# MODELING AND SIMULATION OF HEAT PUMP SYSTEMS COMBINED WITH SOLAR PHOTOVOLTAICS

by

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**A Thesis**

*Submitted to the Faculty of Purdue University*

*In Partial Fulfillment of the Requirements for the degree of*

**Master of Science in Engineering**

Civil and Mechanical Engineering

Fort Wayne, Indiana

December 2018

# THE PURDUE UNIVERSITY GRADUATE SCHOOL
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**I have learned the value of hard work by working hard.**

***Every challenging work needs self-efforts as well as guidance of elders especially those who are very close to our heart. My humble effort I dedicate to my sweet and loving Father, Mother and my all family members.***

***I also dedicate my thesis advisor to Dr. Donald Mueller, who has guided me in every step of my thesis.***

# ACKNOWLEDGMENTS

I express my sincere gratitude towards my advisor Dr. Donald Mueller, Jr. for continuous and constant support of my thesis study and for his patience, enthusiasm, motivation and immense knowledge. He guided me all the time while working on this research thesis; I cannot imagine having such a great advisor and mentor for this thesis study.

I also thank my rest of thesis committee Drs. Hosni Abu-Mulaweh and Nashwan Younis for the interest they have shown in the study by being members of the examining committee and for the helpful comments.

In addition, I would like to thank Drs. Zhuming Bi, David Cochran, and Prasad Bingi for absolute support and encouragement during the thesis.  I also thank my fellow graduate students for their help and support.

Finally, I take this opportunity to express the profound gratitude from my deep heart to my beloved parents, my sister and all my family members for their unconditional love and constant support.

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# ABSTRACT

Author: Busineni, Vijaya, Shyam. MSE
Institution: Purdue University
Degree Received: December 2018
Title: Modeling and Simulation of Heat Pump Systems Combined with Solar Photovoltaic
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Renewable energy systems have received considerable attention as a sustainable technology in the building sector. Specifically, the use of ground-source heat pump (GSHP) and air-source heat pump (ASHP) for heating and cooling of buildings is increasing rapidly, and the combination with photovoltaic (PV) systems and heat pump systems provide energy savings and environmental benefits. This study investigates the feasibility of replacing conventional heating and cooling systems in a multifamily, residential building with GSHP and ASHP systems and their combination with PV. The integration of PV with GSHP and ASHP systems presents an opportunity for increased solar energy usage resulting in a reduction of electricity demanded and a reduction of emissions of greenhouse gases. To analyze different heat pumps systems with and without PV, system modeling and computer simulations are performed with RETScreen Expert software.

A multifaceted verification and validation study is conducted for the system model and computer simulation. The important objective of this part of the study is to understand and develop confidence for modelling individual studies in RETScreen Expert software. To accomplish this, RETScreen Expert is used for modeling and simulating the performance of PV systems in several geographical locations, including Fort Wayne, IN. A comparison is made to performance predictions from System Advisory Model (SAM) software. In addition, a study is done to compare predictions from both software to previously published data.

In the further phase of the study, eQUEST software, a tool for building energy simulation is used to predict outputs such as electricity consumption, heating loads, and cooling loads for the multifamily residential building considered in this study. These outputs, as well as, building parameters are used as inputs to RETScreen Expert. Since, this study focuses on modeling and simulating the heating and cooling systems coupled with PV for feasibility analysis, only a few minor modifications to the eQUEST default settings are made.

The outputs from eQUEST are used as inputs to RETScreen Expert and analysis of ASHP and GSHP systems, as well as their combination with a PV system are performed. The results include the technical performance and financial model of each system, which can be used to indicate feasibility. The results show that both GSHP and ASHP systems are environmentally friendly and reduce energy consumption. These systems are economically feasible, with payback periods of under 10 years, when electricity prices are high. When combined technology is preferred, PV-GSHP systems are more environmentally friendly and have fuel savings far better than any other proposed systems. But the feasibility of the both the GSHP and PV-GSHP systems strongly depends on loop installation cost.

**Keywords: photovoltaic system (PV), ground source heat pump (GSHP), air source heat pump (ASHP), eQUEST, RETScreen Expert, and System Advisory Model (SAM).**

# CHAPTER 1. INTRODUCTION

At the present, the world is facing two important concerns viz. environmental pollution due to fossil fuels and climate effects due to greenhouse gas emissions. Space conditioning systems are among the major contributors towards climatic changes (Forsen, 2005). Environmentally beneficial heating systems introduced on a large scale can help to reduce the production of greenhouse gases. Heat pumps are one of the proven technologies that help reduce greenhouse gas emissions, while efficiently providing space heating and cooling and even helping in the preparation of sanitary water heating (Forsen, 2005).

The world is literally burning through fossil fuel resources. As the world transitions to different energy sources used to produce electricity, renewables play a vital function in reducing environmental problems (Breza, 2013). Solar, wind, geothermal, and biomass are the most popularly used renewable energy sources. Research of these sources, as well as the development of supporting technologies are areas of intense focus and effort (Breza, 2013). Solar energy is the most abundant and cleanest of the renewable energy sources. Solar energy in a form of primary energy can help address the very problem of limited traditional energy sources and also simultaneously help with environmental, economic, health perspectives (Ramos, 2017).

## 1.1 Problem statement

Approximately 76% of the U.S. electricity use and associated 40 % of greenhouse gas (GHG) emissions come from residential and commercial buildings. The share electricity usage of building sector has grown drastically in the last five decades from 25% in 1950s to 40% in early 1970s to 76% by 2012. In 2016, carbon dioxide ($CO_2$) emissions from the electricity sector was 1,821 million metric tons accounting for 35% of U.S. energy related 5,171 million metric tons of $CO_2$ emissions. Figure 1.1 shows the percentage of $CO_2$ emissions by sector, where buildings are the largest contributor of $CO_2$.

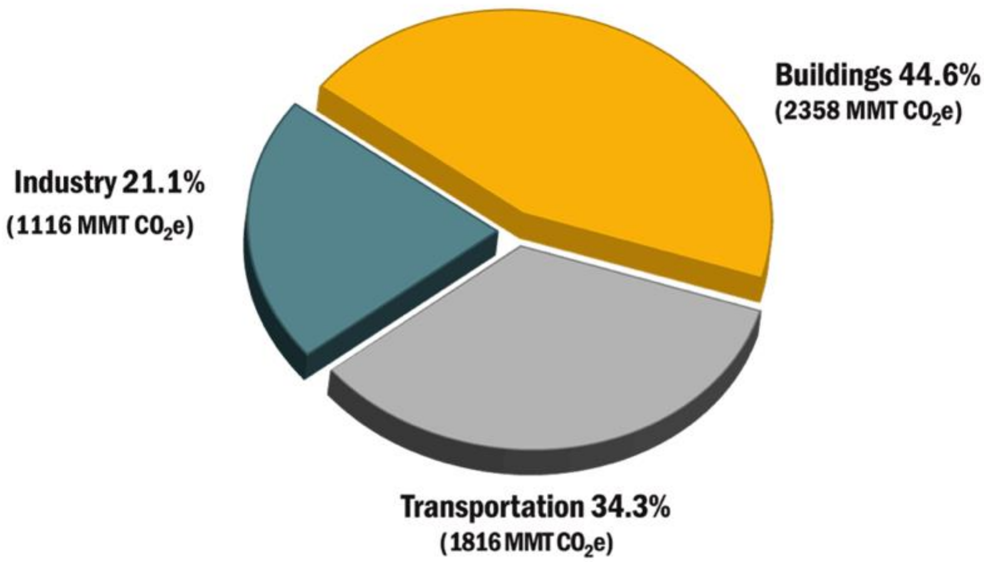


Figure 1.1 $CO_2$ emissions by sector
[Source: U.S. Energy Information Administration 2018]

Figure 1.2 shows the overall electricity distribution in a model commercial building where heating, cooling uses the majority of the electricity in a building. Since buildings consume a huge fraction of the electric utilities output, they impact the utility operations when the building systems have the capability to shift away demand of energy from peak periods. Peak periods include hot summer and cold winters, GHG emissions can be reduced by allowing the utility companies to use the power plants that pollute the least. Coordinated energy systems, energy storage, on-site generation as well as coordination with other buildings and can help the electricity provider decrease overall costs and increase the system-wide reliability.

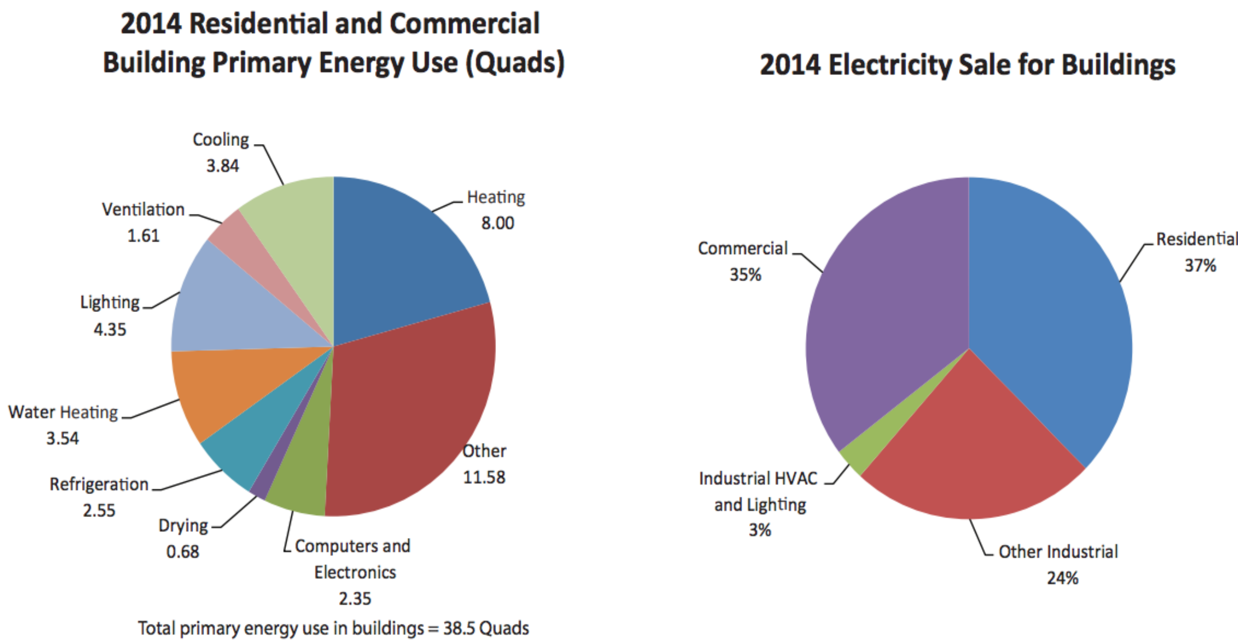


Figure 1.2 Buildings (residential and commercial) energy use in USA
[Source: U.S. Energy Information Administration 2017]

## 1.2 Problem justification

In order to address the above major concerns, combined systems have recently gained popularity and seem to be promising for the application in residential buildings. A heat pump combined with a renewable energy source comprises a low energy cooling and heating system that reduces dependency on the grid. Solar, geothermal, wind, and biomass are possible renewable energy sources for sustainable buildings (Abbasi, 2016). According to the research, renewable systems are used for cooling, heating, and ventilation of residential buildings by vapor cycles or heat pumps (Kwon, 2014). Heat pump systems, when combined with a certain type of the low-temperature distribution system are a more efficient and eco-friendly heating and cooling technology in certain climates (Abbasi, 2016). A PV system heat pump system is an appropriate approach for supplying electricity and providing heating and cooling effects for buildings (residential and commercial), especially in off-network communities and remote areas. To meet the demand requirements of buildings, different combinations of renewable energy sources and different technologies have been widely studied. This study considers two heat pump systems:  ASHP and GSHP. In addition, it considers the performance of these systems combined with a PV system.  The systems are modeled in RETScreen Expert and simulations are performed.

Simulation is a realization of converting the real-world process into the virtual world. It is a modelling and an investigation technique for analyzing system performance. Simulation has broad applications across various fields such as computer and communication system, manufacturing and material handling, automobile industry, transportation, health care and many more fields. Simulation software is designed to perform a set of specific tasks. To simulate a model of grid-connected PV system, different software packages are available. In this study RETScreen Expert software is the primary tool used.

## 1.3 Research objectives

### 1.3.1 Objective

The study objective is to analyze ASHP and GSHP systems as well as ASHP-PV and GSHP-PV combined systems with a high feasibility of implementation due to integration ease and cost efficiency. The systems are modeled using RETScreen Expert software.  Knowledge derived from this study also contributes to better understanding of grid-connected and off-grid PV systems that are combined with heat pump systems with a focus on residential buildings.  The residential building considered in this study is modeled using eQUEST software. The building under consideration is multifamily residential building located in Fort Wayne, IN. It is described by default parameters with minimal changes in eQUEST. Figure 1.3 shows a flowchart illustrating the modeling and simulation process using RETScreen Expert and eQUEST software.

By evaluating the viability of these systems as a replacement for (or complement to) conventional systems, this study gives a means to transition from energy sources of non-renewable that pollute the earth to energy sources that are renewable, cleaner, more abundant, and sustainable.

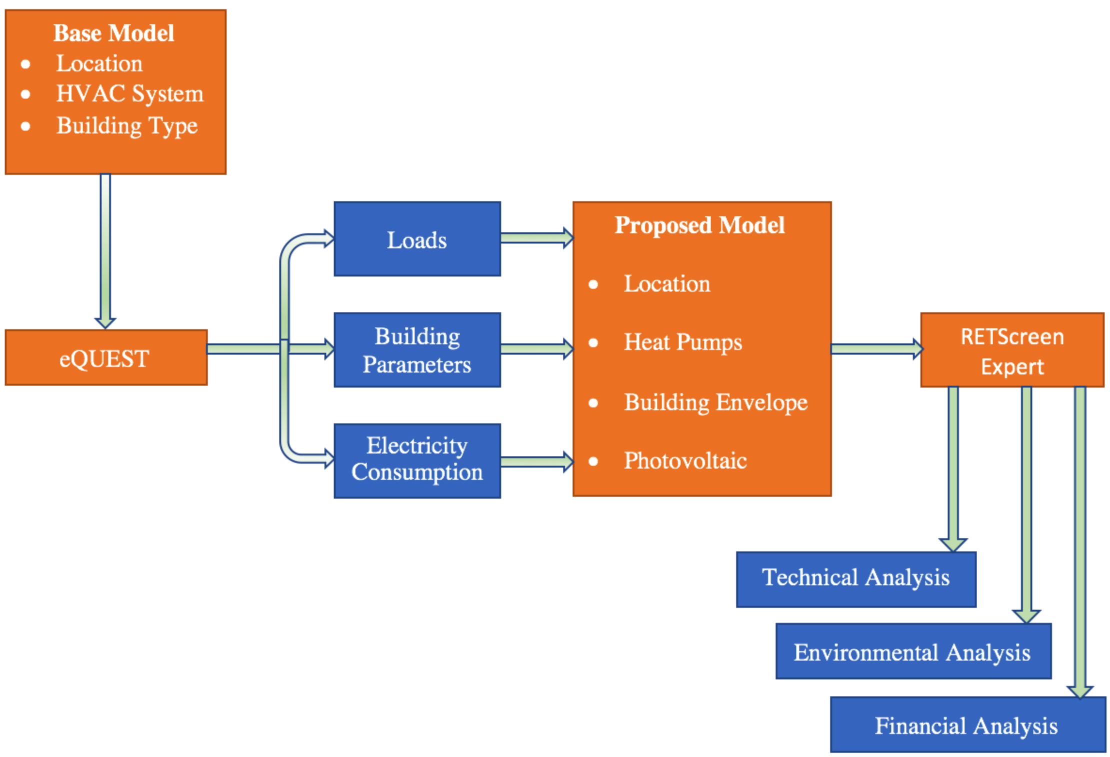


Figure 1.3 Procedure of modeling and simulation flowchart for the research study

### 1.3.2 Specific objective

The specific objectives of the research are the following:

1. Perform a comparison study between of RETScreen and SAM for a PV system with focus on predicted irradiance and energy system production. The purpose is to better understand and verify the modeling capabilities of RETScreen Expert.
2. Evaluate the PV performance models in RETScreen Expert and SAM by comparing to published field data.
3. Model a default multifamily residential building with electric resistance heating and a conventional cooling system and with a GSHP and ASHP using eQUEST software. The software was used to determine building parameters as well as predict the heating loads, cooling loads, and electrical consumption.
4. Use the outputs of the eQUEST software as input to RETScreen Expert to describe the building envelope, natural air filtration, building ventilation as well as electricity consumption including appliances, pumps, fans, and lights.
5. Use eQUEST heating and cooling loads to design and model a heat pump systems in RETScreen Expert.
6. Determine the feasibility and financial analysis of heat pump systems and their combination with PV system using RETScreen Expert by comparing payback period and energy savings as well as GHG emission savings.
7. Recommend whether or not the GSHP or the ASHP systems or the combined GSHP-PV or the ASHP-PV systems are useful for future implementation in residential buildings for heating, cooling and electricity generation.

## 1.4 Chapter outline

The brief summary of the overall layout of the master's thesis is as follows

1. Chapter 1 covers research background, problem statement, and justification, general objectives, specific objectives and scope.
2. Chapter 2 reviews the background of heat pumps, various components of heat pumps, their types, and applications. In addition, it reviews previous studies of PV systems, air source heat pumps, and ground source heat pumps using RETScreen, SAM and eQUEST software.
3. Chapter 3 covers the detailed study of RETScreen Expert and SAM software, as well as a study comparing the RETScreen and SAM in terms of actual, earlier published data for a PV system.
4. Chapter 4 describes about modeling a typical multifamily residential building using eQUEST for finding the required building parameters and heating, cooling and electric consumption to provide as inputs to the model in RETScreen.
5. Chapter 5 covers the modeling of heat pump systems, PV systems, and their combinations using RETScreen Expert to determine whether the systems are feasible and financial viable at Fort Wayne, IN. Furthermore, In-depth discussion of the results such as period of equity payback, annual life cycle savings, and net present value is explained in this chapter.
6. Chapter 6 summarizes the thesis, provides concluding remarks as well as future recommendations.

# CHAPTER 2. LITERATURE REVIEW

As the world's population grows and industries develop, there will be an increasing demand for energy. To meet this increasing demand, renewable energy sources and technologies have seen significant focus (Gupta, 2013). Due to the limitations in availability of fossil fuels and their negative impact on the environmental, sustainable energy systems including heat pumps and PV systems have grown rapidly to fulfill the market demands throughout the world, especially in places that are taking precautions in reducing energy consumption and choosing other clean energy sources to maintain energy balance (Vishwakarma, 2013). In addition, heat pumps and PV systems are becoming economical with higher energy efficiency. PV systems and heat pumps are important for conserving energy and reducing carbon emissions.

## 2.1 Heat pump systems

### 2.1.1 What is a heat pump and how does it function?

A heat pump is a pump that transfers heat energy from a source of heat to a heat sink. Heat pumps are designed to absorb energy from colder spaces and release it to warmer places by sending the thermal energy in the opposite direction from the spontaneous heat transfer using a small amount of external power (Gagneja, 2016). Heat pumps capture heat from outside environment and give it indoor through coils, thus putting it back into the space inside the residential or commercial building. The system or the heat pump that is on the outside has two purposes. In summer, it cools the building efficiently and in winter or spring, it extracts the heat from the outside atmosphere and puts it back in the building. It can extract heat from the outside environment even at low temperatures.

The working fluid is the substance in the heat pump transferring heat by cycles of circulation. Between the two exchanger coils, a compressor pumps the refrigerant. In coil one, the refrigerant evaporates from low pressure and absorbs heat from the surroundings. Thereafter, the compression of refrigerant is done while going to another coil, where it condenses at higher pressure. Then the heat releases from the earlier absorbed cycle. The heat pump can supply heat during the cold winter days since the ground and the air contains some heat in the atmosphere.

### 2.1.2 Various components of the heat pump

The heat pump has four major components, viz. the compressor, evaporator, condenser, and expansion valve. Figure 2.1 illustrates schematic of the typical heat pump cycle. In the compressor, the compression of refrigerant vapor is done for increasing its temperature and pressure. A condenser is a heat exchanger to whose surroundings the refrigerant gives off heat to become a liquid. The condenser is generally placed inside the room to be heated. The expansion valve is a device which reduces pressure. During higher pressure, refrigerant of medium temperature enters the valve of expansion and suddenly the pressure reduces causing the temperature to drop. The expansion valve controls the flow direction of the refrigerant and changes the heat pump's function between heating and cooling.

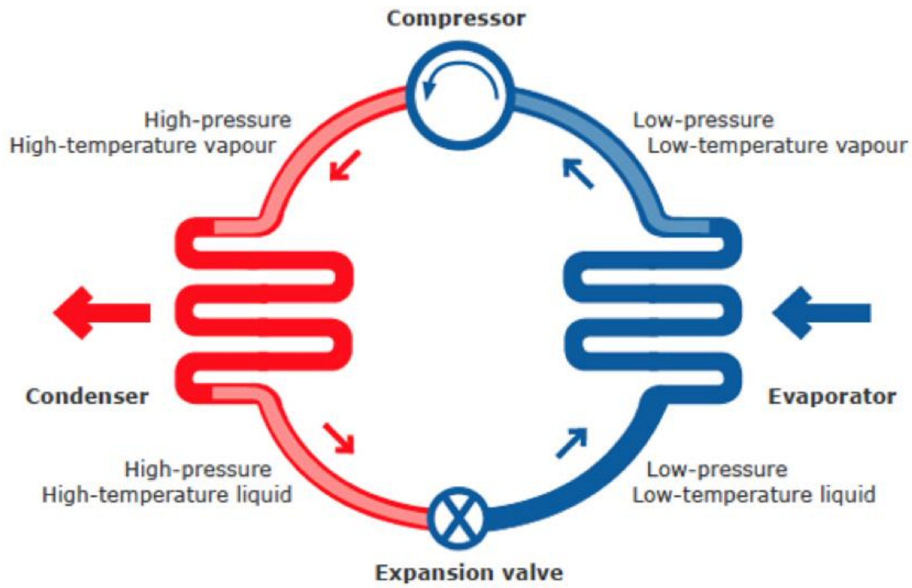


Figure 2.1 Basic heat pump cycle
[Source - Gagneja, 2016]

### 2.1.3 Ground source heat pump systems

GSHP is considered as an inclusive for describing a heat pump using ground and surface water as a heat sink or a heat source. The ground temperature of earth is more constant when compared to air temperatures, and the ground is hotter than air in winter and colder than the air in summer. These systems use the difference in ground-air temperatures. A usual space heating and cooling GSHP system comprises of three subsystems, viz. earth connection, heat pump and heat distribution subsystems.

The earth connection subsystem has a ground loop in which water and antifreeze solution circulates. The burial of loop is in horizontal or vertical ground and circulating fluid extracts heat from its neighboring ground in winter. There are other groundwater systems, where heat exchangers and wells are used with no circulating fluid and buried loops. A subsystem refrigerant loop absorbs heat energy from ground loop and liquid refrigerant conversion into vapor using heat happens by a heat exchanger. Finally, heat distribution subsystem including a refrigerant-to-air heat exchanger, warms the indoor air of building. The whole system works in reverse for cooling in summer.

A GSHP system operation needs a small quantity of electricity. According to Omer, "They use 20–40% less energy for heating and 30–50% less energy for cooling when compared to conventional systems that use fossil fuels or electricity". Hence, replacement of conventional with a GSHP system can reduce GHG emissions by a considerable amount. A GSHP system requires high upfront costs but it is compensated over time by low maintenance and energy utilization costs. Different types of ground systems are explained in the below sections.

#### 2.1.3.1 Closed loop systems

Closed loop systems are the most popularly used systems in which the heat transfer fluid is in a circulating loop having no direct contact with ground allowing the heat transfer with ground through a piping material. In a ground-coupled system, a closed loop of pipe is in horizontal depth of 1-2 m or vertical depth of 50-100m. The loop is placed in water and ground with antifreeze solution circulation in plastic pipes for collecting heat from ground in winter and for rejecting heat to ground in summer. Vertical and horizontal closed loop heat pump systems are illustrated in figure 2.2

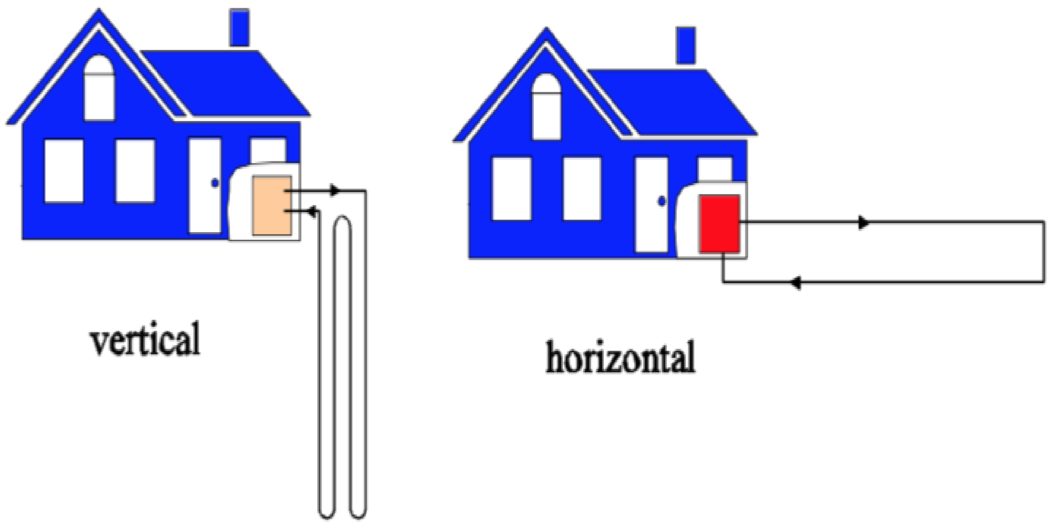


Figure 2.2 Closed loop heat pump system

[Source – Geo-Heat Center]

2.1.3.1.1 Horizontal loop GSHP systems

A horizontal ground loop is an economical system for residential homes having land for a system lay out where it is easy to dig trenches. Horizontal loops require trenches of 100 to 300 ft. along with 600 to 1200 ft. of pipe per ton. The trenches holding pipes are not usually more than a few meters below ground surface, but in areas of frost, they are located below the line of frost line. There is a high interaction between the environment and the soil, where shallow depths result in varying daily and annual ground temperatures, which affect the transfer of heat and performance of the system.

2.1.3.1.2 Vertical loop GSHP systems

A vertical closed loop system has a field loop of vertical pipes for heat exchange. A bored deep hole in the ground ranges between 45 and 75 meters for applications of residence and more depth of more than 150 m is for applications for large industries. Pipe pairs are fed into a hole that is connected by U-shaped connector at bottom. The gap in the pipes and the wall of borehole is filled to enhance heat transfer with a grout material. The diameter of borehole is about 100 mm for residential homes and the space between boreholes is about 5 to 6 m to disallow nearby boreholes from affecting each another and altering conditions of the ground. To have equal multiple borehole system flows, a manifold system located in the building is used. The advantage of vertical loop is that it requires less installation area, being advantageous where there is limited land. Other advantage of this system is that it has a low disturbance of landscape since drilling has a less impact when compared with trenching. The disadvantages include higher installation costs as drilling is more expensive than trenching horizontally. Moreover, vertical loop systems are proven to be economical for applications of large scale industries.

#### 2.1.3.2 Open loop systems

Open loop heat exchange systems interact with directly with the ground. They use surface water or local sources such as ponds and lakes for as medium for heat transfer directly. Through a heat pump heat exchanger, water is extracted and carried forward to discharge back to source or on irrigation ground. Open systems are preferred for huge installations. The largest operating GHP currently uses system of open loop and it supplies heating of 10 MW to a hotel and its immediate offices. Advantages of open loop setup include the fact that source water temperature remains nearly constant and associated losses with extra heat exchanger required for closed-loop are prevented by higher heat pump coefficient of performance (COP). Depending on method of extractions used, the open loop has high loads of pumping but its overall COPs are high thus reducing the cost of operation. Its disadvantage includes the protection of water quality, by following clean and surface water. The heat exchanger among heat exchange loop and heat pump unit is prone to corrosion, scaling and fouling, hence water is fairly neutral and should have a low amounts iron and other minerals. If water is not neutral, wells require additional maintenance, thus having user involvement and higher costs. Figure 2.3 illustrates the open loop GSHP systems.

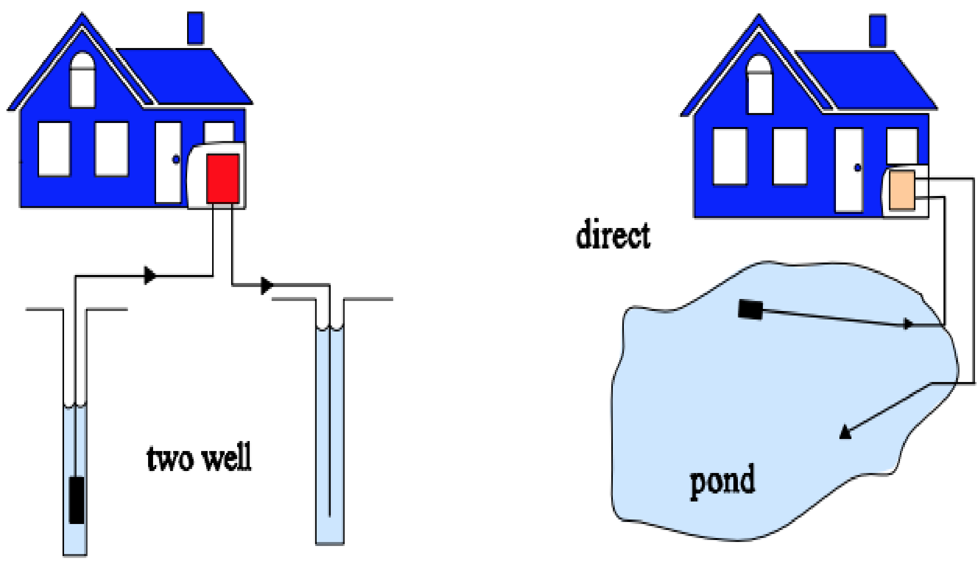


Figure 2.3 Open-loop heat pump system
[Source - Geo-Heat Center]

### 2.1.4 Air source heat pump systems

Air source heat pump systems are a renewable technology that are highly efficient than conventional boilers or heating systems for domestic space heating. Air source heat pumps take heat from outside air during winter heating season and do not allow heat outside during summer cooling season. Air source heat pumps can deliver almost three times more heat energy to a building than its electrical energy consumption. Air source heat pump has various cycles, viz. heating, cooling and defrost cycle. Due to low temperatures, the heating efficiency of air source heat pump systems is very low. Until recently, air source heat pumps have not been used in extended sub-freezing climatic conditions. However, air source heat pump technology has advanced so much in the recent years that it now offers a reliable space heating alternative in cold regions.

An ASHP extracts the heat from surroundings and passes through a heat exchanger where its temperature is elevated to a certain amount and it moves the heat from the air to a hot water supply. Figure 2.4 illustrates schematics of the air source heat pump

The major advantages of ASHPs include a low carbon footprint and they are electricity-powered, which can be generated by sustainable resources such as wind or solar. ASHPs can deliver heat at temperatures as low as -20$^{O}$C. They are very efficient in summer due to high seasonal energy efficiency rating. They have a long lifespan and with proper care, can be operational for over 20 years. ASHPs require no fuel storage.

The disadvantages of the ASHP is that it supplies lower temperature heat compared to oil and gas based boilers, so larger radiators are required. Noise pollution while operation can be an issue. They perform better with underfloor heating or warm air heating. ASHPs are less efficient in winter due to low COP levels.

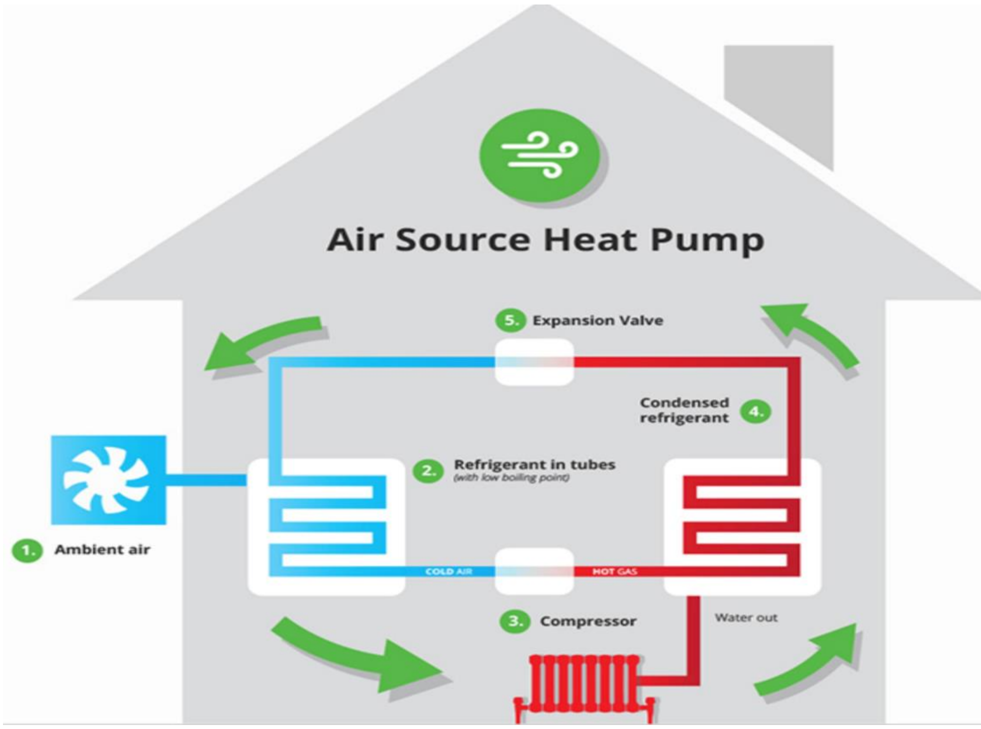


Figure 2.4 Schematic of the air source heat pump
[Source - https://www.ways2gogreenblog.com]

2.1.4.1 Air-air heat pump

In the air-air heat pumps, air's internal heat is extracted by the system and it is transferred inside or outside depending on the existing season. It is the most commonly used heat pump and it is similar to that of air conditioners, operating in reverse.

2.1.4.2 Air-water heat pump

Air-water heat pumps are mainly used for application of hydronic heat distribution systems at homes. During winters, heat pump intakes heat from outside surrounding air and transfers to water in the system of hydronic distribution. During summers, when the weather is very hot and humid, the method is entirely reversed. Heat pump extracts the water's heat stored in distribution system at homes and pumps it outside to provide cooling to the homes, thereby making the indoor environment comfortable for the occupants. The usability of the air-water type of system is very scarce because of its nature of ineffective cooling during the hot and humid days and unable to provide cooling during the winters.

## 2.2 Solar photovoltaic systems

Solar PVs generate electricity from solar irradiation. These systems do not require fuel and releases no pollutants during its operation. PV systems are installed either on wall or roof of the buildings or stand-alone. They require almost no maintenance. Although they are expensive when compared with conventional systems in the installation stages, they are economical in the long run and is a pollution-free way of generating electricity. Due to the technology advancements and economies of scale, the PV market has rapidly grown all over the world. This system is often equipped with batteries for supplying a balanced electricity based on the demand. But grid-connected system gets additional electricity from utility grid, and excessively produce electricity is delivered to grid hence eliminating the need for batteries and it is economical when compared to off-grid system. The system with grid-connection is highly preferred for electricity supply of commercial, residential and industrial purpose. Off-grid systems initially dominated PV market but during the 1990s, systems with grid-connection rapidly grew and crossed the usage of off-grid systems in 1998. PV systems are designed according to needs of user and the characteristics of geography. Several factors in the design process, such as the demand for power, area availability for installing photovoltaic arrays, available solar radiation, etc. are considered. Figure 2.5 shows the idea of the solar photovoltaic rooftop multi-residential building. The production of electricity from the PV system is determined by many factors.

Figure 2.5  Solar photovoltaic rooftop multi-residential building

[Source - https://solarbuildermag.com]

## 2.3 Assessments of previous studies related to research

There are various building appliances such as HVAC systems (including heat pump), lighting, computers, TVs, sanitary hot water and communication equipment. The loads of HVAC system is the largest fraction of total building power consumption, accounting for more than 65%. Currently, many of the PV system designs are on basis of total power load of the building.

Various parts of the U.S. experiences extreme temperatures, from high heat in summer to freezing cold in winter. However, ground temperature remains reasonably constant a few feet below the surface of the earth. In summer, ground below the surface is cooler than air temperature. Whereas in winter, the ground below the surface is warmer than air temperature. This makes the geothermal heat pumps viable and a permanent wintertime heat source and a summertime heat sink due to margin of variation. For such reasons, geothermal heat pumps are among the most efficient heating and cooling method available in market.

Zhang Xingke (2012) did a study on photovoltaic power generation. His study explained that a solar PV combined with GSHP system is an ideal integration of photovoltaic conversion along with heat pump systems. It raises the efficiency of photoelectric conversion, solar-thermal adsorption and provides an integrated usage of solar heat and energy. In addition to raising the solar energy utilization efficiency in the solar irradiation area, this design can also improve the applicability of heat pump systems in the cold regions. Directly converting light energy of solar energy to electricity through photoelectric effect can raise the efficiency of available energy in solar energy. Adding energy storage and inverters options will enable the system to operate off-grid, enhancing the system′s applicability and flexibility.

According to Xingke (2012), "Compared with a conventional air source heat pump, a solar assisted GSHP has higher thermal properties and is multifunctional. Applying a solar heat pump improves heat insulation effect of building, helping the buildings reduce cold and heat loads while greatly reducing environmental pollution".

Singh and Prakash (2017) evaluated the energy simulation of rooftop solar PV system for lecture hall in Allahabad, India. In this city, the deficit of electricity is around 15%, so power failures are common. For this building, a rooftop solar PV system was proposed. The building loads were calculated by using eQUEST 3.65 and the loads were used for a proposed case using RETScreen to perform a technical, environmental and economic analysis and assess feasibility. The modeling and simulation results from the study confirmed field data. The grid electricity in India is produced generally by thermal power using coal and the $CO_2$ emission is 1.195 ton per MWh electricity production by coal. For this particular case study, the annual GHG emission was 9.7 ton of $CO_2$ and it was totally reduced by the PV system. This study demonstrated a PV system that was feasible and financial viable with $7715 total annual savings.

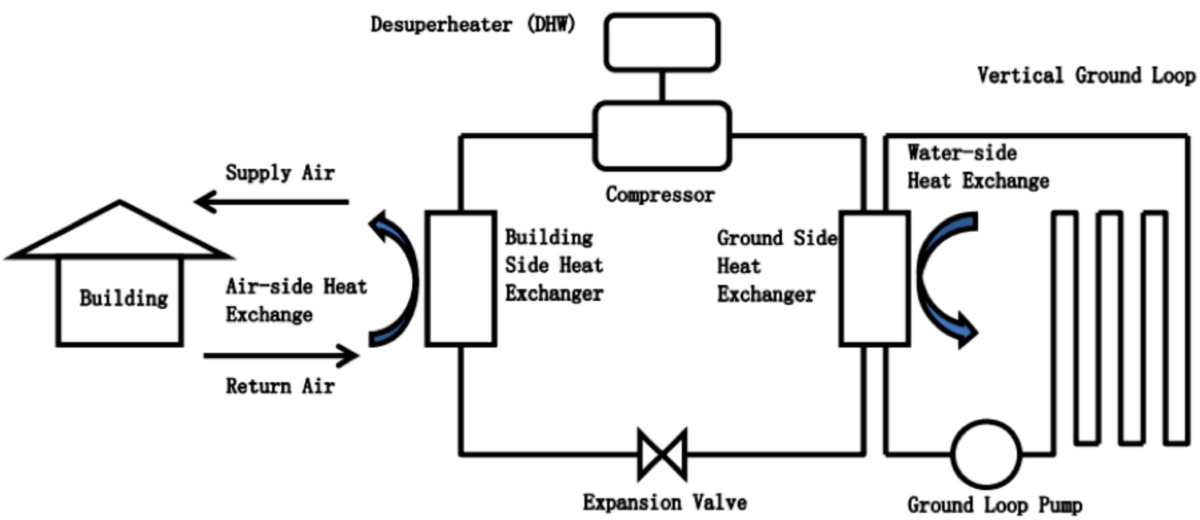


Figure 2.6 Outline for the vertical closed loop GSHP
[Source - Shan, 2015]

Le Du et. al. (2015) provided an energy and economic analysis of domestic GSHP systems in four cities in Canada by using RETScreen. The objective was to determine the internal return rate, net present value and annual savings for a system that was operating under varying climatic conditions and in various states to find if the implementation of a GSHP system was feasible. A GSHP vertical closed loop system was chosen for all four locations as it is well adapted for dense urban areas and requires less space. In this project, pump VLV/Waterfurnace GSHP system and seasonal performance factor (SPF) as 300% was considered. This was because the SPF for heating and cooling was consistent with research studies for the coldest climates. Climatic parameters vary depending on the geographical location. This study states that cost of heating and cooling known in RETScreen depends on key environmental parameters in a given city.

Euy Joon Lee (2005) took an example of a live GSHP project that illustrated how RETScreen could be used at the feasibility study stage to model and predict the technical and financial performance of the projects.

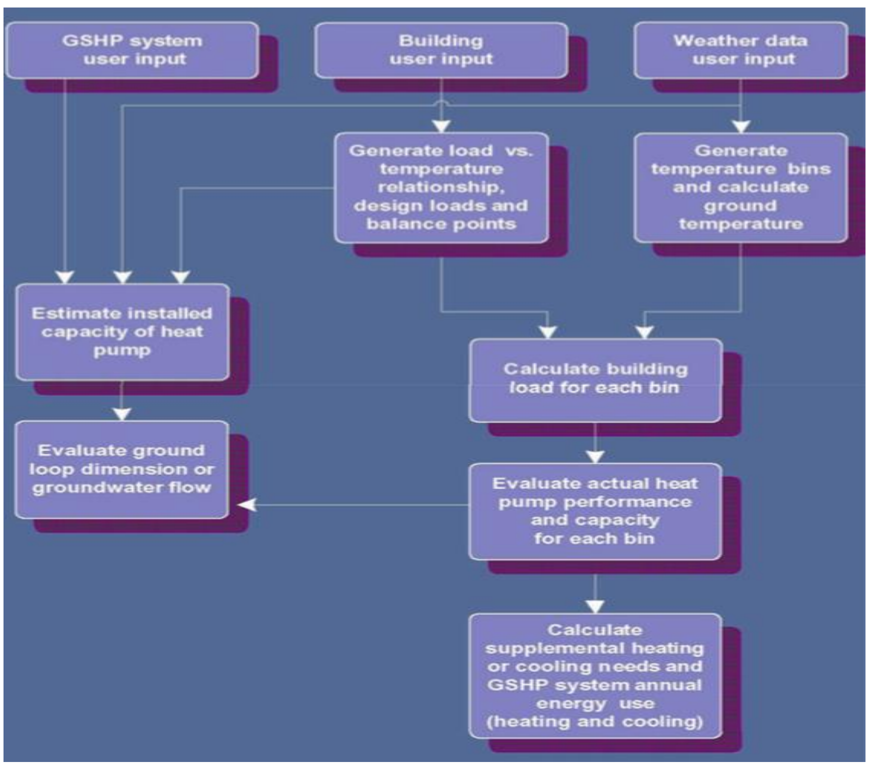


Figure 2.7 RETScreen GSHP model flowchart

[Source - Euy Joon Lee, 2010]

Figure 2.7 shows the RETScreen GSHP flowchart. RETScreen calculated loads of heating and cooling of 62.8 kW and 47.8 kW for building design respectively. Based on this calculation, a GSHP system of 24-ton capacity was suggested. Under the modeled conditions, the simple payback period of this system is about 19 years with IRR of 8.0%. Though the simple payback period is higher due to the higher cost of GSHP in Korea, with a 70% government subsidy on the initial cost, the simple payback period reduces to only 1.4 years making the GSHP a very viable space heating and cooling option in Korea. Whereas in Manitoba, Canada, the simple payback period of the same facility is 11.3 years with IRR of 12.7% which GSHP is a very option to considered. This article proves that RETScreen GSHP model can very effectively evaluate the technical and financial feasibility of GSHP application with levels of accuracy acceptable in the initial stages of the projects.

Knox (2013) researched with an objective to expose users to a simple energy modeling process and to explore the results. In this exercise, users explored the basics of the energy modeling, which included a detailed look at inputs required and outputs generated. The tutorial talks about the process of creating a simplified building located on a university campus in the location of choice using eQUEST 3.65 software. This research takes through series of all the slides and their explanations about the slides and wizards. Most of the tutorial is based on the default settings as to when a user opens a schematic design wizard. This tutorial describes the basic design of eQUEST that helps users easily predict the load of the buildings at chosen locations. A similar procedure is being followed for this thesis work for calculating the energy prediction.

Blair et. al. (2014) conducted studies comparing SAM results to real data based on performance. The case studies show SAM modeling techniques, which include modeling system components that are not found in present SAM libraries. The four released PV case study systems were available for over a year of data. The four sites included: a 205 kW rooftop PV array installed at the James Forrestal Building in Washington, D.C, a 94.5 kW NREL Science and Technology Facility in Golden, CO, a 449 kW NREL Research Support Facility building in Golden, CO and 5.3 kW PV array on a residential building in Oklahoma City. The study compared between measured data and data that was acquired due to the SAM case study modeling. These case studies reveal that it is difficult to get high quality measurement of meteorological data and PV system radiation.

## 2.4 Simulation software for modeling photovoltaic and heat pump system

### 2.4.1 Renewable Energy Technologies Screen (RETScreen Expert)

RETScreen is a clean energy management software developed for clean energy decision making by the Canadian government. It currently has more than 525,000 users in 222 countries. The current and upgraded version released in September 2016, comprises RETScreen 4 and RETScreen Plus. It allows energy efficiency and renewable energy projects to perform with comprehensive identification, assessment, and optimization in terms of technical and financial viability. It also identifies the energy savings/production opportunities along with the measurement and verification of the facilities' actual performance. Electricity generation options include wind, solar, gas generators and turbines, fuel cells, diesel generators, tidal power, geothermal, hydro turbine, wave power and ocean current power. Energy storage options include batteries and this software has the ability to model various types of PV silicon modules of cSi, CdTe CIS, and aSi. For the insolation data, RETScreen uses TMY and NASA-SSE. Financial output includes project cost and savings, financial feasibility and life-cycle cash flows. Figure 2.8 shows the RETScreen Expert home page where all templates, case studies are available for understanding the software

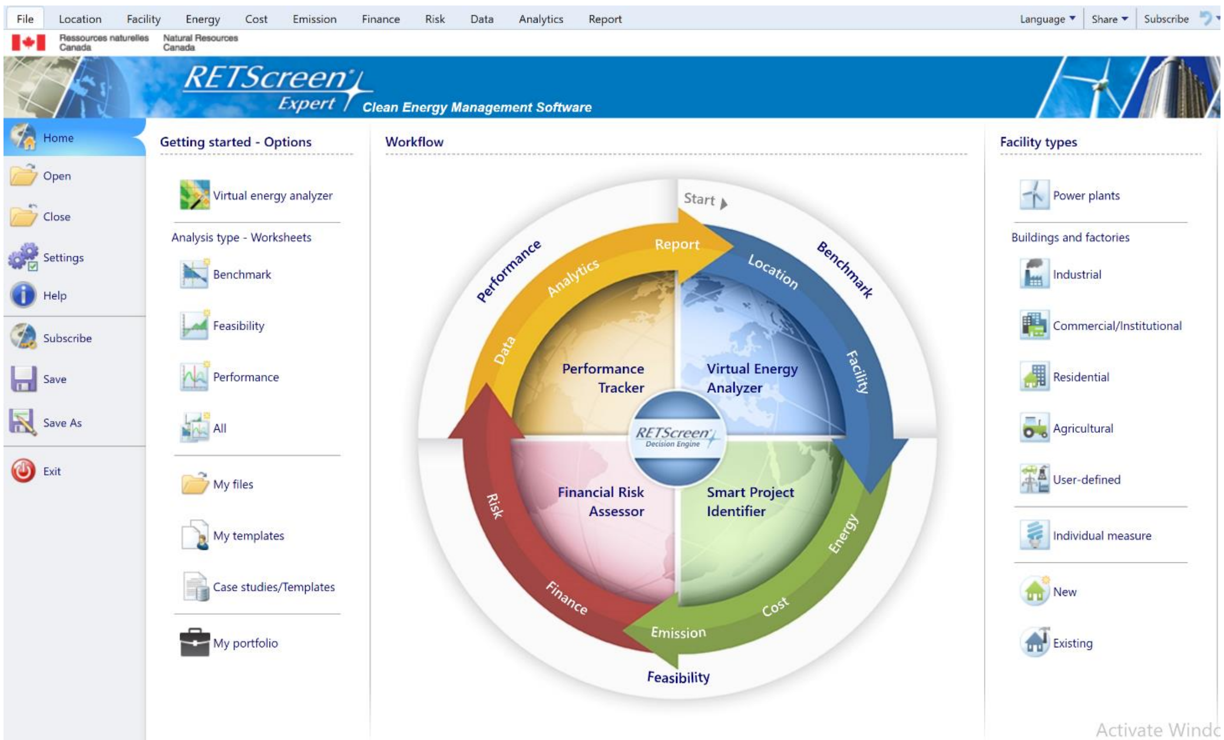


Figure 2.8 RETScreen Expert home page
[Source - http://www.nrcan.gc.ca]

## 2.4.2 National Renewable Energy Laboratory System Advisory Model (NREL-SAM)

SAM is a free software created in 2006 by National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL) by the program of DOE Solar Energy Technology with partnership. It combines the detailed performance and financial models to estimate the cost of energy for a variety of systems. It is designed for people who are involved in the decision making in the industry of renewable energy. SAM has performance models representing parts of the system, and financial models representing a project financial structure. It has a user interface that makes it easy for people with little experience to develop renewable energy projects and make financial and performance projections based on the model result. The software includes data libraries that describes the characteristics of inverters and PV modules, wind turbines and biopower combustion system components.


Figure 2.9  SAM summary output and results window

[Source - https://sam.nrel.gov]

Depending on the modeled system, the data is either selected from the list or downloaded. SAM can also work with solar technologies such as Stirling dish, parabolic trough, and power tower systems. SAM uses Transient Systems Simulation, which is developed by the Wisconsin Solar Energy Laboratory as an engine for array performance model's implementation. Financial analysis includes looking at energy costs, system depreciation, financial options, tax credits, cash flows, and LCOE.

# CHAPTER 3. RETSCREEN EXPERT AND SYSTEM ADVISORY MODEL SOFTWARE COMPARISON

## 3.1 Solar irradiance on tilted and horizontal surfaces between SAM and RETScreen Expert

Solar radiation is classified as direct, reflected or diffused. The direct or normal radiation beam is the radiation on a straight line down to the surface of the earth from sun. Diffuse radiation is sunlight scattered by particles in atmosphere but has still made it down to surface of the earth. Average daily calculation of radiation is by using beam and diffuse radiation. The output of the photovoltaic model solely relies on daily solar radiation average on array surface depending on the orientation of the panel and the tilt. When compared with RETScreen Expert software, SAM version 2017.9.5 photovoltaic model is very well detailed. RETScreen Expert uses Liu and Jordan's isotropic diffuse algorithm to compute monthly radiation average on tilted surface. RETScreen acquires only solar radiation data from a monthly basis and uses the isotropic diffuse model to calculate the irradiance on tilted as well as horizontal surfaces. SAM, on the other hand, has a detailed photovoltaic model that computes solar irradiance by allowing the users to pick from three various sky diffuse models of irradiance on tilted surfaces using option of location and resource input page in SAM software. It compiles the data of irradiance using albedo sky diffuse model. The software observes and generates the data of Global Horizontal Irradiance (GHI), where irradiance is on a horizontal surface and plane-of-array (POA) i.e. on tilted surface on hourly basis.

Moreover, SAM allows its users in weather file irradiance data to pick between diffuse horizontal irradiance (DHI) and direct normal irradiance (DNI). But RETScreen Expert accepts the fewest system specifications because the inputs generated by it are from the monthly average radiation, which extracts total and beams irradiation inputs as an unchangeable default setting.

### 3.2 Conversion of SAM from hourly into average daily solar radiation

Irradiance is the power incident on a surface. The total solar radiation falling on horizontal surface is known as global horizontal irradiance (GHI). The sum total of incident diffuse horizontal irradiation and the direct normal irradiance that is projected on the horizontal surface is known as global horizontal. In RETScreen, the on the horizontal surface solar irradiance for all hours of an average day, and hourly data is converted into monthly data by using the formula known from Erbs, Collares- Pereira and Rabl and Liu and Jordan. Therefore, RETScreen Expert generates the solar radiation output values in a monthly manner. However, System SAM has performance models that run solar radiation hourly data for an entire year. A weather file in SAM contains only hourly data and that results in 8760 hourly output values. The solar radiation hourly data on horizontal surface and tilted surface is converted into daily solar radiation average for horizontal and tilted surfaces. The hourly data of GHI and POA is transferred to the spreadsheet and it forms the data tables from SAM. In the spreadsheet, the hourly data is converted into monthly data using the subtotal option, which adds all the hours data of a particular month. After summing up the hours of every month, the data is in Watts/meter$^2$ (W/m$^2$). In order to convert data from W/m$^2$ to kWh/m$^2$/d, the value has to be divided by number of days in that particular month and multiplied by a thousand times. To calculate average annual solar radiation per day, sum of daily solar radiation for the all the months is divided by 12.

### 3.3 The technical difference between RETScreen Expert and SAM

RETScreen Expert and SAM version 2017.9.5 calculate solar irradiance on horizontal and tilted surface using very different approaches. The solar radiation values are mostly reported for horizontal surfaces, but converting values of average monthly horizontal radiation to its plane of array irradiance is the first job to be done by software. SAM calculates diffuse irradiance incident and hourly beam on the PV subarray for sun position, particular angle, surface orientation and latitude by using a simple incident angle algorithm SAM uses three types of Albedo sky diffuse irradiance methods for calculating solar irradiance on the tilted surfaces. There are three types of albedo sky diffuse models for calculating the tilted surface irradiance, they are isotropic sky diffuse model, the HDKR (Hay Davis Klucher Reindl) sky diffuse model, and the Perez 1990 sky diffuse model. The Perez model uses more complex computational approach compared to HDKR and isotropic model. The tilted surface model on SAM location and resource page allows the user to choose between various sky diffuse irradiance models. RETScreen uses one model—the Liu and Jordon isotropic diffuse algorithm to compute the irradiance on an inclined surface. Direct normal irradiance and diffuse irradiance on the horizontal irradiance are used as inputs for the conversion. The RETScreen technical method is derived detailed in the RETScreen manual published by the Ministry of Natural Resources, Canada. Most of the technical model used in the RETScreen manual and SAM technical report are derived from the book Duffie and Beckman (1991) for calculating solar irradiance.

### 3.4 Solar Irradiance software simulation for RETScreen Expert and SAM version 2017.9.5

The yield energy of the PV module depends on various factors. One of the main important factors is radiation of the sun that is incident on surface of photovoltaic modules that varies based on weather data and climatic conditions. By utilizing both horizontal surfaces and tilted surfaces solar radiation, both software compute energy output of system using weather files. The energy of the photovoltaic system is modifiable by changing tracking, azimuth angle, inclination angle and building orientation etc. RETScreen Expert is comparatively simple; the photovoltaic modeling tool grants the users to determine the technical and financial viability of the renewable projects.

RETScreen simulates the monthly production of energy and takes only weather inputs monthly. On the other hand, SAM produces energy production on the monthly and hourly basis that generates results in data tables in its software. However, SAM only produces horizontal surface solar radiation hourly data in a term known as solar radiation and global horizontal irradiance on the inclined surface that is named as subarray 1 POA with total irradiance nominal ($W/m^2$). Both software are used worldwide by many users. Comparison of the energy yield and solar radiation is made between the recent versions of software viz. SAM version 2017.9.5 and RETScreen Expert using computer simulations in the following sections. The solar radiation and photovoltaic energy output are predicted by RETScreen and SAM using same inputs at three different locations.

### 3.4.1 Location - Fort Wayne, Indiana, USA

The first simulation study for finding the solar radiation was conducted at Fort Wayne, Indiana. RETScreen and SAM software tracked the location either with the name of the city and state or by the inputs of the latitude and longitude as inputs. In RETScreen, “Select climate data location” is selected for entering the inputs of the location. After entering the inputs, the software generates entire climate data for parameters viz. air temperature, precipitation, relative humidity, atmospheric pressure, earth temperature, wind speed, heating, cooling degree-days etc. SAM generates the weather data either by selecting files from the library if the file exists for the location or by downloading the weather file for the location. Once the location is selected, SAM computes weather data for global horizontal, direct normal, diffuse horizontal, average wind speed, average temperature and maximum snow depth. In RETScreen Expert, solar irradiance on horizontal is called as daily solar radiation on horizontal surface ($kWh/m^2/d$). Whereas in SAM, GHI is horizontal surface solar irradiance. As mentioned earlier, SAM produces hourly data of GHI in

$W/m^2$ units from the weather file. Using the procedure mentioned in section 3.2, hourly data in $W/m^2$ units are converted to monthly data in $kWh/m^2/d$. The output results are monthly because the RETScreen can only show the monthly output in either $kWh/m^2/d$ or $MJ/m^2/d$. SAM calculates the solar irradiance output on an hourly basis in $W/m^2$ units for 8670 hours. So, the hourly GHI in $W/m^2$ is converted to $kWh/m^2/d$ for comparison between SAM and RETScreen Expert software.

Table 3.1 Fort Wayne climatic parameters

| **City** | **Fort Wayne, IN, USA** |
|---|---|
| Latitude (degrees) | $41.1^{o}$ N |
| Longitude (degrees) | $-85.2^{o}$ E |
| Elevation (m) | 240 |
| Typical year (file) | TMY3 |
| Tilt Angle (degrees) | $45^{o}$ |
| Azimuth (degrees) | RETScreen: $0^{o}$ (south direction) |
| | SAM: $180^{o}$ (south direction) |

The parameters used for calculating the irradiance on inclined and horizontal surfaces are illustrated in table 3.1. After entering the above inputs, the horizontal surface solar radiation is calculated using RETScreen Expert. Annual daily horizontal surface solar radiation at an elevation of 233 m in RETScreen Expert is 3.86 $kWh/m^2/d$ and in SAM Version 2017.9.5 is 4.03 $kWh/m^2/d$. Figure 3.1 shows average monthly horizontal surface solar irradiance between SAM and RETScreen Expert software.

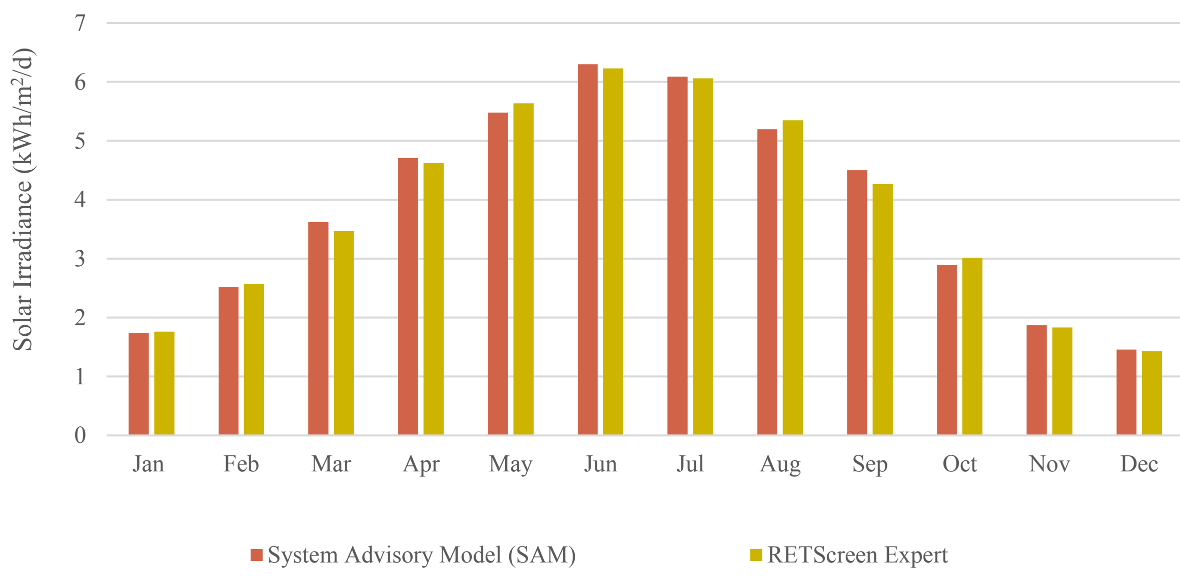


Figure 3.1 Irradiance on horizontal surface at Fort Wayne, IN (kWh/m$^2$/d)

For comparing the solar irradiance for the tilted surface, the POA angle and the azimuth are important parameters that are considered. RETScreen Expert output has the direct values of monthly solar irradiance for tilted surface in kWh/m$^2$/d. In SAM, the solar irradiance for the tilted surface is subarray 1 POA total irradiance nominal in W/m$^2$ units, which displays the hourly data. For comparison, SAM hourly data in W/m$^2$ units are converted to monthly in kWh/m$^2$/d units using the procedure mentioned in section 3.2. For RETScreen, the isotropic sky diffuse model is used to measure solar irradiance on the tilted surface. However, SAM has three different options viz. HDKR, Isotropic, and Perez models as an option for the users to choose. As RETScreen calculates radiation on the tilted surface by only using isotropic model, the same method is also chosen for SAM.

The average monthly output of horizontal surface and tilted surface solar irradiance is found using both software and the percentage difference is calculated by using equation 3.1

$$\% \, difference = \frac{(SAM - RETScreen)}{(SAM + RETScreen)/2} \qquad \text{Equation 3.1}$$

The solar irradiance on horizontal surface at Fort Wayne, IN from both softwares and the percentage difference between two software is illustrated in the table 3.2.

Table 3.2 Percentage (%) difference for Irradiance on Horizontal surface at Fort Wayne, IN

| **Month** | **SAM** | **RETScreen Expert** | **% difference** |
|---|---|---|---|
| Jan | 1.74 | 1.76 | -0.01 |
| Feb | 2.52 | 2.57 | -0.02 |
| Mar | 3.62 | 3.47 | 0.04 |
| Apr | 4.71 | 4.62 | 0.02 |
| May | 5.48 | 5.64 | -0.03 |
| Jun | 6.30 | 6.23 | 0.01 |
| Jul | 6.09 | 6.06 | 0.00 |
| Aug | 5.20 | 5.35 | -0.03 |
| Sep | 4.50 | 4.27 | 0.05 |
| Oct | 2.89 | 3.01 | -0.04 |
| Nov | 1.87 | 1.83 | 0.02 |
| Dec | 1.46 | 1.43 | 0.02 |
| Annual | 3.87 | 3.85 | 0.00 |

Figure 3.2 shows the monthly tilted surface solar irradiance in Fort Wayne, IN. The maximum irradiance is observed in June, where SAM produced solar irradiance of 5.41 kWh/m$^2$/d and RETScreen Expert produced 5.31 kWh/m$^2$/d. Table 3.3 shows the percentage difference between the two software outputs.

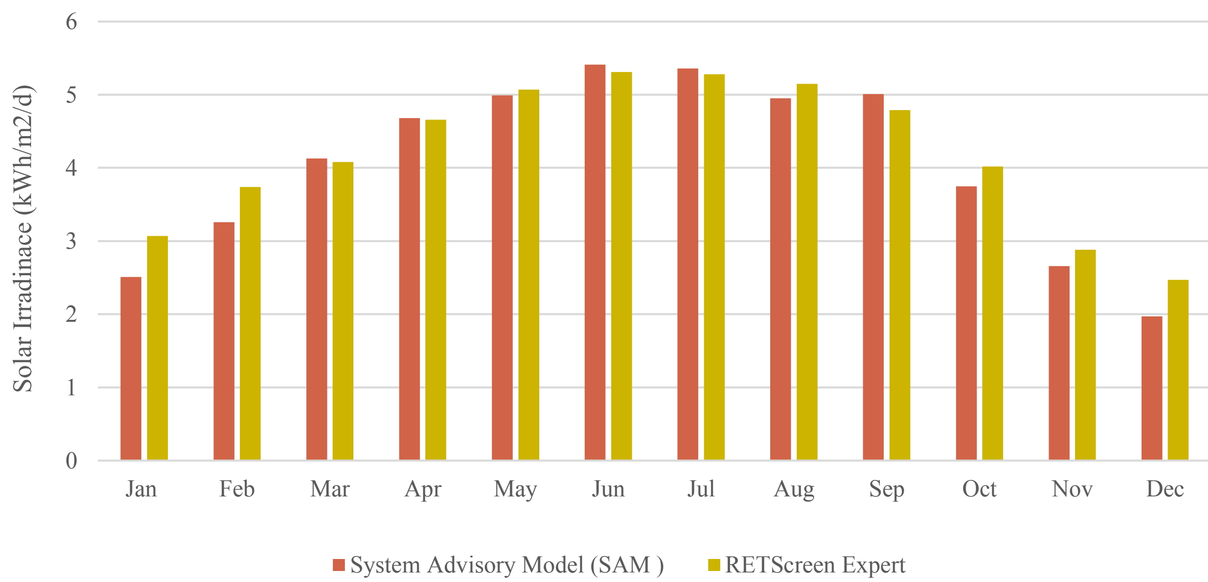


Figure 3.2 Irradiance on tilted surface at Fort Wayne, IN (kWh/m$^2$/d)

Table 3.3 Percentage (%) difference for irradiance on tilted surface at Fort Wayne, IN

| Month | SAM | RETScreen Expert | % difference |
|---|---|---|---|
| Jan | 2.51 | 3.07 | -0.22 |
| Feb | 3.26 | 3.74 | -0.15 |
| Mar | 4.13 | 4.08 | 0.01 |
| Apr | 4.68 | 4.66 | 0.00 |
| May | 4.99 | 5.07 | -0.02 |
| Jun | 5.41 | 5.31 | 0.02 |
| Jul | 5.36 | 5.28 | 0.01 |
| Aug | 4.95 | 5.15 | -0.04 |
| Sep | 5.01 | 4.79 | 0.04 |
| Oct | 3.75 | 4.02 | -0.07 |
| Nov | 2.66 | 2.88 | -0.08 |
| Dec | 1.97 | 2.47 | -0.25 |
| Annual | 4.06 | 4.21 | -0.04 |

#### 3.4.1.1 Optimum tilt angle simulation between RETScreen and SAM at Fort Wayne, IN

To achieve maximum energy use from solar panels, the panels should be pointed in the direction of sun. The solar panels in the northern hemisphere should have aligned with due south. Most of the residential homeowners mount their panels in a fixed position, where the panels can be tilted manually according to the season. To find a suitable angle to produce the maximum energy usage, a study is conducted in RETScreen and SAM by comparing the energy production for tilt angles varying from $0^{o}$ to $90^{o}$. A Sanyo module HIPBA20 and Fronius 5100 Inverter is chosen. At $40^{o}$ tilt angle and facing south direction, SAM and RETScreen are producing near maximum energy output with very agreeable results. So, 40$^{o}$ angle is chosen to model a photovoltaic system in Fort Wayne for additional simulation. Figure 3.3 shows the annual energy production between SAM and RETScreen with multiple angles at Fort Wayne, IN

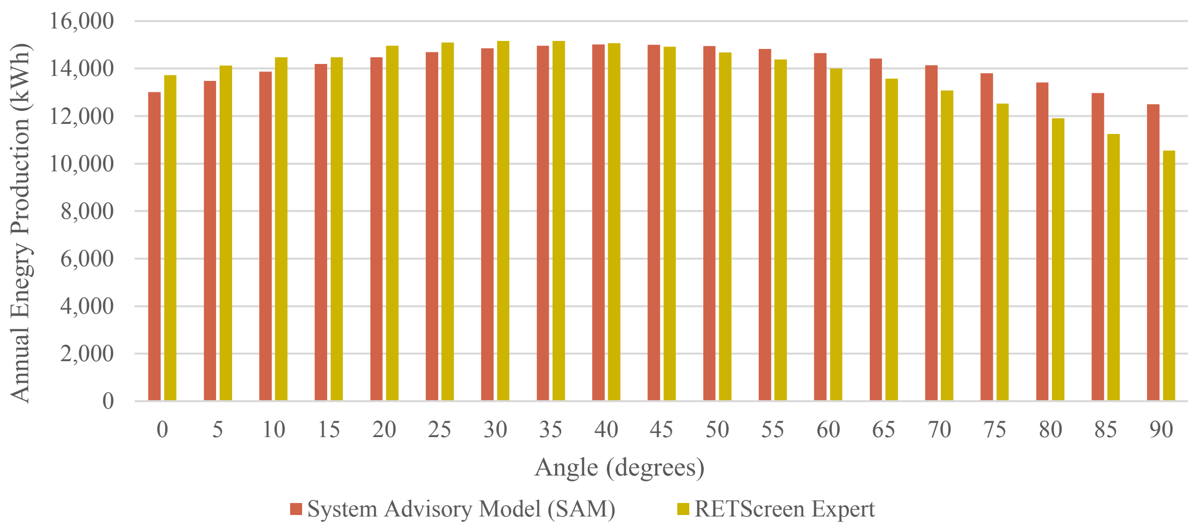


Figure 3.3 Annual energy production using different angles at Fort Wayne, IN

3.4.2 Location - Los Angeles, California, USA

The second location for comparison between both the software is Los Angeles airport, California, USA. The same procedures were followed for calculating the solar irradiance for the horizontal and tilted surfaces. Firstly, the procedure was to change the location setting i.e. latitude, longitude, and elevation mentioned in table 3.5 in both the software. The same unit conversions were considered for the procedures as was used in the first location. The input parameters used for the second simulation is mentioned in table 3.4.

Table 3.4 Climatic parameters of Los Angeles

| **City** | **Los Angeles, CA, USA** |
|---|---|
| Latitude (degrees) | $33.933^{o}$ N |
| Longitude (degrees) | $-118.4^{o}$ E |
| Elevation (m) | 233 |
| Typical year (file) | TMY3 |
| Tilt Angle (degrees) | $45^{o}$ |
| Azimuth (degrees) | RETScreen: $0^{o}$ (south direction) |
| | SAM: $180^{o}$ (south direction) |

After updating the inputs, the isotropic diffuse model is considered in both the RETScreen Expert and SAM software. The annual daily solar radiation horizontal at an elevation of 30 m in RETScreen was 4.95 kWh/$m^2$/d and in SAM was 5.0 kWh/$m^2$/d. Figure 3.4 shows the solar irradiance on horizontal surface at Los Angeles, CA and table 3.5 illustrates the percentage difference between SAM and RETScreen Expert for horizontal surface solar irradiance.

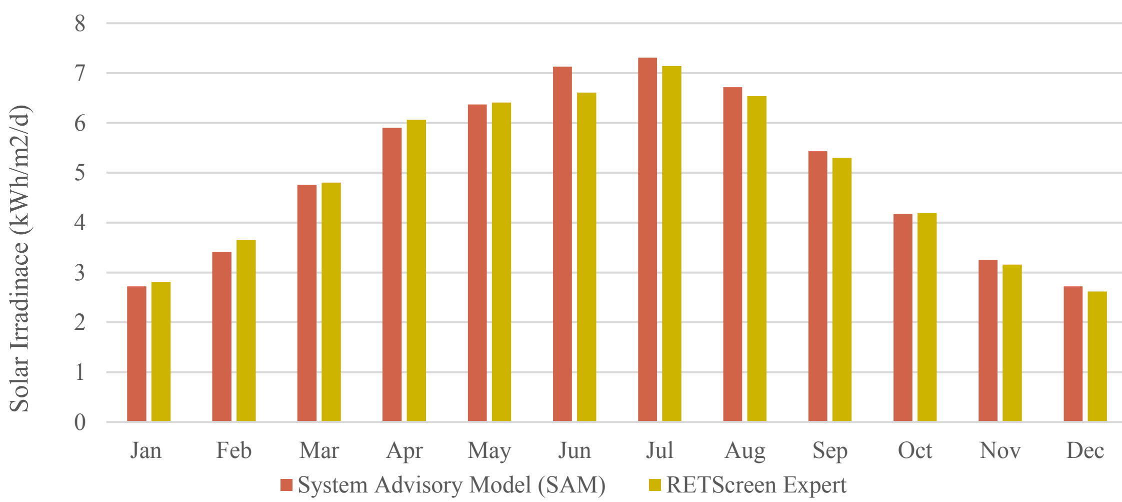


Figure 3.4  Irradiance on horizontal surface Los Angeles, CA (kWh/m$^2$/d)

Table 3.5 Percentage (%) difference for irradiance on horizontal surface at Los Angeles, CA

| Month | SAM | RETScreen | % difference |
|---|---|---|---|
| Jan | 2.72 | 2.81 | -0.03 |
| Feb | 3.41 | 3.65 | -0.07 |
| Mar | 4.76 | 4.8 | -0.01 |
| Apr | 5.9 | 6.06 | -0.03 |
| May | 6.37 | 6.41 | -0.01 |
| Jun | 7.13 | 6.61 | 0.07 |
| Jul | 7.31 | 7.14 | 0.02 |
| Aug | 6.72 | 6.54 | 0.03 |
| Sep | 5.43 | 5.3 | 0.02 |
| Oct | 4.17 | 4.19 | 0.00 |
| Nov | 3.25 | 3.16 | 0.03 |
| Dec | 2.72 | 2.62 | 0.04 |
| Annual | 5 | 4.95 | 0.01 |

Figure 3.5 shows the solar irradiance on tilted surface at Los Angeles, CA. Table 3.6 shows the percentage difference between two software outputs for solar irradiance. August shows maximum solar irradiance on tilted surface between RETScreen and SAM.

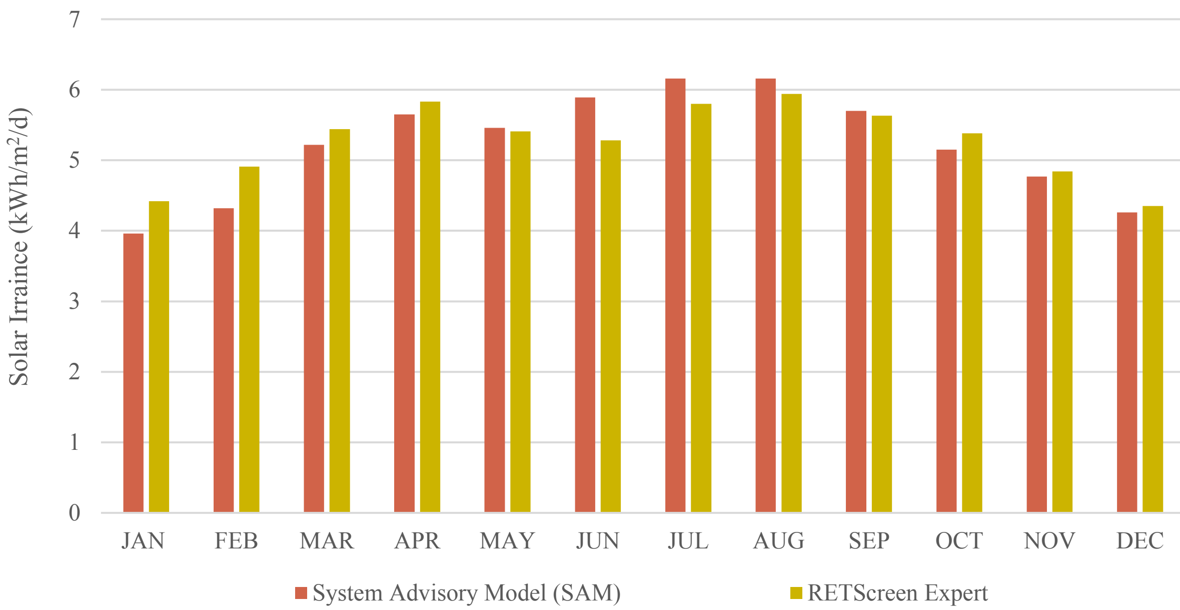


Figure 3.5 Irradiance on tilted surface at Los Angeles, CA (kWh/m$^2$/d)

Table 3.6  Percentage (%) difference for irradiance on tilted surface at Los Angeles, CA

| Month | SAM | RETScreen | % difference |
|---|---|---|---|
| Jan | 3.96 | 4.42 | -0.12 |
| Feb | 4.32 | 4.91 | -0.14 |
| Mar | 5.22 | 5.44 | -0.04 |
| Apr | 5.65 | 5.83 | -0.03 |
| May | 5.46 | 5.41 | 0.01 |
| Jun | 5.89 | 5.28 | 0.10 |
| Jul | 6.16 | 5.80 | 0.06 |
| Aug | 6.16 | 5.94 | 0.04 |
| Sep | 5.7 | 5.63 | 0.01 |
| Oct | 5.15 | 5.38 | -0.04 |
| Nov | 4.77 | 4.84 | -0.01 |
| Dec | 4.26 | 4.35 | -0.02 |
| Annual | 5.23 | 5.27 | -0.01 |

### 3.4.3 Location- Atlanta, Georgia, USA

The third location used for the simulation is the Atlanta airport, Georgia, USA. This location is taken for the energy performance prediction study in section 3.6. The location used in the study was also used by Suniva for predicting the financial analysis and performance of the 1 MW photovoltaic project. Unlike the two locations mentioned above, the solar irradiance on tilted surface data below the surface is taken 30° instead of 45°. Table 3.7 shows the parameters for the simulation at Atlanta, GA at an elevation of 308 m.

Table 3.7 Atlanta climatic parameters

| **City** | **Atlanta, GA, USA** |
|---|---|
| Latitude (degrees) | $33.633^{o}$ N |
| Longitude (degrees) | $-84.633^{o}$ E |
| Elevation (m) | 308 |
| Typical year (file) | TMY3 |
| Tilt Angle (degrees) | $30^{o}$ |
| Azimuth (degrees) | RETScreen: $0^{o}$ (south direction) |
| | SAM: $180^{o}$ (south direction) |

Solar irradiance on horizontal surface at Atlanta is maximum in June when simulated in SAM software. However, RETScreen has maximum horizontal solar irradiance in July that is illustrated in figure 3.6. The percentage difference between the two software is in table 3.8.

The irradiance on tilted surface at Atlanta, GA is in figure 3.7. The percentage difference between two software outputs for tilted surface solar irradiance is in table 3.9. SAM software simulated maximum irradiance on tilted surface on June, whereas RETScreen simulated the maximum irradiance in July. The irradiance difference between the two software is explained in the following section.

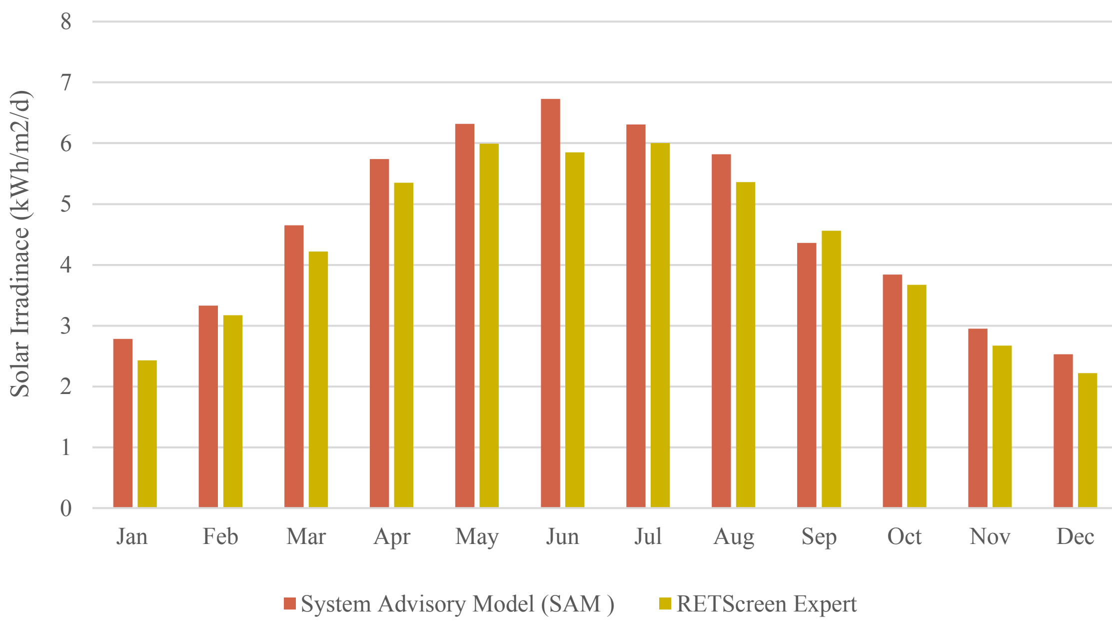


Figure 3.6 Irradiance on horizontal surface at Atlanta, GA ($kWh/m^2/d$)

Table 3.8 Percentage (%) difference for irradiance on horizontal surface at Atlanta, GA

| Month | SAM | RETScreen | %difference |
|---|---|---|---|
| Jan | 2.78 | 2.43 | 0.13 |
| Feb | 3.33 | 3.17 | 0.05 |
| Mar | 4.65 | 4.22 | 0.09 |
| Apr | 5.74 | 5.35 | 0.07 |
| May | 6.32 | 5.99 | 0.05 |
| Jun | 6.73 | 5.85 | 0.13 |
| Jul | 6.31 | 6.00 | 0.05 |
| Aug | 5.82 | 5.36 | 0.08 |
| Sep | 4.36 | 4.56 | -0.05 |
| Oct | 3.84 | 3.67 | 0.04 |
| Nov | 2.95 | 2.67 | 0.09 |
| Dec | 2.53 | 2.22 | 0.12 |
| Annual | 4.61 | 4.30 | 0.07 |

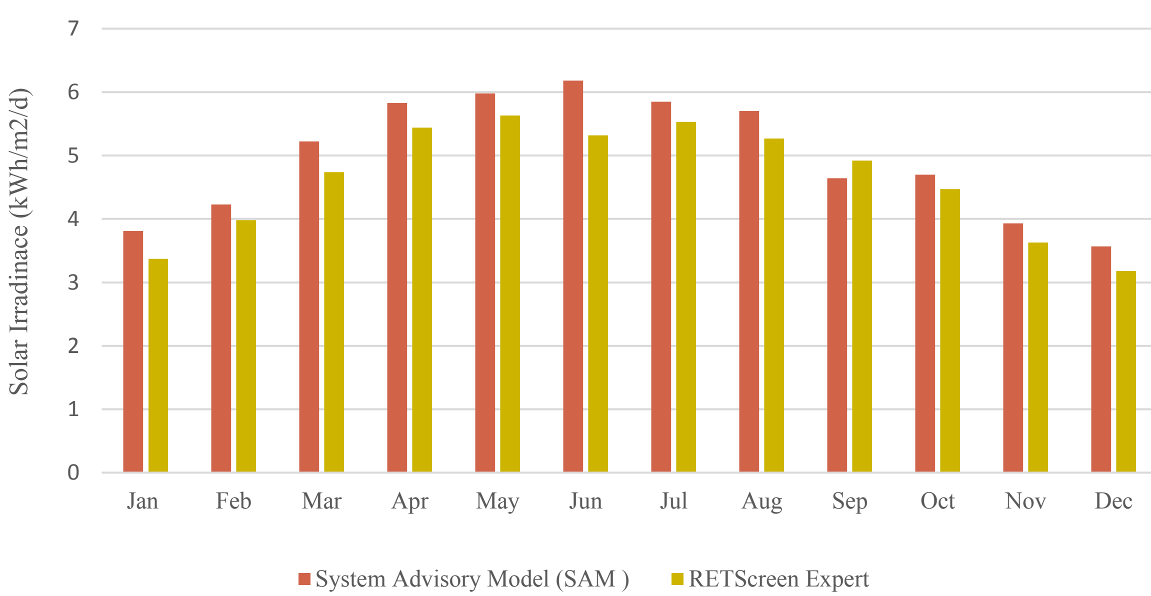


Figure 3.7 Irradiance on tilted surface at Atlanta, GA (kWh/m$^2$/d)

Table 3.9  Percentage (%) difference for irradiance on tilted surface at Atlanta, GA

| Month | SAM | RETScreen | %difference |
|---|---|---|---|
| Jan | 3.81 | 3.37 | 0.12 |
| Feb | 4.23 | 3.98 | 0.06 |
| Mar | 5.22 | 4.74 | 0.09 |
| Apr | 5.83 | 5.44 | 0.07 |
| May | 5.98 | 5.63 | 0.06 |
| Jun | 6.18 | 5.32 | 0.14 |
| Jul | 5.85 | 5.53 | 0.05 |
| Aug | 5.7 | 5.27 | 0.08 |
| Sep | 4.64 | 4.92 | -0.06 |
| Oct | 4.7 | 4.47 | 0.05 |
| Nov | 3.93 | 3.63 | 0.08 |
| Dec | 3.57 | 3.18 | 0.11 |
| Annual | 4.97 | 4.63 | 0.07 |

### 3.4.4 Reason for difference in solar irradiance between SAM and RETScreen software

Energy production prediction is very important to design and install while building a integrated PV systems. This estimation is attained based on easily available factors such as system, size, tilt angle and orientation. The energy yield depends significantly on the important parameters. Solar irradiance input is one of the important parameters to calculate energy output. For estimating the production of energy, a PV system, which is taking the weather features is an important step to make a PV project. Researchers developed software that estimate energy yield. Hourly data is used to know the PV-based energy production considering that hourly data and monthly data is available in the area of interest. The primary purpose of comparing between SAM and RETScreen is to know the advantages and disadvantages of PV model performance. RETScreen takes only the monthly weather inputs and simulates the monthly energy production. It can be used to make a comparison to the remaining software tools including tools such as SAM, which uses data hourly to produce results. As expected, the electric power production (EPP) results are calculated from hourly data and are usually reliable and accurate than those that are calculated from monthly data.

In both the software, energy production estimation relies on meteorological conditions, in which the solar irradiance hourly value is utilized for calculating the PV energy values. RETScreen uses monthly average metrological data from meteorological website of NASA. The data accuracy is taken for assessing energy production but it’s not used directly in RETScreen. On the other hand, SAM uses metrological data from National Renewable Energy Laboratory (NREL), also known as data sets of Typical Meteorological Year (TMY). They wre actually designed for simple calculation of load of heating and cooling of building. TMY has 8760 hours (24 hours x 365 days) data records of a year. Unlike RETScreen, TMY data does not need any mathematical correlation.

A TMY dataset consists of a combination of 12 data Typical Meteorological Months (TMMs) picked from long-term period optimized weighted parameter that matches the frequency distributions characteristics for a given month when compared to long term. The TMY data-sets are mainly utilized for evaluating the relative performance of different conversion system designs to a standard data set and is not considered for optimization of performance.

Due to the above-stated reasons, RETScreen Expert and SAM show both seasonal and monthly differences in the horizontal plane and tilted surface solar irradiance. SAM can calculate the production of energy during each year of production life and evaluate the LCOE. However, RETScreen has only first-year production of energy and does not calculate the LCOE.

### 3.5 Evaluation of performance prediction with actual field data, SAM and RETScreen

To design and install a building PV system, estimation of energy production is crucial. By commonly used factors such as system size, tilt angle, and orientation these energy predictions can be attained. The field data taken from the study is compared with simulation data of RETScreen and SAM to study the output of the models. A sharp manufacturer with module model is ND167U1 is used for all three systems.

- system – 1 uses SMA America inverter model SB2500U, the size of the system is 2672 (DC Watts) with quantity 16 towards 207$^{O}$ orientation and 23$^{O}$ tilt angle. Figure 3. 8 shows the system – 1 monthly energy production and average annual energy production in (kWh – ac)
- system – 2 uses Fronius inverter model IG3000, the size of the system is 3006 (DC Watts) with quantity 18 towards 228$^{O}$ orientation and 23$^{O}$ tilt angle. . Figure 3.9 shows the system – 1 monthly energy production and average annual energy production in (kWh – ac)

- system – 3 uses Fronius inverter model IG3000, the size of the system is 3006 (DC Watts) with quantity 18 towards $169^{o}$ orientation and $26^{o}$ tilt angle. Figure 3.10 shows the system – 1 monthly energy production and average annual energy production in (kWh – ac).

Table 3.10 Seasonal average and maximum deviations between the field data, RETScreen and SAM

| Season | Deviation | SAM | RETScreen Expert |
|---|---|---|---|
| **Winter** | avg dev for 3 systems (+/-) | 6 % | 3% |
| | max dev for 3 systems (+/-) | 26 % | 39% |
| **Spring** | avg dev for 3 systems (+/-) | 9 % | 11% |
| | max dev for 3 systems (+/-) | 21 % | 24% |
| **Summer** | avg dev for 3 systems (+/-) | 1 % | 3% |
| | max dev for 3 systems (+/-) | 30 % | 27% |
| **Fall** | avg dev for 3 systems (+/-) | 17 % | 16% |
| | max dev for 3 systems (+/-) | 32% | 29% |

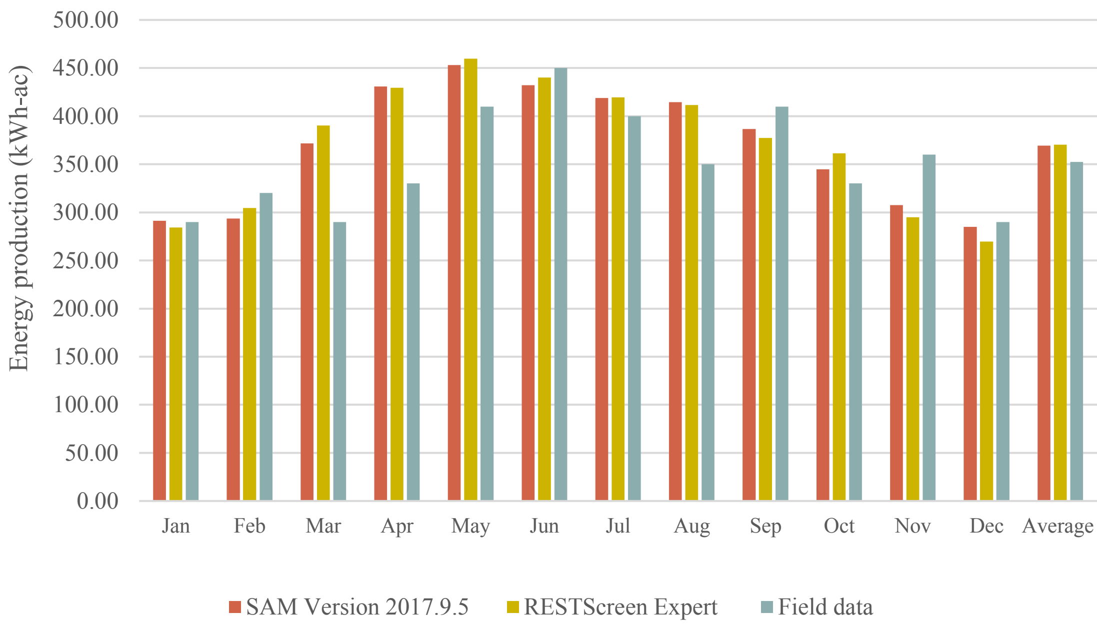


Figure 3.8: System 1 energy production (kWh-ac)

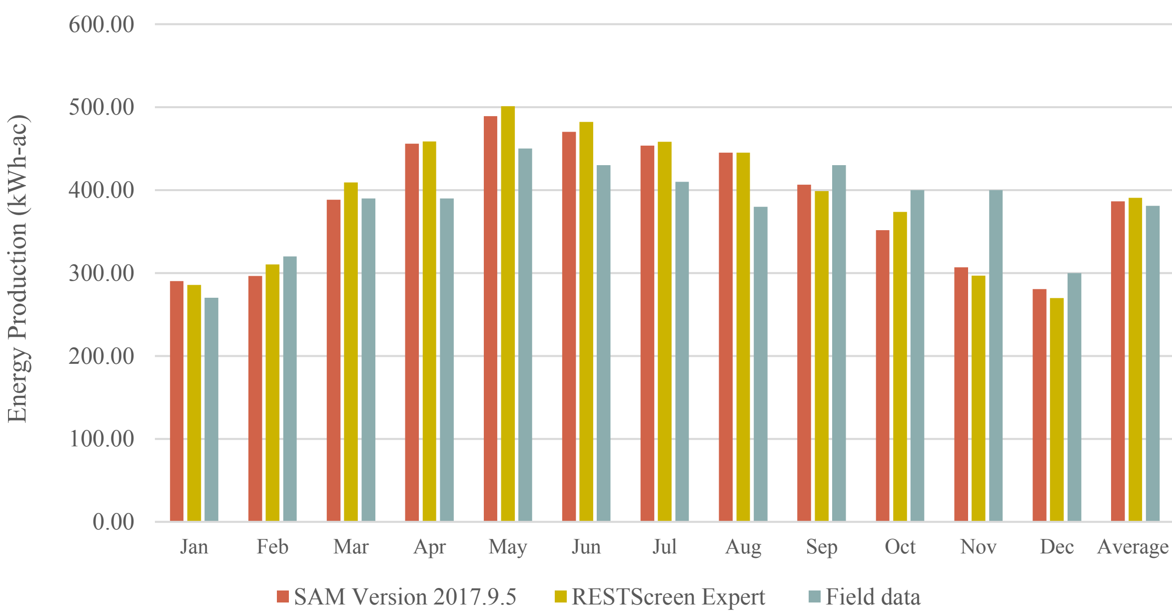


Figure 3.9: System 2 energy production (kWh-ac)

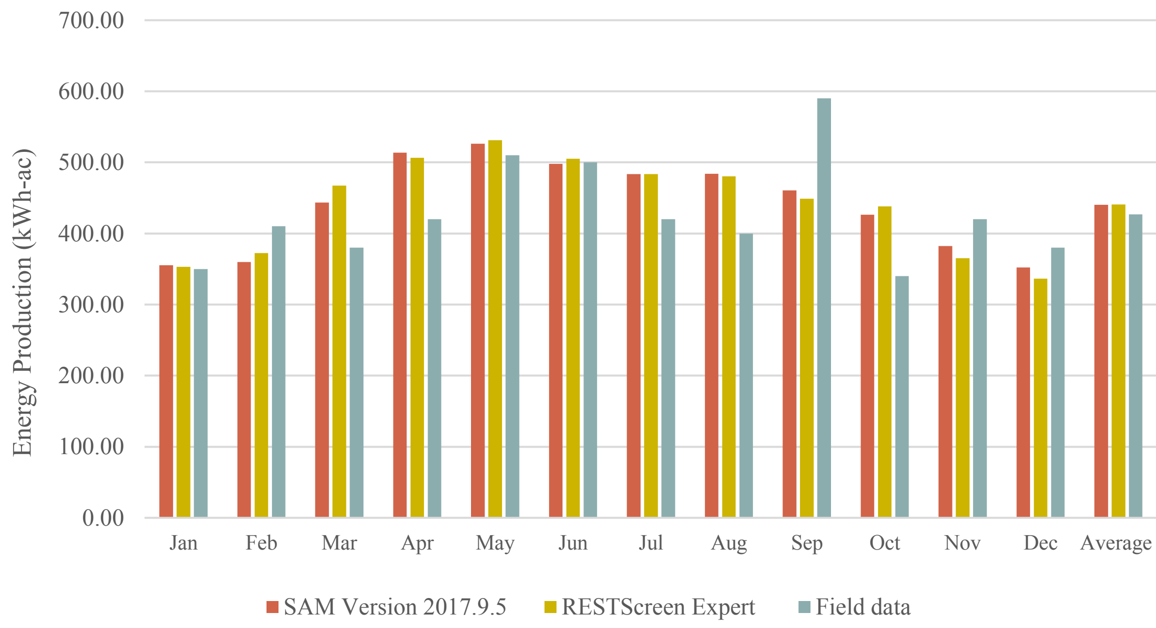


Figure 3.10: System 3 energy production (kWh-ac)

Table 3.10 provides seasonal variations between the field data, SAM, and RETScreen models for three different systems. Irrespective of any season, the two models estimated the monthly energy production with the largest average deviation varying from 17% to 32% in SAM model and the largest average deviation varying from16% to 39% in RETScreen Expert model. The largest deviation for annual energy production was 10% in the field data, SAM and RETScreen models.

## 3.6 Energy performance prediction

### 3.6.1 Study between SAM versions 2012.5.11 and 2017.9.5

To calculate the energy yield, a study is known as “PV performance and yield comparisons, NREL SAM and PVSYST” conducted by Suniva company is used for reference. This study is focused on the engineering side rather the financial side and it compares the performance model between SAM Version 2012.5.11 and PVSYST version V5.56 (May 2012) software. Both tools work towards simulating systems from around the world. Both software packages report the most important engineering results viz. energy yield, performance ratio, and loss breakdown. Using this study as a reference, a new study as part of this thesis was performed between the more recent SAM Version 2017.9.5 and SAM version 2012.5.11. The same parameters such as location, inverter, module and system losses were considered. Compared to the previous version 2012.5.11 of SAM, there are a lot of changes and upgrades made in the newest version of SAM. However, the approach is very similar in both the versions.

The Suniva company study was conducted for 1 MW Suniva 250 OPTIMUS monocrystalline system which has 4004 panels with a string size of 14 (286 strings). This current study was performed to find if the newest version of SAM was predicting the similar energy output. Latest version of SAM, Suniva OPT250-60-4-100 module with a nominal efficiency of 15.85% and two inverters of SMA America: SC500U 480V along with CEC weighted with an efficiency of 96.89% were used. There were modules 14 per string and 286 strings in parallel. The configuration references for nameplate capacity was 1000.295 kWdc, various modules of 4004 and combined module area of 6310.3 $m^2$. The Perez sky diffuse model study with beam as a radiation component was used. Table 3.11 shows the simulation parameters between SAM versions 2017.9.5 and 2012.5.11

Table 3.11: Simulation parameters between SAM 2017.9.5 and SAM 2012.5.11

| **Name of Parameter** | **SAM Version 2017.9.5** | **Name of Parameter** | **SAM Version 2012.5.11** |
|---|---|---|---|
| Climate file | Atlanta Hartsfield Airport TMY3 | Climate file | Atlanta Hartsfield Airport TMY3 |
| Ground Reflectance | 0.2 | Ground Reflectance | 0.2 |
| Sky Diffuse Model | Perez Sky Diffuse Model | Tilted Surface Radiation Model | Perez Sky Diffuse Model |
| Tilt angle (degrees) | 30º | Tilt angle (degrees) | 30º |
| Azimuth (degrees) | 180º | Azimuth (degrees) | 180º |
| Shading (%) | 0 | Shading (%) | N/A |
| Average annual soiling loss (%) | 2 | Soiling loss annual (%) | 98 |
| Module Mismatch (%) | 2 | Module Mismatch (%) | 98 |
| Diodes and connections (%) | 0.5 | Diodes and connections (%) | 99.5 |
| DC Wiring (%) | 1 | DC wiring (%) | 99 |
| Tracking error (%) | 0 | Tracking error (%) | 100 |
| Nameplate (%) | 0 | Nameplate (%) | 100 |
| DC power optimizer loss (%) | 0 | DC power optimizer loss (%) | N/A |
| Total DC power loss (%) | 3.690 | Total Pre-Inverter Derate (%) | 96.5349 |
| AC Wiring (%) | 0.5 | AC Wiring (%) | 99.5 |
| Transformer loss (%) | 0 | Transformer loss (%) | 100 |
| Degradation rate (%/year) | 0.0588 | Estimated total derate factor (%/year) | 94.1312 |

Equation 3.2 is used to change from the previous version data format to current version SAM version 2017.9.5. This equation 3.2 is taken from the SAM version 2017.9.5

$$Power\ Loss = 100\% * [1 - the\ product\ of\ (1 - loss/100\%)] \quad \text{Equation 3.2}$$

To compare the output of two versions of software, energy yield and capacity factor are considered. The results concluded both versions produced 1586 MWh and matched 18.1% capacity factor. The monthly AC electricity to grid followed in the same trend in both versions. Figure 3.11 shows AC electricity to grid by month between SAM version 2017.9.5 and 2012.5.11

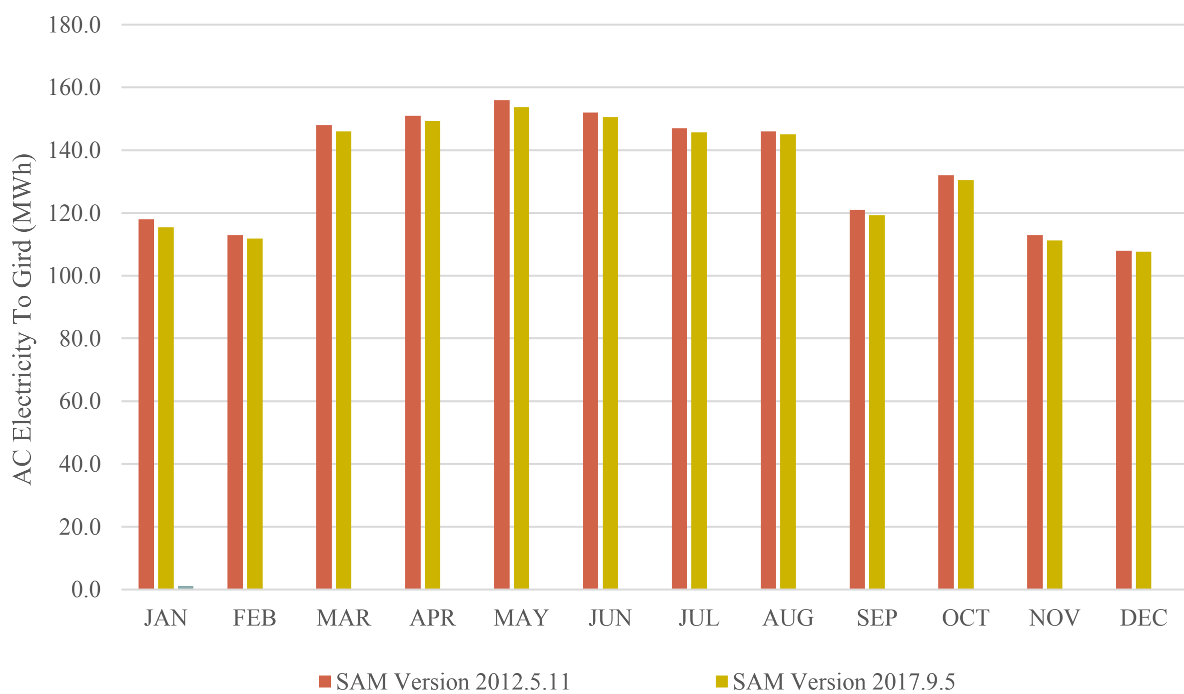


Figure 3.11: AC electricity to grid by month (MWh)

3.6.2 Study between SAM version 2017.9.5 and RETScreen Expert

RETScreen Expert is a clean energy management analysis tool for energy efficiency that is becoming popular around the world recently. RETScreen Expert integrates various databases to assist its user in accessing the database of climate conditions from 6,700 ground-based stations and data from NASA satellite. A study similar to the section 3.6.1 was conducted between the newest versions of RETScreen Expert and SAM in this section. Unlike in the previous study, this study had some changes in considering parameters because RETScreen and SAM follow a different procedure in producing results. Comparing both software, there are not many differences in the location page and while entering the module parameters as RETScreen parameters are also user-defined. However, there are calculations that are done to match the losses in both software.

A similar procedure was followed in RETScreen Expert by taking parameters with the exact location, azimuth angle, tilted surface angle, and module parameters with the same nameplate capacity and module efficiency. However, the only changes needed were between the study in section 3.6.1 and current study in changing the tilted surface radiation model to isotropic sky diffuse model instead of Perez sky diffuse model because RETScreen Expert generates data using Lui and Jordon's isotropic diffuse algorithm. By considering this change as the exception, all the other parameters were same when compared to the Suniva company study. For matching the miscellaneous losses (PV and invertor) in RETScreen Expert and for matching the losses in the SAM Version 2017.9.5, equations 3.3 and 3.4 are derived below for calculations. Table 3.12 shows the parameters between SAM 2017.9.5 and version RETScreen Expert.

**RETScreen** **SAM version 2017.9.5**

*Miscellaneous Losses %(PV)* $= [(1 - Average\ Soiling\ loss\ (\%)) * (1 - Total\ DC\ power\ loss\ (\%))]$ Equation 3.3

**RETScreen** **SAM version 2017.9.5**

*Miscellaneous Losses % (Invertor)* = *AC wiring (%)* Equation 3.4

Table 3.12: Parameters between SAM 2017.9.5 and RETScreen Expert

| **PARAMETER** | **SAM Verision 2017.9.5** | **RETScreen Expert** |
|---|---|---|
| Climate file | Atlanta Hartsfield Airport TMY3 | Atlanta Hartsfield Airport TMY3 |
| Ground Reflectance | 0.2 | 0.2 - 0.7 |
| Tilted Surface Radiation model | Isotropic diffuse model | Isotropic diffuse model |
| Tilt angle (degrees) | $30^{o}$ | $30^{o}$ |
| Azimuth (South direction) | $180^{o}$ | $0^{o}$ |
| Nameplate Capacity (kW) | 1000.295 | 1000.295 |
| Manufacturer | Suniva | Suniva |
| Module | OPT250-60-4-100 | OPT250-60-4-100 |
| Number of Units | 4004 | 4004 |
| Inverter efficiency (%) | 96.89 | 96.89 |
| Shading (%) | 0 | N/A |
| Average annual soiling loss (%) | 2 | N/A |
| Module mismatch (%) | 2 | N/A |
| Diodes and connections (%) | 0.5 | N/A |
| DC Wiring (%) | 1 | N/A |
| Tracking error (%) | 0 | N/A |
| Nameplate (%) | 0 | N/A |
| DC power optimizer loss (%) | 0 | N/A |
| Miscellaneous losses (PV) (%) | N/A | 0.99 |
| Miscellaneous losses (Invertor) (%) | N/A | 0.5 |
| Total DC power loss or Total Pre-Inverter Derate | 3.690 | N/A |
| AC wiring loss (%) | 0.5 | N/A |
| Transformer loss (%) | 0 | N/A |
| Degradation rate or Estimated Total Derate factor (%/year) | 0.0588 | N/A |

In this case, to compare the performance output between both the software packages, energy yield and capacity factor were considered as a reference similar to the section 3.6.1. The results concluded that, both the versions produced the same annual energy production, i.e. 1533 MWh and match the capacity factor of 17.5%. The monthly AC electricity to the grid also follows the agreeable trend between SAM and RETScreen. Figure 3.12 shows the AC electricity to grid by month between SAM and RETScreen Expert. Thus, the above study concludes that an accurate procedure was followed in the RETScreen and SAM 2017.9.5 for finding the performance model.

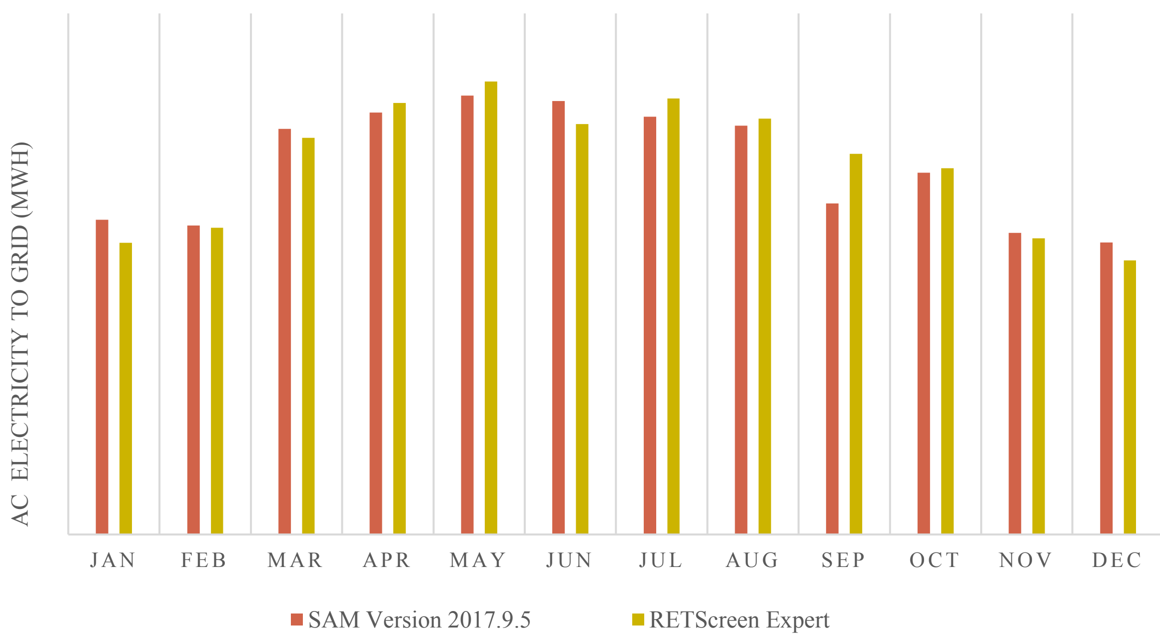


Figure 3.12: AC electricity to grid by month (MW-h)

## 3.7 Conclusion

This chapter discusses an in-depth study of the technical model and software simulation model of RETScreen Expert and SAM. To understand the difference between softwares, energy production with field data of different systems is compared. SAM is utilized to verify performance model of PV system that is designed in RETScreen for a further research study. The main objective is to analyze performance model of PV system and verify that the modeling procedure followed by RETScreen Expert is correct. An investigation of optimum tilt and azimuth angle for PV system is also examined for producing ‘’maximum’’ energy in Fort Wayne, IN.

# CHAPTER 4. MULTI-FAMILY RESIDENTIAL BUILDING MODELING USING EQUEST

## 4.1 Introduction

Buildings consume about 73% of electricity and 41% of total energy produced in United States. Building's energy usage has significant costs and causes a negative environmental impact due to the GHG emissions. But there exists an opportunity to utilize energy modeling software to evaluate design decisions that impact the building's energy performance. Building energy performance is a combination of numerous interdependent external and internal factors such as building types selections, mechanical and electrical systems, material selection, solar orientation, climate, and occupant usage. Energy modeling software is used to compare and evaluate annual building electricity consumption along with heating and cooling loads with multiple selections in the software. The basic building calculation algorithms of most software of this kind are sound and serve as a powerful and valuable tool to accurately compare the relative impact of design alternatives. In addition, this software can inform building component selection in formal and informal design development, value engineering and performance optimization and produce complex interactions that are difficult for building owners to analyze their building's energy performance. This complex and time-taking process of generating a performance report was eased by eQUEST software, which runs on a Department of Energy (DOE) simulation engine and provides a graphically simpler and user-friendly interface.

In this thesis study, eQUEST 3.65 version is utilized to predict annual electricity consumption along with heating and cooling loads and other required building parameters of the multifamily, residential building in Fort Wayne, Indiana. Since the outputs of the eQUEST software are the inputs for RETScreen Expert software, the simulation outputs of eQUEST are inserted into RETScreen to find the feasibility of heat pumps and their combination with photovoltaics in multistory residential buildings.

## 4.2 eQUEST version 3.65 software overview

eQUEST is an analysis tool for building energy that provides results by joining a building creation wizard, which is an energy efficient wizard, and a graphical result display module containing an enhanced DOE-2.2 achieved energy simulation program of building. The building creation wizard processes the creation of a building model. eQUEST calculates energy consumption of building on an hourly basis for the entire year (8760 hours) by using the hourly weather data of the given location. The input of the program consists of description of the analysis of the building, which includes hourly scheduling for the occupants, equipment, thermostat, and lighting settings. It provides real simulation of features of building such as interior building mass, fenestration, shading, envelope mass, and dynamic response to varying heating and air conditioning systems. A baseline building model assuming a baseline efficiency is later developed to estimate energy savings. This alternative analysis is the result of a yearly consumption and cost savings for efficiency measure, which can be used to know the combinations of best alternatives.

## 4.3 eQUEST study model

This case study, developed in schematic design wizard, is more detailed and provides more information to its user when compared to design development wizard. This program provides wizard input screens for HVAC systems and general building information that have default values, which can be amended by the user. Once the users see all these wizard screens, they can direct the program engine to simulate. Then the program provides a screen that identifies errors, and if no errors are found, the user generates the output report. Figure 4.1 shows the general information wizard window input screen in eQUEST software. Using this program simulation direction and building specification, the baseline energy model for the building is generated.

**Note:** In this eQUEST case study model, the majority of the inputs are default settings provided by the software. This helps the users model basic multi-family residential building easily and generate the output report with minimal changes. The only changes that are made in this study are in the first wizard window, which is general information such as:

- Choosing building type of multi-family, mid-rise (interior entities).
- Adjusting the location to Fort Wayne, Indiana in the location settings.
- Changing typical multi-family mid-rise building floors number from five to three stories.
- Scaling down the total building area from 40,000 $ft^2$ to 24,000 $ft^2$

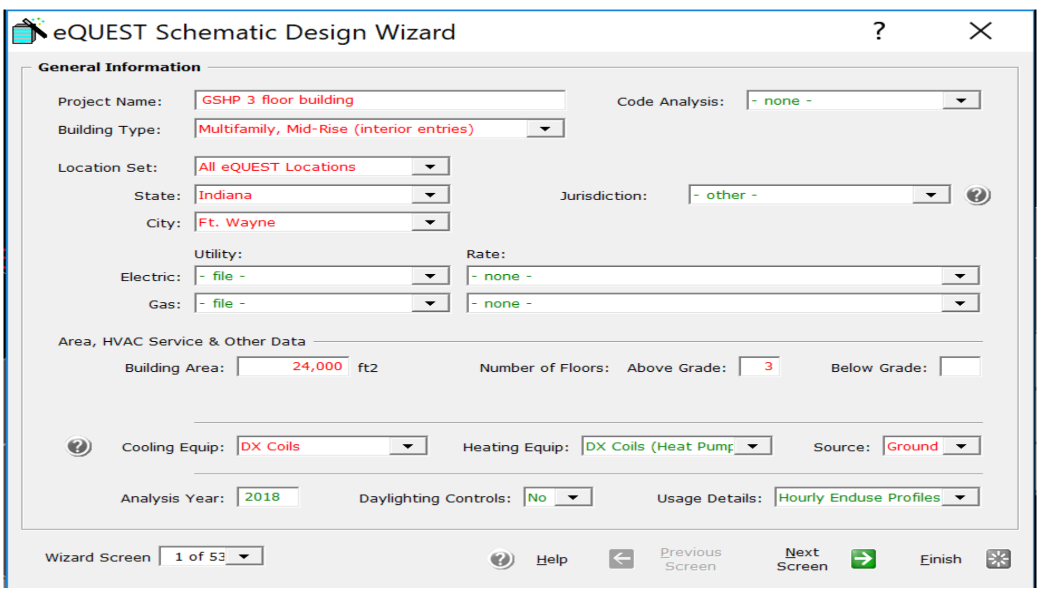


Figure 4.1: General Information wizard window Input Screen in eQUEST
[Source – eQUEST Version 3.65 Software]

### 4.3.1 Building description

Building selected for research is traditional multi-family mid-rise three story residential building in Fort Wayne, Indiana. It is a plain north facing residence in a rectangle shape with length of 123.1 feet and breadth of 65 feet and with a total building area of 24,000 sq. ft. The building envelope construction consists of wood standard frame roof surfaces with above-grade walls of the wood frame and the ground floor is constructed with a concrete base with the stone finish. The building interior is constructed with drywall based ceiling and frame type based vertical walls. The floors are covered with a carpet of fiber pad finish with plywood underlayment. The exterior doors have two glass doors facing north and south and two opaque doors facing east and west with a total of four entrances.

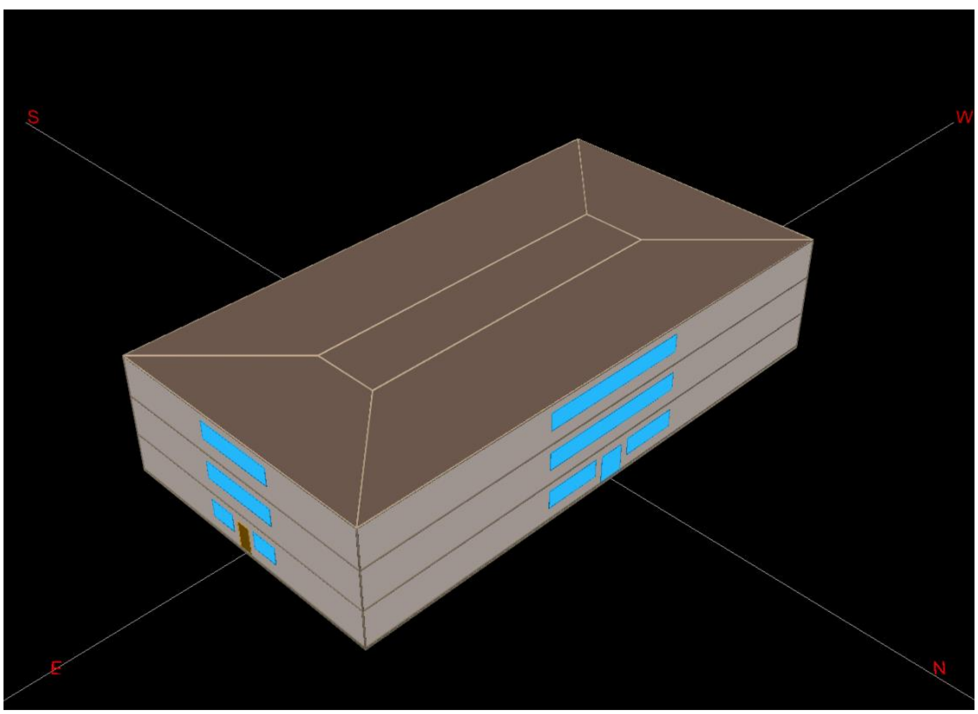


Figure 4.2: Multi-family, mid-rise building (3-D Geometry)
[Source – eQUEST Version 3.65 Software]

The building operation schedule for the entire year consists of occupants leaving at 7 am and returning at 5 pm in the weekdays and leaving at 9 am and returning at 4 pm on the weekends and holidays. Figure 4.2 shows a 3-D geometry of the multi-family mid-rise residential building modeled in eQUEST. The area of the building is assigned for the major activities. The majority of the building is assigned to residential multi-family units with 71% area that has a maximum occupancy of 624 (sq. ft. / person). In addition, the corridor space has 16% area with a maximum occupancy of 1000 sq. ft./ person, the storage space is 7% area and the laundry space is 6% area with maximum occupancy of 500 (sq. ft./ person) and 200 (sq. ft./ person).

### 4.3.2 Building space distribution details

This typical multi-family residential building consists of three floors with an area of 24,000 sq. ft. and a total volume of 216040.5 cu. ft. with a total occupancy of 42 people. The three floors are assumed to be identical with each floor having four apartments and a corridor (core space). The apartments in north and south have an area of 2452 sq. ft. with an occupancy of 4.5 people per apartment and the apartments in east and west direction have an area of 1000 sq. ft. with an occupancy of 1.9 people per apartment. Moreover, the corridor space has an area of 1096.5 $ft^2$ for each floor with a capacity of 1.1 people occupancy. The details about the building are obtained in the eQUEST report when a user clicks on simulate building performance option. The detailed simulation output file option generates over 1500 pages describing the building.

### 4.3.3 Building space heating and cooling loads

Space heating and cooling loads are heating and cooling needs of a building. The load calculation has an effect on occupant comfort, indoor air quality and energy efficiency. The calculation of the load is the first step taken in the procedure of HVAC and a full HVAC design has much more into consideration than just the load calculation. The calculated loads modeled by the heating and cooling load simulation process dictates the equipment selection and duct designs to deliver the conditioned air to the various rooms of the house.

Table 4.1 shows the heating and cooling loads of a given building is simulated on eQUEST. G.S1 represents space 1, which is located at the ground floor south direction, M.S6 represents space 6, which is located at the middle floor south direction, and T.E12 represents the space 12, which is located at the top floor east direction. While designing a heating and cooling system of a building, the system should be capable of heating on the coldest night and cooling the building on the hottest day. These are the peak days and referred to as peak heating and cooling loads.

Apartment has its own specifications, the heating load or cooling load may increase due to wall and roof conduction, window glass solar, underground surface conduction, internal surface conduction, underground surface conduction and occupants to space. It may also depend on the apartment orientation, space and number of people living in the apartment. For instance, the apartment (G.S1) ground floor facing south is considered. It has a floor area of 2453 sq. ft. with 4.9 people occupancy. Peak cooling load of 22.386 KBTU/HR is observed at October 3 at 2 pm in a typical year. At this time, solar radiation is directly transmitted through the glass window of the apartment increasing cooling load to 13.556 KBTU/HR which is a prime parameter. However, the other parameters also have some effect on peak cooling load of the building.

Table 4.1: Heating and cooling loads of the multi-family residential building

| Space Name | Peak Heating Load (KBTU/HR) | Peak Cooling Load (KBTU/HR) |
|---|---|---|
| South Space (G.S1) | 18.094 | 22.386 |
| East Space (G.E2) | 10.152 | 11.650 |
| North Space (G.N3) | 18.64 | 16.676 |
| West Space (G.W4) | 10.591 | 13.869 |
| Core Space (G.C5) | 3.370 | 2.802 |
| South Space (M.S6) | 9.427 | 26.395 |
| East Space (M.E7) | 5.292 | 14.505 |
| North Space (M.N8) | 9.428 | 15.038 |
| West Space (M.W9) | 5.360 | 16.829 |
| Core Space (M.C10) | 0.000 | 2.019 |
| South Space (T.S11) | 14.933 | 27.636 |
| East Space (T. E12) | 7.529 | 14.538 |
| North Space (T.N13) | 14.994 | 17.859 |
| West Space (T.W14) | 7.630 | 17.680 |
| Core Space (T.C15) | 2.396 | 3.314 |

Similarly, peak heating load of 18.094 KBTU/HR is observed at January 10 at 6 am of a typical year for the south space (G.S1) apartment. In this case, 13.051 KBTU/HR of heating load is due to wall conduction which is a major parameter. As such, many parameters affect the apartments heating and cooling loads at different times due to variable weather conditions. The peak loads are used to determine the heat pump system capacity in RETScreen Expert.

### 4.3.4 Building electricity consumption comparison with different HVAC systems

HVAC systems provide heating and cooling comfort to the occupants of building. Heating and air conditioning components help interior climate and airflow. HVAC systems have potential for 40% more electricity consumption in any building since heating and cooling are generally run by electric power. This study compares electric system (electric resistance heating and typical air conditioner), air source heat pump, and ground source heat pump systems. In eQUEST's HVAC system definitions wizard window, the user can change the options for various heating and cooling sources, system type, and their specifications. Figure 4.3 shows the building electricity consumption using ground source and air source and electric system (Furnace, AC). The electricity consumption is found in eQUEST by choosing three different systems for 3 floor multi residential building. In Fort Wayne, for a typical year, the winter can get colder up to 17° F. When compared to electric and ASHP systems, GSHP systems consumes less electricity in winter. During summer, in Fort Wayne, temperature ranges from 55° F - 80° F in a typical year. So, the climates are not extreme compared to winter. Due to warm conditions, the usage of HVAC systems is not much frequent. So, we can observe the trend in figure 4.3, that three systems consume approximately equal amount of electricity during the summer. If the systems are used in hotter regions such as California, Arizona and Florida. The GSHP systems are utilized to their full potential for cooling the building, then the GSHP may consume less amount of electricity compared to other systems during the summer as well.

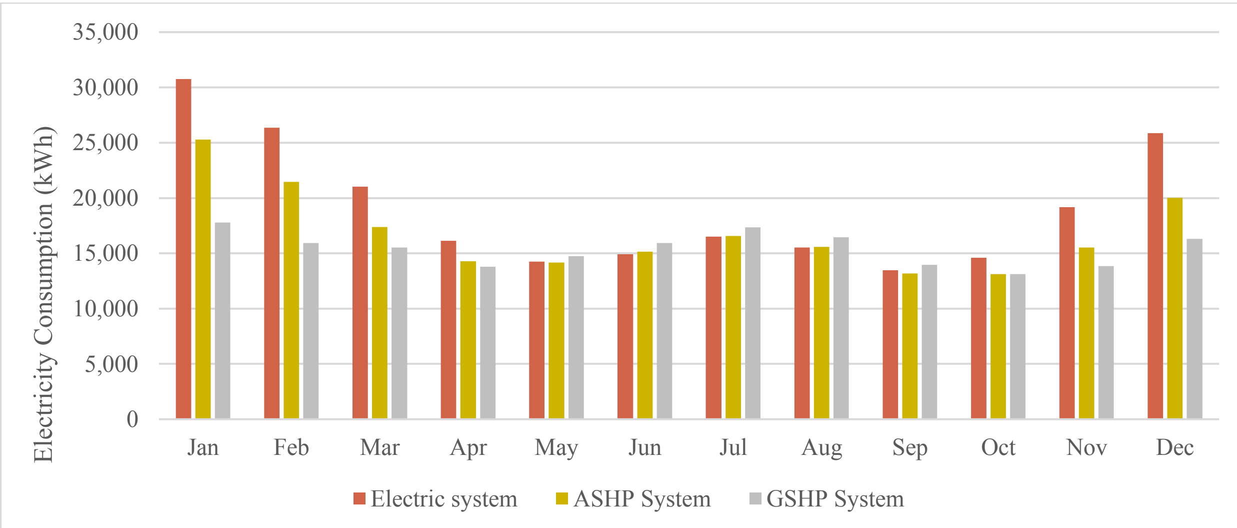


Figure 4.3*:* Building Monthly Electricity Consumption (kWh)

Note: The electric system (resistance heating and AC), air source heat pump and ground source heat pump are the three chosen for comparing electricity consumption in the building.

## 4.4 Conclusion

eQUEST software provides accurate values and additional benefits to their users. This chapter has multi-family residential building, which is modeled in eQUEST software for predicting all the building parameters. The calculations are done with these parameters because the eQUEST output values are inputs of RETScreen Expert to model an accurate heat pump system for a residential building that was already discussed. The important parameters simulated in eQUEST to model a system in RETScreen are the following:

- Electricity consumption, heating and cooling loads, area and volume of each apartment along with their walls, windows and ceilings areas with their respective U-values (in BTU/HR-SQFT-F units) are calculated.
- Number of people, the apartment lights (in W/sq. ft. units), equipment (in W/sq. ft. units) and infiltration method in air change per hour are calculated in eQUEST.
- All these parameters are used to model a building envelope in RETScreen to find the feasibility of heat pump system used for given building.

# CHAPTER 5. MODELING AND SIMULATION IN RETSCREEN EXPERT

RETScreen is one of the best available popular simulation software to predict the feasibility analysis of clean energy technologies. This tool is preferred worldwide for evaluating energy production, GHG emission reductions and life-cycle costs for different renewable energy and conventional energy technologies.

A system in Fort Wayne, IN is modeled using RETScreen Expert to know the impacts of the local conditions of heating and cooling strategy. A multifamily residential building is designed using eQUEST software to calculate all the parameters of the building discussed in the previous chapter. The results of the eQUEST serve as the input to RETScreen that allow modeling of heat pumps as well as combinations of photovoltaic with heat pumps. This includes modeling a residential building envelope in RETScreen Expert with parameters taken from eQUEST, designing a heat pump for heating and cooling compared to conventional system equipped with space heating, cooling and ventilation as base case to reflect current energy use situation. Furthermore, ASHPs are compared with GSHPs to determine performance and economic feasibility. Moreover, photovoltaics is combined with heat pumps i.e., PV-ASHP and PV-GSHP to find feasibility analysis, GHG emissions, period of payback, equity payback, initial costs and total annual savings and revenue including energy savings. In addition, different energy prices are an independent variable in the analysis.

## 5.1 Climatic parameters

Climates vary depending on geographical locations. Considerably, costs of heating and cooling known in RETScreen are based on the each city’s key environmental features. The main parameters required for the simualtion are given in the Table 5.1. Site reference conditions obtained from the RETScreen climate database. RETScreen climate database is expanded to 4,700 ground stations & NASA satellite dataset integrated within the software to cover populated areas across the entire surface of planet. In the Table 5.1, ground refers to 4,700 ground stations and NASA refers to NASA satellite database.

Table 5.1: Location and climate conditions of Fort Wayne in the case study

| **Geographical factors** | **Measured** | **Source** |
|---|---|---|
| Latitude (degrees) | $41^{o}$ N | NASA |
| Longitude (degrees) | $-85.2^{o}$ E | NASA |
| Elevation (m) | 240 | Ground |
| Heating design temperature ($^{o}$C) | -15.7 | Ground |
| Cooling design temperature ($^{o}$C) | 31.3 | Ground |
| Earth temperature amplitude ($^{o}$C) | 21.6 | NASA |
| Annual air temperature ($^{o}$C) | 10.4 | Ground |
| Relative humidity (%) | 73.3 | Ground |
| Daily solar radiation horizontal (kWh/$m^2$/d) | 3.86 | Ground |
| Atmospheric pressure (kPa) | 98.7 | Ground |
| Wind speed (m/s) | 4.1 | Ground |
| Earth temperature ($^{o}$C) | 10.2 | NASA |
| Heating degree days ($18^{o}$C-d) | 3160 | Ground |
| Cooling degree days ($10^{o}$C-d) | 1571 | Ground |

## 5.2 Physical and operational parameters

A general residential building is considered for analysis of all heat pump systems and their combinations with photovoltaics. The residential building has the total area of the 24,000 $ft^2$ and oriented in the direction north. Each floor of the building consists of four apartments and a corridor space equally distributing 8000 $ft^2$ per floor. There are 12 apartments in the residential building. The main factors that have to be considered while determining the heat pump size are square footage of apartment or house. Typically, a heat pump size of 18,000 BTU or 5.275 kW or 1.5 ton is required for 850 $ft^2$ to 1250 $ft^2$ space. But, for the considered residential building, the apartments in the north and south each have an area of 2472 $ft^2$ and apartments in east and west each have an area of 1000 $ft^2$. For heating and cooling 1000 $ft^2$ space, a heat pump size of around 1.5 ton is used. However, for heating and cooling of 2472 $ft^2$ space, two heat pumps with the size of around 1.5 ton is considered for easy evaluation and consistency. A total of 18 heat pumps around 1.5-ton size are taken for the entire multifamily residential building.

### 5.2.1 Operational parameters - Ground source heat pump system

The geothermal system has performances that are nearly independent of external temperature that is advantageous in colder climate conditions. In this project, the heat pump VLV/VXVO18*0 Waterfurnace has a heating capacity of 4.22 kW and cooling capacity of 5.51 kW. The seasonal performance factor (SPF) is 380% and the coefficient of performance (COP) - seasonal is 4.4 kW (heat)/kW (power). RETScreen shows the SPF and COP values of the selected heat pump.

### 5.2.2 Operational parameters- Air source heat pump system

ASHPs are renewable technologies, which are considered more efficient than conventional boilers and furnace in domestic heating and cooling. Different capabilities will yield different coefficients of performance with the outdoor temperature playing important role in functioning of system. There are ten different ASHP manufacturers given with varying capabilities and COPs. The RETScreen software database has fewer models in the capacity range of 1.5 ton or 5 kW system. Arcoaire manufacturer with HHP018A(G)KC*EX*24F****+TD1 model with a capacity of 4.8 kW is considered. The ASHP heating COP is 1.99 and cooling COP is 2.93. This system is chosen because it is sufficient for heating and cooling of 1000 $ft^2$ to 1250 $ft^2$ with minimum initial and installation costs.

## 5.3 Base case

An energy system equipped with space heating, space cooling, and ventilation was analyzed as a base case to reflect the current typical energy use situation in the residential buildings in the US.

In this study, the base case and proposed case building models are similar—the only changes are the heating and cooling systems which are the subject of analysis. The energy performance of the building envelope is determined by specifying various factors. These include elements such as orientation of the building and amount of sunlight penetrating into the inside of living or workspaces. The building envelope also includes walls, windows, doors, and floor. The building envelope energy performance is also influenced by natural air filtration. All of these parameters are same in both base case and proposed case. The parameters that are needed to describe the building envelope are illustrated below in Table 5.2

Table 5.2: Building envelope for natural air infiltration details required for RETScreen simulation

| Building Envelope | | North | East | South | West |
|---|---|---|---|---|---|
| Walls | Area ($ft^2$) | 960.55 | 507.19 | 960.55 | 507.19 |
| | U- value (Btu/h)/$ft^2$/$^oF$ | 0.055 | 0.055 | 0.055 | 0.055 |
| Windows | Area ($ft^2$) | 147.35 | 77.81 | 147.35 | 77.81 |
| | U- value (Btu/h)/$ft^2$/$^oF$ | 0.444 | 0.438 | 0.444 | 0.438 |
| | Solar heat gain coefficient | 0.624 | 0.624 | 0.624 | 0.624 |
| Solar shading-season of use | Solar shading-winter (%) | 10 | 10 | 10 | 10 |
| | Solar Shading-summer (%) | 15 | 20 | 40 | 20 |
| Roof | Area ($ft^2$) | 24,000 | | | |
| | U- value (Btu/h)/$ft^2$/$^oF$ | 0.0029 | | | |
| Floor | Area ($ft^2$) | 24,000 | | | |
| | U- value (Btu/h)/$ft^2$/$^oF$ | 0.249 | | | |
| Natural air infiltration | Volume ($ft^3$) | 216,040.5 | | | |
| | Air change rate (ac/h) | 0.15 | | | |
| | Natural air infiltration (L/s) | 255 | | | |

### 5.4 Combination of photovoltaics

Photovoltaics are cost-effective in small off-grid applications by providing power to commercial as well as residential buildings, rural homes in developing areas, off-grid cottages, and motorhomes in industrialized countries. Combination heat and power systems can be implemented at nearly any scale, as long as a suitable thermal load is present. The usage of photovoltaics effect was estimated on RETScreen Expert. The electricity generated from the photovoltaics vary based on available daily solar radiation in a given city. Electricity usage is increased by installation of a heat pump system, and consumption of natural gas can be reduced. By using heat pumps, the trade-off energy use still causes considerable GHG emissions when associated with grid. The photovoltaic system meets the demand of heating systems, cooling systems and for appliances and lighting.

#### 5.4.1 Photovoltaic system modeling in RETScreen Expert

Building electricity consumption that is predicted from eQUEST is taken as input for RETScreen simulation. In RETScreen, heat pump is chosen as a heating and cooling source for the proposed case. Rooftop photovoltaics systems meet approximately 50% of electric demand. Two types of combinations demonstrated both reductions in total electricity use to meet annual requirements of the electricity as obtained from eQUEST. The multifamily building has a roof area of 8000 $ft^2$, assuming half of the roof area that is 4000 $ft^2$ is available for the system installation. PV module is facing south with a tilt angle of $40^o$ that produces significantly high and comparatively same energy in both the software. Photovoltaic system with a power capacity of 73.6 kW that can cover approximately 4000 sq. ft. is chosen. This power capacity can produce annual energy production of 105.458 MWh. The technical details and attributes of the proposed case of PV module are given in Table 5.3.

Table 5.3: Technical details and attributes for proposed case PV system

| **Variables** | **Specification** |
|---|---|
| Manufacturer | SunPower |
| Model | Mono-Si-SPR-230-WHT |
| Capacity (kW) | 73.6 |
| Number of units | 320 |
| Module Efficiency (%) | 18.49% |
| Solar collector area ($m^2$) | 398 |
| Life (years) | 25 |
| Annual Solar radiation horizontal ($kWh/m^2/d$) | 3.86 |
| PV tracking mode | fixed |
| The slope of PV module (south facing) | $40^o$ |
| Inverter Capacity (kW) | 75 |
| Inverter Efficiency (%) | 96.172 |
| Inverter losses (%) | 0.5 |
| Capacity factor (%) | 16.4 |
| Annual energy production (kWh) | 105,457.831 |

## 5.5 Financial parameters and decision criteria

For heating, natural gas is favored in Fort Wayne with a typical seasonal efficiency of over 90% for the furnace. Cooling is primarily electricity-powered AC for the residential buildings. To perform simulation, energy inflation rate is considered. This rate is forecasts the average annual increase in avoided energy costs between base and proposed case during the project lifetime. According to RETScreen database, the U.S. power companies use an energy inflation for long-term periods between 0% and 5%. Hence, 2.5% inflation rate was for this study. Following the same pattern, inflation rate in the U.S. for next 25 years is predicted to between 2% and 3%. Hence, inflation rate for life of the project was 2.5%. Table 5.4 shows the financial parameters used for all the cases. These inflation rates are similar to (Le Du, 2015) which is very comparable to the current study.

Table 5.4: Common financial parameters for all cases

| **Reference heating energy source** | **Electricity** |
|---|---|
| Seasonal efficiency (%) | 100 |
| Reference energy cost (residential) | 0.812/0.1/0.12/0.14 $/kWh |
| Reference natural gas rate (thousand Mcf) | 6.55 |
| Energy inflation rate (%) | 2.5 |
| General inflation rate (%) | 2.5 |
| Discount rate (%) | 4 |
| Reinvestment rate (%) | 9 |
| Debt ratio (%) | 0/50/99 |
| Debt term (Years) | 10 |
| Debt interest rate (%) | 4.0 |
| Project expected lifetime years | 25 |
| Incentives and grants ($) | 0 |

To perform the financial analysis, multiple cases of the debt ratio is assumed at 10 years debt term. A 4% interest rate was selected as an average value as the present interest rates in the United States are quite low. A 4% discount rate is assumed and it is discount rate for future cash flow statements to get the current day's value in dollars. The initial costs of the heat pumps and the photovoltaics are average default values for Fort Wayne that are included in the RETScreen database.

Table 5.5: Initial costs for all systems

| System Types | Loop cost ($) | Total initial costs ($) |
|---|---|---|
| GSHP – Minimum | 800 | 178,126 |
| GSHP – Average | 2400 | 299,662 |
| ASHP | 0 | 131,204 |
| PV-ASHP | 0 | 351,915 |
| PV-GSHP | 800 | 406,286 |
| PV-GSHP | 2400 | 527,822 |

Table 5.5 shows the initial costs of the all heat pumps and their combination with photovoltaics. All heat pumps unit costs, drilling and installation costs considered are average costs for the systems that were embodied in the software database. Total initial costs of the GSHP systems are $299,662 for the multi-family residential building while considering the average loop value, and when minimum loop value is considered for GSHP systems, the costs are $178,126. The initial costs of ASHP systems are $131,204 and when coupled with PV, the initial costs of PV-ASHP systems are $351,915. Minimum and average loop values of the systems of PV coupled GSHP were $406,286 and $527,822 respectively. To compare the financial feasibility of different systems, the common financial parameters for the study were considered to be constant. To better understand the financial viability of GSHP and PV-GSHP systems, a comparison study was performed between the minimum and average loop costs. Table 5.5 gives the idea of loop cost for average and minimum value.

## 5.6 Results and discussions

This chapter discusses the technical, financial and environmental impacts of heat pump systems and compatibility with PV systems for the application of multifamily residential building in Fort Wayne, IN. The project's investment decisions depend mainly on the financial viability. To determine financial analysis, inputs such as cost of capital, required rate of return, export rate of electricity, escalation rate of base case price, rate of electricity export escalation, debt ratio, inflation rate, debt term and debt interest rate are used. The base case is presented first referring to the conventional energy system (where furnace is used for heating, Air conditioning is used for cooling in our case) in the residential building while proposing the cases involving the GSHP & ASHP systems and their combinations with PV. Cost models are defined for each of the systems viz. heating, cooling and PV systems. These includes building heating, climatic parameters, cooling models and building parameters.

Financial viability such as equity pre-tax internal rate of return (IRR), equity payback period, net present value (NPV) and annual life cycle savings for the complete systems are calculated using the RETScreen Expert. The cumulative cash flows presented for GSHP case with minimum and average loop cost value and debt ratios of 0%, 50% and 99%. The feasibility of the project is estimated by calculating the NPV and annual life-cycle savings (ALCS). Project also involves calculation of cumulative annually cash flow of the project for 25 years.

For analysis of emission, gross annual GHG emission reductions are found using RETScreen. The fuel savings is calculated based on different simulations and debt ratio with different electricity costs and loop costs of GSHP systems. Energy savings of the project between the base case and proposed case is analyzed using fuel saved and total energy consumption.

### 5.6.1 Annual electricity consumption and fuel savings

Electricity consumption is the energy demand made on the existing electricity supply. Conventional systems consume more electricity when compared to the heat pump systems and their combinations with photovoltaic system. Combination systems are used to save energy and reduce electricity bills. Analysis for the fuel and electricity savings comparing the base case (furnace and AC) to the GHSP, PV-GSHP, ASHP and PV-ASHP systems. Figure 5.1 shows that the base case has fuel consumption of 811 MWh. However, the ASHP system is the next in electricity consumption by producing 594 MWh i.e. 73.2% with fuel savings of only 26.8% when compared to the base case. In contrast, GSHP consumes 60% of the energy with fuel savings of 40%. As it is known by comparing conventional systems, the installation of ASHP systems and GSHP system has a tradeoff between two types of energy use i.e., electricity and natural gas. Though GSHP systems need electricity to operate heat pump, circulate fluid through ground loops and heat distribution system, they seem to be a reliable option in terms of energy savings when compared to the base case and ASHP system.

Heat pumps combined with PV is one promising approach to reduce electricity demand in the residential buildings. The electricity generated by PVs depends on the availability of solar irradiance in Fort Wayne. The PV can meet 30-70% of the electricity demanded of heat pumps and supply building energy. The rest demand is supplied the grid. When PV technology is combined with GSHP and ASHP systems, there is a considerable increase in fuel savings. PV-GSHP fuel savings are more than 54%, whereas PV-ASHP fuel savings is 39.7%. PV-GSHP is very tempting choice to consider when compared to any other systems in the study. PV-GSHP can save 15% more than the PV-ASHP, 27% more than the ASHP and 14% more than GSHP system.

However, choice for technology depends on the economic returns and capital cost of the project. In terms of fuel consumption, a PV-GSHP system is a viable technology.

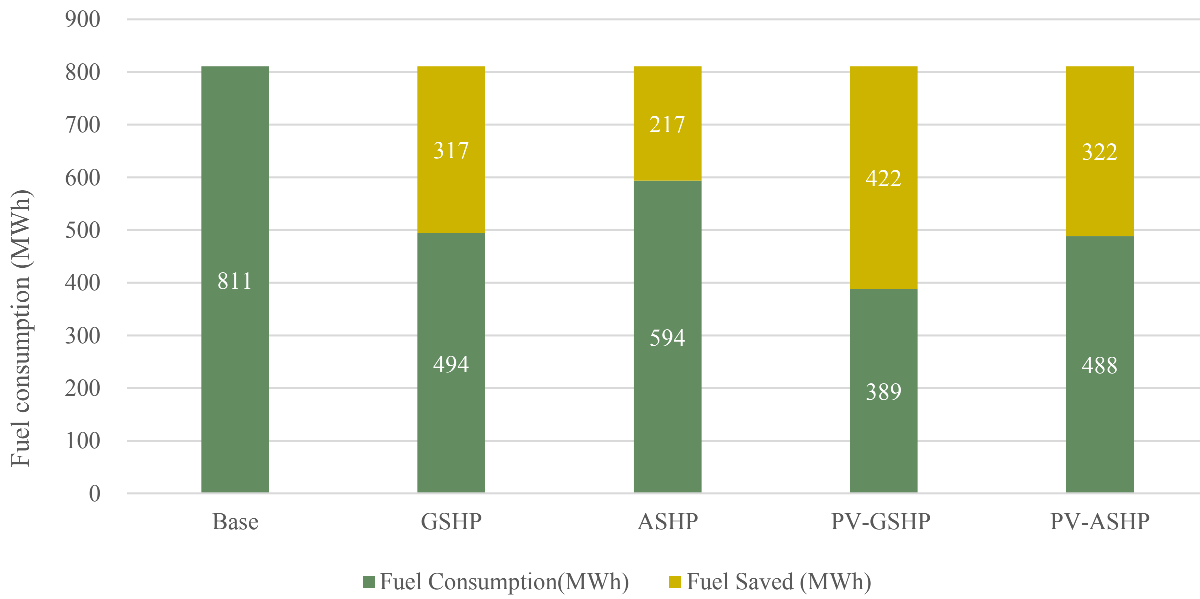


Figure 5.1: Fuel consumption between base case, GSHP, ASHP, PV-GSHP and PV-ASHP systems

### 5.6.2 Environmental impact

This section determines the most practical residential heating system and cooling system to reduce carbon dioxide emissions. Advantages for opting electricity production by renewable energy reduces the GHG emissions. The effectiveness of the technologies is considered on the impacts it has on the environment. The amount of GHG emissions is a reasonable approach for selecting a given system, as energy usage is insufficient measure for sustainable environmental impacts. All the proposed heat pump systems result in a reduction of $CO_2$ production when compared to the conventional system. The reduction of $CO_2$ provided carbon credits as incentives. Figure 5.2 shows GHG emission and annual gross GHG emission reduction of both the base case and proposed case systems. RETScreen Expert uses a technical approach to calculate the annual GHG emission reduction $\Delta_{GHG,Inc}$ as described in the RETScreen manual is shown in equation 5.1.

$$\Delta_{GHG,Inc} = (\Delta_{GHG,heat} + \Delta_{GHG,cool})\,(1- e_{cr}) \qquad \text{Equation 5.1}$$

where $e_{cr}$ is transaction fee for GHG emission reduction credit and $\Delta_{GHG,heat}$ and $\Delta_{GHG,cool}$ are annual reductions of GHG emission from heating and cooling. They are calculated in the equations 5.2 and 5.3

$$\Delta_{GHG,heat} = (e_{base,heat} - e_{prop,heat})\, E_{prop,heat} \qquad \text{Equation 5.2}$$

$$\Delta_{GHG,cool} = (e_{base,cool} - e_{prop,cool})\, E_{prop,cool} \qquad \text{Equation 5.3}$$

where $e_{base,heat}$ and $e_{base,cool}$ are base case factors of GHG emission for heating and cooling, and $e_{prop,heat}$ and $e_{prop,cool}$ are proposed case factors of GHG emission for heating and cooling. $E_{prop,heat}$ is the proposed case energy delivered by end-use annual heating and $E_{prop,cool}$ is the proposed case energy delivered by end-use annual cooling.

PV-GSHP reduces 60% of GHG emissions when compared to the base case, because the electricity produced from renewable sources are clean and free of emissions. The GSHP system alone reduces 40% of the GHG emissions. The PV-ASHP system reduces 40% of the GHG emissions, and the ASHP system reduces only 26% GHG emission. From the environmental point of view, PV-GSHP and GSHP systems are a more viable option in Fort Wayne compared to the ASHP, PV-ASHP and base case.

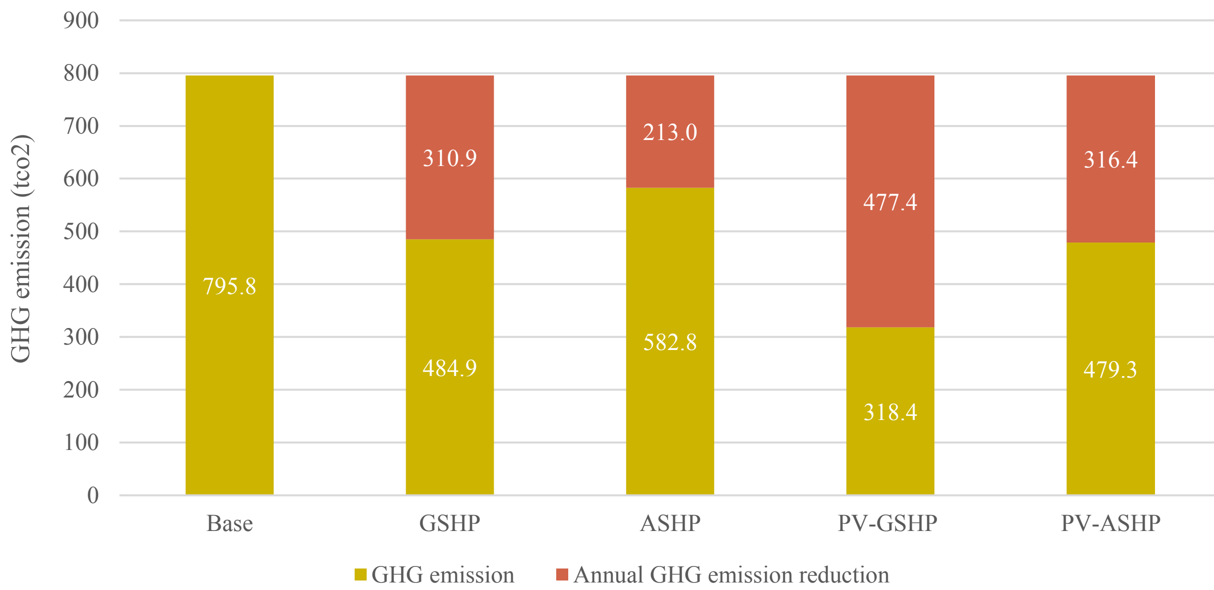


Figure 5.2: GHG emission and gross GHG emission reduction annually of all systems

### 5.6.3 Financial viability using equity payback period

Project equity is the required total investment for the project owner to finance the project. The project equity is determined at the end of the year. It is calculated using the debt ratios, total initial costs, and the initial cost incentives. The equity payback period depends on the debt interest rate, debt ratio and debt term of the project. RETScreen Expert refers the equity payback period as a year for a positive cash flow. It is in first year when cumulative cash flow for project is positive. It is calculated by solving after-cash flow in that year. Formula for simple payback and year to positive flow (also Equity payback period) taken from RETScreen Manual is given below in equation 5.4

$$\text{Simple payback period (SPP)} = \frac{(C-IG)}{(C_{ener}+C_{capa}+C_{RE}+C_{GHG})-(C_{O\&M}+C_{fuel})} \qquad \text{Equation 5.4}$$

$C$ is complete initial cost of project, $C_{ener}$ is annual energy savings, $C_{RE}$ is annual renewable energy production credit income, $C_{capa}$ is annual capacity savings, $C_{GHG}$ is GHG reduction income, $C_{capa}$ is annual capacity savings, $C_{ener}$ is annual energy savings, $C_{fuel}$ is annual cost of fuel or electricity, *IG* is incentives and grants value. The year-to-positive cash flow $N_{PCF}$ is first year when the cumulative cash flow for project is positive (also called as equity payback period). It is calculated by using the following equation 5.5 for $N_{PCF}$

$$0 = \sum_{n=0}^{N_{PCF}} \tilde{C}_n \qquad \text{Equation 5.5}$$

where $\tilde{C}_n$ is after-tax cash flow in year "$n$".

5.6.3.1 Equity pay back at debt ratio zero (%) with GSHP average loop cost

Discounted payback period or equity payback period is calculated comparing GHSP and other proposed system. In this case, GHSP loop cost was taken as $2400, which is the average value embodied in RETScreen Expert. Four different electricity rates, viz. $0.0812, $0.1, $0.12, $0.14 per kW-h have been considered due to uncertainties of electricity rates in the future. To simplify the analysis, in this part of the study, the debt ratio is zero percent, meaning the property owner will pay all the capital costs upfront. Figure 5.3 shows that AHSP system has less than seven years of payback period when the electricity rate is $0.0812 and as the electricity rates are increase, the equity pay period of the ASHP system lowers. Due to the loop cost, the GSHP system equity pay back is larger than the ASHP.

When a PV system combined with ASHP has an equity payback period that is lower than PV-GSHP with the various electricity rates scenarios. However, both the cases have a longer equity payback period when comparing GSHP and ASHP systems. ASHP system and PV-ASHP systems are preferable in contrast to GHSP and PV-GSHP systems in terms of year to positive cash flow because the loop cost of GSHP is high.

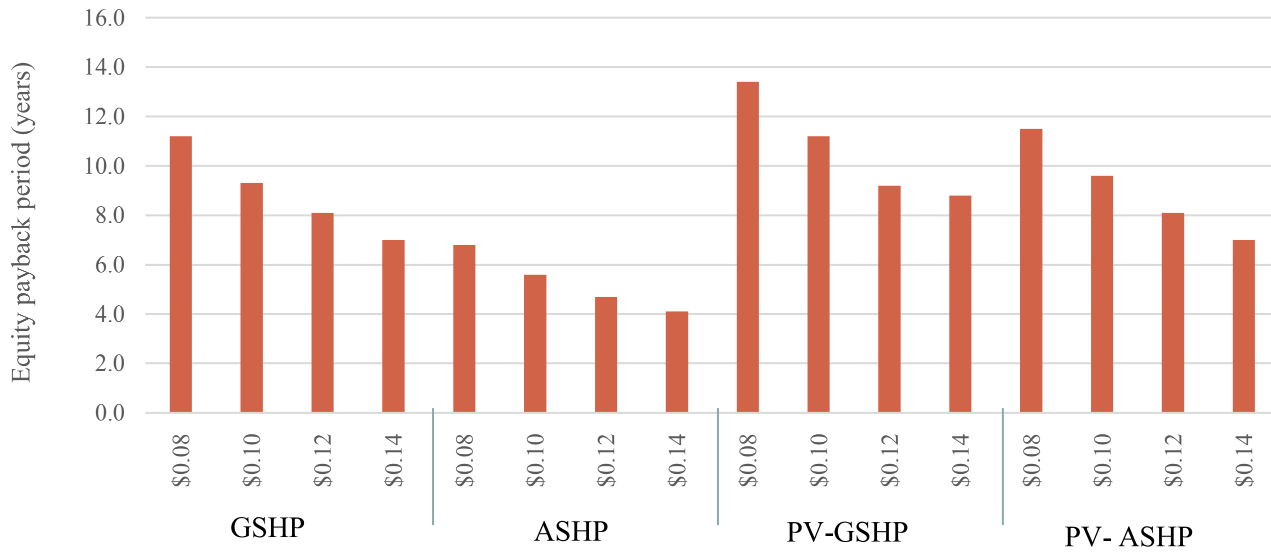


Figure 5.3: Equity payback at debt ratio (0%) when GHSP system loop cost is average

5.6.3.2 Equity pay back at debt ratio zero (%) with GSHP minimum loop cost

All the parameters in this scenario are kept similar to the section 5.6.3.1 except a change in GSHP loop cost that is picked from average to minimum value. The minimum loop cost is now set to $800, which is also embodied in RETScreen. The GSHP and PV-GSHP systems are compared with ASHP and PV-ASHP systems by taking a zero-debt ratio as similar to previous section. When the cost of the loop is decreased, there is a high variation in the equity payback period for the GSHP system when compared to ASHP system considering all the electricity rates fluctuations. As the cost of loop declines, the equity payback period for GSHP and PV-GSHP systems decreases, which is clearly noticeable in the figure 5.4. In addition to this, PV-ASHP payback is higher than the PV-GSHP system, GSHP and ASHP system. GSHP and PV-GSHP systems are a more viable and economic option when the loop cost is decreased.

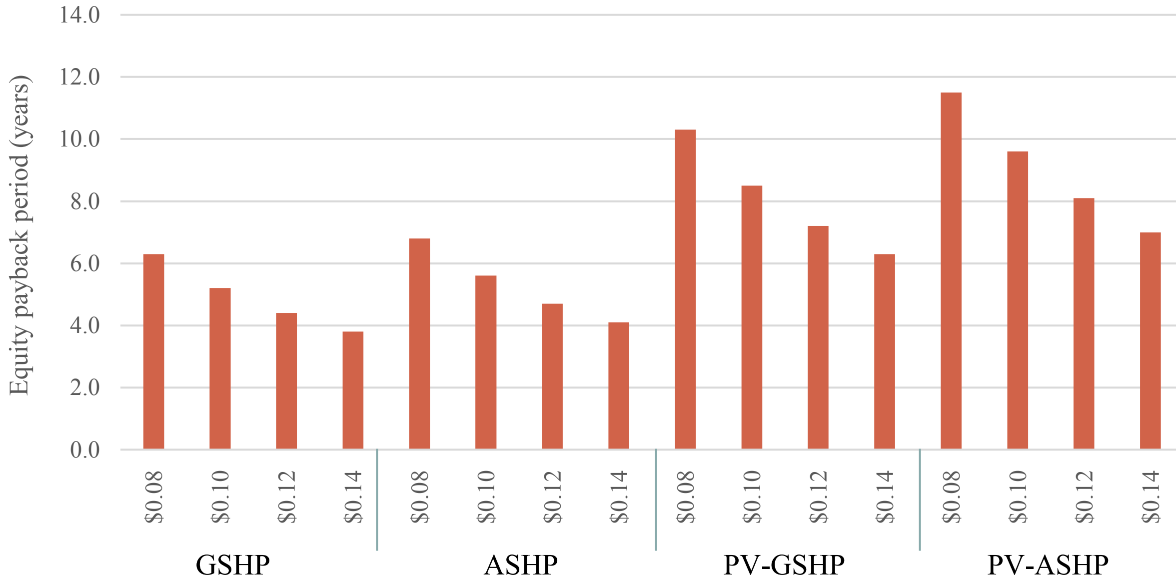


Figure 5.4: Equity payback at debt ratio (0%) when GHSP system loop cost is minimum

5.6.4 Financial viability using net present value (NPV) and annual life cycle savings **(ALCS)**

Net present value (NPV) conveys what dollar value a project adds to the company or any organization. NPV is defined as an investment that lets an investor know whether the investment can achieve a target yield for a given initial investment. It is a summation of cash flow for each period in the holding period, discounted at investor's required rate of return. The technical model for calculating NPV and ALCS is mentioned in RETScreen manual. Note that:

- Positive NPV - If NPV is positive, the investor is paying less than what the asset is worth.
- Negative NPV - If NPV is negative, the investor is paying more than what the asset is worth.
- Zero NPV - If NPV is zero, the investor is paying exactly what the asset is worth.

The formula for calculating NPV is given in equation 5.

$$NPV = \sum_{n=0}^{N} \frac{\tilde{C}_n}{(1+r)^n}$$ Equation 5.6

$$\tilde{C}_n = C_n - T_n$$ Equation 5.7

where $r$ = rate of discount, $\tilde{C}_n$ = after flow of tax cash, $C_n$ = net cash flow and $T_n$ = yearly taxes, $n$ = years.

Though initial costs are important, the detailed cost analysis for a project is often done using the annual life cycle savings (ALCS). ALCS accounts for the initial cost, maintenance costs throughout the life of the project, and the value of money time over life of the project by using NPV and net future value calculation. The formula for calculating ALCS is

$$ALCS = \frac{NPV}{\frac{1}{r}\left[1 - \frac{1}{(1+r)^N}\right]}$$ Equation 5.8

where $N$ is project life years and $r$ is discount rate.

5.6.4.1 NPV with GSHP loop cost considered as the average value

NPV of a project is value of total future cash flows discounted at today's currency rate. NPV determines if a project investment is financially acceptable and if the indicators have a positive value to have a feasible project. In using NPV method, it is required to choose a discounting rate for the cash flows. RETScreen Expert calculates the NPV by using the cumulative after-tax cash flows. The NPV technical model uses cumulative cash flow and a discount rate that is explained in RETScreen manual. In figure 5.5, the comparison for GHSP, PV-GSHP, ASHP and PV-ASHP are performed by considering the average loop cost for the GSHP system and keeping the debt ratio at zero percent. These results show that the systems are all feasible using the common financial parameters set in table 5.4. The results show when the GSHP loop cost is higher, ASHP related systems has higher NPV in all electricity fluctuations and seems to reliable option.

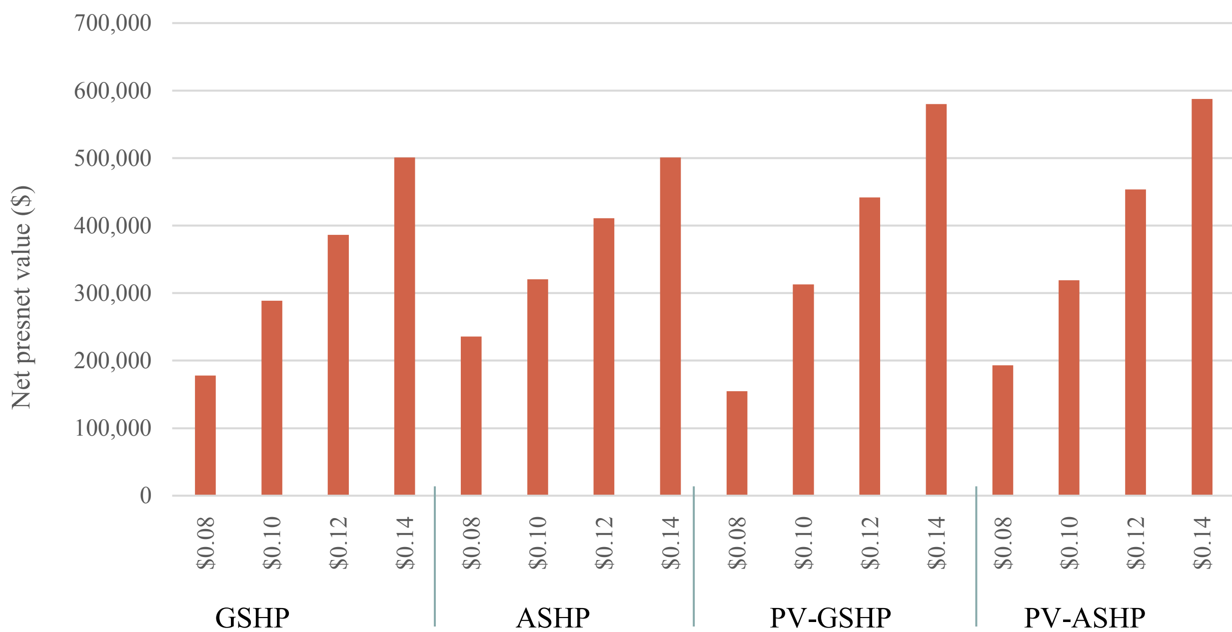


Figure 5.5: Net Present value at debt ratio (0%) when GHSP system loop cost is average

5.6.4.2 NPV with GSHP loop cost as the minimum value

When the GSHP loop cost changes from average value to minimum value in RETScreen, the GSHP and PV-GSHP systems feasibility increases by more than 40% when compared to other proposed systems. The higher the NPV, the higher is the feasibility of the project. The figure 5.6 shows the NPV at zero percent debt ratio when the loop cost is considered minimum for GSHP. PV- GSHP gives high feasibility for a project when electricity rate is $0.14 or more and gives more profitability. The GSHP has a higher NPV than NPV for the ASHP system and PV-ASHP. The only challenge in considering the GSHP system is the loop cost and once it is reduced, the project with GSHP related system becomes more feasible.

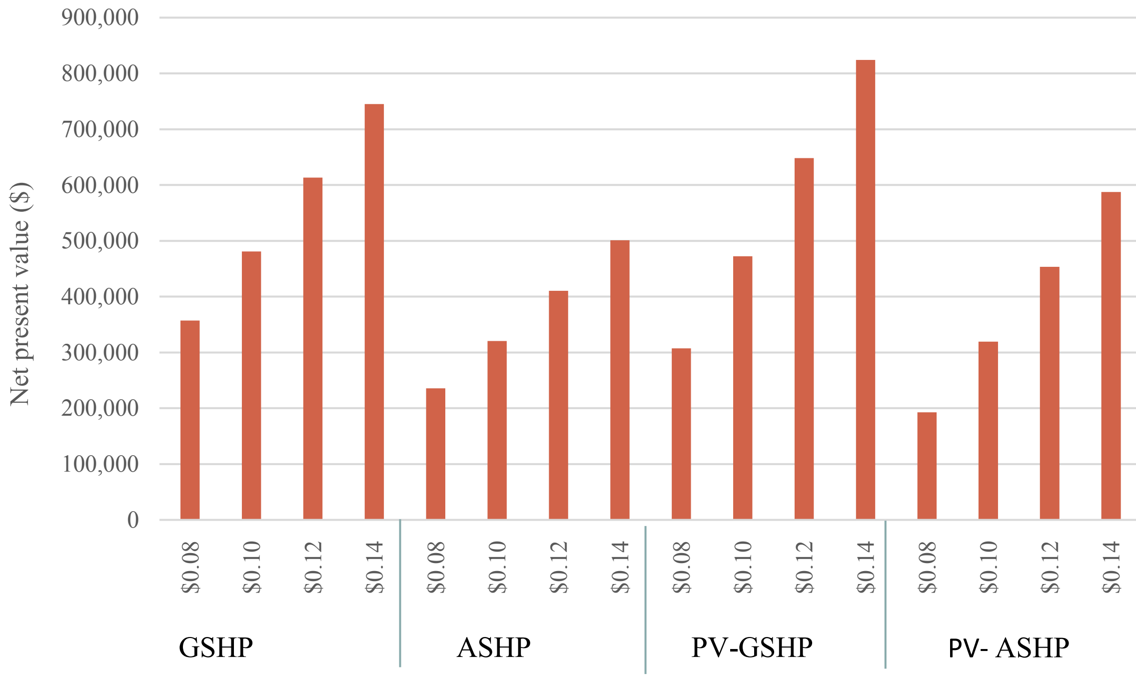


Figure 5.6: Net Present value at debt ratio (0%) when GHSP system loop cost is minimum

### 5.6.4.3 ALCS with GSHP loop cost as the average value

Annual life cycle savings (ALCS) is an annual savings that have the same life and NPV as project. ALCS is calculated by using parameters such as NPV and discount rate. In the figure 5.7, ALCS analysis is between the GHSP, PV-GSHP, ASHP and PV-ASHP systems by considering the average loop cost of the GSHP and keeping the debt ratio zero percent. Similar to the section 5.6.4.1, there are better savings in ASHP and PV-ASHP systems when comparing other systems.

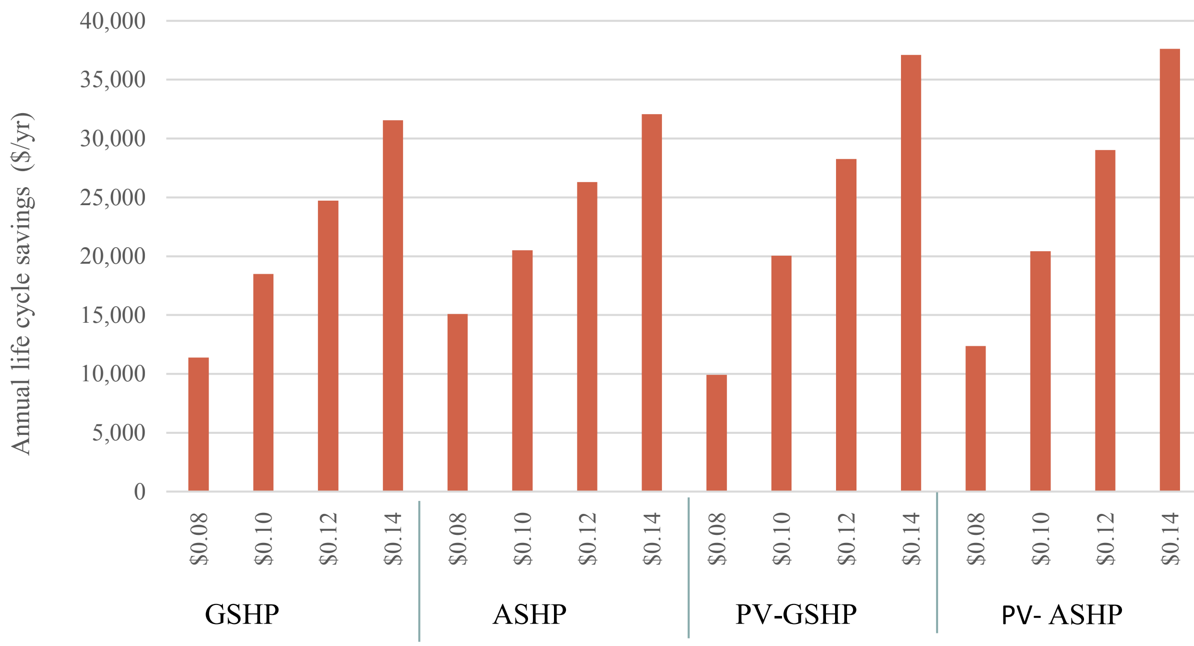


Figure 5.7: ALCS at debt ratio (0%) when GHSP system loop cost is average

5.6.4.4 ALCS with GSHP loop cost as the minimum value

ALCS analysis is done between the GHSP, PV-GSHP, ASHP and PV-ASHP systems by taking the average loop cost of the GSHP system and keeping the debt ratio zero percent illustrated in figure 5.8. Similar to the section 5.6.4.3, all parameters are kept constant except changing the loop cost to minimum value and the ALCS of the project was found. As NPV increases, ALCS of the project also increases. The savings of the project is more for GHSP and PV- GHSP systems when loop installation cost is brought down. This concludes that GHSP and PV-GSHP are advantageous compared to the other proposed system when the loop cost is lesser. ALCS of the GSHP system is more even when the ASHP is integrated along with PV.

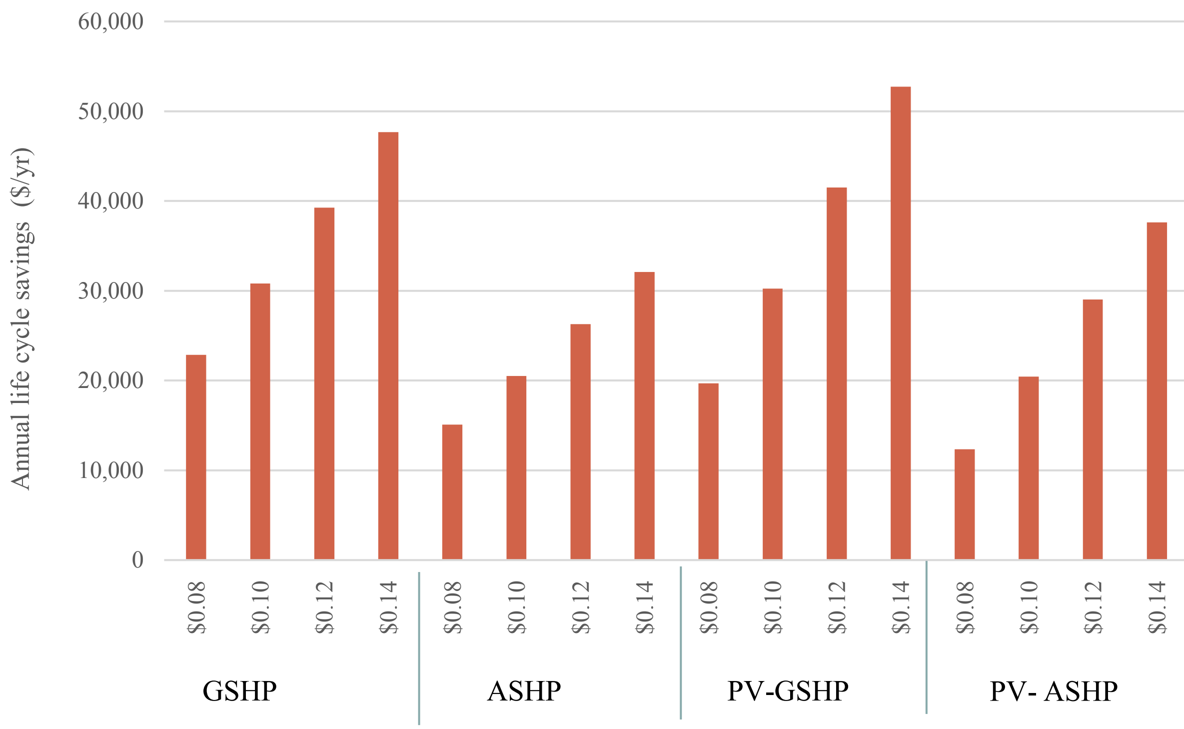


Figure 5.8: ALCS at debt ratio (0%) when GHSP system loop cost is minimum

### 5.6.5 Financial decision-making criteria using cumulative cash flow

Cumulative cash flow represents the net accumulation of after-tax flows from the year zero. Net flows are used to calculate the cumulative flows of the project. Cumulative cash flow is the net cash flow for all the project years. Net cash flow of the project equals the difference between cash inflow and cash outflow.

When the electricity rate is $0.0812, the GSHP system case is chosen to study the trend of cumulative cash flow. Equations 5.9 to 5.13 show the calculation of cumulative cash flow, which are taken from RETScreen manual and (Le Du, 2014). For the year 0, the cash flow is

$$C_{out,0} = C(1 - f_d) \quad \text{Equation 5.9}$$

where $f_d$ is the debt ratio. For later years, cash outflow $C_{out,n}$ is computed as

$$C_{out,n} = C_{O\&M}(1 + r_i)^n + C_{fuel}(1 + r_e)^n + C_{per}(1 + r_i)^n + D \quad \text{Equation 5.10}$$

where $n$ is year, $r_i$ is inflation rate, $C_{O\&M}$ is yearly operation and maintenance costs incurred, $C_{fuel}$ is annual cost of fuel or electricity, $C_{per}$ is periodic costs of system, $r_e$ is energy cost escalation rate and $D$ is annual debt payment. For zeroth year, cash inflow $C_{in,0}$ is equals incentive grants $IG$, i.e.,

$$C_{in,0} = IG \quad \text{Equation 5.11}$$

while for later years, cash inflow $C_{in,n}$ is computed as

$$C_{in,n} = C_{ener}(1 + r_e)^n \quad \text{Equation 5.12}$$

where $n$ is year, $C_{ener}$ is energy savings annually comparing the reference system. Cash flow $C_n$ of year $n$ is the difference of the cash inflow and outflow, i.e.,

$$C_n = C_{in,n} - C_{out,n} \quad \text{Equation 5.13}$$

Figure 5.9 is the graph taken from RETScreen Expert showing the trend of the cumulative cash flows for the GSHP system at an average loop cost and at the electricity rate of $0.0812. In this scenario, a 99% of debt ratio, 10 years of debt term and a 4% of debt interest rate was considered.

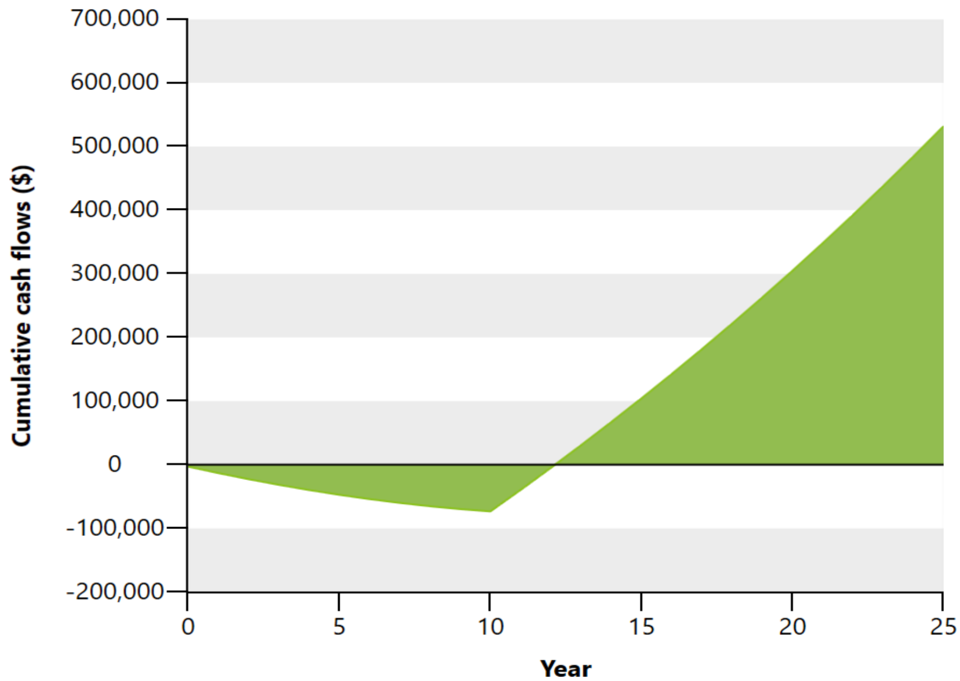


Figure 5.9: Time varying debt ratio (99%) at electricity rate $0.0812 when GSHP system loop cost is average

5.6.5.1 Cumulative cash flow of GSHP system at average loop cost

For the zeroth year, the outflow cash equaled the total investment fraction, which was necessary for financing the project. Different scenarios have been considered to study and find the favorable choice between debt ratio at 0%, 50% and 99%. A 4% debt interest rate and 10 years debt term was considered. When the debt ratio is 50% it means the initial payment was partial and 99% means initial payment was fully borrowed. Zero debt ratio means the initial payments are completely paid up front. When the debt ratio is zero percent, the project is more promising over the years as illustrated in the figure 5.10 when considering the electricity rate at $0.1. The feasibility of the GSHP systems depend on the ground loop cost. GSHP systems are cost competitive when comparing with ASHP and other conventional systems when the loop cost is high. Average loop cost of $2400 was considered for GSHP system loop installation, with increasing loop costs of the GSHP system the feasibility of the project decreases.

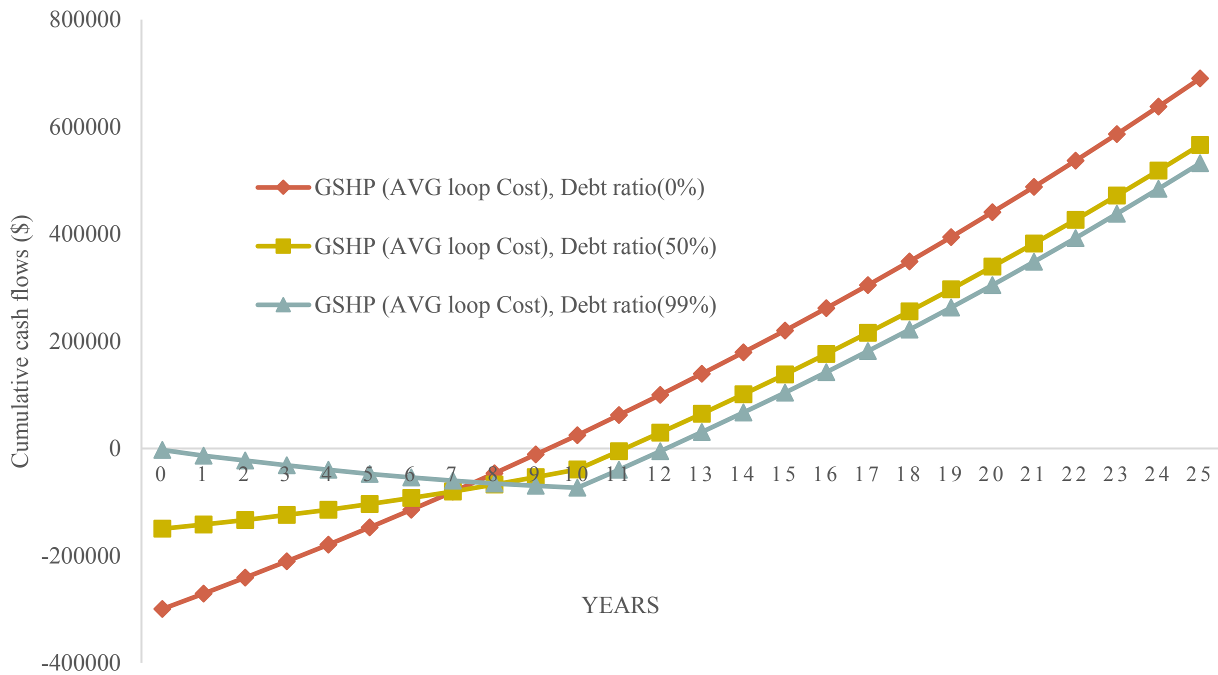


Figure 5.10 Time varying debt ratio at electricity rate $0.1 when GSHP system loop cost is average

### 5.6.5.2 Cumulative cash flow of GSHP system at minimum loop cost

A minimum loop cost of $800 was picked for GSHP system installation for this case. As the loop cost decreases, the feasibility of the project increases. Similar to the section 5.6.5.1, GSHP system was investigated with a minimum loop cost between the debt ratios of 0%, 50 % and 99%. The financial attractiveness of the GSHP systems in the Fort Wayne could not be increased as long as the loop installation costs were high. When the minimum loop cost was $800 per unit in this section, feasibility of the GSHP system was attractive when the debt ratio was at 50%. Figure 5.11 explains cumulative cash flow at debt ratio ratios 0%, 50% and 99% when the cost of GSHP system was minimum and electricity rate was considered \$ 0.1. This explains that GSHP system is more attractive choice at debt ratio 50% when the electricity price is \$0.1 compared to debt ratios at 0% and 99%.

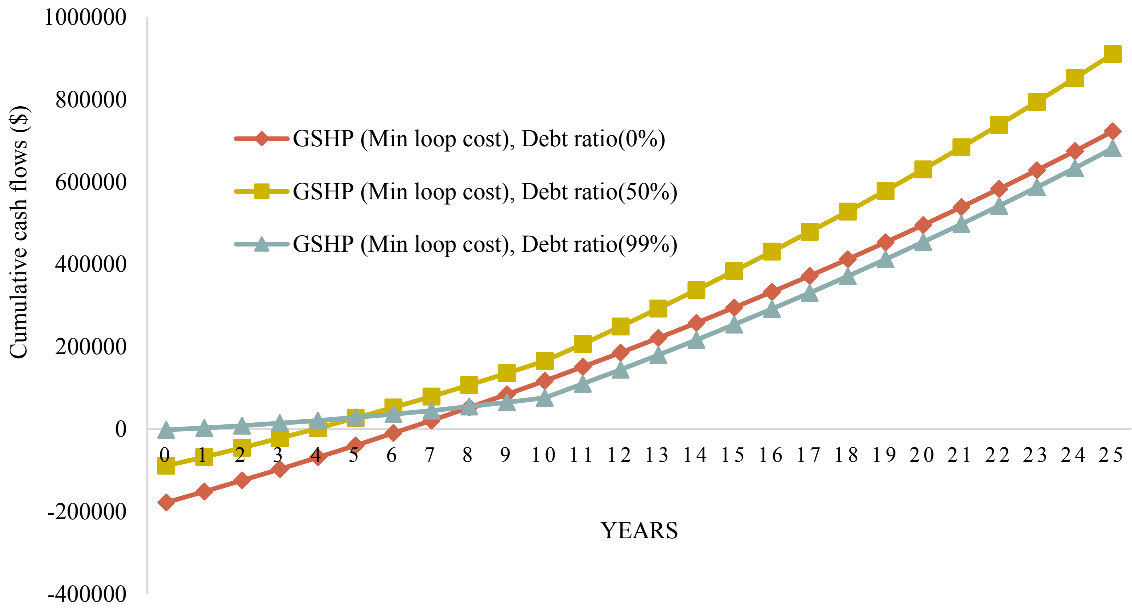


Figure 5.11: Time varying debt ratio at electricity rate \$0.1 when GSHP system loop cost is minimum

# CHAPTER 6. CONCLUDING REMARKS

## 6.1 Summary

The topic of this thesis is the modeling and simulation of heat pumps systems combined with photovoltaic systems used in residential buildings. The primary software used in this study is RETScreen Expert. RETScreen Expert is an energy system modeling tool. A verification study has been performed comparing the predictions from RETScreen Expert to predictions from other software and to previously published field data. The building considered in this study is a multifamily, residential modeled using eQUEST. The building parameters from eQUEST and the determined loads and energy consumption rates are used as inputs to RETScreen Expert. RETScreen Expert is used to perform energy, environmental, and financial studies comparing the different systems.

## 6.2 Conclusions

This thesis study considers the operation of a conventional heating and cooling systems as a base case and examines alternatives to it by using single technology i.e. heat pumps or a combination of technologies, which use heat pumps combined with photovoltaics. Heat pump systems reduce overall energy use compared to the base case, but increase electricity use with heat pump systems, overall GHG emissions are reduced.

When combined technology was considered, PV-GSHP had a promising approach in terms of GHG emissions reductions and annual fuel savings. When single technology was considered, GSHP systems were better in terms of savings of fuel and reductions of GHG emission. The NPV of ASHP and PV-ASHP was better than that of GSHP and PV-GSHP systems when installation loop cost of GSHP was higher. However, when the loop installation cost was reduced, the NPV of GHSP and PV-GSHP systems are viable options to consider in all electricity rates. When compared between various debt ratios, a GSHP system at 50% debt ratio, 4% debt interest rate and 10 years debt term gave a higher internal rate of return to the investor when comparing other scenarios.

In general, single technology GSHP systems are environmentally friendly, save fuel savings and are financially feasible when the loop installation cost is minimum. If combined technology is preferred, PV-GSHP systems are also more environmentally friendly and have fuel savings far more than any of the other proposed systems. But the economic feasibility of the both the GSHP and PV-GSHP systems strongly depends on loop installation cost.

## 6.3 Recommendations

A typical multi-family residential building is modeled in eQUEST by with minimal changes and using primarily the default parameters. This research is limited to typical residential buildings only. Future research can investigate designing a building and finding the outputs according to the user specifications in eQUEST. In RETScreen Expert, the economic parameters are guided by previous research studies, more investigation can be conducted to follow different approaches in economic parameters. Moreover, the single technology and combined technology GHG emissions, fuel savings, and financial outputs can be analyzed and compared using actual field data.

# REFERENCES


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# APPENDIX A - RETSCREEN EXPERT SIMULATION

| | Unit | Climate data location | Facility location | Source |
|---|---|---|---|---|
| Latitude | | 41.0 | 41.0 | |
| Longitude | | -85.2 | -85.2 | |
| Climate zone | | 5A - Cool - Humid | | User-defined |
| Elevation | m | 252 | 240 | Ground – Ground |
| Heating design temperature | °C | -15.7 | | Ground |
| Cooling design temperature | °C | 31.3 | | Ground |
| Earth temperature amplitude | °C | 21.6 | | NASA |

| Month | Air temperature | Relative humidity | Precipitation | Daily solar radiation - horizontal | Atmospheric pressure | Wind speed | Earth temperature | Heating degree-days 18 °C | Cooling degree-days 10 °C |
|---|---|---|---|---|---|---|---|---|---|
| | °C | % | mm | kWh/m²/d | kPa | m/s | °C | °C-d | °C-d |
| January | -3.5 | 77.5% | 100.97 | 1.76 | 98.8 | 5.0 | -5.2 | 667 | 0 |
| February | -1.5 | 75.9% | 93.19 | 2.57 | 98.8 | 4.6 | -2.5 | 546 | 0 |
| March | 3.4 | 70.7% | 93.79 | 3.47 | 98.6 | 4.9 | 3.0 | 453 | 0 |
| April | 10.0 | 66.3% | 95.85 | 4.62 | 98.5 | 4.8 | 10.6 | 240 | 0 |
| May | 16.0 | 68.1% | 115.38 | 5.64 | 98.6 | 4.2 | 17.1 | 62 | 186 |
| June | 21.2 | 69.3% | 114.52 | 6.23 | 98.6 | 3.6 | 21.7 | 0 | 336 |
| July | 23.2 | 72.9% | 118.50 | 6.06 | 98.7 | 3.2 | 23.5 | 0 | 409 |
| August | 21.8 | 76.6% | 111.54 | 5.35 | 98.8 | 2.9 | 22.1 | 0 | 366 |
| September | 17.7 | 74.1% | 90.39 | 4.27 | 98.9 | 3.2 | 17.8 | 9 | 231 |
| October | 11.4 | 72.9% | 79.39 | 3.01 | 98.9 | 3.9 | 11.6 | 205 | 43 |
| November | 5.2 | 76.4% | 83.24 | 1.83 | 98.8 | 4.6 | 4.7 | 384 | 0 |
| December | -1.2 | 79.3% | 89.93 | 1.43 | 98.8 | 4.7 | -2.4 | 595 | 0 |
| **Annual** | **10.4** | **73.3%** | **1,186.69** | **3.86** | **98.7** | **4.1** | **10.2** | **3,160** | **1,571** |
| **Source** | Ground | Ground | NASA | Ground | Ground | Ground | NASA | Ground | Ground |
| Measured at | | | | | m | 10 | 0 | | |

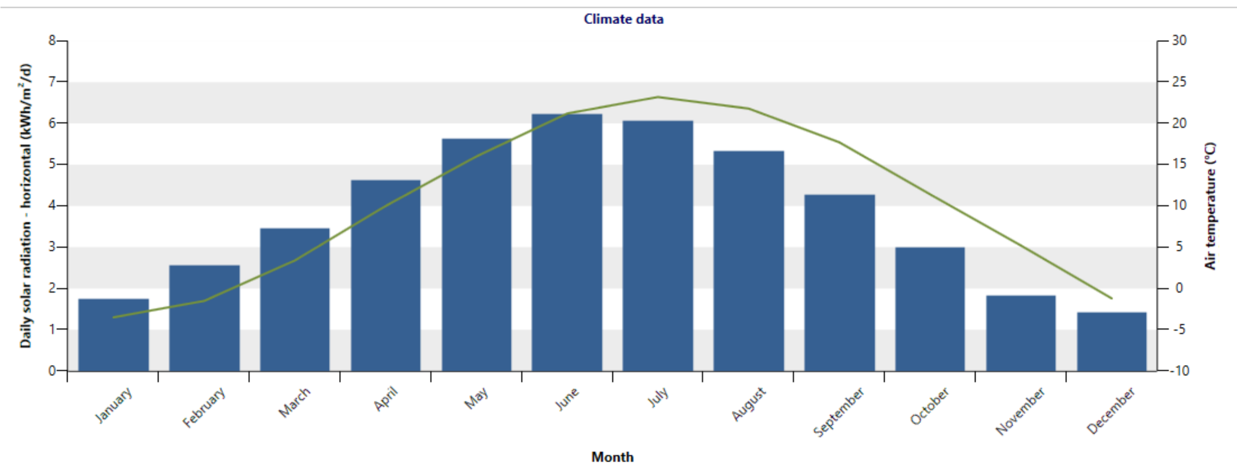


Figure A.1 – RETScreen Expert climatic parameters window

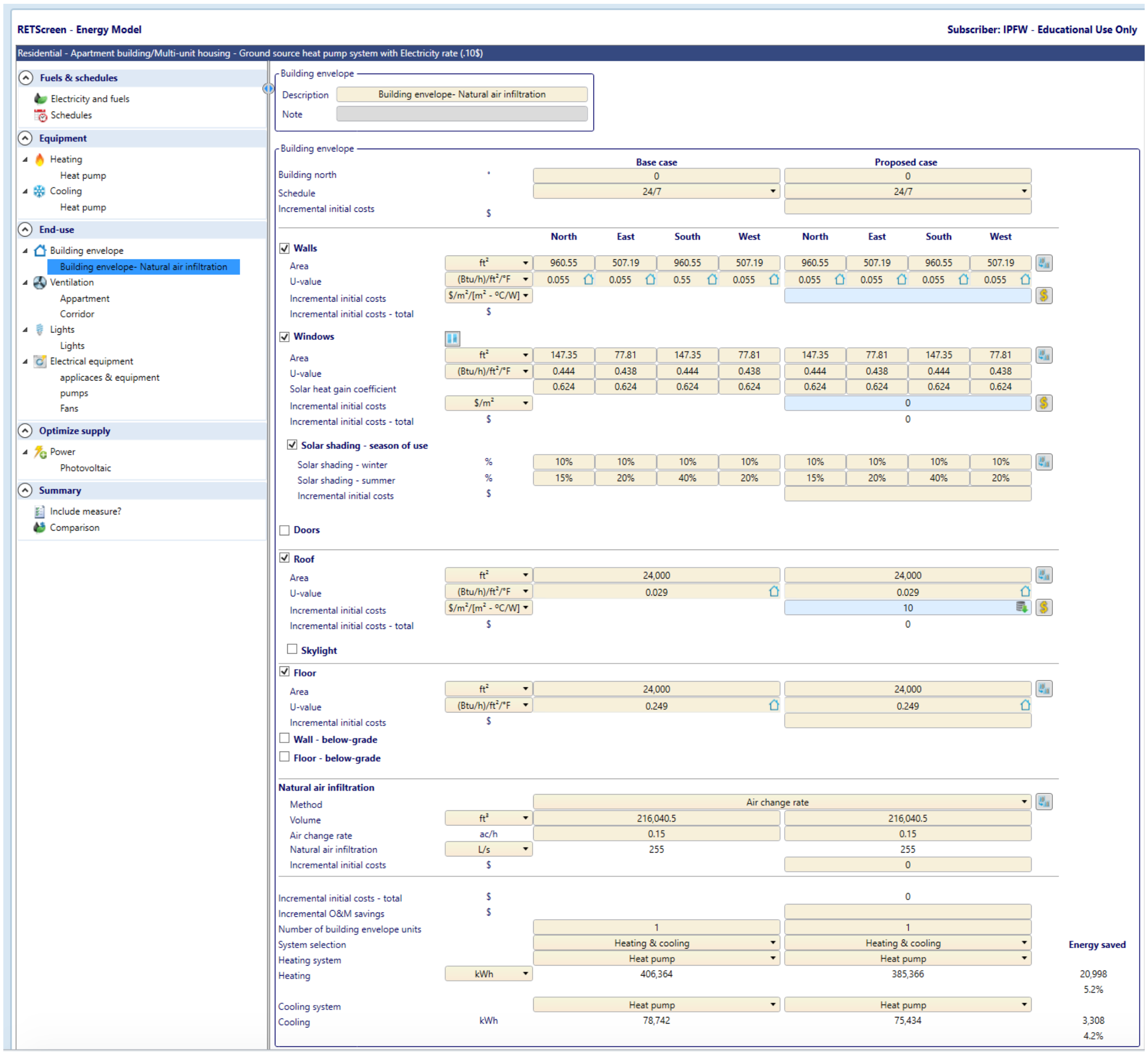


Figure A.2 – RETScreen building envelope inputs window

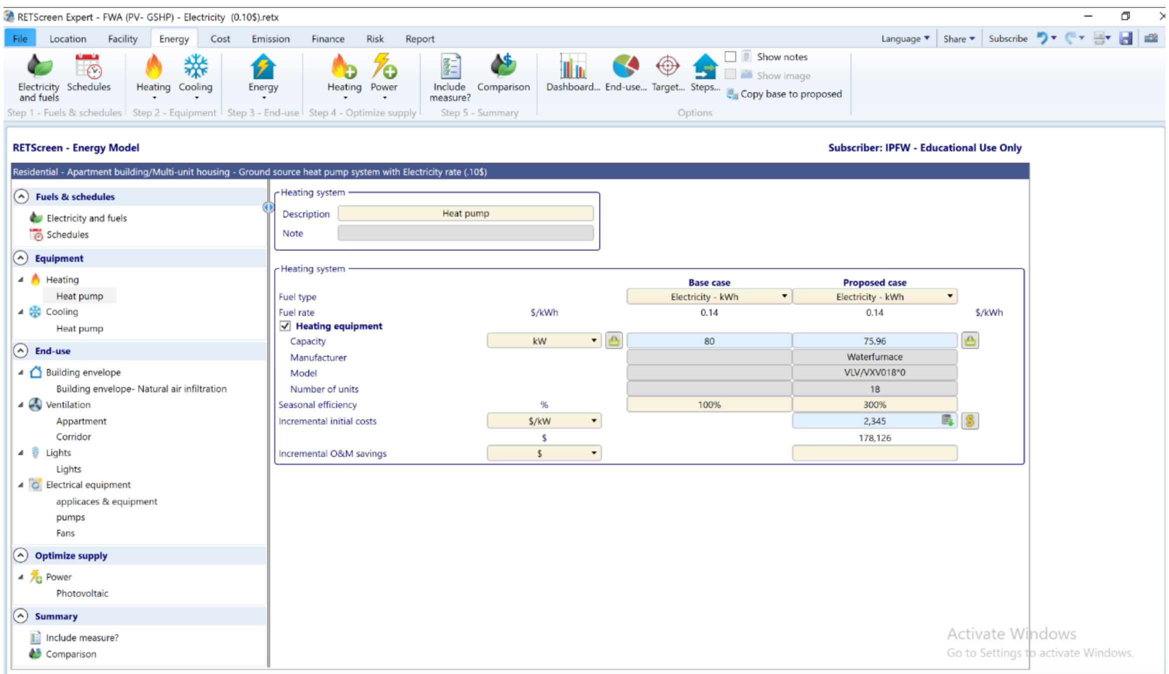


Figure A.3 – RETScreen Expert heat pumps parameters input window

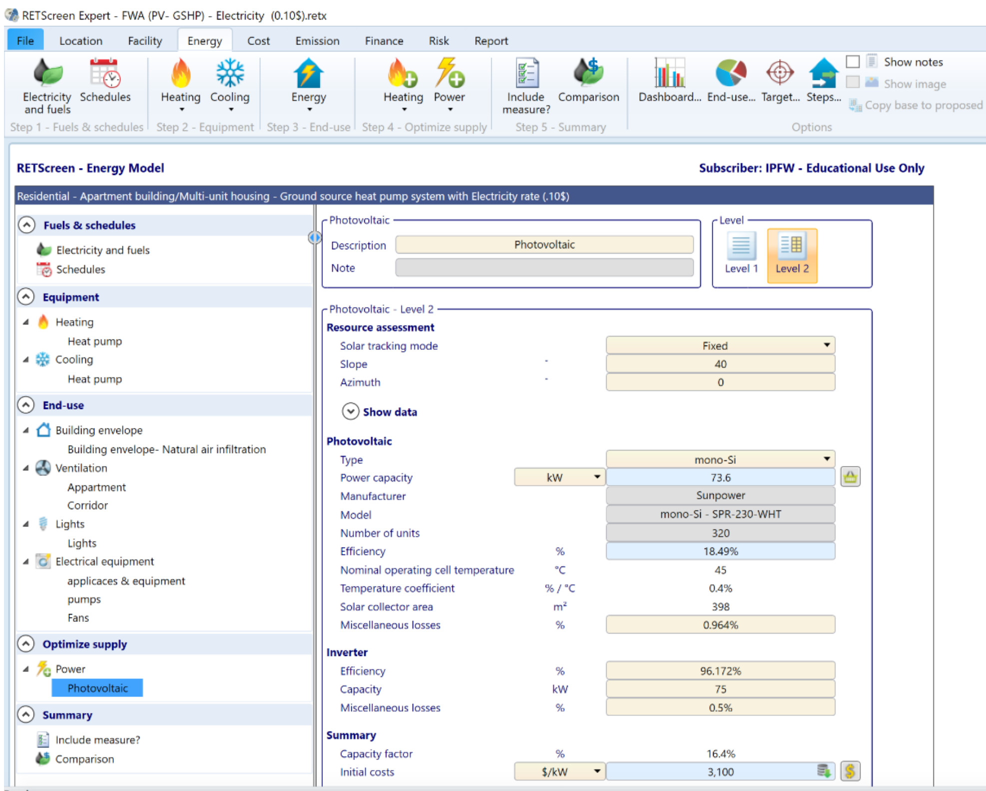

Figure A.4 – RETScreen Expert PV system parameters input window

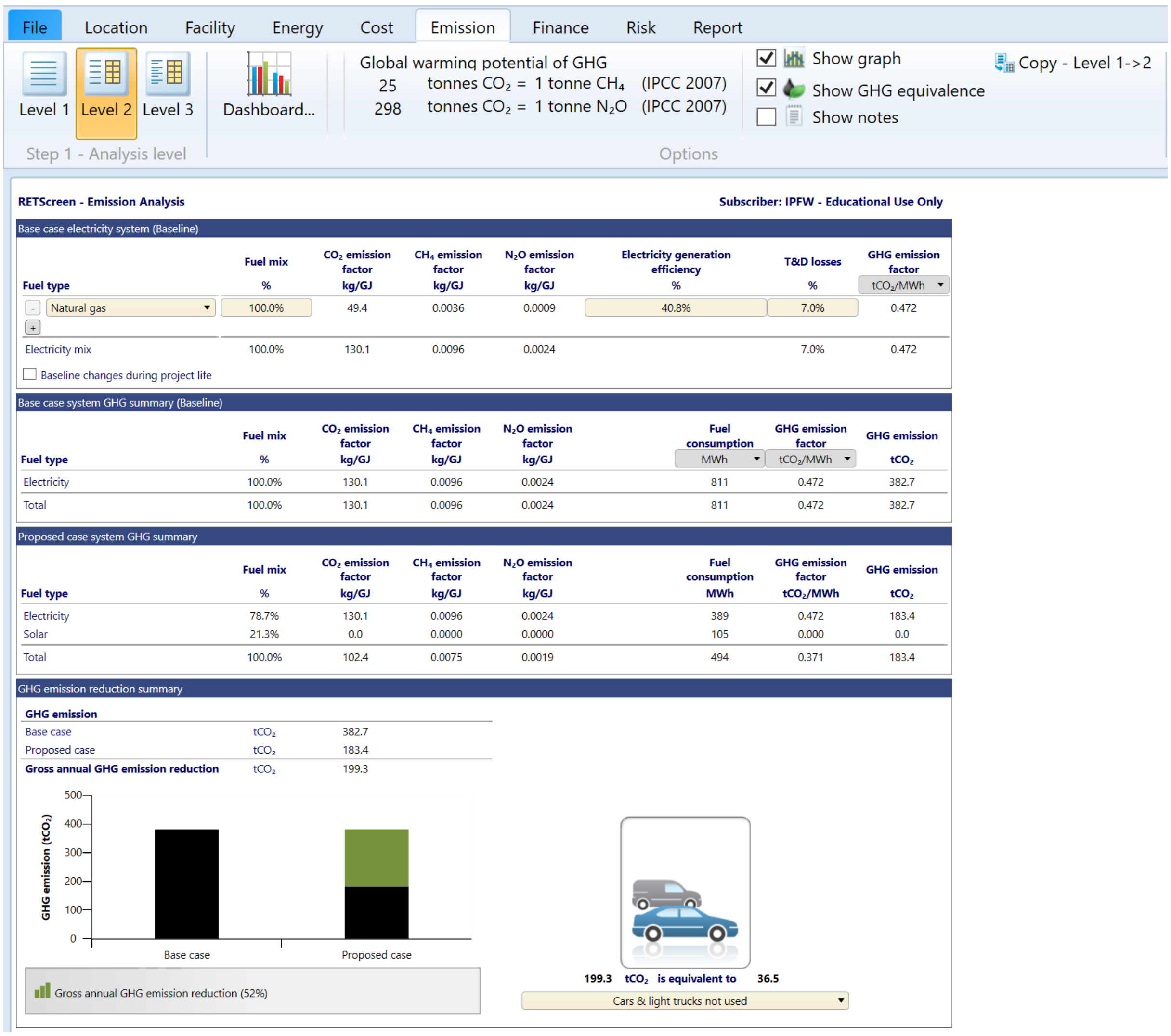


Figure A.5 – RETScreen Expert emissions parameters window

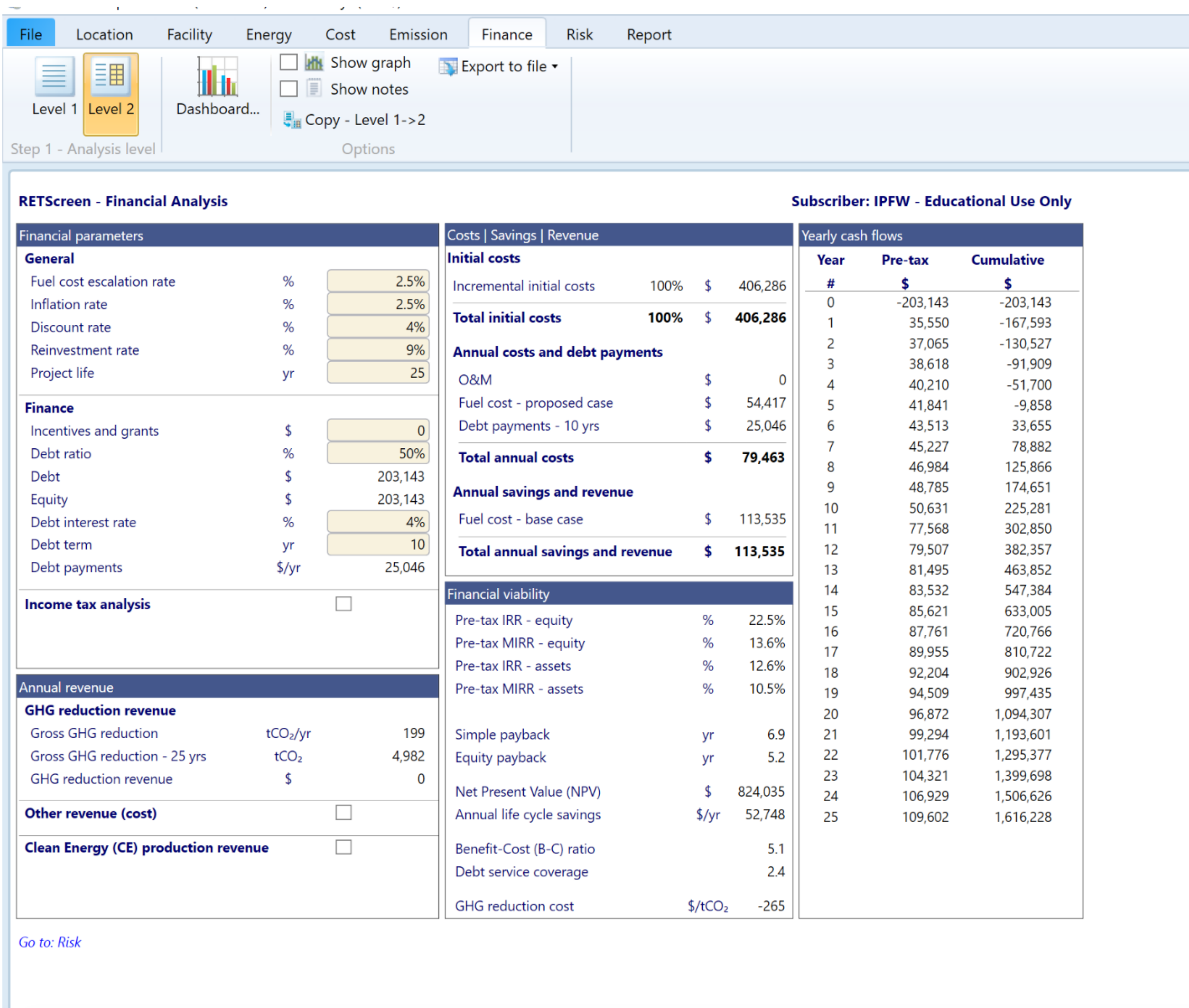


Figure A.6 – RETScreen Expert financial parameters window

# APPENDIX B - SYSTEM ADVISORY MODEL (SAM) SIMULATION PROCEDURE

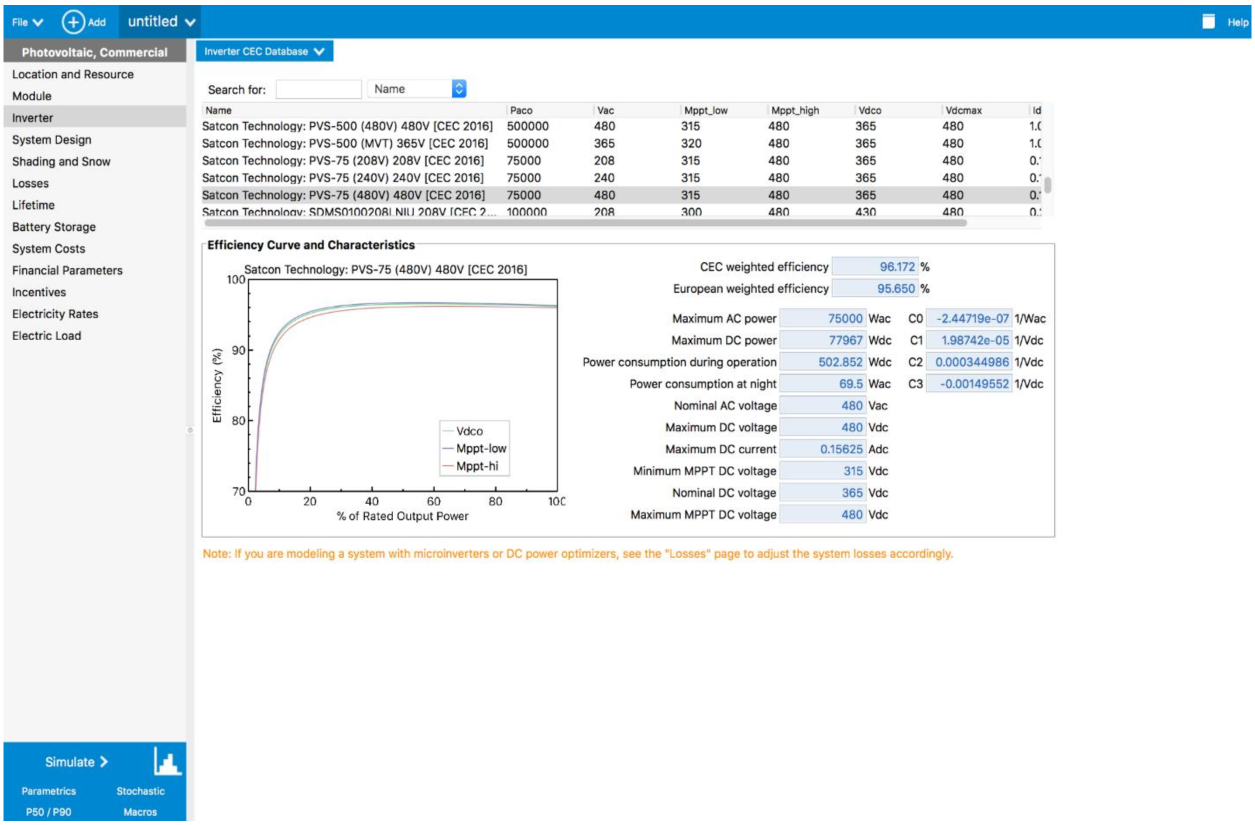

Figure B.1 – SAM module parameters input window

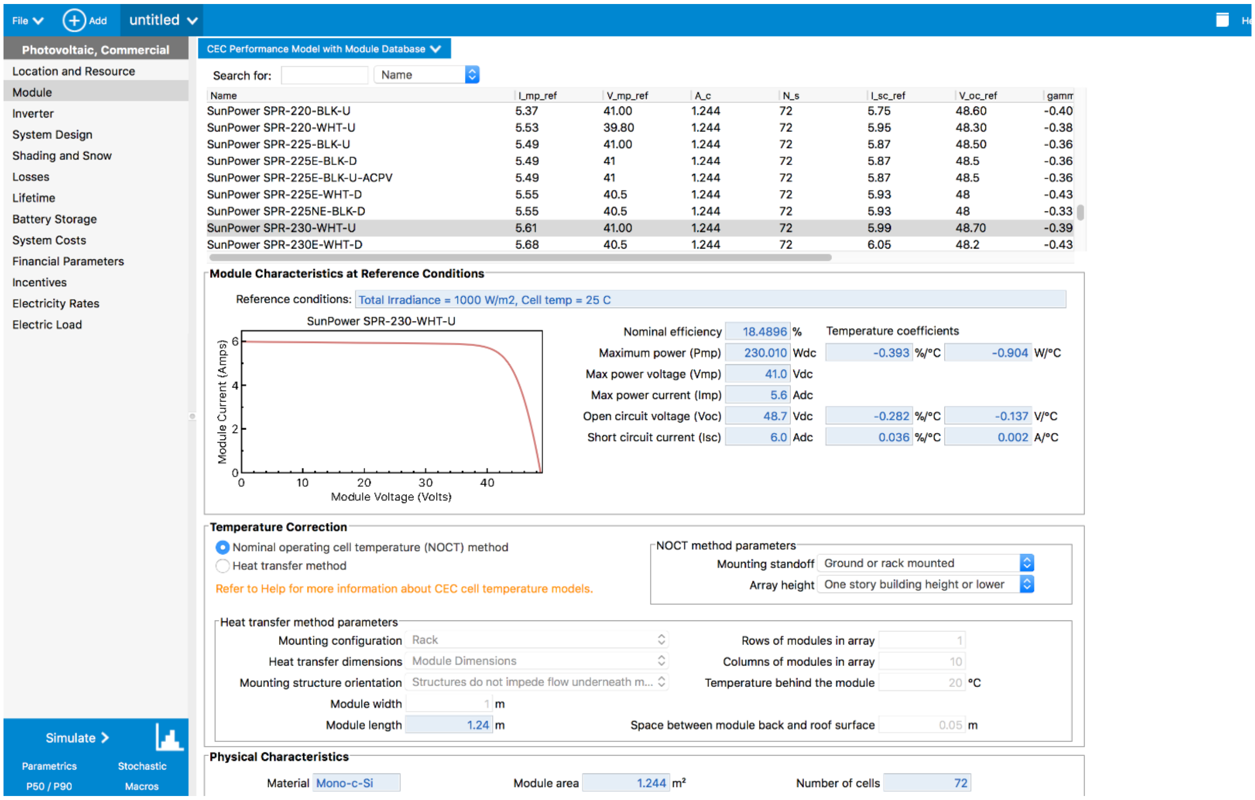


Figure B.2 – SAM inverter parameters input window

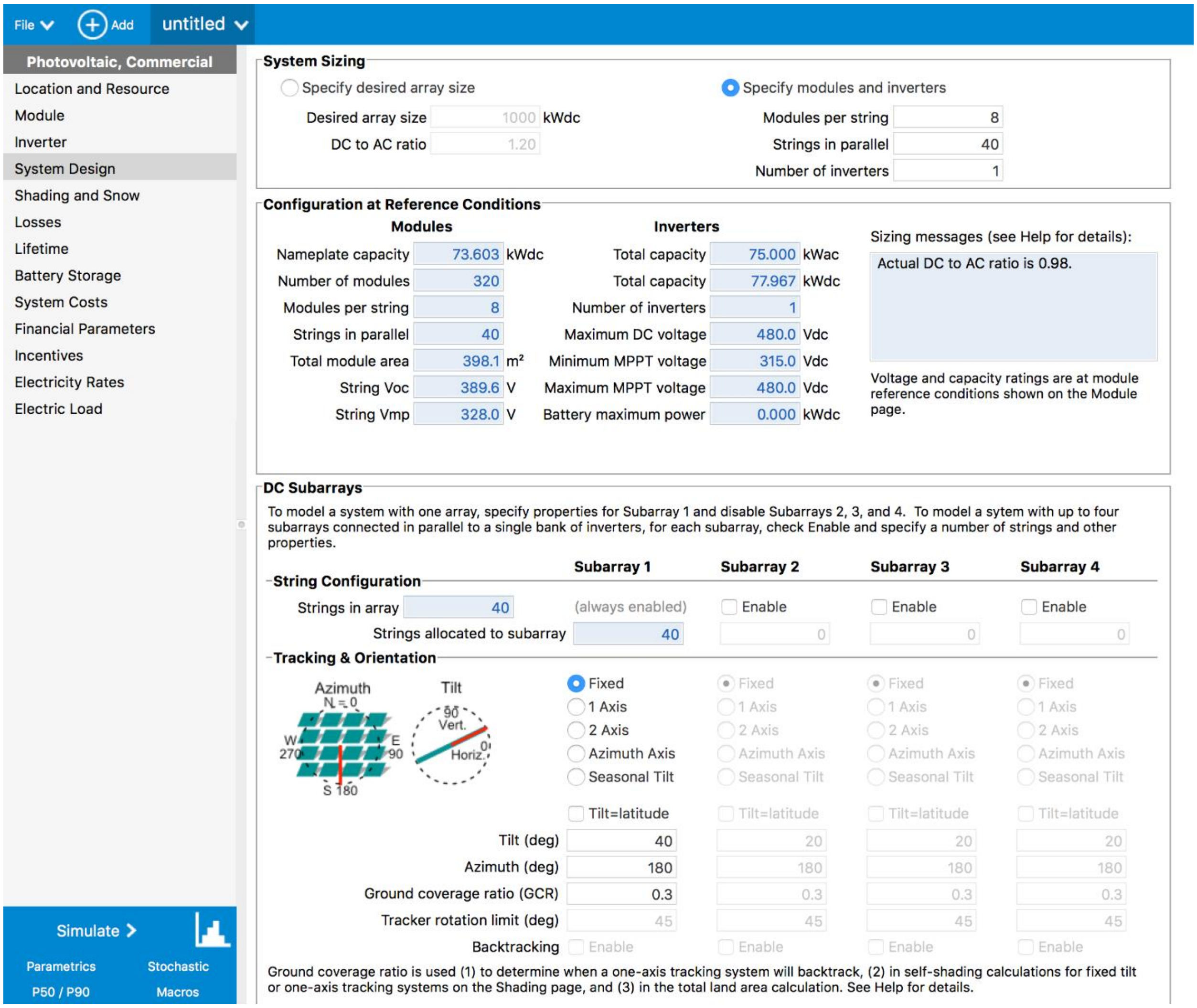


Figure B.3 – SAM system design parameters input window

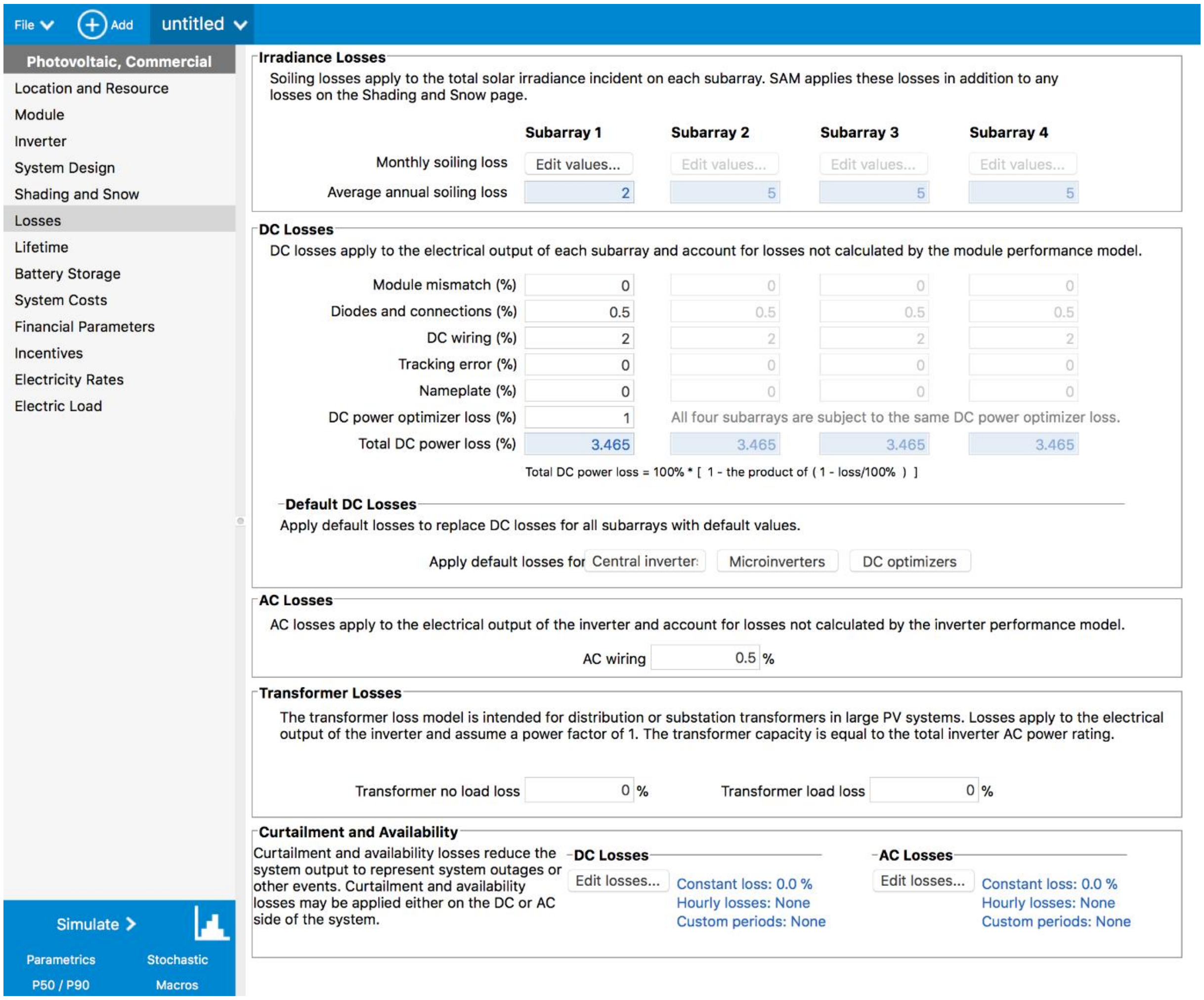


Figure B.4 – SAM system losses parameters input window

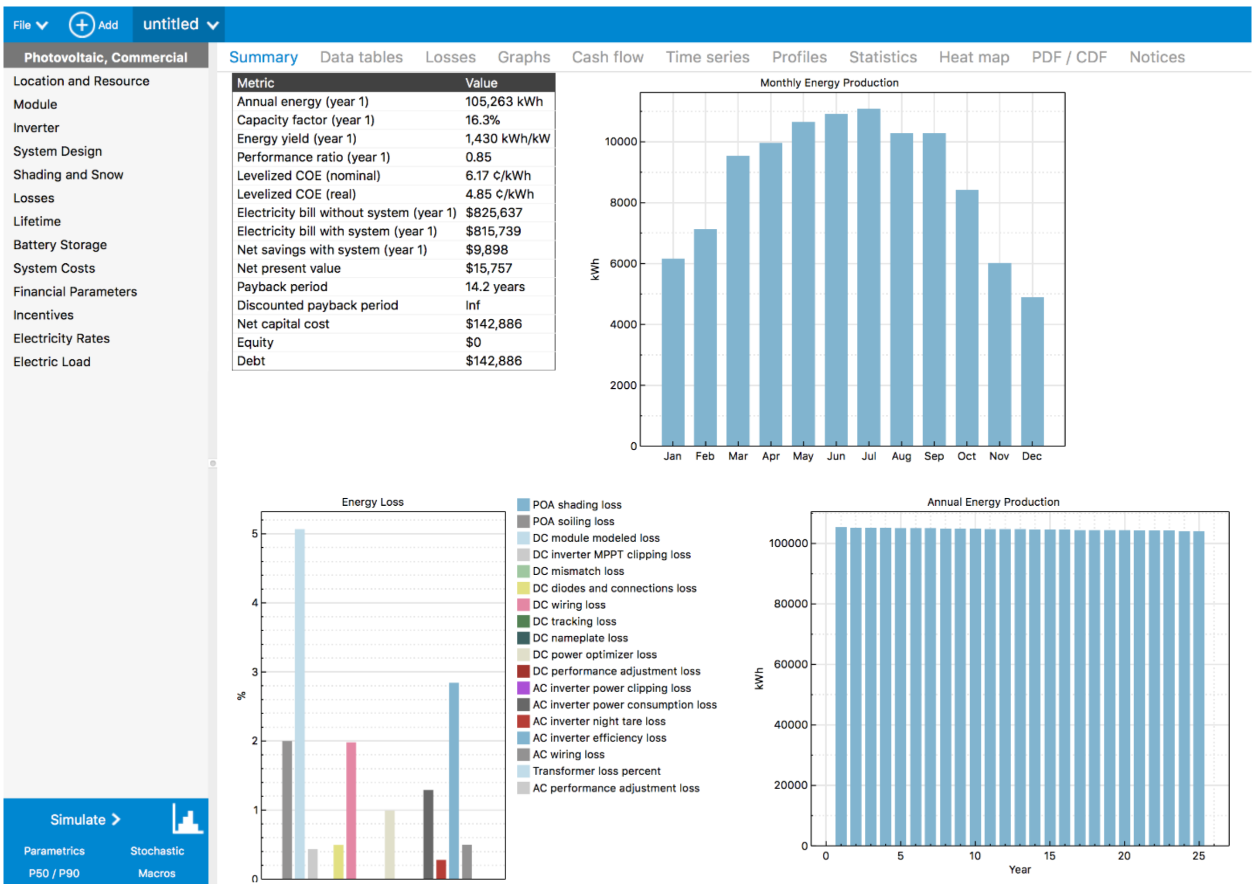


Figure B.5 – SAM results summary window

# APPENDIX C - RETSCREEN EXPERT EXCEL RESULTS

| | | | RETScreen Expert GSHP loop cost | | $2,400 | Debt Ratio - 0% | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| RETSCreen Simulation Fort Wayne | Total initial Costs ($) | Total Annual Costs ($) | Fuel Cost-Base Case ($) | Pre-tax Internal rate of return equity (%) | Simple Pay back period(years) | Equity pay back (years) | Net Pressent value ($) | Annual life cycle savings($/YR) | Gross annual GHG emission reduction (tCO2) | Fuel Saved(kWh) | Fuel Saved-Percent (%) |
| GSHP (0.0812$) | 299,662 | 40,125 | 65,850 | 10.7 | 13.1 | 11.2 | 178,078 | 11,399 | 310.9 | 316,815 | 39.1 |
| GSHP (0.1$) | 299,662 | 49,415 | 81,097 | 12.2 | 10.6 | 9.3 | 288,688 | 18,479 | 310.9 | 316,815 | 39.1 |
| GSHP (0.12$) | 299,662 | 59,298 | 97,316 | 14.7 | 9.1 | 8.1 | 386,392 | 24,734 | 310.9 | 316,815 | 39.1 |
| GSHP (0.14$) | 299,662 | 69,181 | 113,535 | 17.1 | 7.8 | 7.0 | 500,735 | 31,544 | 310.9 | 316,815 | 39.1 |
| ASHP (.0812$) | 131,204 | 48,229 | 65,850 | 15.6 | 7.4 | 6.8 | 235,528 | 15,077 | 213.0 | 217,018 | 26.8 |
| ASHP (0.1$) | 131,204 | 59,395 | 81,097 | 19.1 | 6.0 | 5.6 | 320,436 | 20,512 | 213.0 | 217,018 | 26.8 |
| ASHP (0.12$) | 131,204 | 71,274 | 97,316 | 22.6 | 5.0 | 4.7 | 410,764 | 26,294 | 213.0 | 217,018 | 26.8 |
| ASHP (0.14$) | 131,204 | 83,153 | 113,535 | 26.1 | 4.3 | 4.1 | 501,092 | 32,076 | 213.0 | 217,018 | 26.8 |
| PV-GSHP (0.0812$) | 527,822 | 31,562 | 65,850 | 6.7 | 16.1 | 13.4 | 154,928 | 9,917 | 414.4 | 422,273 | 52.1 |
| PV- GSHP (0.1$) | 527,822 | 38,869 | 81,097 | 8.9 | 13.1 | 11.2 | 313,003 | 20,036 | 414.4 | 422,273 | 52.1 |
| PV-GSHP (0.12$) | 527,822 | 46,643 | 97,316 | 11.0 | 10.4 | 9.2 | 441,562 | 28,265 | 414.4 | 422,273 | 52.1 |
| PV-GSHP (0.14$) | 527,822 | 54,417 | 113,535 | 13.0 | 9.9 | 8.8 | 579,833 | 37,116 | 414.4 | 422,273 | 52.1 |
| PV-ASHP (0.812$) | 351,915 | 39,665 | 65,850 | 8.1 | 13.4 | 11.5 | 193,027 | 12,356 | 316.4 | 322,475 | 39.8 |
| PV-ASHP (0.1$) | 351,915 | 48,849 | 81,097 | 10.4 | 10.9 | 9.6 | 319,196 | 20,432 | 316.4 | 322,475 | 39.8 |
| PV-ASHP (0.12$) | 351,915 | 58,619 | 97,316 | 12.7 | 9.1 | 8.1 | 453,418 | 29,024 | 316.4 | 322,475 | 39.8 |
| PV-ASHP (0.14$) | 351,915 | 68,389 | 113,535 | 14.9 | 7.8 | 7.0 | 587,640 | 37,616 | 316.4 | 322,475 | 39.8 |

| | | | RETScreen Expert GSHP loop cost | | $800 | Debt Ratio - 0% | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| RETSCreen Simulation Fort Wayne | Total initial Costs ($) | Total Annual Costs ($) | Fuel Cost-Base Case ($) | Pre-tax Internal rate of return equity (%) | Simple Pay back period(years) | Equity pay back (years) | Net Pressent value ($) | Annual life cycle savings($/YR) | Gross annual GHG emission reduction (tCO2) | Fuel Saved(kWh) | Fuel Saved-Percent (%) |
| GSHP (0.0812$) | 178,126 | 40,125 | 65,850 | 16.7 | 6.9 | 6.3 | 357,250 | 22,868 | 310.9 | 316,815 | 39.1 |
| GSHP (0.1$) | 178,126 | 49,415 | 81,097 | 20.4 | 5.6 | 5.2 | 481,204 | 30,803 | 310.9 | 316,815 | 39.1 |
| GSHP (0.12$) | 178,126 | 59,298 | 97,316 | 24.2 | 4.7 | 4.4 | 613,070 | 39,244 | 310.9 | 316,815 | 39.1 |
| GSHP (0.14$) | 178,126 | 69,181 | 113,535 | 27.9 | 4.0 | 3.8 | 744,936 | 47,685 | 310.9 | 316,815 | 39.1 |
| ASHP (.0812$) | 131,204 | 48,229 | 65,850 | 15.6 | 7.4 | 6.8 | 235,528 | 15,077 | 213.0 | 217,018 | 26.8 |
| ASHP (0.1$) | 131,204 | 59,395 | 81,097 | 19.1 | 6.0 | 5.6 | 320,436 | 20,512 | 213.0 | 217,018 | 26.8 |
| ASHP (0.12$) | 131,204 | 71,274 | 97,316 | 22.6 | 5.0 | 4.7 | 410,764 | 26,294 | 213.0 | 217,018 | 26.8 |
| ASHP (0.14$) | 131,204 | 83,153 | 113,535 | 26.1 | 4.3 | 4.1 | 501,092 | 32,076 | 213.0 | 217,018 | 26.8 |
| PV-GSHP (0.0812$) | 406,286 | 31,562 | 65,850 | 9.5 | 11.8 | 10.3 | 307,300 | 19,671 | 414.4 | 422,273 | 52.1 |
| PV- GSHP (0.1$) | 406,286 | 38,869 | 81,097 | 12.0 | 9.6 | 8.5 | 472,515 | 30,247 | 414.4 | 422,273 | 52.1 |
| PV-GSHP (0.12$) | 406,286 | 46,643 | 97,316 | 14.5 | 8.0 | 7.2 | 648,275 | 41,497 | 414.4 | 422,273 | 52.1 |
| PV-GSHP (0.14$) | 406,286 | 54,417 | 113,535 | 16.9 | 6.9 | 6.3 | 824,035 | 52,748 | 414.4 | 422,273 | 52.1 |
| PV-ASHP (0.812$) | 351,915 | 39,665 | 65,850 | 8.1 | 13.4 | 11.5 | 193,027 | 12,356 | 316.4 | 322,475 | 39.8 |
| PV-ASHP (0.1$) | 351,915 | 48,849 | 81,097 | 10.4 | 10.9 | 9.6 | 319,196 | 20,432 | 316.4 | 322,475 | 39.8 |
| PV-ASHP (0.12$) | 351,915 | 58,619 | 97,316 | 12.7 | 9.1 | 8.1 | 453,418 | 29,024 | 316.4 | 322,475 | 39.8 |
| PV-ASHP (0.14$) | 351,915 | 68,389 | 113,535 | 14.9 | 7.8 | 7.0 | 587,640 | 37,616 | 316.4 | 322,475 | 39.8 |

Figure C.1 – RETScreen results for all systems