost | Initial Cost | Exp Life | Annual Costs |
|---|---|---|---|---|---|---|
| 1 | Fixed Costs | | | R 318 399.95 | | R 55 068.65 |
| 1.1 | Structure | | | | | |
| 1.1.1 | Steel Construction (m^2) | 240 | R 600.00 | R 144 000.00 | 20 | R 16 914.19 |
| 1.1.2 | Greenhouse Film (m^2) | 500 | R 20.00 | R 10 000.00 | 4 | R 3 154.71 |
| 1.1.3 | Floor Covering (m^2) | 240 | R 10.00 | R 2 400.00 | 4 | R 757.13 |
| 1.1.4 | Raised Bed Structure (units) | 36 | R 500.00 | R 18 000.00 | 10 | R 2 929.42 |
| 1.1.5 | Raised Bed Liners (metres) | 2 | R 1 000.00 | R 2 000.00 | 5 | R 527.59 |
| 1.1.6 | Irrigation System | 1 | R 10 000.00 | R 10 000.00 | 10 | R 1 627.45 |
| 1.1.6 | Control System | 1 | R 15 000.00 | R 15 000.00 | 10 | R 2 441.18 |
| 1.1.7 | Solar Heating System | 17.6 | R 852.27 | R 14 999.95 | 10 | R 2 441.17 |
| 1.1.8 | Plants | 1600 | R 20.00 | R 32 000.00 | 3 | R 12 867.67 |
| 1.1.9 | Land preparation, electricity & water connections | 1 | R 20 000.00 | R 20 000.00 | 20 | R 2 349.19 |
| 1.1.10 | Growing Medium | 200 | R 45.00 | R 9 000.00 | 4 | R 2 839.24 |
| 1.1.11 | Cold Storage | 1 | R 21 000.00 | R 21 000.00 | 10 | R 3 417.65 |
| 1.1.12 | Packing Facility | 1 | R 10 000.00 | R 10 000.00 | 20 | R 1 174.60 |
| 1.1.13 | Equipment (Sprayer, Shears etc.) | 1 | R 10 000.00 | R 10 000.00 | 10 | R 1 627.45 |
| | | | | | | |
| | | | | | | |
| 2 | Running Costs | | | | | R 45 588.00 |
| 2.1 | Fixed Labour Costs (hrs) | 2340 | R 8.00 | | | R 18 720.00 |
| 2.2 | Overtime (hrs) | 200 | R 16.00 | | | R 3 200.00 |
| 2.3 | Fertilizer, chemicals etc. (per month) | 12 | R 300.00 | | | R 3 600.00 |
| 2.4 | Electricity (kWhrs) | 1000 | R 1.88 | | | R 1 880.00 |
| 2.5 | Insurance (%) | 2.00% | R 318 399.95 | | | R 6 368.00 |
| 2.6 | Irrigation water | 1000 | R 7.50 | | | R 7 500.00 |
| 2.7 | Packaging materials | 1600 | R 1.20 | | | R 1 920.00 |
| 2.8 | Monthly repairs | 12 | R 200.00 | | | R 2 400.00 |
| | | | | | | |
| **Item** | **Description** | **% of Total** | **Unit Price** | | | **Expected Income** |
| 3 | Expected Income | | | | | R 49 280.00 |
| 3.1 | Long Stem Cut Roses | 50 | R 2.00 | | | R 35 200.00 |
| 3.2 | Medium Stem Cut Roses | 30 | R 1.00 | | | R 10 560.00 |
| 3.3 | Short Stem Cut Roses | 20 | R 0.50 | | | R 3 520.00 |
| | | | | | | |
| | Expected Gross Profit/Loss | | | | | -R 51 376.65 |
| | Return On Investment | | | | | -51.04% |

**Figure 69 - Typical financial model.**

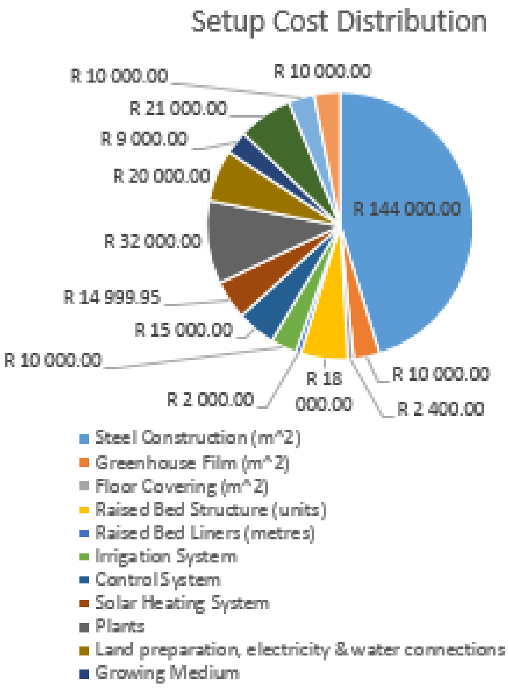


**Figure 70 – Initial setup cost distribution.**

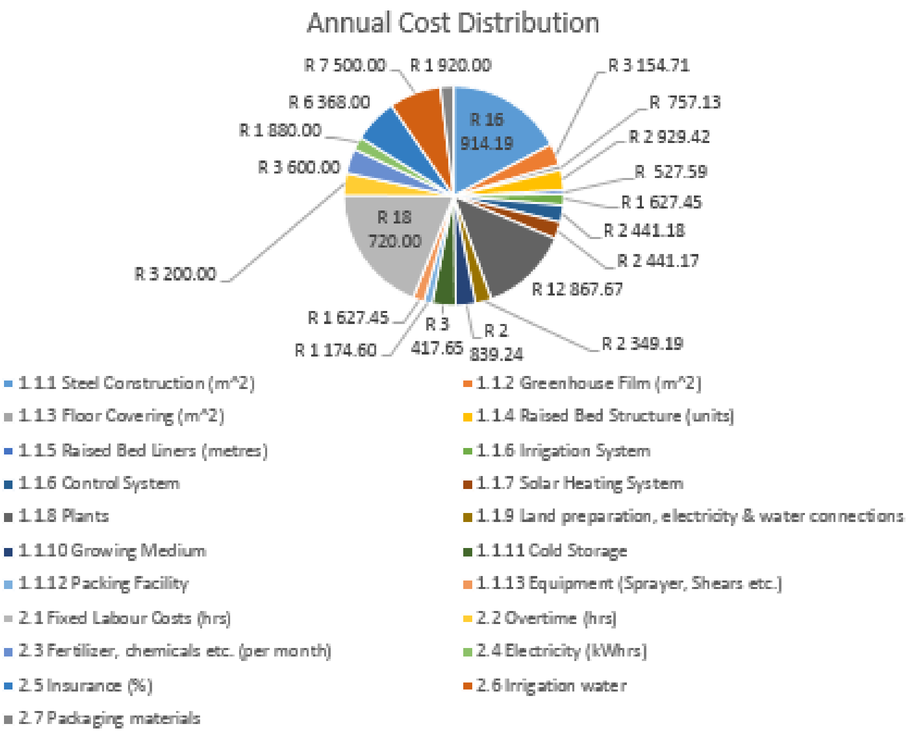


**Figure 71 - Running cost distribution.**

With the size of the solar collector increased to the required capacity, and the estimation of annual production increased from the specified 22 by 50 %, the scaled financial model is presented in Figure 72 below.

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**Financial Model for Cut-Rose Production (Single Span, 613 m^2 Heater)**

| | |
|---|---|
| Current Interest Rate (%) | 10.00% |
| Rate of Insurance | 2.00% |
| Number of plants | 1600 |
| Average annual nr of stems per plant | 33 |

| Item | Description | Qty | Unit Cost | Initial Cost | Exp Life | Annual Costs |
|---|---|---|---|---|---|---|
| **1** | **Fixed Costs** | | | **R 825 841.51** | | **R 137 652.43** |
| **1.1** | **Structure** | | | | | |
| **1.1.1** | Steel Construction (m^2) | 240 | R 600.00 | R 144 000.00 | 20 | R 16 914.19 |
| **1.1.2** | Greenhouse Film (m^2) | 500 | R 20.00 | R 10 000.00 | 4 | R 3 154.71 |
| **1.1.3** | Floor Covering (m^2) | 240 | R 10.00 | R 2 400.00 | 4 | R 757.13 |
| **1.1.4** | Raised Bed Structure (units) | 36 | R 500.00 | R 18 000.00 | 10 | R 2 929.42 |
| **1.1.5** | Raised Bed Liners (metres) | 2 | R 1 000.00 | R 2 000.00 | 5 | R 527.59 |
| **1.1.6** | Irrigation System | 1 | R 10 000.00 | R 10 000.00 | 10 | R 1 627.45 |
| **1.1.6** | Control System | 1 | R 15 000.00 | R 15 000.00 | 10 | R 2 441.18 |
| **1.1.7** | Solar Heating System | 613 | R 852.27 | R 522 441.51 | 10 | R 85 024.95 |
| **1.1.8** | Plants | 1600 | R 20.00 | R 32 000.00 | 3 | R 12 867.67 |
| **1.1.9** | Land preparation, electricity & water connection | 1 | R 20 000.00 | R 20 000.00 | 20 | R 2 349.19 |
| **1.1.10** | Growing Medium | 200 | R 45.00 | R 9 000.00 | 4 | R 2 839.24 |
| **1.1.11** | Cold Storage | 1 | R 21 000.00 | R 21 000.00 | 10 | R 3 417.65 |
| **1.1.12** | Packing Facility | 1 | R 10 000.00 | R 10 000.00 | 20 | R 1 174.60 |
| **1.1.13** | Equipment (Sprayer, Shears etc.) | 1 | R 10 000.00 | R 10 000.00 | 10 | R 1 627.45 |
| | | | | | | |
| | | | | | | |
| **2** | **Running Costs** | | | | | **R 55 736.83** |
| **2.1** | Fixed Labour Costs (hrs) | 2340 | R 8.00 | | | R 18 720.00 |
| **2.2** | Overtime (hrs) | 200 | R 16.00 | | | R 3 200.00 |
| **2.3** | Fertilizer, chemicals etc. (per month) | 12 | R 300.00 | | | R 3 600.00 |
| **2.4** | Electricity (kWhrs) | 1000 | R 1.88 | | | R 1 880.00 |
| **2.5** | Insurance (%) | 2.00% | R 825 841.51 | | | R 16 516.83 |
| **2.6** | Irrigation water | 1000 | R 7.50 | | | R 7 500.00 |
| **2.7** | Packaging materials | 1600 | R 1.20 | | | R 1 920.00 |
| **2.8** | Monthly repairs | 12 | R 200.00 | | | R 2 400.00 |
| | | | | | | |
| **Item** | **Description** | **% of Total** | **Unit Price** | | | **Expected Income** |
| **3** | **Expected Income** | | | | | **R 110 880.00** |
| **3.1** | Long Stem Cut Roses | 50 | R 3.00 | | | R 79 200.00 |
| **3.2** | Medium Stem Cut Roses | 30 | R 1.50 | | | R 23 760.00 |
| **3.3** | Short Stem Cut Roses | 20 | R 0.75 | | | R 7 920.00 |
| | | | | | | |
| | **Expected Gross Profit/Loss** | | | | | **-R 82 509.26** |
| | **Return On Investment** | | | | | **-42.66%** |

**Figure 72 - Scaled financial model.**

The ROI increased slightly from –51.04% to -42.66% but the project will still not be financially profitable. Scaling the operation may sometimes have an influence on the running costs, and in this case the labour cost may be reduced as it will be possible for one labourer to handle more than one greenhouse. More efficient and cost effective solar heaters may also have an influence on the setup cost and ultimately on the profitability of the project. If an operation is scaled, a flower producer may also opt to go for the export market that might enable him/her to obtain better prices for the produce and thereby increasing the profitability.

The experience of the grower will also play a big role - relatively little initial experience was available for this project and this certainly had a huge impact on the ultimate success. The expected crop size, as used in the financial model, was however based on data received from the plant propagator.

# 5. CONCLUSIONS AND RECOMMENDATIONS

In conclusion, the following summarized comments can be made regarding the main objectives that were dealt with in this study.

## 5.1 Natural ventilation system

A natural ventilation system can be a good alternative to a forced-draft ventilation system as long as the external temperatures do not exceed the required maximum growing temperature by more than 5 $^0$C. A natural ventilation system cannot create an internal temperature that is lower than the external temperature and this is of specific concern in the central region of South Africa where the maximum midsummer temperatures may reach 40 $^0$C, which is in itself already 12 $^0$C above the maximum required growing temperature of most greenhouse crops. At these temperatures, an additional cooling system will be required to lower the internal temperature of the greenhouse to a more desirable level. For at least four months of the year this may be the scenario that a grower will have to deal with. Although the prior experience of the grower may have a considerable influence on the quantity and quality of the produce, the plants will still need an optimum environment for optimum production.

## 5.2 Solar water heating system

The steady-state heating model, the transient heating model and the experimental validation showed that the greenhouse needed much more energy that what this basic solar heating system was able to supply. Even if the efficiency of the solar heating system was increased dramatically from the current 40 %, a much larger system would be needed. With the current efficiency, the solar water heating system would need to be in the order of 2.5 to 3 times the growing area of the greenhouse, which may be technically possible but not financially viable. The possible application of more efficient water heating systems may be evaluated in future by applying the heating models that were developed during the course of this research project.

## 5.3 Financial viability of a solar water heating system

Ultimately, the application of a new technology in any industry must be financially sound. The financial viability model provided the final conclusion for this research project. Perhaps a solar water heating system can be used to extend the growing season to a point where it is still financially viable, which may open up an opportunity for further research. For the central region of South Africa, with the type of cladding that was chosen, this does not seem possible. Better cladding materials, such as the double-walled PC panels may provide a much more stable internal environment which does not require so much energy to adjust, but the current cost of this product puts it out of reach of most growers if the current market value of their crops are considered. New, more energy efficient and cost effective covering materials need to be considered in future developments.

## 5.4 Recommendations for future research.

A natural ventilation system will not be able to decrease the internal environment of the greenhouse to the levels that is required for optimum production. Another possibility to investigate could be the application of photovoltaic cells to power a traditional fad-and-pad cooling system for a greenhouse, without the application of a bank of batteries. The application of a high pressure mist cooling can also be very efficient method of cooling if the required source of good quality water is available for the system. The financial viability of using such a system needs to be determined as well.

The possible application of heat pumps in collaboration with a solar water heating system to warm the water can also be investigated.

# 6. LIST OF REFERENCES


[1] J.A. Dieleman, E. Meinen, “Interacting effects of temperature integration and light intensity on growth and developmentof single-stemmed cut rose plants,” *Science Direct,* vol. 113, pp. 182-187, 2007.

[2] N. Mattson, “Effect of temperature on leaf area and flower sizes in roses,” *National horticulture research institute,* vol. Publication 48, pp. 185-191, 2007.

[3] A.M. Abdel-Ghany, I.M. Al-Helal, “Solar energy utelization by a greenhouse: General relations,” *Renewable Energy,* vol. 36, pp. 189-196, 2011.

[4] D.E. Buffington, R.A. Buckling, R.W. Henley, D.B. McConell, “Greenhouse ventilation,” *University of Florida - AFAS Extension,* Vols. AE-10, pp. 1-8, 1993.

[5] “Ventilation and Cooling,” National Greenhouse Manufacturers Association, 2013. [Online]. Available: http://ngma.com. [Accessed 11 Nov 2014].

[6] I.M. Al-Helal, A.M. Abdel-Ghany “Energy partition and conversion of solar and thermal radiation into sensible and latent heat in a greenhouse under arid conditions.,” *Energy and Buildings,* vol. 43, pp. 1740-1747, 2011.

[7] J. Chao, R. Knickerbocker, P. North, D. Swift “Simple Model of Temperature in the Pomona College Organic Farm Greenhouse,” *Pomona College,* Spring 2014.

[8] “Evaluating and monitoring of greenhouse cucumber-crop transpiration under high and low radiation conditions,” *Scientia Horticulturae,* vol. 105, pp. 163-175, 2005.

[9] J. Green, “Photoperiod - a grower management tool for controlling plant growth and development,” *Horticultural Department OSU,* vol. 8, pp. 19-22, 1984.

[10] “Maximumyield,” 2013. [Online]. Available: http://www.maximumyield.com/inside-my-com/asktheexperts/item/12--build-itright. [Accessed 7 May 2013].

[11] I. Grafiadellis, E. Traka-Mavrona “Heating greenhouses with solar energy - new trends and developments,” *National Research Foundation : Agricultural*

*research centre Macedonia and Thrace Thessaloniki,* vol. 31, pp. 119-134, 1990.

[12] P.J.C. Hamer, M.G. Ford, G.S. Virk "Novel methods of heating and cooling greenhouses: a feasibility study.," *Acta Horticulture,* vol. 719, pp. 223-230, 2006.

[13] J. Latimer, "Dealing with the high cost of energy for greenhouse operations," *Virginia cooperative extension,* Vols. 430-101, pp. 1-4, 2009.

[14] V.P. Sethi, S.K. Sharma, "Survey and evaluation of heating technologies for worldwide agriculture greenhouse applications," *Solar Energy,* vol. 82, pp. 832-859, 2008.

[15] "Solar energy system design," Power from the sun - Chapter 1., 1986. [Online]. Available: http://powerfromthesun.net. [Accessed 14 Jun 2014].

[16] R. Meyer, "CSP & Solar Resource Assessment," in *2nd Concentrated Solar Thermal Power Conference and Expo*, Pretoria, 2013.

[17] V.P. Sethi, S.K. Sharma "Experimental and economic study of a greenhouse thermal control system using aquifer water," *Energy Conversion and Management,* vol. 48, pp. 306-319, 2007.

[18] "Average weather for Bloemfontein," 2015. [Online]. Available: https://weatherspark.com. [Accessed 16 Aug 2015].

[19] B. E. Maas, "Effects of light on growth and flowering of rosa hybrid 'Mercedes"," *American Horticultural Society,* vol. 120, no. 4, pp. 571-576, 1995.

[20] L. Mortensen, "The effect of wide-range phosynthetic active radiations on photosynthesis, growth and flowering of Rosa sp. and Kalanchoe blossfeldiana," *American Journal of Plant Science,* vol. 5, no. 11, pp. 1-10, 2014.

[21] C. Kittas, A. Baille "Determination of the spectral properties of several greenhouse cover materials and evaluation of specific parameters related to plant response," *Iniversity of Thessaly - School of agriculture, crop and animal production,* vol. 71, pp. 193-202, 1998.

[22] J. Prenger, "Greenhouse Condensation Control: Understanding and using Vapor Pressure Deficit (VPD)," *Ohio State University Extension fact sheet,*

Vols. AEX-804-01, 1999.

[23] O. Vaisala, *Humidity Conversion Formulaes,* Helsinki: Vaisala, 2013.

[24] M. McPherson, Psychrometry: The study of moisture in air..

[25] T. Blom, “Carbon Dioxide en Greenhouses,” *Ministry of agriculture, foof and rural affairs,* vol. Fact sheet 290/27, pp. 1-9, 2012.

[26] M. Raviv, “Development of alternative cut-flower rose greenhouse temperature set-points based on calorimetric plant tissue evaluation,” *Science Horticulture,* vol. 126, pp. 454-461, 2010.

[27] *Greenhouse Heating Requirements,* Canada Plan Service.

[28] “High Tunnels,” Haygrove, [Online]. Available: http://haygrove.co.za. [Accessed 21 Feb 2017].

[29] M. Jenkins, “Alternative greenhouse heating systems,” *California Agriculture,* vol. May June 1985, pp. 5-7, 1985.

[30] Y. Tong, “Greenhouse heating using heat pumps with a high coefficient of performance (COP),” *Biosystems Engineering,* vol. 106, no. 4, pp. 405-411, 2010.

[31] A. Ganguly, “Model development and experimental validation of a floriculture greenhouse under natural ventilation.,” *Energy and Buildings,* vol. 41, no. 5, pp. 521-527, 2009.

[32] D. Briassoulis, “Analysis and design of low-density polyethylene greenhouse films,” *Biosystems engineering,* vol. 84, no. 3, pp. 303-314, 2003.

[33] “Greenhouse Technologies,” Greenhouse Technologies, [Online]. Available: http://ghtech.co.za. [Accessed 21 Feb 2017].

[34] “Plant Physiology Information website,” [Online]. Available: http://planthys.info/plant physiology/photoperiodism.shtms.. [Accessed 3 Sept 2015].

[35] G. Giacomelli, *Lecture #7 : Greenhouse Energy Balance,* Department of Agricultural and Biosystems Engineering, 2002.

[36] G. Giacomelli, *Control environmental systems, lecture to agricultuare and biosystems engineering students,* 2002.

[37] “Greenenergy Energy Balance of a Greenhouse,” 2009. [Online]. Available:

http://blog.maripositas.org/horticulture/greenhouse-innovations-and-future-productions-technics/attachment/greenenergy-energy-balance-of-a-greenhouse. [Accessed 20 Apr 2014].

[38] Y.Cengel, Fundementals of thermal-fluid sciences, McGraw - Hill (Asia), 2005.

[39] F. Dewitt, Fundementals of heat transfer, John Wiley & Sons, 2007.

[40] "Heating Greenhouses," NSW department of primary industries, 2006. [Online]. Available: http://www.dpi.nsw.gov.au/agriculture/horticulture/greenhouse/structures/heating. [Accessed 22 Aug 2013].

[41] "Greenhousecatalog," 2010. [Online]. Available: http://www.greenhousecatalog.com/greenhouse-light.php. [Accessed 15 June 2015].

[42] E. Fitz-Rodriques, "Dynamic modelling and simulation of greenhouse environments under several scenarios: A web-based application.," *Computers and Electronics in Agriculture,* vol. 70, pp. 105-116, 2010.

[43] "Calculation of Solar Insolation," PVEducation, [Online]. Available: http://www.pveducation.org/pvcdrom/properties-of-sunlight/calculation-of-solar-insolation. [Accessed 10 March 2016].

[44] I. Laribe, "Modeling of a greenhouse temperature : comparison between multimodel and neural approaches.," *I.N.S.A.T. de Tinus, Unite de Recherche RME,* pp. 399-404, 2006.

[45] J. Iga, "Effect of air density variations on greenhouse temperature model.," *Mathematical and computer modelling,* vol. 47, no. 2008, pp. 855-867, 2008.

[46] D. Ciolkosz, "SASRAD : An hourly-timestep solar radiation database for South Africa," *Journal of Energy in Southern Africa,* vol. 20, no. 1, pp. 25-34, 2009.

[47] "Collecting Solar Energy," Power from the Sun - Chapter 4, 1986. [Online]. Available: http://powerfromthesun.net. [Accessed 14 Jun 2014].

[48] J. Roy, "Convective and Ventilation Transfers in Greenhouses, Part 1 ; the Greenhouse considered as a Perfectly Stirred tank.," *Biosystems Engineering,* vol. 83, no. 1, pp. 1-20, 2002.

[49] R. Stull, "Wet-Bulb Temperature from Relative Humidity and Air Temperature,"

*American Meteoroligical Society,* vol. November 2011, pp. 2267-2269, 2011.

[50] P. Silveston, “Energy conservation through control of greenhouse mumidity. I. Condensation heat losses.”.

[51] M. Kindelan, “Dynamic modelling of Greenhouse Environment,” *Transactions of the ASAE,* vol. 23, no. 5, pp. 1232-1239, 1980.

[52] “The sun's energy,” Power from the sun - Chapter 2, 1986. [Online]. Available: http://powerfromthesun.net. [Accessed 14 Jun 2013].

[53] “National Greenhouse manufacturers Association - Greenhouse heat loss calculations,” 2013. [Online]. Available: http://www.ngma.com. [Accessed 14 Nov 2014].

[54] H. Uchida Frausto, “Modelling greenhouse temperature using system identification by means of neural network.,” *Neurocomputing,* vol. 56, no. 2004, pp. 423-428, 2004.

[55] P. Childs, Mechanical Design, Burlington: Elserivier Butterworth-Heinaman, 2004.

[56] J.M. Shigley, Mechanical engineering design. 6th metric edition., Boston: McGrawHill, 2003.

[57] “Horticulture and Science Practises,” 2015. [Online]. Available: http://generalhorticulture.tamu.edu/lectsupl/Physoil/physoil.htms. [Accessed 3 Sept 2015].

[58] V. Sethi, “On the selection and orientation of a greenhouse: Thermal modelling and experimental validation,” *Science Direct,* vol. 83(2009), pp. 21-38, 2008.

[59] “Profitable Plans Digest,” [Online]. Available: http://profitableplansdigest.com. [Accessed 22 02 2017].

[60] “Grozine,” [Online]. Available: www.grozine.com. [Accessed 22 Feb 2017].

[61] “Bradford Research Centre,” [Online]. Available: http://bradford.cafnr.org/passive-solar-greenhouse/. [Accessed 22 Feb 2017].

[62] “The sun's position,” Power from the Sun - Chapter 3, 1986. [Online]. Available: http://powerfromthesun.net. [Accessed 14 Jun 2013].

[63] “Greenhouse Ventilation,” [Online]. Available: http://articles.extension.org/pages/32535/greenhouse-ventilation. [Accessed 22

Feb 2017].

[64] “Rack and Pinion Vents,” [Online]. Available: https://maxpowercn.en.alibaba.com/product/60126939428-801274388/Low_cost_Greenhouse_construction_Sky_window_with_automatic_vent_opener_rack_and_pinion.html. [Accessed 2017 Feb 2017].

[65] “ebay,” [Online]. Available: http://www.ebay.co.uk/itm/PROFESSIONAL-SOLAR-POWERED-GREENHOUSE-VENT-``OPENER-WINDOW-GREENHOUSE-BARS-VINTAGE-/152224828545. [Accessed 22 Feb 2017].

[66] “Energy storage,” Power from the sun - Chapter 11, 1986. [Online]. Available: http://powerfromthesun.net. [Accessed 21 Jun 2014].

[67] “A high-performance, cost effective, solar-heated greenhouse,” Ibiblio, 1995. [Online]. Available: http://www.ibiblio.org/london/renewable-energy/solar/Nick.Pine/msg00002. [Accessed 27 Oct 2010].

[68] “Flat Plate Collectors,” Power from the Sun - Chapter 6, 1986. [Online]. Available: http://powerfromthesun.net. [Accessed 14 Jun 2014].

[69] “Everything about greenhouses,” [Online]. Available: https://sites.google.com/site/everythingaboutgreenhouses/contact-me. [Accessed 22 Feb 2017].

[70] “Verkarde Klimaat,” [Online]. Available: http://www.verkadeklimaat.nl/en/horticulture/references. [Accessed 22 Feb 2017].

[71] “Bio Therm,” [Online]. Available: http://www.biothermsolutions.com/industries/greenhouse/. [Accessed 22 Feb 2017].

[72] “ErfGoed,” [Online]. Available: http://erfgoed.com/technique/. [Accessed 22 Feb 2017].

[73] “Overhead Heating,” [Online]. Available: http://www.ega3.com/. [Accessed 22 Feb 2017].

[74] “Open roof greenhouse projects,” [Online]. Available: http://aesop.rutgers.edu/~horteng/openroof5.htm. [Accessed 22 Feb 2017].

[75] “MadeinChina.com,” [Online]. Available: http://aigeng-agri.en.made-in-

china.com/product/hoQmPLKAsrUF/China-Greenhouse-Curtain-Roll-up-Gear-Winch-Motor-SLC-001-.html. [Accessed 22 Feb 2017].

[76] “GAISMA,” [Online]. Available: http://www.gaisma.com/en/. [Accessed 22 FEB 2017].

[77] S. Diver, “Root zone heating for greenhouse crops,” *Appropiate technology transfer for rural areas,* vol. CT164, pp. 1-5, 2002.

[78] T. Woods, “Single Stem Roses - An Economic Analysis,” *Department of Agricultural Economics : University of Kentucky,* vol. Agricultural Economics Staff Paper #69, no. May 1997, pp. 1-14, 1997.

[79] T. Woods, “Single stem roses - an economic analysis,” *Department of agriculture economics : University of Kentucky,* vol. paper #369, pp. 1-3, 1997.

# 7. ADDENDUM A – GREENHOUSE STRUCTURAL LOADS

As stated previously, a gothic-arch type of greenhouse structure with vertical side walls needs to be designed. The National Greenhouse Manufacturers Association (NGMA) of the USA laid down a standard for the structural design of a greenhouse and because no design standards are available in South Africa, the design standard of the NGMA was used as a guideline in the design of the greenhouse structure. The following types of loads are specified in the design manual:

- Dead load (D) – the load that the structure exerts on itself due to the weight of the structural components and service equipment.
- Live loads (L) – temporary exterior loads as a result of workmen and equipment and temporary interior loads as a result of hanging objects, e.g. heaters, distribution fans, etc. A live load is considered as permanent if it imposed on the structure for a period of 30 days or longer.
- Wind load (W) – the load imposed on the structure by the wind.
- Snow Load (S) – will be excluded from this project.

For this project, the actual load P = D + L + W, while a stress combination factor of 1.33 will be used to increase the actual stresses when compared with the yield stress of the material.

Specific hollow sections will be chosen for the structural design and the wall thickness of these sections will then be adjusted, if necessary, based on the actual expected stresses as indicated by a Finite Element Analysis (FEA). The reasoning behind this iterative process is that the weight of the structure (D) forms part of the total load on the structure and needs to be included in the calculations.

The NGMA specifies a minimum live load, for arched roofs, that is determined as follows:

$L = 20R_1R_2 \geq 574{,}56\ N/m^2$ but limited to $718{,}2\ N/m^2$ (A-1)

Where $R_1 = 1{,}2$ for $A_t = 21{,}818\ m^2$ (actual area supported by truss in this greenhouse)

$R_2 = 1{,}2 - 0{,}05F$ (A-2)

= 1,2 – 0,05(12,8)

= 0,56

Where F is the rise to span ratio for an arched roof multiplied by 32.

From eq. 2.1

L = 20(1,2)(0,56)

= 13,44 N/m$^2$ actual.

Therefore, take L as 574,56 N/m$^2$, the minimum specified value.

All roof purlins must be able to withstand a concentrated load of 22,481 N at its mid-span. For this greenhouse, 38 * 1.6 mm pipe was used for the purlins. For these purlins to act simply as a supported beam with a central load of 22,481 N, the maximum stress can be calculated as follows:

$\sigma$ = BM*y/$I_A$ (A-3)

= (22,481)(1,5)(0,019)/2(3,142/64*0,038$^4$)

= 3,129 MPa – well below the allowable 300 MPa for grade 300 Steel.

Figure 69 shows a wind rose for Bloemfontein for the period 1 Jan to 31 December 2012. The greenhouse will be orientated in a North-South direction, as discussed earlier. From Figure 73 it is clear that the maximum expected wind speed is approximately 10 – 12 m/s (70 mph).

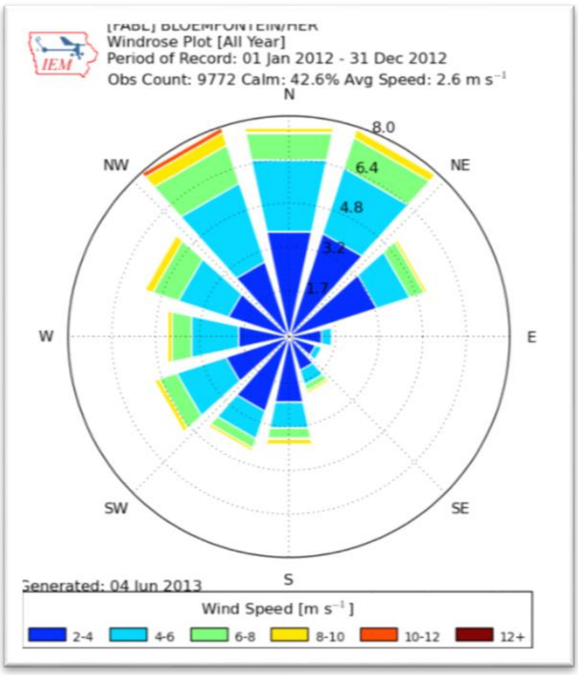


**Figure 73 - Wind rose for Bloemfontein** [18]**.**

The normal variation in wind speed above ground level is indicated in Figure 74. The standard height for measuring the wind speed is at 10 m. The wind speed at other heights above ground level can be determined as follows:

$C_2 = C_1(h_2/h_1)*n$ (A-4)

Where n is an adjustment factor that depends on ground cover and topography. For flat grasslands n is taken as 0,15.

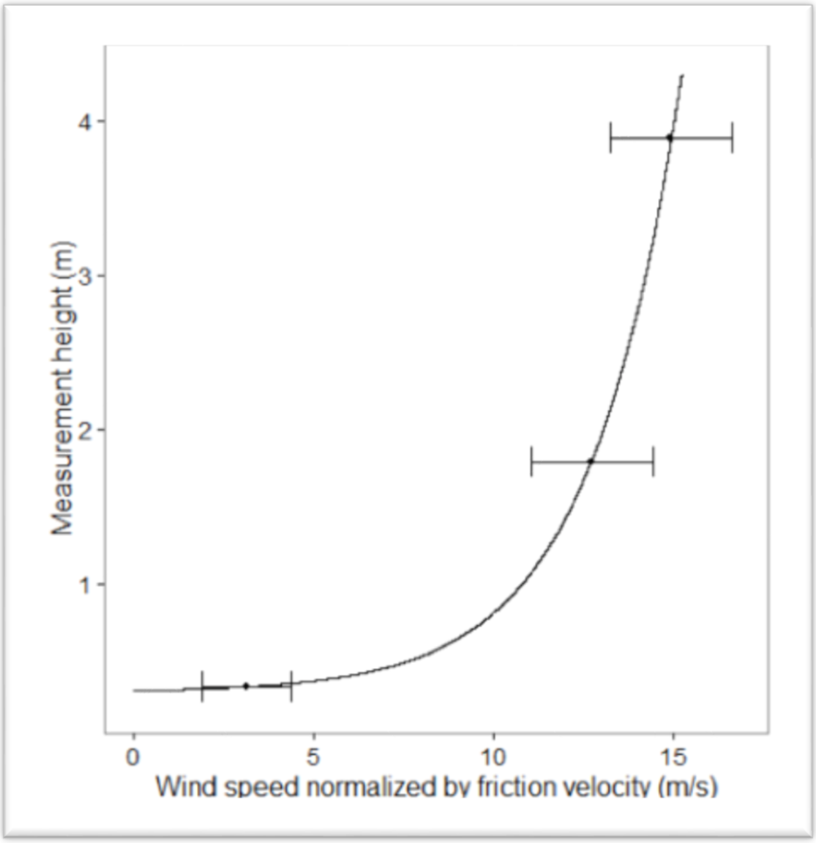


**Figure 74 - Wind speed distribution above ground level** [80]**.**

The design wind load is determined through the following procedure:

1. For the main wind-force resisting system (superstructure)

$P_{wind} = q_zGC_p – q_h(GC_{pi})$ for windward wall (A-5)

where

$q_z = 0{,}00256K_z(IC)^2$ - the velocity pressure at wall height (A-6)

the velocity at wall height $C_2 = C_1(h_2/h_1)^n$

$= 70(2,4/10)^{0.15}$

$= 56,511$ mph

Therefore

$q_z = 0,00256*0,8(0,95*56,511)^2$ (A-7)

$= 5,902$ psf

and

$q_h = 0,00256K_z(IV)^2$ - the velocity pressure at height h (A-8)

the velocity at height h = $C_2 = C_1(h_2/h_1)n$

$= 70(3,2/10)^{0.15}$

$= 59,003$ mph

Therefore from eq. 2.8

$q_h = 0,00256*0,8(0,95*59,003)^2$

$= 6,435$ psf

From eq 2.5

$P_z = q_zGC_p – q_h(GC_{pi})$

$= 5,902(1,32*0,8) – 6,435(0,25)$

= 4,624 psf or 221,397 Pa for the windward direction.

For the leeward side:

$P_h = q_hGC_p – q_h(GC_{pi})$

$= 6,435(1,32*0,8) – 6,435(0,25)$

= 5,187 psf or 248,354 Pa for the leeward direction.

2. For the components and glazing

$P = q_hGC_p – q_h(GC_{pi})$ (A-9)

$= 6,435(1,32*0.8) – 6,435(0.25)$

= 5,187 psf or 248,354 Pa for any direction.

The various wind pressures, as they act on the different walls of the greenhouse is schematically illustrated in Figures 75 and 76. These pressures can now be used to perform a FEA on the preliminary structure design in order to determine the optimum wall thicknesses for the different sections used.

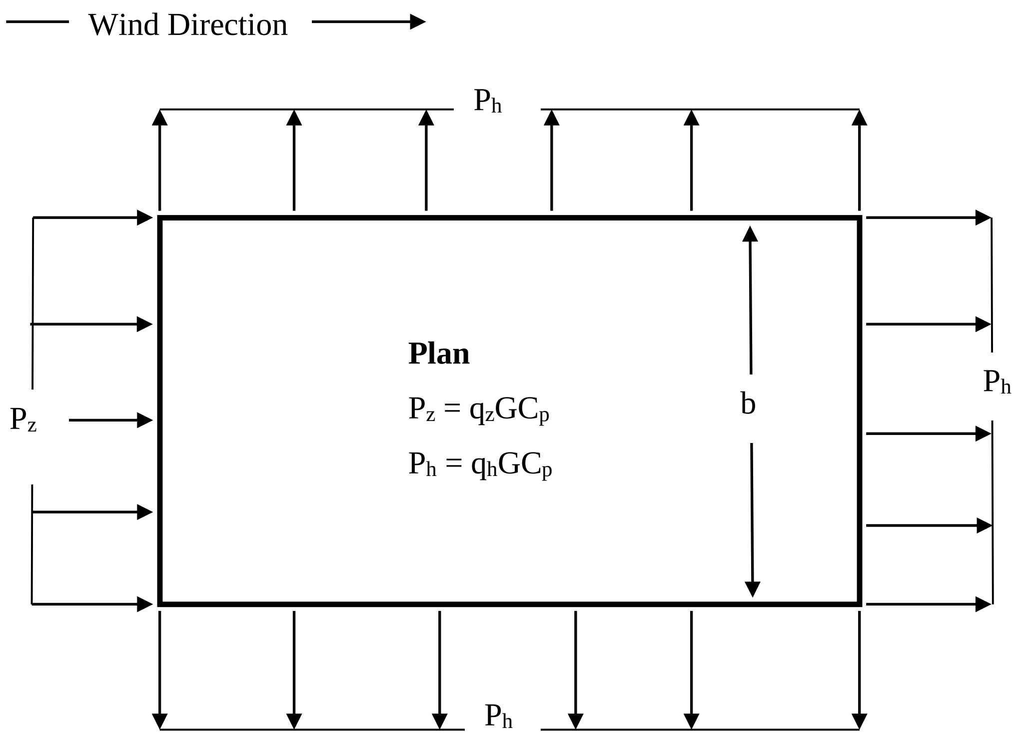


**Figure 75 - Wind pressure on different walls.**

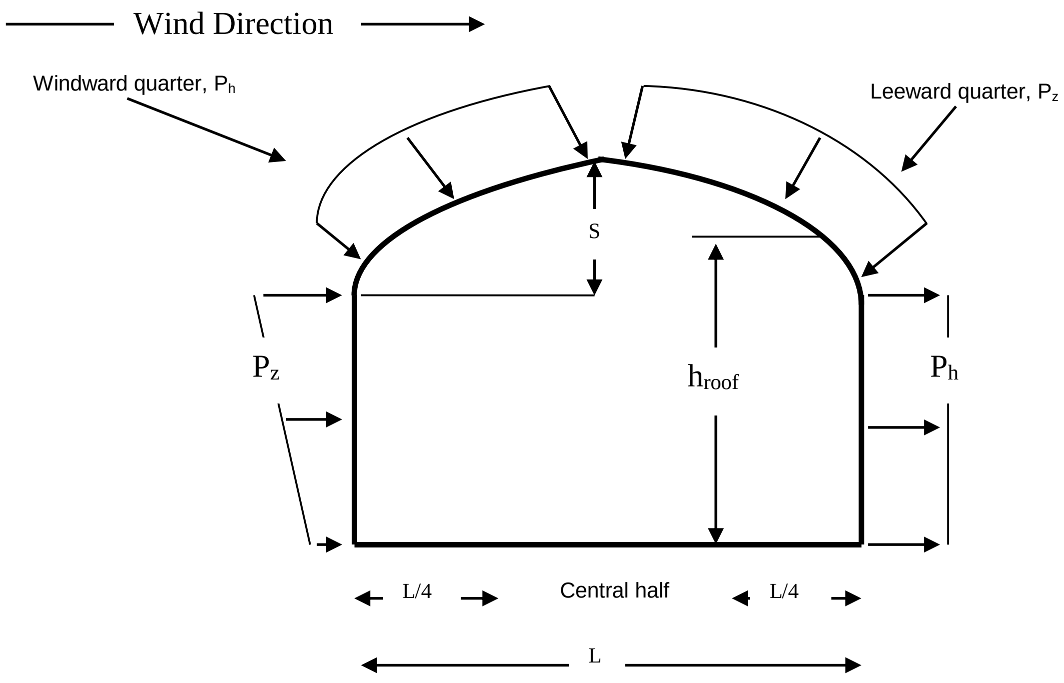


**Figure 76 - Wind pressure loads on greenhouse.**

The distance between the roof trusses is 3 m and the assumption was made that every 3 m section will carry an equal amount of the total wind load. The wind pressure is then multiplied by the respective area to give the distributed load on a single truss with two legs, as indicated in Figure 77.

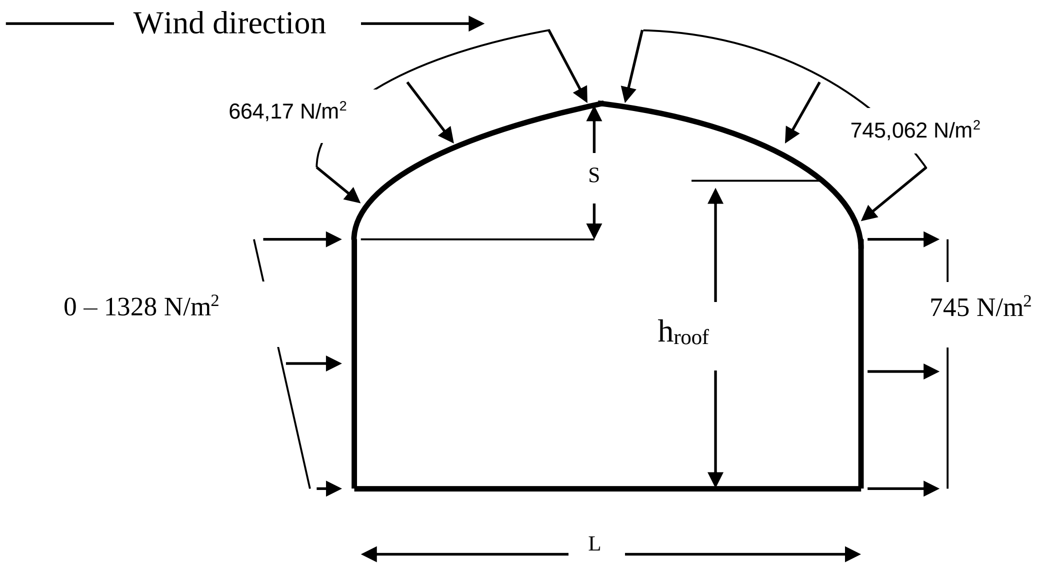


**Figure 77 - Actual loads on superstructure.**

For the design, standard tubular sections were chosen for the different components of which the wall thicknesses can be adjusted to account for the different stresses that may be expected, as determined by the FEA analysis.

# 8. ADDENDUM B – NIGHT TIME HEATING MODEL

An example of the heating model is presented here. Raw data from the automatic weather station was captured, as shown in Figure 78 on the following page. From this data a shorter summarized spreadsheet containing only the relevant data for the specific model was compiled, as shown in Figure 79. Figure 80 shows a typical graphical representation of the variation in internal and external temperatures as measured. The graphical representations can be used to determine the validity of measured data and alterations can be made to somehow “smooth” the data if necessary.

Data from Weather Station

| Date | Time | Temp Out | Hi Temp | Low Temp | Out Hum | Dew Pt. | Wind Speed | Wind Dir | Wind Run | Hi Speed | Hi Dir | Wind Chill | Heat Index | THW Index | THSW Index | Bar | Rain | Rain Rate | Solar Rad. | Solar Energy | Hi Solar Rad. | UV Index | UV Dose | Hi UV | Heat D-D | Cool D-D | In Temp | In Hum | In Dew | In Heat | In EMC | In Air Density | ET | Wind Samp | Wind Tx | ISS Recept | Arc. Int. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2014-07-14 | ##### | -2.2 | -2.2 | -3.3 | 62 | -8.5 | 0 | NNW | 0 | 1.6 | NNW | -2.2 | -2.6 | -2.6 | --- | 1055.5 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.428 | 0 | 0.1 | 79 | -3.2 | -0.1 | 16.31 | 1.3404 | 0 | 701 | 1 | 100 | 30 |
| 2014-07-14 | ##### | -1.3 | -0.4 | -2.2 | 58 | -8.5 | 1.6 | NNW | 0.8 | 4.8 | N | -1.3 | -1.7 | -1.7 | --- | 1055.6 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.41 | 0 | -0.1 | 80 | -3.1 | -0.2 | 16.67 | 1.341 | 0 | 696 | 1 | 100 | 30 |
| 2014-07-14 | ##### | -1.7 | -1.3 | -2.2 | 60 | -8.5 | 0 | N | 0 | 1.6 | WNW | -1.7 | -2.1 | -2.1 | --- | 1055.6 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.418 | 0 | -0.2 | 80 | -3.2 | -0.3 | 16.68 | 1.3416 | 0 | 702 | 1 | 100 | 30 |
| 2014-07-14 | ##### | -1.9 | -1.6 | -1.9 | 60 | -8.6 | 0 | N | 0 | 3.2 | N | -1.9 | -2.2 | -2.2 | --- | 1055.7 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.421 | 0 | -0.4 | 81 | -3.3 | -0.6 | 17 | 1.3429 | 0 | 697 | 1 | 100 | 30 |
| 2014-07-14 | ##### | -3.1 | -1.8 | -3.1 | 65 | -8.7 | 0 | W | 0 | 1.6 | NW | -3.1 | -3.3 | -3.3 | --- | 1055.7 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.446 | 0 | -0.4 | 80 | -3.5 | -0.6 | 16.7 | 1.3432 | 0 | 702 | 1 | 100 | 30 |
| 2014-07-14 | ##### | -3.1 | -3.1 | -3.4 | 66 | -8.6 | 0 | WNW | 0 | 1.6 | W | -3.1 | -3.4 | -3.4 | --- | 1055.6 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.447 | 0 | -0.7 | 80 | -3.7 | -0.8 | 16.72 | 1.3443 | 0 | 697 | 1 | 100 | 30 |
| 2014-07-14 | ##### | -3.2 | -3 | -3.2 | 67 | -8.4 | 0 | WNW | 0 | 1.6 | WNW | -3.2 | -3.4 | -3.4 | --- | 1055.4 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.448 | 0 | -0.9 | 80 | -3.9 | -1.1 | 16.73 | 1.3453 | 0 | 702 | 1 | 100 | 30 |
| 2014-07-14 | ##### | -3.1 | -2.9 | -3.4 | 68 | -8.1 | 0 | NNW | 0 | 1.6 | NNW | -3.1 | -3.3 | -3.3 | --- | 1055.4 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.446 | 0 | -1.1 | 80 | -4.1 | -1.2 | 16.75 | 1.3461 | 0 | 697 | 1 | 100 | 30 |
| 2014-07-14 | ##### | -2.6 | -2.6 | -3.1 | 67 | -7.8 | 0 | N | 0 | 3.2 | N | -2.6 | -2.8 | -2.8 | --- | 1055.1 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.435 | 0 | -1.2 | 80 | -4.2 | -1.3 | -1.3 | 1.3463 | 0 | 702 | 1 | 100 | 30 |
| 2014-07-14 | ##### | -3.5 | -2.4 | -3.5 | 69 | -8.4 | 0 | N | 0 | 1.6 | N | -3.5 | -3.7 | -3.7 | --- | 1055 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.455 | 0 | -1.3 | 81 | -4.1 | -1.4 | -1.4 | 1.3468 | 0 | 699 | 1 | 100 | 30 |
| 2014-07-14 | ##### | -4.1 | -3.5 | -4.3 | 72 | -8.4 | 0 | NNW | 0 | 1.6 | N | -4.1 | -4.3 | -4.3 | --- | 1055 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.466 | 0 | -1.4 | 81 | -4.3 | -1.6 | -1.6 | 1.3477 | 0 | 700 | 1 | 100 | 30 |
| 2014-07-14 | ##### | -4.4 | -4.1 | -4.4 | 70 | -9 | 0 | --- | 0 | 0 | --- | -4.4 | -4.6 | -4.6 | --- | 1055.3 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.473 | 0 | -1.6 | 80 | -4.6 | -1.7 | -1.7 | 1.3487 | 0 | 702 | 1 | 100 | 30 |
| 2014-07-14 | ##### | -4.2 | -4.2 | -4.5 | 70 | -8.9 | 0 | NNW | 0 | 1.6 | WNW | -4.2 | -4.4 | -4.4 | --- | 1055.7 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.47 | 0 | -1.7 | 80 | -4.7 | -1.9 | -1.9 | 1.3501 | 0 | 696 | 1 | 100 | 30 |
| 2014-07-14 | ##### | -4 | -3.8 | -4.3 | 70 | -8.7 | 0 | N | 0 | 1.6 | NNW | -4 | -4.2 | -4.2 | --- | 1055.9 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.465 | 0 | -1.9 | 80 | -4.9 | -2.1 | -2.1 | 1.3513 | 0 | 702 | 1 | 100 | 30 |
| 2014-07-14 | ##### | -2.1 | -2.1 | -4.1 | 67 | -7.4 | 0 | N | 0 | 1.6 | N | -2.1 | -2.3 | -2.3 | --- | 1056.1 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.425 | 0 | -1.6 | 81 | -4.4 | -1.7 | -1.7 | 1.3497 | 0 | 697 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 0.9 | 0.9 | -2 | 57 | -6.6 | 0 | N | 0 | 3.2 | N | 0.9 | 0.5 | 0.5 | --- | 1055.7 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.362 | 0 | 2.7 | 83 | 0.1 | 2.6 | 17.65 | 1.326 | 0 | 701 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 3.4 | 3.4 | 1 | 53 | -5.3 | 0 | N | 0 | 1.6 | N | 3.4 | 2.9 | 2.9 | --- | 1055 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.311 | 0 | 8.2 | 83 | 5.5 | 8.1 | 17.62 | 1.296 | 0 | 703 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 6.6 | 6.6 | 3.4 | 43 | -5.1 | 0 | SW | 0 | 3.2 | SW | 6.6 | 5.9 | 5.9 | --- | 1054.7 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.244 | 0 | 13.1 | 78 | 9.3 | 12.8 | 15.74 | 1.2702 | 0 | 695 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 8.3 | 8.3 | 6.6 | 39 | -4.9 | 0 | SW | 0 | 3.2 | SW | 8.3 | 7.4 | 7.4 | --- | 1054.2 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.209 | 0 | 16.8 | 72 | 11.8 | 16.7 | 13.75 | 1.2505 | 0 | 702 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 11.9 | 11.9 | 8.3 | 33 | -3.9 | 0 | SW | 0 | 3.2 | SW | 11.9 | 10.5 | 10.5 | --- | 1053.7 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.134 | 0 | 20.3 | 65 | 13.5 | 20.3 | 11.88 | 1.233 | 0 | 698 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 14 | 14.2 | 11.9 | 28 | -4.3 | 1.6 | WNW | 0.8 | 8 | WNW | 14 | 12.1 | 12.1 | --- | 1053.2 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.09 | 0 | 23.7 | 59 | 15.2 | 24.1 | 10.77 | 1.2165 | 0 | 698 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 14.9 | 15.1 | 14 | 25 | -4.9 | 1.6 | W | 0.8 | 9.7 | W | 14.9 | 12.7 | 12.7 | --- | 1053.4 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.071 | 0 | 26.2 | 53 | 15.9 | 26.4 | 9.65 | 1.2054 | 0 | 703 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 15.9 | 16.2 | 14.9 | 22 | -5.8 | 1.6 | SW | 0.8 | 6.4 | WSW | 15.9 | 13.4 | 13.4 | --- | 1053 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.05 | 0 | 28.2 | 49 | 16.5 | 28.7 | 8.89 | 1.1961 | 0 | 699 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 16.7 | 16.9 | 15.9 | 20 | -6.4 | 1.6 | SW | 0.8 | 4.8 | SW | 16.7 | 14.1 | 14.1 | --- | 1052.6 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.034 | 0 | 29.7 | 45 | 16.5 | 30.3 | 8.24 | 1.1897 | 0 | 699 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 17.1 | 17.2 | 16.7 | 19 | -6.7 | 1.6 | SW | 0.8 | 6.4 | SSW | 17.1 | 14.3 | 14.3 | --- | 1052 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.025 | 0 | 30.5 | 42 | 16.1 | 30.9 | 7.81 | 1.1866 | 0 | 699 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 17.6 | 17.6 | 16.7 | 17 | -7.8 | 1.6 | SE | 0.8 | 6.4 | WSW | 17.6 | 14.7 | 14.7 | --- | 1051.5 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.015 | 0 | 30.9 | 38 | 14.9 | 30.7 | 7.2 | 1.186 | 0 | 700 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 18.1 | 18.3 | 17.5 | 16 | -8.1 | 1.6 | SW | 0.8 | 8 | WSW | 18.1 | 15.2 | 15.2 | --- | 1050.8 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.005 | 0 | 30.8 | 38 | 14.8 | 30.7 | 7.2 | 1.1858 | 0 | 700 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 18.1 | 18.1 | 17.6 | 15 | -9 | 1.6 | SW | 0.8 | 9.7 | SW | 18.1 | 15.1 | 15.1 | --- | 1050.7 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.005 | 0 | 29.9 | 39 | 14.5 | 29.9 | 7.33 | 1.1893 | 0 | 702 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 17.7 | 18.1 | 17.4 | 15 | -9.3 | 3.2 | E | 1.61 | 9.7 | ENE | 17.7 | 14.7 | 14.7 | --- | 1050.7 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.014 | 0 | 28.7 | 41 | 14.2 | 28.9 | 7.68 | 1.1946 | 0 | 698 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 17.7 | 18.2 | 17.7 | 14 | -10.2 | 1.6 | E | 0.8 | 9.7 | ENE | 17.7 | 14.7 | 14.7 | --- | 1050.6 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.013 | 0 | 27.3 | 37 | 11.4 | 26.6 | 7.13 | 1.2031 | 0 | 699 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 18.2 | 18.4 | 17.7 | 13 | -10.7 | 1.6 | SE | 0.8 | 6.4 | SE | 18.2 | 15.1 | 15.1 | --- | 1050.4 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.003 | 0 | 25.3 | 42 | 11.5 | 24.9 | 7.9 | 1.2107 | 0 | 698 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 18.1 | 18.6 | 18.1 | 13 | -10.8 | 1.6 | SE | 0.8 | 4.8 | SE | 18.1 | 15.1 | 15.1 | --- | 1050.5 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.005 | 0 | 23.3 | 45 | 10.7 | 23 | 8.45 | 1.2199 | 0 | 700 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 17.7 | 18.1 | 17.6 | 14 | -10.2 | 1.6 | SE | 0.8 | 8 | ESE | 17.7 | 14.7 | 14.7 | --- | 1050.6 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.014 | 0 | 21.3 | 54 | 11.6 | 20.6 | 9.94 | 1.2273 | 0 | 702 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 17.6 | 17.7 | 17.4 | 14 | -10.3 | 0 | SE | 0 | 6.4 | SE | 17.6 | 14.6 | 14.6 | --- | 1050.7 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.015 | 0 | 19.3 | 63 | 12.1 | 19.2 | 11.61 | 1.2353 | 0 | 698 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 15.4 | 17.6 | 15.4 | 17 | -9.6 | 0 | SE | 0 | 3.2 | ESE | 15.4 | 12.8 | 12.8 | --- | 1051 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.061 | 0 | 16.6 | 66 | 10.2 | 16.2 | 12.28 | 1.2495 | 0 | 699 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 12.7 | 15.4 | 12.7 | 20 | -9.8 | 0 | ESE | 0 | 1.6 | ESE | 12.7 | 10.7 | 10.7 | --- | 1051.4 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.118 | 0 | 12.7 | 68 | 7 | 12.2 | 12.95 | 1.2698 | 0 | 698 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 9.7 | 12.7 | 9.7 | 25 | -9.4 | 0 | W | 0 | 1.6 | E | 9.7 | 8.6 | 8.6 | --- | 1052 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.179 | 0 | 10 | 70 | 4.8 | 9.8 | 13.35 | 1.2843 | 0 | 703 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 7.5 | 9.8 | 7.5 | 28 | -9.9 | 0 | WNW | 0 | 1.6 | W | 7.5 | 6.5 | 6.5 | --- | 1052.3 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.226 | 0 | 8.1 | 71 | 3.1 | 7.8 | 13.58 | 1.2949 | 0 | 698 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 4.8 | 7.4 | 4.8 | 34 | -9.8 | 0 | N | 0 | 3.2 | N | 4.8 | 3.9 | 3.9 | --- | 1052.8 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.282 | 0 | 6.6 | 73 | 2.1 | 6.3 | 14.12 | 1.303 | 0 | 698 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 3.3 | 4.8 | 3.1 | 39 | -9.4 | 0 | N | 0 | 3.2 | N | 3.3 | 2.6 | 2.6 | --- | 1053.3 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.314 | 0 | 5.4 | 74 | 1.1 | 5.2 | 14.48 | 1.3098 | 0 | 702 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 3.2 | 3.8 | 3.2 | 38 | -9.8 | 1.6 | N | 0.8 | 3.2 | N | 3.2 | 2.5 | 2.5 | --- | 1053.5 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.315 | 0 | 4.5 | 75 | 0.5 | 4.2 | 14.85 | 1.3146 | 0 | 698 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 1.6 | 3.2 | 1.5 | 43 | -9.6 | 0 | N | 0 | 1.6 | N | 1.6 | 1.1 | 1.1 | --- | 1053.1 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.348 | 0 | 3.9 | 76 | 0 | 3.7 | 15.25 | 1.3173 | 0 | 700 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 0.7 | 1.6 | 0.6 | 47 | -9.4 | 0 | NNW | 0 | 1.6 | N | 0.7 | 0.1 | 0.1 | --- | 1053.3 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.368 | 0 | 3.3 | 77 | -0.4 | 3.1 | 15.55 | 1.3207 | 0 | 698 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 1.2 | 1.2 | 0.5 | 43 | -10.1 | 0 | N | 0 | 3.2 | N | 1.2 | 0.6 | 0.6 | --- | 1053.6 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.358 | 0 | 2.7 | 77 | -0.9 | 2.5 | 15.55 | 1.3239 | 0 | 701 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 0.6 | 1.2 | 0.4 | 44 | -10.3 | 0 | N | 0 | 3.2 | N | 0.6 | 0 | 0 | --- | 1053.8 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.37 | 0 | 2.3 | 78 | -1.1 | 2.2 | 15.87 | 1.3262 | 0 | 699 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 1.3 | 1.3 | -0.2 | 39 | -11.1 | 1.6 | N | 0.8 | 6.4 | NNE | 1.3 | 0.7 | 0.7 | --- | 1054.7 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.354 | 0 | 1.9 | 78 | -1.5 | 1.7 | 15.86 | 1.3297 | 0 | 701 | 1 | 100 | 30 |
| 2014-07-14 | ##### | 0.5 | 1.6 | 0.5 | 40 | -11.6 | 0 | N | 0 | 3.2 | N | 0.5 | -0.1 | -0.1 | --- | 1054.8 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.372 | 0 | 1.6 | 79 | -1.6 | 1.4 | 16.25 | 1.3312 | 0 | 698 | 1 | 100 | 30 |
| 2014-07-15 | ##### | 2.2 | 2.6 | 0.4 | 35 | -11.7 | 1.6 | N | 0.8 | 4.8 | N | 2.2 | 1.5 | 1.5 | --- | 1054.5 | 0 | 0 | --- | --- | --- | --- | --- | --- | 0.336 | 0 | 1.3 | 79 | -1.9 | 1.1 | 16.26 | 1.3323 | 0 | 699 | 1 | 100 | 30 |

**Figure 78 - Raw data from automatic weather station.**

**Night Time Data (Summarized)**

| Date | Time | Temp Out (deg) | Temp In (deg) | Out Hum (%) | Out Dew (deg) | Pressure (mBar) | In Hum (%) | In Dew (deg) | In Air Density (kg/m^3) |
|---|---|---|---|---|---|---|---|---|---|
| 2014-07-14 | 07:00 PM | 7.5 | 8.1 | 28 | -9.9 | 1052.30 | 71 | 3.1 | 1.2949 |
| 2014-07-14 | 07:30 PM | 4.8 | 6.6 | 34 | -9.8 | 1052.80 | 73 | 2.1 | 1.303 |
| 2014-07-14 | 08:00 PM | 3.3 | 5.4 | 39 | -9.4 | 1053.30 | 74 | 1.1 | 1.3098 |
| 2014-07-14 | 08:30 PM | 3.2 | 4.5 | 38 | -9.8 | 1053.50 | 75 | 0.5 | 1.3146 |
| 2014-07-14 | 09:00 PM | 1.6 | 3.9 | 43 | -9.6 | 1053.10 | 76 | 0 | 1.3173 |
| 2014-07-14 | 09:30 PM | 0.7 | 3.3 | 47 | -9.4 | 1053.30 | 77 | -0.4 | 1.3207 |
| 2014-07-14 | 10:00 PM | 1.2 | 2.7 | 43 | -10.1 | 1053.60 | 77 | -0.9 | 1.3239 |
| 2014-07-14 | 10:30 PM | 0.6 | 2.3 | 44 | -10.3 | 1053.80 | 78 | -1.1 | 1.3262 |
| 2014-07-14 | 11:00 PM | 1.3 | 1.9 | 39 | -11.1 | 1054.70 | 78 | -1.5 | 1.3297 |
| 2014-07-14 | 11:30 PM | 0.5 | 1.6 | 40 | -11.6 | 1054.80 | 79 | -1.6 | 1.3312 |
| 2014-07-14 | 12:00 AM | -1 | 1.3 | 35 | -11.7 | 1054.50 | 79 | -1.9 | 1.3323 |
| 2014-07-14 | 12:30 AM | -2.2 | 0.1 | 62 | -8.5 | 1055.50 | 79 | -3.2 | 1.3404 |
| 2014-07-14 | 01:00 AM | -1.3 | -0.1 | 58 | -8.5 | 1055.60 | 80 | -3.1 | 1.341 |
| 2014-07-14 | 01:30 AM | -1.7 | -0.2 | 60 | -8.5 | 1055.60 | 80 | -3.2 | 1.3416 |
| 2014-07-14 | 02:00 AM | -1.9 | -0.4 | 60 | -8.6 | 1055.70 | 81 | -3.3 | 1.3429 |
| 2014-07-14 | 02:30 AM | -3.1 | -0.4 | 65 | -8.7 | 1055.70 | 80 | -3.5 | 1.3432 |
| 2014-07-14 | 03:00 AM | -3.1 | -0.7 | 66 | -8.6 | 1055.60 | 80 | -3.7 | 1.3443 |
| 2014-07-14 | 03:30 AM | -3.2 | -0.9 | 67 | -8.4 | 1055.40 | 80 | -3.9 | 1.3453 |
| 2014-07-14 | 04:00 AM | -3.1 | -1.1 | 68 | -8.1 | 1055.40 | 80 | -4.1 | 1.3461 |
| 2014-07-14 | 04:30 AM | -2.6 | -1.2 | 67 | -7.8 | 1055.10 | 80 | -4.2 | 1.3463 |
| 2014-07-14 | 05:00 AM | -3.5 | -1.3 | 69 | -8.4 | 1055.00 | 81 | -4.1 | 1.3468 |
| 2014-07-14 | 05:30 AM | -4.1 | -1.4 | 72 | -8.4 | 1055.00 | 81 | -4.3 | 1.3477 |
| 2014-07-14 | 06:00 AM | -4.4 | -1.6 | 70 | -9 | 1055.30 | 80 | -4.6 | 1.3487 |
| 2014-07-14 | 06:30 AM | -4.2 | -1.7 | 70 | -8.9 | 1055.70 | 80 | -4.7 | 1.3501 |

**Figure 79 - Summarized data.**

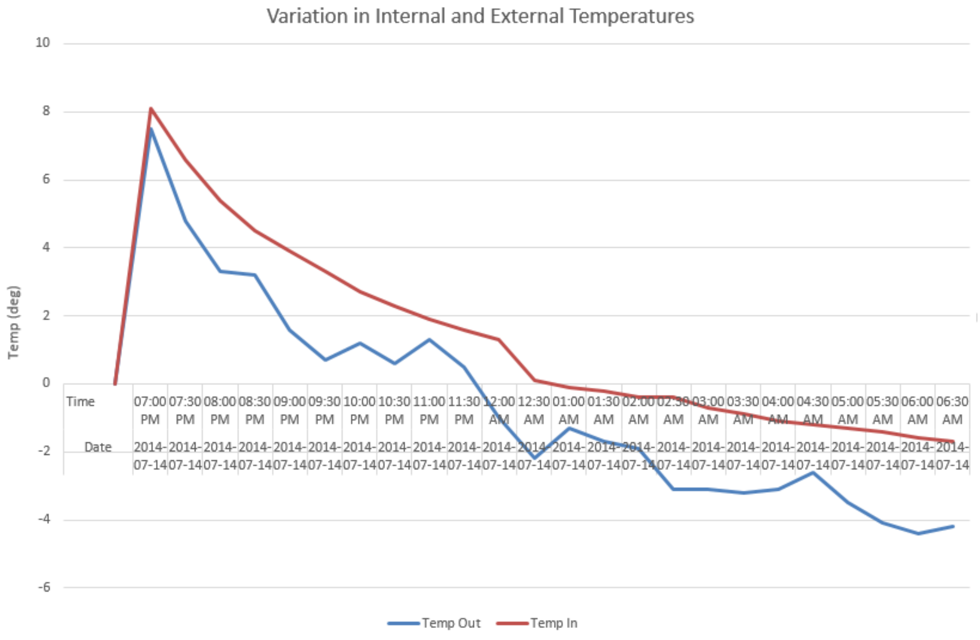


**Figure 80 - Variation in temperatures.**

To be able to determine the saturation enthalpy of the air-vapour mixture at the various temperatures in such a way that it can be used in a temperature model, the values of the enthalpy were plotted against the relevant temperatures and a mathematical model, based on the trend line, was created. An example of this is shown in Figure 81 below.

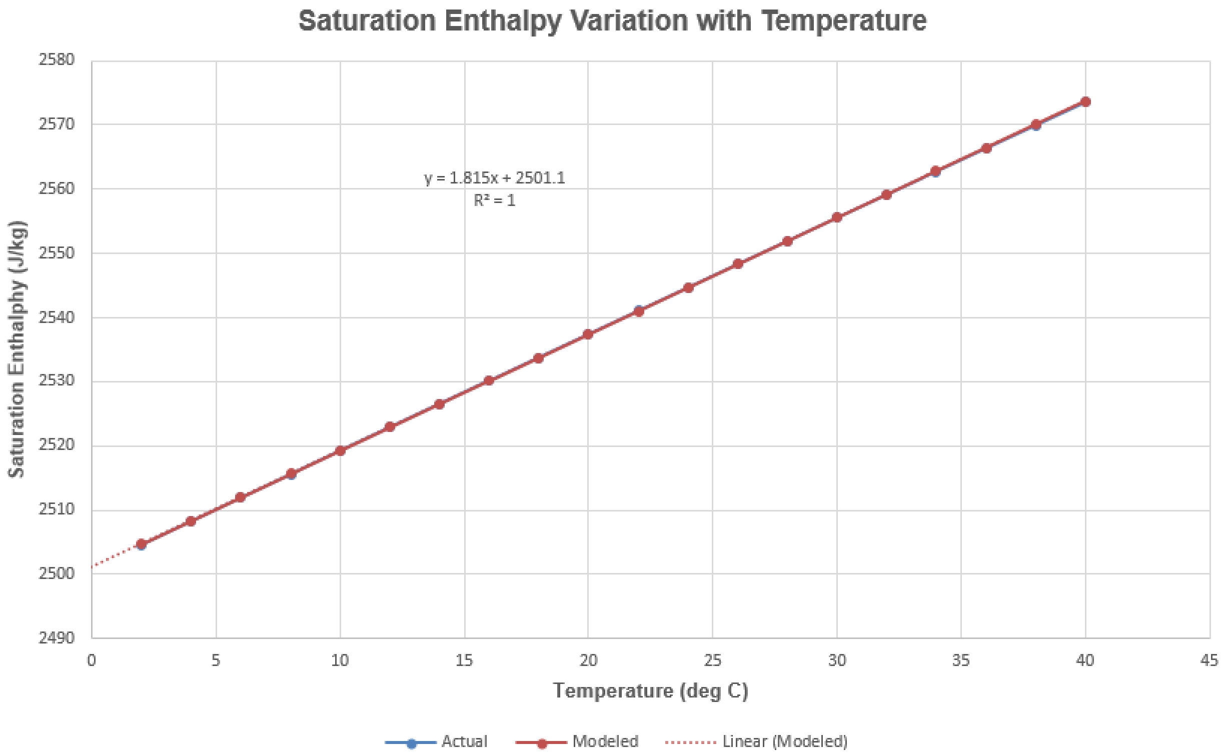


**Figure 81 - Variation in saturation enthalpy of air-vapour mixture.**

With all this data available, a transient night-time heating model, as shown in Figure 82 below, could then be created and used to determine the actual amount of heat that the greenhouse would need at the various time-steps. The required actual amount of heat as compared to the amount of heat that was available from the heating system is represented graphically in Figure 83 below. From the graph, as presented in Figure 83, the heating requirements of the greenhouse at the various stages, could be modelled numerically as presented by the dotted line.

| Time | Timestep | Temperature | | | Pressure | Radiatic | Radiatic | Conducti | Conducti | Convecti | Convection | Evaporation (Actual) | | | | | | Evaporation (Predicted) | | | | | Tot Loss | Tot Loss | Time | Heater | Add Heat Req | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | To | Ti | $T_{ideal}$ | | Qrad act | rad predi | $Q_{cond}$ | cond predi | Qconv | conv predi | RHin | Psd | Pw | ω | hg | Q evap | $P_{sd}$ | Pw | ω | hg | evap pre | Qlost | lost predi | Step | Qsuppl | Qreq | Solar | Q add req |
| | | (deg C) | deg C | deg C | kPa | (kW) | (kW) | (kW) | (kW) | (kW) | (kW) | (%) | kPa | kPa | (kg/kga) | (kJ/kg) | (kW) | kPa | kPa | (kg/kga) | (kJ/kg) | (kW) | (kW) | (kW) | | | (kW) | Fraction | (kJ) |
| 19:00:00 | 0.00 | 7.5 | 8.1 | 15.0 | 89.1 | 0.376 | 4.879 | 1.813 | 22.666 | 0.001 | 0.018 | 71.0 | 1003.8 | 712.7 | 0.005 | 2515.802 | 0.000 | 1499.6 | 1064.7 | 0.008 | 2528.325 | 0.000 | 2.191 | 27.563 | 1.0 | 1.176 | 26.387 | 4.457% | 47497 |
| 19:30:00 | 0.50 | 4.8 | 6.6 | 15.0 | 89.2 | 1.104 | 6.542 | 5.440 | 30.825 | 0.004 | 0.025 | 73.0 | 917.5 | 669.8 | 0.005 | 2513.079 | 0.372 | 1499.6 | 1094.7 | 0.008 | 2528.325 | -0.257 | 6.920 | 37.136 | 1.5 | 1.146 | 35.990 | 3.184% | 64781 |
| 20:00:00 | 1.00 | 3.3 | 5.4 | 15.0 | 89.2 | 1.269 | 7.446 | 6.346 | 35.358 | 0.005 | 0.029 | 74.0 | 853.3 | 631.4 | 0.004 | 2510.901 | 0.332 | 1499.6 | 1109.7 | 0.008 | 2528.325 | -0.126 | 7.953 | 42.707 | 2.0 | 1.116 | 41.591 | 2.683% | 74863 |
| 20:30:00 | 1.50 | 3.2 | 4.5 | 15.0 | 89.2 | 0.781 | 7.506 | 3.929 | 35.661 | 0.003 | 0.029 | 75.0 | 807.7 | 605.8 | 0.004 | 2509.268 | 0.221 | 1499.6 | 1124.7 | 0.008 | 2528.325 | -0.129 | 4.934 | 43.066 | 2.5 | 1.086 | 41.980 | 2.587% | 75564 |
| 21:00:00 | 2.00 | 1.6 | 3.9 | 15.0 | 89.2 | 1.366 | 8.452 | 6.951 | 40.496 | 0.006 | 0.033 | 76.0 | 778.5 | 591.7 | 0.004 | 2508.179 | 0.119 | 1499.6 | 1139.7 | 0.008 | 2528.325 | -0.135 | 8.441 | 48.846 | 3.0 | 1.056 | 47.790 | 2.209% | 86023 |
| 21:30:00 | 2.50 | 0.7 | 3.3 | 15.0 | 89.2 | 1.531 | 8.977 | 7.857 | 43.216 | 0.006 | 0.035 | 77.0 | 750.3 | 577.7 | 0.004 | 2507.090 | 0.120 | 1499.6 | 1154.7 | 0.008 | 2528.325 | -0.129 | 9.516 | 52.099 | 3.5 | 1.026 | 51.073 | 2.008% | 91932 |
| 22:00:00 | 3.00 | 1.2 | 2.7 | 15.0 | 89.2 | 0.883 | 8.686 | 4.533 | 41.705 | 0.004 | 0.034 | 77.0 | 723.0 | 556.7 | 0.004 | 2506.001 | 0.181 | 1499.6 | 1154.7 | 0.008 | 2528.325 | 0.003 | 5.601 | 50.428 | 4.0 | 0.996 | 49.432 | 2.014% | 88977 |
| 22:30:00 | 3.50 | 0.6 | 2.3 | 15.0 | 89.2 | 0.995 | 9.035 | 5.138 | 43.518 | 0.004 | 0.035 | 78.0 | 705.3 | 550.1 | 0.004 | 2505.275 | 0.057 | 1499.6 | 1169.7 | 0.008 | 2528.325 | -0.129 | 6.194 | 52.460 | 4.5 | 0.966 | 51.494 | 1.875% | 92689 |
| 23:00:00 | 4.00 | 1.3 | 1.9 | 15.0 | 89.3 | 0.352 | 8.628 | 1.813 | 41.402 | 0.001 | 0.034 | 78.0 | 687.9 | 536.6 | 0.004 | 2504.549 | 0.119 | 1499.6 | 1169.7 | 0.008 | 2528.325 | 0.009 | 2.286 | 50.073 | 5.0 | 0.936 | 49.137 | 1.904% | 88447 |
| 23:30:00 | 4.50 | 0.5 | 1.6 | 15.0 | 89.3 | 0.641 | 9.093 | 3.324 | 43.820 | 0.003 | 0.036 | 79.0 | 675.2 | 533.4 | 0.004 | 2504.004 | 0.028 | 1499.6 | 1184.7 | 0.008 | 2528.325 | -0.130 | 3.996 | 52.819 | 5.5 | 0.906 | 51.914 | 1.744% | 93445 |
| 00:00:00 | 5.00 | -1.0 | 1.3 | 15.0 | 89.3 | 1.328 | 9.955 | 6.951 | 48.353 | 0.006 | 0.039 | 79.0 | 662.6 | 523.5 | 0.004 | 2503.460 | 0.083 | 1499.6 | 1184.7 | 0.008 | 2528.325 | -0.003 | 8.367 | 58.345 | 6.0 | 0.876 | 57.469 | 1.523% | 103445 |
| 00:30:00 | 5.50 | -2.2 | 0.1 | 15.0 | 89.4 | 1.310 | 10.635 | 6.951 | 51.980 | 0.006 | 0.042 | 79.0 | 614.5 | 485.4 | 0.003 | 2501.282 | 0.328 | 1499.6 | 1184.7 | 0.008 | 2528.325 | 0.010 | 8.594 | 62.666 | 6.5 | 0.845 | 61.821 | 1.368% | 111278 |
| 01:00:00 | 6.00 | -1.3 | -0.1 | 15.0 | 89.4 | 0.686 | 10.126 | 3.626 | 49.260 | 0.003 | 0.040 | 80.0 | 606.8 | 485.4 | 0.003 | 2500.919 | 0.001 | 1499.6 | 1199.7 | 0.008 | 2528.325 | -0.130 | 4.316 | 59.296 | 7.0 | 0.815 | 58.481 | 1.394% | 105265 |
| 01:30:00 | 6.50 | -1.7 | -0.2 | 15.0 | 89.4 | 0.855 | 10.353 | 4.533 | 50.469 | 0.004 | 0.041 | 80.0 | 602.9 | 482.3 | 0.003 | 2500.737 | 0.026 | 1499.6 | 1199.7 | 0.008 | 2528.325 | 0.000 | 5.418 | 60.862 | 7.5 | 0.785 | 60.077 | 1.307% | 108139 |
| 02:00:00 | 7.00 | -1.9 | -0.4 | 15.0 | 89.4 | 0.853 | 10.466 | 4.533 | 51.073 | 0.004 | 0.042 | 81.0 | 595.3 | 482.2 | 0.003 | 2500.374 | 0.001 | 1499.6 | 1214.7 | 0.009 | 2528.325 | -0.130 | 5.392 | 61.450 | 8.0 | 0.755 | 60.695 | 1.244% | 109251 |
| 02:30:00 | 7.50 | -3.1 | -0.4 | 15.0 | 89.4 | 1.526 | 11.138 | 8.160 | 54.700 | 0.007 | 0.045 | 80.0 | 595.3 | 476.3 | 0.003 | 2500.374 | 0.051 | 1499.6 | 1199.7 | 0.008 | 2528.325 | 0.131 | 9.743 | 66.013 | 8.5 | 0.725 | 65.288 | 1.111% | 117518 |
| 03:00:00 | 8.00 | -3.1 | -0.7 | 15.0 | 89.4 | 1.354 | 11.138 | 7.253 | 54.700 | 0.006 | 0.045 | 80.0 | 584.1 | 467.3 | 0.003 | 2499.830 | 0.076 | 1499.6 | 1199.7 | 0.008 | 2528.325 | -0.001 | 8.689 | 65.881 | 9.0 | 0.695 | 65.186 | 1.066% | 117335 |
| 03:30:00 | 8.50 | -3.2 | -0.9 | 15.0 | 89.4 | 1.296 | 11.194 | 6.951 | 55.002 | 0.006 | 0.045 | 80.0 | 576.7 | 461.4 | 0.003 | 2499.467 | 0.049 | 1499.6 | 1199.7 | 0.008 | 2528.325 | -0.002 | 8.301 | 66.239 | 9.5 | 0.665 | 65.573 | 1.014% | 118032 |
| 04:00:00 | 9.00 | -3.1 | -1.1 | 15.0 | 89.4 | 1.126 | 11.138 | 6.044 | 54.700 | 0.005 | 0.045 | 80.0 | 569.4 | 455.6 | 0.003 | 2499.104 | 0.050 | 1499.6 | 1199.7 | 0.008 | 2528.325 | 0.000 | 7.225 | 65.882 | 10.0 | 0.635 | 65.247 | 0.973% | 117445 |
| 04:30:00 | 9.50 | -2.6 | -1.2 | 15.0 | 89.3 | 0.790 | 10.859 | 4.231 | 53.189 | 0.003 | 0.043 | 80.0 | 565.8 | 452.7 | 0.003 | 2498.922 | 0.023 | 1499.6 | 1199.7 | 0.008 | 2528.325 | -0.003 | 5.048 | 64.088 | 10.5 | 0.605 | 63.483 | 0.953% | 114269 |
| 05:00:00 | 10.00 | -3.5 | -1.3 | 15.0 | 89.3 | 1.235 | 11.360 | 6.649 | 55.908 | 0.005 | 0.046 | 81.0 | 562.2 | 455.4 | 0.003 | 2498.741 | -0.024 | 1499.6 | 1214.7 | 0.009 | 2528.325 | -0.132 | 7.865 | 67.183 | 11.0 | 0.575 | 66.608 | 0.863% | 119894 |
| 05:30:00 | 10.50 | -4.1 | -1.4 | 15.0 | 89.3 | 1.509 | 11.692 | 8.160 | 57.722 | 0.007 | 0.047 | 81.0 | 558.6 | 452.5 | 0.003 | 2498.559 | 0.025 | 1499.6 | 1214.7 | 0.009 | 2528.325 | 0.000 | 9.700 | 69.461 | 11.5 | 0.545 | 68.916 | 0.791% | 124048 |
| 06:00:00 | 11.00 | -4.4 | -1.6 | 15.0 | 89.4 | 1.561 | 11.857 | 8.462 | 58.628 | 0.007 | 0.048 | 80.0 | 551.6 | 441.2 | 0.003 | 2498.196 | 0.097 | 1499.6 | 1199.7 | 0.008 | 2528.325 | 0.134 | 10.126 | 70.667 | 12.0 | 0.515 | 70.152 | 0.734% | 126274 |
| 06:30:00 | 11.50 | -4.2 | -1.7 | 15.0 | 89.4 | 1.394 | 11.747 | 7.555 | 58.024 | 0.006 | 0.047 | 80.0 | 548.0 | 438.4 | 0.003 | 2498.015 | 0.025 | 1499.6 | 1199.7 | 0.008 | 2528.325 | 0.004 | 8.981 | 69.822 | 12.5 | 0.485 | 69.337 | 0.699% | 124807 |

**Figure 82 - Transient night-time heating model.**

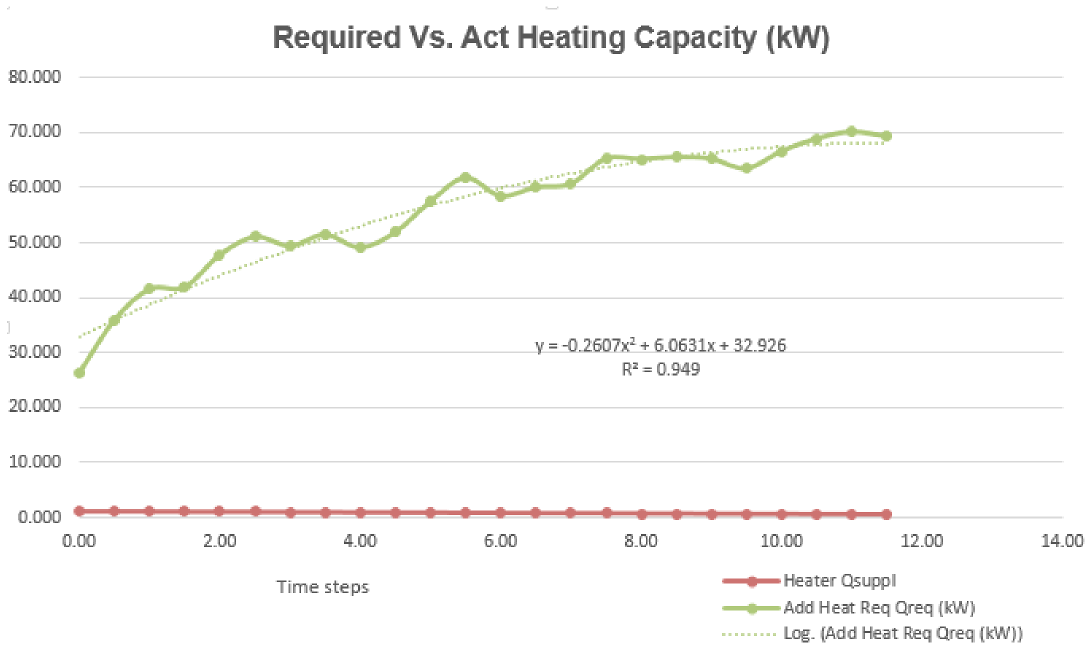


**Figure 83 - Heating Requirements.**

With the heat requirements known, the size and exchange rate of the source could then be modelled, as shown in Figures 84 and 85.

**Required Water Heating System Capacity**

| | |
|---|---|
| Vol water (l) | 45000 |
| Cpwater (J/kgK) | 4183 |
| Time Inteval (s) | 3600 |
| Efficiency | 40.00% |
| T initial | 70 |
| Date | 14 July 2014 |
| Available Ins (kWh/day/m^2) | 3.32 |
| Area Req (m^2) | 706 |

| Time | Hour nr. | Time Step | Q req (kW) | Q req (kJ) | ΔT req (deg) | T2 water (deg) | Temp Grad (deg) |
|---|---|---|---|---|---|---|---|
| 18:30:00 | 0.00 | 1 | 38.947 | 1.402.E+05 | 1.862 | 68.138 | 53.138 |
| 19:30:00 | 1.00 | 2 | 45.690 | 1.645.E+05 | 2.185 | 65.953 | 50.953 |
| 20:30:00 | 2.00 | 3 | 51.823 | 1.866.E+05 | 2.478 | 63.475 | 48.475 |
| 21:30:00 | 3.00 | 4 | 57.348 | 2.065.E+05 | 2.742 | 60.734 | 45.734 |
| 22:30:00 | 4.00 | 5 | 62.263 | 2.241.E+05 | 2.977 | 57.757 | 42.757 |
| 23:30:00 | 5.00 | 6 | 66.569 | 2.396.E+05 | 3.183 | 54.574 | 39.574 |
| 00:30:00 | 6.00 | 7 | 70.266 | 2.530.E+05 | 3.360 | 51.214 | 36.214 |
| 01:30:00 | 7.00 | 8 | 73.353 | 2.641.E+05 | 3.507 | 47.707 | 32.707 |
| 02:30:00 | 8.00 | 9 | 75.832 | 2.730.E+05 | 3.626 | 44.081 | 29.081 |
| 03:30:00 | 9.00 | 10 | 77.701 | 2.797.E+05 | 3.715 | 40.366 | 25.366 |
| 04:30:00 | 10.00 | 11 | 78.961 | 2.843.E+05 | 3.775 | 36.591 | 21.591 |
| 05:30:00 | 11.00 | 12 | 79.612 | 2.866.E+05 | 3.806 | 32.784 | 17.784 |
| 06:30:00 | 12.00 | 13 | 79.653 | 2.868.E+05 | 3.808 | 28.976 | 13.976 |
| 07:30:00 | 13.00 | 14 | 79.086 | 2.847.E+05 | 3.781 | 25.195 | 10.195 |
| Total Amount of Heat Required | | | | 3.374.E+06 | | | |

**Figure 84 - Determining the heating requirements.**

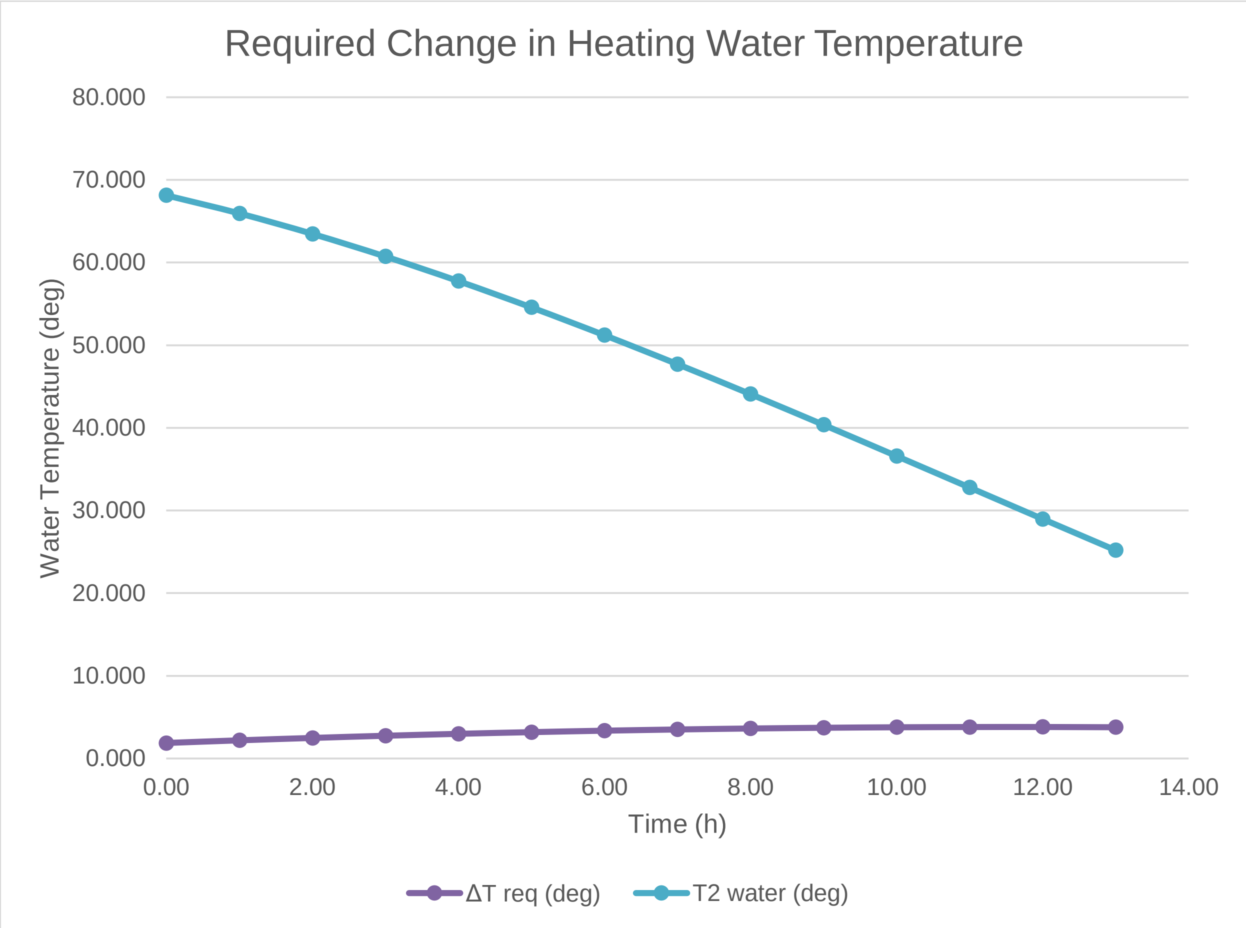


**Figure 85 - Required change in heating water temperature.**

# 9. ADDENDUM C - DAY-TIME VENTILATION MODEL

A day-time ventilation model was also created to determine the required rate of ventilation needed by the greenhouse. Raw data was collected from the weather station and summarized, as shown in Figure 86.

**Day Time Data (Summarized)**

| Date | Time | Temp Out (deg) | Hi Temp (deg) | Low Temp (deg) | Out Hum (%) | Dew Pt. (deg) | Wind Speed (km/h) | Wind Chill (deg) | Heat Index | Pressure (mBar) | In Temp (deg) | In Hum (%) | In Dew (deg) | In Heat | In EMC | In Air Density (kg/m^3) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2014-07-14 | 07:00 AM | -4 | -3.8 | -4.3 | 70 | -8.7 | 0 | -4 | -4.2 | 1055.90 | -1.9 | 80 | -4.9 | -2.1 | -2.1 | 1.3513 |
| 2014-07-14 | 07:30 AM | -2.1 | -2.1 | -4.1 | 67 | -7.4 | 0 | -2.1 | -2.3 | 1056.10 | -1.6 | 81 | -4.4 | -1.7 | -1.7 | 1.3497 |
| 2014-07-14 | 08:00 AM | 0.9 | 0.9 | -2 | 57 | -6.6 | 0 | 0.9 | 0.5 | 1055.70 | 2.7 | 83 | 0.1 | 2.6 | 17.65 | 1.326 |
| 2014-07-14 | 08:30 AM | 3.4 | 3.4 | 1 | 53 | -5.3 | 0 | 3.4 | 2.9 | 1055.00 | 8.2 | 83 | 5.5 | 8.1 | 17.62 | 1.296 |
| 2014-07-14 | 09:00 AM | 6.6 | 6.6 | 3.4 | 43 | -5.1 | 0 | 6.6 | 5.9 | 1054.70 | 13.1 | 78 | 9.3 | 12.8 | 15.74 | 1.2702 |
| 2014-07-14 | 09:30 AM | 8.3 | 8.3 | 6.6 | 39 | -4.9 | 0 | 8.3 | 7.4 | 1054.20 | 16.8 | 72 | 11.8 | 16.7 | 13.75 | 1.2505 |
| 2014-07-14 | 10:00 AM | 11.9 | 11.9 | 8.3 | 33 | -3.9 | 0 | 11.9 | 10.5 | 1053.70 | 20.3 | 65 | 13.5 | 20.3 | 11.88 | 1.233 |
| 2014-07-14 | 10:30 AM | 14 | 14.2 | 11.9 | 28 | -4.3 | 1.6 | 14 | 12.1 | 1053.20 | 23.7 | 59 | 15.2 | 24.1 | 10.77 | 1.2165 |
| 2014-07-14 | 11:00 AM | 14.9 | 15.1 | 14 | 25 | -4.9 | 1.6 | 14.9 | 12.7 | 1053.40 | 26.2 | 53 | 15.9 | 26.4 | 9.65 | 1.2054 |
| 2014-07-14 | 11:30 AM | 15.9 | 16.2 | 14.9 | 22 | -5.8 | 1.6 | 15.9 | 13.4 | 1053.00 | 28.2 | 49 | 16.5 | 28.7 | 8.89 | 1.1961 |
| 2014-07-14 | 12:00 PM | 16.7 | 16.9 | 15.9 | 20 | -6.4 | 1.6 | 16.7 | 14.1 | 1052.60 | 29.7 | 45 | 16.5 | 30.3 | 8.24 | 1.1897 |
| 2014-07-14 | 12:30 PM | 17.1 | 17.2 | 16.7 | 19 | -6.7 | 1.6 | 17.1 | 14.3 | 1052.00 | 30.5 | 42 | 16.1 | 30.9 | 7.81 | 1.1866 |
| 2014-07-14 | 01:00 PM | 17.6 | 17.6 | 16.7 | 17 | -7.8 | 1.6 | 17.6 | 14.7 | 1051.50 | 30.9 | 38 | 14.9 | 30.7 | 7.2 | 1.186 |
| 2014-07-14 | 01:30 PM | 18.1 | 18.3 | 17.5 | 16 | -8.1 | 1.6 | 18.1 | 15.2 | 1050.80 | 30.8 | 38 | 14.8 | 30.7 | 7.2 | 1.1858 |
| 2014-07-14 | 02:00 PM | 18.1 | 18.1 | 17.6 | 15 | -9 | 1.6 | 18.1 | 15.1 | 1050.70 | 29.9 | 39 | 14.5 | 29.9 | 7.33 | 1.1893 |
| 2014-07-14 | 02:30 PM | 17.7 | 18.1 | 17.4 | 15 | -9.3 | 3.2 | 17.7 | 14.7 | 1050.70 | 28.7 | 41 | 14.2 | 28.9 | 7.68 | 1.1946 |
| 2014-07-14 | 03:00 PM | 17.7 | 18.2 | 17.7 | 14 | -10.2 | 1.6 | 17.7 | 14.7 | 1050.60 | 27.3 | 37 | 11.4 | 26.6 | 7.13 | 1.2031 |
| 2014-07-14 | 03:30 PM | 18.2 | 18.4 | 17.7 | 13 | -10.7 | 1.6 | 18.2 | 15.1 | 1050.40 | 25.3 | 42 | 11.5 | 24.9 | 7.9 | 1.2107 |
| 2014-07-14 | 04:00 PM | 18.1 | 18.6 | 18.1 | 13 | -10.8 | 1.6 | 18.1 | 15.1 | 1050.50 | 23.3 | 45 | 10.7 | 23 | 8.45 | 1.2199 |
| 2014-07-14 | 04:30 PM | 17.7 | 18.1 | 17.6 | 14 | -10.2 | 1.6 | 17.7 | 14.7 | 1050.60 | 21.3 | 54 | 11.6 | 20.6 | 9.94 | 1.2273 |
| 2014-07-14 | 05:00 PM | 17.6 | 17.7 | 17.4 | 14 | -10.3 | 0 | 17.6 | 14.6 | 1050.70 | 19.3 | 63 | 12.1 | 19.2 | 11.61 | 1.2353 |
| 2014-07-14 | 05:30 PM | 15.4 | 17.6 | 15.4 | 17 | -9.6 | 0 | 15.4 | 12.8 | 1051.00 | 16.6 | 66 | 10.2 | 16.2 | 12.28 | 1.2495 |
| 2014-07-14 | 06:00 PM | 12.7 | 15.4 | 12.7 | 20 | -9.8 | 0 | 12.7 | 10.7 | 1051.40 | 12.7 | 68 | 7 | 12.2 | 12.95 | 1.2698 |
| 2014-07-14 | 06:30 PM | 9.7 | 12.7 | 9.7 | 25 | -9.4 | 0 | 9.7 | 8.6 | 1052.00 | 10 | 70 | 4.8 | 9.8 | 13.35 | 1.2843 |
| 2014-07-14 | 07:00 PM | 7.5 | 9.8 | 7.5 | 28 | -9.9 | 0 | 7.5 | 6.5 | 1052.30 | 8.1 | 71 | 3.1 | 7.8 | 13.58 | 1.2949 |

**Figure 86 - Summarized day-time data.**

In similar fashion, a simple numerical model was created for the saturation enthalpy, as shown in Figure 87. With all the relevant data available and considering all the mechanisms of heat gains and losses, a transient ventilation model could then be developed, as shown in Figure 88. With the transient heating model in place the actual versus required rate of ventilation for the greenhouse could then be determined, as shown in Figures 89 and 90.

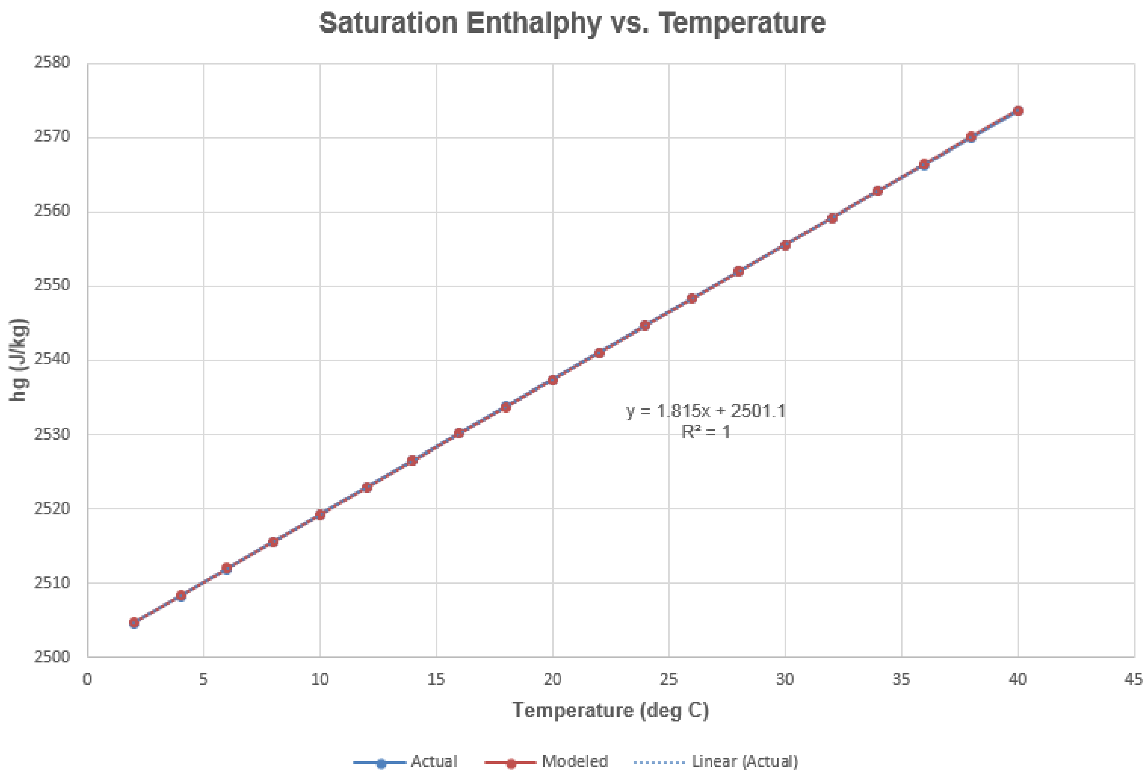


**Figure 87 - Modelling the saturation enthalpy.**

## Greenhouse Day Time Ventilation Model

| | |
|---|---|
| τc | 0.8 |
| αg | 0.06 |
| Aplant (m^2) | 147.6 |
| Vi (m^3) | 864 |
| k (W/m^2K) | 6.2 |
| Aglazing (m^2) | 472.4 |
| Afloor (m^2) | 240 |
| Cpair (J/kgK) | 1005.7 |
| Cpwater | 4.183 |
| ρair (kg/m^3) | 1.225 |
| Time Inteval (s) | 1800 |
| Mwater | 3000 |
| Longitude (deg) | 29.117 |
| Date | ####### |

| Time | Timestep | | Temperatur | | Pressure | Radiation | | Conduction | | Relative Humi | | Latent Energy of Evaporatio | | | | | | | | Latent Energy of Evaporation (ideal) | | | | | | | | Ventilation | | Actual Rate of Ventil | | | Required Rate of Ventilation | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | To | Ti act | Tideal | | Qgr | Qgr in | cond ac | cond ide | RH out | RH in | Psd1 | Psd2 | Pv1 | Pv2 | ω1 | ω2 | hg | Ql | Psd1 | Psd2 | Pv1 | Pv2 | ω1 | ω2 | hg | Ql | Q act | Q ideal | qv act | qv act | m act | qv act | qv act | m act |
| | | (deg C) | deg C | deg C | kPa | (W/m^2) | (kW) | (kW) | (kW) | (%) | (%) | (Pa) | (Pa) | (Pa) | (Pa) | (kg/kga | kg/kga | (kJ/kg) | (kJ/kg) | (Pa) | (Pa) | (Pa) | (Pa) | (kg/kga | (kg/kga) | (kJ/kg) | (kJ/kg) | (kJ/kg) | (kJ/kg) | (m^3/s) | exch/min | (kg/s) | (m^3/s) | exch/min | (kg/s) |
| 07:00:00 | 0.00 | -4.0 | -1.9 | 12.0 | 89.4 | 5 | 0.9 | 6.2 | 46.9 | 70.0 | 80.0 | 454.1 | 531.2 | 317.9 | 424.9 | 0.004 | 0.005 | 2498 | 3.001 | 454.1 | 1402.1 | 317.9 | 1121.7 | 0.004 | 0.013 | 2523 | 23.049 | 2.112 | 16.091 | -0.83 | -0.058 | -1.022 | -0.96 | -0.067 | -1.174 |
| 07:30:00 | 0.50 | -2.1 | -1.6 | 12.0 | 89.4 | 254 | 48.7 | 1.5 | 41.3 | 67.0 | 81.0 | 523.3 | 543.1 | 350.6 | 439.9 | 0.004 | 0.005 | 2498 | 2.496 | 523.3 | 1402.3 | 350.6 | 1135.9 | 0.004 | 0.013 | 2523 | 22.525 | 0.503 | 14.183 | 12.85 | 0.893 | 15.745 | 0.16 | 0.011 | 0.201 |
| 08:00:00 | 1.00 | 0.9 | 2.7 | 12.3 | 89.4 | 495 | 95.1 | 5.3 | 33.5 | 57.0 | 83.0 | 651.8 | 741.5 | 371.5 | 615.5 | 0.004 | 0.007 | 2506 | 6.882 | 651.8 | 1432.8 | 371.5 | 1189.2 | 0.004 | 0.013 | 2524 | 23.495 | 1.810 | 11.494 | 8.43 | 0.586 | 10.330 | 1.44 | 0.100 | 1.760 |
| 08:30:00 | 1.50 | 3.4 | 8.2 | 13.4 | 89.3 | 650 | 124.8 | 14.1 | 29.3 | 53.0 | 83.0 | 779.3 | 1087.1 | 413.0 | 902.3 | 0.005 | 0.010 | 2516 | 13.936 | 779.3 | 1536.7 | 413.0 | 1275.5 | 0.005 | 0.014 | 2528 | 24.871 | 4.827 | 10.055 | 4.82 | 0.334 | 5.899 | 2.23 | 0.155 | 2.733 |
| 09:00:00 | 2.00 | 6.6 | 13.1 | 15.1 | 89.3 | 750 | 144.1 | 19.0 | 24.9 | 43.0 | 78.0 | 974.4 | 1507.1 | 419.0 | 1175.5 | 0.005 | 0.013 | 2525 | 21.700 | 974.4 | 1716.5 | 419.0 | 1338.9 | 0.005 | 0.015 | 2534 | 26.623 | 6.537 | 8.555 | 3.62 | 0.251 | 4.428 | 2.77 | 0.192 | 3.388 |
| 09:30:00 | 2.50 | 8.3 | 16.8 | 17.3 | 89.3 | 818 | 157.1 | 24.9 | 26.3 | 39.0 | 72.0 | 1094.5 | 1912.7 | 426.9 | 1377.1 | 0.005 | 0.016 | 2532 | 27.409 | 1094.5 | 1972.9 | 426.9 | 1420.5 | 0.005 | 0.016 | 2542 | 28.889 | 8.548 | 9.041 | 3.00 | 0.208 | 3.677 | 2.81 | 0.195 | 3.448 |
| 10:00:00 | 3.00 | 11.9 | 20.3 | 19.7 | 89.2 | 865 | 166.1 | 24.6 | 22.9 | 33.0 | 65.0 | 1392.9 | 2381.3 | 459.7 | 1547.8 | 0.005 | 0.018 | 2538 | 31.520 | 1392.9 | 2239.4 | 459.7 | 1494.6 | 0.005 | 0.017 | 2551 | 30.247 | 8.448 | 7.879 | 2.89 | 0.201 | 3.540 | 3.06 | 0.213 | 3.754 |
| 10:30:00 | 3.50 | 14.0 | 23.7 | 22.2 | 89.2 | 897 | 172.2 | 28.4 | 24.0 | 28.0 | 59.0 | 1598.1 | 2929.6 | 447.5 | 1728.5 | 0.005 | 0.020 | 2544 | 37.283 | 1598.1 | 2676.4 | 447.5 | 1579.1 | 0.005 | 0.018 | 2560 | 33.231 | 9.755 | 8.252 | 2.49 | 0.173 | 3.056 | 2.92 | 0.202 | 3.571 |
| 11:00:00 | 4.00 | 14.9 | 26.2 | 24.5 | 89.2 | 917 | 176.1 | 33.1 | 28.0 | 25.0 | 53.0 | 1693.8 | 3400.3 | 423.5 | 1802.1 | 0.005 | 0.021 | 2549 | 40.217 | 1693.8 | 3066.8 | 423.5 | 1625.4 | 0.005 | 0.019 | 2568 | 35.413 | 11.364 | 9.617 | 2.26 | 0.157 | 2.773 | 2.69 | 0.186 | 3.290 |
| 11:30:00 | 4.50 | 15.9 | 28.2 | 26.3 | 89.2 | 929 | 178.4 | 36.0 | 30.4 | 22.0 | 49.0 | 1806.1 | 3822.9 | 397.3 | 1873.2 | 0.005 | 0.021 | 2552 | 43.158 | 1806.1 | 3418.0 | 397.3 | 1674.8 | 0.004 | 0.019 | 2575 | 37.760 | 12.370 | 10.447 | 2.09 | 0.145 | 2.564 | 2.51 | 0.174 | 3.069 |
| 12:00:00 | 5.00 | 16.7 | 29.7 | 27.5 | 89.1 | 933 | 179.1 | 38.1 | 31.6 | 20.0 | 45.0 | 1900.6 | 4169.2 | 380.1 | 1876.2 | 0.004 | 0.022 | 2555 | 43.801 | 1900.6 | 3670.9 | 380.1 | 1651.9 | 0.004 | 0.019 | 2579 | 37.654 | 13.074 | 10.866 | 2.02 | 0.141 | 2.480 | 2.48 | 0.172 | 3.039 |
| 12:30:00 | 5.50 | 17.1 | 30.5 | 28.0 | 89.1 | 929 | 178.4 | 39.2 | 31.9 | 19.0 | 42.0 | 1949.4 | 4364.8 | 370.4 | 1833.2 | 0.004 | 0.021 | 2556 | 42.846 | 1949.4 | 3777.2 | 370.4 | 1586.4 | 0.004 | 0.018 | 2581 | 36.018 | 13.476 | 10.955 | 2.02 | 0.140 | 2.470 | 2.55 | 0.177 | 3.118 |
| 13:00:00 | 6.00 | 17.6 | 30.9 | 27.7 | 89.0 | 917 | 176.1 | 39.0 | 29.6 | 17.0 | 38.0 | 2012.0 | 4465.6 | 342.0 | 1696.9 | 0.004 | 0.019 | 2557 | 39.630 | 2012.0 | 3714.9 | 342.0 | 1411.7 | 0.004 | 0.016 | 2580 | 31.611 | 13.376 | 10.166 | 2.11 | 0.147 | 2.588 | 2.86 | 0.199 | 3.508 |
| 13:30:00 | 6.50 | 18.1 | 30.8 | 26.7 | 89.0 | 897 | 172.2 | 37.2 | 25.1 | 16.0 | 38.0 | 2076.3 | 4440.2 | 332.2 | 1687.3 | 0.004 | 0.019 | 2557 | 39.647 | 2076.3 | 3497.0 | 332.2 | 1328.9 | 0.004 | 0.015 | 2576 | 29.401 | 12.772 | 8.625 | 2.10 | 0.146 | 2.575 | 3.16 | 0.219 | 3.867 |
| 14:00:00 | 7.00 | 18.1 | 29.9 | 25.0 | 89.0 | 865 | 166.1 | 34.6 | 20.2 | 15.0 | 39.0 | 2076.3 | 4217.4 | 311.4 | 1644.8 | 0.004 | 0.019 | 2555 | 38.969 | 2076.3 | 3166.3 | 311.4 | 1234.9 | 0.004 | 0.014 | 2570 | 27.143 | 11.867 | 6.937 | 2.11 | 0.147 | 2.587 | 3.49 | 0.243 | 4.280 |
| 14:30:00 | 7.50 | 17.7 | 28.7 | 22.8 | 89.0 | 818 | 157.1 | 32.2 | 15.0 | 15.0 | 41.0 | 2024.7 | 3935.5 | 303.7 | 1613.5 | 0.003 | 0.018 | 2553 | 38.238 | 2024.7 | 2780.7 | 303.7 | 1140.1 | 0.003 | 0.013 | 2562 | 24.480 | 11.063 | 5.165 | 2.07 | 0.144 | 2.534 | 3.91 | 0.272 | 4.793 |
| 15:00:00 | 8.00 | 17.7 | 27.3 | 20.4 | 89.0 | 750 | 144.1 | 28.1 | 7.9 | 14.0 | 37.0 | 2024.7 | 3627.4 | 283.5 | 1342.1 | 0.003 | 0.015 | 2551 | 30.751 | 2024.7 | 2395.7 | 283.5 | 886.4 | 0.003 | 0.010 | 2553 | 17.535 | 9.655 | 2.713 | 2.34 | 0.163 | 2.870 | 5.49 | 0.381 | 6.726 |
| 15:30:00 | 8.50 | 18.2 | 25.3 | 17.9 | 89.0 | 650 | 124.8 | 20.8 | -0.8 | 13.0 | 42.0 | 2089.4 | 3223.8 | 271.6 | 1354.0 | 0.003 | 0.015 | 2547 | 31.404 | 2089.4 | 2053.3 | 271.6 | 862.4 | 0.003 | 0.010 | 2544 | 17.115 | 7.140 | -0.279 | 2.20 | 0.153 | 2.697 | 6.09 | 0.423 | 7.458 |
| 16:00:00 | 9.00 | 18.1 | 23.3 | 15.6 | 89.0 | 495 | 95.1 | 15.2 | -7.2 | 13.0 | 45.0 | 2076.3 | 2859.9 | 269.9 | 1286.9 | 0.003 | 0.015 | 2543 | 29.433 | 2076.3 | 1777.2 | 269.9 | 799.7 | 0.003 | 0.009 | 2536 | 15.288 | 5.230 | -2.466 | 1.88 | 0.131 | 2.303 | 6.51 | 0.452 | 7.974 |
| 16:30:00 | 9.50 | 17.7 | 21.3 | 13.8 | 89.0 | 254 | 48.7 | 10.5 | -11.4 | 14.0 | 54.0 | 2024.7 | 2532.4 | 283.5 | 1367.5 | 0.003 | 0.016 | 2540 | 31.366 | 2024.7 | 1576.9 | 283.5 | 851.5 | 0.003 | 0.010 | 2529 | 16.359 | 3.621 | -3.927 | 0.89 | 0.062 | 1.090 | 3.95 | 0.274 | 4.836 |
| 17:00:00 | 10.00 | 17.6 | 19.3 | 12.5 | 89.0 | 5 | 0.9 | 5.0 | -14.8 | 14.0 | 63.0 | 2012.0 | 2238.1 | 281.7 | 1410.0 | 0.003 | 0.016 | 2536 | 32.623 | 2012.0 | 1453.1 | 281.7 | 915.5 | 0.003 | 0.010 | 2525 | 18.229 | 1.710 | -5.086 | -0.10 | -0.007 | -0.118 | 0.98 | 0.068 | 1.197 |
| 17:30:00 | 10.50 | 15.4 | 16.6 | 12.0 | 89.0 | 0 | 0.0 | 3.5 | -9.9 | 17.0 | 66.0 | 1749.2 | 1888.5 | 297.4 | 1246.4 | 0.003 | 0.014 | 2531 | 27.326 | 1749.2 | 1403.4 | 297.4 | 926.2 | 0.003 | 0.011 | 2523 | 18.074 | 1.207 | -3.406 | -0.10 | -0.007 | -0.123 | 0.55 | 0.038 | 0.676 |
| 18:00:00 | 11.00 | 12.7 | 12.7 | 12.0 | 89.0 | 0 | 0.0 | 0.0 | -2.1 | 20.0 | 68.0 | 1468.1 | 1468.1 | 293.6 | 998.3 | 0.003 | 0.011 | 2524 | 20.160 | 1468.1 | 1402.1 | 293.6 | 953.4 | 0.003 | 0.011 | 2523 | 18.961 | 0.000 | -0.704 | 0.00 | 0.000 | 0.000 | 0.09 | 0.006 | 0.112 |
| 18:30:00 | 11.50 | 9.7 | 10.0 | 12.0 | 89.1 | 0 | 0.0 | 0.9 | 6.7 | 25.0 | 70.0 | 1203.1 | 1227.6 | 300.8 | 859.3 | 0.003 | 0.010 | 2519 | 15.914 | 1203.1 | 1402.1 | 300.8 | 981.5 | 0.003 | 0.011 | 2523 | 19.558 | 0.302 | 2.313 | -0.04 | -0.003 | -0.054 | -0.25 | -0.017 | -0.308 |
| 19:00:00 | 12.00 | 7.5 | 8.1 | 12.0 | 89.1 | 0 | 0.0 | 1.8 | 13.2 | 28.0 | 71.0 | 1036.4 | 1079.7 | 290.2 | 766.6 | 0.003 | 0.009 | 2516 | 13.541 | 1036.4 | 1402.1 | 290.2 | 995.5 | 0.003 | 0.011 | 2523 | 20.259 | 0.603 | 4.526 | -0.10 | -0.007 | -0.124 | -0.43 | -0.030 | -0.532 |

**Figure 88 - Day-time ventilation model.**

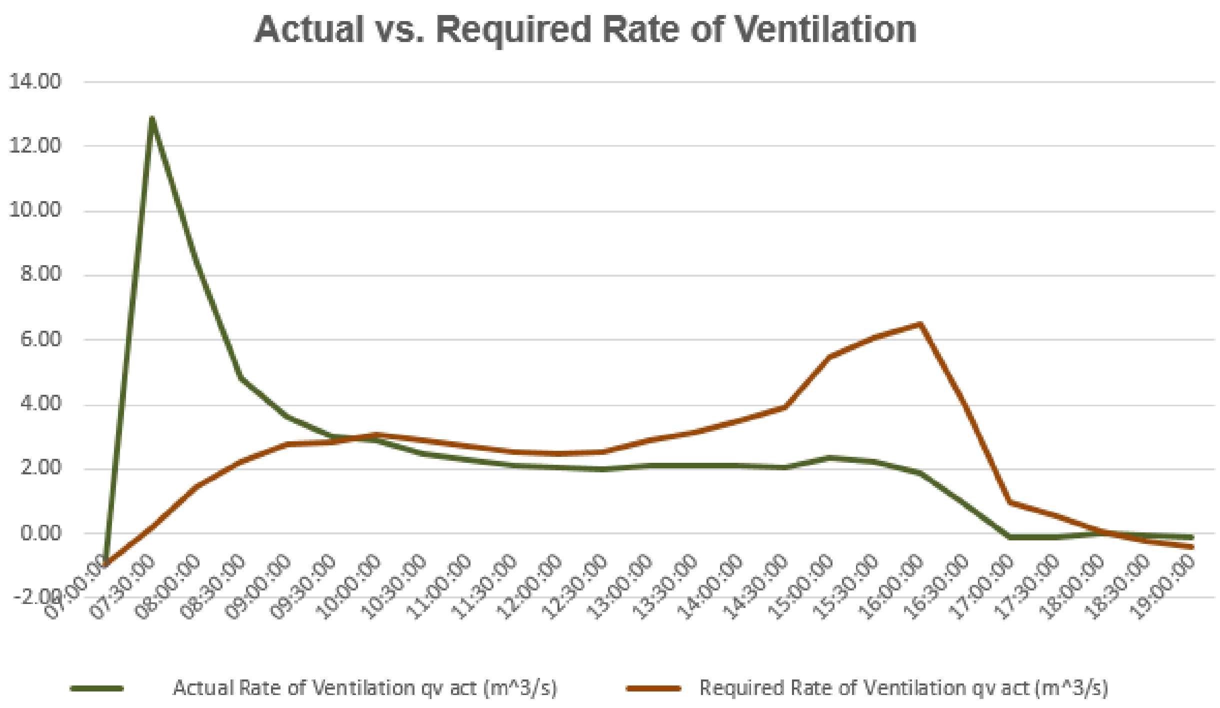


**Figure 89 - Actual vs. required rate of ventilation in m$^3$/s.**

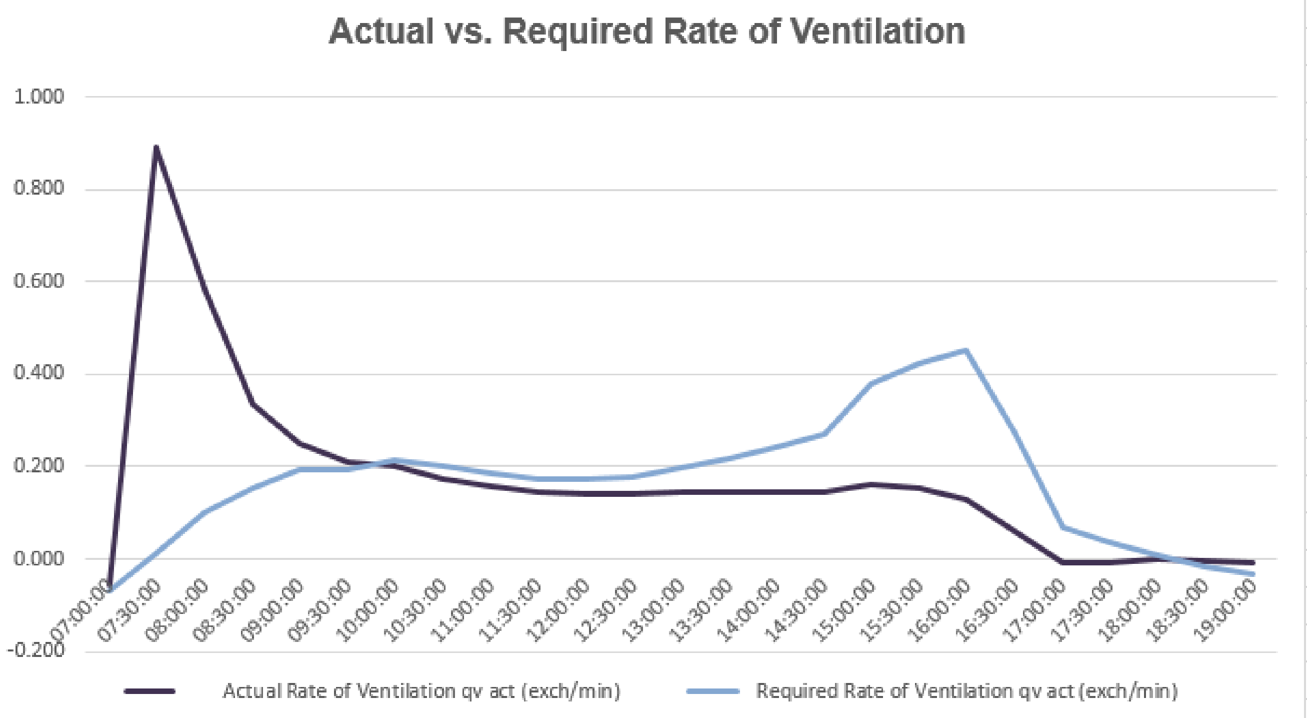


**Figure 90 - Actual vs. required rate of ventilation in exchanges/min.**