THERMO-ECONOMIC STUDY OF HYBRID PHOTOVOLTAIC-THERMAL (PVT) SOLAR COLLECTORS COMBINED WITH BOREHOLE THERMAL ENERGY STORAGE SYSTEMS

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THERMO-ECONOMIC STUDY OF HYBRID PHOTOVOLTAIC-THERMAL (PVT) SOLAR COLLECTORS COMBINED WITH BOREHOLE THERMAL ENERGY STORAGE SYSTEMS

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ABSTRACT

THERMO-ECONOMIC STUDY OF HYBRID PHOTOVOLTAIC-THERMAL (PVT) SOLAR COLLECTORS COMBINED WITH BOREHOLE THERMAL ENERGY STORAGE SYSTEMS

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Photovoltaic-thermal (PVT) technology is a relatively new technology that comprises a photovoltaic (PV) panel coupled with a thermal collector to convert solar radiation into electricity and thermal energy simultaneously. Since cell temperature affects the electrical performance of PV panels, coupling a thermal collector with a PV panel contributes to extracting the heat from the latter to improve its performance. In order to ensure a sufficient temperature difference between the PV cells and the working fluid temperature entering the thermal collector, the circulated water has to reject the heat that has been removed from the PV cells into a relatively colder environment. Borehole thermal energy storage (BTES), which is located underground, often serves as this relatively colder environment due to the stability of underground temperatures, which are usually lower than the working cell temperature. Use of BTES is especially beneficial in summer, when the
degradation in cells efficiency is highest. In this thesis, the electrical, thermal, and
economic performances of a PVT system are evaluated for three types of buildings --
residential, small office, and secondary school -- in two different climates in the United
States, one of which is hot and the other is cold. For each case, two different scenarios are
considered. In the first, a PVT system is coupled with BTES, and a ground-coupled heat
pump (GCHP) is in use. In the second, a PVT system is coupled with BTES and no GCHP
is in use. Each scenarios’ GCHP performance is assessed as well. Both the PVT collectors
and GCHP performances are evaluated over short and long-term to study the effect of
continued ground heat imbalance on both technologies.
To my father who passed away one year before completing this thesis
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CHAPTER 1
INTRODUCTION

Photovoltaic-thermal (PVT) technology comprises a typical photovoltaic (PV) panel and thermal collector coupled together to produce electrical and thermal energy simultaneously. It is well known that PV cells efficiency is a function of their temperature; increasing temperature reduces the photovoltaic conversion efficiency of sunlight to electricity. One of the central advantages of coupling a PV panel with a thermal collector is that the latter can reduce the former’s temperature by circulating a coolant into the collector, thereby increasing the cells efficiency. Many researchers have quantified the impact of a coolant on PV cells performance. Most of this research is focused on the instantaneous impact of a coolant on PV cells, which means that it only demonstrates the increase in PV cells performance when a relatively colder fluid is circulated into a thermal collector coupled with it. In real systems, in fact, the coolant usually is to be circulated in a closed loop between a heat source (PVT collector) and heat sink, especially when the coolant is an anti-freeze solution. Hence, answering the question, where to reject the heat that has been extracted from the PV cells, is more likely to be problematic. Other researchers have conducted research on PVT systems circulating coolant between PVT collector and domestic hot water (DHW) tanks. Using DHW tanks as a heat sink is not likely to work effectively for time periods of more than a few hours due to the time-of-day
mismatch in use of the PV array and domestic hot water. In addition, the unglazed PVT collectors has been shown to have low thermal performance.

1.1. Objectives and Scope of the Thesis

The main objective of this thesis is to assess the viability of coupling PVT collectors to underground thermal energy storage systems (BTES). Specifically:

1. Assess short and long-term performances of PVT collectors coupled with BTES.
2. Identify building types and climate regions where PVT technology is economically feasible.
3. Identify key parameters affecting the feasibility of PVT collectors when they are coupled with BTES with and without GCHP.
4. Evaluate the effect of GCHP on the PVT performance and vice versa.

This work will be accomplished through computer simulation and examination of the performance of PVT panels combined with BTES system. This evaluation is conducted considering two parameters. First, climatic conditions, which play an important role in the functionality of the PVT and GCHP, as climate is a primary driver of a building’s heating and cooling loads. Second, the facility type, which could be residential, small office building, or secondary school, is also a main driver of a building’s heating, cooling, and electricity demands. Finally, an economic study will be conducted to demonstrate the benefits of using BETS as a heat sink for the PVT panels, either with or without using GCHP. The second chapter of this thesis shows background and literature survey of solar and geothermal technologies. The third chapter describes the methodology that was used to build different scenarios and analyze the results. The results are shown in the fourth
chapter. The recommendation and future work are discussed in the fifth and sixth chapters, respectively.
CHAPTER 2
BACKGROUND AND LITERATURE SURVEY

2.1. Solar Energy

This chapter focuses on solar energy and its applications. An overview of solar radiation is discussed in the first section followed by explanation of the photovoltaic phenomenon, which includes a brief description of PV cells and the effect of temperature on cells performance. PVT technology, which is the central scope of this work, is discussed in the last section, which consists of four subsections. The first subsection shows types of PVTs. The second subsection emphasizes the PVT electrical performance, followed by the thermal performance in the third subsection. The cooling effect of PVT is discussed in the last subsection in detail.

2.1.1 Solar Radiation

Not all solar radiation emitted by the sun reaches the earth due to the great distance between them, which is $1.5 \times 10^8$ km $\pm$ 1.7%. In total, 1367 $W/m^2$ of all solar radiation reaches the earth’s atmosphere. This number is known as the Solar Constant (GSC) and is defined as “the energy from the sun per unit time received on a unit area of surface perpendicular to the direction of propagation of the radiation at mean earth-sun distance outside the atmosphere” [1]. Solar radiation is twofold. First, beam radiation, which is the solar radiation that reaches the earth’s surface directly without any disturbance. In other
words, it is the portion of solar radiation that casts a shadow when it falls on an opaque object. Secondly, diffuse Radiation, which is the solar radiation that reaches the earth’s surface after being scattered. This type of radiation could result from disturbance caused by any object in the atmosphere, such as clouds, dust, or even water vapor. The total of both beam and diffuse radiations is known as “total solar radiation”. At noon on a clear day, beam radiation accounts for 70% of the total solar radiation reaching the earth’s surface and diffuse radiation accounts for 7%, while the residual 18% is absorbed by the atmosphere [2]. A commonly used term when calculating the useful solar energy is irradiance (G), which is the rate of radiant energy per unit area, measured in W/m² or Btu/(hr ft²).

2.1.2. The Photovoltaic Effect

The photovoltaic effect is a phenomenon by which electricity is generated by semiconductors exposed to light that has enough energy to induce electrons movement. It was first discovered by Alexandre-Edmund Becquerel in 1839 when he noticed that a certain light induced chemical reactions caused electrical currents [3]. In the 1940s, the first silicon cells were introduced with an efficiency of 6% [3]. Nowadays, PV cell efficiencies are between 10 and 20%, depending on their physical and chemical properties [4]. The following two subsections discuss the different types of PV cells and the effect of temperature on the cells performance.

2.1.2.1. Photovoltaic Cells

Among the many types of materials used to produce PV cells, the most common on the market are mono-crystalline, poly-crystalline, and thin film. Mono-crystalline cells are produced from silicon (SI) and accounts for 80% of all PV cells on the market [5]. The
efficiency of mono-crystalline cells could be as high as 23% [5]. Similarly, poly-crystalline cells are SI-based but have a lower efficiency, about 15%, and they are less complicated to produce [5]. Thin film cells require less material and fewer manufacturing processes to be produced. The efficiency of one type of thin film cells, a CIGS (CuInGaSe₂) for example, has been reported to be 18.7±0.6% [6].

The material a cell is made of determines the electrical efficiency as it determines the parameters of the PV cells. These parameters include the I-V curve, short-circuit current (I_{SC}), open-circuit voltage (V_{OC}), maximum power point (MPP), current at maximum power point (I_{MPP}), voltage at maximum power point (V_{MPP}), and fill factor (FF). The I-V curve, as shown in Figure 2.1.2.1.1, is a curve that shows the relation between PV current and voltage and hence, the output power. I_{SC} is the maximum current through the cells that occurs when the cells voltage is zero. Conversely, V_{OC}, is the maximum voltage across the cells when the current is zero. The point on the I-V curve where the maximum power could be generated is known as MPP. The point where the MPP occurs determines the I_{MPP} and V_{MPP}. FF is the ratio of the MPP of the cells to the product of V_{OC} and I_{SC}. 
These cells parameters are usually given by the manufacturer after undergoing tests to reveal their performance. The most common test used to determine the parameters is the Standard Test Conditions (STC) where cells are exposed to a radiation flux of 1000 W/m² in an ambient temperature of 25°C and air mass of 1.5.

2.1.2.2. Temperature and Photovoltaic Performance

PV cells absorb 90% of incident solar radiation. However, only 15% is converted into electricity, while 75% appears as heat [7]. This heat has been shown to have a negative impact on cells efficiency. The efficiency of SI cell, for example, decreases 15% for every 30 °K increase in temperature [8]. Du et al. [9] reported a cell efficiency degradation at rate of 0.45%/°C for SI cells. In fact, the reduction in efficiency that caused by temperature increase, is due to a reduction in \( V_{OC} \) and FF. Even though the current increases slightly
with temperature increase, it cannot predominate over the reduction caused by the $V_{OC}$ and FF [10]. At excessive temperatures, the cells efficiency becomes zero and energy production ceases [11]. This temperature has been determined to be about 270°C for SI cells [12]. Kawajiri et al. [13] have developed a framework to “evaluate the effect of irradiation and temperature on crystalline-silicon PV potential” globally. They created a global distribution map of annual total irradiation ($H_y$) on an equator-pointed tilted surface, seen in Figure 2.1.2.2.1. The solar irradiation data were taken from NASA database, averaged over 22 years [14]. The solar irradiation map, after that, was applied to a global distribution of annual average temperature ($T_A$) map, Figure 2.1.2.2.2., to consider the performance of the PV cells as a function of the ambient temperature. Finally, a map of global annual energy generation potential ($Y_{py}$) was generated, as in Figure 2.1.2.2.3.

![Global distribution map of annual total irradiation on an equator-pointed tilted surface](image)

*Figure 2.1.2.2.1 Global distribution map of annual total irradiation on an equator-pointed tilted surface* [13]
Figure 2.1.2.2.2 Global map of average ambient temperature [13]

Figure 2.1.2.2.3 Global potential map of PV energy generation [13]
2.1.3. Photovoltaic-Thermal (PVT) Technology

PVT is an amalgamation of a PV panel and a thermal collector that can produce electric and thermal energy, simultaneously. The main two advantages of combining these two technologies are first, heat can be extracted from the PV cells by circulating a working fluid into the thermal collector, hence increasing the cells efficiency, and second, increasing the intensity of energy generated by the footprint. The working fluid in a PVT can be either liquid or air. The aim of this section is to focus on the liquid-type PVT, mainly water-based solution. The first work on liquid-type PVT was conducted during the period from 1978 to 1981 [15]. This work was carried out by Wolf [16] who found that PVT system for heating and electricity generation is feasible and cost effective. In the first subsection of this section, types of PVT technology are differentiated, with a focus on the main purpose of each type. Their electrical performance is discussed in the second subsection, followed by thermal performance in the third subsection. Finally, the PV cells cooling effect is detailed in the fourth subsection.

2.1.3.1. PVT Types

Coupling a PV panel with a thermal collector can result in either a PVT panel or a PVT collector, depending on the way they are connected together. The differences between them in both structure and performance are described in this subsection.

PVT collectors consist of a regular thermal collector coupled with a PV panel, as in Figure 2.1.3.1.1. As the typical thermal collector, the PVT collector consists of absorber, insulation, and single glazing (which is the PV panel in this case), or multi glazing, where the PV panel has an additional transparent cover on top of it. As might be expected, the multi glazing thermal collector retains more heat than the single glazing due to the
additional cover, which results in higher thermal performance and lower cell performance. This additional cover creates a static air layer above the PV cells, which is an essential difference between the two designs [7].

Figure 2.1.3.1.1 PVT collector configuration of (a) double glazing and (b) single glazing

The PVT panel; on the other hand, is comprised of a conventional PV panel with tubes attached to its back, as shown in Figure 2.1.3.1.2. The major difference between a PVT panel and a PVT collector is the absence of extra glazing, absorber, and most
importantly, back insulation. The absence of these parameters leads to higher heat losses, which results in lower thermal performance and higher electrical performance.

![Figure 2.1.3.1.2 PVT panel configuration](image)

### 2.1.3.2. PVT Electrical Performance

Many studies have conducted experiments and research to examine the effect of coupling PV panels with thermal collectors, as a PVT panel or a PVT collector, on the electrical performance. Most of this research show a positive impact of the working fluid on PV cells in PVT panels and unglazed PVT collectors. Conversely, the electrical performance of the glazed PVT collectors has been shown to be negatively affected by adding a conventional thermal collector because of the increase in cells temperature caused by the absorber, insulation, and additional glazing. Bergene and Lovvik [8] examined the cooling effect on solar cells with a rated efficiency of 10.4-12.7%. They found that the working cell temperature of 60-80°C is common and that this temperature resulted in an efficiency of 9.5-10.5%. However, after applying the cooling effect to the cells, they found a relative increase in electrical efficiency of about 10-30%. Fujisawa and Tani [17] compared the electrical energy of a PV, PVT (single cover), and PVT (coverless) with each other, all of which were mono-crystalline cells. They found that PVT (coverless) produced
8% more energy than the PV on annual basis, and that the single-covered had the lowest production. Tripanagnostopoulos et al. [18] tested the electrical performances of a free-to-ambient PV, back-insulated PV, and water-type PVT. Their results showed a performance increase of 3.2% in the PVT over the free-to-ambient PV, and a 13.3% increase in the PVT over the back-insulated PV. On the other hand, Zondag et al. [19] reported a reduction in cells efficiency when they built a prototype multi-crystalline PV-laminate combined with a conventional glass-covered sheet-and-tube collector. The electrical performance of their PVT dropped from 8.5%, for conventional PV, to 6.7% for the PVT prototype. Daghigh et al. [20] simulated glazed and unglazed active PVT systems, with different types of cells, using TRNSYS. They found that all of the different types of cells with the glazed PVT collector produced less electricity than the unglazed.

2.1.3.3. PVT Thermal Performance

As with the electrical performance, the thermal performance of PVT depends mainly on its design. Sacrificing electrical performance by adding a glass cover, absorber, and insulation; benefits the thermal performance; and vice versa. Comparison of the thermal performance of a PVT collector with that of a conventional thermal collector reveals that the performance of the former is not as good as that of the latter. In fact, the PVT collector prototype, built by Zondag et al. [19], resulted in a rather large reduction in the thermal performance, from 54% to 33%. In Fujisawa and Tani’s [17] work, they compared the thermal performances of PVT (single cover), PVT (coverless), and a regular flat-plat collector (FPC). They examined the thermal exergy, which is the available energy, of these three technologies to find that the FPC has the highest thermal exergy, followed
by the PVT (single cover), while the PVT (coverless) showed a much lower thermal exergy. The TRNSYS simulation by Daghigh et al. [20] showed that the average solar fraction of the unglazed PVT collector was less than that of the glazed collector. A simulation by Huang and Huang [21] using TRNSYS resulted in a thermal efficiency of about 26.78-28.41% for unglazed PVT in different locations in Taiwan. A comparative study by Dupeyrat et al. [7] in three different cities in France showed that a larger area of PVT collectors was needed in order to meet the performance of a conventional thermal collectors.

2.1.3.4. PVT Collectors Cooling Effect

As mentioned before, the ability to boost cells performance by extracting heat from them is one of central advantages of PVT panels. Many researchers have conducted research to find parameters affecting the cooling process in PVT panels and, hence, their electrical efficiency. The two most crucial parameters are the PVT working fluid inlet flow rate and temperature [8]. Daghigh et al. [20] reported an increase in the electrical performance of both glazed and unglazed PVT collectors when flow rate was increased from 0.001 to 0.02 kg/s, for all cells types; however, when the flow rate was increased further, the performance stayed constant. Jakhar et al. [22] conducted a TRNSYS model to analyze the electrical performance of a PVT collector coupled with an earth water heat exchanger (EWHE) as a function of different parameters. They found the optimum flow rate entering the PVT collector to be 0.018 kg/s. Bergene and Lovvik [8] studied the effect of tube geometry on PVT performance. They studied cells efficiency as a function of $WD^{-1}$, where W is the fin width and D is the tube diameter, as shown in Figure 2.1.3.4.1.
They noticed that under a low flow rate, the cells efficiency increase is associated with the increase in $WD^{-1}$ and verse versa.

![Diagram](https://via.placeholder.com/150)

*Figure 2.1.3.4.1 PVT tubing geometry*

2.2. Geothermal Energy

This section contains a review of the existing literature about geothermal energy. A literature review on BTES is conducted in the first subsection, followed by a review of GCHP in the second subsection.

2.2.1. Borehole Thermal Energy Storage (BTES)

BTES is a closed loop immersed under the ground’s surface in different configurations to exchange heat between a working fluid and the ground. The main reason of using the ground as heat source and sink is the fact that the circadian fluctuation in ambient temperature does not affect the ground temperature under 1 m instantly [23]. The BTES could be installed in many configurations in the ground; however, the most
common is the vertical ground heat exchanger as shown in Figure 2.2.1.1. Estimating the amount of heat that could be added to or extracted from a ground is crucial to avoid under-sizing or over-sizing the BTES. Heat transferring from boreholes through the ground could be calculated using an analytical cylindrical source model [24] or analytical line source model [25]. Dai et al. [26] developed a three-dimensional unsteady model to study the transient heat transfer between a vertical U-tube and the ground. There are many parameters that have been proven to affect the heat transfer process. Using a TRNSYS model, Li et al. [27] found that increasing the borehole depth, starting from 60 m, or decreasing the borehole diameter, from 250 to 150 mm, resulted in heat exchange reduction. In addition, they concluded that using a smaller U-tube diameter with a thinner wall is better than using one with a larger diameter with a thicker wall, even though the contact area of the latter is larger. The ground water content is another parameter that has been shown to affect heat transfer between the BTES and the ground [28]. However, according to Chiasson [29], not considering the water content in the ground, causes an error of about 25% and 5% for porous and denser soils, respectively.
2.2.2. Ground-Coupled Heat Pump (GCHP)

After global inspection of the progress of GCHP, its efficient utilization of renewable resources and sustainable energy has been confirmed [30]. Compared to air-source heat pumps, it has been proven that the ground-coupled heat pump has higher heating and cooling capacities and, hence, COPs, due to stability in the ground conditions, which ensures a favorable evaporating temperature in winter and condensing temperature in summer [31]. However, in some cases where there is a heat imbalance in the ground utilization, there might be an increase in COP\textsubscript{H} and reduction in COP\textsubscript{C} when heat rejection is higher than heat extraction, and vice versa. Piscaglia et al. [32] presented a case study of
a GCHP coupled with vertical BTES in Urbino (Central Italy) where the heating load is dominant. They observed an increase in COP\textsubscript{C} and a decrease in COP\textsubscript{H} due to the imbalanced use of the ground heat reservoir. Luo et al. [33] reported a 4\% reduction in COP\textsubscript{H} and a consequent 8.7\% increase in the seasonal energy efficiency ratio (SEER) when they examined a ground source heat pump performance for approximately four years in Nuremberg, city of Germany, where the heating load is dominant. Analogously, Michoopoulos et al. [34] reported a seasonal COP increase of a ground source heat pump operating in a public building where cooling is higher than heating load, from 4.4 to 5.2, over three years. Soil quality, on the other hand, has been shown by Bakker et al. [35] not to have a major effect on COP. In their study of soil quality, they classified the soil into low, medium, and high quality, with thermal conductivities and heat capacities of 1.5, 1.8, and 2.4 W/m K and 2.2, 2.3, and 2.5 MJ/m\textsuperscript{3} K, respectively. The effect of the soil quality on the heat pump’s COP was found to be less than 5\%.

2.3. Coupling PVT with BTES and GCHP

The feasibility of combining PVT with BTES, either with or without using GCHP has been examined by few researchers. Bakker et al. [35] carried out a long-term TRNSYS model combining a PVT panel with GCHP and concluded that the system was able to meet 100\% of a one-family dwelling’s heat demand, and about all of its electricity demand, while keeping the long-term ground temperature constant. In addition, they reported an increase in the GCHP’s COP from 2.60 to 2.66 by coupling the PVT, which recovered the heat extracted by the former. In the TRTNSYS model by Jakhar et al. [22], they analyzed changing pipe material, length, and diameter of the U-tube to ensure maximum ground heat
transfer and, hence, PVT electrical performance. They observed that changes in pipe materials and diameter hardly affected the (PVT + EWHE) system’s performance, while changes in the pipe length from 10 to 50 m considerably reduced the PV cells temperature, especially during peak sunshine hours. Chiasson and Yavuzturk [36] describe development of a publicly-available hybrid solar-geothermal simulator tool. Hybridizing a GCHP with solar thermal collectors is advantageous in realizing smaller, lower cost BTES, in addition to achieving a more sustainable geothermal system over the long term. The simulation tool accounts for the numerous, coupled dynamic processes of the building load, heat pump capacity, heat transfer in the Earth, and solar thermal processes. Each of these processes occurs over various time scales on the order of minutes up to many decades. For a heating-dominated school building in the northern United States, they showed a 62% reduction in BTES size with the addition of glazed-solar thermal collectors, resulting in ~30% reduction in system capital cost. Unglazed solar thermal collectors were not studied. Their simulator tool is also capable of simulating unglazed thermal collectors, and it was proposed to apply these to cooling-dominated climates for purposes of unloading stored thermal energy from the ground. However, that concept too, has not been examined in detail.
CHAPTER 3

METHODOLOGY

This chapter consists of six sections. The first section describes the tool that was employed for the simulation. The second section describes the overall simulation approach, while the third section outlines and describes the system’s individual components. Different types of loads are described in the fourth section. The fifth section presents different scenarios for different climates and building types. Finally, the economics of the different scenarios are described in the sixth section.

3.1. Simulation Tool

This study is a synthetic simulation conducted using TRNSYS (TRaNsient SYstems Simulation Program) software, version 16. TRNSYS was developed by The University of Wisconsin, Madison to provide a software environment for transient thermal systems simulations. It comprises different components that manipulate FORTRAN subroutines with built-in mathematical equations to complete a specific task.

3.2. The Overall Simulation Approach

Since the main objective of this study is to assess the performance of PVT collectors coupled with a BTES system, the former’s cells efficiency was measured and compared with those of regular PV panels in two different climates in United States for three different buildings types, and in two scenarios --with and without GCHP. Phoenix, AZ, was chosen
to represent a hot climate, where cooling is dominant, while Minneapolis, MN, was chosen to represent a cold climate, where heating is dominant. The three building types are residential, small office, and secondary school. The PVT system was assumed to share the same BTES with the GCHP (if it was applied), hence the effect of adding GCHP to the PVT system could be assessed.

For the residential building, the monthly and annual PVT electrical performances were compared with those of a regular PV panel with cells rated similarly for power and efficiency in each climate. For residential buildings, the thermal performance was evaluated by measuring the amount of heat that can be added to a pre-heating tank and the BTES. The pre-heating tank assumed to feed a DHW tank, where the water is heated by gas. For the small office and secondary school buildings, the same electrical performance analysis was conducted; however, in these instances, the thermal performance was assessed by measuring the heat that would be added to the BTES only, since the pre-heating tank was assumed to be eliminated from these non-residential buildings.

3.3. Loads

This section describes the different loads of each building type, with respect to both climate conditions. For residential buildings, electricity, heating, cooling, and DHW loads are described. For commercial buildings, including the small office and the secondary school type, electricity, heating and cooling loads are described. These loads are based on DOE (commercial reference building models) and Building America House Simulation Protocols, which provide an hourly load profile data, including electricity, heating, cooling, and DHW loads [37]. Among different type of loads available, “BASE” load has been chosen for the residential buildings, and “Small Office New 2004” and “Secondary School
New 2004” have been chosen for the small office and secondary school, respectively, for each of the climates.

3.3.1. Electrical Load

This subsection is divided by building type. For each building type, graphical comparisons are shown to illustrate monthly and annual electricity consumptions in Minneapolis, MN and Phoenix, AZ.

3.3.1.1. Residential Buildings

Figure 3.3.1.1.1 shows monthly electricity consumptions for Minneapolis, MN and Phoenix, AZ residential buildings. The annual electricity consumption is about 9234.75 and 12917.84 kWh for Minneapolis, MN and Phoenix, AZ, respectively.

![Figure 3.3.1.1.1 Monthly residential electricity consumptions for Minneapolis MN, and Phoenix, AZ](image-url)

Figure 3.3.1.1.1 Monthly residential electricity consumptions for Minneapolis MN, and Phoenix, AZ
3.3.1.2. **Small Office**

The annual electricity consumption of the small office in Minneapolis, MN is about 64.7 MWh, while in Phoenix, AZ is 82.6 MWh, distributed as in Figure 3.3.1.2.1.

![Figure 3.3.1.2.1 Monthly small office electricity consumptions for Minneapolis MN, and Phoenix, AZ](image)

3.3.1.3. **Secondary School**

The secondary school in Minneapolis, MN consumes 2.9 GWh while Phoenix, AZ consumes 5.04 GWh, as shown in Figure 3.3.1.3.1.
3.3.2. Heating and Cooling Loads

As in the previous subsection, this subsection is divided by building type. Each subsection consists of monthly graphical compressions of the heating and cooling loads for the two specified climates. Heating loads are identified by minus sings, while cooling loads are left as positive values.

3.3.2.1. Residential Buildings

The hourly heating and cooling loads are represented in Figures 3.3.2.1.1 and 3.3.2.1.2 for Minneapolis, MN and Phoenix, AZ, respectively.
These loads are monthly-aggregated in Figures 3.3.2.1.3 and 3.3.2.1.4, for Minneapolis, MN and Phoenix, AZ, respectively.
Since air source heat pumps are the typical cooling devices and furnaces are the typical heating devices in the United States, figure 3.3.2.1.4 interprets the high electricity demand from May through October for Phoenix, AZ.
3.3.2.2. **Small Office Buildings**

For small office buildings, the hourly heating and cooling loads are represented in Figures 3.3.2.2.1 and 3.3.2.2.2, for Minneapolis, MN and Phoenix, AZ, respectively.

*Figure 3.3.2.2.1 Hourly heating and cooling loads for small office building in Minneapolis, MN*
These loads are monthly-aggregated in Figures 3.3.2.3 and 3.3.2.4, for Minneapolis, MN and Phoenix, AZ, respectively.

Figure 3.3.2.2 Hourly heating and cooling loads for small office building in Phoenix, AZ

Figure 3.3.2.3 Monthly heating and cooling loads for small office building in Minneapolis, MN
Figure 3.3.2.2.4 Monthly heating and cooling loads for small office building in Phoenix, AZ

3.3.2.3. Secondary School Buildings

Figures 3.3.2.3.1 and 3.3.2.3.2 represent hourly heating and cooling loads for Minneapolis, MN and Phoenix, AZ secondary school buildings, respectively.
Figure 3.3.2.3.1 Hourly heating and cooling loads for secondary school building in Minneapolis, MN

Figure 3.3.2.3.2 Hourly heating and cooling loads for secondary school building in Phoenix, AZ

The average monthly heating and cooling loads are shown in Figures 3.3.2.3.3 and 3.3.2.3.4 for Minneapolis, MN and Phoenix, AZ secondary school buildings, respectively.
Figure 3.3.2.3.3 Monthly heating and cooling loads for secondary school building in Minneapolis, MN

Figure 3.3.2.3.4 Monthly heating and cooling loads for secondary school building in Phoenix, AZ
3.3.3. DHW Loads

For DHW, two loads were used, natural gas and water main consumptions. The hourly gas consumption is based on the standardized reference building loads for DOE climate zones [37], described in section 3.3, and expressed in kWh. This gas consumption was assumed to apply to the DHW tank, which is supplied by a pre-heating tank. The water consumption, however, was assumed to be 180L per day, drawn from the water main for three people, which, according to Lofquist et al. [38], was the average American household population in 2010. This amount of water was distributed over each day similarly to the percent of hourly-to-daily gas consumption. This resulted in an hourly water consumption pattern similar to the hourly gas consumption. For example, Figure 3.3.3.1 shows an identical patterns of energy (gas) and DHW consumptions on January 1st in Minneapolis, MN.

![Figure 3.3.3.1 Energy and generated water main consumption patterns of DHW for the first hour of January 1 in Minneapolis, MN](image)

*Figure 3.3.3.1 Energy and generated water main consumption patterns of DHW for the first hour of January 1 in Minneapolis, MN*
3.4. Individual TRNSYS Components

This section lists and describes the main components that were used to build the 12 different scenarios in the TRNSYS simulation. Each component in TRNSYS is named by “Type” followed by a unique number or number/letter identifier. The main components that were employed in this simulation are weather data reading and processing (Type 15-3), an unglazed PV panel (Type 562h), a PVT collector (Type 560), a storage tank with heat exchanger (Type 534), a vertical U-tube ground heat exchanger (Type 557a), and a TRNSYS/Excel Coupling (Type 62,) which was employed as GCHP. TRNSYS’s components were designed to be linked and, hence, interact with each other. In other words, they exchange information during the simulation process in each time step. The following subsections describes the main components in detail.

3.4.1. Weather Data Reading and Processing

Type 15-3 (Energy+ Weather Files, EPW) reads EnergyPlus weather files, which include hourly weather conditions for a typical year. In addition to reading weather data, such as dry bulb temperatures, available in EnergyPlus files, type (15-3) calculates many other parameters such as water mains and the effective sky temperatures.

3.4.2. Unglazed PV Panel

Type 562h, by Thornton et al. [39], is a simple unglazed PV panel where the efficiency (η_{PV}) is a function of operation cell temperature (T_{PV}) and incidence solar radiation (I_{T}). This component usually receives inputs from the Type 15-3 component. According to these inputs, Type 562h reveals its outputs. More importantly, the power production (\dot{P}_{PV}), PV efficiency (\eta_{PV}), and “PV cells temperature” (T_{PV}). The \dot{P}_{PV} is calculated according to Equation 3.4.2.1.
\[ \dot{P}_{PV} = \dot{I}_T \eta A \]  

(3.4.2.1)

Where A is the total area of the PV array.

In addition to \( T_{PV} \) and \( I_T \), the overall efficiency of this component is calculated as a function of a temperature efficiency modifier (\( \eta_{T,coef} \)), reference temperature (\( T_{ref} \)), which is the cell temperature at which the rated efficiency (\( \eta_{ref} \)) was measured; a radiation efficiency modifier (\( \eta_{I,coef} \)); and reference radiation (\( I_{T,ref} \)), which is the total incidence radiation when the rated efficiency was measured at \( T_{ref} \), as shown in Equation 3.4.2.2.

\[ \eta = \left( 1 + \eta_{T,coef}(T_{PV} - T_{ref}) \right) \left( 1 + \eta_{I,coef}(I_T - I_{T,ref}) \right) \eta_{ref} \]  

(3.4.2.2)

The total energy absorbed by a panel is expressed by equation 3.4.2.3 as follows:

\[ \dot{Q}_{abs} = \dot{I}_T A \]  

(3.4.2.3)

However, some of this energy is lost as a result of convection through the top, \( \dot{Q}_{top,conv} \), and back, \( \dot{Q}_{back,conv} \), of the panel as shown in equation 3.4.2.4 and 3.4.2.5, respectively.

\[ \dot{Q}_{top,conv} = h_{top,conv} A (T_{PV} - T_{amb,top}) \]  

(3.4.2.4)

\[ \dot{Q}_{back,conv} = h_{back,conv} A (T_{PV} - T_{amb,back}) \]  

(3.4.2.5)

Where

\( h_{top,conv} \) is the panel’s top surface convective heat transfer coefficient.
\( h_{back,conv} \) is the panel’s back surface convective heat transfer coefficient.

\( T_{amb,top} \) is the ambient temperature above the PV panel’s surface.

In addition to the convection losses, the PV panel radiates a fraction of absorbed energy to the surroundings through its top, \( \dot{Q}_{top,rad} \), and back surface, \( \dot{Q}_{back,rad} \), according to equations, 3.4.2.6 and 3.4.2.7, respectively.

\[
\dot{Q}_{top,rad} = h_{top,rad} A (T_{PV} - T_{sky})
\] (3.4.2.6)

\[
\dot{Q}_{back,rad} = h_{back,rad} A (T_{PV} - T_{sky})
\] (3.4.2.7)

Where

\( h_{top,rad} \) is the panel’s top surface radiative heat transfer coefficient.

\( h_{back,rad} \) is the panel’s back surface radiative heat transfer coefficient.

\( T_{sky} \) is the temperature of the sky, which is calculated by the type 15-3 component.

Type 562h calculates \( T_{PV} \) by balancing the energy equations until they reach equilibrium.

In order to effectively compare the PV panel’s performances for all scenarios, all of the PV panel’s parameters were fixed for each scenario, except the total PV “Area”, which differs according to building type. These parameters are show in Table 3.4.2.1.
Table 3.4.2.1 Type 562h, unglazed PV panel’s parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Residential Building</strong></td>
<td>19.6461</td>
<td>m²</td>
</tr>
<tr>
<td>Area</td>
<td>65.487</td>
<td></td>
</tr>
<tr>
<td>Back resistance</td>
<td>1.0</td>
<td>h.m².K/kJ</td>
</tr>
<tr>
<td>Top emissivity</td>
<td>0.9</td>
<td>%</td>
</tr>
<tr>
<td>Back emissivity</td>
<td>0.9</td>
<td>%</td>
</tr>
<tr>
<td>Absorptance</td>
<td>0.9</td>
<td>%</td>
</tr>
<tr>
<td>Reference PV efficiency</td>
<td>0.145</td>
<td>%</td>
</tr>
<tr>
<td><strong>Small Office Building</strong></td>
<td>523.896</td>
<td></td>
</tr>
<tr>
<td>Reference temperature</td>
<td>25.0</td>
<td>°C</td>
</tr>
<tr>
<td>Reference radiation</td>
<td>1000</td>
<td>W/m²</td>
</tr>
<tr>
<td>Efficiency modifier</td>
<td>-0.0046</td>
<td>1/K</td>
</tr>
</tbody>
</table>

3.4.3. Unglazed PVT Collector

Type 560 (Photovoltaic-Thermal Solar Collector), as shown in Figure 3.4.3.1, is an unglazed PVT collector. As type 562h, the cells efficiency of this component is a function of operation cells temperature ($T_{PVT}$) and incidence solar radiation ($I_T$). A full mathematical description was written by Thornton et al. [39]. The energy balance on the top of the PVT collector is shown in Equation 3.4.3.1.

\[
0 = S - h_{outer}(T_{PVT} - T_{amb}) - h_{rad}(T_{PVT} - T_{sky}) - \frac{(T_{PVT} - T_{abs})}{R_T}
\]  

(3.4.3.1)

Where

$S$ is the net absorbed solar radiation, which is the total incidence solar radiation minus the electrical power generated by the PVT cells.
$h_{outer}$ is the heat transfer coefficient from the top of the PVT collector’s surface to the ambient air.

$T_{PVT}$ is cells temperature.

$T_{amb}$ is the ambient temperature.

$T_{sky}$ is the sky temperature.

$T_{abs}$ is the absorber temperature.

$R_T$ is the heat transfer resistance from the PV cells to the absorber plate.

$h_{rad}$ is the radiative heat transfer coefficient from the top of the PVT collector’s surface to the sky, and can be calculated as in Equation 3.4.3.2.

$$h = \sigma \varepsilon (T_{PVT} - T_{sky})(T_{PVT}^2 - T_{sky}^2) \quad (3.4.3.2)$$

Figure 3.4.3.1 Type 560, PVT collector, configuration
The area of the PVT collector is 1.30974 m². The length is 1.315 m and the width is 0.996 m. In order to equitably compare the performance of the PVT and the PV, the cells properties of both these technologies were chosen to be identical. Table 3.4.3.1 shows some parameters of the PVT collector for all types of buildings.

Table 3.4.3.1 Type 560, PVT collector’s parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Residential Building</strong></td>
<td><strong>Small Office Building</strong></td>
<td><strong>Secondary School Building</strong></td>
</tr>
<tr>
<td>Number of Collectors</td>
<td>15</td>
<td>50</td>
</tr>
<tr>
<td>Absorber plate thickness</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity of the absorber</td>
<td>385</td>
<td></td>
</tr>
<tr>
<td>Number of tubes</td>
<td>180</td>
<td>600</td>
</tr>
<tr>
<td>Tube diameter</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>Bond width</td>
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<td></td>
</tr>
<tr>
<td>Bond thickness</td>
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</tr>
<tr>
<td>Bond thermal conductivity of the absorber</td>
<td>1386</td>
<td></td>
</tr>
<tr>
<td>Resistance of substrate material</td>
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<td></td>
</tr>
<tr>
<td>Resistance of back material</td>
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<td></td>
</tr>
<tr>
<td>Fluid specific heat</td>
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<td></td>
</tr>
<tr>
<td>Reflectance</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Emissivity</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>1st order IAM</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>PV cell reference temperature</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>PV cell reference radiation</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>PV efficiency at reference condition</td>
<td>0.145</td>
<td></td>
</tr>
<tr>
<td>Efficiency modifier - temperature</td>
<td>-0.0046</td>
<td></td>
</tr>
<tr>
<td>Efficiency modifier - radiation</td>
<td>0.000025</td>
<td></td>
</tr>
</tbody>
</table>
3.4.4. Borehole Thermal Energy Storage (BTES)

Type 557a in TRNSYS is a U-tube Vertical Ground Heat Exchanger that thermally interacts with the ground to act as either a heat sink or source. The BTES’ parameters, including storage volume, borehole depth, and number of boreholes determine the amount of heat that it can store under the ground’s surface. Borehole spacing is implicit in these three parameters, as shown in equation 3.4.4.1.

\[ Storage \ Volume = \tau \times (\text{number of boreholes}) \times \text{borehole depth} \times (0.525 \text{Borehole spacing})^2 \]

This type assumes the U-tube branches are distributed uniformly inside the borehole, as shown in Figure 3.4.4.1. The mathematical description for this component was written by the Department of Mathematical Physics at the University of Lund, Sweden [40].
Figure 3.4.4.1 BTES configuration

The parameters of this component that were suggested for all types of buildings are shown in Table 3.4.4.1.
### Table 3.4.1 Type 775a, U-tube Vertical Ground Heat Exchanger’s parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Storage volume</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential Building</td>
<td>6061.3</td>
<td>m³</td>
</tr>
<tr>
<td>Small Office Building</td>
<td>37883.19</td>
<td>m³</td>
</tr>
<tr>
<td>Secondary School Building</td>
<td>757663.79</td>
<td>m³</td>
</tr>
<tr>
<td>Borehole depth</td>
<td>70</td>
<td>m</td>
</tr>
<tr>
<td><strong>Number of boreholes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential Building</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>Small Office Building</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>Secondary School Building</td>
<td>500</td>
<td>-</td>
</tr>
<tr>
<td>Borehole radius</td>
<td>100</td>
<td>mm</td>
</tr>
<tr>
<td>Storage thermal conductivity</td>
<td>3</td>
<td>W/m.K</td>
</tr>
<tr>
<td>Storage heat capacity</td>
<td>2016</td>
<td>kJ/m³/°K</td>
</tr>
<tr>
<td><strong>Outer radius of u-tube pipe</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential Building</td>
<td>12.5</td>
<td>mm</td>
</tr>
<tr>
<td>Small Office Building</td>
<td>10.5</td>
<td>mm</td>
</tr>
<tr>
<td>Secondary School Building</td>
<td>50.0</td>
<td>mm</td>
</tr>
<tr>
<td><strong>Center-to-center half distance</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential Building</td>
<td>2</td>
<td>W/m.K</td>
</tr>
<tr>
<td>Small Office Building</td>
<td>0.4</td>
<td>W/m.K</td>
</tr>
<tr>
<td>Secondary School Building</td>
<td>4</td>
<td>W/m.K</td>
</tr>
<tr>
<td><strong>Fill thermal conductivity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential Building</td>
<td>4</td>
<td>kJ/kg/°K</td>
</tr>
<tr>
<td>Small Office Building</td>
<td>1000</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Secondary School Building</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td><strong>Insulation indicator</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential Building</td>
<td>0.0254</td>
<td>m</td>
</tr>
<tr>
<td>Small Office Building</td>
<td>1</td>
<td>kJ/hr.m.°K</td>
</tr>
<tr>
<td>Secondary School Building</td>
<td>1.0</td>
<td>kJ/hr.m.°K</td>
</tr>
<tr>
<td><strong>Initial surface temperature</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential Building</td>
<td>20.0</td>
<td>C</td>
</tr>
<tr>
<td>Small Office Building</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Secondary School Building</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td><strong>Initial thermal gradient</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential Building</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Small Office Building</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Secondary School Building</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td><strong>Thermal conductivity of layer</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential Building</td>
<td>2</td>
<td>W/m.K</td>
</tr>
<tr>
<td>Small Office Building</td>
<td>4</td>
<td>W/m.K</td>
</tr>
<tr>
<td>Secondary School Building</td>
<td>1000.0</td>
<td>m</td>
</tr>
</tbody>
</table>

3.4.5. Pre-Heating Tank with Heat Exchanger

Type 534 is a cylindrical storage tank with a vertical configuration divided into vertical isothermal temperature nodes. The number of these nodes can be specified by the user to consider temperature stratification, as shown in Figure 3.4.5.1. The isothermal temperature nodes interact with each other by conduction. A heat exchanger is immersed at the bottom of the tank in order to exchange heat between storage fluid and the fluid.
exiting the PVT collector when the latter is warmer than the former by two degrees Celsius. The storage fluid is the water main, while the exchanger fluid is assumed to be propylene glycol and water, which is an anti-freeze solution, with a specific heat of 4 kJ/kg K. The latter is circulated in a closed loop. A mathematical description of this component is was written by Thornton et al. [39].

![Figure 3.4.5.1 Type 534, pre-heating tank configuration](image)

In consideration of the fact that an unglazed PVT collector produces low-quality thermal energy comparing to a glazed PVT collector, this tank is intended to serve as a pre-heating tank that feeds a main DHW tank. In other words, no auxiliary heating elements
were applied to this tank to keep its bottom as cooled as possible, which would then increase the solar fraction. The storage tank properties are shown in Table 3.4.5.1.

Table 3.4.5.1 Type 534, cylindrical storage tank properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of tank nodes</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Tank volume</td>
<td>0.225</td>
<td>m³</td>
</tr>
<tr>
<td>Tank height</td>
<td>1</td>
<td>m</td>
</tr>
<tr>
<td>Top loss coefficient</td>
<td>5</td>
<td>kJ/(hr-m²-K)</td>
</tr>
<tr>
<td>Bottom loss coefficient</td>
<td>5</td>
<td>kJ/(hr-m²-K)</td>
</tr>
<tr>
<td>Edges losses coefficient</td>
<td>5</td>
<td>kJ/(hr-m²-K)</td>
</tr>
<tr>
<td>Number of ports</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Entry node</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Exit node</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Heat exchanger node</td>
<td>10</td>
<td>-</td>
</tr>
</tbody>
</table>

3.4.6. Ground-Coupled Heat Pump (GCHP)

Even though TRNSYS has a GCHP, for simplicity, an excel sheet was employed to act as a GCHP. Type 62 provides a component that can interact with Microsoft Excel software by sending values to specific cells in Excel as inputs then receives calculated values as outputs based on previous-determined formulas in Excel. By employing an Excel file as a GCHP, TRNSYS sends the GCHP entering water temperature (T_{in,GCHP}), GCHP entering flow rate (m_{GCHP}), and heating (H_{load}) or cooling load (C_{load}) to Excel. The T_{in,GCHP} and m_{GCHP} are assumed to be equal to outlet fluid ground temperature (T_{out,ground}) and outlet ground flow rate (m_{ground}), respectively. Excel then calculates outlet GCHP fluid temperature (T_{out,GCHP}), power consumption ($\dot{W}$), COP_H, and COP_C to TRNSYS as outputs based on given GCHP heating and cooling curve fits. These curve fits were calculated by the manufacturer by measuring the COPs at different entering water temperatures to create a linear fit with specific slopes and y-intercepts for heating and cooling, as shown in figures.
3.4.6.1 and 3.4.6.2, respectively. The heating slope for this heat pump is 0.06 and the y-intercept is 3.187, while the cooling slope is -0.103 and the y-intercept is 7.066.

![GCHP heating curve fit](image1)

*Figure 3.4.6.1 GCHP heating curve fit*

![GCHP cooling curve fit](image2)

*Figure 3.4.6.2 GCHP cooling curve fit*

The $T_{out,GCHP}$, as shown in Equation 3.4.6.1, is calculated as a function of $T_{out,ground}$ ($T_{in,GCHP}$), $m_{ground}$, and the working fluid specific heat, $c_p$, which is assumed to be 4 kJ/kg-$^\circ$C for an anti-freeze polyethylene water solution.
\[ T_{out,HP} = \frac{T_{in,GCHP}}{(\dot{m}_{GCHP} + 0.001) \ cp} \quad (3.4.6.1) \]

Where \( T_{out,HP} \) and \( T_{out,ground} \) are measure in °C and \( \dot{m}_{ground} \) in kg/hr.

The power is calculated as in Equation 3.4.6.2.

\[ P_{HP} = |BTES_{load} - Load_{H/C}| \quad (3.4.6.2) \]

Where \( Load_{H/L} \) is the heating or cooling load, and \( BTES_{load} \) is the ground load, which can be calculated as in Equation 3.4.6.3 for heating and 3.4.6.4 for cooling.

\[ \frac{COP_H - 1}{COP_H} \times Load_H \quad (3.4.6.3) \]

\[ \frac{COP_c + 1}{COP_c} \times Load_c \quad (3.4.6.4) \]

In heating mode, the \( COP_H \) is calculated as a function of the heating slope, \( T_{in,GCHP} \) and the heating y-intercept, as shown in Equation 3.4.6.5.

\[ COP_H = Heating \ slope \times T_{in,GCHP} + heating \ y\_intercept \quad (3.4.6.5) \]
Where $T_{in,GCHP}$ is in °C.

Similarly, in cooling mode, the COP$_C$ is calculated as a function of cooling slope, $T_{in,GCHP}$ and cooling y-intercept, as in equation 3.4.6.6.

$$COP_C = Cooling\ slope \times T_{in,GCHP} + Cooling\ y\_intercept \quad (3.4.6.6)$$

3.5. The Simulation Scenarios

This section depicts each of the different simulation scenarios. Each of the building types was simulated in the two different climates and the information obtained was then analyzed with respect to the differences in electricity, heating, cooling, and DHW loads for each building type. In addition, for each building in each climate, two scenarios were conducted; first, the system without combining a GCHP, and second, the system in combination with GCHP. The climate regions are described in the first subsection. The second and third subsections depict the simulation with and without GCHP, respectively.

3.5.1. Climate Regions

As mentioned before, the simulation was synthetically carried out to be in climates of extreme cold (represented by Minneapolis, MN) and extreme hot (represented by Phoenix, AZ).

Minneapolis, MN is in the northern U.S. with a latitude of 44.98 °N. The maximum annual dry bulb temperature is 37.2 °C and minimum dry bulb temperature is -30.85 °C. The annual hourly dry bulb temperature distribution is shown in Figure 3.5.1.1.
Phoenix, AZ is in the southern U.S. with a latitude of 33.45 °N. The maximum dry bulb temperature is about 45 °C, and minimum dry bulb temperature is -2.55 °C. The annual dry bulb temperature distribution is shown in Figure 3.5.1.2.
Figure 3.5.1.2 Annual hourly dry bulb temperature for Phoenix, AZ.

3.5.2. PVT without GCHP

The first scenario that was applied to all building types in each climate was a PVT coupled with BTES, but without GCHP. For residential buildings, as shown in Figure 3.5.2.1, this system comprises a pump, a PVT array, a PV array, two differential controllers (DC), a pre-heating tank, and a BTES. The pump circulates the working fluid through the system by driving it into the PVT at a pre-determined flow rate and a temperature equal to $T_{\text{out, ground}}$. This pump is controlled by a differential controller that turns on whenever solar radiation is available and the $T_{\text{out, ground}}$ is lower than $T_{\text{PV}}$ by 7 °C or more and remains off otherwise. After that the working fluid flows either to the pre-heating tank or to the BTES. Another differential controller directs the working fluid to the pre-heating tank’s heat exchanger if the PVT exiting fluid temperature is higher than the bottom of the tank by 2 °C or more, then to the BTES; otherwise the PVT exiting fluid is directed to the BTES.
Figure 3.5.2.1 Residential PV and PVT system combined with BTES configuration
For the small office and the secondary school building types, the system consists of a pump, a PVT array, a PV array, a differential controller, and a BTES. The pump only circulates the working fluid between the PVT array and the BTES when solar radiation is available and the $T_{\text{out,ground}}$ is lower than $T_{\text{PV}}$ by 7 °C or more; this process is controlled by the differential controller, as shown in Figure 3.5.2.2.

*Figure 3.5.2.2 Commercial PV and PVT system coupled with BTES*
3.5.3. PVT with GCHP

The next scenario to be applied to each building type was coupling the GCHP to the same BTES that the PVT system uses as a heat sink. This scenario was conducted to permit investigation of the effect of GCHP (or lack thereof) on the PVT’s performance. This scenario has an additional pump that circulates the working fluid between the BTES and the GCHP when there is a heating or cooling load, as illustrated in Figure 3.5.3.1 and 3.5.3.2, for residential and commercial buildings, respectively.

![Residential PVT system coupled with BTES and GCHP configuration](image)

*Figure 3.5.3.1 Residential PVT system coupled with BTES and GCHP configuration*
Figure 3.5.3.2 Commercial PVT system coupled with BTES and GCHP configuration
3.6. Comparative Cost Analysis

This section describes the methodology that was used to evaluate the economic performance of the configurations in the 12 scenarios. For each scenario, the internal rate of return (IRR) was evaluated over 20 years, which is the average lifespan of a PVT system, with the exception to this begin secondary schools with GCHP in Minneapolis, MN and Phoenix, AZ; these were evaluated for seven years due to the BTES under-sizing, which led to dramatic temperature reduction and increase for Minneapolis, MN and Phoenix, AZ scenarios, respectively. The IRRs were calculated as a function of energy rates, components capital costs, and energy savings. The energy rates include electricity rate (Elec\text{rate}) and gas rate (Gas\text{rate}). Due to uncertainty in energy rates, IRRs were evaluated by varying one rate linearly from maximum to minimum, while the other rate was fixed to the average. In addition to Elec\text{rate} and Gas\text{rate}, grid feed-in tariff (FIT) was considered in the savings estimation in cases where the solar fraction exceeded 100% and the excess electricity was sold to the grid; however, this rate was fixed for all building types in both climates. Tables 3.6.1 and 3.6.2 show the Elec\text{rate} and Gas\text{rate} ranges and averages for residential and commercial buildings, respectively.

\textbf{Table 3.6.1 Energy rates for residential buildings in different climates}

<table>
<thead>
<tr>
<th>Rate Type</th>
<th>Minneapolis, MN</th>
<th>Phoenix, AZ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
<td>Average</td>
</tr>
<tr>
<td>\textit{Electricity} \hspace{.5cm} (\text{₵/kWh})</td>
<td>13.11</td>
<td>12.82</td>
</tr>
<tr>
<td>\textit{Feed-in Tariff} \hspace{.5cm} (\text{₵/kWh})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>\textit{Gas} \hspace{.5cm} ($/MCF)</td>
<td>13.46</td>
<td>9.79</td>
</tr>
</tbody>
</table>
Table 3.6.2 Energy rates for commercial buildings in different climates

<table>
<thead>
<tr>
<th>Rate Type</th>
<th>Minneapolis, MN</th>
<th>Phoenix, AZ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
<td>Average</td>
</tr>
<tr>
<td>Electricity (C/kWh)</td>
<td>10.82</td>
<td>9.91</td>
</tr>
<tr>
<td>Feed-in Tarif (C/kWh)</td>
<td></td>
<td>8.00</td>
</tr>
<tr>
<td>Gas ($/MCF)</td>
<td>8.88</td>
<td>7.20</td>
</tr>
</tbody>
</table>

The capital costs for components included the cost of the PVT, BTES, and GCHP. Usually, the installed GCHP cost includes the BTES cost; however, in this work, they were estimated individually. In other words, the BTES\textsubscript{cost} was excluded from the installed GCHP cost. The GCHP\textsubscript{cost} is the increment HVAC cost, which is the difference between the conventional HVAC system and GCHP system costs. The former comprises a typical air source heat pump (ASHP) and furnace. These costs are shown in Tables 3.6.3 for residential and commercial buildings. This table shows capital costs before the 30% tax credit, which was considered when the IRRs were estimated.

Table 3.6.3 Components costs for residential buildings in different climates

<table>
<thead>
<tr>
<th>Component</th>
<th>Installed Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVT ($/collector) [41]</td>
<td>Residential: 397, Commercial: 298</td>
</tr>
<tr>
<td>BTES ($/borehole) [42]</td>
<td>Residential: 3255, Commercial: 2300</td>
</tr>
<tr>
<td>GCHP ($/Ton) [42]</td>
<td>Residential: 800, Commercial: 500</td>
</tr>
<tr>
<td>Gas-Fired Furnace($/Ton) [43]</td>
<td>Residential: 240, Commercial: 105</td>
</tr>
<tr>
<td>ASHP ($/Ton) [43]</td>
<td>Residential: 950, Commercial: 920</td>
</tr>
</tbody>
</table>
The following two subsections describe the methodology used to assess the two different configurations, PVT without GCHP and PVT with GCHP.

### 3.6.1. PVT without GCHP

For the PVT without GCHP scenarios, electricity and gas savings were estimated for residential buildings, while only electricity savings were estimated for commercial buildings. The electricity savings \( (\text{Elec}_{\text{saving}}) \) from PVT were calculated based on two possibilities. First, if the electrical solar fraction was less than or equal to 100%, the \( \text{Elec}_{\text{saving}} \) were calculated by multiplying the PVT electricity production \( (\text{PVT}_{\text{elec}}) \) by the Elec rate, for each scenario, as in Equation 3.6.1.1.

\[
\text{Elec}_{\text{saving}} = \text{PVT}_{\text{elec}} \times \text{Elec rate} \quad (3.6.1.1)
\]

Second, if the electrical solar fraction was more than 100%, the \( \text{Elec}_{\text{saving}} \) was calculated by multiplying the Elec cons by the Elec rate plus the excess PVT electricity production \( (\text{PVT}_{\text{excess}}) \) multiplied by the FIT as in Equation 3.6.1.2.

\[
\text{Elec}_{\text{saving}} = \text{Elec}_{\text{cons}} \times \text{Elec rate} + \text{PVT}_{\text{excess}} \times \text{FIT} \quad (3.6.1.2)
\]

Since the primary energy source for DHW in the United States is natural gas, the \( \text{Gas}_{\text{saving}} \) was calculated by multiplying the amount of energy added by the PVT collectors \( (\text{PVT}_{\text{therm}}) \) to the pre-heating tank, in kWh, by the Gas rate, in $/kWh, according to Equation 3.6.1.3.
\[ \text{Gas}_{\text{saving}} = PVT_{\text{therm}} \times \text{Gas}_{\text{rate}} \] 

(3.6.1.3)

3.6.2. PVT with GCHP

For the PVT with GCHP system, the \( \text{Elec}_{\text{saving}} \) and \( \text{Gas}_{\text{saving}} \) from the use of the PVT collectors were calculated as described previously, while the savings from adding the GCHP were estimated based on a comparison between the GCHP energy consumption cost \( (\text{GCHP}_{\text{cons,cost}}) \) and the energy consumption cost of conventional heating and cooling systems. In a typical American home, this system comprises ASHP for cooling and a furnace for heating. The \( \text{GCHP}_{\text{cons,cost}} \) was calculated as in Equation 3.6.2.1.

\[ \text{GCHP}_{\text{cons,cost}} = \text{GCHP}_{\text{cons}} \times \text{Elec}_{\text{rate}} \] 

(3.6.2.1)

Where \( \text{GCHP}_{\text{cons}} \) is the aggregated power consumed by the GCHP, in kWh, as described in section 3.4.6, plus the energy consumed by Pump 2, which circulates the working fluid between the BTES and the GCHP.

The energy consumption costs of the conventional cooling and heating system, however, equal the sum of the ASHP energy consumption cost \( (\text{ASHP}_{\text{cons,cost}}) \) for cooling and the furnace energy consumption cost \( (\text{Furnace}_{\text{cons,cost}}) \) for heating. The \( \text{ASHP}_{\text{cons,cost}} \) was estimated based on ASHP energy consumption \( (\text{ASHP}_{\text{cons}}) \) and \( \text{Elec}_{\text{rate}} \), as shown in Equation 3.6.2.2.

\[ \text{ASHP}_{\text{cons,cost}} = \text{ASHP}_{\text{cons}} \times \text{Elec}_{\text{rate}} \] 

(3.6.2.2)
The ASHP\textsubscript{cons} was estimated by dividing the cooling load by the modified coefficient of performance COP\textsubscript{C\_modified}. The COP\textsubscript{C\_modified} was calculated by Fairey et al. [44], based on a percentage reduction in the COP (or SEER) provided by the manufacturer as a function of ambient temperature, as shown in Equation 3.6.2.3.

\[
\%\text{Decrease} = -0.5655 + 0.005414 \times T_{amb} + 0.01039 \times SEER
\]  
(3.6.2.3)

Where the SEER was assumed to be 13 for this work.

The Furnace\textsubscript{cons\_cost} was calculated as the product of the furnace energy consumption (Furnace\textsubscript{cons}) and Gas\textsubscript{rate}, as in Equation 3.6.2.4.

\[
\text{Furnace}_{cons\_cost} = \text{Furnace}_{cons} \times \text{Gas}_{rate}
\]  
(3.6.2.4)

Where the Furnace\textsubscript{cons} was obtained by dividing the heating load by the furnace efficiency (\(\eta_{furnace}\)), which assumed to be 83%.

The heating-to-cooling ratio (HCR) was introduced during the IRR evaluation. This term reveals the ratio of the total annual heating load to the total annual cooling load. In addition, it evaluates the Elec\textsubscript{cons\_to-Gas\textsubscript{cons}} ratio to determine the dominant energy rate, whether Elec\textsubscript{rate} or Gas\textsubscript{rate}, affecting the IRR.
CHAPTER 4
RESULTS AND ANALYSIS

This chapter reveals the simulation results of the 12 different scenarios and compares each scenario in terms of both technical performance and economic feasibility. The first section shows the performances of the different components and the second section analyzes the feasibility of the different scenarios. An assessment of the components over short and long-term use was conducted, and an economic evaluation was conducted over long term use only. The short-term assessment looked at the first simulated year, while the long-term was assumed to be 20 years, except for the secondary school type building with GCHP scenarios, which were evaluated over 4 years.

4.1. Performance Assessment

For each building type, the performances of the unglazed PVT and GCHP are described in detail in this section. First, the PVT collector performance is compared with the reference PV panel performance to illustrate the influence of the cooling effect on cells efficiency in different scenarios, and the thermal performance of the unglazed PVT technology is examined by measuring the amount of thermal energy added to the pre-heating tank in residential buildings. Secondly, the effect of adding a GCHP on PVT
performance in the different scenarios is illustrated. In addition, any increases and decreases in GCHP performance as a consequence of BTES energy imbalance is evaluated.

4.1.1. PVT Performance without GCHP

The simulations of PV and PVT technologies in the two different climates revealed that the former’s cells show higher response to the climate than the latter due to the absence of the cooling effect. Figure 4.1.1.1 shows the temperature differences between the PV and the PVT cells for the different types of buildings. Even though none of the PVTs were combined with a GCHP in this simulation, they exhibited different cell temperatures due to the size of the BTES that they rejected the heat into. In the residential building, 15 PVT collectors rejected heat in only four boreholes, while in the small office type, 50 PVT collectors rejected heat in 25 boreholes, and in the secondary school building 400 PVT collectors rejected heat in 500 boreholes.
Even in the winter months, when the average dry bulb temperature is low, the PVT cell temperatures showed a slight reduction compared to the PV cells. This reduction occurred during the middle of the day, when the solar radiation is highest. As the solar radiation increased, the PVT and PV cell temperatures increased. However, when the former’s cells temperature reached seven degrees higher than the BTES outlet fluid temperature, the circulation pump would turn ON and reduce cell temperature. Figure 4.1.1.2. shows this relationship, illustrating the time-of-day variation of PV, PVT, BTES outlet fluid temperatures in combination with amounts of solar radiation of the residential building on January 3rd.
The average monthly cell temperature differences resulted in a reduction in the PV cells’ efficiency compared to the PVT cells’ efficiency. Figure 4.1.1.3 depicts the monthly cell efficiencies for the different PV and PVT scenarios in Minneapolis, MN.
Figure 4.1.1.3 Monthly average PV and PVT cell efficiencies for three different building types in Minneapolis, MN

As can be inferred from the above figure, during winter months, the cooling effect in the PVT collectors has a diminished effect compared to in the summer months. In other words, the higher the ambient temperature, the higher the effect of the coolant on the PVT cells. Figure 4.1.1.4 shows the increment in PVT cell efficiencies compared to those of PV cells in Minneapolis, MN for the three building types.
Due to the low thermal performance of the unglazed PVT collectors, they only met 530.6 kWh of the total annual DHW energy consumption in Minneapolis, MN residential building, which is 6.53 MWh, as shown in Figure 4.1.1.5.
In Phoenix, AZ, both the PV and PVT cell temperatures showed an increase compared to Minneapolis, MN, as shown in Figure 4.1.1.6.

In fact, cell temperatures depend mainly on the solar radiation; the higher the solar radiation, the higher the cells temperature, even in winter when the dry bulb temperature is relatively low. Figure 4.1.1.7 is a time-of-day depiction of solar radiation, cell temperatures, and BTES outlet fluid temperatures on January 3rd in Phoenix, AZ.
Figure 4.1.1.8 illustrates the difference between the PV and PVT efficiencies. It can be seen that the difference in Phoenix, AZ is higher, comparing to the difference in Minneapolis, MN, as in Figure 4.1.1.3.

Figure 4.1.1.7 Time-of-day variation of PV, PVT, BTES outlet fluid temperatures, and solar radiation on 3rd of January in Phoenix, AZ

Figure 4.1.1.8 Monthly average PV and PVT cells efficiencies for three different scenarios in Phoenix, AZ
With respect to the fact that the higher the cell temperature, the more promising the cooling effect, the PVT cells’ efficiency increment in Phoenix, AZ is higher than the increment in Minneapolis, MN, as shown in Figure 4.1.1.9. In July, when the dry bulb temperature reaches its maximum, the PVT cells’ efficiency showed an increment of about 4.15% compared to the PV cells efficiency.

![Diagram showing monthly average dry bulb temperature and PVT efficiency increment for three different scenarios in Phoenix, AZ.](image)

*Figure 4.1.1.9 Monthly average increment of PVT efficiency for the three different scenarios in Phoenix, AZ*

Compared to the energy added to the pre-heating tank in Minneapolis, MN, the simulation results showed a lower fraction met by the PVT in Phoenix, AZ, which is 131.46 kWh of the 4.84 MWh total energy consumption, as represented by Figure 4.1.1.10.
The reason that the DHW solar fraction in Minneapolis, MN was higher than in Phoenix, AZ is that the water main temperature of the former is lower than the latter, as shown in Figure 4.1.1.11, which resulted in more energy savings potential.

In this case, where no GCHP is in use, the outlet BTES fluid temperature slightly affected the cells’ efficiency on an annual basis, as shown in Figure 4.1.1.12 for both climates.
As a consequence of heat imbalance in thermal storages, the BTES outlet fluid temperatures increased while the PVT cells efficiencies decreased. Figure 4.1.1.13 and 4.1.1.14 show the annual BTES outlet fluid temperature and percent of PVT cells efficiency reduction for 20 years, in Minneapolis, MN and Phoenix, AZ, respectively. These two figures represent all buildings since the differences in cells temperature between the three types of buildings are negligible.
4.1.2. PVT with GCHP

The PVT performance in this section is assessed as a function of not only climate conditions but also building type. The latter determines the amount of heat added to and
extracted from the BTES by the GCHP and hence, the BTES outlet fluid temperature that would be circulated into the PVT collector.

4.1.2.1. Residential Buildings

In Minneapolis, MN, where the heating load is dominant, the amount of energy extracted from the ground by the GCHP during heating season is higher than the amount of energy added by the GCHP during cooling season, as illustrated by Figure 4.1.2.1.1. During the first year, the total amount of energy extracted from the BTES by the GCHP was 36.92 MWh, while the energy added was 178.16 kWh. The energy added by the PVT to the BTES, which equaled 2.8 kWh, was low and had a neglected effect on the GCHP performance.

![Figure 4.1.2.1.1 Energy added to and extracted from the BTES by the GCHP in Minneapolis, MN residential building](image)
This BTES heat imbalance resulted in ground temperature reduction, and hence, a lower BTES outlet temperature. This means that the circulated fluid could extract more energy from the PVT cells and boost their efficiency. Figure 4.1.2.1.2 shows the monthly comparison of the electrical performance of the first year of simulation of the PVT cells with and without combining with GCHP.

![Figure 4.1.2.1.2 First year monthly comparison of PVT electrical performance with and without GCHP in Minneapolis, MN residential building](image)

The 20-year simulation revealed greater reductions in ground temperature and in increases in electrical efficiency. Figure 4.1.2.1.3 shows annual average BTES outlet fluid temperature and average PVT cells efficiency percent increases in Minneapolis, MN for the 20 simulated years.
Figure 4.1.2.1.3 Annual average BTES outlet fluid temperature vs. PVT cells efficiency increase after combining GCHP to PVT system in Minneapolis, MN residential building

The continued heat extraction from the BTES resulted in an increase in COP<sub>C</sub> and a slight reduction in COP<sub>H</sub> throughout the 20-year period, as shown in Figure 4.1.2.1.4.

Figure 4.1.2.1.4 The changes in COP<sub>C</sub> and COP<sub>H</sub> over 20 years for the Minneapolis, MN residential building
In Phoenix, AZ the situation is reversed -- the cooling load is dominant and the heat rejected by the GCHP during cooling months is much higher than the heat extracted during the heating months, as represented by Figure 4.1.2.1.5. The first-year simulation revealed that the total amount of energy added to the BTES by GCHP was 4.42 MWh, while the energy extracted was 1.5 MWh. The PVT collectors accounted for 3.47 kWh added to the BTES.

![Graph showing energy added to and extracted from the BTES](image)

*Figure 4.1.2.1.5 Energy added to and extracted from the BTES by the GCHP and PVT collectors in Phoenix, AZ residential building*

During heating-dominant months, when the GCHP extracted heat from the BTES, the PVT cells efficiency was higher compared to the PVT cells efficiency without GCHP. During cooling-dominant months, in contrast, the GCHP rejected heat to the BTES, which resulted in diminishing the PVT cell efficiency to be lower than the scenario with no GCHP. Figure
4.1.2.1.6 a monthly comparison between the electrical performance of the first year of simulation of the PVT cells with and without GCHP.

Figure 4.1.2.1.6 First year monthly comparison between PVT cells performance with and without GCHP in Phoenix, AZ residential building

Contrary to the long-term behaviors of the Minneapolis, MN’s BTES outlet fluid temperature and PVT cells efficiency, in Phoenix, AZ, the former showed an increase while the latter showed a reduction, as Figure 4.1.2.1.7 illustrates.
Figure 4.1.2.1.7 Annual average BTES outlet fluid temperature Vs. PVT cells efficiency reduction after adding GCHP to the PVT system in Phoenix, AZ residential building

As a result of the BTES heat imbalance, the COP_C decreased while the COP_H increased, as Figure 4.1.2.1.8 represents.
Figure 4.1.2.1.8 The COP$_C$ and COP$_H$ change through 20 years of Phoenix, AZ residential building

4.1.2.2. Small Office Buildings

In the Minneapolis, MN small office, the GCHP accounted for 3.8 MWh thermal energy added to and 24.7 MWh extracted from the BTES annually. These loads are distributed in Figure 4.1.2.2.1. The PVT collector contributed to 9.24 kWh added to the BTES.
As in the residential building, this imbalance in heat extracting-rejecting in a cold climate led to a reduction in the BTES temperature and increased the PVT cells efficiency. However, the improvement in PVT efficiency was less than that in the residential building, due to the neglected heat rejection by GCHP compared to the office building. Figure 4.1.2.2.2 offers a 12-month comparison of PVT cells efficiency with and without GCHP in Minneapolis, MN.
The 20-year simulation showed inconsequential BTES temperature reduction, and a slight increase in PVT cell efficiency, as represented in Figure 4.1.2.3.
Figure 4.1.2.2.3 Annual average BTES outlet fluid temperature Vs. PVT cell efficiency increase after adding GCHP to the PVT system in Minneapolis, MN small office building over 20 years

As in Figure 4.1.2.2.4, the 20-year simulation revealed a slight reduction and increase in COP\textsubscript{H} and COP\textsubscript{C}, respectively, as a consequence of higher energy extraction compared to energy rejection.
The Phoenix, AZ small office’s GCHP rejected 18.93 MWh and extracted only 1.5 MWh during the first-year simulation, distributed as in Figure 4.1.2.5. The PVT collectors, however, rejected 12.12 kWh to the BTES.
Figure 4.1.2.2.6 shows the effect of the GCHP on the PVT cells efficiency by comparing it to the PVT without GCHP scenario. The PVT cells efficiency without GCHP was reported to be slightly higher than the PVT cells efficiency with GCHP from April to November, when the heating load is negligible compared to the cooling load.
Figure 4.1.2.2.6 First year monthly comparison of PVT electrical performance with and without GCHP in the Phoenix, AZ small office building

After the 20-year simulation, the heat imbalance resulted in a 5.2 °C increase in the BTES, and about a 0.6% reduction in the cells efficiency, as shown in Figure 4.1.2.2.7.

Figure 4.1.2.2.7 Annual average BTES outlet fluid temperature vs. PVT cell efficiency reduction after adding GCHP to the PVT system in the Phoenix, AZ small office building
In comparison with the Minneapolis, MN small office building, the Phoenix, AZ small office building’s COP\textsubscript{C} and COP\textsubscript{H} showed higher slopes, as Figure 4.1.2.2.8 illustrates.

Figure 4.1.2.2.8 The COP\textsubscript{C} and COP\textsubscript{H} change through 20 years of the Phoenix, AZ small office building

4.1.2.3. Secondary School Buildings

The secondary school buildings extracted and rejected immense amounts of heat in Minneapolis, MN and Phoenix, AZ, respectively. In Minneapolis, MN the GCHP extracted 2.96 GWh and rejected 831.3 MWh of heat to the BTES annually, distributed as in Figure 4.1.2.3.1. The PVT collectors were able to extract 79.3 kWh of heat from the cells and rejected that heat to the BTES, and hence, the effect of the PVT collector on the BTES was neglected.
Due to the vast amounts of energy extraction from the BTES in this scenario, and relatively low heat rejection on an annual basis, the PVT cells efficiency in the first-year simulation increased compared to the efficiency of the cells in the PVT system without GCHP, as shown in Figure 4.1.2.3.2.
While running this scenario in TRNSYS, the average ground temperature decreased dramatically due to under-sizing the BTES and a high-energy imbalance, which forced TRNSYS to cease the simulation in the sixth month of the eighth year. The seven-year simulation revealed about a 9 °C reduction in the BTES outlet fluid temperature, and around 1% cells efficiency increase, as in Figure 4.1.2.3.3.
Even though the simulation lasted for seven years and six months, the COP\textsubscript{H} reduction and COP\textsubscript{C} increase were high due to the large reduction in the BTES temperature, illustrated in Figure 4.1.2.3.4.
Contrary to what happened in Minneapolis, MN, the secondary school building in Phoenix, AZ rejected a high amount of energy throughout the year. The annual rejected heat by the GCHP was about 2.94 GWh while the extracted energy was around 279.4 MWh, as distributed in Figure 4.1.2.3.5. The contribution of the PVT collector to heat rejection to the BTES was 80.8 kWh.
As shown in Figure 4.1.2.3.5, during the first three months of the first simulated year, the differences between the heating and cooling loads were not high. That led to almost the same cell efficiencies for the PVT systems with and without GCHP. Starting from April, however, the cooling load increased significantly, leading to a reduction in the efficiency of the PVT cells to the end of the year, as in Figure 4.1.2.3.6.
As in Minneapolis, MN, TRNSYS ceased the simulation during the fourth year of the Phoenix, AZ secondary school scenario simulation because the BTES volume was not large enough, which led to a dramatic increase in BTES temperature, which reached about 44°C, as shown in Figure 4.1.2.3.7.
A three-year simulation of the BTES outlet fluid temperature and PVT cells efficiency revealed a sharp increase in the former and sharp decrease in the latter, as shown in Figure 4.1.2.3.8.

Figure 4.1.2.3.7 BTES temperature distribution over three years and 11 months

Figure 4.1.2.3.8 Three-year BTES outlet fluid temperature vs. PVT cell efficiency reduction after adding GCHP to the PVT system in Phoenix, AZ secondary school building
The GCHP performance showed a dramatic reduction in the COP$_C$ and a large increase in the COP$_H$ for the simulated three years, as represented by Figure 4.1.2.3.9.

![Graph showing COP change through 20 years of Phoenix, AZ secondary school building](image)

*Figure 4.1.2.3.9 The COP$_C$ and COP$_H$ change through 20 years of Phoenix, AZ secondary school building*

4.2. Economic Feasibility

The aim of this section is to present a feasibility study of each scenario of the PVT systems. The electrical solar fraction and IRR of each scenario are discussed. As mentioned in section 3.6, the IRR is presented as a function of uncertainty in Elec$_{rate}$ and Gas$_{rate}$ for each scenario. This section is divided according to building type, starting with residential buildings, followed by small office buildings, and finally secondary school buildings.
4.2.1. Residential Building Scenarios

Figure 4.2.1.1 shows the electrical solar fraction of the four different residential buildings scenarios. It clearly illustrates the effects of climate and the GHCP on the PVT cells’ performance and hence, on system feasibility.

![Figure 4.2.1.1 Electrical solar fraction of different residential building scenarios](image)

The IRRs of these scenarios when Elec<sub>rate</sub> ranges from 11.99 to 13.88 ¢/kWh for Minneapolis, MN and from 10.9 to 12.94 ¢/kWh for Phoenix, AZ are shown in Figure 4.2.1.2. These IRRs were calculated as a function of fixed Gas<sub>rate</sub> averages, which were 9.79 and 18.30 $/MCF for Minneapolis, MN and Phoenix, AZ, respectively.
Figure 4.2.1.2 infers the positive impact of the GCHP in both climates since the GCHP shares the same BTES with the PVT system. As is evident from this figure, the higher the electricity rate, the more promising the savings in both Phoenix, AZ scenarios and Minneapolis, MN without GCHP scenario. However, in the Minneapolis, MN with GCHP scenario, the higher the electricity rate, the less promising the GCHP savings due to the high $\text{Elec}_{\text{rate}}$ compared to $\text{Gas}_{\text{rate}}$, per kWh. By comparing the PVT without GCHP in both climates, it can be seen that the Minneapolis, MN scenario has a lower IRR than that in Phoenix, AZ, even though the former scenario has a higher PVT cell efficiency. This difference was a consequence of the percent of $\text{PVT}_{\text{elec}}$ consumed to the total PVT production. Since the FIT is low compared to that of $\text{Elec}_{\text{rate}}$, consuming the $\text{PVT}_{\text{elec}}$ is more beneficial than selling it to the grid. Figure 4.2.1.3 and 4.2.1.4 show the $\text{PVT}_{\text{elec}}$ consumed and the $\text{PVT}_{\text{excess}}$ ratios for both Minneapolis, MN and Phoenix, AZ, respectively.
Figure 4.2.1.3 $PVT_{elec}$ consumed and $PVT_{excess}$ ratios for Minneapolis, MN residential building without GCHP

Figure 4.2.1.4 $PVT_{elec}$ consumed and $PVT_{excess}$ ratios for Phoenix, AZ residential building without GCHP
In terms of $\text{Gas}_{\text{rate}}$, the Minneapolis, MN residential building shows higher sensitivity to $\text{Gas}_{\text{rate}}$, and hence, more savings and a higher IRR when the $\text{Gas}_{\text{rate}}$ increases compared to Phoenix, AZ, where gas consumption is lower due to a relatively low heating load. Figure 4.2.1.5 illustrates the IRRs of both scenarios when $\text{Gas}_{\text{rate}}$ ranges from 6.92 to 13.46 $/\text{MCF}$ for Minneapolis, MN and 11.99 to 24.02 $/\text{MCF}$ for Phoenix, AZ. The $\text{Elec}_{\text{rate}}$ for these scenarios were fixed to the averages, which are 12.826 and 12.214 ¢/kWh for Minneapolis, MN and Phoenix, AZ, respectively.

![Figure 4.2.1.5 IRRs of different residential building scenarios as a function of $\text{Gas}_{\text{rate}}$](image)

4.2.2. Small Office Scenarios

Figure 4.2.2.1 shows the electrical solar fraction of the four different small office scenarios.
As in the previous scenarios, the IRRs of these scenarios are presented as a function of Elec\textsubscript{rate} when it increased from 9.46 to 10.82 ¢/kWh in Minneapolis, MN and from 9.59 to 11.24 ¢/kWh in Phoenix, AZ. The Gas\textsubscript{rate}, however, was fixed to the averages, which are 7.198 and 9.66 $/MCF, for Minneapolis, MN and Phoenix, AZ, respectively. These IRRs are shown in Figure 4.2.2.2.
In contrast to the residential with GCHP scenarios, the Minneapolis, MN small office with GCHP scenario is less attractive. By comparing heating and cooling loads for both buildings, it can be seen that the CHR of the Minneapolis, MN small office building is 15.15%, which is higher than that of the residential building in the same climate, which is 0.48%. That increase in CHR led to a reduction in savings, and hence, a lower IRR. Figure 4.2.2.2 shows the IRRs of both climates for buildings without a GCHP. Minneapolis, MN’s IRR is slightly lower than Phoenix, AZ’s, with a higher amount of \( PVT_{elec} \) sold to the grid in MN, as shown in Figures 4.2.2.3 and 4.2.2.4.
Figure 4.2.2.3 $PVT_{elec}$ consumed and $PVT_{excess}$ ratios for Minneapolis, MN small office building without GCHP

Figure 4.2.2.4 $PVT_{elec}$ consumed and $PVT_{excess}$ ratios for Phoenix, AZ small office building without GCHP

Figure 4.2.2.5 represents the IRRs of both climates with GCHP as a function of $\text{Gasrate}$. Both of these are more stable compared to the residential scenarios due to the lower dependence of the small office buildings on gas compared to residential buildings.
4.2.3. Secondary School Scenarios

The results of the secondary school building scenarios reveal a low electricity solar fraction, especially for Phoenix, AZ, where the building depends mainly on electricity rather than gas due to predominating cooling conditions, as show in Figure 4.2.3.1.

*Figure 4.2.2.5 IRRs of different small office building scenarios as a function of $\text{Gas}_{\text{rate}}$*
Because of the under-sizing of the BTES of both schools with GCHP scenarios, and in order to ensure an equitable comparison of these two scenarios, the Phoenix, AZ scenario was evaluated over seven instead of four years. These savings were estimated by applying a 10% savings reduction on the third year to obtain the fourth year, and a 10% savings reduction on the fourth year to obtain the fifth year, and so on until the seventh year was reached. Figure 4.2.3.2 represents the IRRs of all of the secondary school scenarios. As is evident from this figure, Phoenix, AZ shows higher sensitivity to the Elec\textsubscript{rate} than Minneapolis, MN. Moreover, since Phoenix, AZ’s GCHP had a low performance, its IRR would be higher than Minneapolis, MN scenario’s performance only in cases of a high Elec\textsubscript{rate}. The IRRs of both climates without GCHP, on the other hand, show an identical performance since the entire PVT\textsubscript{elec} was consumed by the schools, and no electricity was sold to the grid.
Figure 4.2.3.3 shows the secondary school’s IRRs of both climates as a function of varying the \( \text{Gas}_{\text{rate}} \) from 6.09 to 8.88 $/MCF for Minneapolis, MN and from 8.00 to 11.76 $/MCF for Phoenix, AZ.

Comparing the IRRs of the secondary school to those of the small office scenarios, the former’s show more sensitivity to the \( \text{Gas}_{\text{rate}} \). In Minneapolis, MN, the CHR of the secondary school is 28.05% compared to the 15.15% of the small office, which reveals the
higher sensitivity of the former to the Gasrate. Unexpectedly, the Phoenix, AZ secondary school scenario’s HCR is higher than that of the small office scenario, at 9.5% and 8 %, respectively, which infers the higher sensitivity of the school scenario’s IRR.
CHAPTER 5
CONCLUSION

The main objective of this thesis is to assess the viability of coupling PVT collectors to underground thermal energy storage systems. Specifically,

1. Assess short and long-term performances of PVT collectors coupled with BTES.
2. Identify building types and climate regions where PVT technology is economically feasible.
3. Identify key parameters affecting the feasibility of PVT collectors when they are coupled with BTES with and without GCHP.
4. Evaluate the effect of GCHP on the PVT performance and vice versa.

A transient system simulation model of unglazed PVT collectors coupled with BTES was constructed. The simulation model was used to preliminarily assess the technical and economic performance in 12 different scenarios in the United States. The technical performance included cell efficiency and thermal output. The cell efficiency performance was evaluated in the short and long-term (over 20 years), while the thermal performance was assessed by measuring the amount of thermal energy that the unglazed PVT collectors can add to a pre-heating tank or the BTES to be used by a GCHP. The economic
performance evaluation was conducted by calculating the IRR of each scenario as a function of energy rates and component costs. The energy rates included $\text{Elec}_{\text{rate}}$ and $\text{Gas}_{\text{rate}}$ while the component costs included the PVT, BTES, GCHP, ASHP, and furnace costs. The IRRs were calculated by varying one energy rate from its maximum to minimum, while the other rate was fixed to the average value. The components costs, however, were fixed. The 12 scenarios included six scenarios in Minneapolis, MN as the representative cold climate, and six scenarios in Phoenix, AZ as the representative hot climate. In each climate three building types were simulated: residential, small office, and secondary school. For each building type, two scenarios were assessed: PVT-BTES system without GCHP and PVT-BTES system with GCHP.

For the PVT without GCHP scenarios, cell temperature differences between the unglazed PVT collectors and a reference PV panel in July were observed to be as high as 8.8 °C in Minneapolis, MN and 10 °C in Phoenix, AZ due to the cooling effect in the PVT collectors. Theses temperature differences resulted in a higher PVT cell efficiency compared to the reference PV cells efficiency. In Minneapolis, MN, the increase in PVT cell efficiency was observed to be about 4.2%. In Phoenix, AZ, the increase in PVT cells efficiency was 4.7% comparing to a reference PV cells efficiency. The differences between the PVT cell efficiencies in the different buildings was due to the different BTES sizes. Reduction in PVT cells efficiency due to the heat imbalance in BTES and increase in BTES outlet after 20 years were observed to be negligible at 0.1 and 0.2% for Minneapolis, MN and Phoenix, AZ, respectively.

The energy added to the residential pre-heating tanks in both climates were observed to be as small as 8% of the total DHW energy needed for MN and 3% for AZ, which reveals
the poor thermal performance of the unglazed PVT collectors. The amount of solar energy collected in Minneapolis, MN was higher than that in the Phoenix, AZ scenario due to the low water main temperature of the former compared to the latter.

After adding GCHPs to all scenarios, a positive impact was observed on the PVT collectors in Minneapolis, MN and a negative impact on those in Phoenix, AZ. These impacts, however, were negligible, even though the BTES outlet fluid temperatures decreased 8.6 °C in Minneapolis, MN and increased 11.4 °C in Phoenix, AZ.

The annual energy added to the BTES by the PVT collectors in all scenarios was negligible compared to the annual energy extracted or rejected by the GCHPs. In other words, the PVT arrays were not large enough in either climate to offset annual underground energy imbalance. In Minneapolis, MN, this heat imbalance resulted in a slight COP\textsubscript{H} reduction in the residential and small buildings, and a larger reduction in COP\textsubscript{H} in the secondary school building. In Phoenix, AZ, on the other hand, the excessive heat rejection resulted in a large COP\textsubscript{C} reduction in the residential and small office buildings and an even more dramatic reduction in the secondary school building.

The economic analysis of all scenarios revealed unattractive IRRs for all scenarios. Since the GCHP was assumed to share the same BTES with the PVT system, the scenarios that include GCHPs were more promising than the scenarios where there was no GCHP. In Phoenix, AZ where the cooling loads are dominant, an increase in Elect\textsubscript{rate} has a larger impact on the IRR than in Minneapolis, MN. However, In Minneapolis, MN where the heating load is dominant, the IRRs showed more sensitivity to the Gas\textsubscript{rate} compared to the Phoenix, AZ scenarios.
CHAPTER 6

RECOMMENDATIONS AND FUTURE WORK

After conducting this work, it was concluded that there are some opportunities for improvement in a future work.

- There are numerous degrees of freedom in these systems, and there are tradeoffs between the reduction in the size of the ground heat exchanger, the size of the PVT array, and the control strategy. To more fully understand this, additional research using the simulation techniques developed in this work is needed. A “design of experiments” approach could conceivably be conducted to determine the most important variables.

- Field validation of an actual system would be beneficial, but collecting long-term data on a system is a challenge.

- Optimizing the PVT system to balance the ground load could potentially be achieved by charging the BTES with solar energy in cold climates and using the PVT collectors as nocturnal radiators in hot climates. Since the BTES capital cost accounts for 55% of the total capital cost, reducing the BTES storage volume may contribute to increasing the IRR in both residential and small office buildings.

- Increasing the BTES volume will improve the secondary school with GCHP’s performance; however, rejecting the heating load in a hot water tank before directing it to the BTES is more likely to alleviate the high BTES heat imbalance.
REFERENCES


