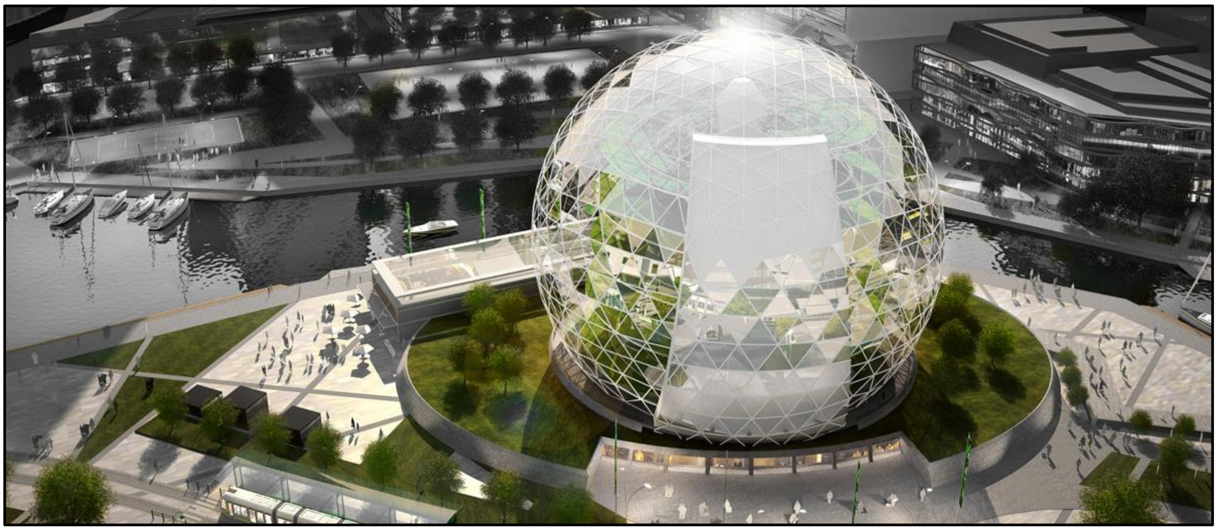
KTH Industrial Engineering and Management

Closed Greenhouses in Tropical Climate

Investigation of a geothermal dehumidification system



Master of Science Thesis

KTH School of Industrial Engineering and Management

Energy Technology EGI-2014-MJ218X

Division of Energy Technology

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Closed Greenhouses in Tropical Climate

Investigation of a geothermal dehumidification system

Masters of Science Thesis

By

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May, 2014

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Investigation of a geothermal dehumidification system

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Sammanfattning

Plantagon, är ett ledande företag inom innovativt urbant jordbruk, som önskade undersöka möjligheten att använda geotermisk energi i slutna växthus för avfuktningsbehov i Singapore. Det slutna växthusens önskade inomhustemperatur var 21 grader Celsius med en relativ luftfuktighet på cirka 70 %.

För att uppskatta avfuktningsbehovet i växthusen, studerades transpirationen från växterna. Transpiration är beroende av den lokala miljön; eftersom Singapore har en ungefärlig konstant medeltemperatur året runt, behövdes avfuktningen året om. Geotermisk energi i Singapore anses vara 40 grader Celsius på 200 meters djup (Palmer, 2011). Med hjälp av en värme sänka och en omvänd Carnot cykel, kunde avfuktningskapaciteten utvärderas. Den föreslagna lösningen visade sig kunna avfukta den totala angivna transpirationen i växthuset.

Livscykelkostnaden var en viktig aspekt för att förstå genomförbarheten av den föreslagna lösningen. Mängden vatten som besparades, samt kostnaden för avfuktning och kylning av växthusen avgjorde återbetalningstiden för projektet och där med lönsamheten. Resultaten visade att återbetalningstiden var kortare än projektets livslängd.

Abstract

Keywords: Ground-Coupled Heat Exchanger, Closed Greenhouses, Vapour-Compression Refrigerant Cycle, Latent Heat Flux, Life Cycle Cost (LCC), and Payback Time.

This study investigated the possibility of using geothermal energy for dehumidification purposes in closed greenhouses in tropical climates. The designed system used geothermal energy equipped with a vapour-compression refrigerant cycle, with R134a as the refrigerant.

The study was divided into three phases. The first phase, transpiration of the crops in the greenhouse was studied and estimated, taking into consideration the local environment. Transpiration is the process of which plants release up to 95% of the water uptake. The release of massive amounts of water vapour in closed greenhouses has undesirable effect on the crop, therefore dehumidification is important. It was found that the transpiration level in the greenhouse is $4115\ m^3 H_2 0/year$.

The second phase consisted of a study of the designed geothermal- and dehumidification system. The heat sink, the COP of the system and the evaporation capacity were analysed. It was found that a system of twenty vapour-compression refrigerant cycle was needed to cover the dehumidification demand in the greenhouse.

During the third phase the life cycle cost was investigated. An economical evaluation of the system was performed and the payback time was estimated. The water recovered from dehumidification was reused for irrigation, recycled water reduced the water consumption in the greenhouse and was evaluated to be a cost saver.

Acknowledgements

I am very grateful to all the people who have made this study possible. Therefore, I would like to thank the project owners, Plantagon and Joakim Ernback, whom without the project would not be possible. Acknowledgements are also in order for SWECO AB; the project was carried out under the supervision of Sergio Arus, the leading HVAC/Energy consultant in SWECO AB.

I would also like to thank Researcher Peter Kjaerboe and Professor Per Lundqvist from the Royal Institute of Technology for the guidance during rough times.

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Nomenclature List

Absorbed short-wave radiation	$\mathbf{S_t}$ **[$\mathbf{Wm^{-2}}$**
Air temperature	T_a [°C]
Air vapour pressure deficit	Δp [Pa]
Coefficients of performance of the condenser	COP_1
Coefficients of performance of the evaporator	COP_2
Cold surfaces temperature	t_2[°C]
Consumed electrical power	E_{el} [W]
Density	ρ [Kgm^{-3}]
Difference in the long-wave irradiance	$L_{in} - L_{out}$ [Wm^{-2}]
Efficiency of the compressor	η_k
Emissivity of leaf surfaces	ε
Enthalpy	h [J/g]
Enthalpy of the air after cooling	h_{after} [kJ/kg]
Enthalpy of the air before cooling	h_{before} [kJ/kg]
Extracted heat rate	Z [Ls^{-1}]
Fraction of reflected short-wave irradiance	ρ_f
Geothermal/Ground-sourced heat exchanger	GSHE
Ground source heat	G [W]
Latent heat flux (transpiration)	LE [Wm^{-2}]
Latent heat of vaporization	L [Jg^{-1}]
Leaf boundary-layer resistance	r_{bl} [sm^{-1}]
Life Cycle Analysis	LCA
Life Cycle Cost	LCC [USD]
Mass flow	$\dot{m}$ [kg/s]
Molecular weight of water	M_w [g mol^{-1}]
Net-irradiance absorbed	Rn [Wm^{-2}]
Power of compressor	E_k [W]
Power of condenser	Q_{cond} [W]
Power of evaporator	Q_{evap} [W]
Psychrometer constant	γ
Sensible heat flux (convection)	H [Wm^{-2}]
Specific heat	c_p [$JKg^{-1}K^{-1}$]

Specific heat capacity of water	S_{VCwat} $[JK^{-1}L^{-1}]$
Stefan-Boltzman constant	σ
Temperature drop	$\Delta\theta$ [K]
Temperature of the air after cooling	t_{airout} [°C]
Temperature of the air before cooling	t_{airin} [°C]
Temperature of the leaf	T_l [°C]
Temperature of the water after the condenser	$T_{water,out}$ [C]
Temperature of the water entering the condenser	$T_{water,in}$ [C]
The condenser temperature,	T_1 [°C]
The log mean temperature difference of the condenser	w [C]
The logarithmic mean temperature difference	ν_m [°C
The overall heat transfer coefficient per area	UA [J/(s·K)]
Total stomatal resistance	r_{st} $[sm^{-1}]$
Volumetric flow	$\dot{V}$ $[m^3/s]$

Table 1: nomenclature list

Introduction

This study investigates the possibility of using geothermal energy for dehumidification purposes in closed vertical-greenhouses. In order to minimize water consumption, efficient dehumidification is an important indicator. Thus hot and moist greenhouse air must be dehumidified in a closed system, where all excessive moist air is treated for water extraction. The advantage of using a geothermal sink for cooling dehumidification is the cheap and reliable source of energy.

Dehumidification with geothermal energy has several benefits. First of all, using geothermal energy could lower the greenhouse indoor temperature. Cooling high indoor temperatures is an energy intensive process and essential for insuring plant survival. Second of all, dehumidification of moist air allows the gathering, saving and reuse of dehumidified water. Humidity in large greenhouses is a current problem, not only could it ruin the plants habitat; but also if water is not reused, the consumption of fresh water exceeds.

Background

Agriculture uses approximately 70% of all used freshwater in the world (Världsvattenforum, 2009). Furthermore, with the quick growth in population, the food demand as well as the fresh water consumption is increasing. Moreover, climate change will also contribute to the change in agriculture as we know it. The challenge is to produce cheap food with less consumed resources, such as water and land. This requires active and responsive planning. Plantagon develops innovative solutions to meet the food demand (Plantagon, 2014); for example, their solutions provide locally grown food in vertical greenhouses in cities, which minimizes the use of land and transportation distances. Plantagons closed vertical greenhouse concept is investigated in this paper for possible geothermal dehumidification capability.

Objectives

The purpose of this study is to investigate the feasibility of installing a geothermal based dehumidification system in closed greenhouses. The aim is to reduce the greenhouses energy and water use, thus decrease its footprint on the environment. The objective of this thesis is to exploit the underground temperature of 40 degrees Celsius at 200 meters depth. The research is based on a theoretical framework, with a case study as a practical example. This makes the study more fit for an actual installation and will clarify problems that cannot be observed from theoretical calculations (Collis, J. and Hussey, H., 2009).

Plantagons Case Study

The buildings various data and specifications, such as façade concept, and desired indoor climate are taken from Plantagons Linköping project (Appendix 1). Plantagon does not have a specific model for the greenhouse in Singapore, therefore necessary data will be taken from Plantagons previously designed greenhouse concept in Linköping, Sweden. Thus, the building itself and indoor conditions are kept the same as in Linköping, while the outdoor environmental is changed to a hotter and more humid climate.

The greenhouse is a 17-floor building and has 4400 square meters in cultivation area. The concept is to minimize the land area used and the environmental footprint of the project. To succeed with this, the building must be integrated to the location and the local light conditions. The building is going to combine workplaces with the greenhouse; workplaces will exploit the excessive heat and excessive cooling from the greenhouse. The building is going to have a total of 15 floors of offices and movable platforms for vertical crop farming (See Appendix 1). The movable platforms will rotate while changing floors, this process will result in a more homogenous distribution of sunlight to the crop during its life cycle (Sweco, 2014). This process will reduce the amount of artificial lighting needed for crop farming in greenhouses. The crops being studied in this paper are Asian leafs, such as Mizuna lettuce.

Problem Statement

The main problem with implementation of a geothermal dehumidification system is to cover the actual variation in energy demand. For example, the humidity in the greenhouse tends to vary massively both during a day and during seasons. This behaviour has severe implications on the capacity demand for dehumidification, such as implementing a flexible dehumidification system that cover the different demand levels. The life cycle analysis is yet another important aspect to consider besides the technical challenges when implementing geothermal dehumidification systems. Balancing the technical and economical perspective might be a challenge.

Research Questions

- Does a geothermal-sourced dehumidification system deliver reliable performance in a closed greenhouse in Singapore?
- Can a geothermal-sourced dehumidification system in a closed greenhouse provide an ideal environment for vegetation in tropical climates?
- Is Plantagons aim of reducing its footprint possible using a geothermal-sourced dehumidification system in closed greenhouses?

Significance

This research will contribute to understand how to construct a geothermal dehumidification system in closed greenhouses. It will also show the practical implications that occur when going from a theoretical concept to an actual product. The methodological contributions of the project will display how to combine such a system with water reuse considerations. Hence, this study will be able to contribute to the design of future vertical greenhouses and their development.

Scope

The project will examine the possibility of using thermal energy for dehumidification. For a case study, Plantagons vertical greenhouse project is going to be investigated. Some of the limitations concerning this project are:

- The case study will be performed at one geographical location. This will limit the study in a sense that the phenomena measured will be those of a nearby area. A direct generalization of the results will hence be hard. Instead the study hopes to highlight important aspects of a geothermal dehumidification system in tropical climates, and the parameters that are needed to be taken into consideration.
- Data and specifications from Plantagon's Linköping building is going to be used for energy calculations in Singapore. This will lead to uncertainties on the account of the building being designed to match the Swedish weather, not the tropical climate. These uncertainties will be overlooked.
- The time constraint of the study will also have an impact on the results. Since the measurements cover a whole year, there are possible climate change effects that will not be measured in this study. The limited time frame provides fewer data points to analysis, which could have an impact on the reliability of the results. Historical weather data is not included in the scope of this paper, the data is collected for the year 2013 only.
- This report will concentrate on the humidity and temperature of the greenhouse, hence not taking into account Carbone dioxide concentration, shading, nutrients and other factors like diseases.
- The implementation of a geothermal dehumidification system might be accountable for more challenges than those investigated in this study. This study focuses mainly on the technical and economic considerations. However there are other perspectives to be taken into account, such as the political, social and environmental perspective. This study will not look further into these issues; instead it is left for another study to investigate.

Assumptions

- The indoor climate is kept constant, at a temperature of 21 degrees Celsius and a humidity of 70%.
- Temperature differences inside the greenhouse are minimal and can be ignored, thus the temperature is assumed to be same at all locations in the greenhouse.
- Due to uncertainties and lack of knowledge of the air stream in the greenhouse, the air ventilation system (mixing and dehumidifying air) will be considered to have an efficiency of about 80%.
- Greenhouse heat losses and gains are neglected, since outdoor temperature is always higher than the indoor temperature.
- Furthermore the intake of radiative energy for the two surfaces of a leaf are equal and transpiration occurs all day long, due to artificial lighting.
- The yearly cooling and dehumidifying need in the greenhouse is assumed to be constant, also the heat supply from the geothermal energy source is assumed to be constant at 40 degrees Celsius.

Literature Study

Indoor crop production needs a set of requirements, such as the right amount of light, temperature, moist, air and growing media. Reviewing the possibility of using geothermal energy to control heat and dehumidification is the aim of this paper.

The Greenhouse Concept

The greenhouse concept suggested by Plantagon is a closed system. Unlike a conventional greenhouse system (see Figure 1), the closed system has better covering and wall insulation, decreases energy costs and improves the energy efficiency. Furthermore, a closed greenhouse has a higher production yield and decreases the water consumption, if the water vapour is dehumidified and reused (Vadiee, 2014).

Figure 1: conventional greenhouse concept vs. closed greenhouse concept (source: Vadiee, 2014)

Environment in Singapore

The mean temperature during a year is about 28 $°C$, humidity levels seldom fall below 70% (Sweco, 2014 and climateandweather, 2014). The climate in Singapore will almost always be hotter and more humid than desired in the greenhouse. Such an outdoor climate encourages having a closed greenhouse system, where only carbon dioxide is added. The outside humidity does not affect the indoor environment of a closed system, thus the outdoor temperature and radiation are the only factors of concern when building the closed greenhouse in Singapore.

Greenhouse Environment

Climate control is very important in greenhouse farming; air temperature and humidity are two strong influences on plants survival. The thermal environment depends mostly on the radiant energy transmitted into the greenhouse compared to the reemitted energy. When transmitted energy into the greenhouse is greater, cooling is needed to reduce the greenhouse temperature and plant survival. With favourable environment in the greenhouse, the crop production increases and thus the transpiration. Plants use only a fraction of the energy received for photosynthesis, the rest contributes to the greenhouse temperature rise (Giacomelli, 2012). Transpiration is a method for plants to loose heat by loss of moisture, although, this process increases the humidity in the greenhouse.

Mollier Diagram

Air is a mixture of oxygen, nitrogen, and water vapour. Mollier diagram illustrates the relationship between air temperature, moisture content and enthalpy. The preferred indoor conditions are obtainable in Figure 2. Dehumidify in the greenhouse will only use recirculated air, as a result of having a closed system, thus no indoor air will be released to the outdoor nor will outdoor air be used in the greenhouse. Warm and humid air from the indoor environment will be cooled and dehumidified (treated) before mixed with untreated hot and moist air again. Later, the air is warmed (if necessary) using excessive heat from the geothermal heat source to reach the desirable air state. This process uses cooling dehumidification, the moisture content in the air should be kept approximately between 9 and 12 [$gH_2O/kg\ dry\ air$] and approximately at a temperature of 21 degrees Celsius as seen in Figure 2.

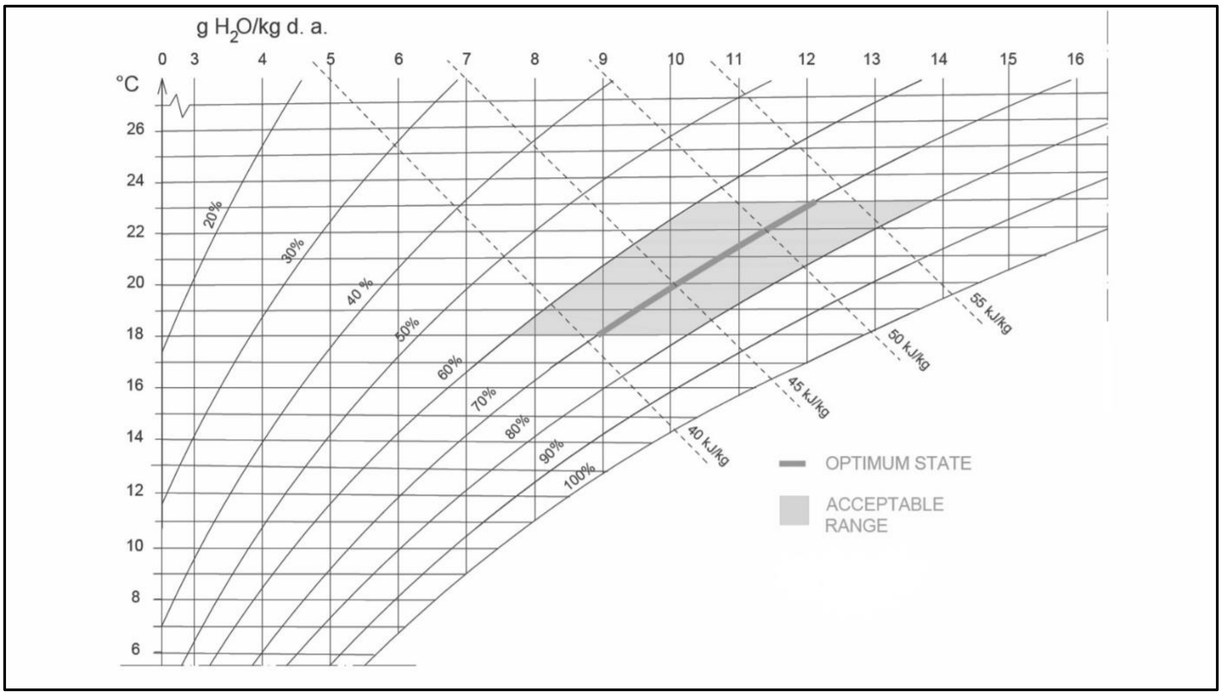

Figure 2: Mollier diagram-the optimal air state diagram (source: Sweco, 2014)

Greenhouse Heat Balance

When the greenhouse indoor temperature rises, the ability of air to carry water content rises as well. Dehumidification by cooling is used to lower the water content in the greenhouse, once the air is treated and dehumidified; the air temperature is lowered to 11 degrees Celsius. When the required indoor temperature is 21 degrees Celsius, the treated air needs to be heated.

Two main methods could be used to heat the cold treated air. First of all, the treated air could be heated with the excessive heat from the geothermal heat source after leaving the air unit, thus not affecting the air-treating unit. After reheating the treated air, it is mixed with the rest of the indoor air. Second of all, the treated cold air could be blended with recirculating hot and moist air before released. Thus using the dry cold air to dehumidify and cool the hot and moist air by blending, this reduces the dehumidification and cooling demand of the greenhouse. With less cooling and dehumidifying need, the operation time of the designed system is lowered.

In this paper the worst case scenario is going to be considered, thus having to dehumidify all air in the closed greenhouse. Although blending dry and cold air with moist and hot air is the more obvious choice to pick for an efficient and sustainable solution for a closed greenhouse in Singapore.

Vegetation

In principal all plants release water as a way to cool down and more importantly to uptake nutrients and balance the carbon dioxide intake (Encyclopedia, 2013). This process is called transpiration and plants could, through this process, release up to 95% of the uptake water through roots (Tgesbiology, 2014). Water release through leafs (transpiration) in closed greenhouses cause problems, such as unwanted humidity.

Leaf Energy Balance

To understand the amount of water released by plants into controlled climatic conditions, the leaf energy balance must be examined. The leaf energy balance is equal to zero, when the absorbed energy in the leaf is equal to the stored energy in the leaf plus the released energy to the environment. The ecophysiological interaction between a leaf unit of area and the surrounding microclimate could be represented in the leaf energy balance, see Equation 1 (Lambers, et. al., 2008):

$$Rn - G - LE - H = 0 \qquad 1$$

Where Rn is the net-irradiance absorbed [Wm^{-2}], LE is the latent heat flux density (transpiration) [Wm^{-2}], H is the sensible heat flux density (convection) [Wm^{-2}] from leaf to environment (Jones, H. 1992) and G is the soil heat flux (conduction) [Wm^{-2}]. When considering energy balance on leafs, both leaf sides need to be considered, see Figure 3. The absorbed radiative energy is lost by transpiration, conduction or convection, as shown in Equation 1 above. In greenhouses where the indoor temperature is lower than the leaf's temperature, convection occurs; on the other hand, when the indoor temperature is higher, the leaf absorbs heat.

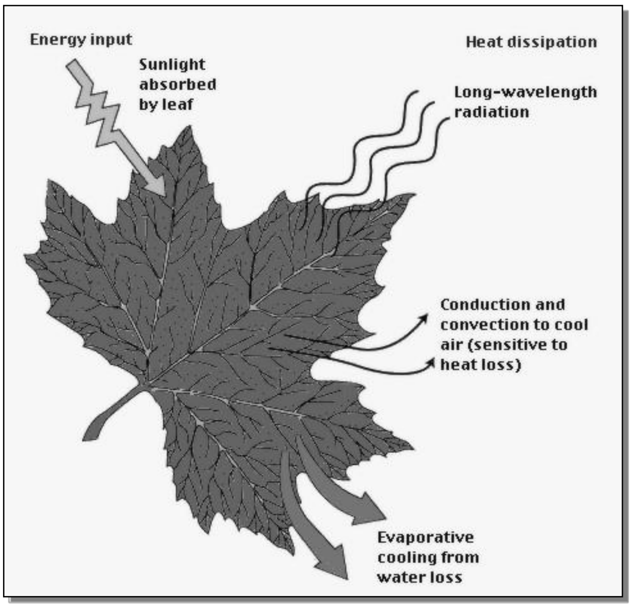

Figure 3: energy balance on leaf, (source: Koning, 1994)

The Net-Irradiance (Energy Absorbed)

The net-irradiance absorbed, Rn, is the most important component in controlled environments. The solar intensity affects the leaf temperature and hence the transpiration. When leafs absorb a higher energy quantity, the convection and transpiration increases. The met-irradiance can be divided into sub-components (Motieth and Unsworth, 2013), see Equation 2:

$$R_n = (1 - \rho_f) \cdot S_t + L_{in} - L_{out} \qquad 2$$

Where ρ_f is the fraction of reflected short-wave irradiance, S_t $[Wm^{-2}]$ is the absorbed short-wave radiation, and $L_{in} - L_{out}$ $[Wm^{-2}]$ is the difference in the long-wave irradiance incoming and outgoing the leaf.

The Latent Heat Flux (Transpiration)

The latent heat flux, LE, describes the rate of the heat loss by transpiration (Papadakis, et. al., 1993 and Tomomichi, et. al., 2003). Stanghellini (1987) describes transpiration as energy conversion from free heat (sensible) to bound heat through moisture vaporization (Gustafsson and Weich, 1991). Different models, due to incompliance, are used to express the latent heat flux. In this paper the model developed by H. Jonas is used; see Equation 3, (Jones, H. 1992):

$$LE = \frac{\frac{\rho \cdot c_p}{\gamma} \cdot \Delta p}{r_{bl} + r_{st}} \qquad 3$$

Where ρ $[Kgm^{-3}]$ is the density of air, c_p $[JKg^{-1}K^{-1}]$ is the specific heat of air, Δp [Pa] is the air vapour pressure deficit, γ is the psychrometer constant, r_{bl} $[sm^{-1}]$ is the leaf boundary layer resistance, and r_{st} $[sm^{-1}]$ is the stomatal resistance.

The Sensible Heat Flux (Convection)

The sensible heat flux, H, describes the heat transmission by conduction/convection from the leafs surface. Equation 4 illustrates the sensible heat flux:

$$H = \frac{\rho_a \cdot c_p \cdot (T_l - T_a)}{r_a} \qquad 4$$

Where T_l [°C] is the leaf temperature, T_a [°C] is the air temperature, ρ_a $[Kgm^{-3}]$ is the density of air and r_a is the leaf boundary layer resistance.

Water Vapour

After studying the leaf energy balance, it is fascinating to understand the quantity of water vapour released to the air at a given condition. To calculate the amount of water released into the air, by evaporation, per meter and second, Equation 5 is used:

$$E = \frac{LE}{L \cdot M_w} \cdot 1000 \qquad 5$$

Where *LE* is the latent heat flux, *L* [J g^(-1)] is the latent heat of vaporization, and M_w [g mole^(-1)] is the molecular weight of water.

Geothermal Energy

Geothermal energy is the energy generated, stored and harvested from below the surface of the earth. By drilling into the earth a nearly constant thermal energy is found, depending on the location this thermal energy varies in temperature.

Ground-Coupled Heat Exchanger

Ground-Coupled Heat Exchanger is an underground heat exchanger that can capture heat or dissipate it to the ground. When thermal energy is moved from a hot space and releasing it into the cold ground, the ground is used as a heat sink. A Geothermal/ground-sourced heat exchanger is an efficient way of transferring energy with the earth. The relative steady earth's temperature leads to a more stable energy transfer during a year (Routsolias, 2007).

Ground-Coupled Heat Exchanger Types

There are two main Ground-Coupled Heat Exchanger technologies, either to exchange heat with ground or exchange heat with ground water. The location chosen in Singapore for the project has a mixture of ground and ground water along the depth of 200 meters. Another critical design is the pipe "loops", vertical and horizontal pipes designs has different heat sink efficiencies, and is dependent on the local preconditions (Lund, et. al., 2004). In this project, vertical pipe loops are used and has a depth of 200 meters.

Dehumidification

When water vapour is condensed on cold surfaces, dehumidification occurs, and the moisture of the air reduces (Nilsson, 2008). For condensation to occur, the air temperature must be higher than the temperate of the cold surface. The grade of dehumidification depends on the cold surfaces temperature, and the temperature and humidity of the air.

Dehumidification Technologies

The dehumidification technology used depends on the application sites temperature and humidity. Other factors to consider when choosing the dehumidification technology are effectiveness, life cycle cost, operating cost, maintenance cost and efficiency in achieving the desired environment. Three main dehumidification technologies are discussed (Rowland and Wendel, 2005):

Cooling

Cooling is the most common method of dehumidification. Cooling dehumidification involves the air stream passing through a coil with fluid circulating in it. The fluid must have a temperature below the dew point of the air, for the air to condense and afterwards collecting the moisture. This method reduces the air temperature, which needs to be reheated. The reheating of the cooled air is done be using heated coils, see Figure 4.

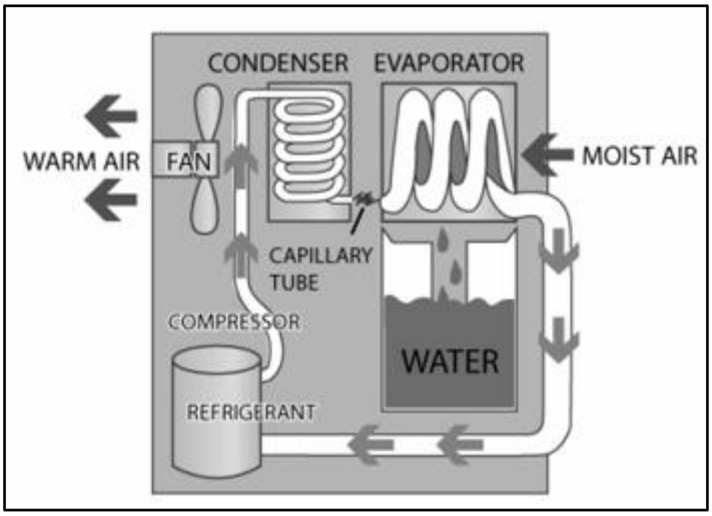

Figure 4: dehumidification process using vapour-compressor refrigeration (source: Schwartz, 2013)

Two methods of dehumidifying with cooling are Absorption refrigerator and vapour-compressor refrigeration (Granryd, 2011). Both methods use a refrigerant with low boiling point, and provide cooling when it evaporates. The difference between the two methods is the technique used to change back the refrigerant to liquid.

Vapour-compression refrigeration consists of four components, a compressor, a condenser, a thermal expansion valve and an evaporator. The compressor maintains two pressures at two appropriate temperatures. At the lower temperature side, a lower pressure is maintained to vaporize the liquid refrigerant. During this process the, the refrigerant absorbs heat from the refrigerated space. At the high temperature side, a high pressure forces the vapour refrigerant to be liquefied (condensed). At the higher temperature side, the refrigerant rejects heat to the environment.

Absorption refrigerator, just like the vapour-compression cycle consists of a condenser, a thermal expansion valve, and an evaporator. Instead of using a compressor, the absorption refrigerator uses a thermal compressor. The thermal compressor consists of an absorber, a pump, a generator, a heat exchanger and a regulating valve. Absorption refrigerators are ideal for locations that cannot support vapour-compressor refrigerator, due to a lack of an electrical current from a power grid. The coefficient of performance of the absorption refrigeration is lower than the vapour-compression refrigeration.

Liquid-Desiccant System

Liquid-desiccant cooling is archived by spraying a liquid solution (typically lithium chloride) to the air stream. Upon which, the liquid will absorb moisture from the air. This application is also beneficial for sites with little desire for bacteria and viruses, as the liquid also works like a biocide. The solution is then reheated and reused in the airflow.

Solid-Desiccant System

Moist air passes through a desiccant wheel (for instance: silica gel), which absorbs moisture. When the desiccant wheel reaches its absorption capacity, it is moved into a warm air stream to reject moisture. Once the moist is removed in the warm air stream, the desiccant is returned to the moist air.

This study is going to focus on vapour-compression refrigerants for dehumidification for its ability to exploit the different temperature levels in Singapore. Also, it is chosen due to the fact that it provides cooling as well as dehumidification.

Dehumidification theory

To determine the amount of energy needed for dehumidification, the required dehumidification power could be calculated with Equation 6:

$$\dot{Q}_{evap} = \dot{m} \cdot c_p(t_{airin} - t_{airout}) \qquad 6$$

Where $\dot{Q}_{evap}$ $[W]$ is the required dehumidification power, $\dot{m}$ [kg/s] is the air mass flow, t_{airin} [°C] is the temperature of the air before cooling, t_{airout} [°C] is the temperature of the air after cooling and c_p $[J/kg \cdot K]$ is the specific heat of air.

To maintain the desired level of humidity in the greenhouse, the moist and hot indoor air must be cooled to reach its dew point. When the moist air reaches the dew point, condensation occurs on the cold surface. The amount of dehumidified water can be achieved by deciding to which level the air is cooled in Mollier diagram, see Figure 2. To decide the cold surfaces temperature, Equation 7 is used.

$$t_2 = \frac{t_{air,in} - C \cdot t_{air,out}}{1 - C} \qquad 7$$

C is defined as Equation 8:

$$C = e^{\frac{t_{air,in} - t_{air,out}}{\nu_m}} \qquad 8$$

Where t_2[°C] is the cold surfaces temperature, $t_{air,in}$[°C] is the air temperature before cooling, $t_{air,out}$ [°C] is the air temperature after cooling, and ν_m [°C] is the logarithmic mean temperature difference.

From Equation 6 and 7 the cooling temperature is calculated, but to estimate ν_m Equation 9 is used.

$$v_m = \frac{\dot{Q}_{evap}}{UA_{evap}} \quad 9$$

Where $\dot{Q}_{evap}$ is the cooling energy is required, and UA_{evap} [J/(s·K)] is the overall heat transfer coefficient per area of the evaporator.

If the dehumidification process cannot dehumidify all moist air in the greenhouse, the dry cold treated air could be blended with the indoor air to lower the water content indoors and to raise the cold treated airs temperature to a more desired temperature.

Dehumidification with Ground-Coupled Heat Exchanger

Dehumidification with cooling is basically done by lowering a surfaces temperature below the dew point of the airflow. Usually, this is achieved by using a heat sink with an evaporator coupled to a condenser (Banks, 2008). The evaporator removes latent heat from water vapour in the air, causing water vapour to condense. After which, the condensed water is then collected to be reused in the irrigation process.

Ground-Coupled Dehumidification Technology

Ground-Coupled Heat Exchanger is a heat sink that uses the grounds energy; this is done by thermal contact with the ground. Generally, all Ground-Coupled Heat Exchanger systems use the same principals, to exchange energy with beneath the earth surface. The main components when using Ground-Coupled Heat Exchanger are the heat sink (ground) and the building itself.

Ground-Coupled Dehumidification System Components

The system design is an important element for reaching a high coefficient of performance (ASHRAE, 2011). The components included in the system are (see Figure 5):

Pumps

Pumps are the most critical components of a Ground-Coupled Heat Exchanger system, and definitely affect the downtime. Therefore careful selection of the pump is important.

Heat exchangers (condenser/evaporator)

The principal of heat exchangers is to isolate geothermal fluid while exchanging the thermal energy. The same principal is used in district heating.

Expansion valves

The expansion valves maintain the pressure difference between high- and low pressure side by controlling the mass flow of the refrigerant.

Compressor

The compressor changes the pressure of the working fluid and circulates it threw the system.

Piping

Pipes in geothermal systems are divided into two groups: indoor piping and buried piping. The buried pipes need to be modified for geothermal use. Elements that affect the buried pipes are: temperature, pH-value, and moisture content.

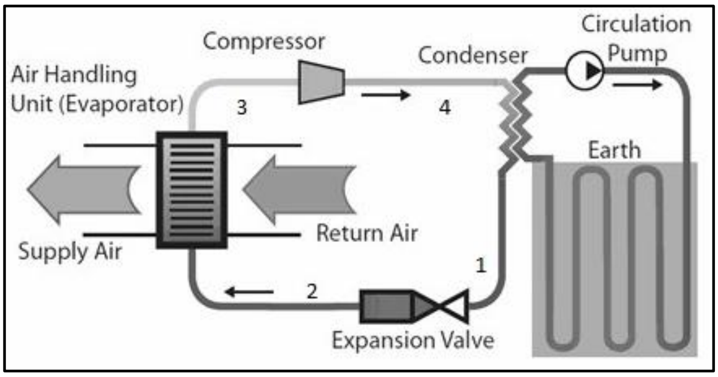

Figure 5: system layout (Ground-Coupled Dehumidification system) (source: e-news, 2010)

In the heat sink, a circulation refrigerant fluid works as a medium for transferring heat from one source to another. The refrigeration unit (condenser) is used to transfer the heat into the heat sink (ground). See Figure 5 for a more descriptive representation. Once the heat is exchanged to the refrigerant goes through a four-part cycle:

- The refrigerant after leaving the heat exchanger with the ground source (1) is transferred through the expansion valve. When the heat is transferred, the expansion valves drop the pressure. Expanding fluids cools them down, thus lowering the temperature of the circulating fluid (2).
- When the fluid (2) reaches the air-handling unit, heat exchange occurs. The hot air is cooled down as it passes through the cold surfaces, while the circulation fluid gains heat from the surrounding air and turns into a gaseous state (3). When the hot air passes through a cold surface for condensation to occur, the air humidity is lowered and water is collected for irrigation.
- The circulating fluid is now a bit warmer (3), and then it passes through a compressor powered by an electrical input. Once the fluid passes through the compressor it is heated up (4).
- As soon as the fluid is compressed it reaches another heat exchanger (condenser), the refrigerant loses heat and it condenses to liquid. At this point (1) the refrigerant reaching the same temperature as it started with.

The indoor air temperature is lowered in the air-handling unit, as evaporation occurs. This process meets two goals: first lowering the closed greenhouses indoor temperature and then reducing the humidity levels to meet the crops comfort level.

Ground-Coupled Dehumidification System Theory

The dehumidification power is calculated in Equation 6, but to understand the operation of the rest of the cycle, the compressor, condenser and expansion valve are explained:

To calculate the compressor capacity, the refrigerant mass flow, the compressor efficiency and the enthalpy difference are needed, see Equations 10, 11 and 12:

$$\dot{E}_k = \dot{m} \cdot (h_{1k} - h_{2k}) \qquad 10$$

$$\dot{m} = \dot{Q}_{evap}/(h_{2k} - h_s\,) \qquad 11$$

$$h_{1k} = h_{2k} + (h_{1kis} - h_{2k})/\eta_k \qquad 12$$

Where $\dot{E}_k$ [W] is the compressor power, $\dot{Q}_{evap}$ [W] is the required dehumidification power $\dot{m}$ $[g/s]$ is the mass flow of the refrigerant, h [J/g] is the enthalpy in different stages in the cycle, and η_k [-] is the efficiency of the compressor.

The power of the condenser is found by adding the evaporator power with the compressors. Using the logarithmic mean temperature difference, the condensation temperature is calculated, see Equations 13, 14, 15, 16, 17and 18:

$$\dot{Q}_{cond} = \dot{Q}_{evap} + \dot{E}_k \qquad 13$$

$$T_1 = \frac{C \cdot T_{water,out} - T_{water,in}}{C-1} \qquad 14$$

$$C = e^{\frac{T_{water,out} - T_{water,in}}{w}} \qquad 15$$

$$w = \dot{Q}_{cond}/UA_{cond} \qquad 16$$

$$T_{water,out} = T_{water,in} + (\dot{Q}_{cond}/(\dot{m}_w \cdot cp_w\,)) \qquad 17$$

$$\dot{m}_w = rho_w \cdot \dot{V}_w \qquad 18$$

Where $\dot{Q}_{cond}$ [W] is the condenser power, $T_1[C]$ is the condenser temperature, $T_{water,out}$ $[C]$ is the temperature of the water after the condenser, $T_{water,in}$ $[C]$ is the temperature of the water entering the condenser, w $[C]$ is the log mean temperature difference of the condenser, UA_{cond} [J/(s· K)] is the overall heat transfer coefficient per area of the condenser, $\dot{m}_w$ [g/s] is the mass flow of the water, cp_w [J/(g· K)] is the specific heat of water, rho_w [g/m^3] is the density of the water, and $\dot{V}_w$ $[m^3/s]$ is the flow of the water.

The expansion changes the pressure zones, from a high pressure level to a low one, this pressure change also results in lowering the temperature of the refrigerant to reach the temperature needed in the evaporator.

The coefficients of performance of the refrigerant cycle and the heat sink cycle are defined as Equations 19 and 20:

$$COP_1 = \dot{Q}_{cond}/(\dot{E}_k + E_{el}) \quad 19$$

$$COP_2 = \dot{Q}_{evap}/(\dot{E}_k + E_{el}) \quad 20$$

Where COP_1 is the coefficients of performance of the condenser, COP_2 is the coefficients of performance of the evaporator, and E_{el} [W] is the power needed for the compressor to function (the electrical input).

Water Recovery

Calculating the amount of water dehumidified per year in the greenhouse is estimated by knowing the amount of water rejected from every kilogram of air treated in the system. In Mollier Diagram (see Figure 2) the treated air state is going to change from 23 degrees Celsius and water content of 15 grams of water per kilograms of air to 11 degrees Celsius and 8 grams of water per kilograms of air. In other words, the water content per kilogram air is going to be reduced with 7 grams of water per kilograms of air. The airs mass flow is calculated, and then multiplied with the amount of reduced water content per kilogram of air, see Equations 21 and 22:

$$\dot{m}_{air}\ [kg/s] = \dot{V}_{air} \cdot \rho_{air} \quad 21$$

$$Water\ recovered[g/s] = \dot{m}_{air} \cdot 7\ [g\ H2O/kg\ of\ air] \quad 22$$

Where $\dot{m}_{air}$ is the mass flow rate of the air, $\dot{V}_{air}$ is volumetric flow rate and ρ_{air} the density. The purpose of water recovery is to reuse the water for less water consumption in tropical climate. And reduce the costs of water used in Singapore. When water is recovered, it will be reused for irrigation in the greenhouse. Other application for the recovered water could be cooling storage. Cooling could be stored in the recovered water for later use.

Life Cycle Analyses

Life Cycle Cost - LCC

The feasibility of a project depends on a set of variables, such as economy, politics & social, and environment. Life cycle cost is developed to determine the total cost of a project during its entire life spam, also it takes into account the energy costs, maintenance costs, and investment costs. For a reasonable assessment of a projects life cycle cost, all the factors that influence the projects costs must be included (Energimyndigheten, 2011), see Equations 23, 24 and 25:

$$LCC_{tot} = investment\ costs + LCC_{energy} + LCC_m \qquad 23$$

$$LCC_{energy} = yearley\ energy\ cost\ \times cost\ of\ capital \qquad 24$$

$$LCC_m = yearley\ maintenance\ cost\ \times\ cost\ of\ capital \qquad 25$$

Investment costs include initial costs, and installation costs. Investment costs are the costs of launching the project and are often a one-time cost.

Energy costs include operation costs, and can be calculated as in Equations 26 and 27.

$$Energy\ cost\ = electrisity\ cost \times energy\ consumption \qquad 26$$

$$Energy\ consumption = effect \times operation\ time \qquad 27$$

Maintenance costs include reparation costs and are the costs of keeping the product maintained for operation, in this particular example the maintenance cost is assumed to be 3% of the investment cost per year. Cost of capital is used to calculate future value in today's worth of money.

Cost of a Ground-Coupled Dehumidification system

The cost of installing Ground-Coupled Dehumidification System depends not only on the components installed, but is very dependent on the site and type of project (ASHRAE, 2011). Some cost factors are:

Well depth

Well depth is dependent on the location, cost and heat required; the cost of well is dependent on the depth. The depth of the well in the case study will be at 200 meters at a price of 40 USD/meter.

Distance between resource application and application site

Geothermal energy is ideal for long distance transportation, as the heat loss is minor. Unfortunately, the high cost of heat transportation bounds the application site nearby the sources. The project site will take place at the source site.

Temperature drop

Heat drop, due to pump extraction of heat flux, will affect the power output. The temperature drop will be assumed to be zero in this paper.

Material and component selection

Depending on the location and the composition of the ground, a design choice considering materials and components differs. Material selection affects corrosion and scaling effects, and in turn affects the maintenance cost. See Appendix 7: Costs for a more detailed component costs.

Dehumidification Cost

The cost of using dehumidification consists of energy cost for fans and pumps, equipment costs and cost of maintenance. The energy cost for fans and pumps are assumed to be 0.22 USD/kWh, meanwhile the yearly maintenance cost is assumed to be 3% of the investment cost. More details on equipment costs is shown in Appendix 7.

Payback Time

To estimate if the project will pay off, the Payback time of the project must be calculated. When using geothermal dehumidification for water reuse, two cost savings are reached. First, the cost of water not bought; second, the cost of cooling the greenhouse, see Equation 28:

$$Payback = \frac{LCC\ of\ project}{Cost\ of\ water\ reused + cost\ of\ cooling} \qquad 28$$

The life span of the investment is assumed to be 15 years. An investment that has a payback time less than its life span is a profitable investment.

Cost of Water Recovered

The purpose of reusing water in the greenhouse is due to the high water cost and more importantly, to reduce the environmental footprint of the greenhouse. The water cost in Singapore is assumed to be 3.2 SGD per cubic meter (1 USD/cubic meter) (Singaporepower, 2014), see Equation 29.

$$Cost\ saved\ [USD/year] = reused\ water\ \cdot cost\ of\ water \qquad 29$$

Cost of Cooling

The greenhouse is also cooled when air is dehumidified. This is the result of choosing cooling dehumidification in the greenhouse. The cost of cooling the greenhouse is the estimated in Equation 30:

$$Cost\ of\ cooling = \dot{Q}_{evap} \cdot electricity\ price \qquad 30$$

Where $\dot{Q}_{evap}$ is calculated in Equation 6, and the electricity price is assumed to be 0.22 USD/kWh (Singaporepower, 2014).

Method and Analysis

Process Scheme

Depending on the chosen location and the geothermal temperature in that specific area, the dehumidification method differs. In Singapore, the high temperature from geothermal energy could be converted to a low temperature using a vapour-compression cycle. Reaching high temperature deference is determined by the method used and the efficiency of the cycle. Once the thermal energy is converted to low temperature, it could be used for dehumidification and cooling the indoor greenhouse air.

In a closed greenhouse system, the dehumidification is as important as cooling the greenhouse, especially in tropical climates. The quantity and sort of the crops in the greenhouse, as well as the location and indoor environment are significant factors in determining the transpiration levels in the greenhouse. As the crops in the greenhouse release humidity to a closed environment, the dehumidification requirements increase. Therefore, controlling the humidity in the greenhouse is important for indoor crop production. The energy required for dehumidification depends on the amount of unwanted humidity in the air, the temperature of that air, the desired conditions and the efficiency of the dehumidifier. When air is treated, condensation occurs and water is collected. The collected water from the dehumidification process is then reused for crop irrigation.

Approach Method

To estimate the amount of energy needed for dehumidification, the difference between the actual level of humidity in the greenhouse and the required humidity must be calculated. This difference is the amount of excessive water vapour in the greenhouse that needs to be dehumidified. The energy requirement for dehumidification varies depending on the amount of excessive humidity in the greenhouse.

Moisture Content

To estimate the humidity in the greenhouse, the Leaf Transpiration Calculator is used. The program is developed by Kevin Tu (Landflux, 2014) and uses measurements of stomatal conductance and inputs like humidity, air temperature, leaf temperature and solar radiation at the leaf surface to estimate the transpiration of a certain crop. The relationship between the transpiration and amount of solar radiation on the leaf is described earlier in Equation 5: $E = \frac{LE}{L \cdot M_w} \cdot 1000$. Knowing the transpiration quantity (per meter and second), the amount of crops and the crop area in the greenhouse enables scheming the water vapour content of the greenhouse (see Appendix 1). The excessive moisture content in the greenhouse was calculated with the Leaf Energy Balance Program, the inputs used are presented in Table 2:

Environmental and Leaf Parameters

Parameter	Description	Units	Typical Range	Value
SWR	Short-wave radiation	Wm^{-2}	100 - 1000	136
WS	Wind speed	ms^{-1}	1.0 - 10.0	1,0
T_{air}	Air temperature	°C	10 - 30	21,0
RH	Relative humidity	%	10 - 100	70
i	Angle from horizontal	degrees	0 - 90	30
a_{SWR}	Absorptance to SWR	%	0.4 - 0.6	0,50
em	Emissivity	none	0.96 - 0.98	0,97
d	Characteristic dimension	mm	1-3000 (pine needle-banana leaf)	100
$shape$	Shape of the leaf	none	flat=1, cylinder=2, sphere=3	1
r_{st}	Stomatal resistance	sm^{-1}	50 - 10,000	4000

Table 2: input parameters for moisture content calculations

Dehumidification Requirements

Even though all the earlier mentioned dehumidification methods are interesting, this paper will focus on cooling dehumidification due to the need of cooling the greenhouse as well as dehumidify it. Comparing absorption refrigerator and vapour-compression refrigerator, the vapour-compression is assessed to be the more suitable refrigerator for closed greenhouses in Singapore.

To determine the temperature if the cold surface, the cooling power must be calculated. Thus, knowing the temperature of the indoor air and the temperature desired to reach, the required energy for dehumidification can be calculated with Equation 6 $\dot{Q_{cool}} = \dot{m} \cdot c_p(t_{airin} - t_{airout})$. Using the equation, the needed energy to cool the air to the desired temperature is calculated. According to Mollier diagram, the airs temperature should be cooled to about 11 ℃ for condensation to occur. Lowering the indoor temperature to 11 ℃ releases almost 5-7 grams water per kilogram air dehumidified.

Meanwhile, the airflow in the greenhouse is not perfect; the dehumidification capacity is not 100% efficient, therefore the dehumidification efficiency is assumed to be 80% of the theoretical capacity calculated with EES. In reality, if the system is not able to dehumidify all the moist air indoors, the dry and cold treated air is blended with the indoor air to lower the moisture content and heat the cold treated air. Consequently, the dehumidification demand is lowered. This study is not able to determine the percentage of the blended air due to lack of a ventilation system.

Geothermal Energy

Engineering Equation Solver (EES) is used to investigate the possibility of using geothermal energy at 40 degrees Celsius to dehumidify moist indoor air for water recovery. The system built with EES (see Appendix 6) uses R134a as a refrigerant; with a predefined geothermal source and indoor condition the system investigates the possibility of using a vapour-compression cycle for dehumidification purposes, see Figure 6:

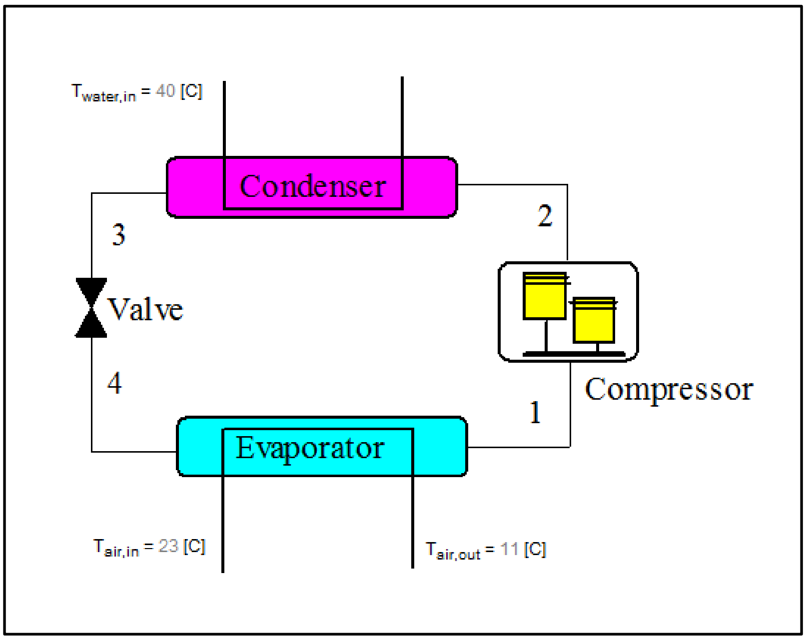

Figure 6: vapour-compression cycle

LCC and Payback

To calculate the life cycle cost of the investment, an excel document developed by Energimyndigheten, the Swedish Energy Agency, was used. The document uses the cost of capital method for estimating the future cost value of the project. The method used takes into consideration, investment costs as well as operation costs and maintenance costs. When the life cycle costs are calculated, it should be compared to the yearly saved costs of water reused and cooling power. The yearly saved costs of water reused depend on the dehumidification capacity of the implemented system and the crop type. The yearly saved costs of cooling depend on the indoor and outdoor temperatures. Once the Life cycle cost is divided with the cost of water reused and cooling power saved, the payback time is found. The life cycle cost and payback time is calculated for the both cases: using geothermal energy as power source, and using outside air as power source.

Results and Discussion

Leaf Energy Balance

The excessive moisture in the greenhouse was calculated according to the Leaf Transpiration Calculator and was estimated to be $4115\ m^3 H_2 0/year$ (see Appendix 5). A monthly description of the crop transpiration in the greenhouse is showed in Figure 7. Due to the constant environment conditions in the greenhouse, the transpiration does not change extremely during a year. This can be explained with the artificial lighting in the greenhouse. Reusing $4115\ m^3 H_2 0/year$ would reduce the greenhouses water consumption in Singapore significantly, thus achieving the goals set by Plantagon.

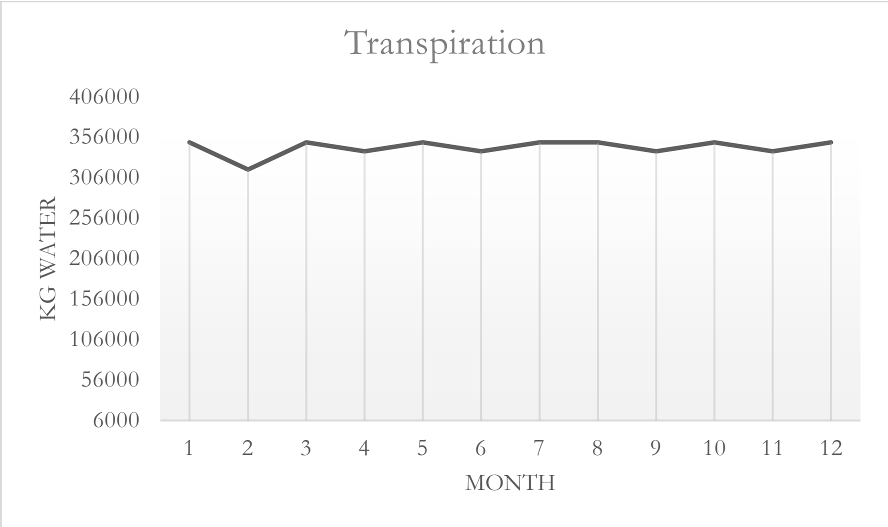

Figure 7: Monthly amount of water released by the crop

Vapour Compression Cycle

When simulating the EES program code, it was found that dehumidification of moist and warm indoor air at 23 degrees Celsius is possible with the geothermal ground water at 40 degrees Celsius. The volume airflow was 1 cubic meter per second and the water content rejection is 5-7 grams of water per kilogram of air treated and a COP1 of 3,6. The COP of a basic theoretical vapour compression cycle varies between 3.99 and 3.13 when the condensing temperature ranges from 38 to 45 degrees Celsius (AL-RASHED, 2011). Therefore, the COP1 of the designed system with ground water temperature of 40 degrees Celsius is considered to be reasonable. Figure 8 shows the different temperatures of air, water and refrigerant while the vapour-compression cycle is in operation and Figure 9 shows the pressure-enthalpy diagram of the refrigerant R134a in the vapour-compression cycle. Due to lack of information about the cycle used, the isentropic enthalpy was calculated.

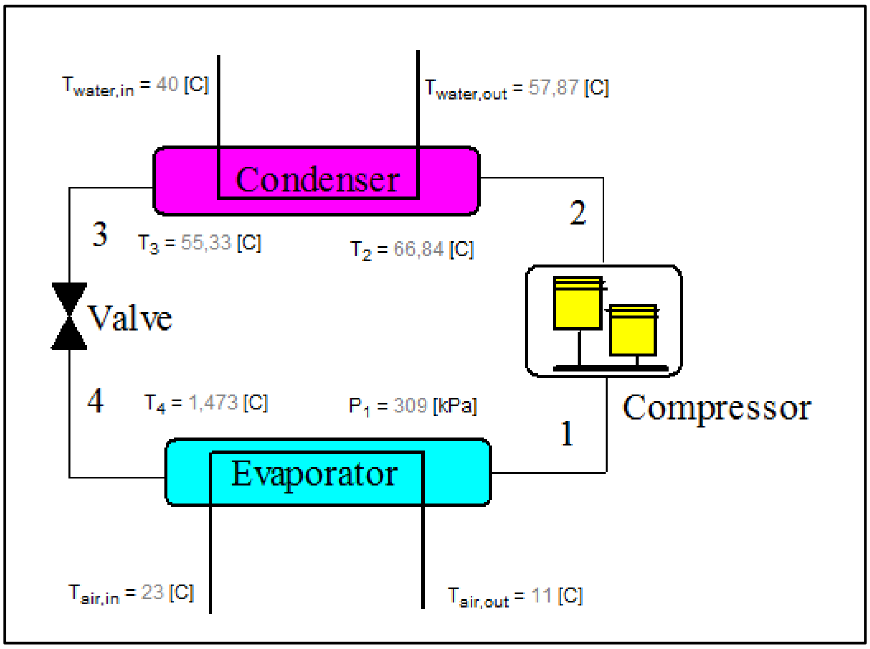

Figure 8: temperatures in different components of the vapour-compression cycle

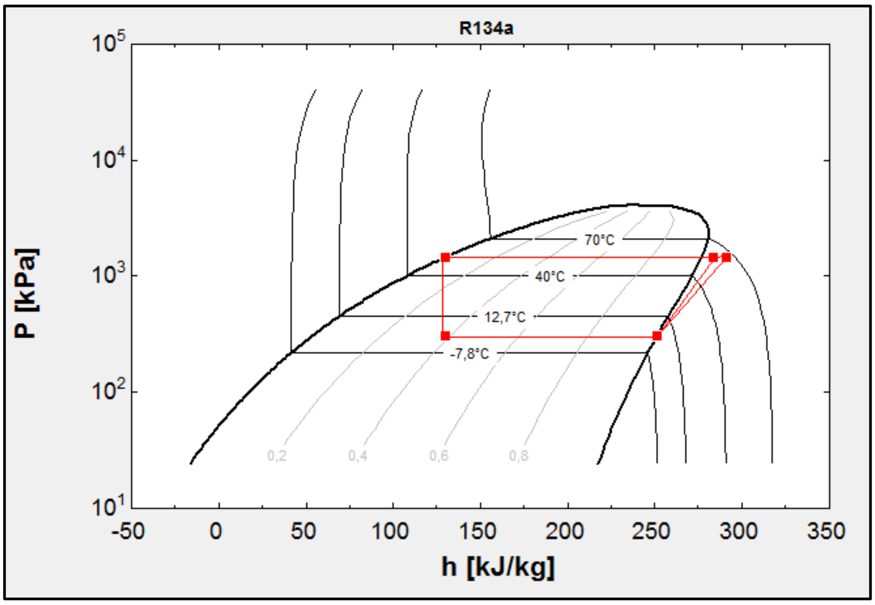

Figure 9: the p-h diagram of the cycle

Dehumidification Capacity

The dehumidification demand in the greenhouse is higher than the capacity of one vapour-compression cycle, as seen in Figure 10. It was noted that, with 80% efficiency in the air ventilation system, twenty geothermal-sourced vapour-compression systems could satisfy the dehumidification demand and provide a reliable solution for the closed greenhouse in Singapore.

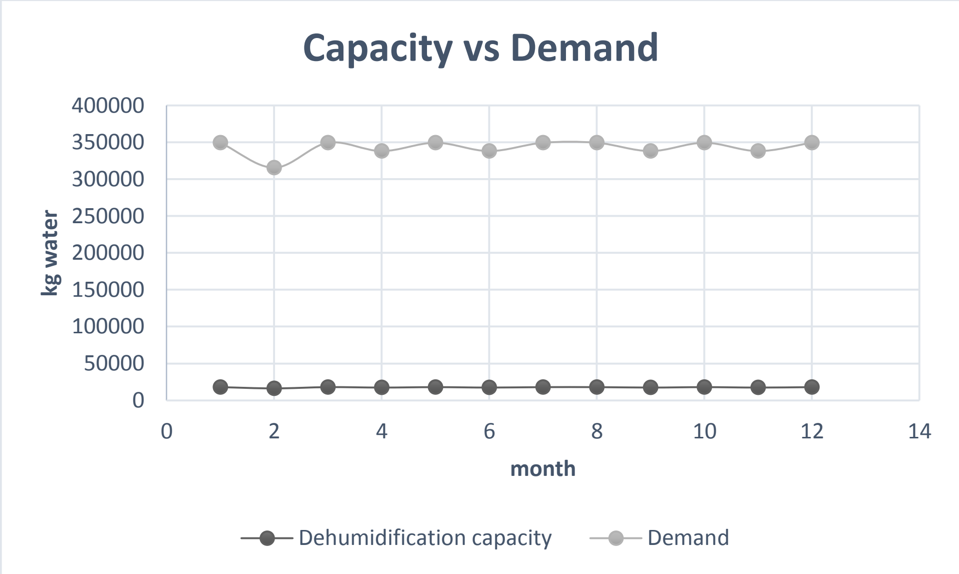

Figure 10: dehumidification capacity of the system compared to the transpiration in the greenhouse.

When using a system of twenty vapour-compression cycles for dehumidification in the entire greenhouse, it resulted in having a higher capacity level than the dehumidification demand, see Figure 11. Thus, twenty vapour-compression cycles would be needed for reaching the goal of dehumidifying $4115\ m^3 H_2 0/year$ and thus creating an ideal indoor environment in the closed greenhouse.

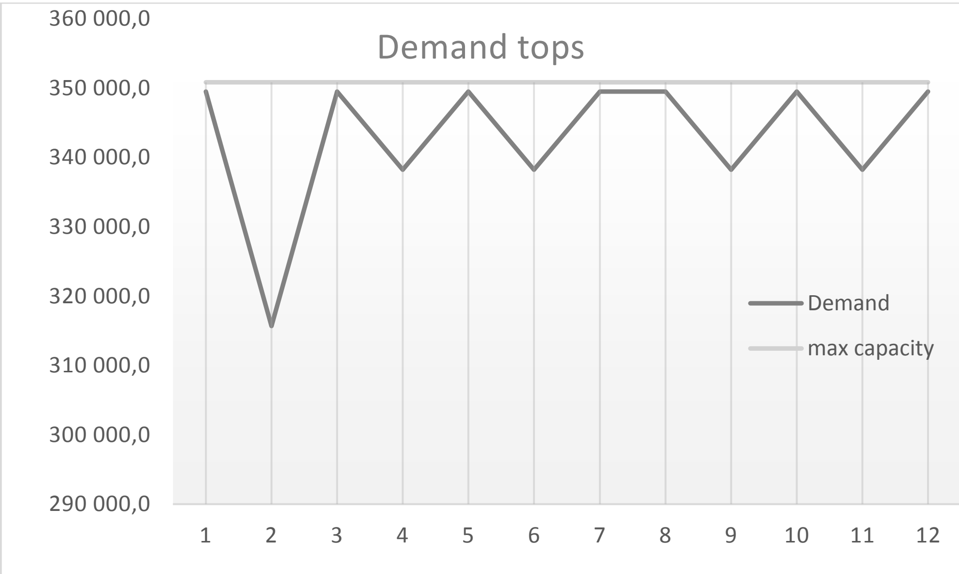

Figure 11: maximal dehumidification capacity with twenty systems.

LCC and Payback Time

Using twenty vapour-compression cycles for dehumidification with geothermal energy in Singapore would have a life cycle cost of 3 826 311 USD. The water recovered from dehumidification was estimated to be 4115 cubic meters of water per year, thus saving 4115 USD per year (at a water price of 1 USD/cubic meter) from using recycled water. The cooling power saved, due to having cooling dehumidification system, was estimated to be a total of 288 kW. Thus, saving a total sum of 554 956 USD per year from not having to cool the greenhouse. The project lifetime was assumed to be 15 years, while the payback time for the geothermal dehumidification project would be 11.9 years. Since the payback time is less than the project lifetime, it is considered to be a cost-effective solution.

The results show that Plantagons aim to reduce the greenhouses footprint on the environment is possible while using a geothermal-sourced dehumidification system. The water consumption and energy use in the greenhouse were low, even though low-emission solutions for dehumidification and cooling were used.

Sensitivity Analyses

Transpiration Analyses

Figure 12 shows different scenarios of transpiration when humidity and temperature is changed. Where series "normal" is the studied case with indoor temperature if 23 degree Celsius and 70% in relative humidity. Series "60% RH" is the case with humidity decrease with 10%, series "80% RH" shows the transpiration if humidity increases with 10%. In both cases, the transpiration level changed slightly. In series "20 deg. C" and "22 deg. C", the temperature is decreased respectively increased with 1 degree Celsius. When changing the temperature with one degree, it was noted that the transpiration levels of the crops changed with roughly 100 $m^3 H_2 0/month$.

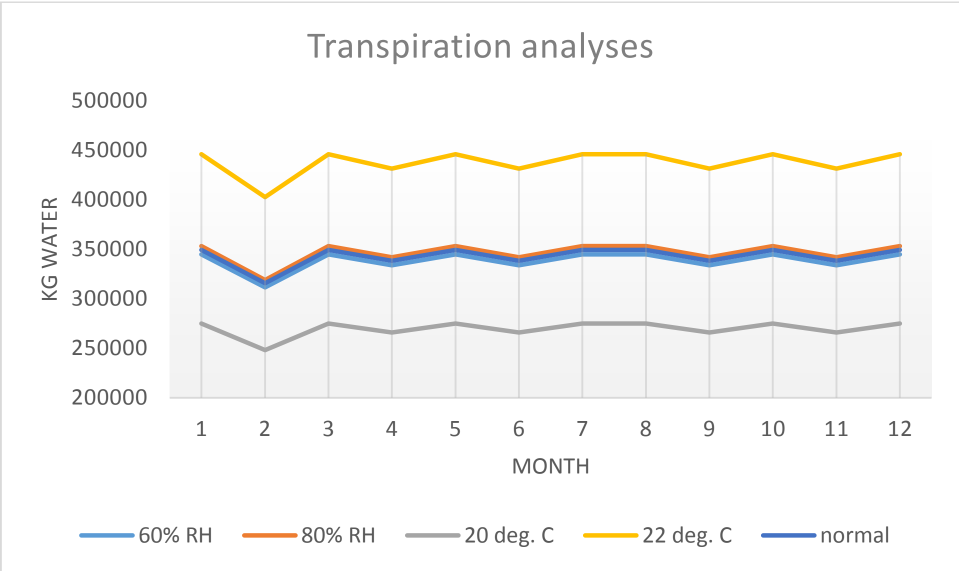

Figure 12: analyses of crop transpiration when temperature differs 1 degree Celsius and 10% in RH

Dehumidification Capacity Analyses

Figure 13 shows the capacity of the dehumidification process depending on the airflow in the greenhouse. Three scenarios are shown; first scenario "60% eff" describes a bad ventilation system. If the airflow is inefficient, meaning that the treated air is not mixed correctly with the indoor air, and the humid air is not dehumidified as desired. In the second scenario "80% eff", the ventilation system blends dry cold air better and gathers moist hot ait for dehumidification. The last scenario "100% eff" has perfect ventilation, thus for this case all air is treated and mixed with the indoor air.

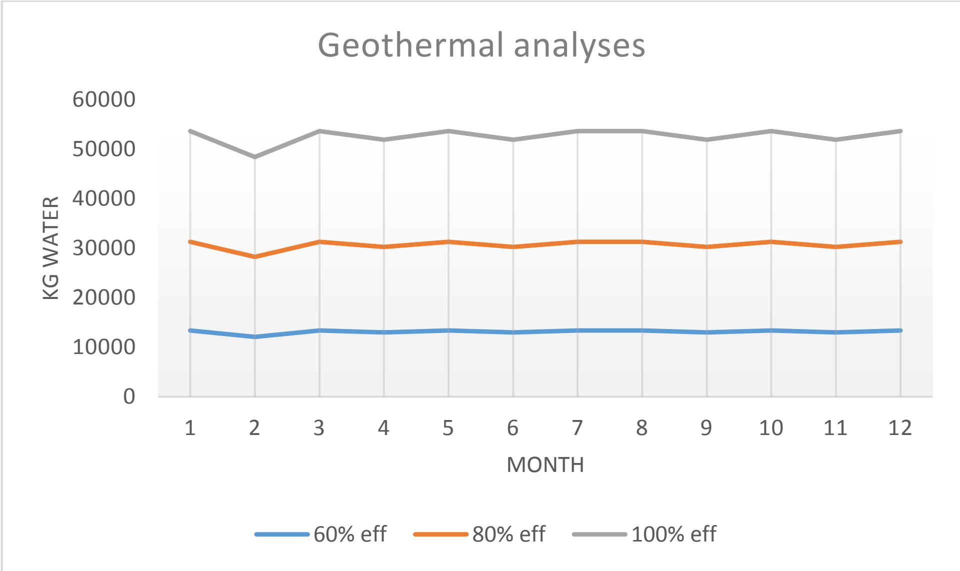

Figure 13: analyses if the geothermal dehumidification system with different airflow efficiencies

Vapour-Compression Cycle Analyses

Figure 14 shows how the COP and power (Q) of the condenser and evaporator changes when the ground water in Singapore changes temperature. It can be seen that the power of condensation increases linearly with an increasing water temperature, while the power of evaporation remains constant. The COP of condensation is approximately 1.0 higher than the COP of evaporation. Both COP decrease with a higher water temperature, which is undesired in the designed system.

This model helps to understand the effects of the water temperature on the system and helps to decide the depth of the boreholes. The ground water temperature affects the condenser power, but the evaporator power is constant due to the constant air temperature and the dehumidification power needed.

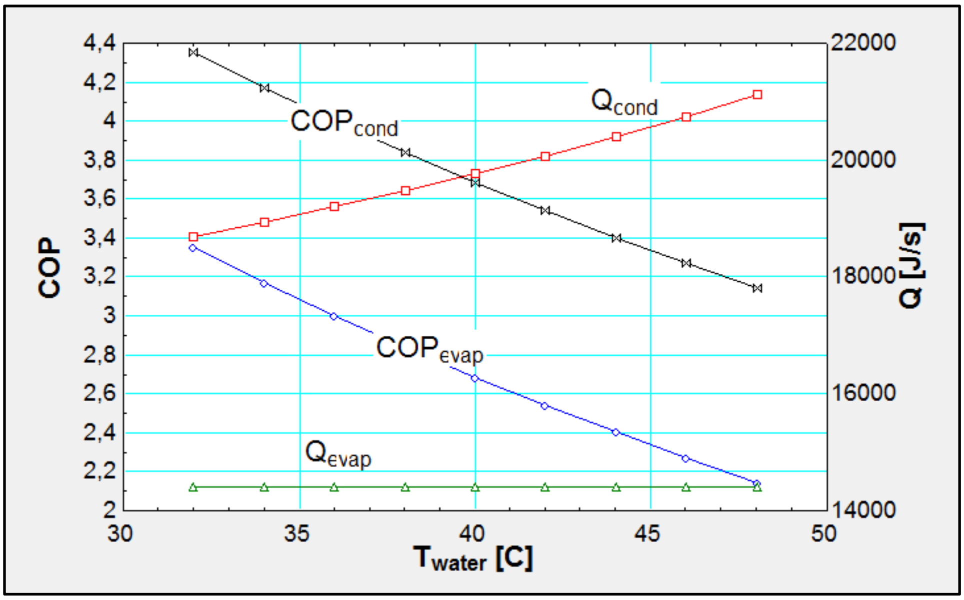

Figure 14: COP and Q variation when ground water temperature changes

Figure 15 shows how the dehumidification need vary, depending on the indoor air temperature variation, when using a geothermal-sourced dehumidification system. The power for condensation and evaporation increase due to the variation (increase) in the dehumidification demand. It is also noted, as the indoor temperature increases and the dehumidification demand increases, the COP of the condenser and the evaporator decreases.

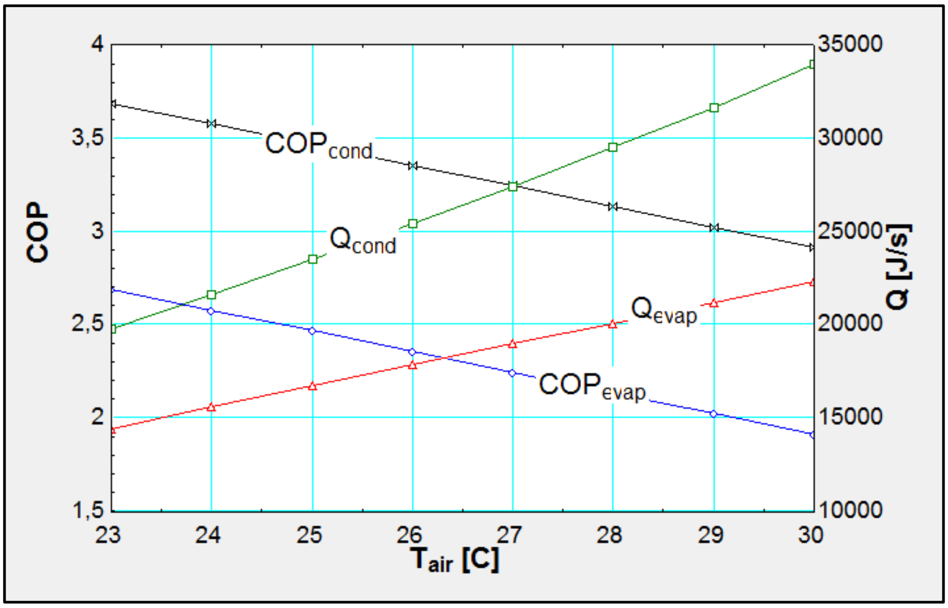

Figure 15: COP and Q variation when indoor air temperature changes

Life Cycle Analyses

Table 3 show the life cycle cost and payback time of the system discussed when the dehumidification demand changes. The worst-case scenario required 26 geothermal-sourced vapour-compression cycles. While the best-case scenario, only needed 16 geothermal-sourced vapour-compression cycles to satisfy the dehumidification demand.

Number of systems	LCC geothermal (USD)	Payback geothermal (years)
26 geo. deh. systems	4129168,3	12,5
20 geo. deh. systems (case study)	3826311,4	11,9
16 geo. deh. systems	3624406,8	11,6

Table 3: LCC and payback time of dehumidification systems when dehumidification demand changes

Table 4 examines the life cycle cost and payback time when the cost of capital changes by 1 percent. **The payback time variation, using different percentage of cost of capital, is not great.**

Cost of capital	LCC geothermal (USD)	Payback geothermal (years)
6%	3710057,0	11,6
5% (cast study)	3826311,4	11,9
4%	3950071,6	12,3

Table 4: LCC and payback time of dehumidification systems when in cost of capital changes

Conclusion

The feasibility of a geothermal-sourced vapour-compression system was evaluated in the study. The study was conducted in three phases: transpiration in the greenhouse, the designed system's performance, and the life cycle assessment of the project.

The designed geothermal-sourced dehumidification system delivered reliable performance, when installing twenty geothermal-sourced dehumidification cycles. The systems' dehumidification capacity was found to be higher than the dehumidification demand in the closed greenhouse. Also a geothermal heat sink was considered to have a reliable temperature variation during a longer period of time. The geothermal dehumidification system is a well-thought-out system for a longer operation period, especially when uncertainties in climate change exist.

The closed greenhouse concept should be able to manage the tropical climate in Singapore. Only solar radiation and outdoor temperature affect the indoor climate, since outdoor air is not used in the greenhouse. To maintain favourable indoor climate, the closed greenhouse must control the humidity levels created from crop transpiration and use artificial lighting. When installing twenty geothermal-sourced dehumidification cycles in the closed greenhouse, it was found that the dehumidification capacity was higher than the demand during a year. Therefore the designed solution for the closed greenhouse would be able to provide an ideal indoor environment for the crop.

The designed solution would have a payback time less than the life span of the project, it would therefore be cost-effective. Conclusively, Plantagons request to investigate the possibility of using a geothermal-sourced dehumidification system in closed vertical greenhouses in Singapore, has shown to be possible and successful. Plantagons aim of reducing its footprint on the environment could be achieved by using the designed solution.

Future Work

It is recommended to investigate the absorber refrigerant cycle for dehumidification as further studies on greenhouses in tropical climate. Deeper boreholes could give up to 150 degrees Celsius in geothermal heat, could this be used for dehumidification with absorber refrigerant cycles? Also could excessive cooling be stored in the recovered water for later use? These questions are interesting for further study in this field of work. Also additional analyses on the study could be to investigate the political and social aspects on closed greenhouses with geothermal-sourced dehumidification systems in tropical climates.

Semi-closed greenhouses are also an interesting concept, further study on semi-closed greenhouses in tropical climate is necessary for a better comparison with closed greenhouses. The alternative solution of just installing the base capacity should be furthermore investigated. Having a semi-closed system will allow the possibility of releasing indoor humid air to the outside, when increased dehumidification demands. Also, allows the possibility of treating outdoor air during the night when dehumidification demand is low for air and water collection. How does a semi-closed system affect the life cycle cost as well as the water usage?

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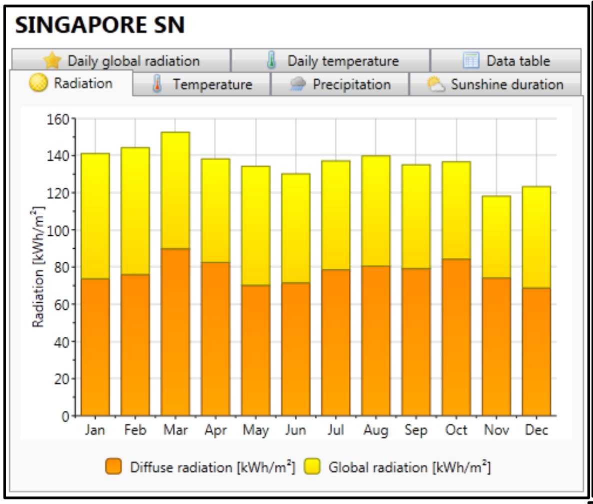
Appendix

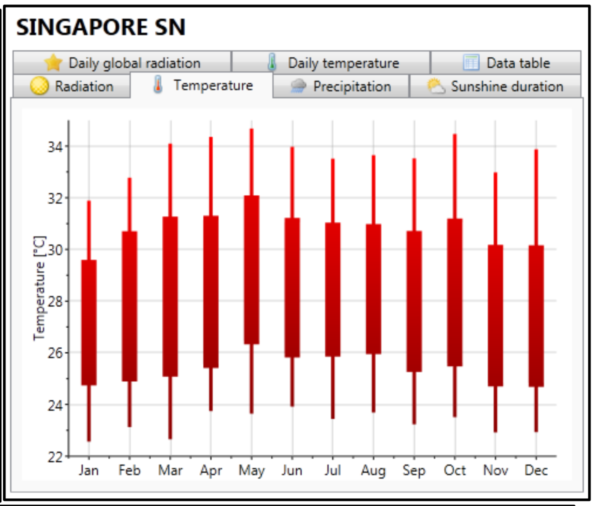
Appendix 1: Specifics

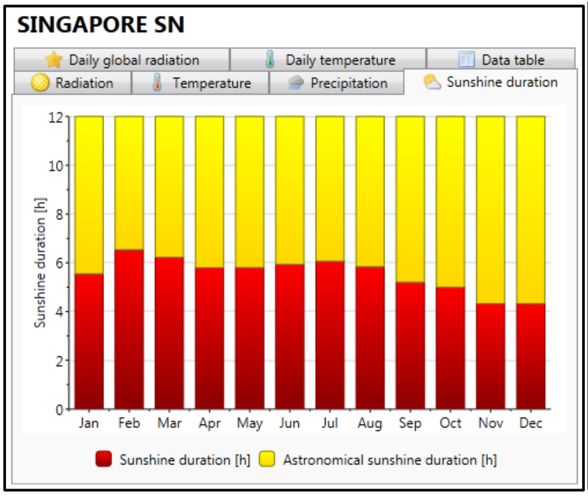
Area for farming in greenhouse	**4400**	**m2**
Number of plants	170000	N
Number of plants per area	38,6	N/m2
Volume of greenhouse	24000	m3

Table 5: facts about Plantagons vertical greenhouse project

Appendix 2: Data Collection







SINGAPORE SN

Radiation | Temperature | Precipitation | Sunshine duration | Daily global radiation | Daily temperature | Data table

	Gh kWh/m²	Dh kWh/m²	Bn kWh/m²	Ta °C	Td °C	FF m/s
January	141	74	99	27,1	23,4	3
February	144	76	96	27,7	23,5	3,2
March	153	90	87	28,1	24,2	2,2
April	138	83	80	28,6	24,7	1,4
May	134	70	96	29,1	24,8	1,8
June	130	71	86	28,8	24,5	2,1
July	137	79	87	28,3	24,4	2,4
August	140	81	85	28,4	24,3	2,5
September	135	79	80	28,3	24,2	2,2
October	137	84	73	28,3	24,2	1,8
November	118	74	64	27,8	24,3	1,6
December	123	69	80	27,4	24,1	2,3
Year	1632	929	1013	28,2	24,2	2,2

Table 6: Document 1: climate data in Singapore (source: meteonorm)

Appendix 3: Constant Values

Density of dry air [ρ]	$\mathbf{1.292}\ [\boldsymbol{Kgm^{-3}}]$
Latent heat of vaporization [L]	2500 $[Jg^{-1}]$
Latent heat of vaporization [λ]	2.45 [MJ kg-1]
Molecular weight of water [Mw]	18,0 [g mol-1]
The atmospheric pressure	$P = 101.3(\frac{293 - 0.0065z}{293})^{5.26}$
The emissivity of leaf surfaces,$[\boldsymbol{\varepsilon}]$	$0.92 - 0.98$
The psychrometer constant [γ]	66.7 $[PaK^{-1}]$
The specific heat at constant pressure [cp]	1010 [J kg-1 K-1]
The specific heat capacity of water [$\boldsymbol{S_{VCwat}}$]	4180 $[JL^{-1}K^{-1}]$
The Stefan-Boltzman constant $[\boldsymbol{\sigma}]$	$5.67\times 10^{-8}\ [Wm^{-2}K^{-4}]$
The von Karman's constant [K]	0.41

Table 7: constants

Appendix 4: Additional Equations

Water content removal:

Using Equations 10 and 11:

$$Mass\ flow_{air}\ \left[\frac{kg}{s}\right] = Volume\ flow\ rate\ \left[\frac{m^3}{s}\right] \cdot density\ of\ air\ \left[\frac{kg}{m^3}\right] = 1 \cdot 1,2 = 1,2\left[\frac{kg}{s}\right]$$

$$Water\ recovered[g/s] = Mass\ flow_{air}\ \left[\frac{kg}{s}\right] \cdot 5\ \left[g\frac{H2O}{kg}of\ air\right] = 1,2 \cdot 5 = 6\ [g/s]$$

$$Water\ recovered = 6 \cdot \frac{3600}{1000} = 21,6[kg/h]$$

From Appendix 2 and the duration of solar radiation per year is known. For the entire building per year, the amount of dehumidified water is:

$$Water\ recovered = 21,6 * 2031,55 = 43,9\ tonne/year$$

Appendix 5: Leaf Transpiration Calculator

Transpiration_Singapore.xlsx

transpiration amount

Month	transp.	g H2O/(h*m2)	kg H2O/h	h/month	kg H2O/month	g H2O/kg and h
1	1,648	106,768	469,780	744,00	349516,236	**16,312**
2	1,648	106,768	469,780	672,00	315692,084	**16,312**
3	1,648	106,768	469,780	744,00	349516,236	**16,312**
4	1,648	106,768	469,780	720,00	338241,518	**16,312**
5	1,648	106,768	469,780	744,00	349516,236	**16,312**
6	1,648	106,768	469,780	720,00	338241,518	**16,312**
7	1,648	106,768	469,780	744,00	349516,236	**16,312**
8	1,648	106,768	469,780	744,00	349516,236	**16,312**
9	1,648	106,768	469,780	720,00	338241,518	**16,312**
10	1,648	106,768	469,780	744,00	349516,236	**16,312**
11	1,648	106,768	469,780	720,00	338241,518	**16,312**
12	1,648	106,768	469,780	744,00	349516,236	**16,312**
year				8760,00	4115271,805	
					m3 H2O/year	
					4115,272	

Appendix 6: EES-Geothermal

```
"!Vapor compression cycle for dehumidification with geothermal energy source"

"$INPUT"
T_water_in=40 [C]                          "Temp of geothermal ground water in
Singapore according to Palmer, 2011"
T_air_in=23 [C]                            "23 C heat in greenhouse"
T_air_out=11 [C]                           "11 C for dehumidification to occur"
UA_ev=978 [J/(s*K)]                        "source: Umer Khalid Awan"
UA_cond=2000 [J/(s*K)]                     "source: Umer Khalid Awan"
V_air=1 [m3/s]                             "airflow"
V_w=0,6 [m3/s]                             "water flow"
"END"

R$='R134a'

T[3]=T_cond                                "Temperature after condenser is assumed to
be equal as the temperature in the condenser"

"!Evaporator"
rho_air=Density(Air_ha;T=T_air_in;P=101,3)*1000      "density of air at 23C"
m_air=rho_air*V_air
cp_air=SpecHeat(Air_ha;T=T_air_in;P=101,3)           "specific heat capacity of air at 23C"
Q_evap=m_air*cp_air*(T_air_in-T_air_out)             "Q of evaporator"
v=Q_evap/UA_ev
v=(T_air_out-T_air_in)/ln((T_air_out-T[1])/(T_air_in-T[1]))
"T[1]=-10"                                 "Guess value of temperature of evaporator"
T_evap=T[1]                                "temp of evaporator, at this temperature the
amount of water removed is 5 gH2O/kg"

"!Compressor"
x[1]=1
P[1]=Pressure(R134a;T=T[1];x=x[1])         "pressure of evaporator"
s[1]=Entropy(R134a;h=h_2k;P=P[1])
s[2]=Entropy(R134a;h=h_2k;P=P[1])
P[3]=Pressure(R134a;T=T[3];x=0)            "pressure of condenser"
h_2k=Enthalpy(R134a;T=T[1];x=x[1])
h_s=Enthalpy(R134a; P=P[3];x=0)
h_1kis=Enthalpy(R134a;P=P[3];s=s[2])
n_k=0,82                                   "an assumption, taken from Applied
Thermodynamics and Refrigeration"
h_1k=h_2k+(h_1kis-h_2k)/n_k
m_dot=Q_evap/(h_2k-h_s)
E_k=m_dot*(h_1k-h_2k)                      "E of compressor"
T[2]=Temperature(R134a;P=P[3];h=h_1k)

"!expansion valve"
"T[4]=T[1]"
T[4]=Temperature(R134a;P=P[1];h=h_s)
P[3]=P[2]
P[1]=P[4]
s[3]=Entropy(R134a;T=T[3];x=0)
s[4]=Entropy(R134a;h=h_s;P=P[1])

"!Condenser"
E_el=680                                   "the electrical motor power is the taken from
Hermetic compressor"
cp_w=Cp(H2O;T=T_water_in)                  "specific heat capacity of water at 40C"
rho_w=Density(Water;T=T_water_in;x=0)      "density of water at 40C"
```

```
m_w=rho_w*V_w                                "the water flow is not known, but is assumed
to be as in Sweden"
Q_cond=Q_evap+E_k+E_el                       "Q_cond is the sum of Q_evap and E_k and
680 W from electrical use in compressor"
T_water_out=T_water_in+(Q_cond/(m_w*cp_w))   "water temperature after leaving the
condenser"
w=Q_cond/UA_cond
w=(T_water_out-T_water_in)/ln((T_cond-T_water_in)/(ABS(T_cond-T_water_out)))
"assumption that the temperature of the condenser is higher than the temperature of the water leaving
the condenser"
"T_cond=60"                                  "Guess value of temperature of condenser"

COP_cond=Q_cond/(E_k+E_el)
COP_evap=Q_evap/(E_k+E_el)

{Array Array1}
Array1[1..6;1]=[h_1k;h_1kis;h_s;h_s;h_2k;h_1k]
Array1[1..6;2]=[P[3];P[3];P[3];P[1];P[1];P[3]]
{Array Array1 end}

{Array Array2}
Array2[1..2;3]=[h_2k;h_1kis]
Array2[1..2;4]=[P[1];P[3]]
{Array Array2 end}
```

Appendix 7: Costs and Savings

Interest rate of the investment	5% (assumption)
Well depth (USD per meter)	40 (bergvarmepumpar.nu, 2014)
Yearly maintenance costs (USD/year)	3% of investment costs
Pumps & equipment for heat sink	16800 (bergvarmepumpar.nu, 2014)
VCR cycle (USD)	500 (tradekey, 2014)
Energy costs (USD/kWh)	0,22 (singaporepower, 2014)
Installation cost of all heat sinks (USD)	40000 (bergvarmepumpar.nu, 2014)
Installation cost of all VCR cycles (USD)	20000
Water recovered (m3/year)	4115
Price of water in Singapore (USD/m3)	1 (singaporepower, 2014)
Total cooling demand (kW)	287,96 (14,398 kw/system*20)
Energy demand in pump (kW)	0,68
Operating time (h/year)	8760

Table 8: costs and savings of geothermal dehumidification systems

Appendix 8: LCC

LCC_Singapore.xlsx

A		
Interest rate of the investment	**5%**	
Well depth (USD per meter)	**40**	
Yearly maintenance costs	**3% of investment costs**	
Pumps & equipment for heat sink	**16800**	
Energy costs	**0,22 USD/kWh**	
Cost of geothermal system	**496000**	*20
installation cost of heat sink	**40000**	*20
B		
Interest rate of the investment	**5%**	
Yearly maintenance costs	**3% of investment costs**	
initial cost of VCR cycle	**500**	
Energy costs	**0,22 USD/kWh**	
total Cost of VCR cycle	**30000**	*20
installation cost VCR	**20000**	*20
savings		
water recovered (m3/year)	**4115,000**	
price of water in singapore (USD/m3)	**1**	
total cost of saved water (USD/year)	**4115**	
cooling demand (kW)	**287,96**	*20
operating time (h/year)	**8760**	
electrisity price (USD/kWh)	**0,22**	
total cost of cooling (USD/year)	**554956,512**	
payback (years)	11,94421061	

Number of systems	**LCC geothermal (USD)**	**Payback geothermal (years)**
20 geo	3826311,4	11,9

Appendix 9: Assumptions

Indoor relative humidity	**75%**
Supply relative humidity	65%
Supply temperature	11 °C
Temperature indoor	21 °C
The life span of the investment	15 years

Table 9: assumption regarding the greenhouse environment and the desired air supply state