This is to certify that the
thesis entitled

AN ECONOMIC COMPARISON OF GEOTHERMAL AND CONVENTIONAL HEATING SYSTEMS FOR GREENHOUSE OPERATIONS

presented by

Elizabeth Dawn Miller

has been accepted towards fulfillment
of the requirements for the

Master of Science degree in Agricultural Economics

James H Hilker
Major Professor's Signature

November 23, 2009
Date

AN ECONOMIC COMPARISON OF GEOTHERMAL AND CONVENTIONAL HEATING SYSTEMS FOR GREENHOUSE OPERATIONS

By

Elizabeth Dawn Miller

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Agricultural Economics

2009

Abstract

AN ECONOMIC COMPARISON OF GEOTHERMAL AND CONVENTIONAL HEATING SYSTEMS FOR GREENHOUSE OPERATIONS

By

Elizabeth Dawn Miller

Greenhouses are hit hard by rising energy costs, with some studies reporting that heating is upwards of 70% of greenhouse energy consumption. Due to the rising cost of heating, as well as increasing demand for renewable sources of energy, alternative options are being considered. This analysis compares the 15-year cost of a solar-assisted ground source heat pump system to a conventional high-efficiency hot water boiler system in a mid-Michigan greenhouse, including the initial investment, operational costs and maintenance costs. Included are the net present value of costs for each system, discussions on the amount of energy purchased compared to the total amount of energy consumed, how changing the inputs will affect the results of the study, and a discussion on the effect of a carbon tax. Initial results indicate that the average annual cost per square foot of the solar-assisted geothermal heat pump system is larger than that of the conventional boiler system while the average energy costs per square foot are smaller for the heat pump system.

Acknowledgements

This thesis would not have been possible if not for the professors who pushed me to go to graduate school in the first place; thank you Dr. Stephen Harsh, Dr. Jim Hilker and Dr. Larry Hamm. Also, a big thank you goes to my committee members, my thesis advisor Dr. Harsh, my academic advisor Dr. Hilker and my third, valuable, committee member Dr. Erik Runkle. Thank you for being patient, and (especially Dr. Harsh) for taking so much time to make sure I would be able to finish well. Your support has been invaluable.

My wonderful husband Rob also deserves a lot of thanks, for being with me through the whole process, understanding when I was stressed, doing everything he could to lighten my load, take care of me, making me happy, giving me flowers, and for just being there. I love you and I look forward to what our future will bring.

Thank you to all of my parents and siblings (direct relations, in-laws, steps, and "adopted"), and all of my friends. You guys have been exactly what I have needed too many times to count; including not giving me grief for never coming around, and making sure I took the time to have fun. A very big thank you especially goes to Nicole Olynk. You shared your home, your dogs, your time, your knowledge, and best of all, your friendship. I will miss being your roommate! To everyone else in Cook hall – It has been fun! Thank you for giving me a good experience in starting a graduate program. I will miss you as I start anew in Illinois! Last but not least; thank you to everyone who kept the surprise secret, even if you were not directly a part of it. It has been the biggest, best surprise yet, and you all made me want to finish even more (and do better) to make it worth it!

Table of Contents

List of Tables

List of Figures

Key to Abbreviations and Symbols

Abbreviations

% BTU from heat pump ...Percent of BTUs supplied by the heat pump

% BTU Purchased ...Percent of total BTUs purchased

% Energy Cost of Total Cost ...Energy cost as a percent of total cost

% Solar ...Percent of BTUs supplied by the solar field

AAC ...Average annual cost per square foot

AAEC ...Average annual energy cost per square foot

AAEC savings ...Average annual energy cost savings over boiler system per square foot

Added AAC...Added annual average cost per square foot over the boiler system

AFUE...Annual Fuel Utilization Efficiency

BTU ...British Thermal Unit

C...Celsius

COP ...Coefficient of Performance

DGH...Direct Geothermal Heating

DLSC ...Drake Landing Solar Community

DoD ...Department of Defense

DOE ...Department of Energy

EIA ...Energy Information Administration

ERS ...Economic Research Service

F...Fahrenheit

Ft ...Feet

GHP...Geothermal Heat Pump

GHPC …Geothermal Heat Pump Consortium

GISAGHPS …Greenhouse Integrated Solar Assisted Geothermal Heat Pump System

GSHP …Ground Source Heat Pump

GWH/yr …Gigawatthours per year

KW …Kilowatt

KWH …Kilowatt-Hour

LIEEF …Low-Income and Energy Efficiency Fund

M-3…Cubic Meters

MACRS …Modified Accelerated Cost Recovery System

MBTU …Thousand BTU

MCF …Thousand Cubic Feet

MDEQ …Michigan Department of Environmental Quality

MmBTU …Million BTU

MRC …Michigan Residential Code

MWT …Megawatt Tons

NG …Natural Gas

NPVC …Net Present Value of Cost

REAP …Rural Energy for America Program

SAGSHP …Solar Assisted Ground Source Heat Pump

tC …Metric tons of Carbon

U.S.…United States

USDA …United States Department of Agriculture

UV …Ultra-Violet

VG …Virtual Grower

Coefficients

$CO2…Total after marginal tax carbon tax amount born by the greenhouse

$KW… Price of a KW of electricity

$KWHP… Total cost for KWs used by the heat pump

$KWSolar…Cost of KWs used by solar system

$MCF… Average price of natural gas in $/MCF

$NG… Total cost of natural gas used

%BTUPurch…Percent of total BTUs purchased

%Dep… Depreciation percentage

%HP…Percent of BTUs supplied by the heat pump

%Solar… Percent of BTUs supplied by the solar field

°C… Degrees Celsius

°F… Degrees Fahrenheit

°F/°C… Conversion of degrees Fahrenheit per degree Celsius (9/5)

AAC… Average annual cost per square foot

AAEC… Average annual energy cost per square foot

AAEC Savings… Average annual cost savings of SAGSHP system over boiler system

Added AAC… Total added AAC of the SAGSHP system over the boiler system

ActualTaxCred… Actual tax credit

ANN… Annuity payment

ATC… Total after tax and depreciation cost

ATDep… After tax value of depreciation

AvailTaxCred… Available tax credit

BTU… BTU heat loss used in the model

BTUC… BTU heat loss predicted by Virtual Grower under an energy curtain

BTU/Ft^2S… BTUs per square foot of solar panels per year

BTUGF… Total BTUs in the geothermal field

BTUGF/°F… BTUs per degree Fahrenheit in the geothermal field

BTUHP… BTUs actually produced by the heat pump

BTUNC… BTU heat loss predicted by Virtual Grower under no energy curtain

BTURem… BTUs removed from the soil

BTUS… BTUs the solar collector collects

BTUsav… BTUs saved by the energy curtain

BTU Set Point… BTUs needed to reach the set point

C… Cost of equipment

$Cal/Ft^3/°C$… Calories per cubic foot per degree Fahrenheit

COP… Coefficient of Performance

COR…Carbon output rate

CT… Carbon tax

Dep… Total depreciable cost of the investment

DepValue… Depreciable value after depreciation

DR… Discount rate

E… Boiler efficiency

ElecProd… Electricity produced

Energy Cost… Present value of the total energy costs of the system

Energy Cost %... Percent of total costs that are energy costs

FC… Field capacity

Ft^2/M^2… Conversions from square feet to square meters

Ft^3GF… Total cubic feet in the geothermal field

Ft^3/M^3… Conversion from cubic feet to cubic meters

g/cm^3… weight of the soil at field capacity in grams per cubic centimeter

Growth… Projected growth

HrsSolar… Hours the solar system runs

IMainB… Initial maintenance cost of the boiler system

IMainG… Initial maintenance cost of the geothermal heat pump system

IMainS… Initial maintenance cost of the solar system

Ins… Insurance

Int… Interest payments

InvCost… Investment cost

IR… Interest rate

$KWHP_t$… Actual KWs used by the heat pump in hour t

KWHP… Total KWs used by the heat pump in a year

KW/HsP… Conversion of horsepower to kilowatts

KWS… Kilwatts the solar system used

L… Life of equipment

Labor… Cost of labor

LBal… Loan balance

LbCO2… Pounds of CO2

Loan… Total amount of loan

M^2S… Total square meters of solar panels

Main… Total yearly maintenance of all systems

MainB… Yearly maintenance of the boiler system

MainG… Yearly maintenance of the GSHP system

MainS… Yearly maintenance of the solar system

MargTR… Marginal tax rate

MBTUG… Rating of the GSHP system in thousand BTUs

MBTUB… Capacity rating of the boiler system in thousand BTUs

MCF… Thousand cubic feet of natural gas

MCF Used… MCF used by boiler

MKWHP… Kilowatts used by the heat pump motor

MmBTU… Million BTUs

MTCO2… Total metric tons of CO2 attributed to the greenhouse

MTConv… Short tons to metric tons conversion

MTE… Metric tons of CO2 produced

MTNG… Metric tons of CO2 from NG

NATC… Net after tax cost

NGCO2conv… BTUs of NG to metric tons of CO2 conversion

NonDep… Total non depreciable costs

NPVC… Net present value of cost

NPVEC… Net present value of energy cost

OpInv… Total operating investment

PostMTaxC… Post marginal tax cost

PostTaxCD… After tax cost with depreciation

PostTaxDep… After tax value of depreciation

PotBTU... Potential BTUs the heat pump can produce

PotKW… Potential KWs the heat pump will use

PreTaxC… Total pre-marginal tax cost

Prin… Loan principle

PT… Property taxes

PVC… Present value of cost

PVDR… Present value discount rate

S… Salvage value of equipment

$S°F_{+}$… Temperature added to the geothermal field by the solar panels

SFT… Square feet in the greenhouse

SH… Specific heat

SHFC… Specific heat of the soil at field capacity

SolarInv… Total investment in solar system

ST... Soil temperature in degrees Fahrenheit

TaxLiab… Tax liability

T-1… The previous year

TKW… Total kilowatts consumed by the heating system

Total Cost… Present value of the total costs of the system

UnitsB… Number of boiler units

UnitsG… Number of GSHP units

Superscripts:

US… United States

MI… Michigan

T-1… Previous year

i… Electricity source

Subscripts:

B… Boiler

e… Equipment

H… Heat pump

M… Maintenance

S… Solar

t… Hour

T… Year

t-1…Previous hour

T-1… Previous year

T+1… Next year

W… Water

Chapter 1

INTRODUCTION

With the right temperature, light, and culture almost any crop may be grown year round, if a greenhouse owner is willing to pay for it. In Michigan, in order to grow most crops in a greenhouse, a heat stabilizing system is needed. This temperature stabilization can be done with a myriad of technologies, including a boiler system that may burn natural gas, liquid propane or another material, electric space heaters, and geothermal heat pumps. These energy sources, among others, have seen large price increases since the early 2000's, leading individuals and business searching for ways to decrease the cost of their energy usage. In most greenhouse operations, a major factor of energy cost is heating (Uva and Richards 2000; Boyd 2008). Wen-fei Uva and Steve Richards indicate that heating fuel alone costs an average of 5.4% of sales in a study of New York Greenhouses in 2000 (Uva and Richards 2000). Studies from the Geo-Heat Center by Tonya Boyd in 2008 indicate that utility costs are between 6 and 16% of the total greenhouse budget for costs depending on the location of the greenhouse (Boyd 2008).

Unfortunately, with rising energy costs in the United States, the cost of heating a greenhouse is rising as well, possibly making these earlier findings from Uva and Richards, as well as from Boyd, below what might be reported today. One way that a decrease in energy costs, as well as a decrease in reliance on non-renewable energy sources, can be achieved is through the use of geothermal heat pump (GHP) systems, through which heat is extracted from the earth or a qualifying water source and utilized in structures like greenhouses and homes (IGSHPA 2008). GHP systems have been used in greenhouses, homes and commercial businesses for over 30 years. For example, a greenhouse of over four acres in Quebec, Canada that specializes in cut flowers uses a GHP system which has been found to handle 89% of the annual heating load (Boyd and Lund 2006). The cost of installation was about $1.2 million, and the annual operating cost savings are reported to be about $115,000.

Another Canadian example of an alternative heating system is in Drake Landing Solar Community (DLSC), which started operating in Okotoks, Alberta, Canada in 2007 (DLSC 2005). The DLSC system utilizes geothermal technology as well as solar heat collectors to heat the homes and hot water of 52 residences. Solar heat is collected year round, stored in the ground, and utilized as needed. DLSC explains that in a few years, it is expected the solar heat collected will increase the heat of the geothermal field enough to be used as a direct heat source. The geothermal field can store a high amount of heat because part of the storage field includes granite rock, which has a very high capacity for holding heat.

Two Michigan GHP examples include vertical bore hole ground source heat pump systems installed at a greenhouse in the Kalamazoo area, and another at a home for retired sisters from the Immaculate Heart Of Mary, "Mother house", in Monroe (Monacelli 2008; Rackley 2008). The Motherhouse consists of a 450 ton high efficiency heat pump, with 232 bore holes each 450 feet deep (Rackley 2008).

This research does not focus on how to improve energy use or efficiency of the greenhouse; rather, this project investigates whether or not a ground source heat pump system (GSHP), which is a type of GHP, exhibits a cost effectiveness over the more popular boiler system in a Michigan greenhouse. As the name implies, GSHP utilizes heat that is stored in the ground to heat above-ground spaces. One reason this is possible is because temperature stability of the earth increases with depth. At about 5 feet down, the ground does not freeze; in fact, it stays at a fairly constant temperature of somewhere between 45 and 55 °F (7.2 to 12.7 °C) (Klaassen 2006). Currently, uncertainty over installation costs, maintenance and operational costs, and reliability over the life time of the system have led to slow adoption of the technology (Bloomquist 2000).

Another reason to invest in GHP technology includes reducing the carbon footprint of the greenhouse, as well as cultivating more environmentally friendly production practices (Hanova, Dowlatabadi et al. 2007). Many individuals and businesses are not only becoming more aware of the impact they have on the environment, they are also trying to reduce that impact. Companies are changing production practices, ingredients, and labels to reflect this increasing awareness, letting customers know that they are increasing the amount of "green" energy they are using (SC Johnson & Son 2008). For example, the label on SC Johnson's Windex® now boasts that it is a "greenlist™" product, which is intended to indicate that the product is less detrimental to the environment than similar products. SC Johnson has also invested in television advertising to highlight and spread that word of their further commitment to being environmentally friendly. For example, in one commercial it is made clear that Windex® is made in a facility that uses a "significant" amount of electricity produced through landfill and natural gases. By investing in renewable resources, not only will a greenhouse or any other business reduce their usage of non-renewable resources, but they may also create a "new" product for customers (for example plants or flowers grown using renewable resources), which capture the public's attention in a good way.

Whether or not GSHPs are a viable option in greenhouses depends on multiple factors including size, specifics of the geothermal system, crops grown, seasonal utilization, energy prices, location, and more. In the process of analyzing the use of GSHP for the main heating load of a greenhouse, this research will examine the feasibility of storing solar heat in the geothermal field to replenish the heat removed by the heat pump. There are two reasons this assistance is being examined. Primarily, if heat is removed from the geothermal field during the heating season, and none is returned, the average temperature of the ground will decrease over time. The solar panels may be a way to keep the temperature of the ground constant, or perhaps increase the average temperature over time. Additionally, this increase in ground temperature will likely increase the efficiency of the heat pump.

The hypothesis of this part of the research is that the antifreeze solution will be heated by the solar panels and sent to the geothermal field until it starts snowing or air temperatures drop too low to collect heat efficiently, thereby increasing the temperature of the field. In the best-case scenario, the heat of the source will be high enough to be used directly, without having to engage the heat pumps, which will lead to a decrease in energy usage. In the most likely scenario, although the geothermal field will be at least recharged every year, it will not hold enough heat for direct heating. This dual mode of operation is assumed more efficient than if solar panels were not used; the temperature of the source at the time the heat pump is turned on, after the solar collectors have been operating during the summer, will be closer to the set point of the greenhouse than if solar collectors were not used. In other words, the *lift* will be smaller. "Lift" is the difference between the temperature of the heat source and the target temperature of the space being heated; the smaller the lift, the more efficient the heat pump will be (Lund, Sanner et al. 2004). The lift of the system is expected to increase over the course of the heating period, which means that the efficiency of the heat pump is expected to decrease over that same period.

This research focuses on the feasibility of heating a greenhouse with a solar-assisted ground source heat pump (SAGSHP) compared to a conventional boiler system using a model created to compare the economics and carbon impact of installing and running the two differing heating systems in a mid-Michigan greenhouse. A representative commercial greenhouse with characteristics similar to what is typically found in Michigan is used to better align conclusions with what may be found if the research was applied to a greenhouse in an area with similar characteristics to those assumed in this thesis.

The heating systems are modeled to run in identical greenhouses, using the same heat distribution system; the comparison is done on the differing costs of the two systems over fifteen years. For example, the cost of building the greenhouse, or of running the greenhouse as a whole, are not included; however, all the costs of installing and running each heating system are singled out and analyzed.

The main objectives of this study are:

1. To explore the economics of investing in a horizontal solar-assisted ground source heat pump system compared to a conventional boiler system in a Michigan greenhouse.

2. To explore issues that may affect the feasibility of the solar-assisted ground source heat pump system.
3. To explore the effects a carbon tax may have the feasibility of the solar-assisted ground source heat pump system.

The hypothesis of this study is that the SAGSHP will be the lower cost system in the long run, as well as will have reduced consumption of non-renewable fuels. Initially, it is expected that the boiler system will be lower cost; however, the system costs comparisons will contend with differing operating and maintenance costs, as well as differing efficiencies, with efficiency indicating the amount of output energy produced from one unit of input energy.

Assumptions of this research

Assumptions made in this research include:

1. The model uses today's information; it does not predict what will happen tomorrow.
2. This study compares the feasibility of a ground source heat pump system compared to a conventional system focusing on costs that differ between the two systems; it does not compare two whole systems of production.

a. The quality of the plants produced in and the revenues from the greenhouse are the same, regardless of the heating system.[1]

3. Once the heating technology is invested, the greenhouse will not invest in an alternate system during the lifetime of the chosen system.
4. The greenhouse is 1 acre of new, polycarbonate bi-wall construction located in Lansing, Michigan.
   a. The greenhouse is built the same regardless of the heating option chosen, the only differences are those directly related to the heating option (i.e. pipes, equipment, maintenance).
5. The greenhouse is heated to 70 °F (21.1 °C) during the day and 65 °F (18.3 °C) at night.
   a. Day is from 7 am to 6 pm.
6. The greenhouse is not heated from May 1 through September 30
7. The greenhouse has an hourly air exchange rate of 1.
8. The greenhouse is passively cooled through natural ventilation.

An introduction to previous research

Although the basic topic of this research has been gaining attention, and much has been published, the research contained here is different from what has been done before in a few ways. Much of the focus in previous research has been on direct geothermal heat use or includes vertical borehole GHP system; for examples, see research from the

[1] There are indications that "green" products may be sold for a premium similar products not produced with "green" technology, however that is not discussed in this research.

Geo-Heat Center in Oregon, or research by Bakos, Fidanidis et al in Greece (Bakos, Fidanidis et al. 1999; Geo-Heat Center 2008).

Another difference is in geography; this research focuses on Michigan in particular. Although extreme temperature fluctuations make the state an interesting focus, most current research does not specifically include Michigan. Thermal solar-assisted heat pump studies have been performed in Turkey. One example is a research study by Ozgener and Hepbasli at Ege University in Turkey (Oxgener and Hepbasli 2005). The research had two objectives: 1) to introduce a decision-making method for the geothermal integrated solar assisted geothermal heat pump system installed in Ege University, and 2) to review geothermal heat pump use in Turkey's greenhouses. The decision-making model introduced uses an analytical hierarchy process, and the findings of the study were that the solar-assisted heat pump system was economically preferable to that of a conventional split heating/cooling system under the conditions of the study.

This thesis is presented in six chapters. Chapter one, Introduction, has been an introduction to the topic of study, including the objectives of the research. Chapter two, Greenhouse Heating Overview, provides an overview the greenhouse industry for Michigan in particular, and for the role Michigan plays in the United States' greenhouse industry; additionally, past and possible future energy prices will be discussed. Chapter three, Heating with Geothermal Heat Pumps, consists of a further review of literature available on geothermal heat pump technology, including where it is used and how, feasibility studies under certain conditions, and the economics and models that have been used to study them. State and Federal incentive programs that may be available to greenhouses installing and using alternative energy, and heat pumps in particular, will be included in chapter three as well. Chapter four, The Model, describes the analytical model that is used to compare the GSHP system to the conventional boiler system. This chapter explains how the model calculates the NPV of the cost of each system, as well as details on how the base specifications of model are chosen and how it can be applied to more than the representative greenhouse used for this research. Chapter five, Results, presents the results from the model, as well as some sensitivity analysis. Included are the effects of changing the geothermal field size, energy prices, and carbon tax rate. Also included are the effects of reaching certain goals, for example only purchasing 50% of the energy used for heating. Chapter six, Conclusion and Discussion, provides a summary of the findings, conclusion about what they actually mean, and recommendations for future use of the model.

Chapter 2

GREENHOUSE HEATING OVERVIEW

The Economic Research Service (ERS) reported that the nursery and greenhouse industry was the fastest growing segment of agriculture in the U.S. in 2005 (Burden 2008). This section will explain types of greenhouses and building materials most commonly used in greenhouses. Styles of private greenhouses are briefly presented, however this research focuses on commercial production greenhouses. Private greenhouses are, in general, smaller and often very seasonal, and these smaller and/or seasonal greenhouses do not usually produce enough sales to offset the higher cost of a GHP system.

Following this general overview, specific information related to Michigan, as well as Michigan's position in relation to the rest of the U.S. greenhouse industry, is presented. The next section presents choices a potential greenhouse owner/operator faces in choosing a heating system, followed by an outline of historical and possible scenarios regarding future energy prices.

Greenhouse Design Overview

When deciding to build a greenhouse, an owner must consider location, cost and purpose of the greenhouse (e.g., extending the growing season for personal use, or commercially producing crops), among other design options. A homeowner who wishes to grow plants out of season may decide on a structure that fits on a windowsill, attaches to the side of a house, or is a stand-alone structure. Other greenhouses, those designed for commercial purposes, may contain many acres of production under a single roof.

Some personal and commercial greenhouses are temporary or seasonal structures (e.g., hoop-houses), which are only meant to elongate the growing season by several weeks. These greenhouses can be for personal or commercial use. These are not strictly controlled environments, meaning that among other things, they are not heated and/or artificially lit, which makes them inexpensive to operate.

This research focuses on large, permanent commercial greenhouse structures that may be used all year. Temporary structures are not included in this research because they are not meant to operate while the majority of heating is required. GSHP technology generally has a higher total initial investment than other more commonly used heating systems; therefore, in order to get an economic benefit within the life span of the system, it is important to make intensive use of the system (IGSHPA/OSU 2008). This concept will be explored in more detail later in this thesis.

There are two main categories of commercial greenhouses: 1) freestanding and 2) ridge and furrow, or gutter connected (Schnelle and Dole 2007). Freestanding greenhouses are single structures, and are usually seen in the Quonset style (Figure 1), which presents constrictions on height at the sidewalls, or single gable design (Figure 2), which have more height at the sidewalls as well as a variety of roof styles (Schnelle and Dole 2007). Ridge and furrow greenhouses (Figure 3) are also referred to as gutter-connected greenhouses or as a greenhouse range because, unlike the freestanding houses, a gutter connected house may have multiple houses sharing common walls, or gutters. However, similar to the single gable greenhouse design, gutter-connected greenhouses have a variety of roof structures available (Schnelle and Dole 2007). Many larger greenhouses are gutter-connected because it is easier to close off one or more sections of the greenhouse when they are not in use, saving in the cost of heating unused space (Schnelle and Dole 2007).

Figure 1. Quonset style greenhouse

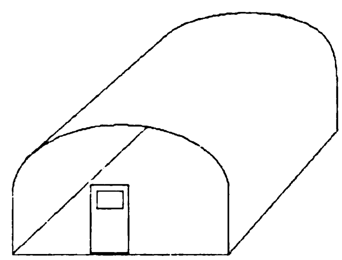


Figure 2. Single gable greenhouse

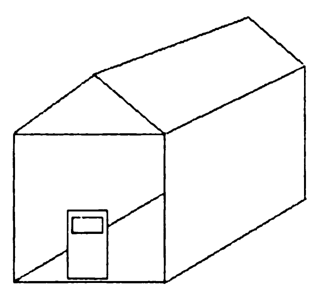
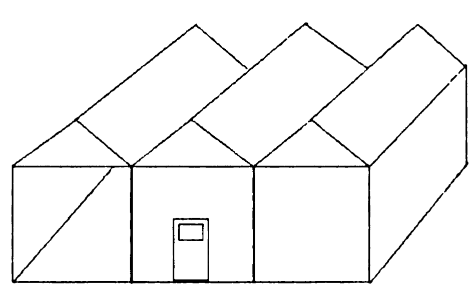


Figure 3. Ridge and furrow, or gutter-connected greenhouse



Greenhouse frames are most often made of wood, steel, or aluminum, and historically, wood was the most popular framing material; however, wood is not used in most applications today because even treated lumber decays easily in the high and constant humidity level of a greenhouse (Schnelle and Dole 2007). Steel has a longer life span than wood and provides better overall support for larger greenhouses than either wood or aluminum; however, due to its weight, it needs more support than an aluminum frame (Schnelle and Dole 2007). Steel also requires more maintenance than aluminum, in part because it must be coated to survive the greenhouse environment (Schnelle and Dole 2007). Aluminum, which is commonly used today, may have a higher initial cost than the other options, but it lasts longer, requires limited maintenance after installation, weighs less than wood and steel, and has the added bonus of being able to reflect light and heat (Schnelle and Dole 2007).

There are many options when it comes to covering the chosen frame, including materials that are rigid (e.g., glass and fiberglass) and those that are flexible (e.g., polyethylene). The decision on which material to choose is, in part, based on cost, lifetime of the material, crops to be grown, light transmission, insulation properties (also called heat transfer coefficients or U-values), and expectations of how the greenhouse will be managed. For example, if a greenhouse owner/operator decides that the inexpensive cost of covering a greenhouse with a double layer of polyethylene (which is separated by a layer of inflated air) outweighs having to replace it every three or four years, it may be a good choice for their situation. The relatively low cost of "double-poly", or a double layer of polyethylene separated by a layer of inflated air, has led to its current popularity (Schnelle and Dole 2007).

Heat transfer coefficients, or U-values, are a measure of the rate of heat transfer of specific materials; the smaller the U-value, the lower the heat transfer (Darling 2009). In greenhouses, a small U-value paired with a lot of light transmission is a good thing. Some U-values are presented below in Table 1 (USDA-ARS 2006). As can be seen below, the best insulation is in polycarbonate tri-wall with polycarbonate and acrylic bi-wall following behind. Glass has the highest U-value, which means it is the worst of the listed covering materials in terms of insulation.

Table 1. U-values of select greenhouse covering materials

Covering material	**U-Value (BTU/Hr F° ft)**
Glass	1.13
Fiberglass	1
Polycarbonate bi-wall	0.65
Polycarbonate tri-wall	0.58
Acrylic bi-wall	0.65

Glass is the oldest, still used rigid material option in covering a greenhouse, however, compared to other options currently used, glass is heavy and has a high U-value; therefore, the cost of support and heating with glass have to be weighed against the benefit of higher light transmission (Schnelle and Dole 2007). Also, Glass has one of the highest maintenance costs due to breakage, and any joint located between two panes, or between a pane and the frame, is a possible air leakage point (Schnelle and Dole 2007). The smaller the pane, the more panes are needed, and thus more leaks are possible. Larger panes do mean less possible joints, however the panes may break easier. Glass comes with a few options other than the size; besides clear, it can be frosted and "hammered", which results in better distribution of light (Schnelle and Dole 2007).

Another option in rigid greenhouse covering is fiberglass. A down side of fiberglass is that it degrades fairly quickly when exposed to ultra-violet (UV) rays, causing the life span to be as short as five years; however, better (or higher) grades of fiberglass may last as long as 20 years if coating materials are utilized to prevent UV damage (Schnelle and Dole 2007).

Polycarbonate, a newer material, has a high initial cost and a life span of around ten to fifteen years (Schnelle and Dole 2007). It is rigid, yet flexible enough to be used for Quonset styles, and double and triple walled forms, which increase the strength and insulative properties of the walls, are available (Schnelle and Dole 2007).

An even newer option on the market, acrylic, has high light transmission, impact resistance and strength (Schnelle and Dole 2007). A manufacturer's warranty of about ten years is common; however, the high cost has slowed its adoption (Schnelle and Dole 2007).

Michigan's Role in the U.S. Greenhouse Industry

Between 2005 and 2006, the greenhouse and nursery industries of fifteen states, including California, Florida, Texas and Michigan, were surveyed by the United States Department of Agriculture (USDA) (Jerardo 2007). Although these fifteen states are only about a third of U.S. states, they represent 75% of total U.S. floriculture sales (Jerardo 2007). During the survey period, the number of large growers (those with $10,000 or more in sales) dropped from 7,178 to 6,546, and total acreage included in the survey fell by 3,889 acres (Jerardo 2007). The average covered production area increased by about 2% from 2005 to 2006, while the average open field area decreased by about 4%. Sales per (large) grower increased from 577,823 to 610,426 (Jerardo 2007). Total floriculture sales dropped between 2005 and 2006, while production are fell by 19%, leading to a decrease of about 7% in average floriculture sales per acre of production for large growers (Jerardo 2007).

Total reported domestic floriculture production in the states surveyed decreased between 2005 and 2006 from about $3,969 million to $3,835 million, while the total value of floriculture sales decreased from $4,931 million to $4,890 million (Jerardo 2007). This $134 million decrease in domestic production combined with the smaller $41 million decrease in sales, indicates an increase in the relative value of imports (Jerardo 2007). To support this, the USDA recorded an increase in the price of many domestic and imported floriculture goods during the year (Jerardo 2007). This increase in price is mainly attributed to higher freight costs, higher energy costs, and higher fertilizer costs (Jerardo 2007).

Michigan has consistently been one of the top seven floriculture and nursery producers in the U.S., and has recently been in the top six, behind California, Florida, Texas, Oregon, and North Carolina (Jerardo 2007)[2]. This rank of states is impacted by their geographic size and climatic ability to produce crops for longer periods with lower heating or cooling costs. For example, greenhouses in Florida may be able to produce roses when it is not be economically feasible in states like Michigan due to higher heating costs and lower light levels.

---

[2] This rank is for all greenhouse, nursery and floriculture crops combined, including those not under cover.

The report also separates floriculture crops by the type of cover it is grown under: glass greenhouses, fiberglass and other rigid greenhouses, film plastic greenhouses, shade and temporary cover, and open field. For greenhouse producers with at least $100,000 of sales, Michigan is ranked third in greenhouse production area, total covered and open ground area, and value of sales at wholesale as of 2006 (Jerardo 2007). The trend in grower numbers for the U.S. as a whole, as seen above, is repeated in Michigan. The number of large growers (those with at least $100,000 of sales) decreased by seven between 2005 and 2006, and total covered greenhouse production area in the state decreased from 45,878 thousand square feet (about 1,053 acres) to 47,034 thousand square feet (about 1,079 acres) (Kleweno and Matthews 2007).

For Michigan, and for all the U.S., the largest covered greenhouse acreage in 2006 was under film plastic, followed by fiberglass and other rigid greenhouses, with glass greenhouses seeing the least acreage among greenhouse crops (Kleweno and Matthews 2007). Across the U.S., all three categories dropped in total acreage from 2005 to 2006; however, in Michigan only glass greenhouses saw a decrease in production area (Kleweno and Matthews 2007). As the decrease of the acreage under glass was smaller than the increase of acreage in the other two categories, the total covered acreage in Michigan increased; in other words, there are fewer producers, but they are producing in a larger area (Kleweno and Matthews 2007).

The Michigan Greenhouse Industry

The Michigan greenhouse industry is a large part of Michigan agriculture; in 2005, the industry was second only to the dairy industry in terms of total farm receipts (Birchmeier 2005). Michigan is also an important part of the floriculture and greenhouse industry of the U.S., being one of the top three states in terms of floriculture crop production in 2005 (Jerardo 2007). In most greenhouses across the nation, temperature, light and water are important factors affecting quality, quantity and rate of growth in production. With regard to these, the climate of a state plays a major role in the management of a greenhouse. For example, when the outside temperature is low, the greenhouse must be heated, or when the days are short, it may need artificial light.

Agricultural statistics for Michigan are tracked by the Michigan Field Office of the USDA. In 2006, the Michigan Field Office reported that the floriculture and nursery commodity group was the third largest commodity group in Michigan in terms of cash receipts, ranking behind livestock and products, and total field crops (Kleweno and Matthews 2007). In terms of single commodities produced in Michigan, floriculture and nursery cash receipts were the second largest percentage of total cash receipts behind milk (Kleweno and Matthews 2007). Michigan was also ranked third nationally in value of wholesale floriculture sales in 2007 (USDA 2007).

Total greenhouse cover in Michigan increased from 2002 to 2006 from 45,038 thousand square feet to 47,034 thousand square feet; however, glass greenhouse area decreased by about 500 thousand square feet, and plastic film greenhouse area increased a relatively small amount, about 300 thousand square feet (Kleweno and Matthews 2007).

The majority of the increase was in fiberglass and other rigid greenhouse material, rising from 3,884 thousand square feet to 6,055 thousand square feet over the survey period.

Michigan experiences wide climate variation throughout the year, with average temperatures in mid-Michigan ranging from a low of about 14 degrees °F (-10 °C) in January to high of 83 °F (28.3 °C) in July (The Weather Channel 2008). In Lansing, the average monthly high temperature is below 60 °F (15.5 °C) for six months, from November to April (The Weather Channel 2008). Depending on the variety of plants grown, and the month they are grown in, the outside temperature may be out of the range of greenhouse set points, or the temperature the greenhouse is set to for optimum plant growth. The variation in outside temperature makes it easy to see why heating and cooling is a large part of the expense for Michigan greenhouses.

Considerable temperature variation, as well as average temperatures below 60 °F for half of the year, may lead to surprise that Michigan is ranked in the top three states in terms of nationwide floriculture production. It is also a reason why Michigan is a good candidate for research on how to lower the cost of heating in the floriculture industry. The state experiences below freezing conditions for part of the year, making heating an expensive part of production; however, producers around the state persevere, and even prosper during the production of bedding plants, for example, which is done during the coldest part of the year. As energy prices rise, however, the cost of heating increases, making it harder for producers across the country to cover their costs. Due to Michigan's high rank in nationwide floriculture production, and the large degree of temperature variation, the representative greenhouse used in this analysis is located in Michigan.

Popular heating methods currently used in commercial greenhouses in Michigan are discussed below. This includes an explanation of possible alternative heating methods, which are intended to reduce the cost of heating through a decrease in fuel used. The main alternative method focused on in this research is the ground source heat pump (GSHP), which is explained in chapter three.

Following the heating methods discussion, a brief history of energy prices and information on possible future scenarios in regards to those prices is introduced. The future prices discussed are from the Energy Information Administration (EIA), which estimates prices for up to thirty years in the future.

Popular Greenhouse Heating Options

The cost of operating a greenhouse is largely related to energy prices, including heating decisions, fertilizer use, fuel for machines, overhead, and more; some estimate that that heating is 75% of the annual energy usage for a greenhouse located in a temperate climate (Bartok 2001; Sanford 2006). This is also supported in research by Wen-fei Uva in 1999, which was conducted through a survey of New York greenhouses; Uva reported that the fourth highest cost for greenhouses was that of heating fuel (Uva 1999). The Uva study, however, was conducted with the average cost of No. 2 fuel oil in the U.S. at 82.9 cents per gallon (nominal), compared to the average U.S. (nominal) cost of No. 2 fuel oil in 2007 around 233.1 cents per gallon (EIA 2008). With the price of No.2 fuel oil almost tripling from 1999 to 2008, the cost of heating fuel is likely an even high portion of greenhouse heating today.

Currently, one of the most popular ways to heat a greenhouse is to use a natural gas or propane fired hot water boiler. In Michigan, natural gas is used more than propane in heating, with over 80% of homes heated with natural gas (MPSC 2008). The price of both of those fuel options, along with the price of all fuels, has been increasing steadily since 2002, causing more research attention to be focused on how to decrease consumption of these higher cost fuels (EIA 2008).

There are many heat source options, as well as many distribution systems that can be used for greenhouse heating; fuel fired hot water boilers, fuel fired steam boilers, electric heaters, unit heaters, vented, non-vented, radiant, under bench, above bench, root heating, forced air, natural gas, propane, wood chips, corn, No. 2 heating oil, etc. With so many options available, including options not listed above and combinations of options, it is not feasible to explain all of them. Therefore, a few of the more popular system options will be discussed: fuel types, heating units, the difference between vented and non-vented, and heat distribution systems (National Greenhouse Manufacturers Association 1998; Evans 2005; Sanford 2006).

Fuel Types

Heaters can operate on many fuels; some heaters use electricity to produce heat although this can be an expensive option; other heaters burn either liquid or solid fuels (Evans 2005). Natural gas, liquid propane gas and heating oil are the major liquid fuels used; kerosene is rarely used in greenhouses and mostly in smaller applications (e.g., spot heating) (Evans 2005). Solid fuels that are used include coal, wood, wood chips, corn, straw, wood pellets and biomass briquettes, among others (Evans 2005).

Unit Heaters

Unit heaters, which consist of a fan mounted in front of a heat supply to circulate warm air through the greenhouse, can usually be found hanging from the top of a greenhouse, although they may also be mounted to the floor (Sanford 2006). The heater can come in electric, oil fired or gas fired, hot water or steam, as well as vented or non-vented (Sanford 2006). They can be used to propel heat directly into the air of the greenhouse by a fan moving air over warm pipes, or they can be used in conjunction with ducts to provide overhead or below-bench heating (Sanford 2006). Unit heaters can be found in many greenhouses, and are sometimes only used to provide additional heating when the base system may not be able to handle the entire heating load (Sanford 2006).

Steam Boilers

A steam boiler system in a greenhouse can be compared to heating a home with radiators: steam is sent through finned pipes that can be placed near the bottom, the top, or around the perimeter of the greenhouse to heat the space (National Greenhouse Manufacturers Association 1998). The steam is made through the burning of some sort of fuel (propane, natural gas, heating oil, etc.), which turns water into steam, and then moves the steam through a radiator system to heat the greenhouse (National Greenhouse Manufacturers Association 1998).

Hot Water Boilers

Hot water systems are very similar to steam boiler systems in that water is used to heat an area, the heated water can be distributed through a radiator type system, and most fuel sources can be used to produce the hot water; however, the hot water system has more distribution options than a steam system (National Greenhouse Manufacturers Association 1998). For example, bare pipes with hot water flowing through them can be used around the perimeter or under benches, hot water can be used for radiant under-floor heating, or it can be used on top of the bench to provide heat closer to the plants (National Greenhouse Manufacturers Association 1998). Hot water boilers can also be used in conjunction with a fan that blows air over the heated pipes to heat the greenhouse (National Greenhouse Manufacturers Association 1998).

Electrical Resistance Heaters

Electrical resistance heaters provide heat produced through electricity and are primarily installed to provide spot heating to specific areas of the greenhouse (National Greenhouse Manufacturers Association 1998). These heaters are usually costly to operate compared to other options and are, thus, not commonly used.

Vented Fuel Fired Heaters

Vented heaters come in four types; gravity vented, power vented, separated combustion and high efficiency condensing (Sanford 2006). Gravity venting consists of a pipe that runs up through the top of the greenhouse, allowing the unwanted gases from combustion to naturally rise up the pipe and out of the greenhouse. Wind traveling across the top of the pipe draws the gases up, and air from inside the greenhouse is used for combustion (Sanford 2006).

Power venting uses a fan, which aids in exhausting combustion gases, as well as in drawing the correct amount of air for combustion in from the greenhouse (Sanford 2006). The venting pipe can exit the greenhouse through the side, which can save on installation costs (Sanford 2006).

Separated combustion uses a fan for exhausting the combustion gases, as in power venting; however, instead of drawing air in from the greenhouse, a separate pipe connected to outside the greenhouse is used for air intake. This is useful if the heater will be running fairly often in a greenhouse with a low infiltration rate (Sanford 2006). This setup prevents back drafts from being inadvertently drawn back into the greenhouse through the exhaust flue (Sanford 2006).

High efficiency condensing heaters are similar to separated combustion heaters; they also use power venting with a separate air intake pipe (Sanford 2006). The difference is that the system condenses some of the gases in the flue to extract out a bit more energy from the same amount of fuel, which requires a disposal system to neutralize the acidic liquids condensed from the exhausting gases (Sanford 2006).

Unvented Heaters

Unvented heaters expel gases produced by combustion into the greenhouses, which are mostly carbon dioxide and water vapor (Sanford 2006). Both of these gases can aid production in the greenhouse; however, like with most things, too much can cause problems. Water vapor production can be very high, with some estimates at about 1½ pounds of water for every gallon of liquid propane gas that is burned (Sanford 2006). Higher levels of water vapor can lead to an increase in the probability of fungal diseases, and if the water vapor condenses on the glazing material, it can block light entering the greenhouse (Sanford 2006). Unvented heaters also require a fresh air intake pipe to pull oxygen rich air in from outside of the greenhouse (Sanford 2006).

Heat Distribution Systems

Heat can be distributed through the greenhouse in a few ways. The air can be warmed by a fan blowing over heated pipes, hot water being pumped through pipes placed around the greenhouse, or steam being sent through pipes around the greenhouse (Evans 2005). The pipes can be placed near the top of the greenhouse, around the base of the perimeter, under benches, above benches, in the floor for radiant heating, or be provided directly to the roots by heating the soil in which the plants are grown (Evans 2005).

Alternative Greenhouse Heating Options

Extensive research is being done with alternative energies (e.g., wind, solar, and bio-fuels) to reduce electricity and fuel consumption, and some of this research is focused on decreasing non-renewable resource use in heating. Thermal solar collectors, geothermal heat exchangers, and various types of GHP are gaining the attention of the public eye.

Thermal solar collectors are being used in many applications to heat water, of which the most well known are domestic solar pool heaters. They are also used in building heating applications, both as the main source of heat, and as a supplement to an existing heating system. An example of thermal solar collectors being used for heating both domestic water and homes is Drake Landing Solar Community (DLSC) in Okotoks, Alberta, Canada, which was launched in September of 2007 (DLSC 2005). DLSC also uses geothermal exchange technology in conjunction with the solar thermal collectors. Heat exchangers are different from heat pumps in that a heat exchanger is a form of geothermal direct heating, which will be explained more in chapter three. On cold, sunny days, the solar panels will collect heat to send directly to the 52 homes in the community. On warm, sunny days, the solar panels collect heat to store in the geothermal field, which is located under the community playground (DLSC 2005). On cloudier days, or when the solar panels do not provide sufficient heat to homes, the heat exchanger is used; the heat that was stored in the field is used to heat the homes (DLSC 2005). DLSC also has a back-up heating system in case the solar panels and heat exchanger are not enough, or if one of the components encounters a problem.

Geothermal options, or using the earth's own heating and insulative properties, have been used in various forms around the world for heating homes and businesses on a commercial scale since the 1920's (Omer 2008). As of 2006, some form of geothermal energy is used in all 50 states in the U.S. (Green and Nix 2006). Direct geothermal heating (DGH), or using geothermal heat exchange, has been used in many applications, including to heat schools, jails, homes, businesses, and a few greenhouses, for many years (Geo-Heat Center 2008). DGH involves using water from warm springs, geysers and similar hot water sources (over 140 °F or 60 °C) to directly heat a building. This is not a very practical option in many instances, however, as the availability of appropriate hot water sources are not widespread across the country. In places that have an appropriate source available, DGH may be an economically acceptable alternative to using non-renewable resources in heating applications.

Due to the difficulties in using DGH in many areas throughout the country, an option gaining more attention is that of GHP. Heat pump systems can be used with water sources, with the air, or with the ground; the system extracts heat from the source, consolidates it and uses it to heat buildings. They may also be used to cool buildings by working in reverse; taking heat from the building and sending it back to the source. GHP technology has been used in heating and cooling applications for over 50 years, and it has been gaining more attention over time (Bloomquist 2000). Between 2000 and 2006, the total GHP capacity shipped from U.S. manufacturers increased from 35,581 tons to about 63,682 tons, an approximate increase of 10.2% per year. In discussing heating capacity, tons measure the rate that heat moves, and British thermal units (BTUs) are a measure of heat; one ton is equal to 12,000 BTUs per hour, and one BTU will raise the temperature of one pound of water by 1 °F, (Sima 2008). Of the total GHP capacity shipped in 2006, the majority of it went to the Midwest, including Michigan, Illinois, Ohio and Indiana (EIA 2008).

Heat pumps that rely on air for the heat source are not very efficient in climates similar to that found in Michigan because the air can get very cold during the winter, when heat is needed the most. The larger the difference in temperature between the heat source and the temperature required inside, the less efficient the heat pump will be. The concept of using water or the earth revolves around the idea that water and the ground itself does not freeze below certain depths. In fact, as depth increases, the temperature first becomes constant throughout the year, and eventually starts to increase by small amounts. This constancy means that the source will be warmer than the air in the winter and colder than the air in the summer; in other words, it will be closer to the desired indoor temperature.

A potential problem in using GHP in a greenhouse is that during extremely low outside air temperatures, the heat pump may not be able to handle the heat load alone (Rybach and Eugster 2002). This can be solved with a back-up heating system, which may also function as an emergency heating system in case of a power outage. As the heat pump system is run on electricity, a generator that can produce enough power to run the heat pump system and the heat distribution system may be very expensive. Another potential problem with this research is that the GHP will only be used to heat the greenhouse. Without sending heat back to the ground, the temperature of the ground is expected to fall over time. The solution in this research is to use thermal solar collection; this will be explained in chapter four.

When deciding on a heating option for a greenhouse, one thing to consider is the quality of the plants being produced. Different species of plants require slightly different temperatures, irradiances, and day lengths to be grown to a high level of quality in an acceptable amount of time (Runkle 2007). In this research, it is assumed that the representative greenhouse will be managed the same way regardless of the heating option. Therefore, the quality, quantity, and type of plant produced would be the same whether a heat pump or a conventional boiler is used.

Another situation to consider when deciding on a heating option is the efficiency of the heater. Heating efficiency in heat pumps and other electric heaters is measured by the coefficient of performance (COP) (Sima 2008). COP specifies the amount of heat emitted per unit of electrical power used to achieve that performance, measured in the same units. For example, a COP of 3.5 indicates that for every unit of electricity that is used, three and a half units of heat may be produced. An electric heater usually has a COP of about one, while a heat pump may have a COP higher than four (USDE 2008).

For boilers, heating efficiency is measured by the annual fuel utilization efficiency (AFUE) (USDE 2008). An AFUE rating of 85%, for example, indicates that 85% of the heat produced by the boiler is actually used to heat the space, while the last 15% is lost through the chimney or equivalent structure; this rating does not include the heat lost through ducts or piping, which can be as high as 35% (USDE 2008). The "mid-efficiency heating systems" category ranges from 80% to 83%, while the "high-efficiency" category ranges from 90 to 97% (USDE 2008).

Energy Price History and Forecast

The Department of Energy's Energy Information Act (EIA) records prices of energy and fuel commodities over time, and through this source, it can be seen that the cost of all fuel has been on the rise (Table 2). From 2001 to 2007, the average price of regular gasoline in the United States has risen by about 12.2% per year since 2001 (EIA 2008). In 2001, the price was an average of about $1.38 per gallon for regular unleaded gasoline, and in 2007, the price was $2.77 (EIA 2008). Industrial propane prices have risen by about 9.4% per year from an average across the U.S. of about $1.07 per gallon in 2001 to about $1.84 per gallon in 2007 (EIA 2008). The industrial price of natural gas has increased by about 6.3% per year from about $5.24 per thousand cubic foot (MCF) to

$7.59 per MCF in the same time period (EIA 2008). The industrial price of electricity itself has also risen across the board, increasing 3.8% per year - going from a national average of 5.05 cents/Kilowatthour (Cents/KWH) in 2001 to about 6.30 cents/KWH in 2007 (EIA 2008).

Table 2. Past energy prices

Energy Source	2001	2007	% Change
Regular gasoline ($/gal)	1.38	2.77	12.2
Industrial propane ($/gal)	1.07	1.84	9.4
Industrial natural gas ($/MCF)	5.24	7.59	6.3
Industrial electricity (cents/KWH)	5.05	6.3	3.8

The EIA estimates future prices in addition to tracking past and current prices; however, in the estimation of future prices, the EIA only considers what has happened to affect future prices; it does not predict what might happen to affect future prices (EIA 2008). The most recent report, published in December of 2008, estimates that the forecasted price in real dollars for imported light-sweet crude oil will slowly increase to $130.50 in 2030, from its low of about $60.89 in 2009, an increase of about 3.7% per year (Table 3) (EIA 2008). Industrial prices for natural gas are expected to rise from about $6.79 per MCF in 2009 to about $9.32 in 2030, an average yearly increase of about 1.5% (EIA 2008). Industrial electricity prices, on the other hand, are expected to fall by about 0.6% per year from about $0.07 per KWH to about $0.062 per KWH in 2014, then increase by about 0.8% per year, reaching $0.074 per KWH in 2030, an overall increase of about 0.3% per year (EIA 2008).

Table 3. Estimated future energy prices

Energy Source	2009	2030	% Change
Light sweet crude ($/barrel)	60.89	130.5	3.7
Industrial natural gas ($/MCF)	6.79	9.32	1.5
Industrial electricity (cents/KWH)	7	7.4	0.3

Chapter 3

HEATING WITH GEOTHERMAL HEAT PUMPS

In 2007, a study by Florides and Kalogirou estimated that there were over 550,000 heat pump units installed worldwide, with over 66,000 units being installed annually (Florides and Kalogirou 2007). A previous study, however, estimated that there were over 900,000 units installed worldwide as of 2004, with the figure more likely to be over 1.1 million (Lund, Sanner et al. 2004). Lund et al. also indicated that the U.S. had an estimated 600,000 units installed at the time of their study. Table 4 shows the estimation of units installed in the top six geothermal heat pump using countries worldwide.

Table 4. Leading countries using geothermal heat pumps (Lund, Sanner et al. 2004)

Country	Units Installed
USA	600,000
Sweden	230,000
Germany	46,400
Switzerland	30,000
Canda	36,000
Austria	23,000

Geothermal heat pumps may represent a small percentage of the heating systems in the world, however they are also one of the fastest growing applications of alternative energy use in the world (Bloomquist 2000). This chapter consists of an introduction to geothermal heat pumps, including heat pump options and definitions. The system chosen for this research is explained, followed by a review of literature found on the topic, including results from previous feasibility studies, and descriptions of how these results were found. The last part of the chapter includes incentives for using ground source heat pumps and solar collectors, including those that are found nationally and in the state.

Geothermal Heat Pump Introduction

What is a geothermal heat pump?

To better understand this research, it is important to define some terminology related to geothermal technology. For example, a "geothermal heat exchanger" and a "geothermal heat pump" are different; a geothermal heat exchanger is the mechanism that transfers thermal energy from one fluid to another, while a heat pump is the mechanism that extracts the heat from the source (USDOE EERE 2008). In order to make advances in research, policy, and understanding of geothermal technology, these terms should be identified and defined.

Geothermal Heat

The term geothermal heat is usually used in reference to direct heating from the earth; direct heating is used where the temperature underground, in hot springs, or in other earth features, is high enough to directly heat spaces (Geo-Heat Center 2008).

Geothermal Heat Exchanger

Also called a plate heat exchanger, or geo-exchange, this refers to low temperature direct heating; when the heat source is between 100 °F (38 C) and 300 °F (149 °C), the heat can be taken from the source and sent directly to heat spaces (Geo-Heat Center 2008).

Geothermal Heat Pump

These are used when ground temperatures are not high enough for direct heating, when the temperature is between 40 °F (4 °C) and 100 °F (38 °C) (Geo-Heat Center 2008). Heat is taken from the earth by a water source or the air through a liquid medium, condensed to raise its temperature, and then sent through a heat distribution system (Sima 2008).

Ground Source Heat Pump

This refers to a geothermal heat pump system that uses heat from the earth itself and may also be referred to as a ground-coupled heat pump, geoexchange system, and more (Bloomquist 2000). Pipes, or the geothermal field, can be arranged vertically in boreholes, or horizontally in trenches; furthermore, the pipes may be straight, or in a "slinky" configuration (Klaassen 2006). The pipes carry heat from the earth to the heat pump, which condenses the heat to increase the temperature of the fluid high enough to be used for heating (Sima 2008).

Water Source Heat Pump

This term refers to a geothermal heat pump system that uses water as the heat source; it works the same way as the ground source heat pump system, with the exception of the heat source or heat sink, depending on how the heat pump is being used (Sima 2008). Other terms referring to this system are well water heat pump, groundwater source heat pump and more. Water source heat pumps may be a closed loop or open loop system.

Air Source Heat Pump

Air source heat pumps also work the same way as ground and water source heat pumps, however they use outside air as the heat source or heat sink; an air conditioning unit that can be found in a window of a home is a good example of an air source heat pump used to cool a room (LeFeuvre 2007). In heating applications, outside air is taken into the heat pump, the heat is extracted, and is then sent to heat a room. This is not a very efficient way to heat the majority of the time, especially in areas like Michigan due to the differences in the air temperature and the desired temperature of the area that is being heated (Lund 1990).

Closed Loop Systems

"Closed loop" and "open loop" refer to the pipes in the ground or water in a geothermal heat pump unit. In closed loop systems, the pipes pass through the heat source or sink without exchanging fluid; instead, fluid is circulated through the pipes, and exchanges heat with the source without coming into direct contact with it (Klaassen 2006).

Open Loop System

In this system, the heat pump pulls groundwater from a water source, for example a pond, well or underground stream; after the water is pumped through the heat pump system, it is returned to another or the same well, pond or other water source (Klaassen 2006).

Water to Water system

In a water to water system, the fluid from the source is heated by the heat pump; the heat either stays in the fluid or is transferred to another fluid, which is then circulated through the heat distribution system. The heat distribution system is a pipe system like a radiator, or in-floor radiant heating, which replaces low temperature fossil fuel fired boiler systems (Chiasson 2006).

Water to Air system

For water to air systems, heat is taken from the water and transferred to the air for heating the space. A blower moving air over heated pipes transfers the heat from the fluid in the pipes to the air. This type of system would replace a more conventional blower or fan system (Chiasson 2006).

In-floor heating or radiant heating

In radiant heating, heat is transferred to pipes that run under the floor. The heat transfers from the pipes to the floor, and then rises to heat the air of the space. This heat distribution system can be used with a water to water system (National Greenhouse Manufacturers Association 1998).

How does a geothermal heat pump work?

A heat pump is a way to *transfer* heat, which is different from a boiler or furnace, which *creates* heat by burning fuels. This heat transfer process is thought to be more efficient, less costly in the long run, as well as more environmentally friendly than conventional systems (LeFeuvre 2007).

A simplified way to think of how a heat pump works is to envisage how a refrigerator works. The fridge does not *make* cold air, but instead *takes* the heat out of the contents of the fridge. Warmth can be felt coming out of the back of the fridge; this is the heat that has been pulled from the fridge's contents. Similarly, a heat pump does not create heat, but takes it out of the fluid, which absorbed it from the heat source.

There are three parts to a heat pump; the heat pump unit, the heat exchanger, and the heating/cooling distribution system (MDOEQ 2007). In the heat pump system, water or an environmentally safe antifreeze solution is pumped through pipes laid in the ground or a water source. The fluid in the pipes reaches the temperature of the source and is then pumped through the heat pump unit, where the heat is extracted from the solution and condensed, which raises its temperature; it is then sent through the heating distribution system.

Different heat pumps explained

Heat pumps rely on water, earth, and air as sources of heat. Air source heat pumps are considered the least efficient, as they use the outside air to heat spaces. In Michigan, air temperatures can be below freezing during the heating season. An air source heat pump may not be able to extract enough heat out of the freezing air to heat a space to a comfortable level. The earth and some water sources do not freeze below certain depths, even when air temperatures are below freezing, and are therefore more likely to contain enough heat for the space to be heated to the level desired.

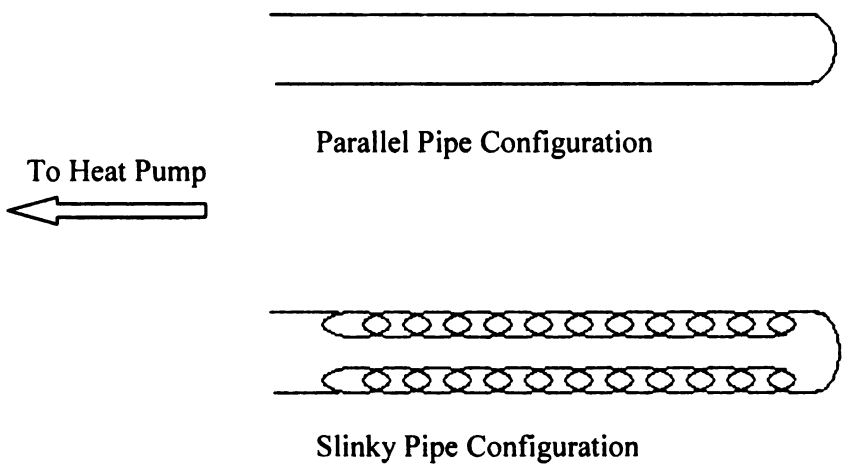
Choices must be made regarding which source to use and how to place the pipes. One choice is to use a water source; it must be large enough, or have enough movement, that it does not freeze all the way through, even in the coldest part of the year. Pipes placed either on or near the bottom of the water source will carry the solution to the heat pump. If the heat pump is used for cooling, they will transfer heat back into the water as well.

Another choice is a ground source heat pump with vertical pipes. The ground does not freeze under a certain depth (usually around 4 to 6 feet), and is therefore warmer than the air above it for part of the year; southern Lower Michigan soil temperatures range from about 35 to 58 °F at 4" under bare soil (NOAA/USDA 2008).

Pipes are placed in holes bored vertically into the ground, and the heat pulled from the geothermal field is sent to a heat pump. As with the water source, the heat pulled from buildings during the cooling process may be stored in the geothermal field as well. Vertical bores are used when there is a constraint on the amount of land, or if the ground is overly rocky (Florides and Kalogirou 2007).

A third option is to use horizontal pipes placed at least 4 to 6 feet under the ground in trenches. The idea behind them is the same as that of the vertical pipes, however more land area is needed. The pipes can be configured mainly in two ways: parallel and slinky (Figure 4). Slinky pipes were designed as a way to fit more pipe surface area into the same amount of space as parallel pipes. Water source heat pumps may also have straight or slinky configurations in the pipes as well, depending on the size of the heat source.

Figure 4. Parallel and slinky pipe configurations



The ground source heat pump system for this research

GMB Architects and Engineers[3] designed an appropriate ground source heat pump system for the representative greenhouse. The heat pump used in this research is

[3] 85 East Eighth St, Suite 200, Holland, MI, 49423

the MultiStack Chiller, Model MS50Z6[4]. The geothermal field modeled in this research has horizontal slinky pipes buried 8 feet under the greenhouse and a radiant floor heat distribution system; the slinky loop consists of 36" diameter loops overlapped 18", and fills the entire footprint of the greenhouse[5] (Figure 5). The slinky tubing is located under the greenhouse to save land space, as well as possibly decrease the total heat loss for both the greenhouse and the trench; however, this may cause problems, as the soil will not get any natural temperature recharge from the sun. In many circumstances, this is not a problem because the heat pump is used to cool the space as well; however, in this project, the greenhouse will be cooled through natural ventilation. The solution here is the use of solar heat collectors, or thermal solar collectors. The thermal solar collectors will absorb heat when viable and send it to the slinky loops, which will distribute it into the earth.

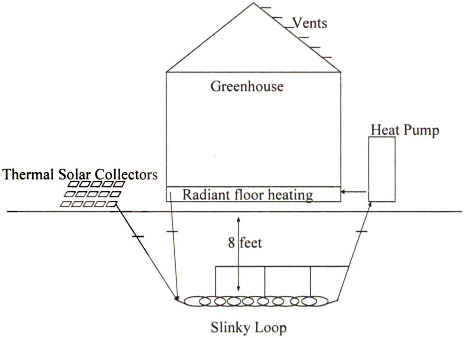
The pipes that connect the slinky loops to the heat pump, the greenhouse and the solar collectors can be closed off independently of the other connecting pipes. This is so the heat that is being stored underground does not enter the pipes unless it is needed. There is also an override pipe, in case one section of the slinky tubing fails. The slinky loop is separated into sections, with each section joining into one main loop, which runs to the heat pump. This is done in case a problem with the pipe arises; the failed section can be closed off, and the heat pump can still run.

---

4 http://www.multistack.com/

5 From personal communication with GMB Architects and Engineers

Figure 5. Ground source heat pump diagram



Studies have shown that ground source heat pumps are more cost effective when installed as part of new construction, in climates with cold winters, hot summers or high daily temperature swings, where electricity cost is higher than average, or where natural gas is either unavailable or more costly than electricity (Omer 2008). The results from Omer's study support the hypothesis for this research, as the greenhouse modeled is of new construction, and is located in Michigan, which experiences cold winters, hot summers, and occasional high daily temperature swings. For example, the average high temperature in July in Lansing is 82 °F and the average low is 58 °F in the same month (The Weather Channel 2008).

Support for Geothermal Heat Pumps

Geothermal heat pumps have been used in U.S. commercial buildings since as early as 1946, and as of 2004 geothermal heat pumps are in use at schools, jails, hotels, greenhouse and aquaculture facilities, laundry facilities, and industrial applications (Geo-Heat Center 2008). Two of these facilities are a heat pump installed in Gault House East Hotel in Louisville, Kentucky in 1945 and a heat pump installed at President George W. Bush's Texas Ranch in 2000 (Lund, Sanner et al. 2004). In addition to geothermal applications being used for heating, there are about 220 "geothermal resorts" in the U.S. with many more in the rest of the world, some examples of which are Fairmont Hot Springs Resort in Fairmont, Montana; Geothermal Spas in Czechoslovakia; and Beppu Hot Springs in Japan (Geo-Heat Center 2008).

Multiple applications of GHP technology are currently in use around Michigan, including a vertical borehole ground source heat pump system at a four acre greenhouse in the Kalamazoo, Michigan area, which was installed in 2007. This system is an example of greenhouse growers becoming more aware of alternative heating options. Other examples of heat pumps in Michigan are a vertical ground source heat pump installed at Selfridge Air National Guard Base in 1995 for use in family housing, and a water source heat pump installed in Goodwillie Environmental School in Ada, Michigan in 2001.

The United States Department of Defense (DoD) has been installing heat pumps since the late 1980's (ODUSD 2007). As of January of 2007 there are over 52,000 tons of water and ground source heat pump systems installed on DoD facilities around the country that heat and cool housing, offices and training facilities, and more (ODUSD 2007). Locations include administrative offices in Fort Knox, unaccompanied personnel housing in Naval Air Station Oceana in Virginia Beach, Virginia and 276 GHP systems installed in the 184,607 DoD buildings in climate zone 5, which includes the Selfridge Air Force Base housing installation. The report on their installation of heat pumps at defense facilities, published in 2007, states that the Midwest region (including Michigan) is quite favorable for successful GHP installations (ODUSD 2007). At least 138 out of 264 currently operating GSHP systems at DoD facilities experience annual positive energy savings, as well as operations and maintenance savings and reduced energy consumption (ODUSD 2007).

A study published in 2000 examined case histories of over 20 GHP systems in the U.S., with an emphasis on systems at least 20 years old (Bloomquist 2000). The results include positive feedback from most owners and operators of the GHP systems with lower maintenance and operational costs cited as the main reason of satisfaction, and a high level of satisfaction with the reliability of older systems, those installed 25 to 30 years ago, when routine maintenance was performed (Bloomquist 2000).

An article by A. Omer comparing GSHP systems, an oil-fired boiler, a gas-fired boiler, a condensing gas boiler and low temperature system, and electrical heating revealed that the systems involving GSHPs were the more efficient choices (Omer 2008). Additionally, the heat pump systems were estimated to have significantly lower CO_2 emissions than all but the condensing gas boiler and low temperature system, which had emissions that averaged close to the middle of the GSHP emission range (Omer 2008).

In 2006, Andrew Chiasson compared the net present value over a 20-year life cycle of both closed and open loop heat pump systems for greenhouse heating for four locations across the United States: Boston, Massachusetts; Dallas, Texas; Denver, Colorado; and Seattle, Washington (Chiasson 2006). With the specifications of the research, feasibility of a closed loop system was found only under levels of low installation cost or high natural gas cost. Although the underlying setup of the greenhouse heating system was similar to that of this research (the greenhouse was an acre in size; the majority of the heat was supplied by a closed loop, water-to-water, ground source heat pump; cooling was assumed to be done through natural ventilation; and the heat load was determined using typical meteorological year data in place of averages over time), differences between the assumptions for this thesis and those of Chiasson exist (Chiasson 2006). The major differences are that in Chiasson's research, 1) the heat pump system in his is a vertical bore hole, 2) there is no thermal solar collection, 3) the cost information is from 2005, 4) electricity costs were held constant over the life of the investment, and 5) there is no inclusion of a possible carbon tax. Whereas for this research, 1) the heat pump is a horizontal slinky loop, 2) there is solar collection, 3) cost information is updated, 4) electricity costs vary over time, and 5) carbon tax and carbon footprint issues are examined.

The study concluded that a closed loop system was feasible for 30% to 50% of the heating, when natural gas prices are between \$0.45 and \$0.60 per cubic meter (\$16.67 to \$22.22 per MCF), and closed loop installation costs were between \$5 and \$8 per foot, respectively (Chiasson 2006). For the closed loop system to be considered feasible for 50% to 70% of the heating load, natural gas prices would have to be between \$0.54 and \$0.65

per cubic meter ($20 to $24.07 per MCF) with coinciding loop installation costs between $4 and $7 per foot (Chiasson 2006). In 2005, the Energy Information Administration (EIA) reported industrial prices for natural gas at an average of about $8.56 per MCF, and industrial natural gas prices were not expected to reach over $9.00 per MCF until after 2028 (EIA 2008). With these reported prices and costs, the GSHP system did not seem like a viable idea; however, as the assumptions for this and Chiasson's research are different, different results are expected.

Table 5. Chiasson's feasible range for GSHP system

Feasible Heating Range	$/M-3	$/MCF	$/Ft
30-50 %	0.45-0.60	16.67-22.22	5-8
50-70 %	0.54-0.65	20-24.07	4-7

A vertical bore heat pump installed at the Lincoln Schools in Lincoln, Nebraska, was found to have lower maintenance costs per year per cooling square foot in a report comparing the cost of this system to an air cooled chiller and gas fired hot water boiler, a water cooled chiller and gas fired steam boiler, and a water cooled chiller and gas fired hot water boiler (Martin, Durfee et al. 1999). The maintenance cost per year per cooling square foot attributed to the heat pump was $9.27, followed by the air cooled chiller system and the air cooled gas fired steam boiler, with the most expensive system, the water cooled chiller and gas fired hot water boiler system, estimated at $20.71 per square foot per year (Martin, Durfee et al. 1999).

As in the U.S., greenhouse heating costs in Turkey are a large part of operating costs; one study indicates that greenhouse heating costs in Turkey were 60% to 80% of operating costs (Ozgener and Hepbasli 2006). In the study, a greenhouse integrated solar assisted geothermal heat pump system (GISAGHPS) was analyzed using the analytical hierarchy process. The conclusion of the GISAGHPS research was that heating with GHP was cheaper than conventional heating systems (Ozgener and Hepbasli 2006). The authors of the research also state that the primary barrier to GHP use in Turkey is the incremental cost of installing ground heat exchangers, which makes the total investment cost of a GHP system higher (Ozgener and Hepbasli 2006).

In another study, Ozgener and Hepbasli concluded that in climates where the heating load is the leading design factor, solar collectors, or solar heat supplementation, can increase the efficiency of the heat pump and reduce the required size of a closed-loop ground source system (Ozgener and Hepbasli 2005). In their experiment, a flat plate solar collector installed to increase the temperature of the heat transfer fluid for a vertical pipe heat pump system was performed on a heating system established in Ege University in Izmir, Turkey (Ozgener and Hepbasli 2005).

A study in France was conducted to evaluate a combined thermal solar collector water source heat pump system installed in a newly constructed 1,620 ft^2 (150.5 m^2) home in France in October 2004 (Trillat-Berdal, Souyri et al. 2006). The heat pump installed had a vertical bore hole, closed loop system, and solar collectors were placed on the roof and consisted of about 108 ft^2 (10.03 m^2) of collection space. During the eleven months the researchers collected data on the house, the indoor temperature was maintained at 66.2 °F (19 °C), and the house only needed heating. The system is set up so the heat collected through the solar panels is first used to heat domestic hot water to the desired level, and excess heat collected is sent to the bore holes. In the second winter of use, 2121 Kilowatts (KW) (7.2 million BTU (MmBTU)) of thermal solar heat was sent to the bore holes, and the heat pump ran for about 298 hours, extracting 6253 Kw (21.4 MmBTU) of heat from the ground (Trillat-Berdal, Souyri et al. 2006). This means that about 34% of the heat extracted from the ground was returned through the thermal solar collectors.

The COP of the system averaged 3.75 during the eleven months, however, it was higher in the beginning of the heating period, having an average value of about 4.0 in September, and decreased through the colder months, reaching its average low of about 3.5 in April (Trillat-Berdal, Souyri et al. 2006). It was also noted that the ground temperature was affected by the addition of solar heat; the initial ground temperature at a depth of about 5 meters (16.4 feet) in October was 52.8 °F (11.6 °C), and at the end of August, the temperature was recorded as 53.6 °F (12 °C) (Trillat-Berdal, Souyri et al. 2006). At the end of the eleven months, the conclusion drawn by the researchers was that the combination of thermal solar collectors and the heat pump used was a viable option in home heating (Trillat-Berdal, Souyri et al. 2006).

A study by Chiasson and Yavuzturk in 2003 was conducted to compare a GSHP system with vertical ground loops to a hybrid GSHP and thermal solar collector system in six heating-dominated areas around the United States (Chiasson and Yavuzturk 2003). In this research, thermal solar collectors were not used to recharge ground temperature; instead, they were used to reduce the load on the heat pump by adding heat to the school modeled. The study used heat load data from a school building along with typical meteorological data from each city to evaluate the costs of the systems over 20 years in an attempt to determine if adding solar thermal collectors could reduce the length of the bore holes enough to cover their cost. The conclusion of the study is that the hybrid system was viable for the conditions in the study when drilling costs were between $6 and $10 per square foot (Chiasson and Yavuzturk 2003).

In addition to the long-term cost savings reported, heat pumps do not consume the same level of non-renewable fuels as conventional heating systems. The Geothermal Heat Pump Consortium (GHPC) estimates that as of 2007, geothermal heat pump use in the United Sates reduced CO2 emissions by 5.8 million metric tons annually, and carbon equivalents by 1.6 million tons (GeoExchange 2008). They also estimate that installations in the U.S. have reduced annual demand for fossil fuels by almost 40 trillion BTU's, and for electricity by at least 2.6 million KW (GeoExchange 2008).

Another benefit attributed to using GSHPs is that the maintenance of a heat pump system is low compared to other systems, as reported in studies such as the Lincoln Schools study above, and the lifetime of the parts is long. The compressor may have a life of about 20 years, and the piping may have a lifetime of 50 or more years (Energy Savings and Trust 2007). Once the pipe is placed in the ground, it should stay there for a long time with little to no maintenance. Upgrading or replacing other parts of the GHP system is necessary; however, it should be at the same rate as a more traditional boiler system.

The research presented here suggests that the Michigan climate is favorable for GSHP systems; GSHP are proven cost-effective in the situations studied, the level of annual maintenance is low, the system's lifetime is long, and reliance on non-renewable fuels is decreased. This research needs to be done, however, because Michigan greenhouse owners and operators require a set of characteristics different from those used in previous research; for example, the climate of Michigan is different from that of Turkey or France. In addition, greenhouses in general encompass a different set of needs than homes, schools, or office buildings, and the inclusion of thermal solar collectors change the system's likelihood of payback due to a higher initial investment and a change in the thermal capacities of the soil.

Federal and State Aid Programs

State Aid

Energy Efficiency Grants:

The Michigan Public Service Commission provides Energy Efficiency Grants to encourage increasing energy efficiency across the state. Businesses, non-profit organizations, government agencies, and schools can apply for the grants, which support projects that involve increasing energy efficiency, including those related to solar, wind, biofuels, and more. The grant program is funded by the Low-Income and Energy Efficiency Fund (LIEEF). More information can be found by contacting the Michigan Public Service Commission.

Federal Aid

The Business Energy Tax Credit:

Commercial, industrial and utility companies that use geothermal heat pumps, solar heating systems and other renewable resources are eligible to receive this tax credit, however passive solar heating systems are not eligible. Solar systems that are not passive and are not used as pool heaters are eligible for a tax credit of 30% of expenditures, which can be taken for up to 20 years if the tax credit total is greater than the businesses tax liability for the year. The tax credit for geothermal systems is up to 10% of expenditures, and eligible systems are those that are placed into service after October 3, 2008. The grant can be used in conjunction with other aid; however, the other aid must be accounted for in calculating the tax credit. More information can be found on the business.gov website.

The Modified Accelerated Cost Recovery System (MACRS) + Bonus Depreciation:

Qualifying businesses may recover investments in certain property through depreciation deductions, and for geothermal and solar projects, this property class is 5 years. Among other requirements, the property must have a recovery period of 20 years or less under normal depreciation rules. For more information, visit the IRS website, specifically *IRS publication 946, IRS Form, 4562: Depreciation and Amortization*, and *Instructions for Form 4562.*

The U.S. Department of Energy (DOE) Loan Guarantee Program:

The U.S. DOE is authorized to issue loan guarantees for projects that aid in reducing greenhouse gases or air pollutants, and that use new or improved technologies as compared to current technologies used at the time the guarantee is issued. Manufacturing projects, stand-alone projects and large scale integration projects that combine multiple renewable energy or energy efficiency technologies are eligible. The guarantee is intended to encourage early adoption of new or greatly improved energy technologies. Increasing the number of new projects employing these energy technologies causes the visibility of alternative or more efficient options to increase. Seeing others use the technology may reduce the level of risk those embarking on new projects attach to new technology, which may lead to improving energy efficiency in production. Visit www.lgprogram.energy.gov for more information.

The USDA Rural Energy for America Program (REAP) - Grants and Loan Guarantees:

REAP was enacted to promote both energy efficiency, and renewable energy. Commercial and agricultural sectors, among others, are eligible to receive this grant, which is provided by through the United States Department of Agriculture (USDA) farm bill. The grants are available to agricultural producers and rural small businesses to purchase renewable energy systems, to make energy efficiency improvements, and to conduct relevant feasibility studies. The grant is limited to 25% of the proposed project's cost, the loan guarantee may not exceed $25 million, and the grant and loan guarantee together cannot exceed 75% of the project's costs. For more information on REAP, visit the USDA's farm bill website at www.usda.gov/farmbill.

For more information on tax incentives for specific U.S. states, on federal incentives, or contact information for each incentive, visit the Database of State Incentives for Renewables & Efficiency website at www.dsireusa.org.

Considerations /Permit requirements

For a heat pump project to be lawfully completed, there are requirements that must be fulfilled. Some of these may be similar for closed and open loop systems, however, due to open loop systems expelling water into the ground or a water source, there are more strict regulations guiding the operation and set-up of open loop systems. As the system being examined for this project is a closed loop system, the regulations for open loop systems will not be discussed.

The Michigan Residential Code (MRC) contains provisions to regulate the installation of closed loop heat pumps, including standards for joining pipes and tubes, and criteria for pressure testing the system before backfilling any trenches. Michigan's Department of Environmental Quality (MDEQ) also advises certain practices for installation of heat pumps. As vertical bore holes may extend into drinking water sources, MDEQ reports specific procedures that must be followed when drilling bore holes, including using certain types of grout for backfilling the wells. Special permits must be acquired if pipes are going to be installed in a water source, in wetlands, or in a floodplain, and a soil erosion permit is needed if more than one acre of land will be disturbed or if the installation will be within 500 feet of a body of water. In addition, mechanical, electrical or plumbing permits may be needed before work is started on the project (MDOEQ 2007).

Chapter 4

THE MODEL

This chapter explains the model built to facilitate this research; included are how the model was created, how information was gathered, and steps taken in using the model. The model is run in Microsoft Office Excel (Microsoft 2007), and determines the net present value of the cost (NPVC) of two different heating systems over the course of 15 years. The model does not include all costs of the systems, but only costs that are different between the systems. For example, the cost of building the greenhouse itself is not included because the greenhouse will be built the same regardless of the heating system. Also, many of the parameters of the model can be easily changed to simulate different environments. For example, the area of the greenhouse, the area of the solar panels, or the start and end of the heating cycle for the greenhouse. Included as well are estimates of tax credits available from the installation of a solar heating system, and estimates of results from possible carbon tax rates.

A few assumptions made in creating the model are:

1. It is uses today's information; it does not predict what will happen tomorrow.
2. This study compares the feasibility of a ground source heat pump system compared to a conventional system and only focuses on areas in which differences are expected; it does not compare two whole systems of production.
    a. The revenues from the greenhouse are the same, regardless of the heating option chosen.

b. The quality of the plants produced is the same under both options[6].

3. Once the heating technology is invested, it is assumed the greenhouse will not invest in an alternate system during the lifetime of the chosen system.

4. The greenhouse is 1 acre of new, polycarbonate bi-wall construction located in Lansing, Michigan.

    a. The greenhouse is built the same regardless of the heating option chosen, the only differences are those directly related to the heating option (i.e. pipes, equipment, maintenance).

5. The greenhouse is heated to 70 °F (21.1 °C) during the day and 65 °F (18.3 °C) at night.

    a. Day is from 7 am to 6 pm.

6. The greenhouse is heated from January 1 through April 30 (though provisions are available to check the results in other situations).

7. The greenhouse has an hourly air exchange rate of 1.

8. The greenhouse is passively cooled through natural ventilation.

The first step in finding the NPVC is to determine initial investments for each system, without the addition of possible solar tax credits or carbon taxes; this in itself is a multistep process. In order to correctly determine investment information, heater size must be assumed; to find the size of the heater, the amount of heat loss the system has to negate must be quantified. For this research, the hourly heat loss of the greenhouse for the entire year was estimated with Virtual Grower 2.01 + Hourly BTU Loss (USDA-ARS 2008). The entire year of hourly BTU heat loss information is estimated in order to examine the difference in cost between heating from January through April and heating from October through April. Detailed information from the representative greenhouse is

---

[6] Related to both a and b, above - there are indications that "green" products may be sold for a premium over similar products not produced with "green" technology, however that is not discussed in this research.

entered into the program, including size, location, building material, and a specific heating schedule; the program then uses typical meteorological data for the chosen location to calculate estimates of heat loss per hour for the greenhouse for the entire year, and highlights the maximum BTU loss per hour.

For this study, industry researchers were consulted to determine typical characteristics for a greenhouse in Michigan that may be constructing a new greenhouse or adding onto an existing house (Runkle 2008). Characteristics established include the size, construction material, and heating schedule of the greenhouse, as described above.

BTU Heat Loss Information

The BTU heat loss estimation from Virtual Grower (VG) was calculated under the assumption of no energy curtain, and with an energy curtain. The energy curtain is used to decrease heat loss from the greenhouse. The estimate with the energy curtain is lower than that with no curtain, as energy curtains are used to reduce heat loss. VG uses the best estimates for energy savings with an energy curtain; this is not representative of actual energy loss because it assumes no tears, gaps, or holes in the curtain. Therefore, BTU heat loss savings of the energy curtain was increased by 20% to represent a more representative heat loss savings; this new BTU heat loss amount was assumed to be the same for every year modeled (Equation 1). To do so, the heat loss savings are found by subtracting the heat loss with a curtain from the heat loss with no curtain. This savings is increased by 20% and added to the heat loss estimates with the energy curtain. The total and maximum BTU heat loss per hour after adjusting for the energy curtain was then calculated for the entire year, as well as for the spring heating schedule assumed in this thesis (Table 6). The hours that are heated under the full year and not the spring schedule are assumed to be taken care of through natural means; high air temperatures in the summer.

Equation 1.

$$BTUsav_t = BTUNC_t - BTUC_t$$

Where:

$BTUsav_t$ are the BTU savings of the curtain for every hour t,
$BTUNC_t$ are the BTU estimates under no curtain for every hour t, and
$BTUC_t$ are the BTU estimates under an energy curtain for every hour t.

Equation 2.

$$BTU = (BTUsav_t * 1.2) + BTUC_t$$

Where:

BTU is the BTU heat loss for every hour t used in the model.

Table 6. Summary statistics

Heat Loss Info	Full Year	Spring
Total MmBTUs	3,909.6	2,356.1
Maximum MmBTUs/hour	3.5	3.5
Total Hours/year	8,760	8,760
Hours Heated	4,330	2,441

The hourly BTU heat loss and the characteristics of the greenhouse were taken to professionals[7] in the field of designing and installing heat pumps for help in designing the SAGSHP system for this project efficiently and with the least cost. Their calculations determined that with the basic design chosen, 500 square meters of unglazed solar panels enable the SAGSHP system to handle 50% of the total heat load. If the area of solar panels were increased to 1,000 square meters, the SAGSHP would be able to handle 87% of the annual heat load. In their calculations, the supplemental heating system would therefore have to handle 50% and 13% of the annual heating load, respectively.

After estimating the initial investment of both options, including materials, installation, labor, and infrastructure costs, the maintenance and operating cost of the systems was estimated. The maintenance costs were estimated by industry professionals and previous research studies (ASHRAE 2004). The operating costs were estimated using the efficiency of the system. For example, a boiler system rated with an 85% efficiency will lose 15% of the heat it generates, therefore the amount of fuel it needs to generate a certain level of BTU's will have to be increased by 15%. In the case of the GSHP, as the heat pump pulls heat from the ground, the lift of the system changes, which affects the efficiency of the system. This will be explained better later in the chapter.

Initial Investment, Depreciable Investment and Operating Investment Calculations

The initial investment (heat pump units, boiler units, geothermal pipe, solar panels, installation costs, etc.) is estimated on a per unit basis, multiplied by the number of units

[7] GMB Architects and Engineers has designed almost 2 million square feet of facilities that use geothermal heat pumps as the primary energy source.

used, and example is given in Table 7. The heat pump modules are modeled to be 50 tons, the boiler modules are modeled to be 25 tons (300 thousand BTU (MBTU)), and the insulation panels are 4x8 feet. The loan for the system is assumed to be 60% of the total cost of depreciable equipment (Table 8). The rest of the investment, that not accounted for in the loan, is labeled as operating investment, and is counted as a cost in year zero.

Table 7. System costs

Equipment and Installation	Price Per Unit	Units Needed	Total Cost
Solar Heat Collectors, incl install. (Sq-Ft)	$9.00	11840.3	$106,563
Heat Pump (Module)	$30,000	1	$30,000
Hot Water Boiler (Module)	$9,400	11	$103,400
Insulated Water Tank (Gal)	$4.00	2000	$8,000
Slinky Loop, incl install. (Ft)	$2.67	43008	$114,831
Side Insulation under Greenhouse (Panel)	$4.60	824	$3,790
Top Insulation Under Greenhouse (Panel)	$5.60	1344	$7,526
Side Instalation under Expanded GT Field (Panel)	$4.60	0	$0
Top Insulation Under Expand GT Field (Panel)	$6.60	0	$0
Pumps, Valves & Pipes (install.) In-floor heating (Sq-Ft)	$2.00	43008	$86,016
Pumps & Valves Heat Pump/Solar heating (System)	$5,000	1	$5,000
Control System (System)	$40,000	1	$40,000
Special Controls System of Heat Pump	$5,000	1	$5,000
Electrical (System)	$10,000	1	$10,000
Electrical Extra for Heat Pump System (System)	$2,000	1	$2,000
Antifreeze Fluid (gal)	$5.00	5000	$25,000
Engineering & Design & Permits	$10,000	1	$10,000
Extra Engineering & Design	$5,000	1	$5,000

Table 8. Depreciable equipment

Solar Heat Collectors, including installation
Heat Pump
Hot Water Boiler
Insulated Water Tank
Slinky Loop, including installation
Side Insulation under Greenhouse
Top Insulation under Greenhouse
Side Insulation under Expanded GT Field
Top Insulation under Expanded GT Field
Pumps, Valves & Pipes, including installation for In-floor Heating
Pump & Valves for Heat Pump and Solar Heating
Control System
Special Controls System for Heat Pump System
Electrical
Electrical Extra for Heat Pump System

Equation 3.

$$Loan = Dep * 0.6$$

Where:

Loan is the size of the loan, and
Dep is the total depreciable costs (see Table 8 for a list).

Equation 4.

$$OpInv = InvCost - Loan$$

Where:

OpInv is the operating investment, and
InvCost is the cost of purchasing and installing the equipment.

Maintenance Costs

The total cost of repairs and maintenance for each system are calculated using initial maintenance values for the GSHP, the boiler and the solar panels, and are increased by 1.5% per year (Chiasson and Yavuzturk 2003). This value includes the cost of labor that can be directly attributed to each system. The GSHP initial maintenance cost is multiplied by the BTU rating of the heat pump, and then multiplied by the number of units used (Equation 5). The boiler maintenance cost is calculated the same way (Equation 6). Solar maintenance is estimated on a yearly basis, and is therefore multiplied by 1.5% every year (Equation 7). The total maintenance cost for each year is found by adding together the results from equation 5 through 7.

Table 9. Initial maintenance costs

GSHP Maintenance ($/MBTU)	1.35
Boiler Maintenance ($/MBTU)	0.3
Solar Maintenance ($/Year)	30

Equation 5.

$$MainG_T = IMainG * MBTUG * UnitsG * 1.015^{T-1}$$

Where:

$MainG_T$ is the maintenance cost of the GHSP system in year T,
IMainG is the initial maintenance cost of the GHSP system,
MBTUG is the rating of the GHSP system in thousand BTUs, and
T-1 is the previous year in the research.

Equation 6.

$$MainB_T = IMainB * MBTUB * UnitsB * 1.015^{T-1}$$

Where:

$MainB_T$ is the maintenance cost of the boiler system in year T,
$ImainB_T$ is the initial maintenance cost of the boiler system,
MBTUB is the rating of the boiler system in thousand BTUs, and
UnitsB is the number of boiler units.

Equation 7.

$$MainS_T = IMainS * (T-1) * 1.015^{T-1}$$

Where:

$MainS_T$ is the maintenance cost of the thermal solar system in year T, and
$IMainS_T$ is the initial maintenance cost of the thermal solar system.

Equation 8.

$$Main_T = MainG_T + MainB_T + MainS_T$$

Where:

$Main_T$ is the total maintenance cost of the investment in year T.

Property Taxes

This section contains explanations of property tax, loan interest and insurance costs. Property taxes are calculated as 0.55% of depreciable costs (Equation 9). This figure was decided on through discussions with Dr. Stephen Harsh regarding the property taxes calculated in other agricultural studies in the area (Harsh 2008). The loan is spread evenly over seven years, using a loan interest rate of 9%. Insurance is calculated as 5% of total investment costs. Estimates of insurance as a percent of costs were seen to be about 2% in one study; it was increased for this thesis to cover additional risks that may be associated with the geothermal heat pump and the thermal solar collectors (Dr. Wilkerson, Dr. Barnes et al. 2008).

Equation 9.

$$PT = DepCosts * 0.0055$$

Where:

PT are the property taxes.

Loan Calculations

To calculate the interest paid on the loan over the seven year payback period, the first calculation was that of the equal payment annuity on the loan balance for seven years. The beginning balance of the loan in year T is used to determine how much interest is paid that year, as well as how much of the loan principle is paid off that year. If the loan balance in the beginning of the year is greater than zero, interest will be paid (Equation 10).

If interest is paid, some loan principle is paid off as well, to find the principle that has been paid, an annuity payment must be determined. The annuity payment is calculated assuming equal payments at the end of the year for seven years with an annual interest rate of 9% (Equation 11). The principle that is paid down every year is calculated from the interest paid and the annuity paid every year (Equation 12).

The loan balance of year T is used to find the beginning balance of year T+1. If the balance in year T minus the principle paid is smaller than an arbitrary small number, then the loan balance in year T+1 is zero. The arbitrary small number chosen is greater than zero due to rounding that may happen in calculations, causing the calculated loan balance and principle to end up unequal by a very small amount in the last period of payment.

Equation 10.

If $LBal_T \leq 0,$

Then $Int_T = 0$

Otherwise $Int_T = LBal_T * IR$

Where:

$LBal_T$ is the loan balance in the beginning of the period,
Int_T is the interest on the loan in the period, and
IR is the interest rate (9%).

Equation 11.

$$Ann = \frac{Loan}{\left(\left(1 - \left(\frac{1}{1.09^7}\right)\right) \Big/ .09\right)}$$

Where:

Ann is the value of the equal annuity payment

Equation 12.

$$\text{If} \quad Int_T > 0,$$

$$\text{Then} \quad Prin_T = Ann - Int_T$$

$$\text{Otherwise} \quad Prin_T = 0$$

Where:

$Prin_T$ is the principle that is paid off in year T.

Equation 13.

$$\text{If} \quad LBal_T - Prin_T \leq 0.00001$$

$$\text{Then} \quad LBal_{T+1} = 0$$

$$\text{Otherwise} \quad LBal_{T+1} = LBal_T - Prin_T$$

Where:

$LBal_{T+1}$ is the beginning loan balance in year T+1.

Insurance

The cost of insurance related to the heating system is calculated at 5% of the total investment cost. As was stated above, 5% is a higher number than found in previous studies, however research suggests that a higher insurance estimate should be used for new or uncertain projects, as is the SAGSHP system of this study.

Equation 14.

$$Ins = InvCost * .05$$

Where:

Ins is the insurance cost.

Conventional Boiler Calculations

For this research, natural gas is used as the fuel source for the conventional boiler due to the availability of natural gas in most of Michigan. The main operating cost of a boiler is based on the price of its fuel and the consumption rate of fuel. To determine fuel consumption, BTU heat loss was converted to MCF of natural gas (Equation 15). If the boiler was 100% efficient, this could then be multiplied by the cost per MCF, however, conventional boilers are not 100% efficient. In this project, the boiler chosen is a high efficiency boiler, which is a boiler rated at a level of 95% efficient or higher (Equation 16) (Evans 2005) . The U.S. average price of natural gas is forecast by the EIA; however, this research focuses on Michigan. To get the estimated forecast prices for Michigan, the difference in the U.S. average price from year *t* to year *t+1* is added to the Michigan average price in year *t* (Equation 17). The total cubic feet of natural gas is then multiplied by average price of natural gas for the year (Equation 18).

Equation 15.

$$1{,}000{,}000\ BTU = 1000\ cubic\ feet\ of\ Natural\ Gas$$

Or

$$MmBTU_T = MCF_T$$

(Alternate Energy Resource Network 2008)

Where:

$MmBTU_T$ is million BTUs needed in year T, and
MCF_T is thousand cubic feet of natural gas needed in year T.

Equation 16.

$$MCF_T / E = MCF\ Used_T$$

Where:

E is the efficiency of the boiler, and
$MCF\ Used_T$ is the amount of natural gas needed to produce the level of BTUs to reach the set point of the greenhouse in year T.

Equation 17.

$$\left(\$MCF_T^{US} - \$MCF_{T-1}^{US}\right) + \$MCF_{T-1}^{MI} = \$MCF_T^{MI}$$

Where:

$\$MCF_{T-1}^{US}$ is the U.S. average price of natural gas in year T-1 in dollars/MCF,
$\$MCF_T^{US}$ is the U.S. average price of natural gas in year T in dollars/MCF,
$\$MCF_{T-1}^{MI}$ is the Michigan average price of natural gas in year T-1 in dollars/MCF, and
$\$MCF_T^{MI}$ is the Michigan average price of natural gas in year T in dollars/MCF,

Equation 18.

$$MCF\ Used_T * \$MCF_T^{MI} = \$NG_T$$

Where:

$\$NG_T$ is the total cost of natural gas used in year T.

Soil Calculations

The operational cost of the heat pump is dependent on the COP of the heat pump, and the COP is determined by the temperature of the soil at that hour, however different types of soil have different properties. Clay, loam and sand were examined for this model because they are the three basic types of soil. The difference in soil temperature between clay and loam is negligible, and other studies using soil properties in GHP studies around the area have used specific heat amounts close to those found for clay and loam; because of the similarities in the final values, loam was arbitrarily chosen as the soil type (Chiasson and Yavuzturk 2003).

An assumption for this research is that the solar field will collect heat starting the summer previous to the heat pump becoming operational and it will continue to run until November 1; the soil temperature on November 1, therefore, determines the initial COP of the system. Every hour the heat pump operates, it pulls BTUs from the soil, lowering the soil temperature and affecting the COP of the heat pump. The level of BTUs pulled from the soil depends on the COP and the actual BTUs produced by the heat pump. In the main study, the heat pump does not run in the summer (from May 1 through September 30), and the greenhouse is only heated from January 1 through the end of

April, which gives the soil a chance to recharge without the heat pump negating the solar gain of the soil. This assumption is dropped later, and the results of a possible full year of heating are compared to those obtained for restricting the heat pump to summer use only.

The total BTUs in the soil begin with the properties of the soil; the soil type and water content determine the heat holding capacity of the soil (Bi, Guo et al. 2004). The higher the water content of the soil, the more heat the soil can hold; if the soil is kept at field capacity (the highest percentage of water in the soil before it becomes mud) it will hold the most heat (Bi, Guo et al. 2004).

From the field capacity of the soil, the total BTUs in the geothermal field for every °F of the soil can be calculated. First, the specific heat of the soil at field capacity is determined (Equation 19). This is converted into calories per cubic foot per °C of the soil (Equation 20), and then into total BTUs in the geothermal field for every °F of the field (Equation 21).

The total BTUs in the geothermal field before adding heat from the thermal solar collectors depends on the temperature of the soil in that hour, which is determined using the base temperature of the soil (Equation 22). This research assumes an initial base temperature of 35 °F (1.7 °C); this is done in order to estimate the long run soil temperature over time. If the soil temperature is decreased to around 35 °F, using this base will illustrate what may happen to the COP of the heat pump over time if the temperature of the soil is taken down to this value by the heat pump. Mainly, what is discovered is whether or not the solar collectors can increase the temperature of the soil enough that the heat pump can be used the following year.

The total BTUs in the soil at the start of the heat pump's operation include the BTUs added by the solar collectors during the summer, therefore the BTUs the thermal solar collector adds every year must be determined (Equation 23). The BTUs per square foot of solar panels is an estimate from a previous installation of thermal solar collectors by GMB Architects and Engineers (GMB Architects and Engineers 2008). This is used to find the increase in soil temperature from the solar panels by the end of the solar collection period (Equation 24). The increase in temperature from the solar panels is added to the base temperature of the soil to get the initial soil temperature, which is used to calculate the COP.

Equation 19. (Foth 1990)

$$SHFC_S = \frac{\left((100 * SH_M) + (FC_S * SH_W\right)}{(100 + FC_S)}$$

Where:

$SHFC_S$ is the specific heat of the soil at field capacity,
SH_M is the specific heat of dry mineral soil (Foth 1990),
FC_S is the field capacity of the soil (Foth 1990), and
SH_W is the specific heat of water (Foth 1990).

Equation 20.

$$\frac{\frac{Cal}{Ft^3}}{°C}_S = \frac{SHFC_S * (\frac{g}{cm^3})_S}{\frac{Ft^3}{M^3}} * 1{,}000{,}000$$

Where:

$Cal/Ft^3/°C_S$ is the amount of calories per cubic foot per °C in the soil,
Ft^3/M^3 is the conversion from cubic feet to cubic meters (Unit-Conversion 2003), and
$g/cm^3{}_S$ is the weight of the soil at field capacity in grams per cubic centimeter (NRCS 2008).

Equation 21.

$$\frac{BTUGF}{°F}_S = \frac{\frac{\frac{Cal}{Ft^3}}{°C}_S}{(252)} * \frac{Ft^3GF}{\left(\frac{°F}{°C}\right)}$$

Where:

$BTUGF/°F_S$ is the BTUs per °F in the geothermal field,
252 is the number of calories per BTU (Unit-Conversion 2003)
Ft^3GF is the total cubic feet in the geothermal field, and
°F/°C is the conversion of °F per °C (9/5).

Equation 22.

$$BTUGF_t = \frac{BTUGF}{°F}_S * °F_t$$

Where:

$BTUGF_t$ is the total BTUs in the geothermal field at hour t, and
$°F_t$ is the temperature of the soil at hour t.

Equation 23.

$$BTUS = \frac{BTU}{Ft^2S} * \frac{Ft^2}{M^2} * M^2S$$

Where:

BTUS is the amount of BTUs the solar collector collects per year,
BTU/Ft^2S is the amount of BTUs per square foot of solar panels per year (GMB Architects and Engineers 2008),
Ft^2/M^2 is the conversion from square feet to square meters (Unit-Conversion 2003), and
M^2S is the total square meters of solar panels.

Equation 24.

$$S°F_+ = \frac{BTUS}{\left(\frac{BTUGF}{°F}S\right)}$$

Where:

$S°F_+$ is the temperature added to the geothermal field by the solar panels.

Geothermal Heat Pump Calculations

A large difference in determining the cost of the boiler and heat pump systems is that the heat pump calculations are made on an hourly basis due to the changing COP of the heat pump over the year, while the boiler calculations are made with yearly totals. The efficiency of the GSHP system relies on the temperature of the heat source; as this temperature changes, the COP will change as well, leading to changes in the amount of BTUs that can be produced by the heat pump, as well as the amount of KWs needed to produce those BTUs. Due to this, the COP is estimated as a function of soil temperature in °F (Equation 25). The output temperature of the system is assumed to be 120 °F (48.9 °C) and the inputs for the regression can be seen in Appendix 1 (GMB Architects and Engineers 2008). The initial COP estimation is calculated using the soil temperature from November 1 because it is assumed the thermal collectors will deposit heat into the geothermal field during the summer months prior to the start up of the heat pump. This is done to increase the temperature of the geothermal field and insure the efficiency of the heat pump, as well as to increase the length of time the heat pump can be effectively operated.

The BTUs produced by the heat pump determine the energy used by the heat pump, as well as how much heat is needed from a backup system. The potential BTUs the heat pump can produce are dependent on the COP, which is dependent on the soil temperature; this means that the potential BTUs are dependent on soil temperature as well (Equation 26). The BTUs the heat pump actually produces are dependent on what it can potentially produce, as well as BTUs needed to reach the set point (Equation 27). If the heat pump cannot produce enough BTUs to reach the set point, a backup system is needed, which is why the cost for a SAGSHP system includes enough boiler units to heat the greenhouse.

The KWs used by the heat pump need to be calculated to determine operating cost (Equation 28). The potential KWs the heat pump will use are regressed on soil temperature for the same reasons as the potential BTUs; the COP affects the KWs used to reach a certain level of BTUs, therefore, the ground temperature will also directly affect it. This level of KW use is valid when the heat pump runs at full capacity; because the heat pump does not run at full capacity every hour, the electricity use every hour must be determined as well. This is done by multiplying the potential KWs used by a ratio of actual BTUs produced to the potential BTUs the heat pump can produce (Equation 29).

To get the KWs needed to run the pumping motors to move fluid through the geothermal field, a one horsepower motor is assumed to move the fluid completely through the system in one hour. Therefore, every hour the heat pump runs, the motor is using electricity. The ratio of actual to potential BTUs is multiplied by number of heat pump modules used as well as the ratio of horsepower to kilowatts to get the total KWs used by the motor (Equation 30).

The KWs to run the motor and the KWs used by the heat pump are added together to get the total KWs used for the year (Equation 31), which are then multiplied by the price of electricity in that year (Equation 32). Similar to natural gas prices, the Michigan average price for electricity is calculated using the difference in the U.S. average prices between years.

The soil temperature must be estimated at the end of every hour to determine if the heat pump can be used for the next hour and, if so, what the COP of the heat pump will be. To do this, the KWs and BTU production of the heat pump are used to determine how many BTUs are taken out of the soil in that particular hour (Equation 33). The BTUs remaining in the soil are found (Equation 34), and the temperature of the soil is then calculated (Equation 35), leading back to the new COP.

The heat pump will no longer be used when the temperature of the soil reaches the base temperature again; this is to insure that the heat pump will not consume more BTUs from the soil than what the solar collectors can deposit. The base soil temperature for this research was set at 35 °F (1.7 °C); international standards for the heating capacity of a heat pump in a closed loop system is rated at 32 °F (0 °C) and if the entering fluid temperature is below that, the assumptions about the heat pump will no longer be valid (Chiasson and Yavuzturk 2003).

Equation 25. COP regressed on Ground Temperature

$$COP_t = 1.6 + (0.06 * ST_t)$$

Where:

COP_t is the Coefficient of Performance at hour *t*, and
ST_t is the soil temperature in °F at hour *t*.

Equation 26. Potential BTUs regressed on Ground Temperature

$$PotBTU_t = 228432.38 + (10852.57 * ST_t)$$

Where:

$PotBTU_t$ is the potential BTUs the heat pump can produce in hour *t*.

Equation 27.

If	$BTU\ Set\ Point_t > PotBTU_t$,
Then	$BTUHP_t = PotBTU_t$
Otherwise	$BTUHP_t = BTU\ Set\ Point_t$

Where:

$BTU\ Set\ Point_t$ is the amount of BTUs needed to reach the set point in hour *t*, and
$BTUHP_t$ is the amount of BTUs actually produced by the heat pump in hour *t*.

Equation 28. Potential KWs regressed on Soil Temperature

$$PotKW_t = 45.53 + (0.078 * ST_t)$$

Where:

$PotKW_t$ are the potential KWs the heat pump will use in hour t.

Equation 29.

$$KWHP_t = (BTUHP_t / PotBTU_t) * PotKW_t$$

Where:

$KWHP_t$ is the actual KWs used by the heat pump in hour t.

Equation 30.

$$MKWHP = (BTUHP_t / PotBTU_t) * \left(\frac{KW}{HsP}\right) * UnitsG$$

Where:

MKWHP is the KWs used by the heat pump motor,
KW/HsP is the conversion of horsepower to kilowatts, and
UnitsG is the number of GSHP units.

Equation 31.

$$KWHP = MKWHP + \sum_{t=1}^{8760} KWHP_t$$

Where:

KWHP is the total KWs used by the heat pump in a year, and
8,760 are the total hours in a year.

Equation 32.

$$\$KWHP_T = KWHP * \$KW_T^{MI}$$

Where:

$\$KWHP_T$ is the total yearly price for KWs used by the heat pump, and
$\$KW_T^{MI}$ is the price of a KW of electricity in Michigan in that year.

Equation 33.

$$BTURem_t = BTUHP_t - (KWHP_t * 3413)$$

Where:

$BTURem_t$ is the amount of BTUs removed from the soil in hour t, and
3414 is the amount of BTUs per KW hour (Unit-Conversion 2003).

Equation 34.

$$BTUGF_t = BTUGF_{t-1} - BTURem_t$$

Where:

$BTUGF_{t-1}$ is the amount of BTUs in the geothermal field in the previous hour.

Equation 35.

$$ST_t = \frac{(BTUGF_{t-1})}{\left(\frac{BTUGF}{°F}_S\right)}$$

Solar Thermal Collector System Calculations

The solar panels are assumed to run from May 1 through September 30 due to possible low temperatures and snow outside of that range, which is a total of 3,672 hours.

Similar to the assumption for the heat pump, it is assumed that a one horsepower motor can circulate the fluid through the solar heating system in one hour. To get the total cost of running the solar heating system, the total hours the system is run is multiplied by the conversion rate of kilowatts per horsepower to get the KWs used (Equation 36), and then multiplied by the cost of electricity (Equation 37).

Equation 36.

$$KWS = HrsSolar * \left(\frac{KW}{HsP}\right)$$

Where:

KWS is total KWs used by the solar heating system,
HrsSolar is the total hours the solar heating system is run.

Equation 37.

$$\$KWSolar_T = KWS * \$KW_T^M$$

Where:

$\$KWSolar_T$ is the total cost of running the solar heating system in year T.

Post Marginal Tax and Depreciation Cost Calculations

The pre-tax cost of investing is found by adding all the costs of purchasing, installation, operating, maintenance, interest on the loan, insurance, and property taxes together (Equation 38). The post tax value of the investment is found by multiplying the pre-tax cost by one minus the marginal tax rate (Equation 39). The depreciable value of the initial investment is calculated using MACRS seven year depreciation schedule

(Appendix 2) (Equation 40). The post tax depreciation value is calculated by multiplying the depreciable value of the investment by the marginal tax rate (Equation 41). The post tax cost with depreciation accounted for in calculated by subtracting the post tax depreciation value from the post tax cost of the investment (Equation 42). In appendix 3, the calculations done in the Results chapter are shown in pre tax form. These calculations were found the same way as the post marginal tax calculations, with the exception of Equation 42. In the pre-tax calculation, the pre-tax cost with depreciation is found by subtracting the pre-tax value of depreciation from the pre-tax cost of the investment. All the following calculations built on the pre tax cost of the investment calculation in Equation 42. The post marginal tax cost and the loan principle in that year are then added together to get the total after tax cost (Equation 43).

Equation 38.

$$PreMTaxC_T = Sum(Nondep_T, Labor_T, Main_{T,} PT_T, Int_T, \$NG_T, \$KWHP_T, \$KWSolar_T)$$

Where:

$PreMTaxC_T$ is the cost of the investmet before marginal taxes,
$Nondep_T$ is the non-depreciable costs of the initial investment in year T (positive in year zero and 0 in the following years), and
$Labor_T$ is the labor cost for the year (assumed to be \$500/year).

Equation 39.

$$PostMTaxC_T = PreMTaxC_T * (1 - MargTR)$$

Where:

$PostMTaxC_T$ is the after tax cost of the investment in year T,
$MargTR$ is the marginal tax rate assumed (here assumed to be 41%).

Equation 40.

$$DepValue_T = Dep * \%Dep_T$$

Where:

$DepValue_T$ is the depreciable value of the investment in year T, and
$\%Dep$ is the depreciation percentage in year T.

Equation 41.

$$PostTaxDep_T = DepValue * MargTR$$

Where:

$PostTaxDep_T$ is the after tax value of depreciation in year T.

Equation 42.

$$PostTaxCD_T = PostMTaxC_T - PostTaxDep_T$$

Where:

$PostTaxCD_T$ is the after tax cost of the investment with depreciation accounted for.

Equation 43.

$$ATC_T = PostTaxCD_T + Prin_T$$

Where:

ATC_T is the total after tax and depreciation costs of the investment in year T.

Salvage Value

With the values in Table 9, salvage values for the equipment can be calculated. A percentage of life left is calculated, then reduced by twenty percent to adjust for possible over calculations. This reduced salvage percent estimation is then multiplied by the total value of the equipment at purchase (Equation 44). Some of the equipment contains no salvage value (such as antifreeze fluid or engineering design). The pumps and valves equipment was given an estimated 10% salvage vale for the left over steel that may be taken out. The electrical equipment was given a 0.05% salvage value for the copper that is in the wires. The final salvage value percentages are shown below in Table 10.

Equation 44.

$$S_e = \left(\left(1 - {}^{15}/_{L_e}\right) * 0.8\right) * C_e$$

Where:

S_e is the salvage value of the equipment *e*,
15 is the length of time covered in the model,
L_e is the life of the equipment *e*, and
C_e is the calculated cost of the equipment *e* (as seen in Table 8).

Table 10. Salvage value percentage

Equipment and Installation	Salvage Percent
Solar Heat Collectors, incl. install.	0.32
Heat Pump	0.4
Hot Water Boiler	0.2
Insulated Water Tank	0.4
Slinky Loop, incl. install.	0.56
Side Insulation under Greenhouse	0.56
Top Insulation under Greenhouse	0.56
Side Instalation under Expanded GT Field	0.56
Top Insulation under Expanded GT Field	0.56
Pumps, Valves & Pipes (install.) In-floor heating	0.1
Pumps & Valves Heat Pump/Solar heating	0.1
Control System	0
Special Controls System of Heat Pump	0
Electrical	0.05
Electrical Extra for Heat Pump System	0.05
Antifreeze Fluid	0
Engineering & Design & Permits	0
Extra Engineering & Design	0

Solar Credit Calculations

The tax credit for the solar heating system is calculated as 30% of the total solar heating system investment, including equipment and installation (Equation 45). The yearly credit cannot exceed the tax liability for the business, and if the total tax credit is greater than the tax liability for the business, it can be spread over up to 20 years (Equation 46). In this thesis, the tax liability is assumed to be $20,000.

Equation 45.

If $T = 1$

Then $AvailTaxCred_1 = 0.3 * SolarInv$

Otherwise $AvailTaxCred_T = AvailTaxCred_{T-1} - ActualTaxCred_{T-1}$

Where:

$AvailTaxCred_T$ is the available tax credit in year T (T=1 is year 1),
SolarInv is the initial investment in the solar heating system, and
$ActualTaxCred_{T-1}$ is the actual tax credit for the solar system that is applied in the previous year.

Equation 46.

If $AvailTaxCred_T < TaxLiab$

Then $ActualTaxCred_T = AvailTaxCred_T$

Otherwise $ActualTaxCred_T = TaxLiab$

Where:

TaxLiab is the tax liability for the greenhouse that year (here assumed to be $20,000), and
$ActualTaxCred_T$ is the actual tax credit for the solar system that is applied in year T.

Carbon Tax Calculations

The carbon tax amount is calculated on the total CO2 that can be attributed to the greenhouse including that attributed to the greenhouse through producing the electricity used, and the CO2 produced through burning natural gas in the greenhouse boiler. The first step is to determine the CO2 output attributed to the electricity used. Electricity is produced through several sources, the main ones being coal, natural gas, pumped storage (hydroelectricity), nuclear power, petroleum and renewable sources other than pumped storage (including biomass, geothermal, wind and solar), and each source produces different levels of CO2. Therefore, the relative levels of electricity produced by each source must be determined; these levels may change over time however, so the proposed growth of electricity compared to the proposed growth of the use of each source is used to determine the relative growth of each source over time (Equation 47) (EIA). The total KWs used by the system are found (Equation 48) and used to estimate how much electricity used by the greenhouse is from each source (Equation 49), which is then multiplied by its estimated CO2 output rate and converted into metric tons of CO2 attributed to the heating electricity use of the greenhouse (Equations 50 and 51). Natural gas used in the greenhouse is multiplied by its carbon equivalent rate to get metric tons of CO2 produced through burning of the natural gas every year (Equation 52).

The CO2 from each source is added together to get total metric tons of CO2 per year (Equation 53) and multiplied by the carbon tax rate, which is assumed to be an after tax penalty (Equation 54).

Equation 47.

$$ElecProd_T^i = \frac{1 + Growth^i}{1 + Growth}$$

Where:

$ElecProd_T^i$ is the relative growth rate of electricity source i in year T,
$Growth^i$ is the estimated yearly growth rate of electricity source i and,
$Growth$ is the projected yearly growth rate of electricity.

Equation 48.

$$TKW = KWHP + KWS$$

Where:

TKW is the total KWs used by the system.

Equation 49.

$$KW_T^i = TKW * ElecProd_T^i$$

Where:

$KW^j{}_T$ is the kilowatts used by the greenhouse attributed to each electricity production Source in year T.

Equation 50.

$$LbCO2_T^i = KW_T^i * COR^i$$

Where:

$LbCO2_T^i$ is the pounds of CO2 equivalent produced by source i in year T, and
COR^i is the carbon output rate for source i in pounds per kilowatt hour.

Equation 51.

$$MTE_T^i = \frac{LbCO2_T^i}{2000} * MTconv$$

Where:

MTE_T^i is the metric tons of CO2 prodcuded by source i in year T, and
$MTconv$ is the short to metric ton conversion factor (about 1.1023).

Equation 52.

$$MTNG_T = MCFused_T * 1000000 * NGCO2conv$$

Where:

$MTNG_T$ is the metric tons of CO2 from natural gas in year T, and
NGCO2conv is the conversion rate from BTUs of natural gas into metric tons of CO2.

Equation 53.

$$MTCO2_T = MTNG_T + \sum_i MTE_T^i$$

Where:

$MTCO2_T$ is the total metric tons of CO2 equivalent attributed to the greenhouse in year T.

Equation 54.

$$\$CO2_T = CT * MTCO2_T$$

Where:

$\$CO2_T$ is the total carbon tax amount the greenhouse bears and,
CT is the carbon tax rate (assumed to be the after tax penalty rate).

Net Present Value of Cost and Present Value of Energy Cost Calculations

The net after tax cost in each year is found by adding the after tax cost found above, the tax credit from the thermal solar collectors and the carbon tax cost (Equation 55). The net present value discount rate is calculated for each year from the discount rate of 10% (Chiasson 2006). For years 1 through year 15, this discount rate must be adjusted for marginal tax, so it is multiplied by one minus the marginal tax rate (Equation 56). In year zero, this discount rate must be one (meaning the cost cannot be discounted further), so the discount rate is calculated without adjusting for the marginal tax rate. The discount rate is then multiplied by the net after tax cost of the system in each year to get the present value of cost in each year (Equation 57), and added together to get the net present value of cost (Equation 58). The pre-tax calculations in appendix three use a pre-tax discount rate, which is the same as Equation 56 with the exception of the marginal tax. Also important to this research is the effect the different systems have on energy costs; therefore, the net present value of energy cost is found as well. The sum of energy cost in each year is multiplied by one minus the marginal tax rate, and then multiplied by the discount rate for that year (Equation 59). These are then added together to get the net present value of energy cost after tax. In appendix three, the pre-tax energy cost results of the analyses done in the Results chapter are displayed. These results are found through the process described above, with the exception of the marginal tax rate being used.

Equation 55.

$$NATC_T = ATC_T + \$CO2_T - AvailTaxCred_T$$

Where:

$NATC_T$ is the net after tax cost of the system.

Equation 56.

$$PVDR_T = \frac{1}{(1 + DR)^T} * (1 - MargTR)$$

Where:

$PVDR_T$ is the after tax present value discount rate in year T, where T starts in year 1 and, DR is the discount rate (assumed to be 10%).

Equation 57.

$$PVC_T = PVDR_T * NATC_T$$

Where:

PVC_T is the present value of cost in year T.

Equation 58.

$$NPVC = \sum_{T=0}^{15} PVC_T$$

Where:

$NPVC$ is the net present value of cost for the heating system.

Equation 59.

$$NPVEC = \sum_{T=0}^{15} \left(\left(\left(\$NG_T + \$KWHP_T + \$KWSolar_T \right) * (1 - MargTR) \right) * PVDR_T \right)$$

Where:

$NPVEC$ is the after tax net present value of energy cost.

Comparison Calculations

To compare the difference in costs through changing the parameters of the SAGSHP system, average annual cost, average annual cost per square foot, average annual energy cost, and average annual energy cost per square foot are compared. In addition, the effect changing parameters have on energy cost as a percent of total cost within each system are compared. The average annual cost of the system per square foot is found (Equation 60) and used to find the additional cost of the SAGSHP system over the boiler system. The average annual cost of the boiler system is subtracted from that of the SAGSHP system to get the total added annual cost of the SAGSHP system (Equation 61). The average annual energy cost per square foot (Equation 62) is used to find the savings in energy cost of using the SAGSHP system over the boiler system (Equation 63).

To find the energy cost as a percent of total cost, the energy cost is divided by total cost (Equation 64). Another useful figure calculated is the percent of BTUs that are purchased. In the boiler system, this is 100%; all the BTUs used in heating are purchased. However, in the SAGSHP system, some of the BTUs are pulled from the ground (Equation 65). As a portion of the BTUs pulled from the ground are from those stored there by the solar collectors, the percent of BTUs supplied by the heat pump and the percent of BTUs supplied by the solar collectors are found (Equations 66 and 67).

Equation 60.

$$AAC = \frac{DR}{1-(1+DR)^{-15}} * NPVC * \frac{1}{SFT}$$

Where:

AAC is the average annual cost per square foot, and
SFT is the total square feet in the greenhouse.

Equation 61.

$$AAC_H - AAC_B = added\ AAC$$

Where:

AAC_H is the average annual cost per square foot of the SAGSHP system,
AAC_B is the average annual cost per square foot of the boiler system, and
Added AAC is the added average annual costs of the SAGSHP system.

Equation 62.

$$AAEC = \frac{DR}{1-(1+DR)^{-15}} * NPVEC * \frac{1}{SFT}$$

Where:

$AAEC$ is the average annual energy cost per square foot.

Equation 63.

$$AAEC_B - AAEC_H = AAEC\ Savings$$

Where:

$AAEC_B$ is the average annual energy cost per square foot of the boiler system,
$AAEC_H$ is the average annual energy cost per square foot of the SAGSHP system, and
AAEC Savings is the average annual cost savings of the SAGSHP system.

Equation 64.

$$\frac{Total\ Cost}{Energy\ Cost} = Energy\ Cost\ \%$$

Where:

Total Cost is the present value of the total costs of the system,
Energy Cost is the present value of the total energy costs of the system, and
Energy Cost % is the percent of total costs that are energy costs.

Equation 65.

$$\%BTUPurch = \frac{\sum_{t=1}^{8760}(MCFUsed_t * 1000000 + KWHP_t * 3413)}{BTU}$$

Where:

%BTUPurch is the percent of total BTUs used to heat the greenhouse that are purchased.

Equation 66.

$$\%HP = \frac{\sum_{t=1}^{8760} BTUHP_t}{BTU}$$

Where:

%HP is the percent of total BTUs provided by the heat pump.

Equation 67.

$$\%Solar = 1 - \%BTUPurch$$

Where:

%Solar is the percent of total BTUs provided by the solar panels.

Base Model Specifications

The BTU heat loss information from Table 6 and the capacity of the boiler units are used to determine the present costs for the conventional boiler system; many of the specifications altered in this study do not affect the costs of the boiler system. The model is then used to estimate the present costs of the SAGSHP system, which are compared to the boiler system results to find the differences in average annual cost and average annual energy cost. The percentage of BTUs that are purchased, the percent of heat supplied by the heat pump, the percent of heat supplied by the solar panels and energy cost as a percent of total cost are also compared. If the specification altered may affect the boiler system cost, the boiler system cost is recalculated to compare the new SAGSHP cost. Presented in the cost information given below are the post-tax costs for average annual cost, average annual energy cost and post tax energy as a percentage of total post tax cost. In appendix three, the tables for pre-tax costs are given.

The base specifications for the research were decided on through experimentation with some of the model's parameters. To get the base parameters, many characteristics were not changed from initial values, for example, the size of the greenhouse, the depth of the geothermal field, and the length of time the greenhouse is heated. The three characteristics that are flexible in the model are the initial size of the solar field, the number of minimum boilers used with the heat pump(s), and the number of heat pump units. Also, the tax credit from installing the solar field is included in the calculations, though the carbon tax is not. The carbon tax will be discussed later.

Many businesses and homes that use GSHP systems for heating also use the system for cooling, which aids in regenerating the soil temperature. The greenhouse has a large heat load, and does not use the system for cooling; therefore, the investment includes a solar thermal collection system. To get the initial size of the solar field, the results under 5,381.9, 10,763.9, 11,840.3, 12,916.7, 13,993.1 and 16,145.8 square feet (500, 1,000, 1,100, 1,200, 1,300 and 1,500 square meters respectively) were compared, leaving all other parameters constant. The results in average annual cost and average annual energy cost per square foot are shown rounded to the nearest tenth of a cent due to the very small changes in dollar per square foot (Table 11.)

Table 11. Solar panel results

	Solar Panel Square Meters					
Measurements	**500**	**1,000**	**1,100**	**1,200**	**1300**	**1,500**
AAC ($/sq-F)	1.211	1.250	1.262	1.253	1.265	1.288
added AAC ($/sq-F)	*0.465*	*0.504*	*0.516*	*0.507*	*0.519*	*0.542*
AAEC ($/sq-F)	0.276	0.251	0.245	0.239	0.234	0.221
AAEC savings ($/sq-F)	*(0.013)*	*(0.038)*	*(0.044)*	*(0.051)*	*(0.055)*	*(0.068)*

The average annual cost per square foot increases with the size of the solar field with the exception of the change from 11,840.3 to 12,916.7 square feet (1,100 to 1,200 square meters), where it drops by a little under $0.01. This is accompanied by a decrease in the average annual energy cost of just over $0.005 (which is close to the same for every 100 square meter change). Moving from 12,916.7 to 13,993.1 square feet (1,200 to 1,300 square meters) causes an increase in average annual cost per square foot of a little more than $0.01, which is accompanied by $0.005 change in the average annual energy cost per square foot. The average annual cost of 10,763.9 square feet (1,000 square meters) is more than that of 12,916.7 square feet (1,200 square meters). The AAC of 5,381.9 square feet (500 square meters) is less than that of 12,916.7 square feet (1,200 square meters), however the AAEC of 12,916.7 square feet (1,200 square meters) is almost $0.04 less than that of the smaller solar panel area. This indicates that the best option would be to use 12,916.7 square feet (1,200 square meters) for the base size of the solar field.

When there is a minimum number of boiler units operating are set in the model, the system simulation first uses the BTUs provided by these boilers to meet the greenhouse needs, and then uses the potential BTUs available from the heat pump. When the minimum boiler unit(s) and the heat pump unit(s) are not enough to heat the greenhouse to the level necessary, more boiler units are used. The number of supplemental boiler units needed to reach the necessary BTUs under the maximum heat load is determined by the model.

In experimenting with the system set up, leaving solar area constant at 12,916.7 square feet (1,200 square meters) and the heat pump units constant at one, increasing the number of minimum boiler units from zero to one does not affect average annual cost per square foot or average annual energy cost per square foot. The only output that sees a substantial change is the length of time the heat pump unit is used before the soil temperature drops to the shut off point (34°F) for the heat pump. Under zero minimum boiler units, the heat pump runs until the end of February, with one minimum boiler unit the heat pump runs until early March, and with two minimum boiler units the heat pump does not shut off during the heating period. The heat pump not shutting down is not an acceptable result in the model. The heat pump extracts the heat from the soil, so if the heat pump does not shut off, there will still be useable BTU's left in the soil at the end of the heating cycle, which means that more heat was purchased in the form of natural gas than necessary. This can also be seen in Table 12, below, through the percent of heat supplied by the heat pump and the percent of BTUs purchased, as well as the other results that are shown.

Table 12. Minimum boiler units results

	Min. number supplmental boilers		
Measurements	**0**	**1**	**2**
AAC ($/sq-F)	1.253	1.253	1.254
AAEC ($/sq-F)	0.239	0.239	0.241
% BTU Purchased	73.570	73.560	75.080
% Energy Cost of Total Cost	19.100	19.100	19.200
% BTU from HP	35.400	35.400	32.800

Increasing the minimum number of supplemental boilers from one to two increases AAC, AAEC, the percent of BTUs purchased and energy cost as a percent of total cost, as well as decreases the percent of BTUs provided by the heat pump, which is not ideal. Therefore, the feasible minimum number of boilers is not two or greater. Between zero and one, there is no change in the cost factors shown above. As mentioned previously, the only change came from the fact that the heat pump will be used longer in the heating season. For this reason, the results seem indifferent the whether or not there is one or no minimum boilers set in the model; zero minimum boilers is chosen for the base model.

Another decision to be made for the base model is the number of heat pump units to install. Increasing the number of heat pump units from one to two while holding the minimum boiler units constant at zero increases average annual cost per square foot by about $0.09, and decreases the average annual energy cost per square foot by just over $0.02, as can be seen in Table 13. Adding a third unit increases average annual cost per square foot by about six cents and decreases average annual energy cost by less than one cent. The percent of BTUs that are purchased and energy cost as a percent of total cost also fall with each addition.

Table 13. Heat pump unit results

	Heat Pump Units		
Measurements	**1**	**2**	**3**
AAC ($/sq-F)	1.253	1.345	1.406
AAEC ($/sq-F)	0.239	0.215	0.206
% BTU Purchased	73.570	69.090	67.600
% Energy Cost of Total Cost	19.100	15.960	14.680
% BTU from HP	35.400	35.400	35.400

From this, it does not seem to make sense to use more than one heat pump unit – the average annual cost is increasing, and the BTUs provided by the heat pump units is not changing. Average annual energy cost is falling, as is the percent of BTUs that are purchased. However, one reason for this may be that the less time the heat pump runs, the less KWs are needed to operate it; this would lead to less total BTUs being purchased. Also, the length of time the heat pump is used falls from late February to early February when the number of units goes to two, and falls to late January when three heat pumps are installed. For these reasons, the number of heat pump units is set to one in the base case.

After experimenting with values to get the lowest average annual cost and average annual energy cost, the base model specifications are chosen (Table 14). In the Results chapter, some of these, including size of the geothermal field and solar field, energy prices and carbon tax values, are adjusted.

Table 14. Base model specifications

Specification	Value
Size of Solar Field (Sq-M)	1,200
Length of Greenhouse (Ft)	384
Width of Greenhouse (Ft)	112
Footprint of Greenhouse (Sq-Ft)	43,008
Added Length of Geothermal Field (Ft)	0
Footprint of GT Field (Sq-Ft)	43,008
Depth of Geothermal Field (Ft)	8
Number of Heat Pump Modules	1
Minumum Sup Heat Modules	0
Output of Sup Heater Module (BTU)	300,000
Output of Heat Pump Module (BTU)	600,000
HsP to run coils for 1 Heat Pump Module	1
Marginal Tax Bracket (%)	41
Loan (%)	60
Loan Size ($)	313,449
Length of Loan Payback (Yrs)	7
Interest Rate (%)	9
Properity Tax Rate (%)	0.55
Total Solar Credit ($)	36,375
Discount Rate (%)	10
Total Present After Tax GHPS Cost ($)	410,047
Total Present After Tax Boiler Cost ($)	243,949

Chapter 5

RESULTS

Under the base conditions simulated (Table 14), the model shows a large (about 40%) increase in average total cost per square foot of the greenhouse from the conventional boiler system to the solar-assisted ground source heat pump system. However, when the difference in average cost of energy per square foot is compared, the SAGSHP system has about 21% lower average annual energy cost. The parameters modeled also lead to about 35.4% of the heat for the greenhouse being supplied by the heat pump, and almost 73.6% of the energy used to heat the greenhouse being purchased (with the other 26.4% is being from the solar collectors). Table 15 reports the base cost results for the boiler system and the SAGSHP system.

Table 15. Base heating system cost results

Measurement	SAGSHP	Boiler	Difference
AAC ($/sq-Ft)	1.253	0.746	0.507
AAEC ($/sq-Ft)	0.239	0.289	(0.050)
% BTU Purchased	73.570	100.000	
% Energy Cost of Total Cost	19.100	38.770	
% BTU from Heat Pump	35.400		
% BTU solar	26.430		
Heat Pump Shut Down	Feb. 23		

These costs will be examined and compared under different circumstances below. First, the effects of changing thermal solar collector size and cost are examined, leaving all other aspects of the model constant. Then, the effect of changing the price of the slinky loop is explained. Also analyzed is the effect of changing the size of the geothermal field, first by leaving all else constant and then by increasing the size of the thermal solar collectors with an increase in the geothermal field size. The effect of fuel prices rising higher than forecasted is discussed, including a determination of how far fuel prices must rise before the SAGSHP system exhibits lower average annual cost per square foot than the boiler system. Another assumption that is changed is the length of time the greenhouse is heated. Under the base assumption, the greenhouse is heated from January through April; this is compared to the costs of heating from October through April (May through September is assumed to not need heating due to the warm summer temperatures). The last part of this section will examine the effects of a carbon tax on the relative attractiveness of the two systems. The effects of carbon tax rates ranging from $10 per metric ton to $50 per metric ton will be compared, and the minimum carbon tax value that causes the relative cost of the SAGSHP system to be lower than that of the boiler system will be found.

Thermal Solar Collector Analyses

In the Netherlands, goals have been set to reduce greenhouse gas emissions from greenhouses through 1) zero greenhouses using fossil fuels by 2020 and 2) greenhouses producing at least as much energy as they consume by 2020 (KNAW 2008; Os 2008). In order to comply with the second goal, the set up for this system would entail reducing the amount of purchased energy to 50%, which is possible if the solar panel size is increased to about 22,884 square feet (2,126 square meters). Increasing the size of the solar field is expensive, as the cost per square foot is set at $9.00, however the tax credit available for the investment in solar equipment offsets some of that increase. The costs under the increased solar collector field is shown in Table 16, with the boiler difference showing the difference between the boiler system cost and the increased solar field system cost. The original SAGSHP system costs are shown for easier comparison.

Table 16. Increased solar field size cost results

Measurement	Base SAGSHP	Increased Solar	Boiler Difference
AAC ($/sq-Ft)	1.253	1.341	0.595
AAEC ($/sq-Ft)	0.239	0.182	(0.107)
% BTU Purchased	73.570	50.030	
% Energy Cost of Total Cost	19.100	13.540	
% BTU from Heat Pump	35.400	62.700	
% BTU solar	26.430	49.970	
Heat Pump Shut Down	Feb. 23	Mar. 27	

Although the amount of purchased energy falls to just under 50%, the added annual cost of the SAGSHP system rises about eight cents per square foot to $1.34, or almost $0.60 over the boiler system. Average annual energy cost per square foot falls about five cents per square foot to a little more than $0.18, or $0.10 under the average annual energy cost per square foot of the boiler system. Also, the heat pump runs until late March, about a month longer. At first blush, it seems that a restriction in the percent of total BTUs purchased would not harm this greenhouse too much, however it must be remembered that the values shown must be multiplied out by the total square footage of the greenhouse, about 43,008 square feet, which would amount to about an extra $25,589 annually.

A reason the solar panels are used is to regenerate the temperature of the geothermal field. If the solar panels are not used, but all other aspects of the model remain the same, the cost of the GHP system does decrease due to the high cost of the solar panels, however more is spent on energy. This is because the available heat for the heat pump falls quickly and is not replenished, causing much more reliance on the boiler units, which can be seen in the rise in percent of BTUs purchased (Table 17). Also, the difference in annual average energy cost savings of the SAGSHP system falls to under one penny; this is only about $300 a year.

Table 17. No solar assistance

Measurement	Base SAGSHP	No Solar	Boiler Difference
AAC ($/sq-Ft)	1.253	1.141	0.395
AAEC ($/sq-Ft)	0.239	0.282	(0.007)
% BTU Purchased	73.570	93.140	
% Energy Cost of Total Cost	19.100	24.670	
% BTU from Heat Pump	35.400	10.500	
% BTU solar	26.430	0.000	
Heat Pump Shut Down	Feb. 23	Jan. 22	

In researching prices for this research, a lower estimate of the cost of the solar field was given at about $6.00 per square foot (GMB Architects and Engineers 2008). If the price of the solar field were to drop from the $9.00 price in the model to $6.00 per square foot (and the solar field size is set to 12,916.7 square feet (1,200 square meters)), the average annual cost of the SAGSHP system decreases fourteen cents from about $1.25 to about $1.19. This drops the added AAC by six cents per square foot from about $0.50 to $0.44. The price paid for energy does not change because the other parameters of the system do not change. Energy cost as a percent of total cost does increase because total cost increases and energy cost stays constant (Table 18).

Table 18. Lower solar panel cost results

Measurement	Base SAGSHP	Lower Solar $	Boiler Difference
AAC ($/sq-Ft)	1.253	1.193	0.447
AAEC ($/sq-Ft)	0.239	0.239	(0.050)
% BTU Purchased	73.570	73.570	
% Energy Cost of Total Cost	19.100	20.060	
% BTU from Heat Pump	35.400	35.400	
% BTU solar	26.430	26.400	
Heat Pump Shut Down	Feb. 23	Feb. 23	

Lowering the cost of the thermal solar collectors does increase the attractiveness of the SAGSHP system, however it is mitigated by the inclusion of the solar tax credit. Without the solar tax credit, this average annual cost per square foot of the original SAGSHP is $1.311 and drops almost eight cents (instead of the six seen with the tax credit, above) to $1.233 with the lower cost thermal solar collectors.

Also observed with the above data, is that the average annual cost per square foot under no tax credit for the solar heating system is almost six cents higher per square foot than the original cost with the tax credit. This indicates that the inclusion of the tax credit under the base circumstances drops the average annual cost per square foot by about $0.058 cents. When multiplied over the area of the greenhouse, this is about $2,494 per year; therefore, it is seen that the solar tax credit is important to the relative attractiveness of the SAGSHP system.

Geothermal Field Analyses

As expected, changing the price of the slinky loop leads to a positively related change in the average annual cost per square foot; when the slinky loop price is changed in $0.50 increments, the average annual cost per square foot changes by about $0.04 (Table 19). Only the average annual cost per square foot, the difference in average annual cost per square foot between the SAGSHP system and the boiler system, and the energy cost as a percent of total cost are reported here, as the other values are not affected. There is about one acre of pipe assumed, and as such the effect of increasing or decreasing the cost of that large amount of pipe is a large factor in the total cost of the SAGSHP system.

Table 19. Changing slinky loop price results

	Slinky Loop Price ($/ft)				
Measurement	**1.67**	**2.17**	**Base**	**3.17**	**3.67**
AAC ($/sq-Ft)	1.172	1.217	1.253	1.294	1.335
added AAC ($/sq-F)	*0.426*	*0.467*	*0.447*	*0.548*	*0.589*
% Energy Cost	20.430	19.740	19.100	18.490	17.930

Changing the size of the geothermal field leads to similar changes in the cost of the SAGSHP system. There is slightly more energy available in the soil as the size of the geothermal field increases. However there are more initial investment expenses as well, including extra insulation, pipes and pumps. Increasing the length of the geothermal field by 10 feet increases the average annual cost of the system by less than one cent per square foot. The length of time the heat pump can run, however, only increases by five hours; this is not a large amount of time in terms of the heating season, which is 2,441 hours. The percent of BTUs purchased increases less than 0.1%, and energy cost as a percent of total cost falls by about the same degree. This is because there is no significant change in energy cost and there is an increase in average annual cost, though it is very small. Increasing the field by 100 feet leads to a six and a half cent increase in average annual cost per square foot and about 0.4 cent increase in average annual energy cost per square foot. The results of increasing the length of the geothermal field by ten, fifty and one hundred feet can be seen in Table 20, with AAC and AAEC rounded to the thousandth.

Table 20. Changing geothermal field size cost results

	Added Length to Geothermal Field (Ft)			
Measurement	**Base**	**10**	**50**	**100**
AAC ($/sq-Ft)	1.253	1.260	1.286	1.318
AAEC ($/sq-Ft)	0.239	0.240	0.242	0.243
% BTU Purchased	73.570	73.650	73.940	74.280
% Energy Cost of Total Cost	19.100	19.030	18.780	18.470
% BTU from Heat Pump	35.400	35.400	35.400	35.400
% BTU solar	26.430	26.350	26.060	25.720
Heat Pump Shut Down	Feb. 23	Feb. 23	Feb. 25	Feb. 27

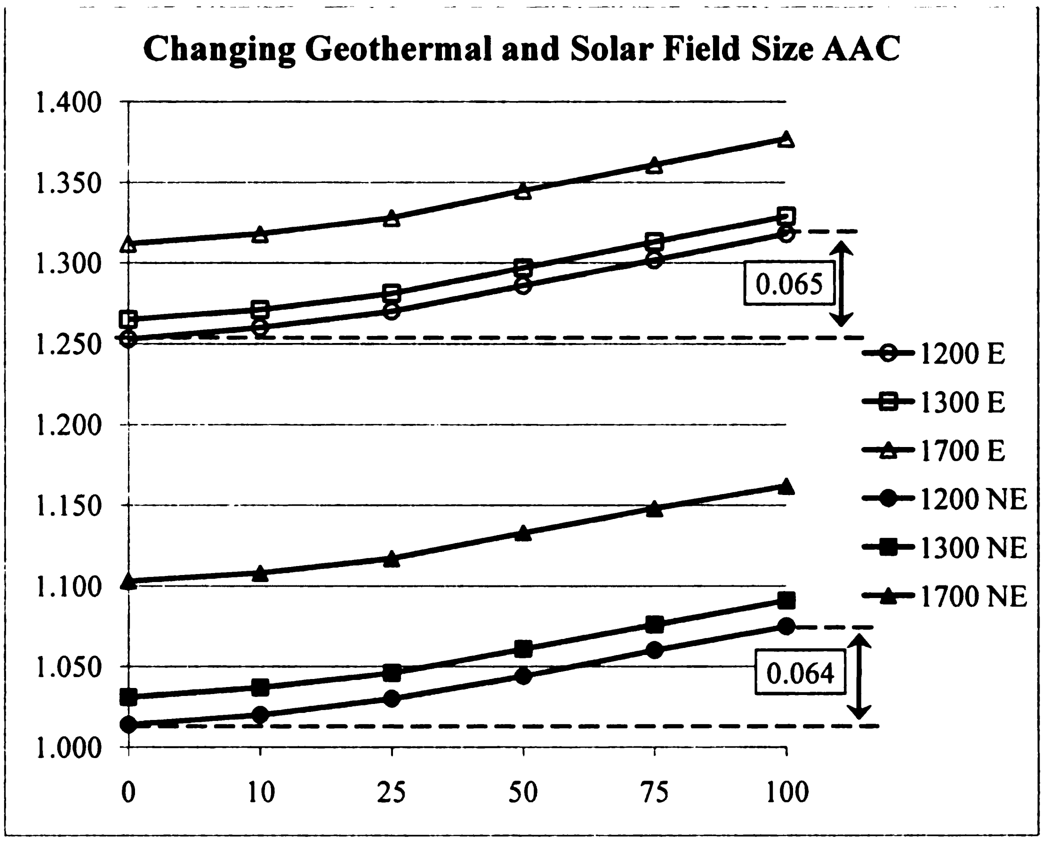
Increasing the length of the geothermal field may be more effective with an increase in the size of the solar field. An interesting result is found when the geothermal field length in increased with an increase in the size of the solar field. As above, the change in average annual cost and average annual energy cost per square foot are small. Increasing the length of the geothermal field means more energy is needed to run the heating system; as can be seen below, this increase in energy needs is greater than what can be provided by the extra space in the geothermal and solar fields; more energy is purchased than can be appropriated from the ground. Table 21 compares the cost effects of changing both the size of the geothermal field and the size of the solar field.

Table 21. Changing geothermal field size and solar field size results

	Added Length to Geothermal Field (ft)					
	Base		10		100	
	Added Solar M-2					
Measurement	**100**	**500**	**100**	**500**	**100**	**500**
AAC ($/sq-Ft)	1.265	1.312	1.271	1.318	1.329	1.377
AAEC ($/sq-Ft)	0.234	0.209	0.234	0.210	0.238	0.215
% BTU Purchased	71.09	61.02	71.18	61.13	71.87	62.04
% Energy Cost of Total Cost	18.46	15.94	18.40	15.90	17.89	15.60
% BTU from Heat Pump	38.30	50.10	38.30	50.10	38.30	50.10
% BTU solar	28.91	38.98	28.82	38.87	28.13	37.96
Heat Pump Shut Down	Feb. 26	Mar. 12	Feb. 27	Mar. 13	Mar. 3	Mar. 18

The results for the effect of changing solar field size and geothermal field size on AAC of the SAGSHP can also be seen in Figure 6, below. Both the total average annual cost and the average annual cost not including the average annual energy cost are shown. This illustrates that the energy prices are also rising with increased geothermal field size, as the AAC with the energy included rises faster than that of the AAC without energy costs included. The x-axis represents increasing the size of the geothermal field, while the lines each represent the AAC with and without energy costs for 12,916.7, 13,993.1, and 18, 298.63 square foot (1,200, 1,300 and 1,700 square meter) solar fields.

Figure 6. AAC and changing geothermal and solar field size



Fuel Price Analyses

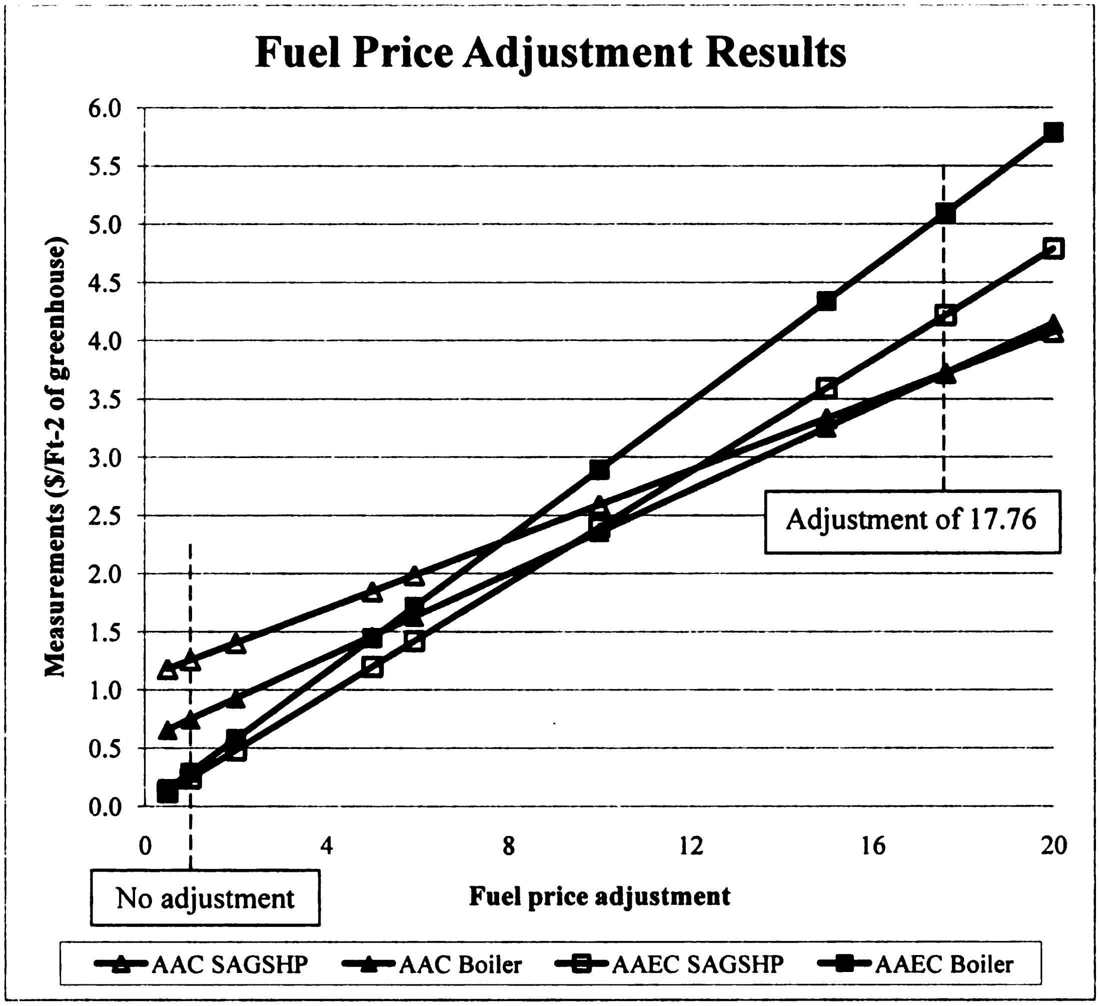
The future fuel prices used in this thesis are projections, and as such, they may actually be higher or lower than predicted. The SAGSHP system is accompanied with lower energy cost than the boiler system. Therefore, as prices rise, the present value of cost of the SAGSHP system and boiler should converge, and if prices rise enough, the cost of the boiler system will exceed that of the SAGSHP system. If fuel prices are lower than projected, the costs will deviate further – the difference between the SAGSHP and boiler system average annual cost will increase because the average annual energy cost difference will decrease. To see the sensitivity of the results to the price of fuel, natural gas and electricity prices are both multiplied by an adjuster, and eight results are shown below (Table 22). Included in the table is the multiplier that causes the average annual cost of the two systems to be equal, 17.62 (5.93, also included, is the multiplier that causes pre-tax average annual costs to be equal). When fuel prices are cut by half, the costs are decreased, but the average annual cost of the boiler system benefits relatively more than the SAGSHP system, with the difference in the average annual cost increasing to just over fifty-two cents per square foot. Between five and six times higher than the estimated energy prices, energy cost as a percent of total cost for the boiler system reaches over 100%, which means that the present value of energy cost is greater than the present value of all other costs. This is possible due to depreciation and salvage values and for the solar tax credit in the SAGSHP system. At fuel prices that are between ten and fifteen times higher than projected, the present value of energy cost for the SAGSHP system is greater than the present value of all other costs.

Table 22. Changing fuel price estimates results

	Measurements							
Fuel Price Adjustment	AAC ($/sq-ft)			AAEC ($/sq-ft)			% Energy Cost of Total	
	SAGSHP	Boiler	*Diff.*	SAGSHP	Boiler	*Diff.*	SAGSHP	Boiler
0.5	1.179	0.656	*0.523*	0.120	0.145	*(0.025)*	10.15	22.03
Base	1.253	0.746	*0.507*	0.239	0.289	*(0.050)*	19.10	38.77
2	1.402	0.925	*0.477*	0.479	0.578	*(0.099)*	34.15	62.53
5	1.847	1.462	*0.385*	1.197	1.445	*(0.248)*	64.80	98.90
5.93	1.985	1.628	*0.357*	1.419	1.714	*(0.295)*	71.57	105.31
10	2.589	2.356	*0.233*	2.394	2.891	*(0.497)*	92.45	122.70
15	3.331	3.251	*0.080*	3.590	4.336	*(0.746)*	107.79	133.39
17.62	3.720	3.720	*0.000*	4.218	5.094	*(0.876)*	136.94	113.38
20	4.073	4.146	*(0.073)*	4.787	5.782	*(0.995)*	117.54	1309.47

This can also be seen in the graph below. AAEC for the boiler system is rising faster than AAEC for the SAGSHP system, which leads to the AAC for the systems converging. At an adjustment of higher than 17.8 times the base estimated fuel prices given, the AAC of the boiler surpasses that of the SAGSHP system. The open markers represent the SAGSHP system, while the filled-in markers represent the boiler system.

Figure 7. Fuel price adjustment effects on cost measurements



If energy prices were to increases enough, the value of the SAGSHP system would increase with the savings in energy cost, as shown above. Above, the results of changing the size of the solar field are discussed; as the solar field increases, fewer BTUs are purchased for the SAGSHP system, leading to lower AAC. If increased energy costs are combined with an increased solar field, the SAGSHP system's net cost value shifts closer to that of the boiler system. For a simple example, Table 23 compares the AAC and the added AAC of the SAGSHP system under the base circumstances, as well as under fuel prices that are five times higher than estimated, with the size of the solar field increasing from 12,916.7 to 13,993.1 and 18, 298.63 square foot (1,200, 1,300 and 1,700 square meters).

Table 23. Higher fuel prices and larger solar field

Measurements		Base Fuel and Solar	5X higher fuel prices Added Solar M-2		
			Base	100	500
AAC ($/sq-ft)	SAGSHP	1.253	1.847	1.844	1.831
	Boiler	0.746	1.462	1.462	1.462
	difference	*0.507*	*0.385*	*0.382*	*0.369*
AAEC ($/sq-ft)	SAGSHP	0.239	1.197	1.168	1.045
	Boiler	0.289	1.445	1.445	1.445
	difference	*(0.050)*	*(0.248)*	*(0.277)*	*(0.400)*

Heating Schedule Analysis

If the greenhouse is used to grow plants during the winter months previous to January, growing Christmas poinsettias for example, it will need to be heated for the full year (with the exception of the warm summer months). When this is done, more fuel is consumed and the costs of running both systems increases. The difference between the average annual cost of the SAGSHP system and the boiler system decreases to just under $0.48 from the $0.507 difference under the base circumstances. The difference in average annual energy cost about doubles to ($0.102) from ($0.05). The model indicates that the cost of using the boiler system for longer periods of time is greater than the cost of using the heat pump for longer periods of time, making the heat pump more attractive as total BTU heat loss increases. Table 24, below, shows the change from spring heating to a full year of heating.

Table 24. Full year of heating cost results

Measurements	SAGSHP		Boiler		Difference	
	Orig.	Full	Orig.	Full	Orig	Full
AAC ($/sq-Ft)	1.253	1.340	0.746	0.864	0.507	0.476
AAEC ($/sq-Ft)	0.239	0.378	0.289	0.480	(0.050)	(0.102)
% BTU Purchased	73.57	68.14	100.0	100.0		
% Energy Cost of Total Cost	19.10	28.22	38.77	55.54		
% BTU from Heat Pump	35.40	42.60				
% BTU solar	26.43	31.86				
Heat Pump Shut Down	Feb. 23	Feb. 21				

Carbon Tax Analyses

Generating one BTU through the burning of natural gas gives off less CO2 than generating one BTU through electricity on average, mostly due to the majority of electricity being produced through coal, which is a very high emitter of CO2 (NaturalGas.org 2004). The SAGSHP system generates BTUs through both purchasing electricity and through burning natural gas, while the boiler system generates BTUs only through burning natural gas; this would lead to the assumption that the boiler system produces fewer CO2 emissions. From the calculations in the model, however, it is seen that this is not true – the boiler system produces 2.8 metric tons of CO2 more than the SAGSHP system per year, or about 41.9 metric tons for the entire 15 year life of the analysis. This is because of the volume of natural gas burned in the boiler system compared to electricity and natural gas used in the SAGSHP system. The SAGSHP system utilizes BTUs in the soil and those collected by the solar field to heat, and therefore the level of BTUs that are purchased decrease. This enables the CO_2 output of the SAGSHP system to be lower than that of the boiler system.

Norway, Finland and Sweden have employed carbon taxes since 1991, with Norway's average about \$21/ton of CO_2 released and Sweden starting at a rate of \$100/ton, raising it to \$150/ton in 1997 (Bryner 2007). In 2006, a carbon tax based on the amount of kWh of electricity used was voted in by the residents of Boulder, CO (Bryner 2007). British Columbia introduced the idea of a carbon tax starting at \$10/tC, increasing \$5/year for four years (Litman 2008). In 2007, representative Pete Stark of California proposed a carbon tax of \$25/tC (Bryner 2007).

In the system modeled for this thesis, the amount of electricity purchased by the SAGSHP system is broken down by the sources used to produce electricity; coal, petroleum, natural gas, pumped storage/other (hydroelectricity), and renewable sources. Coal is the largest contributor of electricity, with natural gas second, followed by nuclear power, pumped storage, renewable sources and then petroleum (EIA 2007). Coal is also has the largest carbon output rate, followed by petroleum, pumped storage, and natural gas with nuclear power and renewable sources tied at no contribution (USDE 2000).

The percent of each sources contribution to total electricity production in 2007, the projected rate of growth of electricity from 2007 through 2030, and the projected annual growth of each electricity source through the year 2030 are used to calculate the contribution of each electricity source per year through the life of the study. This is used to determine the amount of kilowatts produced from each source, which is then used with the carbon output rate of that source to determine the total carbon output from the electricity used by the SAGSHP system. This is added to the total carbon output from the burning of natural gas from the boilers, when they are used after the heat pump shuts down. The calculation for metric tons of carbon output from the boiler system is determined through the total metric tons of natural gas burned and the carbon output rate of natural gas.

In this thesis, five levels of carbon tax are compared, the lowest at $10/tC, the highest at $50/tC. The effect of the carbon tax is small, with the difference in average annual cost between the two systems staying relatively the same for all levels, though it does fall to $0.506 under $50/tC (Table 25). The average annual cost per square foot and energy cost as a percent of total cost change with the carbon tax; however, because the carbon tax is not included in the cost of energy, the average annual energy cost per square foot does not change. Also, because the carbon tax is a tax, there are no pre-tax cost results in appendix three.

Table 25. Changing carbon tax cost results

Measurements		**Base**	**Carbon Tax** 10	20	30	40	50
AAC ($/sq-ft)	SAGSHP	1.253	1.270	1.287	1.304	1.321	1.338
	Boiler	0.746	0.763	0.780	0.797	0.814	0.832
	difference	*0.507*	*0.507*	*0.507*	*0.507*	*0.507*	*0.506*
%Energy Cost	Boiler	19.10	18.84	18.60	18.36	18.12	17.90
	SAGSHP	38.17	37.89	37.06	36.26	35.50	34.77

Chapter 6

CONCLUSION AND DISCUSSION

This research uses capital budgeting and present value techniques to determine the 15 year life cost of installing and running two different heating systems in a mid-Michigan greenhouse. The conventional natural gas boiler system is found to be the lower cost option under the base conditions modeled, due to both the necessary reliance of the solar assisted ground source heat pump (SAGSHP) system on the solar thermal collectors, which include a large initial investment, and the larger initial cost of the heat pump unit investment and installation. The model includes discounted values to estimate the present value of the cost in each year. Though the present value of energy cost for the SAGSHP system in all situations presented is smaller than that of the boiler system, the larger initial invest of the SAGSHP overshadows this lower energy cost. This is in part due to the initial investment being in the first year of the study (or year zero); the large initial investment is not discounted back to the present value because it is in present value, lending the initial investment a greater weight on the present cost of the systems.

The long term costs of the SAGSHP system are smaller than the boiler system, however they are discounted back to present value, which decreases its weight on the total present cost. Under a discount rate different from the 10% used, the results would be different. For example, a higher discount rate emphasizes the larger cost of the SAGSHP initially by minimizing the effect of lower energy prices in the future. A smaller discount rate would play up the effect of future energy cost savings, diminishing the effect of the larger SAGSHP initial investment.

A few ways the results from this study may change are if the geothermal field was modeled differently, the study was lengthened, or if energy prices are different than the current forecast. If the field is modeled as vertical, more energy may be able to come from it; the pipes could be longer, located in a smaller surface area, and in a good scenario the pipes may go through an underground river, receiving at least some heat replenishment naturally. If a greenhouse is close to a feasible water source, the system may be modeled as a water source; a water source system would have lower initial investment due to no excavation being required and would likely not need solar thermal collectors. If the water source system does require assistance to recharge, the solar field would not have to be as large because of water's higher specific heat and ability to move heat.

If the study was estimated over a period of 20 years, the results may also be different. The higher energy prices of the boiler system would continue, and the life of the heating system itself would come into play. The initial investment of the solar assisted heat pump unit as a whole is larger than that of the boiler system; however, the cost of the boiler units needed is much higher than the cost of the total heat pump and boiler units modeled in the SAGSHP system. Over 20 to 25 years, it is feasible that the boiler unit(s), the heat pump unit(s) and the solar thermal collectors may need replacing, though the pipes have a warranty of 50 years. As modeled above, the cost of replacing the heating units modeled in the SAGSHP system (not including the thermal solar collectors) is about $7,600 (or about $0.18 per square foot) less than the cost of replacing the required number of boiler units needed in the boiler system scenario. Assuming the boiler units will need replacing at the same time the heat pump units do, the heat pump replacement costs is a lower cost investment.

The two most expensive parts of the heat pump system installation are the solar panels and the slinky loop; the slinky loop has a warranty of about 50 years, and would therefore not need replacing in the 20 to 25 year scenario. The solar panels on the other hand, the most expensive part of the project, will likely need replacement. If it can be assumed that either 1) the price of the solar panels falls over the course of the 20 years, or 2) the efficiency of the solar panels increases enough that not as many square feet are needed, the cost of the solar panels will fall. Whether or not it will fall to the price required for the two systems to become equal is the question.

For the SAGSHP and the boiler systems to have the same investment cost for the replacing the units and the solar panels (no pipes, etc), the solar thermal collectors would have to fall to about $0.64 per square foot (not including the solar credit). If the price did not fall that far, but only to about $6.50 per square foot, the units needed to reach the same level of collection would have to fall from about 11,840 square feet to about 108 square feet. At the current time, this does not seem feasible.

The present value of the cost of energy for the greenhouse is changed if the study is lengthened as well. The natural gas boiler system costs more to run than the SAGSHP system, so the difference in the total energy cost will continue to increase, causing the heat pump system to earn a better energy cost savings over the boiler system.

Also, as the study is lengthened, the total metric tons of CO2 released increases; however, under the base parameters of the study, this difference may not be very large, as discussed in the Chapter 5, Results. The CO2 released that can be attributed to the greenhouse under the boiler system are about 2.8 metric tons per year greater than that of the SAGSHP system. Over time, this difference would continue to increase, and at the end of 20 years, the total difference would be over 55 metric tons. If the efficiency of the SAGSHP system were to increase or the heat pump could be used longer in the season, however, this difference would get larger. Two ways this may be possible is to change the horizontal slinky configuration to a vertical configuration, or use a suitable water source instead of the earth. Another option is to purchase electricity from renewable sources such as wind, hydroelectricity, solar or geothermal; not only would this reduce the CO2 output of the greenhouse leading to lower carbon tax being paid, but it would also increase the greenhouse's level of "green".

The model may be modified in other ways, to decrease possible errors. For example, the heat loss through the insulation around the geothermal field was not accounted for. This will likely decrease the available BTUs in the soil, perhaps enough to cause greater dependence on the back up boiler system. It may also cause the geothermal field to absorb a little heat from the surrounding soil, causing the heat loss and heat gain through the insulation to be close to equal.

The research presented here is important for a few reasons. For one, the model created allows for easy comparisons between two different heating systems. It can also altered to include information for specific greenhouses, including size, heat loss, heating schedule, fuel burned, energy prices, depth of the geothermal field, base soil temperature, output of the boilers or heat pump units, BTU collection of the thermal solar collectors, and can easily be modified to include different policies (for example, the solar credit or carbon tax). For another, the research presented above aids in understanding which aspects of the costs of the systems are the biggest influences. This can be helpful when creating policies, or in deciding on features of the system; knowing that a larger geothermal field does not pay under the conditions in the model, is important in deciding the size of the field. In addition, the model is a tool that provides only the present value of the costs that are different for the two systems, which eliminates some noise that may occur and simplifies the interpretation of results.

Another important result of the study is the illustration of how policies affect the relative attractiveness of the SAGSHP system, as shown in Chapter 5, Results. Without the solar credit, the SAGSHP system would be over five cents per square foot more expensive than with the inclusion of the solar credit; multiplied out over 43,008 square feet, this is about $2,494 a year. However, even with the addition of the solar credit, the SAGSHP system is about $0.507 more annually per square foot than the more conventional boiler system.

With this model, potential (and current) policies can be analyzed for their affect on the relative costs of the alternative geothermal heat pump system. The results shown here illustrate that in knowing the affects of policies, they can be altered to create the intended effect. The results above also indicate that if policy makers are attempting to make systems like the SAGSHP system modeled here more attractive to business that consume a lot of non-renewable resources, like large greenhouses, more work needs to be done.

The most important future value of this research is the versatility of the model. With a little bit of work, the model can evaluate many different heating systems or versions of heating systems. For example, in applications of GHP systems in Michigan, the vertical bore-hole system seems to be a popular option, this model can be adapted to the situations under that system instead of the horizontal slinky loop used.

The results of the model under the characteristics chosen indicate that if the greenhouse owner is looking for the lowest price option, it is not currently found in the SAGSHP system. If the greenhouse owner is looking for the system with the lowest CO2 emissions attributable it, the SAGSHP system experiences slightly lower emissions, and the difference can be increased through the purchasing of electricity from renewable sources. If the most important aspect in choosing a system is the cost of fuel, the SAGSHP system is the choice; under the base circumstances, the cost of fuel is about five cents less annually per square foot (about $2,150 per year) than the boiler system. As fuel prices climb, the difference in fuel cost is only going to get larger.

Appendix 1

Product Information for MS50Z6 Water to Water Heat Pump from MultiStack

Leaving Hot Water	Model MS50Z6																	
	Leaving Source Water Temp																	
	30			35			40			45			50			55		
Temp (F)	COP	kW	MBH	COP	kW	MBH	COP	kW	MBH	COP	kW	MBH	COP	kW	MBH	COP	kW	MBH
100	4.4	39	580	4.7	39	630	5.1	40	685	5.4	40	744	5.8	41	807	6.2	41	876
105	4.1	41	574	4.4	41	624	4.8	42	678	5.1	42	735	5.5	43	797	5.9	43	864
110	3.9	43	570	4.2	44	618	4.5	44	671	4.8	44	727	5.2	45	788	5.5	45	853
115	3.6	46	566	3.9	46	613	4.2	46	664	4.5	47	719	4.9	47	779	5.2	47	843
120	3.4	48	562	3.7	48	608	4	49	658	4.3	49	712	4.6	49	770	4.9	50	833
125				3.5	51	604	3.7	51	653	4	52	705	4.3	52	762	4.6	52	823
130				3.3	53	600	3.5	54	648	3.8	54	699	4	55	755	4.3	55	815

Appendix 2

7 Year MACRS Table

Year	0	1	2	3	4	5	6	7	8	9
0-Yr	0	0	0	0	0	0	0	0	0	0
3-Yr	0	0.3333	0.4445	0.1481	0.0741	0	0	0	0	0
5-Yr	0	0.2	0.32	0.192	0.1152	0.1152	0.0576	0	0	0
7-Yr	0	0.1429	0.2449	0.1749	0.1249	0.0893	0.0892	0.0893	0.0446	0

Appendix 3

Pre-Tax Tables

Table 26. Pre-Tax solar panel results
Associated Table: Table 11

	Solar Panel Square Meters					
Measurements	**500**	**1,000**	**1,100**	**1,200**	**1300**	**1,500**
AAC ($/sq-F)	1.473	1.498	1.506	1.493	1.501	1.515
added AAC ($/sq-F)	*0.719*	*0.744*	*0.752*	*0.739*	*0.747*	*0.761*
AAEC ($/sq-F)	0.289	0.263	0.257	0.252	0.245	0.233
AAEC savings ($/sq-F)	*(0.014)*	*(0.040)*	*(0.046)*	*(0.051)*	*(0.058)*	*0.07*

Table 27. Pre-Tax boiler unit results
Associated Table: Table 12

	Min. number supplmental boilers		
Measurements	**0**	**1**	**2**
AAC ($/sq-F)	1.493	1.493	1.496
AAEC ($/sq-F)	0.252	0.252	0.253
% BTU Purchased	73.570	73.560	75.080
% Energy Cost of Total Cost	16.840	16.840	16.920
% BTU from HP	35.400	35.400	32.800

Table 28. Pre-Tax heat pump unit results
Associated Table: Table 13

	Heat Pump Units		
Measurements	**1**	**2**	**3**
AAC ($/sq-F)	1.493	1.564	1.623
AAEC ($/sq-F)	0.252	0.225	0.217
% BTU Purchased	73.570	69.090	67.600
% Energy Cost of Total Cost	16.840	14.410	13.340
% BTU from HP	35.400	35.400	35.400

Table 29. Pre-Tax base model specifications
Associated Table: Table 14

Specification	Value
Size of Solar Field (Sq-M)	1,200
Length of Greenhouse (Ft)	384
Width of Greenhouse (Ft)	112
Footprint of Greenhouse (Sq-Ft)	43,008
Added Length of Geothermal Field (Ft)	0
Footprint of GT Field (Sq-Ft)	43,008
Depth of Geothermal Field (Ft)	8
Number of Heat Pump Modules	1
Minumum Sup Heat Modules	0
Output of Sup Heater Module (BTU)	300,000
Output of Heat Pump Module (BTU)	600,000
HsP to run coils for 1 Heat Pump Module	1
Marginal Tax Bracket (%)	41
Loan (%)	60
Loan Size ($)	313,449
Length of Loan Payback (Yrs)	7
Interest Rate (%)	9
Property Tax Rate (%)	0.55
Total Solar Credit ($)	36,375
Discount Rate (%)	10
Total Present Pre Tax GHPS Cost ($)	346,863
Total Present Pre Tax Boiler Cost ($)	99,213

Table 30. Pre-Tax base cost results
Associated Table: Table 15

Measurement	SAGSHP	Boiler	Difference
AAC ($/sq-Ft)	1.493	0.754	0.739
AAEC ($/sq-Ft)	0.252	0.303	(0.051)
% BTU Purchased	73.570	100.000	
% Energy Cost of Total Cost	16.840	40.220	
% BTU from Heat Pump	35.400		
% BTU solar	26.430		
Heat Pump Shut Down	Feb. 23		

Table 31. Pre-Tax increased solar field size cost results
Associated Table: Table 16

Measurement	Base SAGSHP	Increased Solar	Boiler Difference
AAC ($/sq-Ft)	1.493	1.536	0.782
AAEC ($/sq-Ft)	0.252	0.191	(0.112)
% BTU Purchased	73.570	50.030	
% Energy Cost of Total Cost	16.840	12.440	
% BTU from Heat Pump	35.400	62.700	
% BTU solar	26.430	49.970	
Heat Pump Shut Down	Feb. 23	Mar. 27	

Table 32. Pre-Tax no solar assistance
Associated Table: Table 17

Measurement	Base SAGSHP	No Solar	Boiler Difference
AAC ($/sq-Ft)	1.493	1.394	0.640
AAEC ($/sq-Ft)	0.252	0.295	(0.008)
% BTU Purchased	73.570	93.140	
% Energy Cost of Total Cost	16.840	21.200	
% BTU from Heat Pump	35.400	10.500	
% BTU solar	26.430	0.000	
Heat Pump Shut Down	Feb. 23	Jan. 22	

Table 33. Pre-Tax lower solar panel cost results
Associated Table: Table 18

Measurement	Base SAGSHP	Lower Solar $	Boiler Difference
AAC ($/sq-Ft)	1.493	1.422	0.668
AAEC ($/sq-Ft)	0.252	0.252	(0.051)
% BTU Purchased	73.570	73.570	
% Energy Cost of Total Cost	16.840	17.690	
% BTU from Heat Pump	35.400	35.400	
% BTU solar	26.430	26.430	
Heat Pump Shut Down	Feb. 23	Feb. 23	

Table 34. Pre-Tax changing slinky loop price results
Associated Table: Table 19

	Slinky Loop Price ($/ft)				
Measurement	**1.67**	**2.17**	**Base**	**3.17**	**3.67**
AAC ($/sq-Ft)	1.421	1.457	1.493	1.529	1.565
added AAC ($/sq-F)	*0.667*	*0.703*	*0.739*	*0.775*	*0.811*
% Energy Cost	17.690	17.260	16.840	16.450	16.070

Table 35. Pre-Tax changing geothermal field size cost results
Associated Table: Table 20

	Added Length to Geothermal Field (Ft)			
Measurement	**Base**	**10**	**50**	**100**
AAC ($/sq-Ft)	1.493	1.500	1.524	1.555
AAEC ($/sq-Ft)	0.252	0.252	0.254	0.256
% BTU Purchased	73.570	73.650	73.940	74.280
% Energy Cost of Total Cost	16.840	28.480	16.650	16.450
% BTU from Heat Pump	35.400	35.400	35.400	35.400
% BTU solar	26.430	26.350	26.060	25.720
Heat Pump Shut Down	Feb. 23	Feb. 23	Feb. 25	Feb. 27

Table 36. Pre-Tax changing geothermal field size and solar field size results
Associated Table: Table 21

	Added Length to Geothermal Field (ft)					
	Base		**10**		**100**	
			Added Solar M-2			
Measurement	**100**	**500**	**100**	**500**	**100**	**500**
AAC ($/sq-Ft)	1.501	1.529	1.507	1.536	1.563	1.594
AAEC ($/sq-Ft)	0.245	0.220	0.246	0.220	0.250	0.226
% BTU Purchased	71.090	61.020	71.180	61.130	71.870	62.040
% Energy Cost of Total Cost	16.350	14.370	16.310	14.360	16.000	14.170
% BTU from Heat Pump	38.300	50.100	38.300	50.100	38.300	50.100
% BTU solar	28.910	38.980	28.820	38.870	28.130	37.960
Heat Pump Shut Down	Feb. 26	Mar. 12	Feb. 27	Mar. 13	Mar. 3	Mar. 18

Figure 8. Pre-Tax AAC and changing geothermal and solar field size
Associated Figure: Figure 6

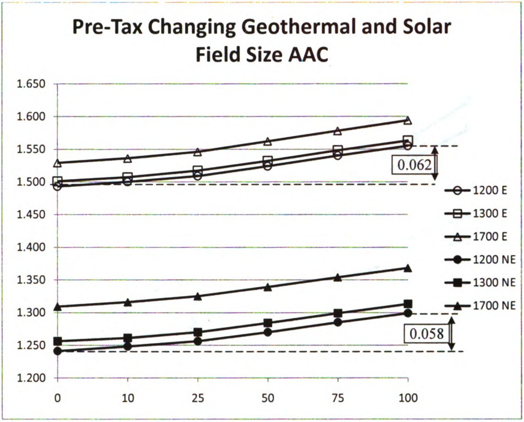


Table 37. Pre-Tax changing fuel price estimates results
Associated Table: Table 22

	Measurements							
Fuel Price Adjustment	AAC ($/sq-ft)			AAEC ($/sq-ft)			% Energy Cost of Total Cost	
	SAGSHP	Boiler	*Diff.*	SAGSHP	Boiler	*Diff.*	SAGSHP	Boiler
0.5	1.280	0.803	*0.477*	0.126	0.152	*(0.026)*	9.82	18.88
Base	1.493	1.060	*0.433*	0.252	0.303	*(0.051)*	16.84	28.60
2	1.920	1.574	*0.346*	0.503	0.607	*(0.104)*	26.20	38.53
5	3.199	3.117	*0.082*	1.258	1.516	*(0.258)*	39.32	48.66
5.93	3.595	3.595	*0.000*	1.491	1.799	*(0.308)*	41.49	50.03
10	5.330	5.687	*(0.357)*	2.515	3.033	*(0.518)*	47.19	53.33
15	7.461	8.257	*(0.796)*	3.773	4.549	*(0.776)*	50.56	55.10
17.62	8.578	9.604	*1.026*	4.432	5.344	*(0.912)*	55.64	51.66
20	9.593	10.827	*1.234*	5.03	6.066	*(1.036)*	52.55	56.02

Figure 9. Pre-Tax fuel price adjustment effects on cost measurements
Associated Figure: Figure 7

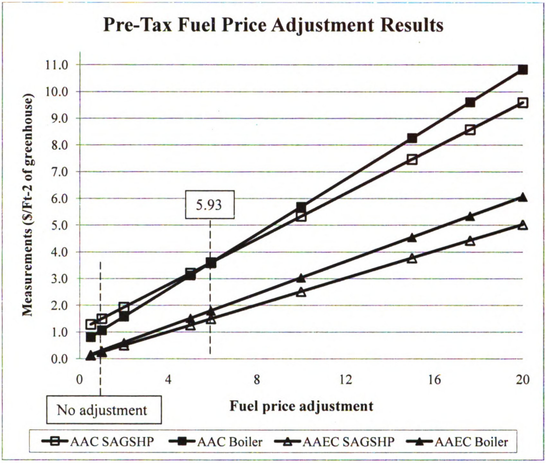


Table 38. Pre-Tax higher fuel prices and larger solar field
Associated Table: Table 23

Measurements		Base Fuel and Solar	5X higher fuel prices Added Solar M-2 Base	100	500
AAC ($/sq-ft)	SAGSHP	1.493	3.199	3.165	3.019
	Boiler	1.060	3.117	3.117	3.117
	difference	*0.433*	*0.082*	*0.048*	*(0.098)*
AAEC ($/sq-ft)	SAGSHP	0.252	1.258	1.227	1.099
	Boiler	0.303	1.516	1.516	1.516
	difference	*(0.051)*	*(0.258)*	*(0.289)*	*(0.417)*

Table 39. Pre-Tax full year of heating cost results
Associated Table: Table 24

Measurements	SAGSHP		Boiler		Difference	
	Orig.	Full	Orig.	Full	Orig	Full
AAC ($/sq-Ft)	1.493	1.741	0.754	1.399	0.739	0.342
AAEC ($/sq-Ft)	0.252	0.397	0.303	0.503	(0.051)	(0.106)
% BTU Purchased	73.57	68.14	100.0	100.0		
% Energy Cost of Total Cost	16.84	22.83	28.60	35.97		
% BTU from Heat Pump	35.40	42.60				
% BTU solar	26.43	31.86				
Heat Pump Shut Down	Feb. 23	Feb. 21				

Works Cited

Alternate Energy Resource Network. (2008). "Energy Equivalents." Retrieved November, 2008, from http://www.alternate-energy.net/energy_ref06.html.

ASHRAE (2004). Owning and Operating Costs. ASHRAE Applications Handbook. Atlanta, GA: 36.1- 36.14.

Bakos, G. C., D. Fidanidis, et al. (1999). "Greenhouse Heating Using Geothermal Energy." Geothermics **28**: 759-765.

Bartok, J. (2001). Greenhouse Energy Conservation Checklist, Natural Resources Management and Engineering Dept., Univ. of Conneticut.

Bi, Y., T. Guo, et al. (2004). "Solar and Ground Source Heat-Pump System." Applied Energy **78**: 231-245.

Birchmeier, C. (2005). Michigan Greenhouse and Nursery Financial Study. Agricultural Economics. Manhattan, Kansas State University. **Master of Agribusiness:** 65.

Bloomquist, R. G. (2000). Geothermal Heat Pumps Five Plus Decades of Experience in the United States. World Geothermal Congress 2000, Kyushu - Tohoku, Japan.

Boyd, T. (2008). Geothermal Greenhouse Information Package. Klamath Falls, OR, Goe-Heat Institute, Oregon Institute of Technology.

Boyd, T. and J. Lund (2006). Greenhouse and Aquaculture Applications of Geothermal Energy. 2006 ASABE Annual International Meeting. Portland, Or, ASABE.

Bryner, G. (2007). The Idea of a Carbon Tax. Utah Climate Policy Symposium. Utah.

Burden, D. (2008, May 2008). "Nursery Trees Profile." Nursery Trees Profile Retrieved August, 2008.

Chiasson, A. (2006). Greenhouse Heating With Geothermal Heat Pump Systems. 2006 ASABE Annual International Meeting. Portland, Oregon, ASABE.

Chiasson, A. and C. Yavuzturk (2003). "Assessment of the Viability of Hybrid Geothermal Heat Pump Systems with Solar Thermal Collectors." ASHRAE Trasactions **109**(2): 487-500.

Darling, D. (2009). "The Encyclopedia of Alternative Energy and Sustainable Living - U-Value." World of David Darling, January, 2009, from http://www.daviddarling.info/encyclopedia/C/AE_coefficient_of_heat_transmission.html.

DLSC. (2005, March 2008). "Drake Landing Solar Community." Retrieved May 15, 2008.

Dr. Wilkerson, D., L. Dr. Barnes, et al. (2008). "The Texas Poinsettia Producers Guide; Economics and Marketing." 2009, from http://aggie-horticulture.tamu.edu/GREENHOUSE/NURSERY/GUIDES/POINSETTIA/econ.html.

EIA. (2007, July 2008). "Energy in Brief." Retrieved August, 2008, from http://tonto.eia.doe.gov/energy_in_brief/electricity.cfm.

EIA. (2008, December, 2008). "Forecasts and Analyses." Retrieved November, 2008, from http://www.eia.doe.gov/oiaf/forecasting.html.

EIA. (2008, April, 2008). "Geothermal Heat Pump Shipments by Model Type, 2000-2006." Retrieved October, 2008, from http://www.eia.doe.gov/cneaf/solar.renewables/page/heatpumps/heatpumps.html.

EIA. (2008). "No. 2 Distallate Prices by Sales Type." Retrieved October, 2008.

EIA. (2008). "Official Energy Statistics from the U.S. Government." Retrieved October, 2008, from http://www.eia.doe.gov/.

EIA. (2008). "Official Energy Statistics from the U.S. Government." Retrieved December, 2008, from http://www.eia.doe.gov/.

Energy Savings and Trust (2007). Domestic Ground Source Heat Pumps: Design and Installation of Closed-Loop Systems. Best Practice Guide. London, England, Energy Savings and Trust.

Evans, M. R. (2005). "Greenhouse Heating Systems." Retrieved November, 2008, from http://www.uark.edu/~mrevans/4703/learning_units/unit_05/unit_05.html.

Florides, G. and S. Kalogirou (2007). "Ground Heat Exchangers - A Review of Systems, Models and Applications." Renewable Energy **32**: 2461-2478.

Foth, H. (1990). Fundamentals of Soil Science. New York, John Wiley & Sons.

Geo-Heat Center. (2008, January, 2007). "GHC Bulletin Article Comprehensive Index." Retrieved October, 2008, from http://geoheat.oit.edu/ghcindex.htm#econ.

Geo-Heat Center. (2008, January 1, 2008). "What is Geothermal?" Retrieved August, 2008, from http://geoheat.oit.edu/whatgeo.htm.

GeoExchange (2008). GeoExchange Heating and Cooling Systems: Fascinating Facts. GeoExchange.org.

GMB Architects and Engineers (2008). GSHP Characteristics. E. Miller. Holland, MI.

Green, B. D. and R. G. Nix (2006). Geothermal - The Energy Under our Feet, Geothermal Resource Estimates for the United States, National Renewable Energy Laboratory, USDoE.

Hanova, J., H. Dowlatabadi, et al. (2007). Ground Source Heat Pump Systems in Canada, Resources for the Future.

Harsh, S., Dr. (2008). Property tax rate discussion. E. Miller.

IGSHPA. (2008, 2006). "What is Geothermal." Retrieved August, 2008, from http://www.igshpa.okstate.edu/geothermal/geothermal.htm.

IGSHPA/OSU. (2008). "International Ground Source Heat Pump Association." Retrieved September, 2008.

Jerardo, A. (2007). Floriculture and Nursery Crops Yearbook. S. Lee, Economic Research Service.

Klaassen, C. J. (2006). Geothermal Heat Pump Systems, Iowa Energy Center, ERS.

Klaassen, C. J. (2006). Geothermal Heat Pump Technology, Iowa Energy Center/Energy Resource Station.

Kleweno, D. D. and V. Matthews (2007). Michigan Agricultural Statistics 2006-2007, USDA, NASS, Michigan Fiels Office.

KNAW (2008). Program: BO-03-006 Energy in glasshouse horticulture, NOD; Dutch research database.

LeFeuvre, P. (2007). An Investigation Into Ground Source Heat Pump Technology, it's UK Market and Best Practice in System Design. Mechanical Engineering, University of Strathclyde. **MSc:** 180.

Litman, T. (2008). Carbon Taxes: Tax what you burn, not what you earn. Victoria, British Columbia, Canada, Victoria Transport Policy Institute.

Lund, J. (1990). "Geothermal Heat Pump Utilization in the United States." Geo-Heat Center Quarterly Bulletin **11**(1).

Lund, J., B. Sanner, et al. (2004). Geothermal (Ground-Source) Heat Pumps A World Overview. GHC Bulletin. Klamath Falls, OR, Geo Heat Center. **25**.

Lund, J., B. Sanner, et al. (2004). "Geothermal (Ground-Source) Heat Pumps A World Overview." Geo-Heat Center Quarterly Bulletin **25**(3).

Martin, M. A., D. J. Durfee, et al. (1999). Comparing Maintenance Costs of Geothermal Heat Pump Systems with other HVAC Systems in Lincoln Public Schools: Repair, Service, and Corrective Actions. ASHRAE Annual Meeting. Seattle, Washington.

MDOEQ (2007). Well Construction Considerations and Permit Regulations Affecting Geothermal Heat Pump Systems. Lansing, MI, Michigan Department of Environmental Quality.

Microsoft (2007). Microsoft Office Excel.

Monacelli, E. (2008). Greenhouse going 'green'. Kalamazoo Gazette. Kalamazoo, MI.

MPSC (2008). MIchigan Energy Overview. Michigan Public Service Commision Dept. of Labor and Economic Growth.

National Greenhouse Manufacturers Association (1998). Greenhouse Heating Efficiency Design Considerations, NGMA.

NaturalGas.org. (2004). "Natural Gas and the Environment." 2009, from http://www.naturalgas.org/environment/naturalgas.asp.

NOAA/USDA (2008). Average Soil Temperature (degrees F, 4" Bare) May 11-17, 2008: Joint Agricultural Weather Facility.

NRCS. (2008). "Estimating Moist Bulk Density by Texture." Soil SUrvey Guides and References Retrieved November, 2008, from http://www.mo10.nrcs.usda.gov/references/guides/properties/moistbulkdensity.html.

ODUSD (2007). Ground-Source Heat Pumps at Department of Defense Facilities. Offfice of the Deputy Under Secretary of Defense (Installations and Environment).

Omer, A. M. (2008). "Ground-Source Heat Pumps Systems and Applications." Renewable and Sustainable Energy Reviews **12**: 344-371.

Os, E. v. (2008). Greenhouse production: water management and energy, Wagenungen UR Greenhouse hirticultue.

Oxgener, O. and A. Hepbasli (2005). "Experimental Investigation of teh Performance of a Solar-Assisted Ground Source Heat Pump System for Greenhouse Heating." International Journal of Energy Research **29**: 217-231.

Ozgener, O. and A. Hepbasli (2005). "Experimental Investigation of the Performance of a Solar-Assisted Ground Source Heat Pump System for Greenhouse Heating." International Journal of Energy Research **29**: 217-231.

Ozgener, O. and A. Hepbasli (2005). "Experimental Performance Analysis of a Solar Assisted Ground-Source Heat Pump Greenhouse Heating System." Energy and Buildings **37**: 101-110.

Ozgener, O. and A. Hepbasli (2006). "An Economical Analysis on a Solar Greenhouse Intergrated Geothermal Heat Pump System." Journal of Energy Resource Technology **128**.

Rackley, J. (2008) Geothermal System Helps Sisters Fulfill Spritual, Moral Mandate. GeoOutlook Online **Volume**, DOI:

Runkle, E. (2007). Managing Temp for the Best Spring Crops, GMPro.

Runkle, E. (2008). Greenhouse Characteristics. E. Miller. East Lansing, MI.

Rybach, L. and W. J. Eugster (2002). Sustainability Aspects of Geothermal Heat Pumps. Twenty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford, California, Stanford University.

Sanford, S. (2006). Greenhouse Unit Heaters: Types, Placement, and Efficiency. U. o. W. Extension. Madison, Wisconsin.

SC Johnson & Son, I. (2008, 2008). "www.SCJohnson.com/environment/growing.asp." Retrieved November, 2008.

Schnelle, M. and J. Dole (2007). Greenhouse Structures and Coverings. OSU Fact Sheets. Stillwater, OK, Oklahoma State University Extension.

Sima, J. F. (2008). Geothermal Heat Pumps. Southington, CT, Hydro Dynamic Engineering, LLC.

The Weather Channel. (2008). "Monthly Averages for Lansing, MI." Retrieved November, 2008, from http://www.weather.com/weather/wxclimatology/monthly/graph/USMI0477?from=36hr_bottomnav_undeclared.

Trillat-Berdal, V., B. Souyri, et al. (2006). "Experimental Study of a Ground-Coupled Heat Pump Combined with Thermal Solar Collectors." Energy and Buildings **38**: 1477-1484.

Unit-Conversion. (2003). "Area Conversion." Unit Conversion Retrieved November, 2008, from http://www.unit-conversion.info/area.html.

Unit-Conversion. (2003). "Energy Conversion." Unit Conversion Retrieved November, 2008, from http://www.unit-conversion.info/energy.html.

Unit-Conversion. (2003). "Volume Conversions." Unit Conversion Retrieved November, 2008, from http://www.unit-conversion.info/volume.html.

USDA-ARS (2006). Virtual Grower Manual.

USDA-ARS (2008). Virtual Grower 2.01.

USDA, N. (2007). Michigan Agricultural Statistics, United States Department of Agriculture.

USDE (2000). Carbon Dioxide Emissions From the Generation of Electric Power in the United States, USDE, EPA.

USDE. (2008, January 11, 2008). "A Consumer's Guide to Energy Efficiency and Renewable Energy." Retrieved October, 2008, from http://apps1.eere.energy.gov/consumer/your_home/space_heating_cooling/index.cfm/mytopic=12480.

USDOE EERE. (2008, 7/10/2008). "Geothermal Glossery." Retrieved October, 2008, from http://www1.eere.energy.gov/geothermal/glossary.html.

Uva, W.-f. (1999). An Analysis of the Economic Dimensions of the New York State Greenhouse Industry, Cornell Univerisity Department of Agricultural, Resource and Managerial Economics.

Uva, W.-f. and S. Richards (2000). New York Greenhouse Business Summary and Financial Analysis, 2000. Ithica, New York, Cornell University.