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PV/T Software Coherence and Applicability

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Abstract

Much research has been conducted on hybrid photovoltaic/thermal (PV/T) solar systems. This system is advantageous over photovoltaics alone in many cases as the combined system yields higher electrical outputs due to the cooling effect of the air or water medium. This waste heat can then be used to offset space heating or hot water loads. Parallel to this, research-based software, not meant for the average user, has been developed to model such systems. This software has a steep learning curve and can be difficult for a homeowner to manipulate in order to perceive system yields. In more than 30 years of exploration, this gap has not been bridged. Currently, available software meant for those not in the building industry are not sophisticated enough, modeling PV or solar thermal systems separately.

This dissertation attempts to make PV/T performance more accessible to the people who would benefit from it, such as homeowners or designers, by having created a spreadsheet-based tool that is designed to give reasonable performance predictions with minimal user input. Focusing on water-based sheet-and-tube collectors, electrical and thermal yields are then compared across nine US cities, each with distinct climates or topographical characteristics. The tool is based on calculations and validated against measured data from technical literature. A sensitivity analysis is done to observe system behavior by varying inlet temperatures. Finally, four collectors available on the market have been compared to understand the effects of altering system parameters.

This study finds that benefits of PV/T are case sensitive, affected by both the climate in which the application is installed and system settings. More electrical and thermal gains can be seen with inlet temperatures of 10ºC, however, with constant mass flow, outlet temperatures in northern climates may compromise tank temperature due to losses. Similarly, inlet temperatures affected primary energy savings, improving with cooler temperatures. Additionally, southerly latitudes achieved the best year-round performance. Improvements of up to 18% were seen in electrical production over PV alone in southern climates.

Acknowledgments

I'd like to thank my advisor, Paul Tuohy, for his guidance and positive attitude, Dr. Paul Strachan for supplemental information on my dissertation topic, Dr. Nick Kelly for his class notes, as well as all my lecturers for contributing to my education as a whole.

Additionally I'd like to thank my colleagues and friends in the engineering department for their meaningful, thought-provoking discussions throughout the year.

1. Introduction

1.1 Differences of Solar Systems

The Sun provides more than enough energy each day than we currently use in a year. For this reason, solar renewable energy is a plausible solution to relieving the world's dependency on fossil fuels in most applications. The term "solar system" in this case is an all-encompassing word for energy producing devices that convert the sun's radiation. Photovoltaic and solar thermal systems have been in existence for decades. The two systems often get confused with each other. PV converts the sun's radiation into high grade energy, electricity. Solar thermal converts the sun's radiation into low grade energy, heat. Both have useful applications in the built environment by reducing system loads.

1.1.1 Photovoltaics

A PV cell's semiconductor is commonly made of a mono-crystalline silicon, although other materials such as amorphous, polycrystalline, gallium arsenide and cadmium sulfide can be used. The bottom layer of silicon has an electron deficiency (a positive charge), while the top layer has an excess of electrons (a negative charge), with a metal layer acting as a barrier to free electron flow sandwiched between. These charges are a result of doping the silicon with boron and phosphorous, respectively. When a photon collides with crystalline structure, an electron is knocked loose, flowing through the barrier to the positively charge silicon, thus creating a current. To paraphrase Duffie and Beckman (1991), the most energetic photon have a high frequency and short wavelength, and for silicon the maximum useful wavelength is 1.15µm, resulting in a maximum theoretical efficiency of 23% for these types of PV cells. This efficiency is also a function of temperature, degrading the warmer the cell is heated. This occurs when the unusable wavelengths bombarding the cell are converted to heat.

1.1.2 Solar Thermal

Solar thermal systems are based on a simple concept: heat water by exposing it to solar radiation. This can happen in a flat-plate collector, evacuated tubes or in concentrating systems, each system result in a higher temperature yield than the previous. Residential applications will most often use flat-plate collectors, with system efficiencies of 70% or more as was demonstrated by Zondag, et al's (2002) experiment which obtained 72-83%. The output of solar thermal systems can be used for domestic hot water, pool heating, or space heating.

The systems can be passive or active. In a passive system, a thermosyphon allows the density of hot water to naturally govern the mass flow rate. Pumps in an active system can be powered by a small PV, so that it only runs when there is solar radiation.

1.1.3 The Hybrid System

Hybrid systems produce more energy per unit area than separate systems according to a study reviewed by Ibraham, et al. (2011). They come in either of three heat transfer media: air, water or a water/glycol mixture. Each fluid offers its own useful purpose. Air is primarily used to offset space heating demands, where water (or water/glycol for indirect transfer) often is used in domestic hot water or pool heating applications. PVT Roadmap (Zondag n.d.) also provides examples of application based on building type. Hospitals, for example, require large amounts of both electricity and hot water. It seems, however, that the residential sector leads in PV/T installations.

The flat-plate collector is the most well-known and widely used for home applications. Flat-plate collectors are categorized by their heat transferring medium– air, water, or a combination of both. Figure 1, below, demonstrates types of collectors. Designs such as these optimize thermal production. The four sections show glazed collectors, however unglazed collectors have their place too as they have a lower operating temperature for improved electrical output. Thermal output can be used for various applications, however, the main employment of this energy is either for domestic water heating or space heating. Electrical output can be divided in to three possible systems as well– grid-connected, battery (off-grid) or a combination of the two.

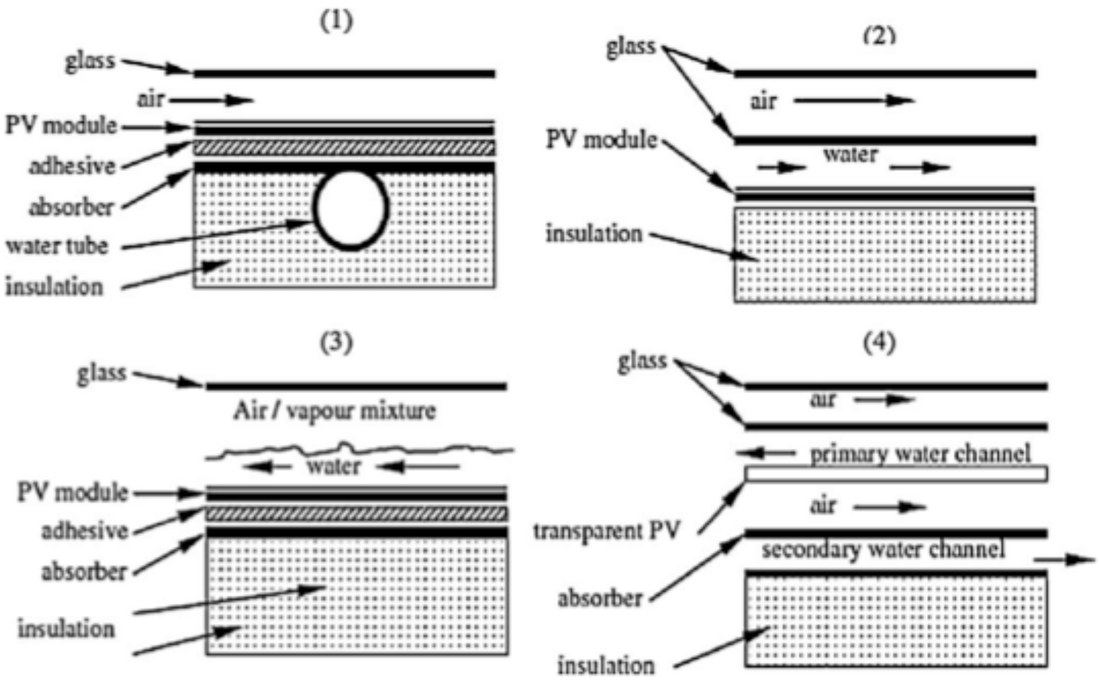


Figure 1
Type of Flat Plate Collectors
(Ibrahim 2011)

The air-based system requires the least amount of change to already existing systems. It can be achieved by venting the back of a PV.

2. Literature & Software Review

2.1 PV & Electrical Considerations

Electrical performance of photovoltaics are known to be dependent on temperature. Hishikawa and Okamoto (1994) investigate the I-V characteristics of silicon regarding illumination and temperature. They conclude that the current based on solar intensity is straightforward, considering the dark and short circuit currents, whereas temperature-dependency is more complicated. Their equations,

$$I_{T_b} = I_{T_a} + \alpha(T_b - T_a)$$
$$V_{T_b} = V_{T_a} + \beta(T_b - T_a)\frac{V_{T_a}}{V_{OC}}$$

show this relationship, where
I_{Ta}= output current at T_a
I_{Tb}= output current at T_b
T_a= first sample temperature
T_b= second sample temperature
V_{Ta}= applied voltage at T_a
V_{Tb}= applied voltage at T_b
V_{OC}= open circuit voltage at T_a
and α and β are dependent on illumination intensity, representing the change per degree Celsius for short circuit current and open current voltage, respectively. In other studies, further temperature dependancies are investigated. Bergene and Løvvik (1995) state that crystalline silicon cells loose 15% in efficiency when temperatures increase 30 K.

Initial expensive at its inception, PV has reduced in price as its place in the market has become more established. In 2005, the cost per megawatt-hour of energy produced by PV was between 140-430 (€/MWh) according to a report from the CEC

(2007). They projected this to decrease to 55-260 (€/MWh with €20-30/tCO_2) by 2030. As prices reduce, increases in growth are more likely to occur. This will also be advantageous for PV/T as it too will become more competitive. This expectation is echoed by the PV/T Roadmap (Zondag n.d.).

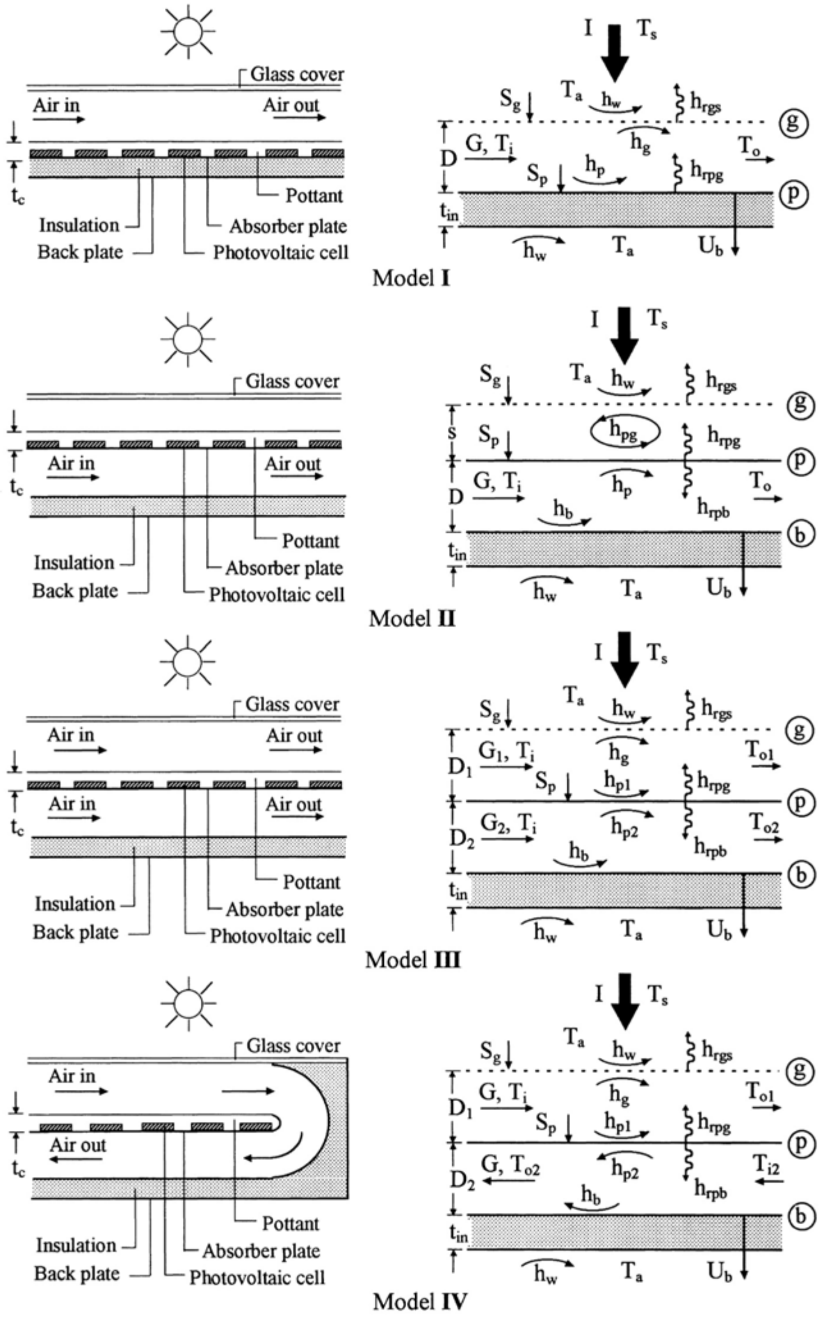


Figure 2
Four Air-based PV/T Configurations
(Hegazy 2000)

2.2 Previous Research in Solar Thermal

Early studies were conducted in the solar thermal field by people now synonymous with their findings. Hottel and Whillier, and Duffie and Beckman (1991) are among these pioneers. The physics of a flat-plate collector are detailed in Solar Engineering of Thermal Processes (Duffie and Beckman 1991).

Jaisankar et al. (2011) also review solar thermal systems. They cover many concerns of flat plate collectors including optical issues and relationships with the storage tank, particularly focusing on thermosyphon systems. This in turn, ties into the mass flow of the systems, which the authors credit Duffie and Beckman with many valuable assumptions for calculations. Other characteristics they review include Whiller and Saluja's finding that a soldered bond results in a higher heat removal factor. Continuing, they affirm the heat removal factor is influential in the system performance. A majority of their research deals with twisted tape in the pipes to assist heat transfer, however they find that it is not best practice.

Otanicar, et al. (2009) also researched improving the thermal efficiency of the collector. Their investigation compared four working fluids including water and common antifreezes, finding water had the highest absorption factor of the four.

These studies are interesting to consider when applications of systems deviate from ideal conditions. When distributed throughout a very large country, such as the United States, the local climates of northern regions emphasize the need for improved thermal performance. For example, although water is the best conductor, it would freeze in a majority of the states during winter. Also because of temperature concerns, thermosyphons may result in more losses, or poorer mass flow, limiting their applicability.

Since its introduction, solar thermal technology has become a reliable technology for Europe. In 2007, solar thermal met 2% of heating demands with 13 GWth installed capacity according to a report by the Commission for European Communities (2007). The CEC projects that it will increase to 52 GWth by 2020 and 135 GWth by 2030.

This expected increased capacity presents the opportunity for PV/T to assist in meeting these projections.

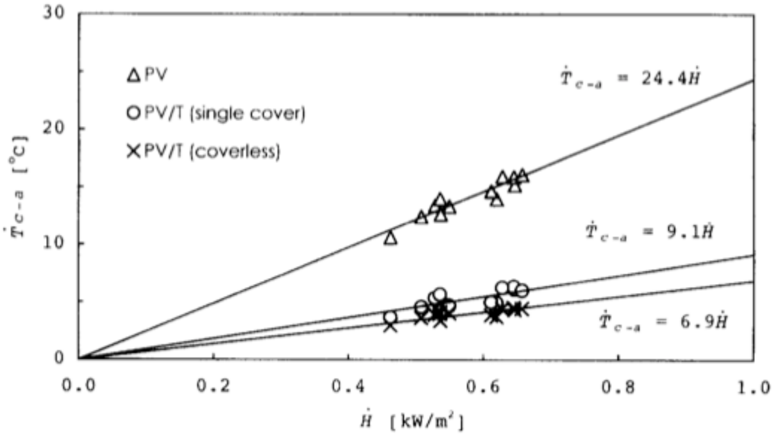


Figure 3
Irradiance-Cell Temperature Relationship for PV, and PV/T
Fujisawa and Tani (1997)

2.3 Current state of PV/T

2.3.1 Air-based PV/T

Sopian, et al. (1996) examined the performance of a double-pass air PV/T collector with that of a single-pass system. In a single-pass system the air flow through the collector once; the double-pass allows the air to exit from the same side from which it entered, giving the air a longer path to travel as well as more time to heat in the process. In Figure 2, models I-III are single-pass, whereas IV is a double-pass. Their results showed that double-pass systems have a thermal efficiency greater than its single-pass counterpart, between 31-34% to 21-23% respectively. Not all PV/T applications will achieve the same efficiencies, as the university where the researchers were based is in Miami, Florida, a sunny, warm location. Similarly, they reported greater electrical efficiency as well, between 7-7.25% compared to 6.45-6.55%. Direct effects of absorber plate temperature, mass flow rates, duct depth, collector length, inlet temperatures, solar radiation and packing factor were seen. Although the outlet temperatures of the double-pass system were elevated slightly from the single-pass results, a more drastic increase, about 10-15ºC, was noticed in the first-pass to the second-pass within the double-pass system. Length also resulted in higher temperature changes, where the 0.5 m double-pass performed similarly to the single-pass collector, the 2.0 m collector showed an increase of about 5ºC. Lower mass flow rates led to higher outlet temperatures for both collectors types, with slightly greater performance enhancement from the double-pass collector. Electrical efficiency increased when the mass flow increased. A lower packing factor, or ratio of cell to collector area, led to a lower electrical efficiency. They report the combined system efficiency was significantly greater for the double-pass system, reaching a maximum of approximately 45% with mass flows of about 300 kg/hr. The single-pass collector under the same conditions produced a combined efficiency of between 25-27%. Sopian, et al. (1996) attribute these results to the reduced losses from the top plate during the first-pass and cooling the PV. Economic ramifications of these more desirable results are minimal between the two collector types.

Further PV/T with air as the heat transfer medium was studied by Hegazy. He discusses the practicality of PV/T in developing countries for agricultural purposes, overcoming the challenges that accompany a limited or unreliable grid. Comparing four designs of an air collector, see Figure 2, he also examines the extra power required for a double-pass configuration. Hegazy reports that models II-IV have approximately the same efficiency, all higher than model I. Outlet air temperature showed an inverse proportion to mass flow rate. This is consistent with Sopian's findings.

2.3.2 Liquid-based PV/T

Combined efficiencies, electrical plus thermal, of a perfect PV/T collector can reach over 70% according to Chow (2003) who goes on to explain that the mass flow rate needed to acquire such results are much higher than designed rates. This is important to note as it will affect not only system performance, but pump performance as well. It should also make the buyer cautious about the figures reported by manufacturers and under what conditions their systems were tested.

PV/T is similar to the idea of combined heat and power (CHP), for readers who are familiar, in that one side of the system or the other can be optimized. Depending on the focus, one can obtain higher performance from the photovoltaics by introducing cooler inlet temperatures or minimize domestic hot water (DHW) demand to the sacrifice of electrical generation. This was demonstrated by Fujisawa and Tani (1997), who said cooler inlet temperatures would allow the system to function in electrical priority operation (EPO) versus thermal priority operation (TPO) which would reduce electrical power due to higher cell and fluid temperatures. Figure 3 below shows the relationship of irradiance that causes the cell temperature to rise. This idea is also in agreement with Othman, et al.'s (2005) findings that there is a trade off between maximizing electrical production and producing useful fluid temperatures as well as the International Energy Agency's (IEA) Solar Heating & Cooling (SHC) Task 35 report (2008) that shows decreased thermal production when electricity is produced.

Florschuetz (1979) adapted the knowledge of solar thermal collectors in his work "Extensions of the Hottel-Whillier Model to the Analysis of Combined Photovoltaic/Thermal Flat-Plate Collectors". He concludes that hybrid sheet-and-tube systems can be calculated as solar thermal collectors, with modifications to the losses and solar radiation, by considering cell efficiency and absorption. A key variable of these equations, discussed in greater detail in section 4.2, is the heat removal factor. Zondag (2008) goes on to illustrate to maximize heat transfer, the tubes should be small since

$$h = \frac{Nu \cdot k}{D}$$

where

D= hydraulic diameter.

Zondag, et al. (2002) conducted research on 3D dynamic, 3D steady state, 2D and 1D mathematical PV/T models, comparing the results to measured data. The 1D model was based on the Hottel-Whillier equations. They noted that all models remain within 5% deviation from the measurements. Because of its accuracy, this will later play an important role in this dissertation (see sections 4.2.3-5.1.1). A lower thermal efficiency was also seen from the 1D model when electricity was produced. Comparisons with PV performance were also undertaken, where it was found that PV/T performs slightly better. In some cases, they found that the effects of cooling the PV/T cells did not overcome the electrical losses, thus the PV performed with a higher efficiency, when the inlet water temperature increased.

Auxiliary components, such as a heat pump, can augment performance. Bakker, et al. (2005) examined a 25 m^2 array coupled with a ground-source heat pump. They found it was able to cover 100% of the heating demand for a typical new-built Dutch one-family house and covered nearly all the electricity required for the heat pump.

Kalogirou (2001) modeled a water-based PV/T system in TRNSYS looking specifically at the climate of Cyprus. The model utilized a TYPE 49-PV/T collector, TYPE 38-Hot water cylinder, Type 3-Pump, the electrical subcomponents of the TYPE 49 collector (an inverter, battery and load), DHW loads, as well as climate data and processor, among others. TRNSYS required the components to be defined mathematically and their relationships to one another. A consistent DHW demand profile was used, which Kalogirou commented would not be completely accurate, as consumption changes, especially in the summer. His results showed that the hybrid system reached a maximum efficiency of 51.6%, where a non-hybrid system was only 8.2%. It was unclear if Kalogirou was referring to a solar thermal system or photovoltaics, but knowledge of system efficiencies suggest he compared with PV. He goes on to state that the average efficiency of PV is 2.8% which increases to 7.7% for PV/T and a system efficiency of 31.7%. Solar fractions, or percentage of demand met by the solar system, reported a value of 80% in July and low of approximately 17% in January and December, with an annual average of 49% for this climate. With these results, an economical analysis was conducted, concluding that with no financing required, the system payback period could be 4.6 years with a life cycle savings of Cy£790. This price is likely market-sensitive and based on a DIY conversion of PV by adding piping to the back of the collector. Pricing have been quoted to the author at much higher prices due to PV/T's infancy in the market. Additionally, because of the sunny climate where this study was conducted, the average price of PV technology may be lower.

2.3.3 System Configurations & Storage Options

Liquid PV/T requires a place to store the medium once it has passed through the collector(s). Like traditional solar thermal, system configurations can vary, depending

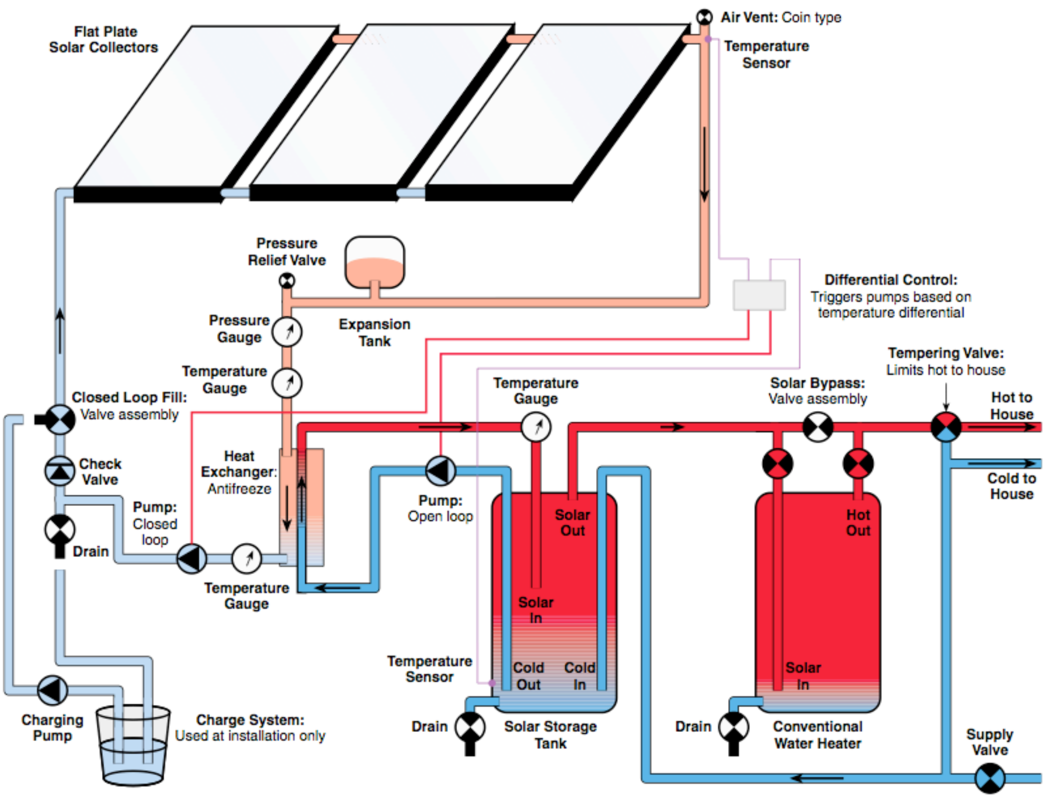


Figure 4
Closed Loop Antifreeze SHW
(Olson 2001)

on the intended use of the water. Ken Olson discusses (2001, Vol. 85) practicalities of a solar hot water (SHW) system. Figure 4 is an example of one configuration from his work. Because of the antifreeze in the line to the collector in cold climates, a heat exchanger is used to transfer the useful heat to the solar storage tank. A second tank contains an auxiliary heater to augment the thermal energy provided by the solar collector. In an earlier work (2001, Vol. 84), Olson describes the advantages and disadvantages of the different configurations for both open– where water is used directly– or closed loops– where heat is transferred by a heat exchanger. Table 1 is his summary. It is obvious most systems are more conducive to a warm climate. Only two, the closed loop heat exchanger and drainback systems, are capable of withstanding the colder climates and another, draindown, can tolerate some cold weather, but with limitations.

H.S. Fath (1998) discusses thermal storage options including sensible (temperature change) or latent (phase change) storage. Although water has a high ability to hold heat, common construction materials or earth are appropriate for low (below 100ºC) temperature applications. Fath states that the size and insulation for sensible storage can be significant. He continues that water systems can cause corrosion, leading to a water tank life of about 10 years, which will add to total system costs. He also states that phase changing materials (PCMs) require half the volume as a water storage system, however, PCMs require a large surface area and have a substantial cost.

2.3.4 Latest Technology

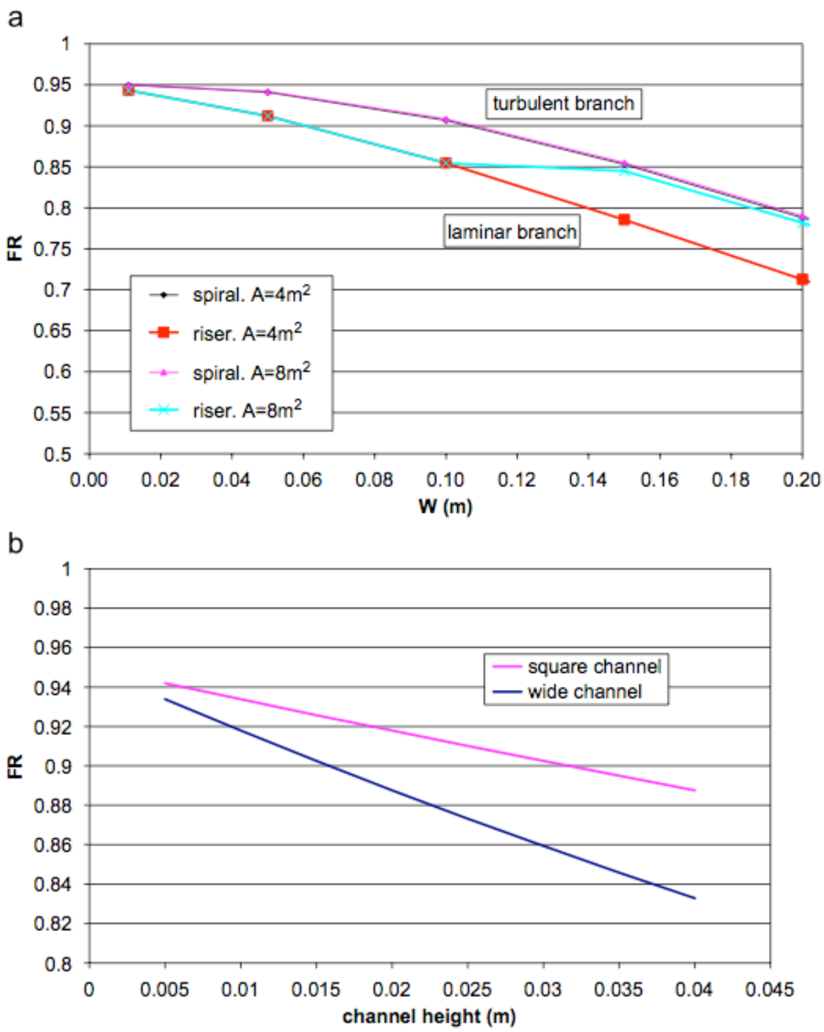


Figure 5
a) Sheet-and-Tube Collector (8mm tube, 50 l/m²)
b) Channel Plate Collector
(Zondag 2008)

There are continual attempts to advance the PV/T field. Design has an important role in the output of the solar collector. Changing the shape of the tube, and therefore the surface area for heat transfer, from round to rectangular is one such improvement. In the article, “Recent advances in flat plate photovoltaic/thermal (PV/T) solar collectors,” Ibrahim, et al. (2011) investigate a design’s affect on performance. They tell of Sandnes and Rekstad’s experiment filling the channels with ceramic granulates to increase thermal efficiency. Material is an

Solar Hot Water System Types: Advantages & Disadvantages

System Type	*Characteristic & Use*	*Advantages*	*Disadvantages*
Solar Batch Water Heater	Open loop; Integrated collector & storage; Freeze protection generally limited to infrequent or light freeze climates	Simple; No moving parts	Freeze protection typically poor; Inefficient in cold climates; Small systems only
Thermosiphon	Typically open loop; May be closed loop with heat exchanger & antifreeze	Simple; Requires no electricity for operation	Collector must be located below tank; Inappropriate for use with hard water (open loop system)
Direct Pump System	Open loop; Freeze-free climates	Flexible placement of tank & collector; can be powered by PV	No freeze protection; Inappropriate for use with hard water
Direct Pump Recirculation System	Open loop; Climates where freezing is an unexpected occasion	Simple; can be powered by PV	Freeze protection is limited to infrequent & light freezes; Inappropriate for use with hard water
Draindown	Open loop; Designed to drain water when near freezing	Can be powered by PV	Freeze protection is vulnerable to numerous problems; Collectors & piping must have adequate slope to drain; Inappropriate for use with hard water
Closed Loop Heat Exchanger	Closed loop; Cold climates	Very good freeze protection; Basic principles well understood by conventional plumbing trades; No problems with hard water; can be powered by PV	Most complex of all systems, with many parts; Heat exchanger & antifreeze reduce efficiency; Fluid may break down at high stagnation temperatures
Drainback	Closed loop; Cold climates	Very good freeze protection if used with antifreeze; No problems with hard water; Simplest of reliable freeze protection systems; Fluid not subject to stagnation temperatures; Simple to homebrew; can be powered by PV	Heat exchanger & antifreeze reduce efficiency; Collectors & piping must have adequate slope to drain; Requires larger pump to lift

Table 1
SHW System Types: Advantages & Disadvantages
(Olson 2001)

important factor as well. Ibrahim, et al. (2011) reports Huang, et al. (2001)'s finding that a corrugated polycarbonate panel increased thermal efficiency.

Zondag's (2008) extensive review of PV/T examines the heat removal factor based on design parameters. He states that the ratio of W/D (See Figure 16 in section 4.1), which effects thermal efficiency, is a balance between thermal production and economic ramifications as larger uses of copper increase cost. Figure 5 shows the results.

It is seen that the spiral piping configuration generally has a higher F_R, but the riser with a greater area and distance between tubes perform almost as well when flow becomes turbulent. Also, in Figure 5b, the square channel performs with greater heat removal capabilities, especially when the channel height is increased. This may be due to the reduced surface area-to-volume ratio when square channels are employed, thus more of the fluid is effective at taking the heat away.

2.4 The Implications of PV/T for Designers & Homeowners

After considering its technical feasibility, one might question why PV/T is not more prevalent. There is an overall push from most governments and NGOs, such as the United Nations, to pursue a carbon neutral built environment, ultimately in an attempt to curb global warming. To entice homeowners to make the first steps towards these goals, governments have begun to offer financial incentives on renewable technology. Another way of implementing changes occurs by targeting the building industry. Designers often have a standard to meet when designing a building, whether it's LEED, SAP, or PHPP. PV/T can typically help achieve the desired target.

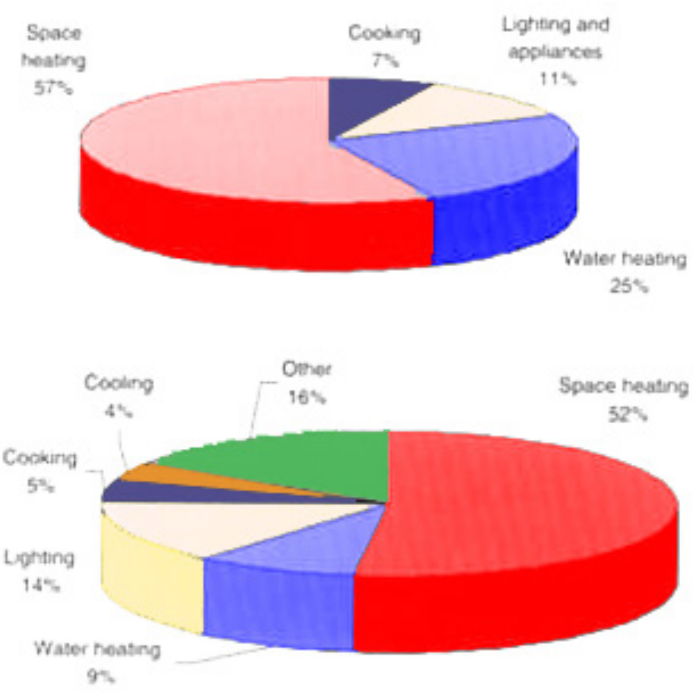


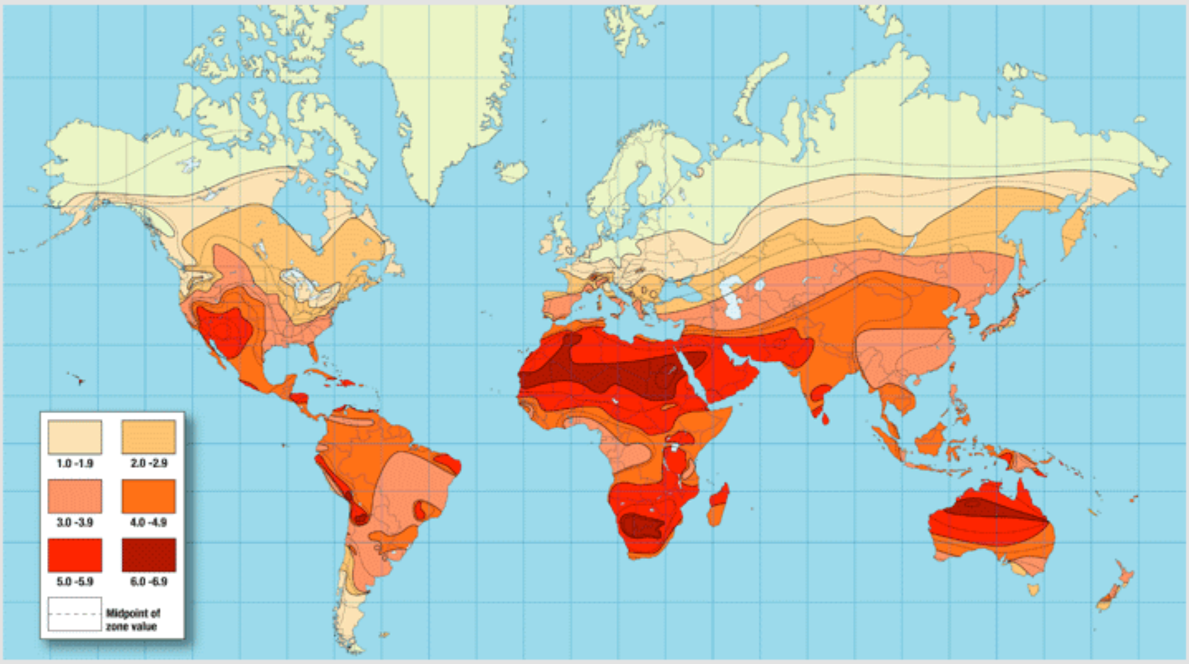
Figure 6
a) Energy Consumption Breakdown For Residential Buildings in the EU
b) Energy Consumption Breakdown For Commercial & Public Buildings in the EU
(Weiss 2003)

2.4.1 Applicability of PV/T

2.4.1.1 Resources

In a report, the IEA (Weiss 2003) summarizes by saying to prevent global warming, a drastic 90% cut in CO_2 emissions per capita is required in industrialized countries. They continue by stating that 75% of buildings' energy consumption is hot water and space heating (see Figure 6), and installation projections of solar combisystems, by which they mean solar water heating for the aforementioned purposes, could have met 1.18% of demands for residential, commercial and public buildings by 2010.

The United States generally receives more solar insolation that Europe as can be seen in Figure 7. Photovoltaic/thermal systems have been deployed in Europe and could contrastingly perform better in the US due to the higher solar resources in North America.



This map shows the amount of solar energy in hours, received each day on an optimally tilted surface during the worst month of the year.
(Based on accumulated worldwide solar insolation data.)

Figure 7
Worldwide Solar Insolation (Jh/d)
(AltE Store 2011)

In a technical report published in 2007, the National Renewable Energy Laboratory (NREL) looked at the potential of SHW in the United States (Denholm). Figure 8 depicts the regional percentage of fuel consumption for DHW, with natural gas as the preferred method of heating. Other fuel sources are connected to the modernity of the structure, according to Denholm, citing that 64% of New England homes using oil were built before 1960. With figures from a 2006 report, he concludes that CO_2

emissions saving can range from 50-75 million metric tons annually with SHW, or $8+ billion in energy costs for consumers.

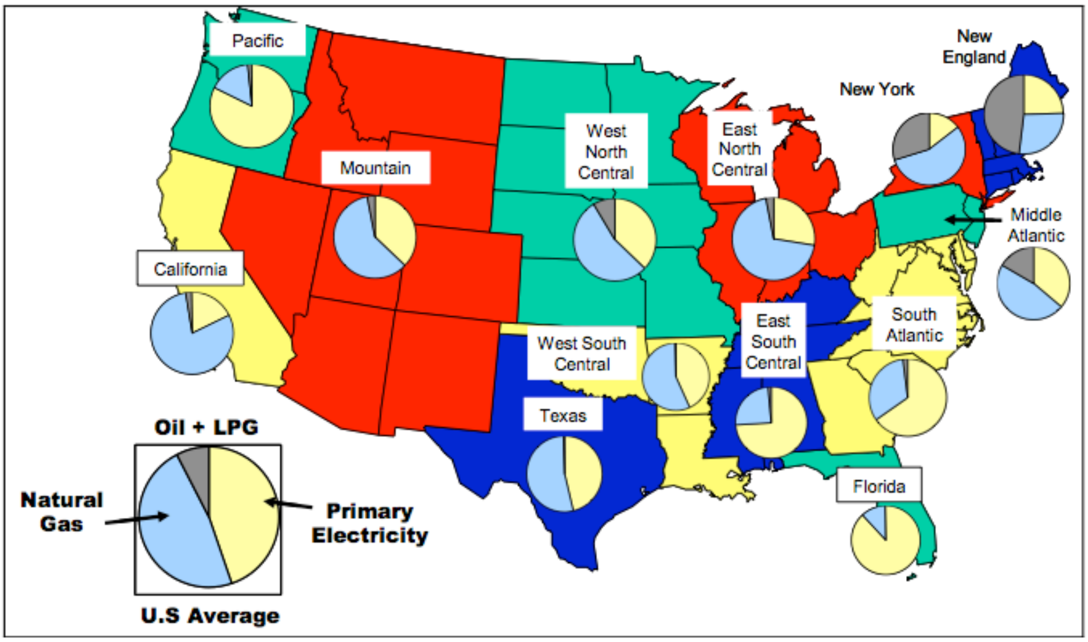


Figure 8
Regional Distribution of Fuels Used For DHW In the US (Denholm 2007)

Using updated numbers from the latest publication from Annual Energy Outlook, the US Energy Information Administration (EIA) (2011) offers a unique picture of the changing trends in residential demand, from which one can perceive where PV/T can play a role. They show a decrease in electrical energy per capita and a population shift to warmer climates requiring less space heating, however, population growth of 26.7% and an increased number of electrical devices, coupled with an increase in the prolificacy and square footage of homes causes the overall electrical portion of residential energy demand to rise 5% by 2035. Figure 9a shows this per capita decrease which is technology dependent. From Figure 9b, PV/T's contribution to water heating reduces or negates entirely the 5th and 6th largest residential demands, while the electricity it produces contributes to the remaining demands.

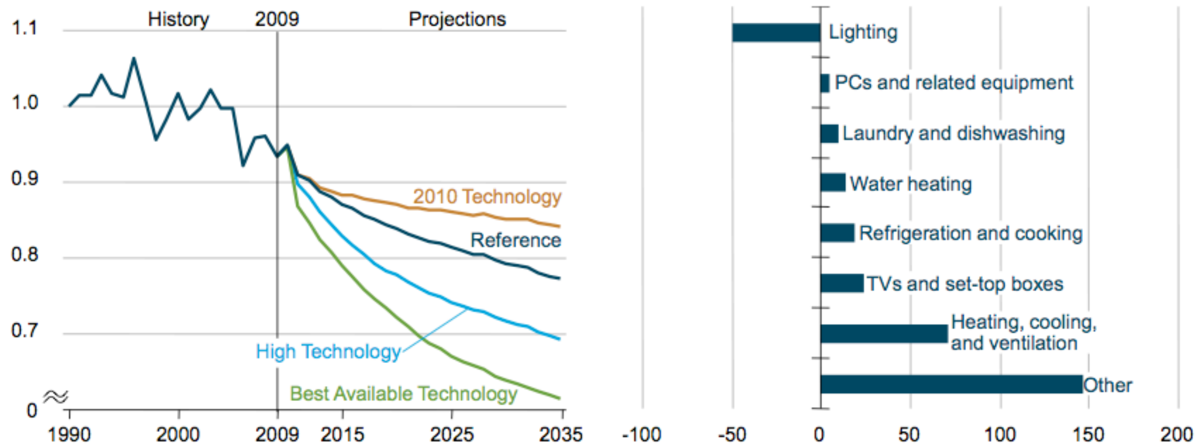


Figure 9
a) Electrical Trends in US
b) Residential Electrical Demands by Device
(US Energy Information Administration 2011)

Other graphs (Figure 10) show from where the energy is sourced, thus a sense of the potential savings in primary energy is assessable.

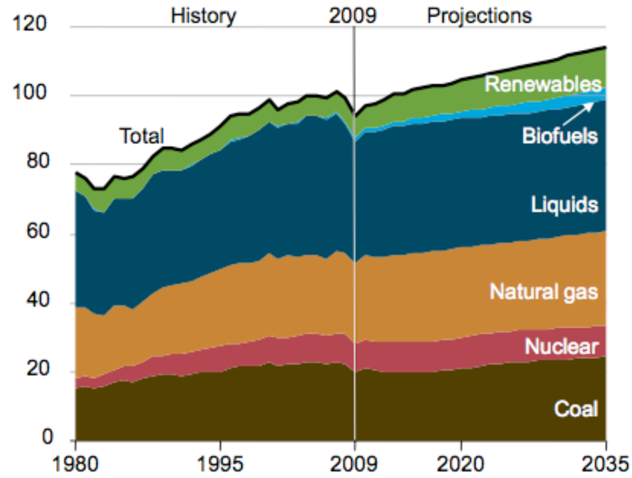


Figure 10
Primary Energy Use By Fuel
(US Energy Information Administration 2011)

2.4.1.2 Markets, Feasibility & Hindrances

The documents included in the literature review thus far have mostly been research on the performance, generally academically rooted. Composed by people in the industry as well as pedagogues, PVT Roadmap (Zondag n.d.), is a useful guide to the European market. It clearly lists the benefits and challenges for 7 fields– manufacturers, policy makers, Researchers, architects, energy consultants & engineers, building industry professionals, and installers. Certification, a key to establishing reliability, is not yet in place for PV/T. Solar thermal and PV each have their own, (EN 12975) and (IEC 61215), respectively, but the hybrid brings unique challenges with the generation-temperature relationships and can conflict with the aforementioned standards, they state. The IEA's SHC Programme (2008) elaborates, saying it is unclear if a factor in performance calculations relating to PV temperatures is representative of PV/T.

The PV/T Roadmap enumerates the potential of hybrid market applications. PV/T can be employed in many respects. Air-based systems can offset a building's heating demand, or be put to use drying crops. Liquid-based systems can supply DHW, heat pools or mitigate heating demands of hydronic systems. Bakker, et al, (2005) conclude that PV/T has a promising residential market and is best suited for low-energy homes.

In a press release from the Commission of European Communities in 2007 sites that there are a quarter of the funds available for the research and development of energy technologies as there once was if monetary support had continued as in the 1980s. Simultaneously, it continues, market introduction has a significant lag time, up to decades, along with the higher price tags for innovative clean technology than that which they replace, impeding the process. They also say that barriers to implementation regarding solar thermal include a lack of financial incentives for heating, heat storage challenges, building integration challenges, lack of skilled professionals and regulations and administration; photovoltaics' barriers include a high cost of electricity, building integration challenges, lack of skilled professionals, techno-economic issues, access to the grid, and regulations and administration.

Another hinderance is the lack of support for PV/T systems in the green building industry in the form of training. The North American Board of Certified Energy Practitioners (NABCEP), Solar Energy International (SEI) and Building Performance Institute, Inc. (BPI), among others, offer certification for professionals, often focusing on one system specifically, rather than a more holistic approach to renewable micro-generation. NABCEP and SEI distinguish between PV and solar thermal, BPI separates building analyst, heating, and air conditioning and heat pumps. Although BPI focuses more on overall energy efficiency than micro-generation, all certifying bodies mentioned would require a team of professionals to fully understand the potential benefits of PV/T.

Although some systems have been installed, PV/T still remains at the time of this work, cost prohibitive. For example, according to a renewable micro-generation sales representative in the Edinburgh, UK area, a PV/T system costs 4 times that of just PV alone. It should be noted that this system incorporated a heat pump which increased the price steeply. Another supplier in southeast England said PV/T is roughly twice the cost of PV, but depends on systems specifics. To ease the financial burden, governments often offer incentives, discussed in section 2.4.3, which PV/T has double the potential to gain from the amalgamation of two systems.

2.4.2 Legislation & Existing Guidelines

The European Energy Building Performance Directive (EPBD) was initiated to require an energy efficiency calculation standard among member nations and certification of energy performance of all buildings (Directive Implementation Advisory Group 2011). The UK government's Standard Assessment Procedure (SAP) is a way for designers to calculate the energy performance of dwellings, and therefore cost of energy, per square meter in accordance with the Building Directive (Building Research Establishment 2011). Although SAP encompasses attributing factors to energy costs such as lighting, ventilation and other factors outside the scope of this dissertation, it also considered renewable technology and efficiency of the heating system. Programs like Simplified Building Energy Model (SBEM), help calculate the Energy Performance Certificates (EPC), which are the certificates required from the EPBD. This is applicable to all types of buildings, although only public buildings larger than a certain area are required to display them. In the US, the Residential Energy Services Network (RESNET) established the Home Energy Rating System (HERS) Index, which is based on the 2004 International Energy Conservation Code, for measuring building efficiency. When a score of 0 is met, it is a Zero Energy building, producing as much energy as it consumes annually.

Other guidelines look at sustainability as a whole. The Building Research Establishment created the Environmental Assessment Method (BREEAM), evaluating building performance in several categories, one of which is energy. Similarly, in the United States, the US Green Building Council (USGBC) created the

Leadership in Energy and Environmental Design (LEED) which also considers energy, amongst other issues which are not limited to residential, schools, healthcare and retail, and new construction. The Living Building Challenge is also gaining ground, taking sustainable guidelines to the next level by requiring net zero energy.

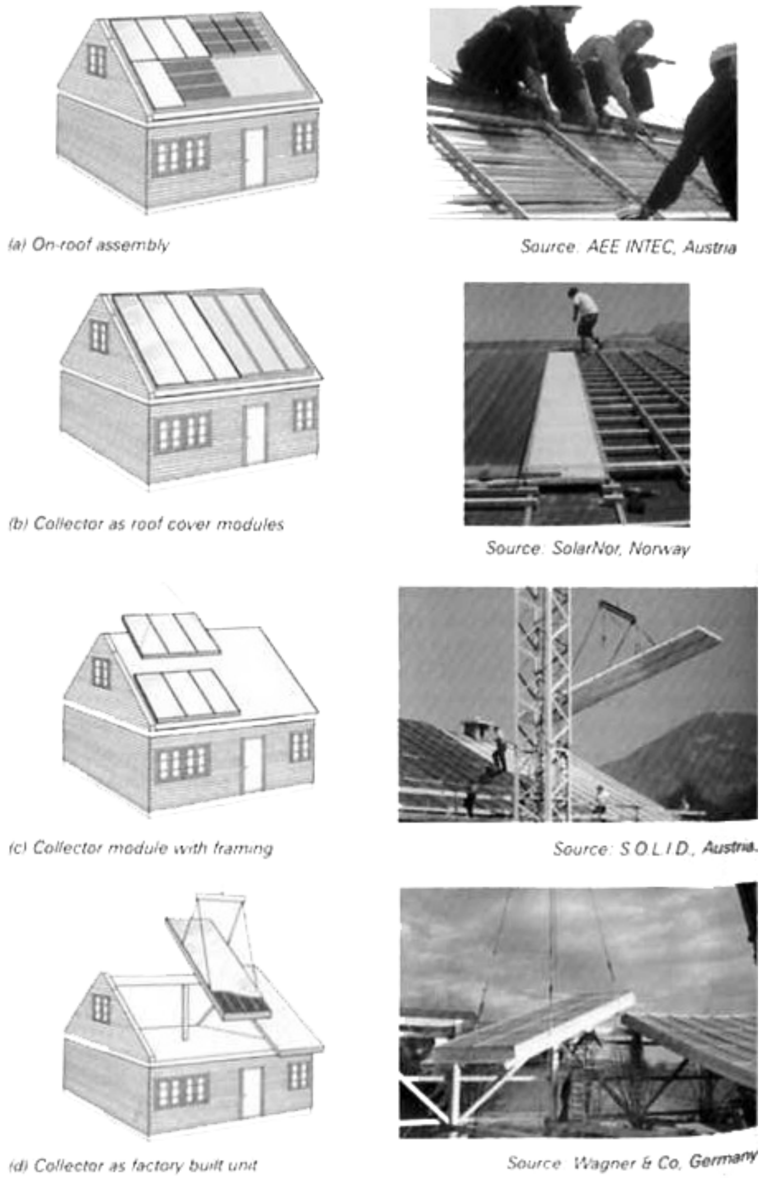


Figure 11
Types of Solar Collectors for Roof Applications (Weiss 2003)

2.4.3 Financial Considerations

Many governmental bodies, at both the national and state levels, offer subsidies to help home owners with the costs of a renewable energy system. These cover costs of purchasing and installation. Additionally, benefits from feed-in-tariffs (FITS) make renewables even more appealing. Unfortunately, in the UK, in order to be eligible, the technology has to be approved by the Microgeneration Certification Scheme (MCS) or equivalent. The International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) established guidelines to account for national greenhouse gas emissions. The EN45011 scheme, part of this project to mitigate carbon emissions, determines eligibility for financial incentives of which MCS and the CEN Solar

Keymark (for solar thermal products) are accredited. PV/T is in transition at the moment, being considered for approval from the MCS. Consumers can still take advantage of the FITs available on the individual systems. For example, a German manufacturer promotes its product by saying increased efficiency of the PV “virtually co-funds” the thermal. A system coupled with a heat pump may also be available for more incentives.

The Renewable Heat Incentive (RHI), supported by the Department of Energy and Climate Change (DECC) was added in April 2011 for non-domestic applications in Britain. This has expanded into the domestic sector in August 2011 with Renewable Heat Premium Payments. In a document from the DECC (2011) regarding the RHI, they state that the government has earmarked £15 million for a long-term tariff for Renewable Heat Premium Payment customers and those who have installed an eligible system since July 15, 2009. Systems considered eligible will also be expanded. The Renewable Heat Premium Payment has a short lifespan due to the limited budget; homeowners are only able to take advantage of this offer for 8 months until its expiration on March 31, 2012. An additional incentive launching in 2012 is the Green Deal for Homes, an energy efficiency program that has no initial costs up to £10,000 for homeowners’ renovations. These subsidies can shorten payback period of systems and help the government achieved their carbon-emission goals, to which the DECC website reiterates they are legal bound.

In the US, the NREL administers the Database of State Incentives for Renewables and Efficiency website in conjunction with North Carolina State University, listing the available incentives for the United States at utility, local, state and federal levels. Because many programs are state-specific, the details of each are too prolix. Among federal incentives is the Renewable Energy Production Incentive, offering 2.2 ¢/kWh for 10 years and the Residential Energy Conversion Subsidy Exclusion, which is a personal tax exemption for 100% of subsidies received for solar water heating (North Carolina 2011). There are also grant and loan programs to help with the remaining costs. Furthermore, the site lists the Federal Appliance Standards which is applicable to water heaters, furnaces, boilers (that may be used as auxiliary heaters in PV/T systems) and others, showing that manufacturers must meet energy efficiency criteria from the Energy Policy and Conservation Act of 1975, thus considering the primary fuel consumption. This legislation is updated as required to reflect the changing trends. Incentives are time sensitive, with the investment tax credit ending in 2016. The EIA (2011) projects the current 39% rate of growth per year for PV to slow to less that 1% per year, or a capacity of 8.9 gigawatts, once this program ends. With extended policies, they project an increased capacity of 47.8 gigawatts in 2035.

2.4.4 Architectural Considerations

The integration of solar collectors is an issue that has plagued designers for years. As façades, PV/T systems behave as rain screens or cladding. For a roof, there are other challenges. There are four solutions for a roof described by the IEA (Weiss 2003), shown in Figure 11: on-roof assembly, roof cover as modules, modules with framing and factory built unit. On-roof assembly applies smaller collectors on an existing roof. Aesthetically, these types of collectors can stand out from their inconsistency in material from the rest of the roof or if a large percentage of the roof is covered, visually continuity will be broken by lines from the modules' perimeters. The structural integrity of the roof must be ensured, as well as the weatherproofness. Once on, any leaks will be difficult to repair. With the second option, larger collectors can mitigate the tessellated pattern of the first option. These extend most of the length of the roof, and reduce breaks in material where leaks can occur. Modules with framing, option c, can be applied directly as roofing with insulation built-in. This makes the assembly lighter. The final solution is a prefabricated unit that acts as the roof structure as well. This reduces labor costs, however, the IEA points out that there would need to be co-ordination between trades, contractors building the north roof, as well as consideration of warranty.

2.4.5 Putting in to Practice: Available Software

The reasons why a homeowner or designer would want to consider PV/T have been investigated. This section discusses by what methods planning and implementation are possible. A quote from the RESNET 2009 Conference Summary states

“Modeling is an incredibly valuable tool and can be promoted to generate more business as Raters assist design teams in better understanding the influence of relative energy benefits of different design options, improving the design, and performing cost-benefit analysis.”

With any model, the quality of the results is dependent on the quality of the data input. For a person unfamiliar with typical value ranges for the parameters, it would be easy to have an error without recognizing it. The expected generation would then be specious. Another point to consider is manufacturer’s data. The necessary parameters may not be disclosed at all. Their goal is to sell their product which can lead to higher than actual performance claims. The consumer may be especially confused by PV/T performance. Instead of quoting the electrical and thermal efficiencies separately, often manufacturers will advertise the combined efficiency which is a significantly higher value. Therefore, a consumer may be expecting 60% electrical production, when the system is actually 10% electrical and 50% thermal.

There are several tools available to designers to help predict the performance of a given renewable technology. This is often limited to individual systems versus hybrid. Research-based software, such as TRNSYS, ESP-r, and EnergyPlus, all have the capability of modeling hybrid PV/T systems, often with incredible accuracy, however, they may befuddle most users.

2.4.4.1 Online Tools

There are several online tools that model photovoltaics or solar thermal systems. These free calculators are usually not very detailed, resulting in ballpark figures only. Some of these include PVWatts, PVSol Online and TSol Online. The latter two are both less sophisticated versions of simulation software that can be purchased from

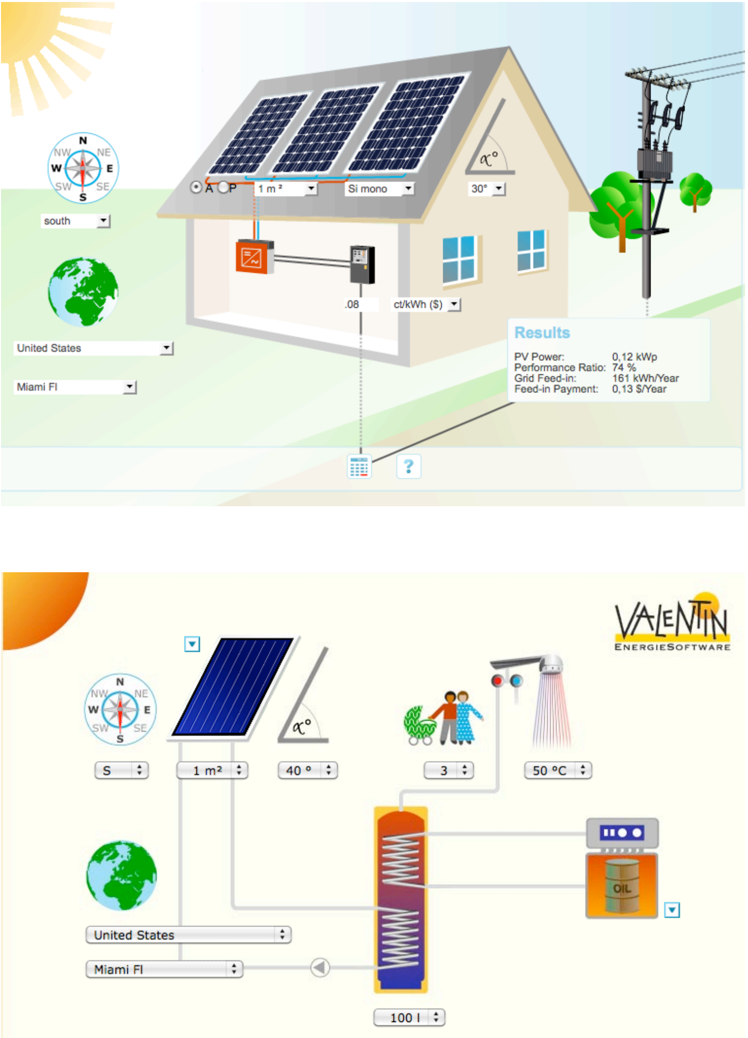


Figure 12
Graphical User Interface of Online Tools from Valentine Software
a) PVSol Online
b) TSol Online

Valentin Software. Examples of the GUI are to the left in Figure 12. The graphics inherent in the calculators help those unfamiliar with technical systems understand how solar systems function. Online calculators are meant to give homeowners an impression of the benefits a solar system could bring them. They are not meant for designers or engineers who require the ability to manipulate parameters for more accurate predictions. Additionally they do not have the ability to model the complexities of the system relationships in a hybrid system.

Other solar-renewable software tools are available from both the NREL's Energy Analysis (2011) and the EERE's Building Energy Software Tools Directory (2011) websites.

2.4.4.2 SAM

System Advisor Model (SAM), was originally developed in 2006 by the DOE, Sandia National Laboratories & NREL. SAM has the capacity for analyzing micro-generation to utility scale projects on an hourly basis using TMY2, TMY3 or EPW files.

Computations are done on a TRNSYS platform. Figure 13 is an example of charts in the user interface.

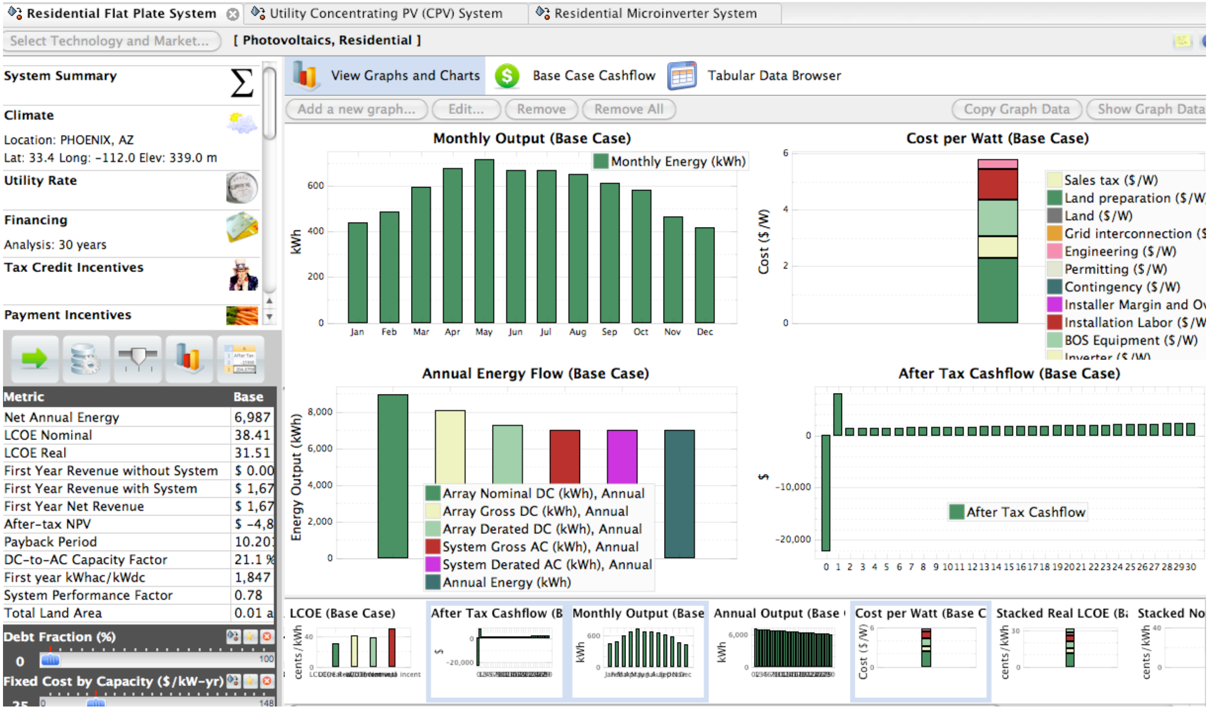


Figure 13
SAM User Interface

Although SAM does not have PV/T, it is a useful tool for calculating predicted performance and excepted financial implications for other renewable systems. Blair, et al. (2008) discuss the software's capabilities, as well as model overviews. According to the report, the Sandia Photovoltaic Array Performance Model calculates the maximum power point for each hour. Additionally, PVs available on the market are tested, which because of the time involved, results in the library not updating at the speed new models are released. A more simple Single-Point Efficiency Performance Model is also available which multiples the efficiency of the PV with the area, and incident radiation.

Financial computation is also part of the program, returning the levelized cost of electricity to reflect the cost of generation with respect to the capital investments, operation and maintenance. SAM also has sliders to instantly view how modifying a parameter will affect the overall system. Various sliders can be selected to show different parameters based on the criteria in the subcategory tabs.

2.4.4.2 CombiSun & F-Chart

F-Chart is a software developed by Klein and Beckman, who also developed the f-chart method which is detailed in the 1977 publication, Solar Heating Design By the f-Chart Method. This tool covers a number of collectors including flat-plate, CPCs, evacuated tube and tracking systems in conjunction with numerous systems such as water heating storage, DHW, and pool heating. However, it does not seem to have a PV/T collector.

In recent years, the gap in software hybrid modeling capability has been addressed by organizations such as the IEA which set forth Task 26 whose job it was to investigate solar "combisystems". CombiSun was a tool meant to assist with performance prediction of hybrid systems. It is based on the Fractional Solar Consumption method explained in Solar Heating System for Houses (Weiss 2003), which considers a reference consumption and usable solar energy. Models included various storage systems, boilers and applications, i.e. heating, hot water, however PV/T does not appear to be a capability of this software.

2.4.4.3 RETScreen

RETScreen was developed by the Canadian institution, Natural Resources Canada, and evaluates Renewable-energy and Energy-efficient Technologies (RETs). Because one can model a base case and an improved case, it is a particular useful tool for energy savings comparisons on renovations. A Microsoft Excel-based application, RETScreen is user-friendly and has the capability to model various renewable technology, like PV and solar thermal but excludes PV/T. Another advantage of RETScreen is its ease at converting units and languages, making it a cohesive tool for international building & development teams.

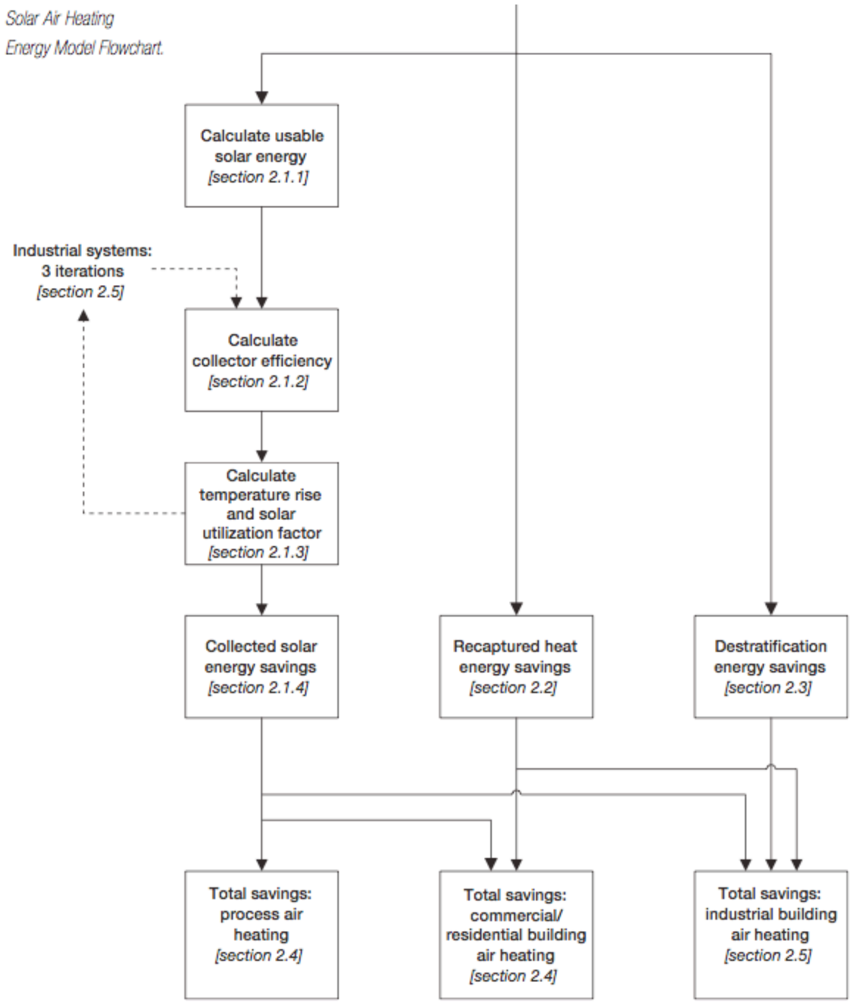


Figure 14
RETScreen Solar Air Heating Energy Model Flowchart
(Natural Resources Canada n.d.)

RETScreen can be used to model a renewable technology from early planning stages or in greater detail once a particular system in specified to assess yield and profitability, simply by changing the calculation method. Climate data is provided by NASA. One drawback from this data source is its monthly versus hourly air temperature, relative humidity, earth temperature, atmospheric pressure and wind speed data. Solar radiation is displayed in W/m^2/day. Another drawback to the weather data is the heating and cooling set points vary from location to location. This means that the number of heating or cooling degree days cannot be directly compared to that of another location. There are six sheets on which to enter data. The Energy Model and Solar Resource sheets establish the performance and yield. From this a financial analysis, green house gas emissions, and risk analysis can be calculated on successive sheets.

RETScreen states it is capable of modeling hybrid PV, but this refers to a PV, genset and battery system. Solar air and water heating are both capable in RETScreen. In the Clean Energy Project Analysis: RETScreen Engineering & Cases Textbook (Natural Resources Canada n.d.), refers to "SolarWall", a product developed by Conserval Engineering, Inc. On the SolarWall website, PV/T is listed, with photographs of case study installations, however, it does not appear that the full product line is available in the software. The textbook goes on to reiterate the use of the unglazed transpired collector as cladding which can offset heating demands or for use in an agrarian setting, dry crops, as well as bolster the system's low cost. Figure 14 demonstrates the energy flow for a solar air heater in the software. Equations for the system are also available in this document. RETScreen considers not only the energy provided from the sun's radiation, but also the heat recaptured, and benefits from destratification (Natural Resources Canada n.d.).

2.4.4.4 ESP-r

ESP-r certainly has the capabilities to model a PV/T system, however no model exists, as of yet, in the library. Dr. Paul Strachan modeled an air-cooled PV system by passing air behind a PV façade. His conclusions from a presentation archived online state PV/T air pre-heating systems are best for a sunny, cold climate, but are not generally applicable; these systems work best when ventilation is a significant portion of a building's heating loads; batteries should be employed in residential applications; and liquid systems have more potential, but safety and structural issues arise (Strachan n.d.).

2.4.4.5 EnergyPlus

At the time of this writing, EnergyPlus is one of the few software available with an exemplar model utilizing PV/T. It is also capable of modeling PV and solar thermal systems individually. Information regarding calculation methods and program operation are revealed in the accompanying documentation.

Unfortunately, upon contacting EnergyPlus support, it was learned that the PV/T model has not been validated and is not necessarily a best practice model. The PV/T exemplar model is also a commercial building which is out of the scope of focus for this dissertation. For this reason, the modeling and analysis that had been completed is in Appendix C.

2.4.4.6 TRNSYS

TRNSYS is the software on which many researchers and industrial professionals rely. Additionally, many of the aforementioned software use TRNSYS to calculate system performance. Originally developed by Klein, an author of Solar Heating Design By the F-Chart Method, TRNSYS has PV, SHW, and PV/T collectors in its library of components. Its range of renewable technology makes it a valuable resource in building science and energy modeling.

Kalogirou and Tripanagnostopoulos (2006) and other researches have use TRNSYS to model their experiments. The former has modeled with this program on several accounts, yielding complex systems. Figure 15 illustrates the layout of their system. Researchers at the University of Waterloo have designed a model for a similar type of unglazed transpired collector described in the RETScreen section, 2.4.4.3 (Delisle and Collins n.d.). Modeled in TRNSYS, it considers the corrugations of the the absorber plate. Their experiment modeled two configurations, one with PV on the protruding surface, and

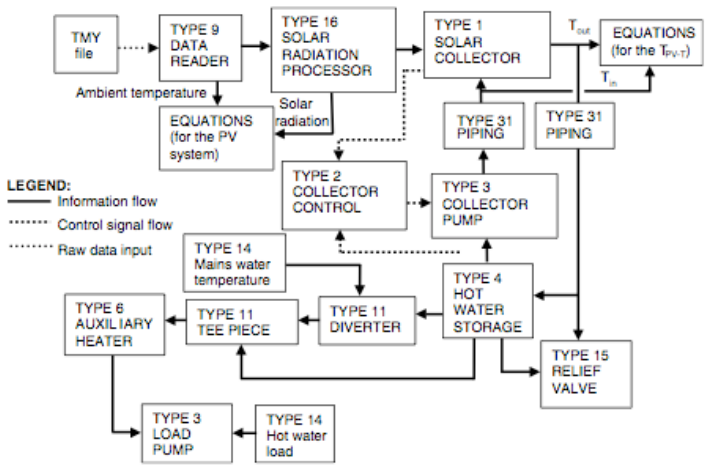


Figure 15
Configuration of TRNSYS PV/T Model
(Kalogirou and Tripanagnostopoulous 2006)

the other entirely covered with PV. They concluded that the former scenario has more potential.

The flexibility and benefit of this software is easily perceived, yet for early planning phases, it is not appropriate. The required knowledge of system physics is also high, thus it is not intended for a person outside of the industry or feasibility studies, when specific parameters are not yet known.

3. Methodology

3.1 Objectives

From the literature & software review, the need to assist designers and homeowners in predicting performance of this emerging technology is apparent. The PV/T Roadmap (Zondag n.d.) states "good design tools are essential for the application of PVT systems", which continues by saying spreadsheet-based tools as well as more advanced programs would be beneficial. PV/T has the potential to reduce primary energy consumption thus lowering the carbon footprint, as well as provide savings for system owners. Project objectives are listed below.

I. Produce a tool to assist PV/T performance prediction
II. Locate the areas that have the greatest potential for PV/T the US
III. Identify what improvements over PV exist, if any
IV. Conduct a preliminary analysis of the financial implications of a PV/T system in the various chosen climates

3.2 Approach

The software review section prior to this chapter revealed that there is not currently a PV/T modeling program for those who are not trained in engineering or building science. Even those with this background knowledge invest considerable time to master the complex software. The literature review covered many aspects of the hybrid system, yet never pinpointed locations where this system is most beneficial.

The main feature of this dissertation is a spreadsheet-based tool developed by the author with specifications of 11 hydronic PV/T models available on the market. Specifications were obtained from manufacturer's websites or by emailing requests to distributors. Manufacturers were selected from around the world, to consider any optimized parameters which may have been designed for its local climate. With little user input, the goal is to predict reasonable expected yields and initial economic benefits.

Zondag's (2002) 1 dimensional model and measured data is used as a case study against which the model is validated. Various climatic impacts are studied to determine where PV/T is best suited, attempting to quantify in broad terms advantages, if any. The nine cities chosen are Anchorage, Alaska, a cold, northernly climate with little sunlight in winter and significant amounts in the summer; Seattle, Washington, known for its cloudy and rainy climate; Minneapolis, Minnesota, known for its bitterly cold winters and relatively close to the Great Lakes; Jackson, Wyoming, located in the Rocky Mountains; New York, New York, located on the Atlantic coast and in the heart of the largest area of most dense population in the US; Flagstaff, Arizona, in the southwest, known for the dry climate and amount of solar radiation received; Orlando, Florida, another sunny location potentially affected by the Gulf of Mexico and the Atlantic; and Honolulu, Hawaii, a warm location in the Pacific known for the mild trade winds it receives which maintain a relatively consistent, comfortable temperature. Finally, an inter-collector comparison to observe the effects of altering system parameters is also undertaken.

Data analysis will be done by comparing one collector type across the nine locations for both thermal and electrical production, in kWh, over a given period of time, typically by year or a particular day. Along these lines, the solar fraction, or percentage of demand met by the PV/T system, will also be compared since demands are consistent for each location. The yield of the PV/T will be compared to the output of a PV alone. Inlet temperatures will also be modified from 10ºC, to represent water from the mains, to 40ºC, to represent warm water in a stratified tank. This is likely to occur as the day goes on, and the mean storage temperature increases. For the multiple collector comparison, yields will be given in kWh/m^2.

A preliminary study of financial and primary energy implications is included so that a homeowner could comprehend how PV/T would directly affect his/her budget and environmental impact. This is done through the cost of solar energy, payback period and percentage of primary energy saved. Further description and calculations follow in sections 4.1 and 4.2 respectively.

4. The Tool

4.1 Description

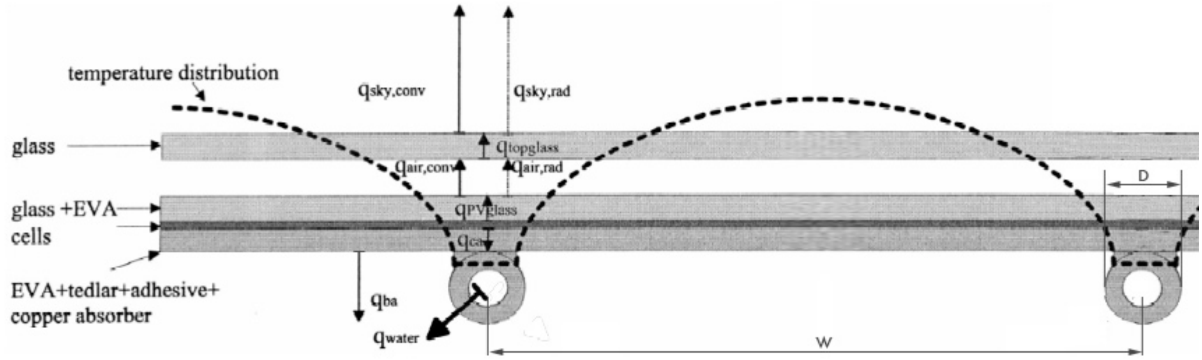


Figure 16
Diagram of a Sheet-and-Tube Collector
Based on (Zondag 2002)

A tool for designers to calculate the expected output of a liquid-based sheet-and-tube PV/T system has been created based on the calculations discussed in section 4.2. Often, there were more than one set of equations to choose from in order to calculate certain parameters for the tool. For example, there was the choice between isotropic or anisotropic sky models to calculate radiation on a sloped surface. Mathematical models for performance calculation have been previously derived in 1D, 2D, and 3D, static or dynamic. The work of Zondag (2002), discussed in Charalambous, et al. (2007), states that the efficiency of results of the various types of models are relatively close.

Because this tool was meant to give performance predictions with little input from the user, there are only two sheets on which to enter data. The initial sheet, “User Input”, will display the energy produced for both electrical and thermal and their respective efficiencies once all parameters are defined. A series of macros, functions in the spreadsheet program that automatically do a task, were put in place to coordinate the appropriate information selected by the user in to the appropriate cells. First the climate is selected from a drop-down list. More locations can be added by simply copying the appropriate macro and specifying a new file. Typical Meteorological Year

(TMY3) weather data was obtained from the NREL. This was chosen for its hourly time-steps and number of locations available, as the tool is intended to be applicable for multiple climates. Initial versions of the tool attempted to use climate data from NASA, the same source for RETScreen's climate data, however it was found the averages for solar data was inappropriate for electrical and DHW demand load comparisons, which were in 5 minute and 15 minute increments respectively.

Next, the tilt angle of the collector from vertical (Φ) and angle from south (ϒ) are specified. This can be done in two ways. The first is a default based on the location selected in the first entry list. This is based on a rule of thumb, latitude + 10° suggested by Beckman, Klein and Duffie (1977). The second option is for the user to enter the angle manually. This is useful if a collector is being installed on an existing roof where these parameters cannot be altered by a designer without significant cost or introducing increased losses due to exposing the back of the collector by increasing the angle.

The user then specifies a system. Specification sheets were collected from manufacturers' websites or obtained through email requests from distributors. A list of 5 manufacturers and a total of 11 different sheet-and-tube collectors was compiled. Manufacturers were mostly European (German, UK and France), with one from Asia (China). Performance of systems is dependent on minute differences between configurations. In the tool, if needed parameters were not disclosed, a value would be assumed, shown in Table 2.

Values for Zondag Collector		Assumed Values for Other Collectors		Other Constant Values	
Area (m^2)	0.94	**Area (m^2)**	Varies	**h_{ca} (W/m^2K)**	45
D (m)	0.01	**D (m)**	0.01	**Ccopper (J/kgK)**	390
W (m)	0.95	**W (m)**	0.136	**Cwater (J/kgK)**	4183
mass flow (kg/s)	0.02	**mass flow (kg/s)**	Varies	τ	0.92
				α	0.72
				ε_p	0.95
				ε_{glass}	0.88
				N	1

Table 2
Parameters and Assumed Values for the Tool

Other assumptions include:

I. Back and side losses from the collector are minimal and can be neglected as there is typically insulation on the back of the collector. This consistent with Zondag's (2002) approach.
II. The inlet water temperature is constant
III. All collector configurations have one glass cover, and PV cells are adhered to the collector plate (See Figure 16)
IV. Resistance of bond can be neglected
V. No wind sheltering from roof orientation is considered; wind direction is neglected
VI. Collector pipes are straight; the serpentine nature of the tubes is neglected, as was demonstrated by Zondag (2002)
VII. Transmittance (τ) is a constant and not angularly dependent
VIII. As mentioned earlier, parameters not discernible from the specifications were estimated according to literature and manufacturer's drawings. W/D=13.6 (Refer to Figure 16)
IX. If there is no solar radiation or the thermal generation is negative, there is no flow, i.e. the pump operates only when there is solar radiation and a positive heat gain
X. Freezing considerations are neglected, therefore the liquid in the system is only water instead of containing an antifreeze which would alter the specific heat of the fluid. In this way, systems in the south can be directly compared to systems in the north. According to Otanicar, et al. (2009), ethylene glycol and propylene glycol have absorption factors of 9.25% and 9.06% respectively, compared to that of water, 13%.
XI. The module has a packing factor (defined in section 2.3.1) of 1.
XII. The energy required to operate the pump is subtracted from the electrical yield displayed on the user input page.

The number of panels is defined by the user. This allows the user to see the amount of difference between generation and demand that exists– results that can be seen graphically and inputs can be adjusted accordingly, i.e. increasing the number of panels in the array.

This is followed by the flow speed. Options of low, average and high are available in the list, with “average” being the default value. This affects yields, as Chow (2003) demonstrated. Some manufacturers do not detail their systems further than the average flow rate, in which case only the average flow is available for all selections.

In the second sheet of the workbook, “Monthly Charts”, the months of June and December are plotted in greater detail, illustrating the DHW demand, the electrical demand, the respective generation and the associated efficiency. Additionally, there are graphs that plot the ambient temperature, mean plate temperature and outlet temperatures over the same months.

Thermal and electrical demand profiles also have to be defined, dependent on occupancy. Each person is attributed 25 liters per day. Although precedence on this can conflict from Beckman, Klein and Duffie’s (1977) recommendation of 100 liters per person per day and the IEA’s (Weiss 2003) 50 liters per day per person, there is agreement between the modern sources– Passive House Planning Package, which recommends 25 liters per person per day, and SAP, which uses 25 liters per person per day plus 35. It has been suggested by Tuohy (2011) that the cause for this discrepancy is due to installations of low-flow plumbing fixtures and appliances as well as habitual changes over the last 40 years. One of the most common reasons for deviation of actual performance to calculated performance is a result of the occupants’ lifestyle. Domestic hot water and electrical demand loads were obtained from the IEA/ECBCS (Energy Conservation in Building & Community Systems) Annex 42, which compiled profiles from Canada. DHW profiles were available for 100, 200 & 300 l/day consumption in a residential setting. Electrical profiles were available in 1, 5 & 15 minute time-steps, for low, average and high consumption in Canada (referred to as “North America” in the tool). Consumption for the UK is available, making it possible to expand the tool’s scope in the future. Ideally, if a home-owner had monitored data, from a post-occupancy evaluation for example, his/her own data could be pasted into the appropriate cells. Advanced options include modifying the desired tank temperature and the water inlet temperature. Tank temperature affects the amount of energy required for the DHW demand and the inlet temperature affects PV performance and thermal yield. The tool considers a constant temperature throughout the day.

On the “Economics” sheet of the workbook, the preliminary outcome of financial inputs from the first worksheet are seen. The user enters the cost per panel, inverter (the tool considers 2 over the system lifetime), and batteries, if applicable, the cost of kWh paid for electricity, the cost paid for kWh of water heating (if the fuel source is something other than electricity), the amount received per kWh exported to the grid, expected life of the system, as well as interest and inflation rates. Costs for fuel and electricity were taken from utility companies’ webpages, using the national average whenever possible. Figure 17, is an example of how the rates vary nationally.

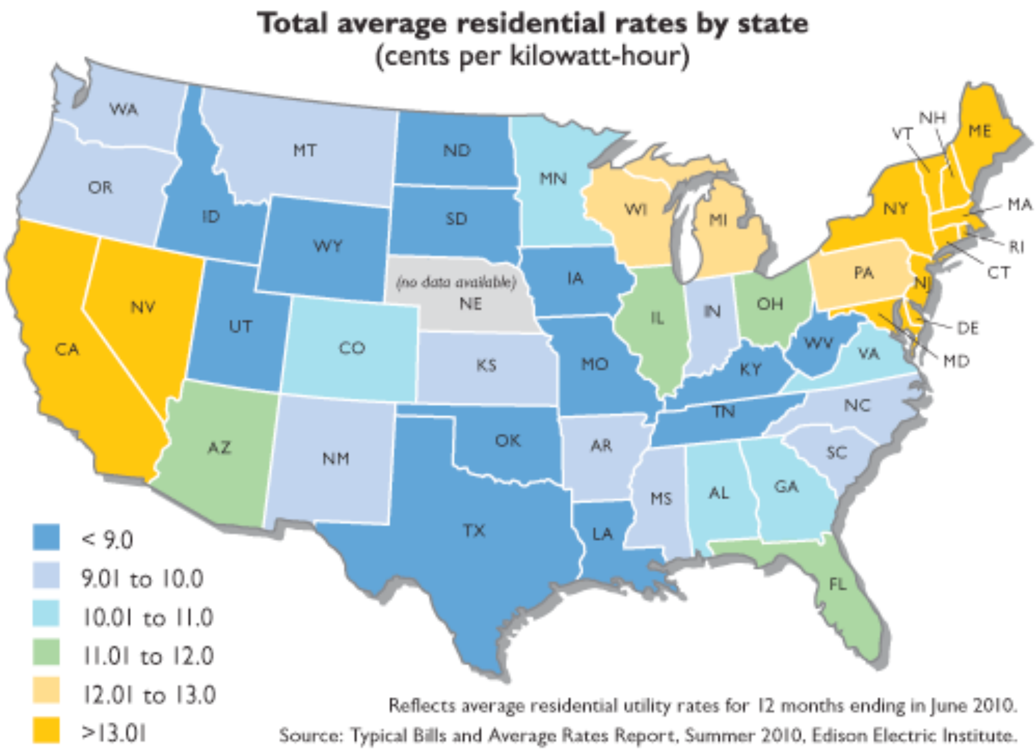


Figure 17
National Average Residential Electrical Rates By State
(Rocky Mountain Power 2011)

Many installations of PV/T focus on the thermal production. Because DHW is generally a smaller demand than the electrical load, and thermal production of the PV/T system is higher than the electrical side, typical installations optimized for SHW will not have much excess electricity to export to the grid. The payback period is also calculated.

Performance predictions are based on accurate parameters. Transmittance was assumed equal in all PV/T systems at 92%, to be consistent with the Zondag model. This is in accordance with a data sheet from the glass manufacturer, Stegbar (n.d.), which listed 91.7%. The absorptance factor is also important. It is the amount of the transmitted radiation, absorbed by the PV laminate. In reality, a portion would the be reflected to the back of the cover, which would be re-reflected, and so on, mathematically detailed by Duffie and Beckman (1991) but this has been neglected in the tool. Specific heat capacities were taken from online sources (Engineering 2011), as well as the Zondag (2002) article. Pipes, 10 mm in diameter, were assumed to be 136 mm apart, based on a drawing from one of the manufacturers and examples from Duffie and Beckman (1991). If further development of the tool is undertaken, this parameter can be modified to match that of the selected PV/T model for greater accuracy.

The model uses simple functions as controls over the system that mimic reality. If there is no solar radiation or the thermal generation for that hour would be negative, the flow is stopped. Another option is to set the function to limit the flow to times when the change in temperature across the collector is equal to or greater than the desired amount. This idea is supported by the research of Huang, et al (2001), who said a differential-temperature controller would shut the pump off if the difference between the tank temperature and collector output was 3ºC.

If in the future, development of the tool occurs, the energy consumption of the pump can be more accurately reflected. For now, in the tool, the energy consumed by the pump is relative to the mass flow selected: 5 kWh each month for low; 6.25 kWh for average; and 7.5 kWh for high. This is subtracted from the monthly readout of “Electrical Production for Selected Time Period”. Because the focus of this investigation is on the performance of the collector, not the whole system, the pump energy is not subtracted from the electrical yield shown in the graphs.

For economical considerations, panel prices were estimated according to discussions with PV/T distributors in the UK and PV collector prices in the US. Although the distributors would not give an exact figure for PV/T, one stated in an interview that a system is twice that of PV alone. The second industry representative stated it was four times as expensive but did not know if this included the price of a heat pump which is likely to account for the discrepancy between prices. This is in line with Kern and Russell's findings, stated in Zondag (2008), that although a heat pump reduced demand on auxiliary equipment, the lower cost of a direct solar heating system was more affordable for residential application. Photovoltaic sales in the US for a collector producing a similar amount of power to the median power (190 W) of the manufacturers' models was about $900 per panel, therefore this was doubled to account for the difference in pricing of the systems as the first UK distributor suggested. Even this number seems to be high when compared to the figures from Bakker, et al. (2005) which lists a 25 m^2 PV/T array only 5.7% higher than the cost of a reference array (separate PV and thermal) with a 32% increase in area. Because the electrical and thermal production of both arrays were within 5% of each other, they conclude that PV/T is cost competitive with separate systems.

Users are able to see their expected performance through small table displays and graphs inspired by other software such as PHPP.

4.2 Calculations

Numerous mathematical models have been developed over the year regarding solar resources, flat plate collectors and PV/T collectors. These have been in 1, 2 and 3 dimensions, and can be either static or dynamic. Significant contributions to the prediction of solar energy have been made as early as the 1940s, such as models developed by Hottel, Woertz and Whillier. Duffie and Beckman (1991) also published equations that are staples to the solar industry.

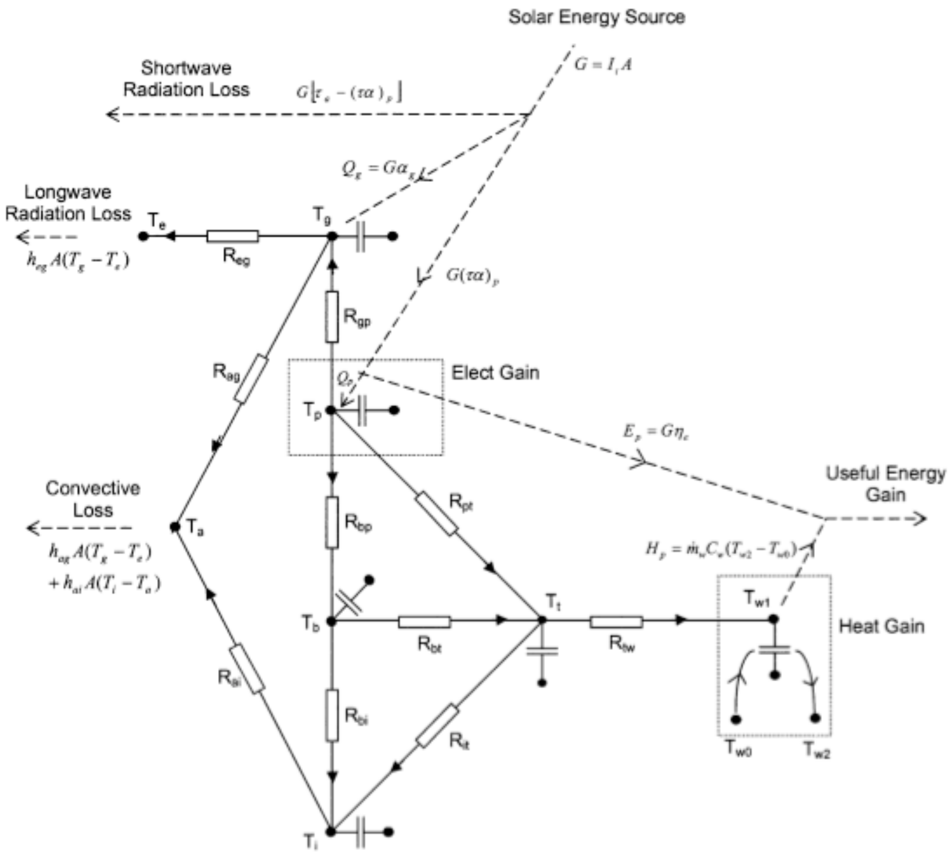


Figure 18
PV/T Energy Flow
(Chow 2003)

The diagram in Figure 18 is a helpful aid to understand what happens in a PV/T collector. Solar irradiance passes through the cover where some will be reflected or absorbed, leaving a certain percentage that is transmitted. Then the irradiance passes through the layer of air, a portion of which is absorbed by the next layer– the PV cells, encapsulated in a laminate or under glass. Duffie and Beckman (1991) describe how some of this is reflected back and forth between the cover and the laminate, but this is neglected in the tool. While the photovoltaic cells convert a percentage to electricity, the remaining energy will heat the layer, affecting its efficiency. The heat is transferred to the absorber plate to which the cells are adhered. Finally, water passing through pipes that are soldered to the back of the plate cools the cells by removing some of this heat. Conduction will also be affected by the temperature of the water. Losses occur by convection and radiation between the cells and cover, and can be seen mathematically in the energy balance described in section 4.2.3.

4.2.1 Solar Radiation Incident To the Collector

Because TMY3 climate files report solar irradiance on a horizontal plane, the first step in calculating the useful energy of a selected PV/T system was modifying the data to reflect the orientation and angle of the collector. The scope of this investigation only includes fixed flat-plate collectors, therefore tracking systems are not included although it would result in higher yields. Equations (1) through (9) are from the notes of Kelly (2010). Equations (1) and (2) respectively give the diffuse and direct beam radiation corrected for a tilted surface.

$$I_{b\phi} = I_b(\cos\beta\cos\alpha\cos\phi + \sin\beta\sin\phi) \qquad (1)$$

$$I_{d\phi} = I_{dH}\left(\frac{1+\sin\phi}{2}\right) \qquad (2)$$

where

$I_{b\Phi}$= Direct radiation incident on the collector
I_b= Direct beam radiation on a horizontal plane
β= Altitude of sun from horizontal
α= Angle between surface normal and solar beam azimuth
Φ= Collector angle from vertical

and

$I_{d\Phi}$= Diffuse radiation received by the collector
I_{dH}= Diffuse radiation on a horizontal plane

Calculations to obtain β, α and Φ are described below.

$$\beta = \sin^{-1}(\cos l \cos h \cos \delta + \sin l \sin \delta) \tag{3}$$

$$\gamma_s = \cos^{-1}\left(\frac{\sin l \cos h \cos \delta - \cos l \sin \delta}{\cos \beta}\right) \tag{4}$$

$$\delta = \delta_0 \cdot \sin\left(\frac{360(284+n)}{365}\right) \tag{5}$$

where

n= Day of the year

δ_0= 23.5

$$t_{sol} = t_{ref} + \frac{4(L_{ref} - L) + E}{60} \tag{6}$$

$$h = 15 \cdot |12 - t_{sol}| \tag{7}$$

$$E = 9.87\sin(2B) - 7.35\cos B - 1.5\sin B \tag{8}$$

$$B = \frac{360(n-81)}{364} \tag{9}$$

where

t_{sol}= Solar time for the longitude

t_{ref}= Unadjusted reference time

L= Longitude

L_{ref}= Longitudinal reference from Greenwich (0°)

E= Correction factor

h= Solar hour

Once the the irradiance is calculated, electrical and thermal yields can be determined. This is affected by the transmittance-absorptance product, defined by the TRNSYS manual (Klein, et al. 2004) as:

$$\tau\alpha = \frac{I_{bT}(\tau\alpha)_b + I_d\left(\frac{1+\cos}{2}\right)(\tau\alpha)_s + \rho I\left(\frac{1-\cos\beta}{2}\right)(\tau\alpha)_g}{I_T}$$

where the terms marked by b, s, and g, respectively, represent the direct beam, sky diffuse and ground diffuse radiation. This determines how much solar energy reaches the cells and absorber.

4.2.2 Electrical Generation

Once the incident solar radiation to the collector is calculated, the process for calculating system yield begins. System output, in electrical terms, is a function of the amount of solar radiation received and the efficiency of the cells. Efficiency is also affected by temperature of the collector. Each panel will produce energy based on the equation:

$$Q_{el} = A_{pv} G \eta_{el} \quad (10)$$

where the electrical efficiency is a function of the cell temperature.

This is modified in the tool to consider transmittance and absorptance so that

$$Q_{el} = A_{pv} G \eta_{el} \tau\alpha \quad (11)$$

Cell efficiency varies with temperature. Zondag (2002) gives the equation:

$$\eta_{cell} = \eta_0 \left(1 - \eta_{PT}\left[T_{cell} - 25^{\circ}C\right]\right) \quad (12)$$

where η_{PT} is the percentage of electrical loss per degree, given by the manufacturer. The absorber, cells and protecting layer are amalgamated to find the mean plate temperature, therefore it is assumed

$$T_{cell} = T_{mp}$$

Because it was assumed no mass flowed in the tool when there was no solar radiation, the calculation of the mean plate temperature was changed from Zondag's:

$$T_{pm} = T_{in} + \frac{\Delta T_{collector}}{2} + \Delta T_{ca} = T_{in} + \frac{P}{2\dot{m}c} + \frac{P}{A_{pv}h_{ca}} \qquad (13)$$

to

$$T_{pm} = T_a + \frac{P}{2\dot{m}c} + \frac{P}{A_{pv}h_{ca}} \qquad (14)$$

The mean plate temperature will be used later in calculating the overall heat loss coefficient.

4.2.3 Thermal Generation

The useful heat of a PV/T flat plate collector will produce less than that of a solely solar thermal flat plate collector due to the PV cell utilizing a portion of the solar radiation that would have otherwise been converted to heat. Mathematical formulas have been derived in L.W. Florscheutz's 1979 work, "Extention of the Hottel-Whillier Model to the Analysis of Combined Photovoltaic/Thermal Flat Plate Collectors". Florsheutz accounts for the "loss" of solar radiation to the transfer fluid by the PV. He shows that the steady-state formula for a hybrid collector is the same as a thermal collector with a few substitutions for U_L and S.

Heat transfer can occur in all 3 dimensions of a PV/T collector, however, because the purpose of this tool is be user-friendly and require as few inputs as possible to achieve reasonable results, a 1D model for a sheet-and-tube collector presented in Zondag (2002) from Duffie and Beckman (1991), based on a Hottell-Whillier model was used. The heat balance is described below.

$$q_{water} = q_{ca} - q_{ba} \quad (15)$$

where in the tool, losses from the back to the surroundings are neglected, consistent with Zondag's (2002) methods, therefore

$$q_{water} = q_{ca} - 0 \quad (16)$$

$$q_{ca} = (\alpha - \tau\eta_{el})G - q_{PVglass} \quad (17)$$

$$q_{PVglass} = q_{air,\text{cov}} + q_{air,rad} \quad (18)$$

$$q_{air,conv} + q_{air,rad} = q_{topglass} \quad (19)$$

$$q_{topglass} = q_{sky,conv} + q_{sky,rad} \quad (20)$$

This was used in Zondag's two- and three- dimensional models. Substituting the above equations into one another, the Equation (21) is derived.

$$q_{water} = (\alpha - \tau\eta_{el})G - q_{topglass} \quad (21)$$

The correlation is seen in calculating the yield. The yield of the collector can be written in several forms, however for the tool and Zondag's model, Equation (22) was used.

$$P = A_{pv}F_R((\alpha - \tau\eta_{el})G - U_{loss}(T_{in} - T_a)) \quad (22)$$

The heat removal factor, F_R, dependent on the plate efficiency factor (F'), is calculated by:

$$F_R = \frac{\dot{m}c}{A_{pv}U_{loss}}\left(1-\exp\left[\frac{-A_{pv}U_{loss}F'}{\dot{m}c}\right]\right) \tag{23}$$

$$F' = \left\{\frac{1}{F_t} + \frac{U_{loss}}{h_{ca}} + \frac{U_{loss}W}{(\pi D h_{tube})}\right\}^{-1} \tag{24}$$

$$F_t = \left(1-\frac{D}{W}\right)F + \frac{D}{W} \tag{25}$$

$$F = \frac{\tanh\left[\frac{m(W-D)}{2}\right]}{\frac{m(W-D)}{2}} \tag{26}$$

$$m = \sqrt{\frac{U_{loss}}{k\delta}} \tag{27}$$

$$U_{loss} = \left\{\frac{N}{\frac{C}{T_{pm}}\left[\frac{(T_{pm}-T_a)}{(N+f)}\right]^{e}} + \frac{1}{h_w}\right\} + \frac{\sigma(T_{pm}+T_a)(T_{pm}^2+T_{pm}^2)}{(\varepsilon_p+0.00591Nh_w)^{-1} + \frac{2N+f-1+0.1333\varepsilon_p}{\varepsilon_g} - N} \tag{28}$$

where

$$f = (1+0.089h_w - 0.1166h_w\varepsilon_p)(1+0.07866N)$$

$$C = 520(1-0.000051\beta^2) \text{ for } 0° < \beta < 70°$$
$$\beta = 70° \text{ for } 70° < \beta < 90°$$

$$e = 0.430(1-100/T_{pm})$$

N= Number of glass covers

β= Collector tilt

ε_g= Emittance of glass

ε_p= Emittance of plate

T_a= Ambient temperature

T_{pm}= Mean plate temperature

h_w= Wind heat transfer coefficient

h_{tube}= Heat transfer coefficient from the tube to the water

which was found by

$$\mathrm{Re} > 2300 \Rightarrow u_{tube} = 0.023\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \quad (29)$$

for natural convection.

The value of 3200 for the Reynolds number was measured by Zondag (2002) and used as a constant in the tool. The Prandtl number, representing a relationship between viscosity, specific heat, and thermal conductivity of the fluid, varied based on the temperature of the water.

With no mass flow, overall losses decrease as the plate approached ambient, thus causing the convective losses to become 0 from the zero temperature difference in a term on the denominator of the equation. This leaves only radiation and wind losses. This approach neglects the heat storage, and is a comparable method to the 1D model of Zondag, as these are steady state models.

4.2.4 Economics & Environmental Impact

From the literature review, it is evident that an appealing financial component is necessary to make a new technology enticing. A study done in 1977 by the National Science Foundation (McGarity), investigates the economics of solar heating and cooling. Updated with more current prices, the tool emulates this study's methods.

For the life cycle cost analysis, the annual cost method was preferred over the present value method. This accounts for all costs and increases in one amount even distributed over the life of the project.

$$\text{Uniform Annual Cost}=\left(\text{Initial Expenses}\cdot\frac{r(1+r)^n}{(1+r)^n-1}\right)+\text{Constant Annual Costs} \qquad (30)$$

where

r= Interest rate

n= Lifetime of equipment

The annual solar “fuel” cost represents the collector and storage. Since the storage tank and associated cost is not considered in the tool, the annual solar fuel cost will be slightly lower than in reality.

$$\text{Annual Solar "Fuel" Cost}=\text{Initial Cost of Collector \& Storage}\cdot\frac{r(1+r)^n}{(1+r)^n-1} \qquad (31)$$

The annual savings from conventional fuel is then written as:

$$\begin{array}{l}\text{Annual Conventional}\\ \text{Fuel Cost}\end{array}=\frac{(\text{Cost of Fuel per Unit of Energy}\cdot\text{Annual Energy Supplied}\cdot\text{D})}{\eta_{eq}} \qquad (32)$$

where

$$D=\left(\frac{r(1+e)}{r-e}\right)\left(\frac{r(1+r)^n}{(1+r)^n-1}\right) \qquad (33)$$

e= Annual cost increase

η_{eq}= Efficiency of the conventional equipment

The conventional equipment efficiency is assumed to be 85% in all financial calculations.

The payback period is calculated by:

$$\text{Payback Period}=\frac{\text{Capital Costs}}{(\text{FITs + Savings})} \qquad (34)$$

Using the cost calculated for the solar “fuel”, the savings are calculated annually and as well as FITs.

It is also important for the system to mitigate the users’ environmental ramifications. The primary energy efficiency, or savings, was reported by Huang, et al. (2001) as:

$$E_f = \frac{\eta_e}{\eta_{power}} + \eta_{th} \tag{35}$$

where

η_e= Electrical efficiency

η_{power}= Efficiency for a conventional power plant

η_{th}= Thermal efficiency

It is important to note the SHC’s (Collins and Zondag 2008) statement regarding the efficiencies of power plants by country, where non-OECD countries tend to have a lower efficiency than OECD countries. However, even within these 35 countries, efficiencies vary between 28-55%.

5. Results

5.1 Validation

5.1.1 Zondag Model Comparison

Validation was achieved by creating a “manufacturer’s model” using the parameters described in the Zondag (2002) article, “The Thermal and Electrical Yield of a PV-Thermal Collector,” and comparing results with those reported. Because the Dutch KNMI meteorological file used by Zondag could not be obtained and the format of climate data for the tool required a TMY3, a format not used for European locations, Corvallis, Oregon, USA was selected. Near the Pacific coast, it’s average monthly temperatures and solar irradiance were similar to that of the Netherlands. Figures 19 & 20 show the solar radiation for each location, followed by Figure 21, showing a comparison of the temperatures. Figure 22 shows the data’s correlation for the selected day of comparison in the summer.

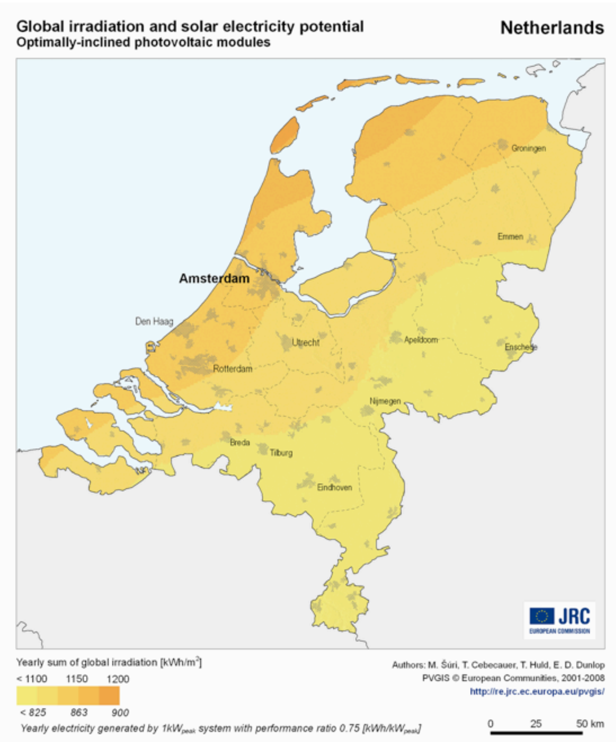


Figure 19
Global Irradiation in the Netherlands
(Renewable Energy Sources 2009)

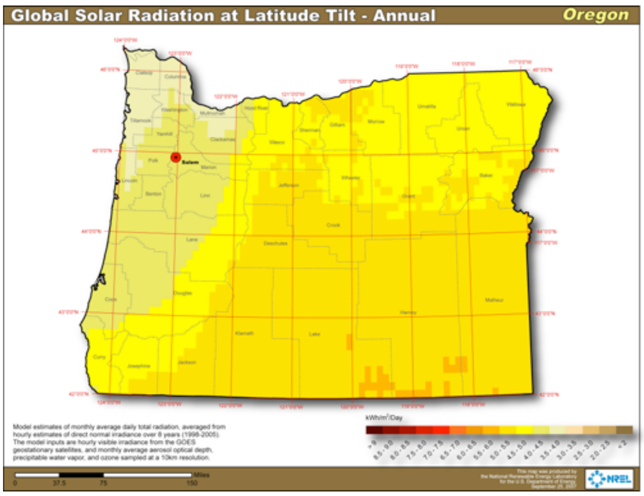


Figure 20
Solar Irradiance on Oregon State
Corvallis, the city of which the climate data was used, is in the same green band as the capitol, Salem, shown as the red dot.
(NREL 2007)

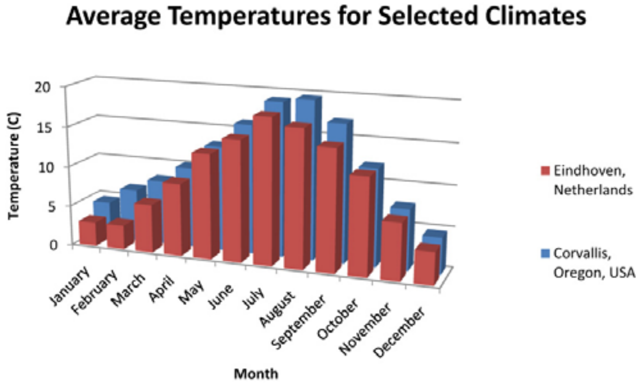


Figure 21
Average Monthly Temperatures of Selected Climates

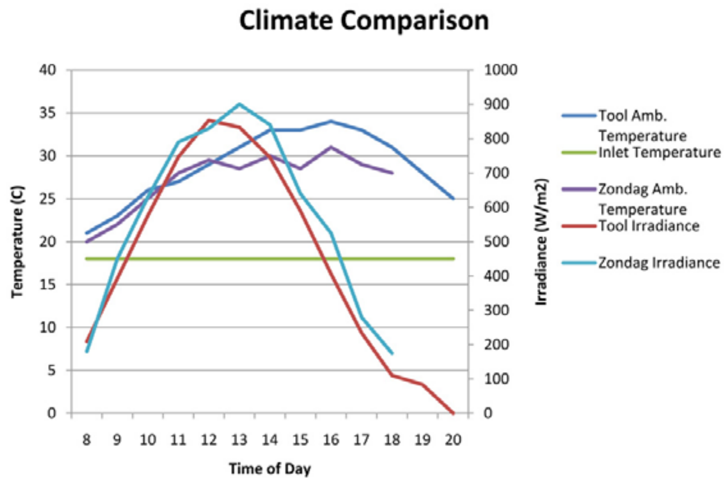
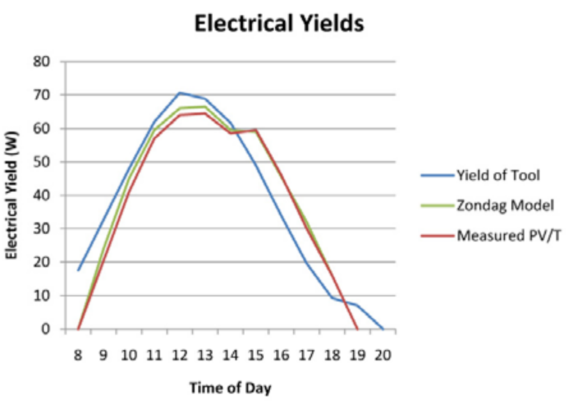


Figure 22
Correlation of Climates

The date of June 25th was selected, as the most critical parameters, irradiance and ambient temperatures, of the two locations mimicked each other. The data from Zondag was at a higher resolution, plotting in finer detail the effects of clouds, shadows and other changes. In both models a constant inlet temperature of 18ºC was maintained. It can be seen in Figures 24 & 25 that the tool predicts a higher yield, both electrical and thermal, until about 3 pm, when it under estimates. Referring back to the climate comparison, it can be seen that the irradiance of the tool is fairly similar to that of the Dutch model, however deviation increases after noon, which may attribute to this lower prediction.



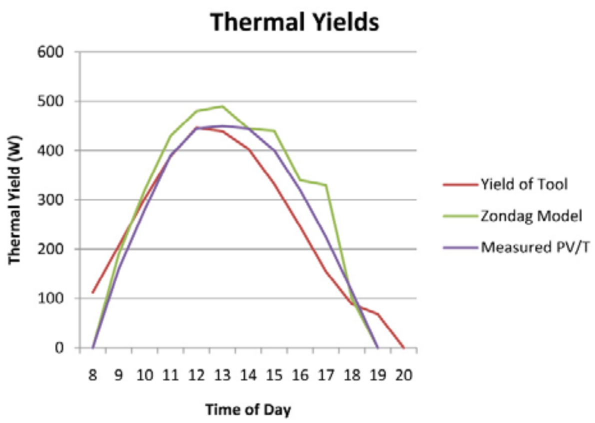


Figure 23
a) Electrical yield comparison between Zondag's model, measured data and the tool
b) Thermal yield comparison between Zondag's model, measured data and the tool

For initial simulations, the yields were about three times higher than the Zondag model. A high absorptance (<0.9) was used based on the assumption that the cells would be a black color, however, Zondag had the opportunity to measure this factor for his experiment and found it to be 0.74. Once this change was made, the tool's yields more closely resembled that of its precedent.

The yields have been verified and in the following two sections, the energy demand of the DHW is compared against respected European calculation tools, SAP and PHPP.

5.1.2 SAP Model Comparison

After validating the model according to Zondag's parameters, the manufacturer's data was input and the thermal yield compared to SAP's SHW calculations. This assessment procedure calculates energy consumption per square meter in a building. Because SAP considers the storage of the SHW, a feature not included in the tool, assumptions were made. Other parameters were kept constant between the two models, shown below. The heat loss coefficient for the tool was averaged over hours that received solar radiation. Criteria that is shaded blue represents values input by the user; orange shading represents calculations within SAP; green is a recommended value from SAP in Table 3.

	SAP	**The Tool** *Zondag Model*	**The Tool** *Manufacturer's Collector*
Aperture Area	0.94	0.94	1.168
Zero-loss Efficiency	0.75	0.75	0.715
Heat Loss Coefficient	6	4.18	4.18
CollectorPerformance Ratio	8	5.573	5.846
Annual Solar Radiation	1054	1054	1054

	SAP	The Tool *Zondag Model*	The Tool *Manufacturer's Collector*
Overshading Factor	1	1	1
Solar Energy Available	743.07	743.07	708.393
Solar-To-Load Ratio	0.108	0.108	0.103
Utilization Factor	0.999	0.999	0.999
Collector Performance Factor	0.715	0.784	0.776
Solar Storage Volume	100	100	100
Effective Solar Volume	100	100	100
Daily Hot Water Demand	110	110	110
Volume Ratio	0.909	0.909	0.909
Solar Storage Volume Factor	0.981	0.981	0.981
Annual Solar Input	520.971	571.477	539.169
Accounting for Electrical Production of PV/T	**442.825**	**485.755**	**458.293**

Table 3
SAP Comparison

Since the zero-loss efficiency was taken from the SAP table, the annual solar input of the Zondag model is then adjusted to account for 15% of electricity production. The result is 6.8% lower than SAP's calculation. Although, ideally the manufacturer's thermal efficiency should take into account electrical production, it is like that the efficiency reported is optimized for thermal production, therefore the same approach for reducing the annual solar input is taken. The result is 3.5% greater than the SAP calculation, making it a reliable estimate.

5.1.3 PHPP Comparison

The Passive House Planning Package (PHPP) spreadsheet is a useful tool for calculating overall energy consumption per area of a home based on the construction and MEP demands within the dwelling. Therefore, the PHPP considers the whole system, including losses from pipes and the storage tank, whereas the tool does not. Because of this, losses in the PHPP were set to zero so the two could be more directly compared. The location for the comparison was Orlando, Florida with 1.16 m^2 of collector. With the IEA profiles discussed in section 4.1, the tool calculates a DHW demand of 1907 kWh/a. PHPP resulted 1829 kWh/a. In turn, the SHW calculations of PHPP expected a 1026 kWh/a to be supplied, which is a solar fraction of 56%. The average monthly thermal solar fraction of the tool estimates 55%. The figures below compare the graphical output from the PHPP and the tool. The demands and solar radiation in the tool have greater swings between seasons, but follow a similar pattern to that of PHPP. Again, August sees a higher solar fraction met due to a lower demand, which is discussed further in section 7.

When inlet temperatures are changed to 40ºC, it can be seen that the DHW demand is 635.91 kWh/a for the tool and 876 kWh/a for PHPP, which without 241 kWh/a for a separate “DHW Non-Electric Wash and Dish” category, is 635 kWh/a.

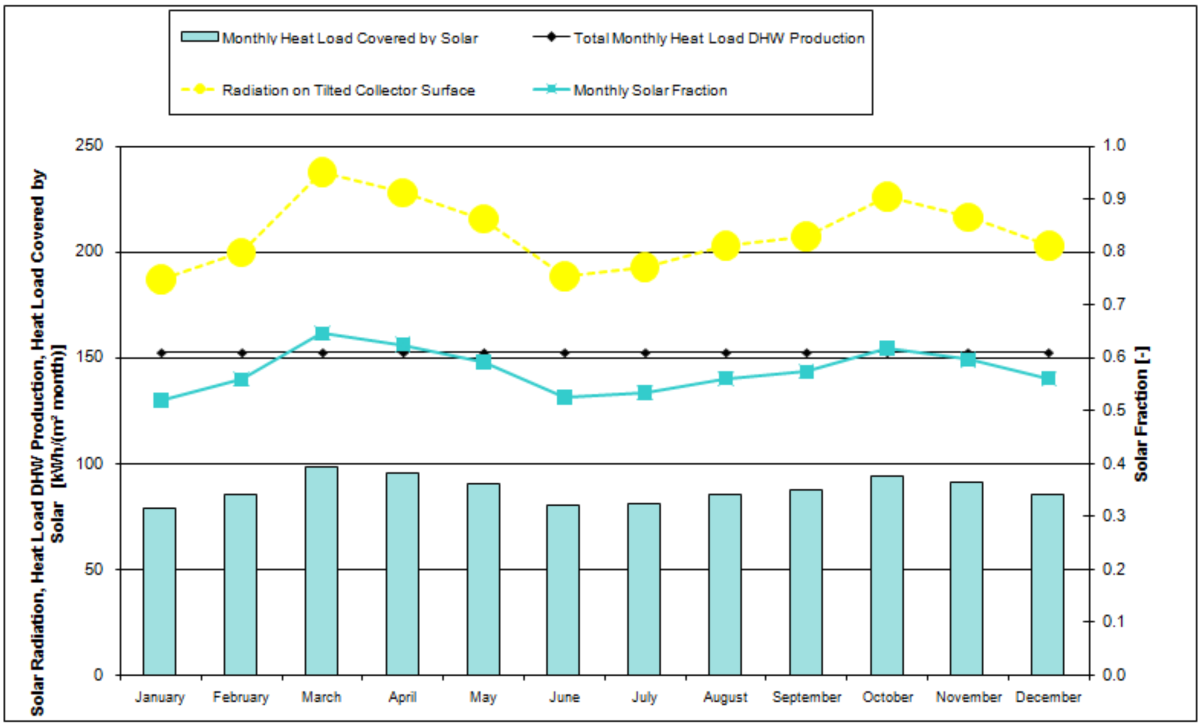
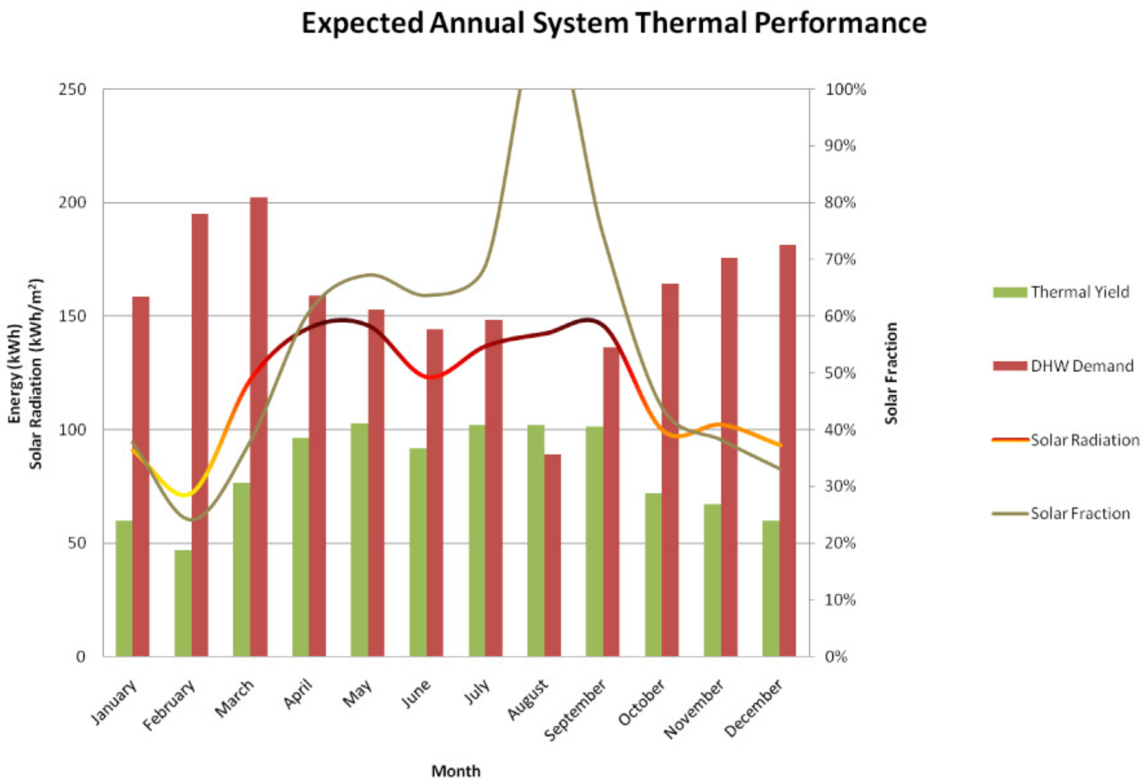


Figure 24
PHPP SHW Graphical Output for Orlando, FL (Feist 2011)

Figure 25
The Tool's Graphical Output for Orlando, FL



5.2 Analysis

5.2.1 Zondag Model

This analysis looks at one PV/T panel available on the market in Corvallis, Oregon, USA, which as discussed previously, has a similar climate to the validation model. The panel's peak power is 180 watts at standard testing conditions (STC) which is 1000 W/m^2 at 25ºC. As mentioned in section 3.2, 10ºC has been taken for the low analysis value, as it is a likely temperature from the mains. A temperature of 40ºC is taken to represent a likely temperature after heat exchange with the storage tank towards the end of the day.

Cell temperatures are significant to electrical production. The cell temperature– or the equivalent in the tool's case, the mean plate temperature– of a PV/T should then be compared to PV, so that system performance variance can be seen.

From Figure 26, system relationships on July 28th, a typical summer day, are shown. As solar radiation reaches the system at 5 am, the pump turns on and the mass flow

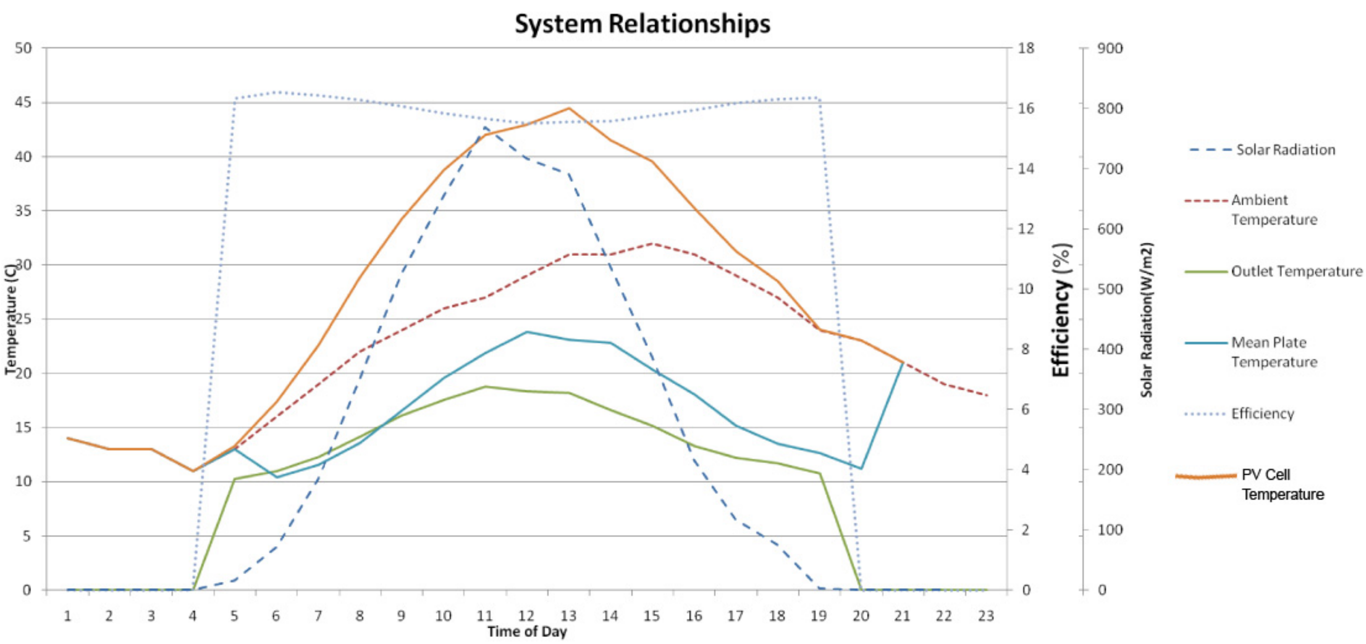


Figure 26
System Relationships

begins. With an inlet temperature of 10° C, the mean plate temperature is cooled from its equilibrium with the ambient temperature, yielding an efficiency of over 16% from it's STC cell efficiency of 15.4%. As the day progresses, layer temperatures diverge. The cell temperature is kept low from the exchange of heat to the absorber plate and ultimately the water. The combined mean plate temperature is significantly lower, 23.7°C, than its PV counterpart, which reaches a maximum of 44.5° C. The mean plate temperature increases with solar radiation, as does the water temperature. Due to the iterative process of the mean plate temperature calculations in the tool, peak temperatures appear delayed by one hour. When the tool's electrical output is compared to a standard PV as in Figure 27, results behave as expected. System electrical production and efficiency reflect the PV/T's improved performance. The PV reaches a maximum yield of 83.9 watts with a noticeable drop in performance midday to 13.9%. The hybrid system trumps with an electrical yield of 93.2 watts and remains more steady throughout the day, reaching a low of 15.5% in the same hour that the PV reaches its lowest efficiency. Overall on this day, the PV/T produces 9.8% more than the PV, and 11% more at the systems' peaks. Once the sun sets, the flow stops and the mean plate temperature returns to ambient.

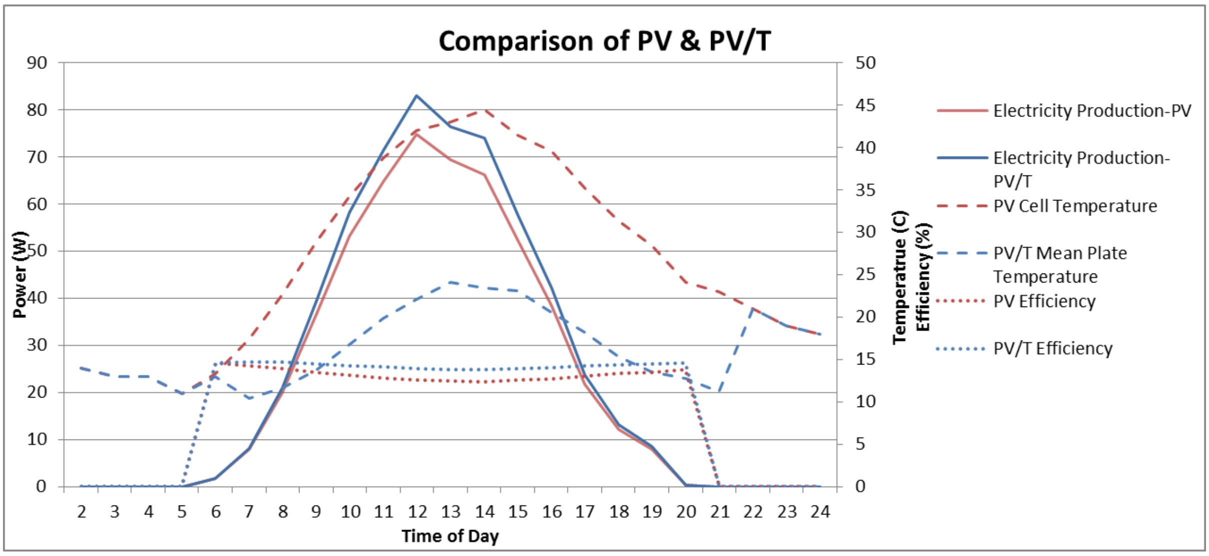


Figure 27
Comparison of PV & PV/T

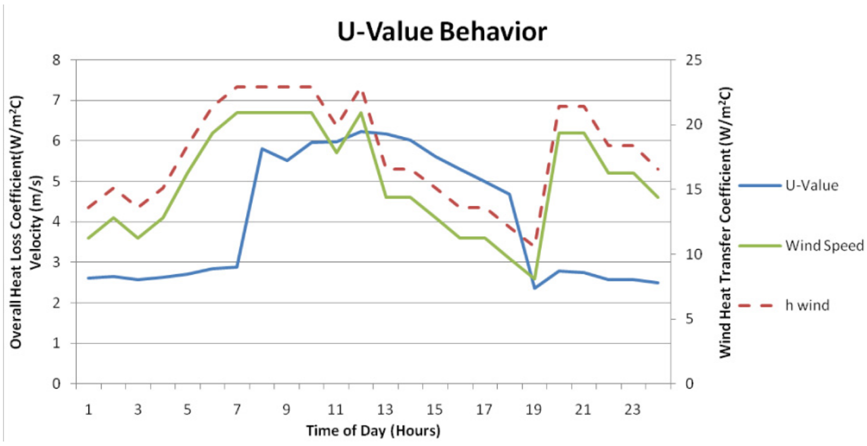


FIgure 28
U-Value Behavior

Throughout the process of creating the tool, calculated variables for the manufacturer's collector were compared to expected values from Duffie and Beckman (1991). The overall top loss coefficient while the system was operational, for example, were generally found to be between 5 and 6 W/m2K, where it was demonstrated, for a plate with similar emissivity, was in the same range in the text. For higher h_w values, Duffie and Beckman illustrate that the subsequent U-value will also increase. As such, it was found that with increased wind speeds, the model behaved appropriately, calculating a higher h_w and U_{loss}. In the tool, these are top plate losses only. Figure 28, illustrates how the wind speed plays a crucial role in the U-value. As the wind dies down from 1 pm to 7 pm, a direct correlation is seen in the overall loss coefficient. The lowest values are seen when there is no mass flow in the early morning and night, and essentially, there is no heat to loose. Even at these times, however, the wind speed is mirrored at a smaller scale.

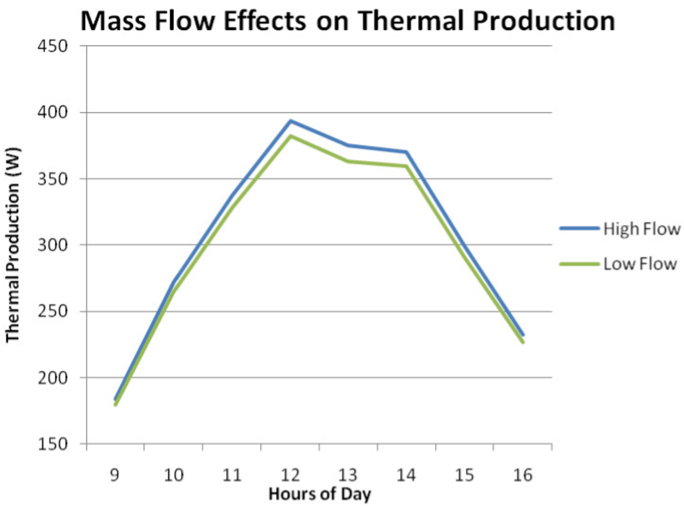


Figure 29
Mass Flow Effects of Thermal Production

In Figure 29, the effects of the change in mass flow can be seen. In this graph, the high flow is equal to 0.0184 kg/s, whereas the low reduces to 0.0085 kg/s. With a high mass flow, the water is able to take away more heat. For the remaining simulations, the average flow is taken. Since the mass flow has an effect on thermal production and efficiency, it will ultimately influence the payback period.

Economically, with just one panel, installation costs, no batteries and two inverters assumed over the life of the system this system has a payback period of 11.3 years. This is much longer than the expected payback for a system in Cyrus that was analyzed by Kalogirou (2001), however, his calculations did not consider financing or inflation. Additionally, the climate has a large impact. For a more accurate comparison, an analysis of the system in a warm climate is required. For the portion of demand covered by the system, there is a savings of 89.0% in primary energy, compared to an oil boiler. The cost of solar energy is $0.450 compared to an assumed value of $0.117 for electricity and $0.113 for conventional DHW. For natural gas, there is a primary energy savings of 80.2% and conventional DHW of $0.042. Annual solar fuel costs are $370.27, where electricity combined with oil or natural gas are $921.99 and $739.58 respectively.

The next sections of analysis look at manufacturers' collectors in nine climates.

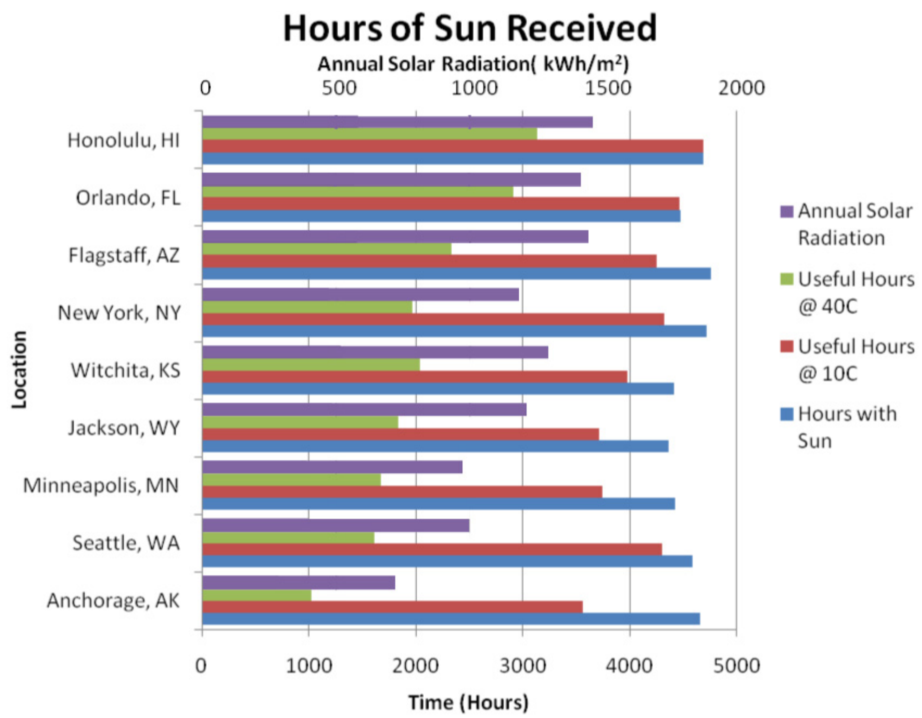


Figure 30
Hours of Sun Received

5.2.2 National Comparison

Certain trends form when comparing the PV/T system in a variety of climates throughout the United States. Nine cities were selected, each with it's own unique climate or topographical characteristics. These cities are arranged by latitude in the graphs, with the most northerly at the bottom in Figure 30 and to the left in Figures 31-35. By keeping demands and collector parameters constant, the effects of climate alone can be viewed. It is not surprising to see that locations with higher annual solar radiation, as shown in Figure 30, produce more useful hours of thermal generation at an inlet temperature of 40ºC. However, some anomalies occur, stressing the importance of the characteristics of the local climate. The fraction of useful thermal generation hours to hours of sunlight received generally has an inverse relationship to the latitude. Despite this trend, Seattle, Washington, produces more useful hours of thermal production at 10ºC inlet temperature than Minneapolis, Minnesota, which receives similar solar radiation, and has a similar amount of useful thermal hours at 40ºC. From this, one can infer that Minneapolis's colder climate results in more losses from the collector. Similarly, Figure 31 shows the overall national comparison of PV/T at two inlet temperatures compared to PV.

Like the comparisons discussed in section 5.2.1, the greater production of electricity comes with lower inlet temperatures. In warm, sunny climates this difference is a larger percentage, thus a greater impact, than in cold, cloudy climates. This is shown in Figure 31. The general trend is for warmer climates to produce more thermal generation. This is no surprise and is applicable for both inlet temperatures of 10ºC and 40ºC, however with cooler inlet temperatures, a greater amount of thermal production is achieved. All of these factors affect the cost of solar energy. Section 4.2.4 discussed how the this is calculated. Because of Anchorage's frigid temperatures, it has the highest cost of solar energy due to the low thermal and electrical yields. It is also seen that the difference between the costs at different inlet temperatures generally increases with higher latitudes. This shows that a system would have to be optimized more accurately in the north, relying on more skilled installers. In the south, the effects of non-optimization would have a lesser impact.

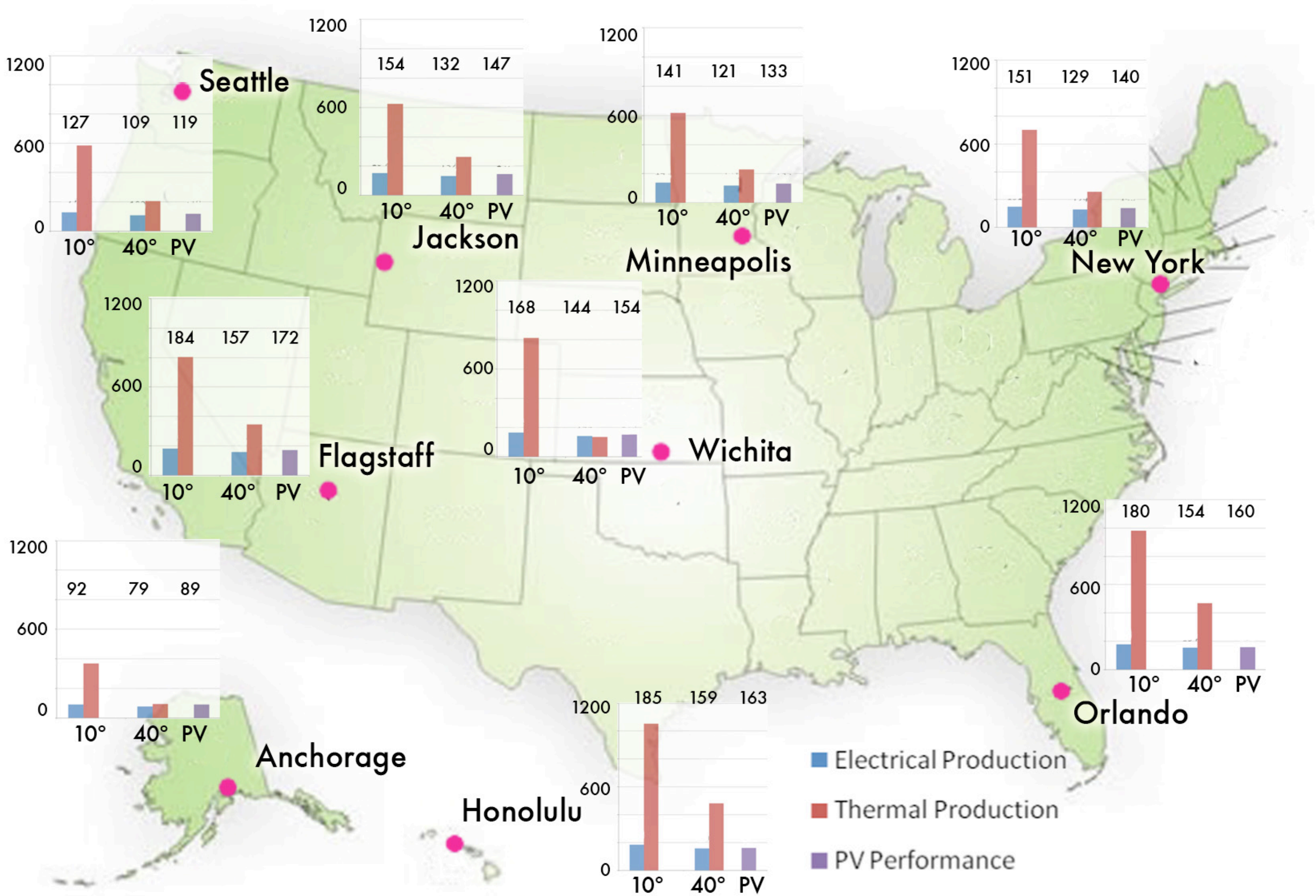


Figure 31
National Comparison of PV/T Performance
Based on (US Map, n.d.)
Numbers above the bars are electrical performance with inlet temperatures of 10°, 40° and PV respectively

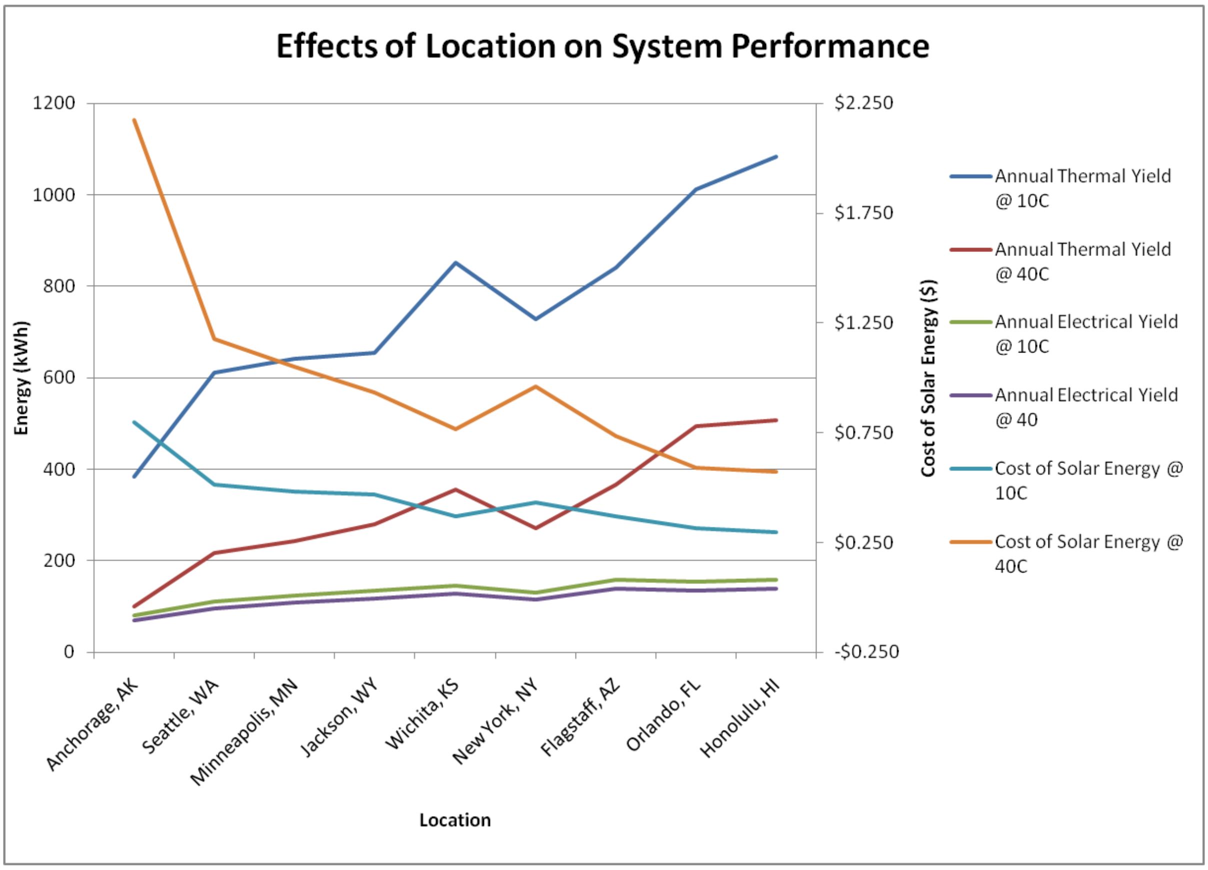


Figure 32
Effects of Location on System Performance

When the two inlet temperatures are compared to each other nationally in Figures 32-35, it is clear that the lower inlet temperature leads to a higher electrical efficiency in all seasons. The highest latitudes performed the poorest in all four charts, yet the best performing was not always the lowest latitudes. The middle latitudes often performed better, in cases such as July in Figures 33 & 34, when Jackson, Wichita and New York all performed better than Honolulu, Flagstaff and Orlando. Similar trends occur when the inlet temperature is raised. It should also be noted that the southerly climates will likely have an increased electrical demand in the summer due to air conditioning, therefore the solar fraction would be further reduced.

The improvement over PV can be seen nationally as well as in summer months. The cities at the most northerly, most southerly and median latitudes, Anchorage (61.18°N), Honolulu (21.32°N) and Wichita (37.75°N) respectively, were compared on the solstices. Water inlet temperatures were kept at 10°C. In Figure 37, during

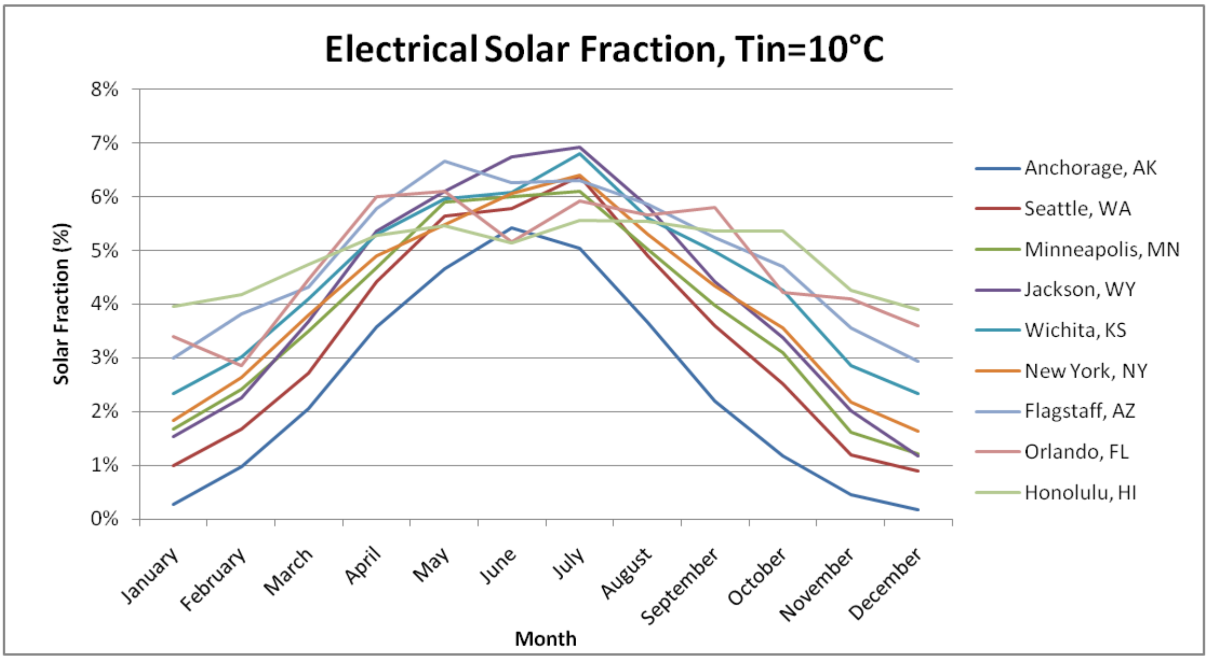


Figure 33
Electrical Solar Fraction When Inlet Temperature is 10ºC

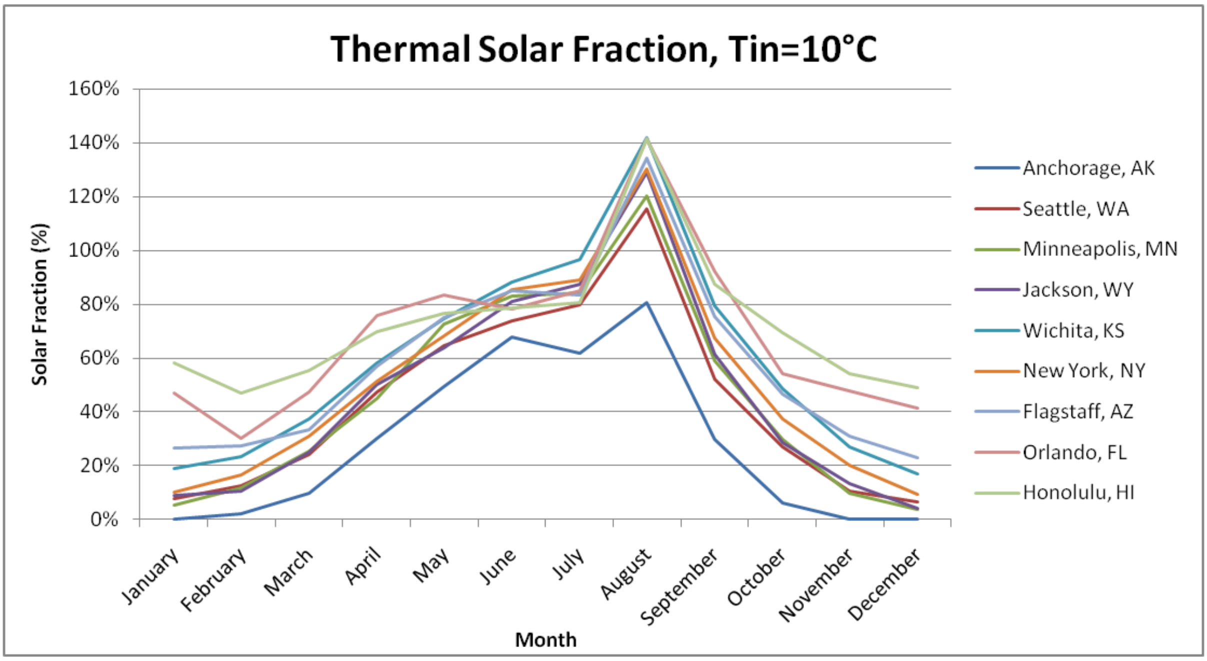


Figure 34
Thermal Solar Fraction When Inlet Temperature is 10ºC

summer, all three latitudes show improved electrical performance of PV/T over PV alone, although locations where temperatures are warmer show a greater percentage improvement, up to 18%, that cooler climates.

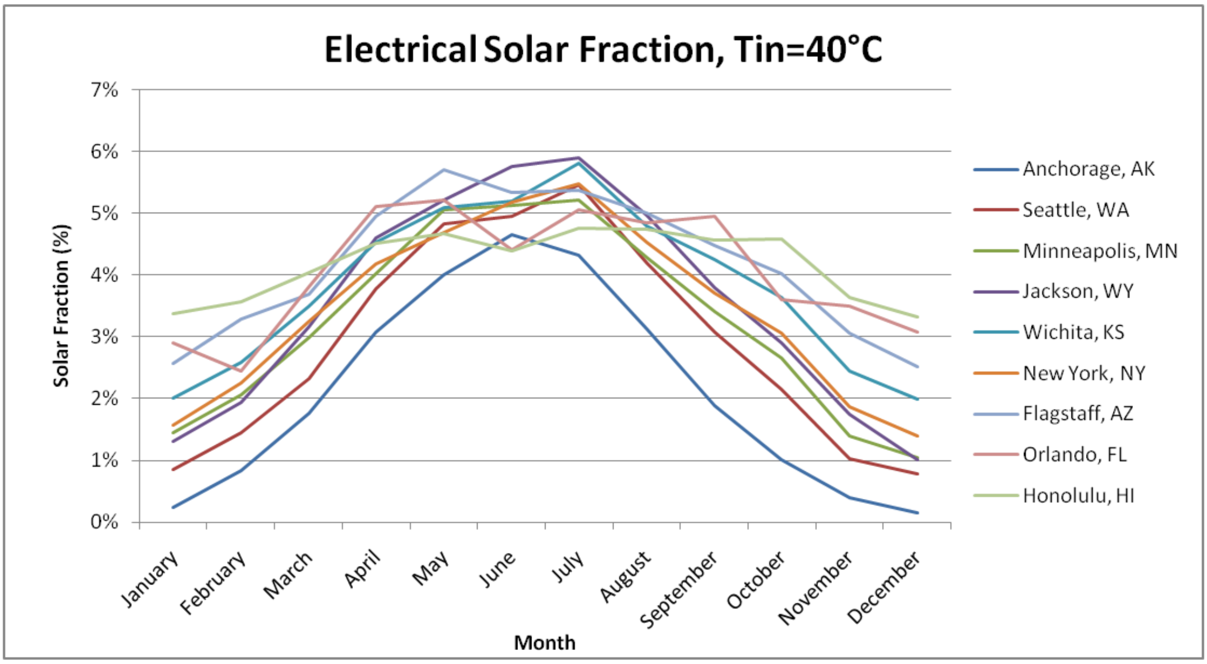


Figure 35
Electrical Solar Fraction When Inlet Temperature Is 40°C

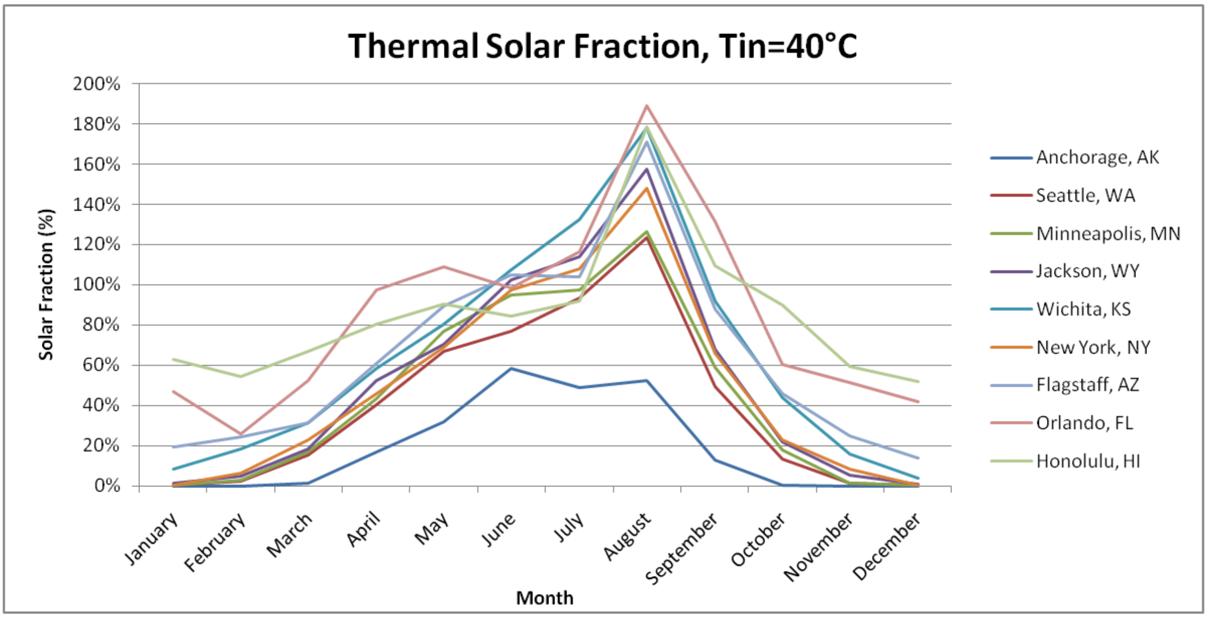


Figure 36
Thermal Solar Fraction When Inlet Temperature is 40°C

Analyzing the three climates, it is also seen that the median latitude's climate has greater swings, i.e. temperatures in summer are greater than the most southerly location and colder than the most northerly in winter. For this reason, the water inlet temperature warms the cells in the PV/T when ambient is very cold, decreasing electrical efficiency, thus the PV performs better in the winter for the northern and median latitudes, as shown in Figure 38. This finding is consistent with results of Kalogirou and Tripanagnostopoulos (2006). Because the southern latitude's

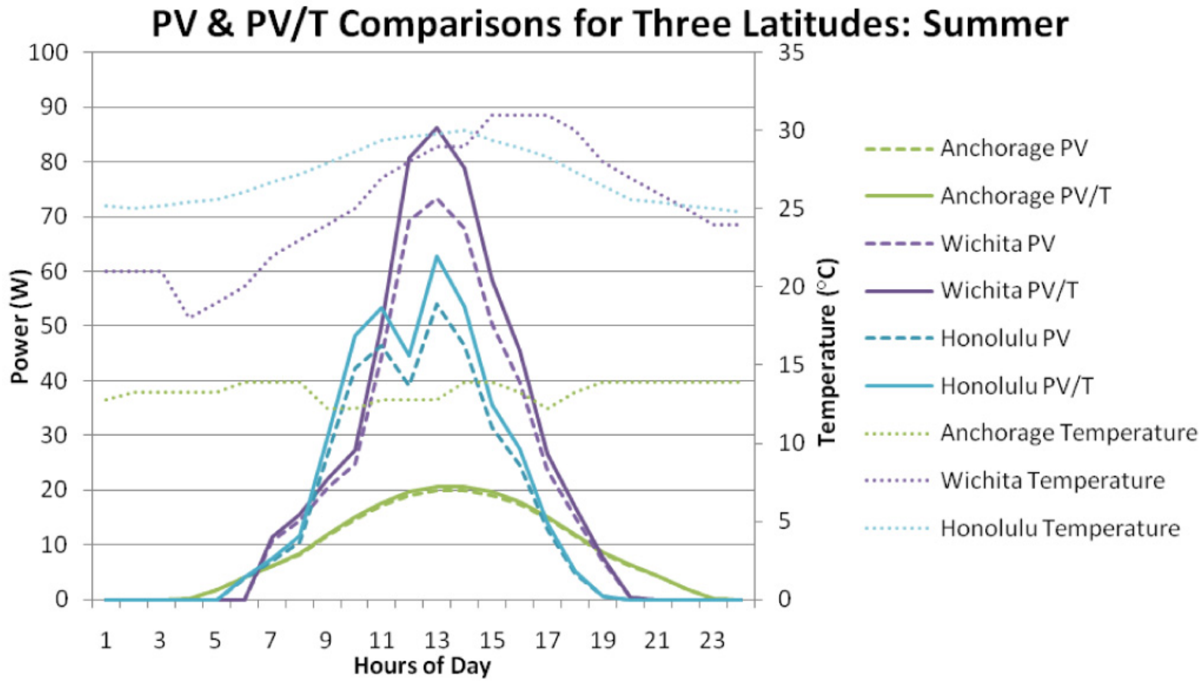


Figure 37
PV & PV/T Comparison for Three Latitudes in Summer

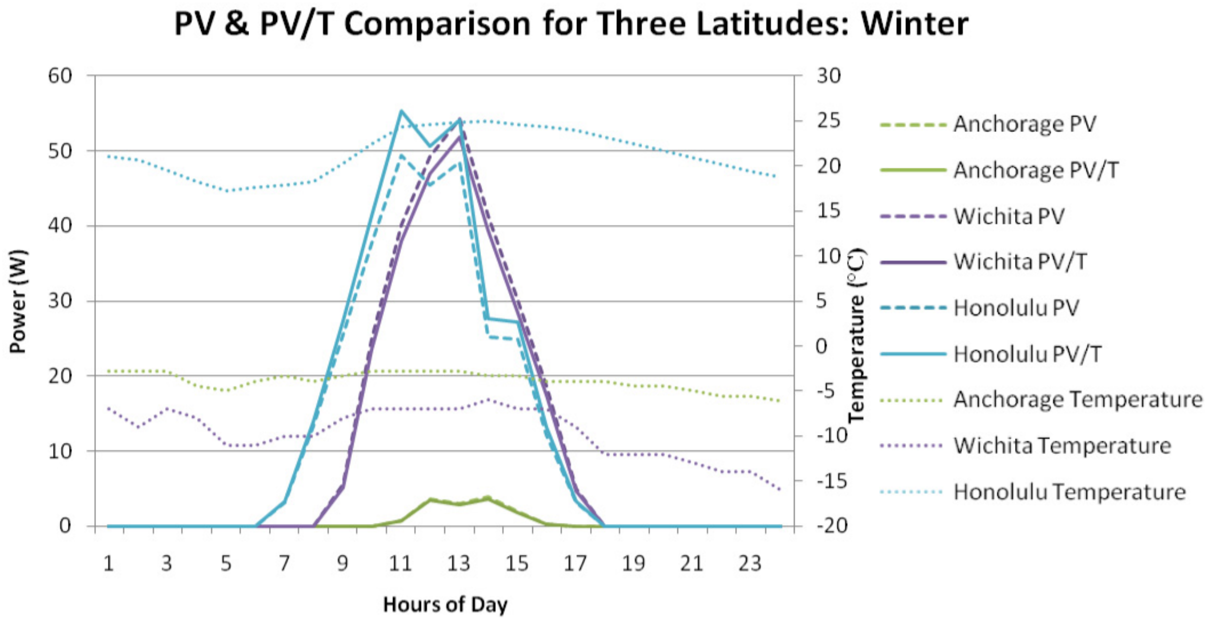


Figure 38
PV & PV/T Comparison For Three Latitudes in Winter

temperatures remain relatively constant in comparison, an improved performance of PV/T over PV is observed.

The lower temperature of 10ºC is unlikely to come from recirculated water in a storage tank, but rather "fresh" inlet water from the mains. Correspondingly, the maximum temperature gains across the collector with constant mass flow, as in the tool, is around 5ºC, ipso facto, the outlet temperatures from the collector would cool the tank. Figure 39 demonstrates the outlet temperatures for the three latitudes in winter. Honolulu gains 6.2ºC, Wichita benefits by 3.2ºC and Anchorage looses 0.5ºC. The losses seen in Anchorage is detrimental to system performance. If the outlet temperature of the collector were to compromise the thermal effectiveness of the tank, the water could be discharged to a separate location. This would still allow the PV to operate with improved efficiency. In this respect, it may be important to determine which side of a PV/T system to optimize, the electrical or thermal, as suggested by Fujisawa and Tani (1997).

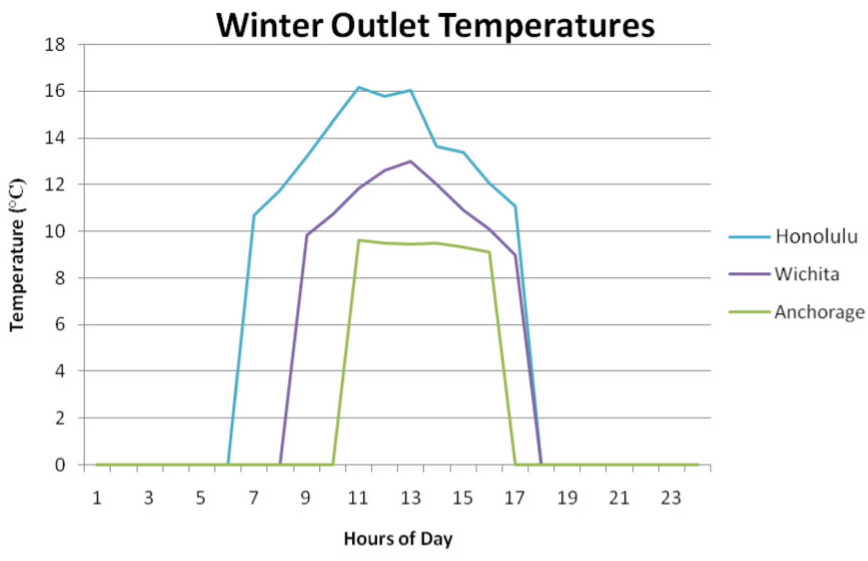


Figure 39
Outlet Water Temperatures in Winter for Three Latitudes

Because a PV/T system is so reliant on temperatures and solar radiation, the seasonal performance was compared in Orlando, Florida. The electrical and thermal yields on the days of June 4th and December 4th are plotted in Figures 39 & 40.

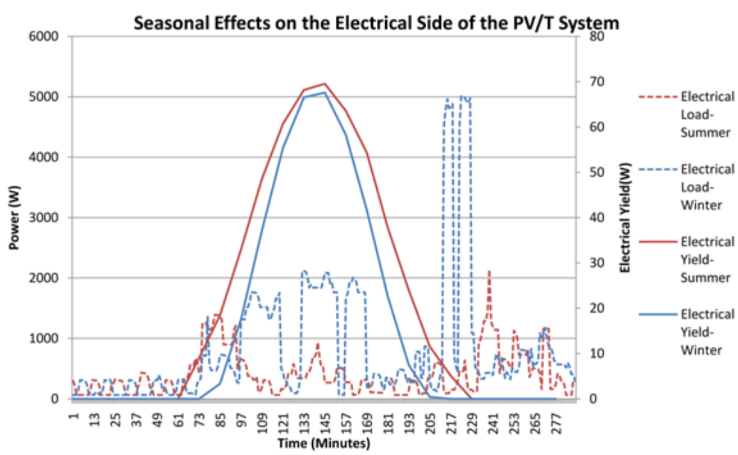


Figure 40
Seasonal Effects on the Electrical Side of PV/T in Orlando, FL

The temperature remained in the 30s from 9 am to 5 pm on June 4th, peaking at 37°C at 2 o'clock. Maximum solar radiation peaked at 640.8 W/m² in the 13 hours received. In December, the day remained mostly in the upper teens, peaking at 21°C at 2 o'clock. Additionally, this day received a 11 hours of sunlight, reaching a maximum of 624.16 W/m² of solar radiation. Because Orlando receives only a relatively small amount less of radiation in the winter than the summer, the electrical yield does not drop drastically, where June 4th generates 424.82 W and December 4th generates 318.83 W, a 25% drop. The thermal yield for these respective days are 1938.93 W and 899.54 W, a 54% decrease, which is more than double the decrease of the electrical system. This reiterates the importance of the ambient and inlet water temperatures. It can also bee seen in the graphs that the loading at night is heavier than in the day, as well as in the winter. Loads are more substantial for both electrical and thermal than in the summer, persisting the discrepancy between when the sun's radiation is available with when it is needed.

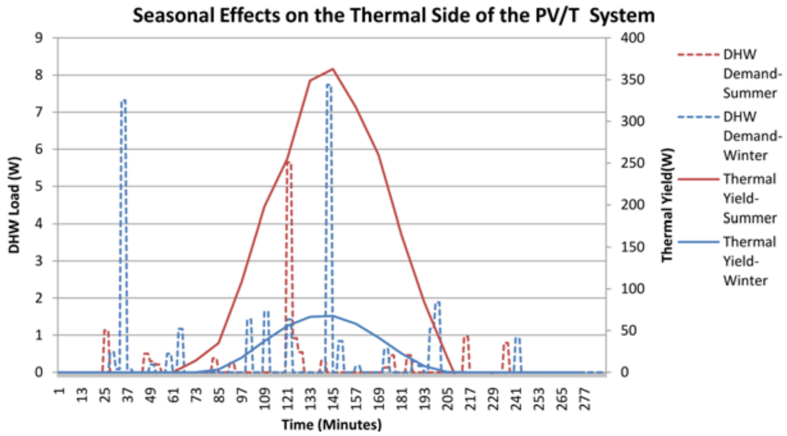


Figure 41
Seasonal Effects on the Thermal Side of PV/T in Orlando, FL

5.2.3 Inter-Model Comparison

The following analysis compares different systems on the market today. The goal of this exercise is not to promote one over the other, but to observe the changes in the system due to various parameters. As such, these collectors will be kept anonymous, identified by the terms "Collector A", "Collector B", "Collector C" and "Collector D". The New York climate was selected for all three scenarios because of the population that resides there and in similar climates. An array of two collectors was specified. Table 4, below, displays important parameters for each collector.

	Area (m^2)	Rated Power (W)	Electrical Efficiency (%)	Temperature Efficiency$_{Pmmp}$ - (%/C)	Average Mass Flow (l/h)
Collector A	1.65	230	13.9	0.45	108
Collector B	1.37	190	17.5	0.4 (estimated)	65
Collector C	1.28	190	16.25	0.4 (estimated)	120
Collector D	1.33	190	16.27	0.5	65

Table 4
Collector Parameters

Since one of the main reasons to install a PV/T system is the benefit of hot water, a key aspect to explore is the outlet temperatures produced. It is logical that the outlet temperatures are a function of the inlet temperature. In Figure 42, the outlet temperatures of four different manufacturers' collectors are seen with inlet temperatures of 10° and 40° C respectively.

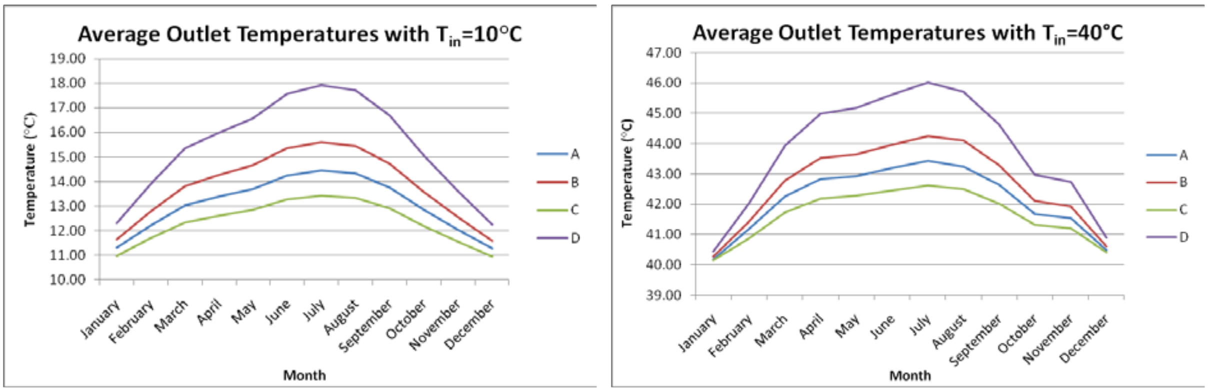


Figure 42
a) Average Outlet Temperatures with an Inlet Temperature of 10°C
b) Average Outlet Temperatures with an Inlet Temperature of 40°C

Greater temperatures can be reached if the water is allowed to remain in the collector for a longer period of time, however, to reiterate, this tool employs a constant mass flow, the level of speed which is designated by the user within the manufacturer's specifications. A higher outlet temperature is seen from Collector D which has the greatest liquid capacity of 3.8 liters, thus it can remove the most heat. The other collectors' capacities range from 1.2-1.6 liters. Additionally, both Collectors B and D have lower average mass flow, 65 liters per hour, whereas A and C have mass flows of 108 and 120 l/h respectively. Unless outlet temperatures from the

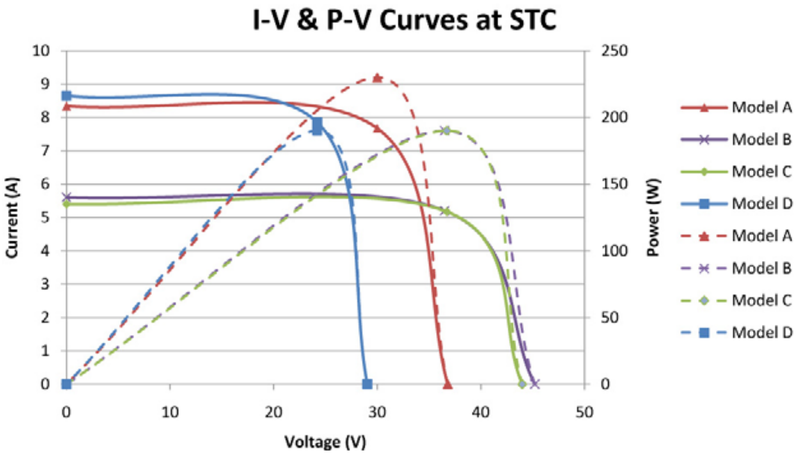
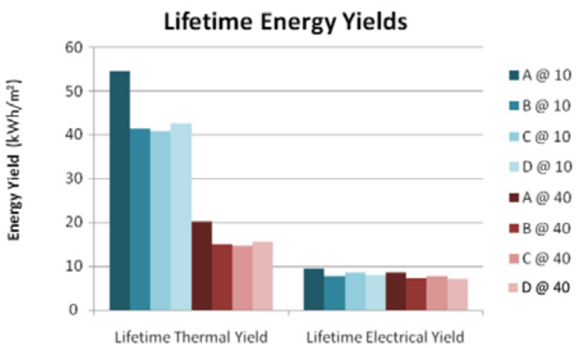


Figure 43
I-V & P-V Curves For Four Collectors

collector reach the desired tank temperature, an auxiliary heater would be needed to supply a portion of the energy for DHW.

As demonstrated in previous sections, the major advantage of incorporating a heat-removing fluid is to increase performance of the cells. Figure 43 demonstrates the varying relationships between the current and voltage for the four collectors, as well as the voltage and power. It can be seen that Collector A is indeed the greater producer of power. It is expected that Collectors B, C & D will perform relatively equally. It is also noticeable that the currents and voltage produced by B & C are nearly the same. Collector D, which has a similar power, utilizes a higher current to reach its maximum power point and a lower voltage. These differences will not be an issue, however, as the DC power produced will be controlled and converted by the inverter.

Another consideration is how this will affect the homeowner over the system's life. The financial outcomes of a system are dependent on it's performance. Figure 44 shows the lifetime performance of a system of the four collectors and the direct correspondence with the solar energy costs and payback periods in Figure 45.



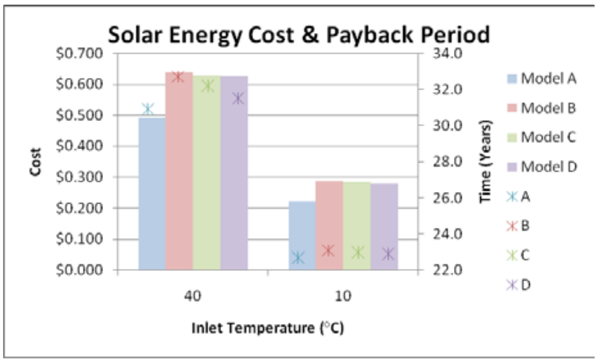


Figure 44
Lifetime Energy Yields

Figure 45
Solar Energy Cost & Payback Period

Collector A, with the highest rated power, generates the greatest yields for both sides of the system. The remaining collectors, all with similar power ratings, perform relatively equally, noting a slight augmented thermal performance from Collector D and electrical performance from Collector C. The effects of raising the inlet temperature are also seen graphically. Higher inlet temperatures lead to a lower thermal and electrical yield, amounting to longer payback periods ranging from 31.4 to 33.2 years, compared to lower inlet temperatures that reach payback in 28.0 to 28.7. It is interesting to note that increasing inlet water temperature by 30ºC, the overall electrical yields do not decrease as significantly as the thermal. However, because of the higher household demands in electricity over DHW, the value of the electricity is heightened. Also, even with higher yields, the more powerful collector (17.39% more) reaches payback only 2.4% faster because the greatest increase in production comes from the thermal side. With multiple collectors, DHW demand can be surpassed, thus rendering the surplus thermal yield useless unless another purpose can be found.

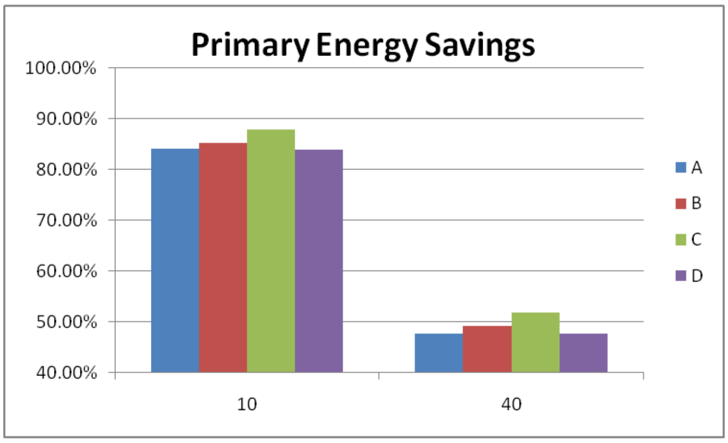


Figure 46
Primary Energy Savings of Four Collectors

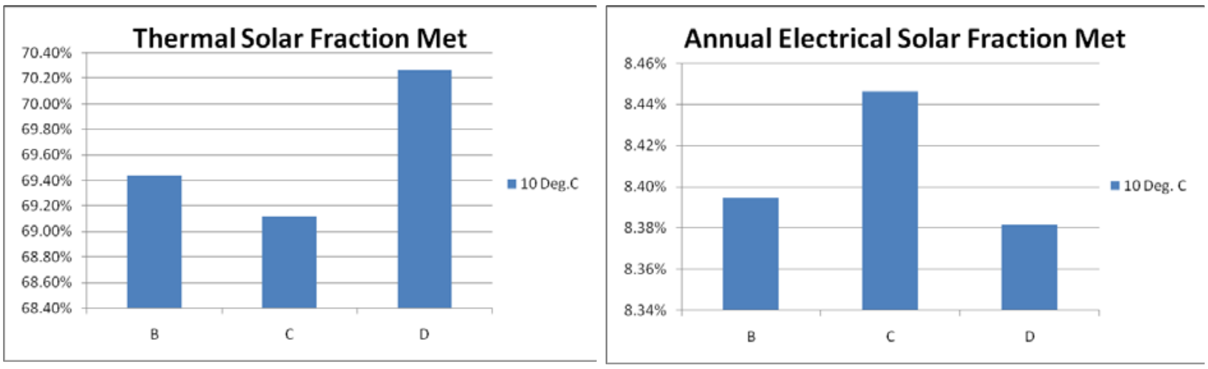


Figure 47
a) Thermal Solar Fraction Met By Three Collectors
b) Electrical Solar Fraction Met By Three Collectors

The yields produced by a solar renewable resource amount to a percentage of primary energy saved rather than relying on a conventional water heater or the grid. Figure 46 illustrates these savings across the collectors and how it varies with system performance. With greater generations from the lower inlet temperatures, a larger environmental benefit is seen.

Further investigation reveals that the annual solar fractions met by the three collectors with a rated power of 190 watts can vary. The electrical solar fraction differs by less than 0.1%, however the thermal solar fraction fluctuates by approximately 1.2% as shown in Figure 47. Similarly, the trends seen between the collectors are similar to those seen in Figure 44.

Homeowners have the option to export surplus electricity to the grid if there are no batteries in the system. Figure 48 illustrates how Collectors B, C & D perform. Again, the trends between the collectors are seen here, as well as the greater benefit of cooler inlet temperatures. The difference of 30°C for inlet temperatures results in up to a 67% increase in electricity exported, as seen in Collector D. Collectors B & C perform similarly, each exporting approximately 56% more with cooler inlet temperatures. Compared to each other, a 10°C inlet temperature yields in about 6.5% difference, or 33% with 40°C.

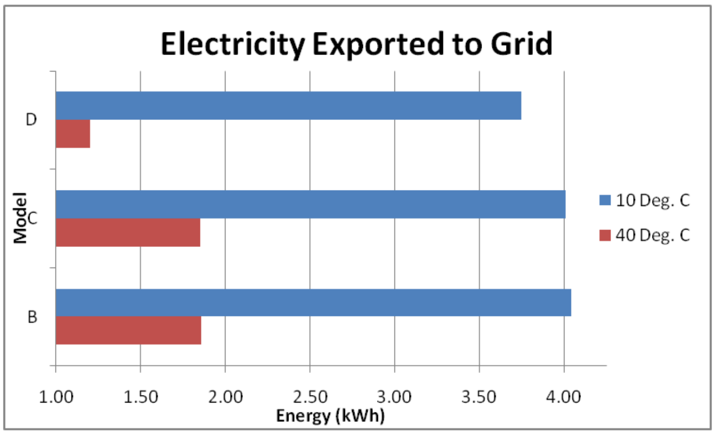


Figure 48
Electricity Exported to Grid From Three Collectors

6. Conclusions

From the analysis above certain relationships became clear, therefore the following conclusions can be made.

Thermal demands are met before the electrical due to it's higher thermal efficiency. Therefore, the system would typically have to include supplemental PV panels to met the higher electrical loads. To achieve the most from the system, sizing the system for winter is an option, however the system would be grossly oversized in summer unless an alternative purpose for the thermal yield is found. The thermal generation would be particularly beneficial as RHI is expanded into the residential sector. Despite incentives, with system costs still remaining high, payback period can be lengthy.

PV/T systems can help designers & homeowners toward a net-zero energy building. Primary energy savings of over 80% were seen in some cases. Depending on the particulars of the system, outlet temperatures may require auxiliary heating. Although the energy gained by the water at lower inlet temperatures is greater, the constant mass flow of the tool only allowed for a rises in temperature of about 5ºC.

Climates that will benefit the most from PV/T systems supplying DHW are moderate and sunny, to warm and sunny. PV/T systems generate higher yields for both thermal and electrical with lower inlet temperatures. The warm sunny climates benefit from PV/T systems as long as the ambient temperatures are not too extreme, as seen in the work of Al Harbi, et al. (1998), where in Saudi Arabia the hot climate negates benefits of the PV. A greater increase in PV performance is seen in the warmer climates. These climates also reap the benefit of thermal gains year round, as opposed to the middle and northern latitudes that can have greater losses due to low ambient temperatures. These climates also have great risk of freezing and precautions must be taken to obviate this. From this research, identifying inappropriate climates begin to bookend a range of climates where PV/T is most suited. Figure 49 shows the population density of the US in relation to the solar radiation received per day on a collector facing south, tilted at an angle equal to latitude.

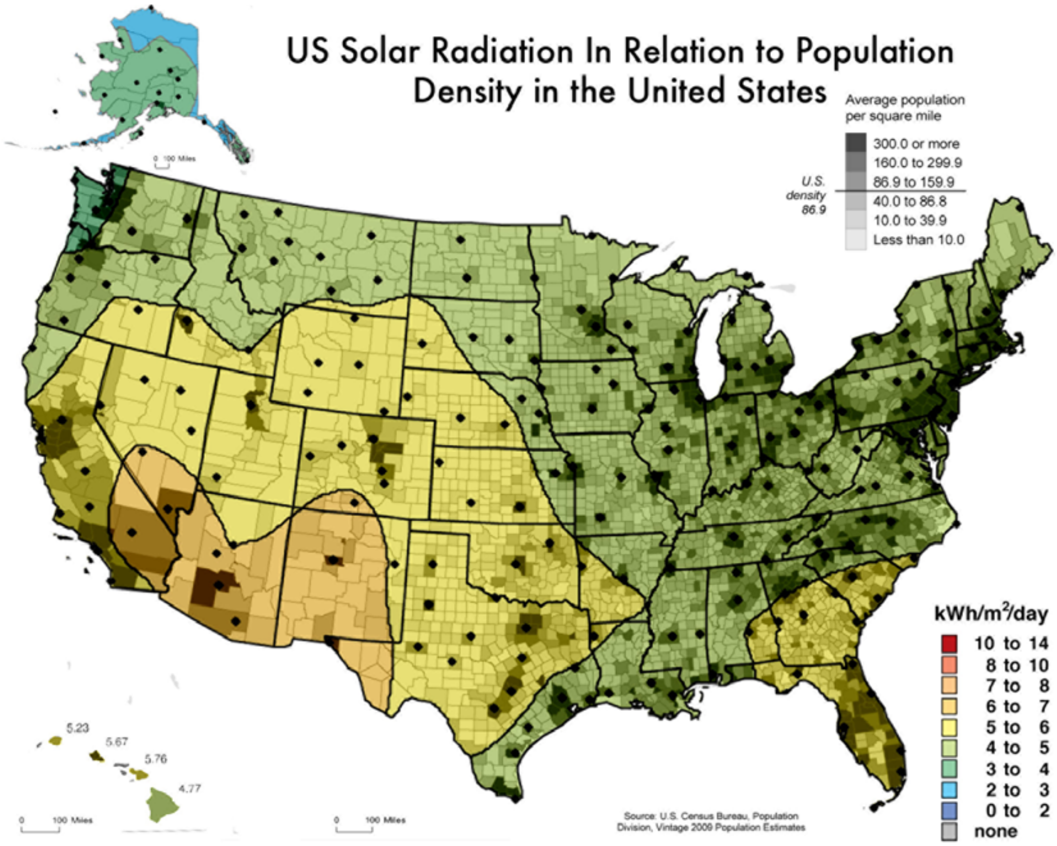


Figure 49
Solar Radiation In Relation to Population Density in the United States
(NREL 2007, US Census 2009)

Below in Figure 50 is a combination of maps of the global total irradiance in Europe and the location of the population. The purpose is to demonstrate that many people in Europe can also benefit from solar renewable technology. Comparing solar radiation between the US and Europe, the green region in the US map equates to a greenish-yellow in the European map. However, one should note that temperatures are generally milder in Europe compared to similar latitudes in the US, therefore PV/T may be applicable at higher latitudes in Europe than the US. This is advantageous since the highest densities in Europe occur mostly in the green region, equating to solar radiation similar to that received in Seattle, WA.

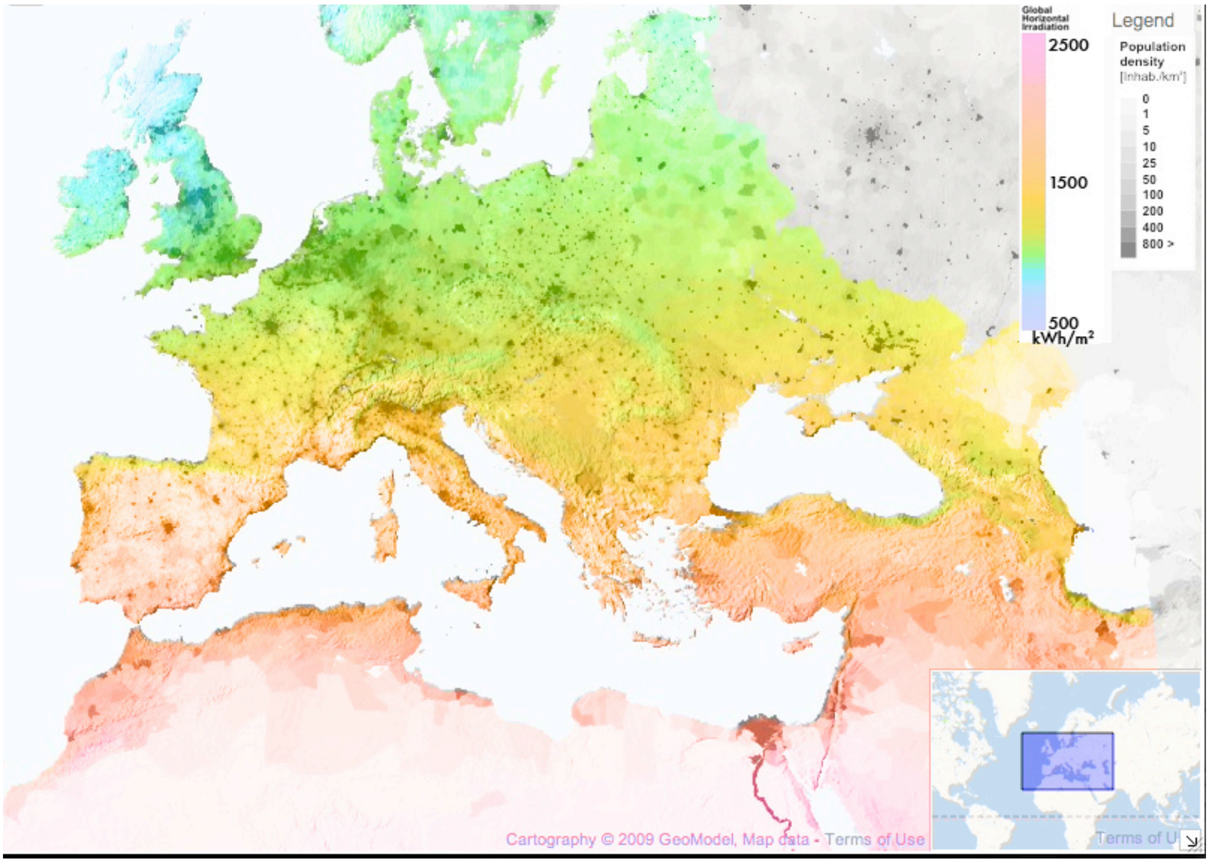


Figure 50
Solar Radiation In Relation to Population Density in Europe
Super imposed maps, one of annual global horizontal irradiation and one of population density, illustrate that a majority of European cities that could benefit from solar renewable technology
SolarGIS (2011)

7. Future Work

Known limitations to this research come from not knowing further details of the PV/T manufacturer's collectors. Although the specifications tell a great deal, more technical parameters are not given. Attempts were made to contact the manufacturers for clarification, with disappointing results. One company responded saying its system was still in research and development, and therefore could not disclose the requested data. This information can affect predicted performance. Parameters that were not disclosed by the manufacturers were estimated, trying to emulate the drawings available. Any remaining gaps in information resulted in reasonable values being taken from other manufacturers or from Duffie and Beckman (1991) and applied to all collectors.

Because the efficiencies of the PV at STC were taken from the manufacturers, who often exaggerate the system's abilities, the electrical performance in reality might not behave as such. In an ideal situation, the efficiencies should be tested by a third party before being entered into the tool.

Another limitation comes from the demand profiles. Despite the ability of the tool to use climate data from across the US, the demand profiles do not reflect this change in location and climate. This means that the electricity consumed in Orlando, Florida in July, where people are likely to use air conditioning, is the same as Anchorage, Alaska. Ultimately this affects the solar fraction that is expected from the PV/T system. On the other hand, it is favorable for directly comparing the responding performance of the collector in various climates. Another point to note regarding the demand profiles, is the month of August. It has a significantly lower demand that the surrounding months. This is likely due to occupants vacationing during the summer, thus reducing the electrical and thermal loads. For this reason, August has a consistently higher solar fraction. Additionally, once the DHW demand has been met, this tool has no control in place to limit mass flow, ergo, solar fractions can reach over 100%.

Because ongoing research is advancing PV/T technology that one day may reach the market, further considerations may be added to the tool. Further model parameters could be increased to include channel geometry and material selection for both pipe and glazing. Knowing specific details of the collector construction will result in more accurate calculation of losses and heat transfer. As consumers become increasingly aware of the potential benefits of PV/T, the market will expand. This could be reflected by including more commercial or industrial applications of PV/T, such as solar concentrators. Although they have aesthetic implications, compound parabolic concentrators intensify the solar radiation received, thus returning a higher thermal yield.

A water/propylene glycol mix is listed in the tool for future expansions of options. The glycol solution has a lower specific heat than that of pure water, which would result in slightly lowered thermal generation or a different flow requirement to obtain the equal generation of pure water.

This tool did not include a parameter to subtract shadows, as does the PHPP. If shading of neighboring buildings, trees and the like are blocking the collector, the expected output of the collector can be significantly compromised.

Several of the PV/T models currently available on the market are coupled with heat pumps. Although heat pumps require energy to operate, many consider them “sustainable” as they generate more energy than they require, which is known as the coefficient of performance (COP). Perhaps another worksheet could be incorporated to more accurately reflect a realistic system configuration.

The best tools also assist in the design of the intended system. Incorporating design degree days into the climate data would enhance the tool’s efficacy.

Finally, modeling a liquid-based PV/T system in ESP-r could be a heavy undertaking. However, it could advance the future of the system.

Appendix A- Nomenclature

A	Area (m^2)
c	Specific heat (J/kgK)
D	Tube diameter (m)
F	View factor
F_R	Heat removal factor
G	Irradiation (W/m^2)
h	Hour angle, Heat transfer coefficient (W/m^2K)
I	Current (A)
k	Thermal conductivity (W/mK)
L	Length (m)
$\dot{m}$	Mass flow (kg/s)
N	Number of glass covers
P	Power (W)
T	Temperature (K, ºC)
U	Overall heat loss coefficient (W/m^2K)
V	Voltage (V)
W	Tube spacing (m)

Greek Letters

α	alpha	Angle from surface normal to solar azimuth; Absorption
β	beta	Solar altitude, Collector tilt
δ	delta	Declination, Thickness of layer (m)
ε	epsilon	Emittance
γ	gamma	Angle from South
η	eta	Efficiency
μ	mu	Micro-
π	pi	3.14
ρ	rho	Density (kg/m^3)
σ	sigma	Stefan-Boltzmann constant (5.67×10^{-8})
τ	tau	Transmittance
Φ, φ	Phi	Angle of collector from vertical

Subscripts

a	Ambient
abs	Absorber
b	Direct beam incident to the collector
bH	Direct beam on a horizontal plane
ca	From cells to absorber
cell	PV cell
d	Diffuse radiation received by the collector
dH	Diffuse radiation on a horizontal plane
el	Electrical
g, glass	Glass cover
in	Inflow
mpp	Maximum power point
p	Plate
pm	Mean plate
th	Thermal
w	Wind

Appendix B-Abbreviations & Acronyms

ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BPI	Building Performance Institute, Inc.
CHP	Combined Heat & Power
COP	Coefficient of Performance
DECC	Department of Energy and Climate Change (British authority)
DOE	Department of Energy (US authority)
DX	Direct Expansion
ECBCS	Energy Conservation in Building & Community Systems
EPBD	European Energy Building Performance Directive
FITS	Feed-In-Tariffs
HERS	Home Energy Rating System
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LEED	Leadership in Energy & Environmental Design (USA)
MEP	Mechanical, Electrical & Plumbing
NABCEP	North American Board of Certified Energy Practitioners
NASA	National Aeronautics & Space Administration
NOCT	Nominal Operating Cell Temperature
NREL	National Renewables Energy Laboratory
OECD	Organization for Economic Cooperation and Development
PHPP	Passive House Planning Package (originally Germany, now worldwide)
PV	Photovoltaic; output is electric only
PV/T	Photovoltaic/Thermal, hybrid system with PV and solar thermal components; output is both electric and heat
RESNET	Residential Energy Services Network
RHI	Renewable Heat Incentive
SAP	Standard Assessment Procedure (UK)
SEI	Solar Energy International
SHC	Solar Heating and Cooling Programme (IEA)
SHW	Solar Hot Water
TMY3	Typical Meteorological Year version 3
TOU	Time of Use
USGBC	US Green Building Council

Appendix C- EnergyPlus Model

C.1 EnergyPlus

EnergyPlus is one of the few tools that contains a PV/T exemplar model. Unfortunately it has not been validated and the model is for a commercial building and not directly comparable to the residential setting of the tool.

C.1.1 PV/T

Initial simulation was done on the exemplar model called “ShopWithSimplePVT”. Parameters of the model are listed below.

Model characteristics:

Location	Oklahoma City, Oklahoma, USA
Latitude/Longitude	35.4ºN 97.6ºW
Elevation	397 m (1302 ft)
Area	390.19 m2 (4200 sf)
Stories	1
Use	Repair shop
Schedule	Monday-Friday; 45 hours/week
Gains	
Lighting	15 W/m^2
Equipment	8.3 W/m^2
Occupants	3
Infiltration	0.5 ac/h
Natural Ventilation	None
Zones	4 Interior, 1 Exterior
Envelope	Meets ASHRAE Standard 90.1-2004
Timesteps	10 minute intervals
Internal Mass	yes
HVAC System	Central Forced Air, with recirculation

	Cooling	DX single speed coil
		COP=2.7835
	Heating	
PV/T Air System		
	RatedPower	14kW
	Battery Capacity	200 MJ (max)
	Thermal Area	50%
	Thermal Efficiency	30%
	Surface Emittance	0.84
	Cell Efficiency	20%
	Packing Factor	0.65
PV/T Water System		
	Thermal Area	50%
	Thermal Efficiency	20%
	Packing Factor	0.50
	Cell Efficiency	10%
	Surface Emittance	0.84

For simplicity, pipes in the SHW system are considered adiabatic.

The PV/T collector is quite simplistic at its current state. From the list of parameters under “SolarCollector:FlatPlate:PhotovoltaicThermal,” we see the surface name is listed along with it’s performance characteristics which are defined under “SolarCollectorPerformance:PhotovoltaicThermal:Simple.” The PV cell is defined (as a generator), as well as the working fluid type, either air or water, and the corresponding inlet and outlet nodes.

When investigating the properties of the PV, years of development have lead to a more sophisticated model. Here a surface name is required, as well as the PV performance object type and module performance, which in this model is 65% of the area and is 20% efficient. The heat transfer integration, relative to the cell temperature, has a list of six choices, however this model uses one “Photovoltaic Thermal Solar Collector” and “Decoupled” for the remaining four collectors. The

“Decoupled” option ignores Module Heat Loss Coefficient and Module Heat Capacity inputs, instead calculating the energy balance relative to the Nominal Operating Cell Temperature (NOCT), according to the Input Output Reference (EnergyPlus 2010). It goes on to explain the latter option calculates the cell temperature based on the PV/T model, i.e. incident solar radiation is modified to reflect the given parameters if the PV is encapsulated in the collector. The collectors do not appear to be linked electrically to each other, i.e. in series or in parallel.

Zone boundaries, shown as black lines on the roof of the model in Figure 51, are defined as “interior walls” inside the building and the exterior wall is defined appropriately. The south wall has 3.9% of glazing. One must note that this model may give a general indication to performance in a shop but is not completely representative of reality due to the unusual floor plan, as well as window geometry and placement.

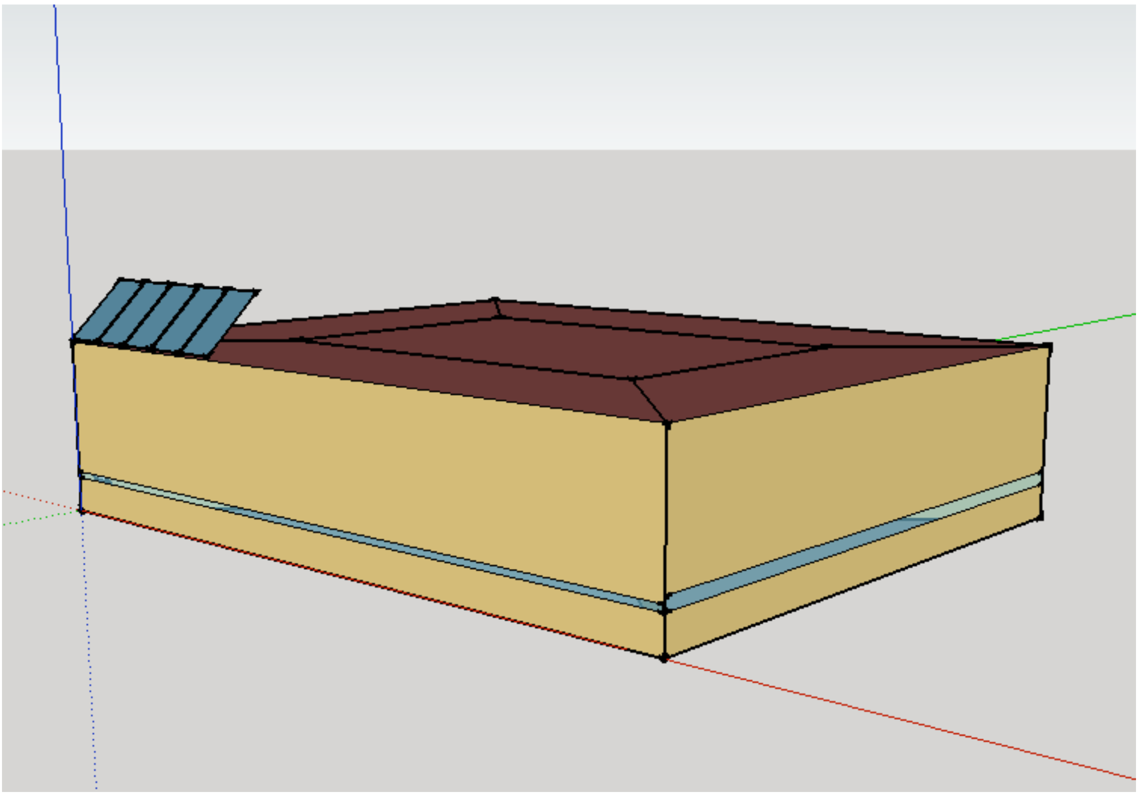


Figure 51
ShopWithSimplePVT Model

Currently, the PV/T model available is only a simple model. A user can alter system efficiencies, but has little control over the other parameters. More detailed models are under development. The model employes both air and water as transfer media, the air offsetting the heating demand and the water in a SHW system.

Figures 52 & 53 diagram the layout of the HVAC and SHW systems respectively. One downfall of the SVG file is it does not include an electrical diagram. The HVAC system's components are as follows: outdoor air mixing box; DX coil; heating coil; fan; supply air splitter; zone; and return air mixer. The SHW system is comprised of: collectors; collector mixer; collector outlet pipe; collector loop pump; storage tank source splitter; water heater; storage tank source mixer; storage tank source outlet pipe, which becomes the collector inlet pipe. The water heater in the collector loop has a heat exchange with a second storage tank linked to the demand loop. This consists of: the water heater; supply mixer; supply outlet pipe which becomes the demand inlet pipe; demand splitter; demand in zone (or demand bypass pipe); demand mixer; demand outlet pipe; pump; supply splitter returning to the second storage tank or bypass pipe.

This model was then split to isolate the heat transfer medium.

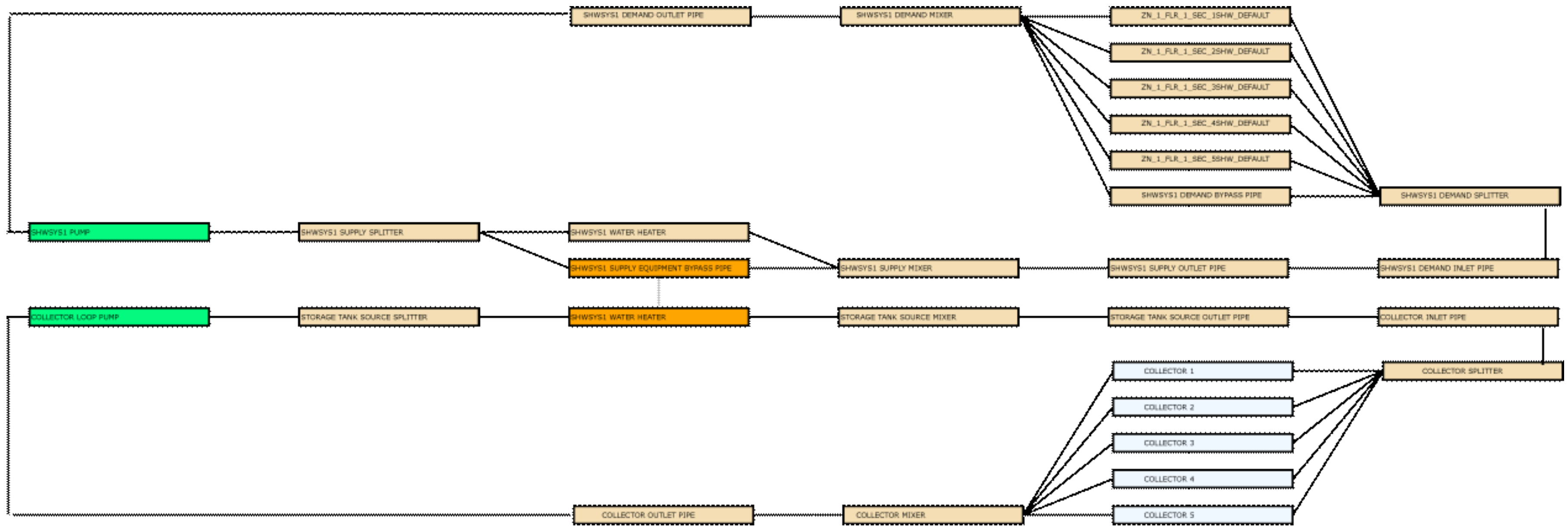


Figure 52
Plant (SHW) Layout Diagram

Figure 53
HVAC Layout Diagram

C.1.2 Results

Results can be seen in Figures 53- 56, showing the affects of the heat transfer medium. A greater amount of energy is produced on site in the water-based system due to water's greater ability to hold heat. From Figure 54, it is discernible that the solar heated air makes a contribution to the heating demands, reducing them by 20.1%. For most of the end uses– cooling, lighting, equipment, and fans– are the same between both models. The liquid-based PV/T model has additional consumption for the pumps and water system. Finally, in Figure 55, the surplus electricity that would be exported to the grid is seen between the two systems. Again, water's ability to remove more heat than air results in cool, and therefore more efficient PV.

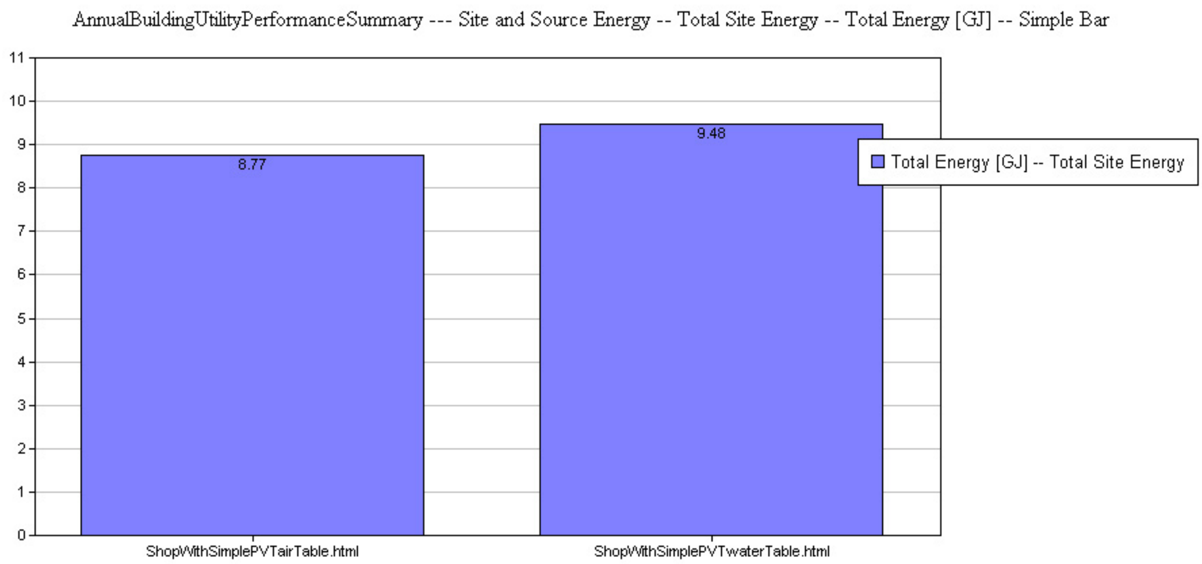


Figure 54
Total Energy Produced on Site For Air vs. Water PV/T

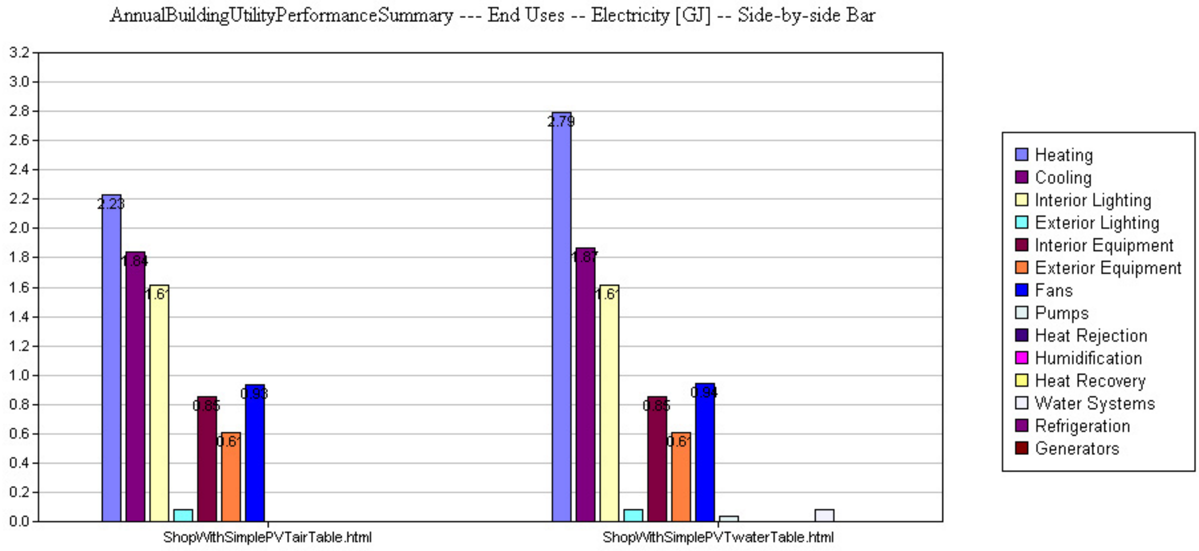


Figure 55
End Uses of Electricity

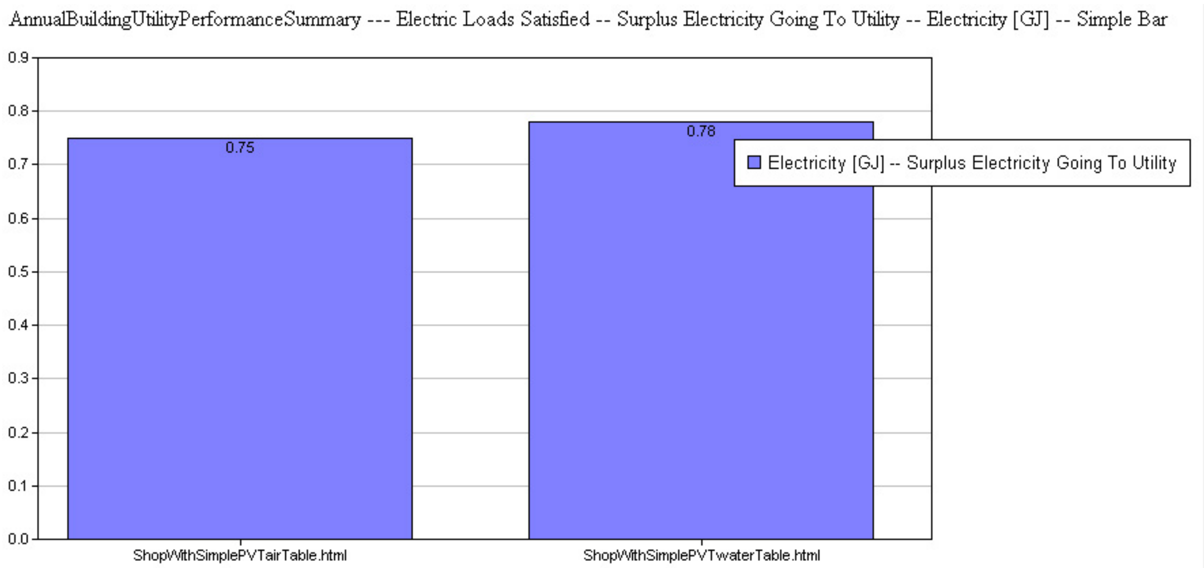


Figure 56
Surplus Energy Exported to Grid

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