Characterization of Flat-Plate Hybrid Photovoltaic-Thermal Solar Collectors for Varying Climates and Hot Water Demands

A Project

Presented to the Faculty

of Oregon Institute of Technology

in Partial Fulfillment for the Requirements for the Degree

of Master of Science

by

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May 2018

Oregon TECH

Final Approval of Project/Thesis

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For the Master of Science in: Renewable Energy Engineering

Project or Thesis: Project

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I dedicate this work to my wife, Marlena Adams, to my sister, Heather Adams, to all my family and friends that have supported me throughout my education.

Heather provided me with the discipline and tools necessary for success during the formative years of my adolescence, and has been there for me at every turn of life. Her guidance and support have helped me to make the right decisions and formed me into the man I am today. I could never thank her enough for everything she has done for me.

Marlena's unrelenting support and encouragement are the drivers the led me to return to school and pursue my education. Without her by my side, I would never have been able to accomplish all that I have. Nobody succeeds on their own. We all need help and support, and I could not ask for a better partner in this journey of life.

Acknowledgements

I would like to thank my thesis advisor, Dr. Aaron Scher, for his guidance throughout the course of this work. His critical thinking and probing questions helped to develop the design and analysis processes of the work in this thesis project. His assistance guided the scope of this project. I truly appreciate the time and effort Dr. Scher has put into advising this thesis project.

I would also like to thank the other members of my thesis defense committee, Dr. Hope J. Corsair and Dr. Teshome Jiru, for their willingness to evaluate my thesis project in consideration toward the degree of Master of Science in Renewable Energy Engineering. I understand their time is valuable, and I appreciate them dedicating it to this endeavor.

Abstract

Hybrid photovoltaic-thermal systems that utilize solar radiation to generate a combination of thermal and electrical energy offer many benefits to energy efficiency and production. Exploiting what would otherwise be waste heat can provide dual functionality of cooling photovoltaic cells and using heat directly or converting it into other forms of energy. There are many different variables that impact the performance of a hybrid photovoltaic-thermal system, including solar irradiation, ambient temperature, cooling fluid temperature, fluid mass flow rate, glazing, and many more. Significant literature published recently suggests that hybrid photovoltaic-thermal systems offer both economic and technical feasibility in most cases. However, due to the wide range of configurations and lack of commercial availability, further studies need to be performed to determine the most appropriate types of systems for a variety of economic and climatic conditions. The purpose of this work was to characterize a hybrid photovoltaic-thermal solar collector system for a variety of sizes and hot water demands to establish the cost and energy performance in five different climate zones. The objective is to gain a general consensus about the economic feasibility of hybrid photovoltaic-thermal systems over standard photovoltaic or concentrating solar power systems. It was found that the optimum flow rates for photovoltaic-thermal collectors, for water preheating, is 0.2 to 0.4 kilograms per minute per square meter of collector area. The most important variables are collector flow rate and demand flow rate. Most systems tested were discovered to be economically beneficial in all climates, as long as the ratio of demand flow to collector flow is at least one, with better economic performance as that ratio increased. With the desired ratio and known demands, the system can be properly sized to optimize electrical outputs, heat gains, and economic feasibility.

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I. Introduction

Current solar energy collection systems waste a tremendous amount of available energy, either in the form of heat or photon energy, which is where hybrid photovoltaic-thermal (PVT) systems can present the ability to optimize efficiency. Standard photovoltaic (PV) panels waste 100% of heat energy, and flat-plate solar-thermal collectors or concentrating solar power (CSP) systems waste 100% of the photon energy. However, a hybrid PVT system can capture energy from both sources simultaneously.

History of Hybrid Photovoltaic-Thermal Collectors

With the global energy crisis in the mid-1970s, accompanied by a decrease in the cost of PV cell manufacturing, the incentive to invest research into the advent of cleaner and more efficient sources of energy production was on the rise. This need for new energy developments made way for the concept of cooling photovoltaic cells with a fluid to prevent overheating and maximize cell efficiency. Using a working fluid for cooling PV inevitably led to the advent of hybrid photovoltaic-thermal (PVT) technology to utilize the generated heat, which was first introduced by Martin Wolf in the middle of the 1970s [1-3]. Hybrid photovoltaic-thermal systems that use solar radiation to generate a combination of thermal and electrical energy offer many benefits to efficiency and production. Absorbing what would otherwise be waste heat can serve a dual purpose of cooling the photovoltaic cells and offering the option of using the heat directly or converting it into mechanical or additional electrical energy. Hybrid PVT technology continues to be explored and improved due to its various benefits. Fossil-fuel energy production accounts for up to 80% of worldwide energy, but resources are being depleted and production has begun to decrease after a peak in 2015, showing continuing trends to 2050 [1]. Due to the volatility of the oil price in combination with the meltdown of the nuclear plant in Fukushima, Japan, policy makers have also begun to reduce their efforts in pursuing nuclear energy and started focusing more on the viability of solar [1].

Research into solar PVT since the year 2000 has gone beyond assemblies and into control methods, operation, weather data analyses, and economic performance, and such research has been described as “omnifarious and extensive” [2]. Renewable energy (RE) is quite cost effective, reliable, and friendly to the environment, so it is no surprise that RE’s contribution to global energy production has increased from 13.3% in 2006 to 20% in 2011 and is predicted to rise to 28% by 2030 [1]. Numerous studies, comprehensive energy and exergy analyses, and environmental impact studies all suggest that hybrid photovoltaic-thermal systems almost always increase efficiency over standalone PV or solar thermal systems, reduce overall emissions, and have an expected payback period that is significantly less than the expected lifetime of the system, dependent on the region and optimization in design [2-5].

At the 17th European PV Conference in 2001, Tripanagnostopoulos et al. introduced the concept of PV/T Combi, which combines both air and water as heat exchange fluids, instead of just one or the other [1-3]. Tripanagnostopoulos performed extensive studies on hybrid PVT technology and is referenced in much of the literature reviewed in this paper [1-3, 6, 7]. There are peripheral methods that allow the hybrid PVT systems to more efficiently absorb solar energy including a thin metallic sheet placed at varying distances between the front and rear panels of the assembly, fins protruding out from the heat absorbing rear panel, small ribs protruding from the rear panel, and an external diffuse reflector to apply additional solar radiation uniformly across the surface of the photovoltaic cells in horizontal (usually rooftop) installations [1]. The most common flat-panel PVT module consists of a sheet-and-tube design (usually water-based) and are most useful for installation on rooftops and easy access areas [1, 5]. Flat-panel is not the only PVT design structure. Technologies in concentrated solar power (CSP) have been increasing in recent years, which allow for the hybrid PVT technologies to branch out into that type of format as well. Concentrated solar power usually uses a parabolic reflective surface, commonly a trough or a dish, but there are also concentrating linear Fresnel and solar power tower methods [2, 5]. Solar energy is a very diversified source, as the full spectrum of radiation via photon transfer and heat generation can be utilized, which is propelling the drive towards more PVT technologies.

By integrating multiple energy production and storage methods, the benefits of one system can offset and overcome the limitations of its companion, offering improvements in overall efficiency accompanied by a reduction in operation costs and payback periods [1, 2, 4]. The efficiency of commercially available PV cells ranges from 6 – 16%, whereas the utilization of PVT technology has been shown to increase efficiency by 50 – 70% compared to standalone PV or solar thermal generation [1, 3]. A large portion of the efficiency gain is due to a counterproductive feature of photovoltaic cells, which is that as more sun shines and cell temperature increases, the efficiency of the cells decreases [1, 3, 5, 6, 8-13].

Challenges and Drivers of Hybrid PVT Development

Global Issues Driving the Necessity for Hybrid PVT Technology

Certain regions, such as many countries in the European Union, face a lack of land availability as a limiting factor toward the expansion of renewable energy implementation, which could be benefitted by hybrid PVT [2]. Another significant limitation of photovoltaic cells is the low energy conversion efficiency [2, 5]. With ambitious renewable energy and carbon emission reduction goals set by many countries [14] and states in the U.S., namely California with a goal of 50% RE by 2030 and now the fifth largest economy in the world [15-18], the need to maximize energy captured within a given area has been amplified. As mentioned, PV efficiency suffers from degradation as the temperature of the cells increases. In most cases, the degradation of efficiency is reported as approximately 0.5% for every 1°C of temperature increase [1, 5, 9, 19], with reports ranging as high as a 3-6% decrease per °C [6]. This decline in solar efficiency with greater solar irradiation has paved the way for PVT technologies to generate improvements, as preventing the temperature from rising on the PV cells is imperative, and natural convection cooling is not adequate to properly cool cells for maximum efficiency [5].

Inherent in the drive toward renewable energy and the reduction of greenhouse gas (GHG) emissions is the transition from using fuels for water and space heating, such as natural gas, heating oil, and diesel, to using electrical energy and heat from natural phenomena, like the solar radiation and geothermal, or implementing energy efficiency measures. Hybrid PVT optimizes the use of features while overcoming limitations, weaknesses, and drawbacks [1-5, 10, 13]. This optimization is achieved by occupying less space than PV and thermal solar collectors (SC) separately, reducing installation time and costs due to decreased use of materials [3, 9] and shared components [10], utilizing different parts of the solar spectrum [1, 5, 10, 13], and reduced operation costs [1].

Solar energy production has become one of the most sustainable renewable energy sources in recent years, primarily due to it being one of the most abundant and unexhausted energy sources and significant developments in related conversion technologies and installation methods [8]. Standalone PV and CSP are mature technologies, but hybrid PVT systems are still quite immature [5]. While there have been numerous prototypes developed over past decades, very few commercially available PVT systems exist [9]. The range of technologies for hybrid photovoltaic-thermal (PVT) collector assemblies can generally be designated into two specific primary categories and a third much broader category. The two primary categories include concentrated solar power (CSP) and flat-panel solar cells with integrated methods for heat exchange. The third category essentially pertains to all other niche forms of photovoltaic-thermal energy generation. These designated categories are assigned by the author and only represent the author's method of analyzing the findings of the materials reviewed.

A hierarchical breakdown of Hybrid PVT systems and the various components is represented in Figure 1. A variety of different styles of concentrating photovoltaic-thermal (CPVT) collectors, as presented in patents US8455755B2 [20], US9240510B2 [21], US9270225B2 [22], and US8642880B2 [23] are shown in Figure 2 and Figure 3, illustrating the diversity of the technology. With such diversity, however, comes a lack of standardization. The necessity for novel PV cells is likely another reason CPVT is analyzed in few publications [10, 24]. A great majority of research investigates flat-plate technologies [6-9, 11-13, 25], which is the focus of this work. A flat-plate PVT solar collector module, as described in US9263986B2 [26], is displayed in Figure 4, illustrating how the components are arranged. Figure 5 demonstrates how an array of PVT collectors can be interconnected on an angled rooftop, as presented in US9401676B2 [27]. While photovoltaic-thermal technology is promising, there are still hurdles that need to be overcome before widespread adoption will occur.

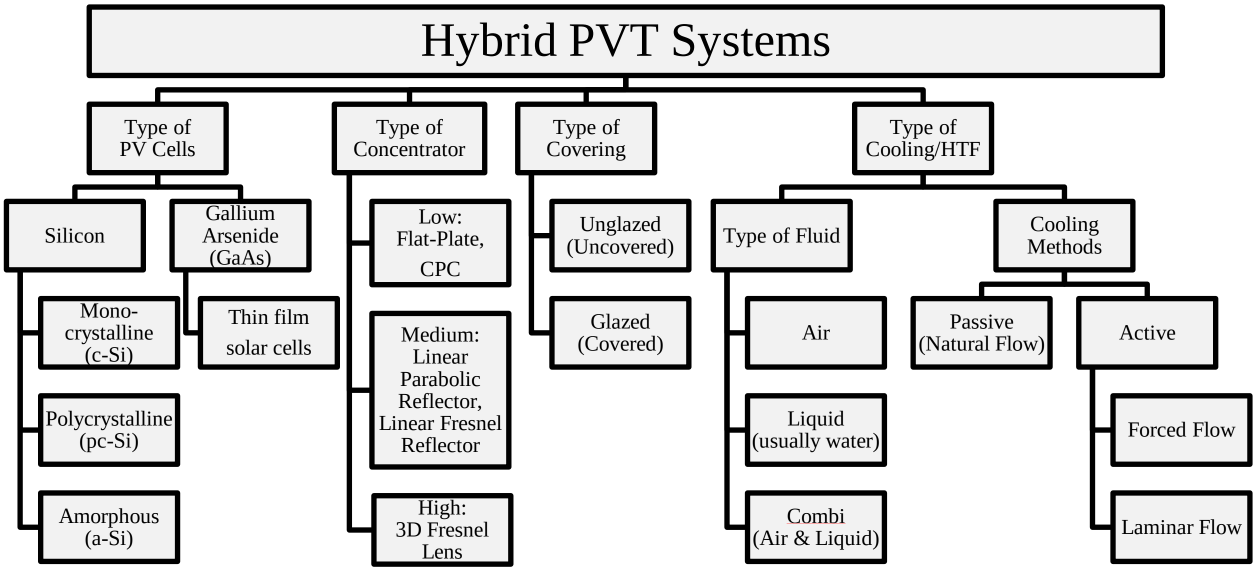


Figure 1. Hierarchical breakdown of hybrid PVT systems and components

Challenges Faced by the Development and Implementation of Hybrid PVT

Currently, there is no consensus on which type of physical format of hybrid PVT, flat-plate or concentrating, or which climates are best suited for this type of system to offer the lowest levelized cost of energy and optimize efficiency. This gap in knowledge prevents hybrid PVT systems from reaching commercial viability and being implemented in locations that would offer greater benefits than that of standard photovoltaic or concentrating solar power systems.

The long-term goal of this research is to accelerate the timetable for the reduction of greenhouse gas (GHG) emissions and transition to a fully renewable energy infrastructure by advancing the utilization of hybrid photovoltaic-thermal systems in regions and applications in which they are feasible. By generating a consensus for which type of system is most applicable for certain conditions and uses, properly sizing systems to meet all energy needs at the lowest cost will be a much simpler process. As flat photovoltaic panels are the most common for residential, small business, and even many large-scale applications, this research focuses on flat-panel hybrid PVT systems.

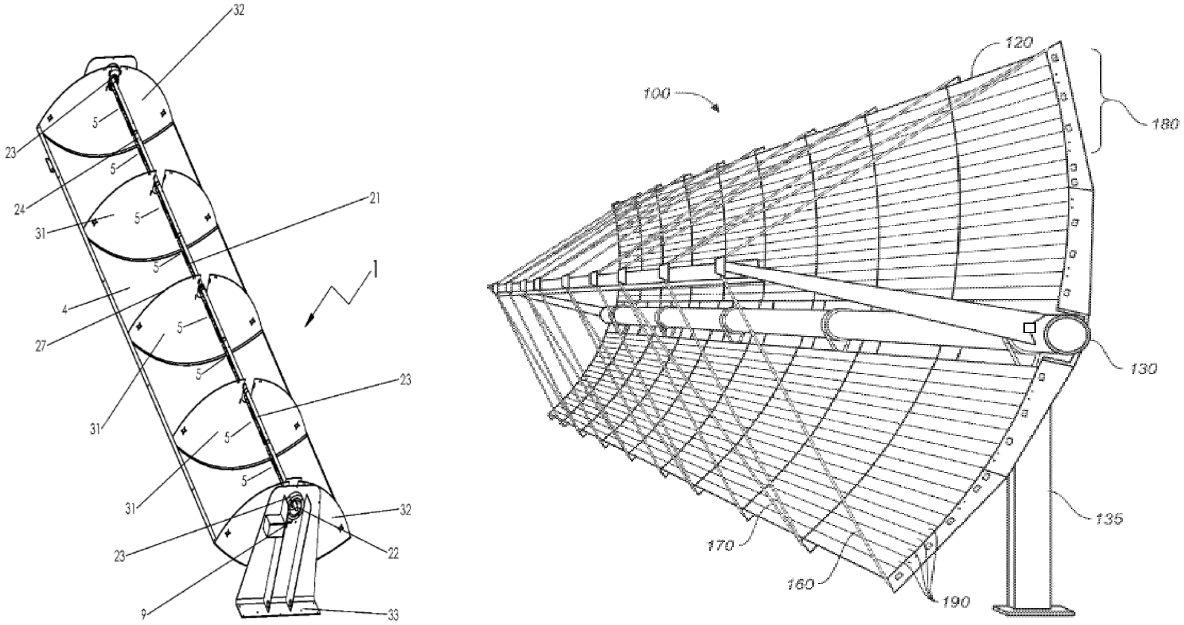


Figure 2. CPVT solar collector as illustrated in US8455755B2 and US9240510B2 (left), and concentrating solar energy collector assembly as illustrated in US9270225B2 (right).

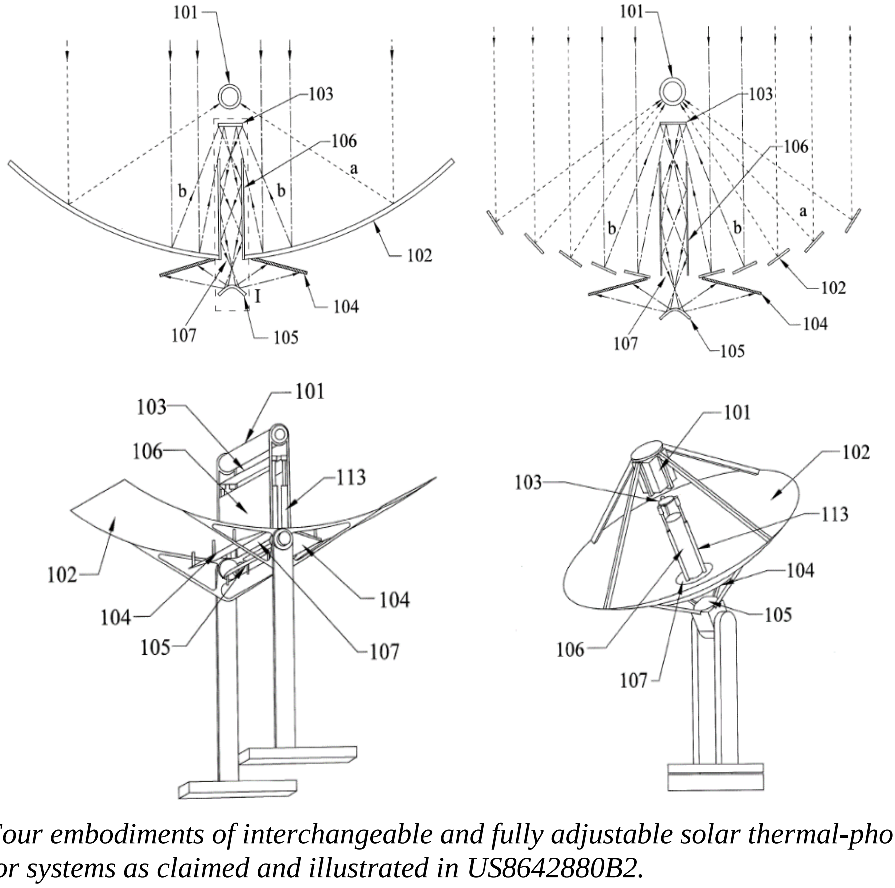


Figure 3. Four embodiments of interchangeable and fully adjustable solar thermal-photovoltaic concentrator systems as claimed and illustrated in US8642880B2.

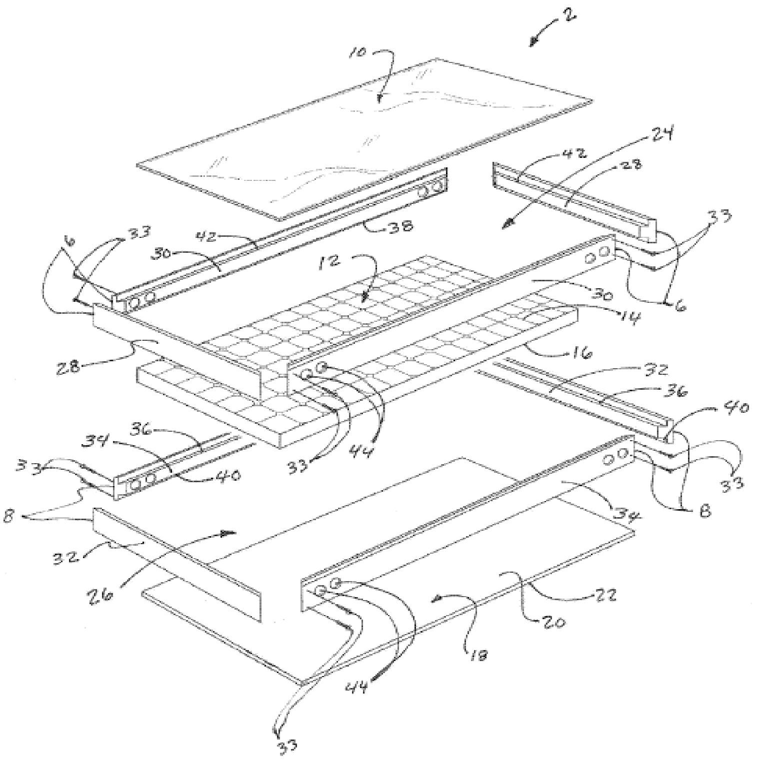


Figure 4. Flat-plate hybrid photovoltaic-thermal collector as illustrated in US9263986B2.

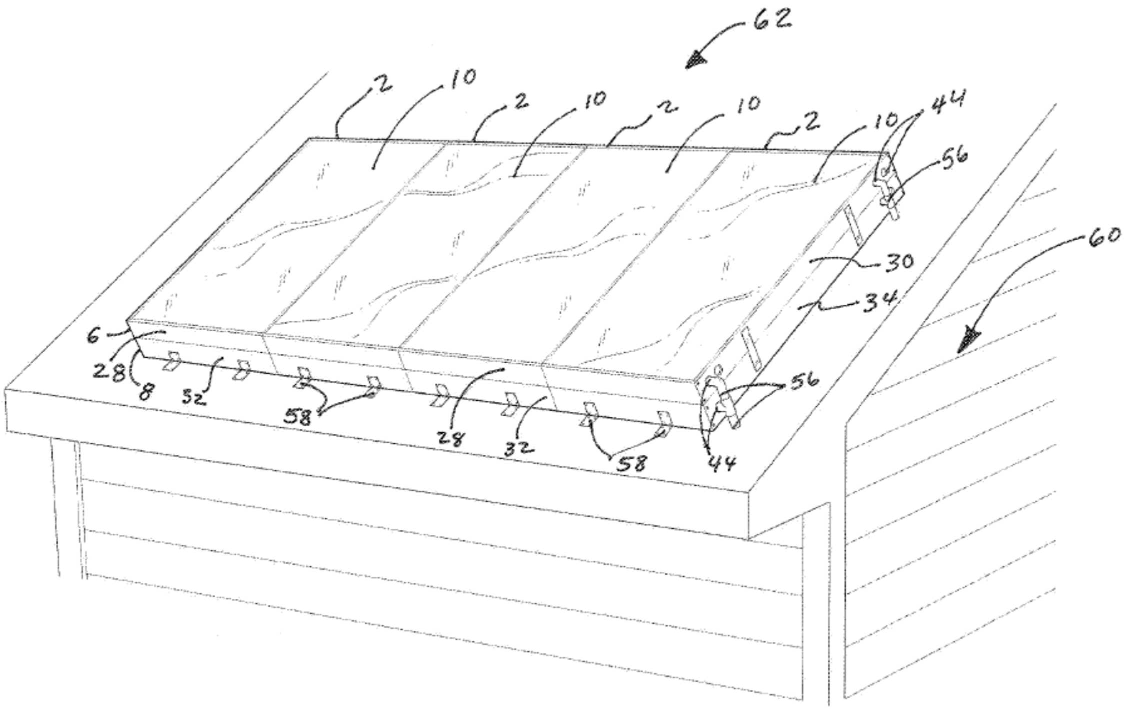


Figure 5. Array of interconnected photovoltaic-thermal assemblies as illustrated in US9401676B2.

Objective of Research and Central Hypothesis

Research Objective

The objective of this research is to generate guidelines as to which climates and applications may offer economic benefit for selecting hybrid PVT over standard PV for new installations or for retrofitting existing PV installations into hybrid PVT systems. This work should lend some credence to hybrid PVT systems and instill confidence for investors to move forward with more commercial manufacturing, thus leading to further reductions in costs and solidifying the viability of such systems, inspiring even greater investments in the technology. Research is performed for unglazed flat-plate hybrid photovoltaic-thermal solar collectors with a packing factor of one. The packing factor represents the percentage of the collector glazing area that comprises solar cells. This configuration was chosen because it most closely mimics the adaptation of a thermal solar collector affixed to the rear of a photovoltaic panel.

The PVT system is analyzed for five different locations across varying climate zones and solar radiation intensities, spanning from the southern edge of California north and east to include the pacific northwest and the colder climate of central Wyoming. This will test a variety of solar irradiation levels and ambient temperatures to help generate a consensus as to which regions and applications are most suitable for flat-panel hybrid PVT systems. Investors are hesitant to put their money into systems that provide uncertain outcomes, and this work should help to remove such uncertainties in hybrid photovoltaic-thermal systems. The potential for hybrid photovoltaic-thermal systems to generate much greater energy yields within the same physical footprint is likely to result in lower levelized costs of energy and reductions in GHG emissions, which will draw the attention of financiers and philanthropists.

Central Hypothesis

The hypothesis is that flat-panel hybrid photovoltaic-thermal systems will produce the greatest PV efficiency gains and hot water production in the hottest, most humid climates closest to the southern United States border, whereas progressing further north may only offer significant efficiency and heat gains in the summer months. Colder climates may still gain some benefit from hybrid PVT in the winter, however, as any amount of preheating results in an energy savings that does not need to be supplied by another source, such as natural gas or grid power. For economic benefit to be maximized, all heat energy produced must be used, which suggests that commercial applications with higher hot water demands may experience greater benefits in hotter climates, while residential and small business applications may not gain much advantage due to lower demands. No matter how much heat is generated, it offers no benefit if it is not utilized. That is, unless the electrical efficiency improvements of the PV cells offset the lack of heat demand to accommodate the cost of the system.

Integrated PV and SC systems have been found to be economically and technically feasible [1, 5], able to provide higher quality main/backup power generation [2], more efficient, economically competitive, and offer reduced energy payback times (EPBT). Hybrid systems have been reported to provide higher solar energy conversion efficiency than standalone solar thermal systems [2, 9, 11, 13] due to the higher power density of utilizing more of the solar spectrum in the same physical footprint [9, 11]. Hybrid photovoltaic systems offer great potential for use in many applications, but investors are wary due to the lack of consensus on the subject. The purpose of the work to be performed is to alleviate a significant degree of such uncertainty in hybrid photovoltaic-thermal technology.

The objective of this research is to create general guidelines for understanding where and when a hybrid photovoltaic-thermal collector system may offer economic feasibility. To generate said guidelines, simulations are performed for a variety of different system settings. The following will begin by explaining the specific aims of this research and what type of characterization analysis was performed. Then the research methodology and simulation design specifics will be discussed. Finally, an analysis of the simulation results is discussed, guidelines are set for determining the economic feasibility of potential hybrid PVT projects, and a conclusion is reached.

II. Specific Aims of Research

The main objective of the research is to characterize the cost and performance of unglazed, flat-plate hybrid photovoltaic-thermal collectors across five different climate settings and varying applications of heat demand. The results of this work will help provide guidelines for those with impending or existing solar photovoltaic installations as to whether hybrid PVT will definitively be cost effective, not offer any economic feasibility, or may require further investigation for the particular needs of the user.

Three Specific Aims

The first aim is to determine how the system performs under varying climatic conditions of solar irradiation and ambient temperature. This was tested by simulating an array in TRNSYS (Transient System Simulation Tool) using weather data from the National Renewable Energy Laboratory's (NREL) National Solar Radiation Database (NSRDB) [28] for five locations throughout the western half of the United States for one full year.

Another aim of the research is to analyze the data for the flat-plate PVT collectors to determine how the system is best suited for applications with varying ratios of electricity to hot water demands. Demands for strictly heat would only be applicable for concentrating solar power systems, and may defeat the purpose of integrating PV cells into solar concentrators, aside from powering parasitic loads, which is beyond the scope of this research. In addition, demands for only electricity will make PVT only useful when the heated fluid can be used to spin a turbine to generate electricity or when it sufficiently cools the PV cells to compensate for the extra capital and maintenance costs of hybrid PVT over standard PV.

The final aim for the research is to determine which applications and climate settings produce the lowest levelized cost of energy. After analyzing the PVT modules under five different climatic conditions and varying demands, a cost analysis is performed for each scenario to discover the lowest levelized cost of energy. The analysis includes a comparison of energy produced as well as energy saved for each climate and application tested.

Expected Outcomes

The initial expectation is that the flat-plate technologies will offer a wide range of benefits for applications that require at least some low-grade heat generation and may potentially provide economic benefits in any climate for specific applications. This expectation is primarily due to recent advancements in flat PV panel technology making it easier to adapt a thermal collection unit onto, or around, the panel or to modify the manufacturing processes of photovoltaics to include thermal collection, resulting in fewer increases to capital costs.

The levelized cost of energy (LCOE) is expected to vary depending on the application of the energy produced. Applications in the hottest climates with high heat demands are expected to produce the lowest levelized cost for hybrid PVT systems. Purely electricity or low heat demands will likely result in a higher LCOE, perhaps greater than that of standalone PV. With an improved understanding of where and when hybrid photovoltaic-thermal collector systems will be most applicable, depending on the climatic conditions and applications for use, greater commercial investments will result, thus further lowering the cost and significantly reducing uncertainties. With greater confidence in the technology, the implementation of hybrid PVT systems will maximize the energy produced within the same physical footprint, greatly assisting in the transition to renewable energy and accelerating reductions in greenhouse gas emissions leading to climate change.

III. Research Methodology

The strategy for performing the research involves running a succession of simulations for flat-panel hybrid PVT modules in series using solar irradiance and temperature data from the NREL NSRDB [28] for five different climates. The simulations were performed in the Transient Energy System Simulation Tool (TRNSYS). For statistical significance to obtain a 95% confidence interval with an 80% power rating, simulations are required for 196 days of solar data. This study will simulate the systems using typical meteorological year (TMY) data for the entire calendar year (365 days), which will not only provide a range of data for all seasons but will increase the statistical significance of the results.

An innovative model was developed to allow for the DHW demand data, system size, and NSRDB weather data to be easily input and simulated for specific locations. The data from the TRNSYS simulations can be output to a text or comma-separated value (CSV) file, which can then be imported into MATLAB, Excel, or any other data analytics software for processing to generate accurate pricing and energy generation data for particular applications. The results of this model will make it easier for potential residential or commercial investors in PVT to determine the feasibility of implementing or retrofitting a hybrid system.

The approach of this research is to simulate the electrical and thermal energy output results of the PVT system starting in the southwest corner of the continental United States, in Imperial, California, progressing north and east through five different climate zones. A multitude of array sizes along with varying domestic hot water (DHW) demands and flow rates are tested for each location. Once the electricity and heat production characteristics are simulated for each climate, the data is imported into Excel for processing. Using a progressing scale of hot water demands with capital and operations and maintenance (O&M) costs, performance and cost analyses are completed to identify climates and energy applications with economic feasibility.

Climate Analysis

Hybrid PVT systems can offer excellent benefits when deployed under the proper circumstances. In warmer climates, thermal energy can be used for direct applications in domestic hot water (DHW) [5-9, 12], for swimming pools or drying substances [5], floor heating and desiccant cooling [9]. If the region is too cold, or if solar radiation is not high enough, the fluid in the system may provide a cooling effect that could be beneficial if it improves the solar cell efficiency, but it could also be less cost effective than standard PV if gains to efficiency and usable heat are negligible. The first objective of this research is to perform an analysis of the energy performance of flat-plate PVT systems to determine suitable climates for the use of photovoltaic-thermal technologies.

Justifications and Feasibility

The basic structure of hybrid PVT uses a thermal fluid for cooling PV cells, increasing efficiency and recovering waste heat usually dissipated to the environment [3, 5, 13]. PVT system performance depends on many variables: temperature of fluid, fluid mass flow rate, the quantity and thickness of glass covers [1, 5, 9-11, 25], collector length [1], ambient temperature, fluid pressure, solar radiation [9, 24], supervisory and control systems [5, 8, 9], packing factor [6, 11, 13], and the shape of the absorber plate [11]. Ambient temperature and solar radiation are the major focus of this study, as the other factors can be variable depending on the design of the module and control methods. To instill confidence in PVT for commercial investment, it will be important to know which climates can provide benefits for such systems.

Review of Relevant Literature

A significant majority of the literature reviewed for this research involves case studies regarding flat-plate photovoltaic-thermal systems and collectors to assess their economic, technical, and environmental feasibility [4, 6-9, 11-13, 25]. While most of these systems focus on a sheet-and-tube design, described in [7] as a “hamburger structure,” a few publications branch out from this fundamental design to investigate open cavity fluid flow [6], photovoltaic and thermoelectric (PV-TE) conversion [13], and separate PV and thermal solar collectors for a green school [4]. A popular area for such studies is in the Mediterranean region [4, 6, 8, 9, 12], specifically Naples, Italy [8, 9], the island of Cyprus [6], and Athens, Greece [12]. Other regions examined in the reviewed literature include Hunan Province, China [7], Bhopal, India [25], Munich, Germany and Dundee, Scotland [12]. Most of the case studies provided positive results for economic feasibility aside from those performed in colder climates.

Research Design

The design of the research uses TRNSYS simulation software to analyze the electric and thermal output of a hybrid PVT panel. TRNSYS is a simulation software that is widely adopted for commercial and academic purposes, which allows for importing models written in certain coding languages such as Fortran [8] and has been demonstrated to accurately align with experimental results [12]. Among the literature reviewed, a significant portion used TRNSYS for analysis of hybrid PVT systems [1, 2, 5, 7-9, 12]. Typical meteorological year (TMY) data for solar irradiance, wind speed, and ambient temperature are obtained from NREL’s National Solar Radiation Database [28], which can be adapted for input into TRNSYS. The hybrid systems are simulated using weather data from five locations in the western United States, spanning to the north and east from the southern tip of California. The specific locations, from the US – Mexico border going north then east are: Imperial, California; Sacramento, California; Portland, Oregon; Salt Lake City, Utah; and Riverton, Wyoming. These locations were chosen because they fall under different solar irradiance levels and International Energy Conservation Code (IECC) climate zones (zones 2-6). Figure 6 shows the five locations superimposed onto the map of solar radiation from the NSRDB Data Viewer [29] to illustrate the varying scales of solar radiation tested. The five locations on a map of the IECC climate zones, courtesy of Pacific Northwest National Laboratory [30], is displayed in Figure 7.

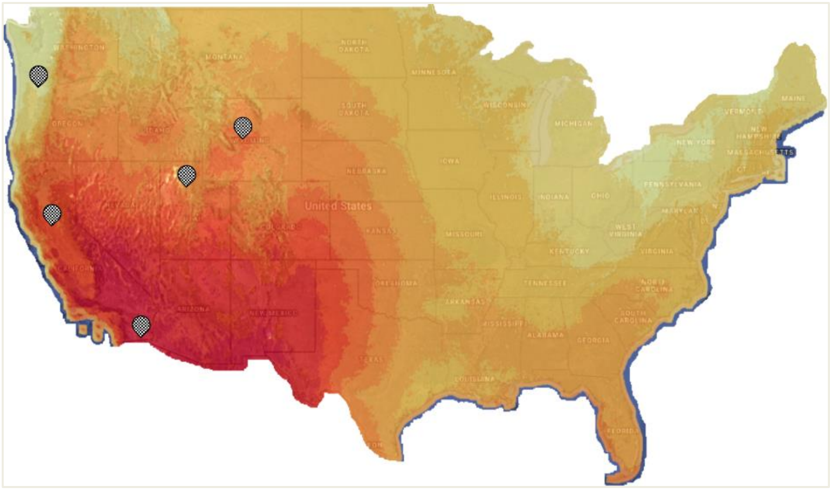


Figure 6. NSRDB Data Viewer map with locations designated.

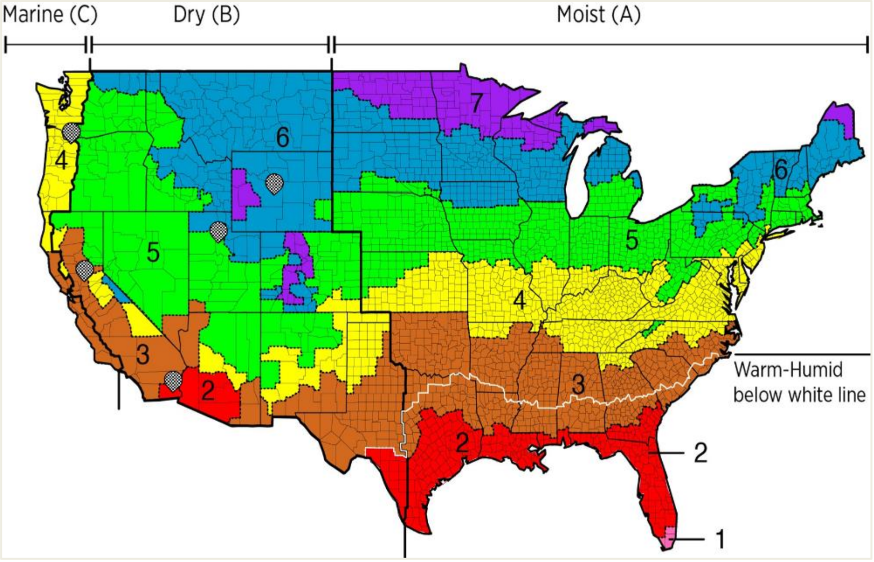


Figure 7. IECC climate zone map with locations designated.

The hybrid PVT collector for this research uses water as a working fluid with a flow rate of approximately 0.2 kg/min/m^2. Analyzing the PVT collector as a single unit, the power input to the system is the total solar irradiance striking the surface of the photovoltaic cells. The total power output of the photovoltaic-thermal collector consists of both the electrical and thermal output components. The efficiency of the PVT collector (n), power output divided by power input, is calculated as such:

$$n = \frac{P_e + P_{th}}{P_S} \quad , \qquad \text{Equation 1}$$

$$P_S = AR \quad , \qquad \text{Equation 2}$$

$$P_e = I_{\max} \cdot V_{\max} \quad , \qquad \text{Equation 3}$$

$$P_{th} = f \cdot C_p \left(T_o - T_i\right) \quad , \qquad \text{Equation 4}$$

where n is the total efficiency of the PVT collector, P_S is the total solar power input, A is the surface area of the system, R is the incoming solar radiation normal to the collector surface, P_e is the electrical output power, I_{max} is the maximum current, V_{max} is the maximum voltage, P_{th} is the thermal output power, f is the fluid mass flow rate, C_p is the specific heat of the fluid, and the temperature change of the fluid from inlet to outlet is $(T_o - T_i)$. Separating the components into their own efficiency equations, the resulting electrical efficiency (n_e) and thermal efficiency (n_{th}) are:

$$n_e = \frac{I_{\max} \cdot V_{\max}}{AR} \quad , \qquad \text{Equation 5}$$

$$n_{th} = \frac{f \cdot C_p \left(T_o - T_i\right)}{AR} \quad . \qquad \text{Equation 6}$$

Incoming solar radiation (R) is assumed to be normal to the surface because this would produce the highest possible efficiency, and to properly analyze collector capabilities, efficiency losses from external sources (i.e. incidence angles other than normal) need to be eliminated or reduced to a minimum. The average efficiencies for each system are then calculated for each climate, and the systems are compared. It is important to note that, while the solar radiation is not directly striking the thermal heat exchanger, it is still the external input for the PVT collector. The effectiveness of the internal heat exchanger between the solar collector and the PV panel is calculated using a different equation than that of efficiency, in which the temperature reduction of the PV cells is divided by the total possible temperature reduction, such that,

$$\varepsilon = \frac{T_{PV} - T_{PVT}}{T_{PV} - T_i} \quad , \qquad \textit{Equation 7}$$

where ε is the effectiveness of the heat exchanger, T_{PV} is the average cell temperature of the reference PV panel with no fluid, T_{PVT} is the average cell temperature of the cooled PV cells on the PVT collector, and T_i is the temperature of the inlet fluid to the PVT collector. For the purposes of this research, total energy output of the system relative to the energy input to the system (i.e. the efficiencies) are key point of interest.

As discussed previously, photovoltaic cells experience a decrease in efficiency when operating at temperatures greater than the nominal operating temperature of 25°C. The hidden benefit to that inefficiency, in respect to PVT collectors, is that as more heat energy is collected in the fluid, the temperature of the cells will decrease and the efficiency will increase. In that case, the thermal and electrical efficincies of the PVT collector have a symbiotic, self-promoting relationship. A simple equation to describe the electrical power output (P_{out}) of a PV panel based on the effective efficiency (n_{eff}) of the PV cells is

$$P_{out} = P_{in} \cdot n_{eff} \quad , \qquad \text{Equation 8}$$

$$n_{eff} = n_{nom} \cdot (1 - \frac{\alpha_P}{100})^{(T_{PV} - T_{nom})} \quad , \qquad \text{Equation 9}$$

where P_{out} is the electrical power output of PV cell (either standalone PV or PVT), P_{in} is the solar irradiance striking the PV cells, n_{eff} is the effective efficiency relative to operating temperature of the photovoltaic cell, T_{PV}, n_{nom} is the reference efficiency at the nominal operating temperature, T_{nom} (25°C), and α_p is the temperature coefficient representing the percent decrease per degree of PV cell temperature increase (0.5 %/°C).

Expected Outcomes

The expected outcome of the climate analysis is that hybrid systems will offer significant efficiency gains in the lower three latitude climates tested. While beyond the scope of this research, concentrating solar systems would be expected to provide the greatest overall efficiency in the hottest climates with dramatic declines as the latitude moves further north. The flat-plate systems simulated in this work will likely provide the greatest overall efficiency in the median climates, with a slight decrease in the hottest climates and significant decrease in the coldest. For the coldest and darkest climates, in Riverton, Wyoming and Portland, Oregon, the economic benefits were expected to be negligible or only offer efficiency gains by cooling PV panels. The systems were not expected to generate adequate heat for direct DHW use, especially during the winter months, but may still provide preheating benefits. In these colder climates, potentially including Salt Lake City, Utah, there is a risk of water freezing and damaging the system. Those regions will likely require a working fluid with antifreeze, such as a water/glycol mixture, to be able to operate at temperatures below freezing. Such a working fluid would eliminate the ability for an open-loop system, requiring a use of a heat exchanger. A heat exchanger will not be used in the scope of this work. Applications for specific heat demands will be analyzed as the second specific aim of this research.

Heat Demand Analysis

The heat energy produced from a hybrid PVT system can serve many purposes like domestic water heating and possibly conversion to electricity. However, heat energy may also offer no benefits if it is not within the desired temperature range. The second aim of this research is to determine how the system performs for varying heat demands.

Justification and Feasibility

Heat energy does not have much value if it is near ambient temperature or unusable for the desired application. Flat-plate systems in milder climates may not generate high enough temperatures in the heat transfer fluid (HTF) to accommodate even low-grade heating applications such as DHW or pool heating. However, temperature outputs that do not meet demand may still provide sufficient energy savings from preheating to offer economic benefits. Thus, it is important to assess performance on a varying scale of heat and electricity demand.

Review of Relevant Literature

For extreme heat or purely electricity demands, concentrating photovoltaic-thermal (CPVT) systems may offer the greatest benefits. Although CPVT is beyond the scope of this work, it is still important to note the capabilities of such systems. Abdelhamid *et al.* [24] and Xu *et al.* [10] published case studies involving CPVT solar collector modules that implement world record thin film gallium arsenide (GaAs) solar cells for quality electrical conversion at extremely high temperatures. Crystalline silicon (Si) is more efficient than GaAs, but GaAs is less affected by temperature increases, having lower temperature coefficients (0.08% per °C) than conventional solar cells in high concentration PVT systems [24]. GaAs cells serve two purposes; they generate electricity as well as act as a spectrum splitter/concentrator, separating visible and infrared light bandwidths. Absorption at sub-bandgap wavelengths (<870nm) is reportedly 90% with high reflectivity (92%) in the infrared spectrum [24]. A transmissive concentrating dish PVT design, as presented in [10], can maintain GaAs PV cell temperatures to less than 110°C, while the output temperature of the HTF can be tuned from 100°C to above 570°C, depending on need. The thermal outlet temperature of the fluid in the parabolic trough, two-stage concentrator in [24] reached temperatures as high as 365°C. Both systems produce HTF temperatures in ranges that can easily be used for electricity generation through a turbine.

Economic analysis of PVT systems for an indoor/outdoor swimming pool and a university building in Naples, Italy, suggests that incentive policies are necessary to improve economic profitability of hybrid PVT systems [6,7] for those applications. However, hybrid PVT systems for DHW applications demonstrate excellent economic potential in China [7], Cyprus [6], Greece [12], and India [25]. Much of the analyses within the literature regarding heat production disregarded any benefits from the heat produced if it did not meet all demands. It is important to consider, though, the energy savings achieved by preheating water before the standard heating process. Even a mere five-degree increase in temperature at the inlet to a water heater represents an energy, and thus cost, savings. An analysis of how PVT systems will be able to meet specific heat demands, or at least offer a savings, for the different climates will help investors identify the feasibility of hybrid PVT for their requirements.

Research Design

The design for the research to determine the performance for hot water demands will be to perform deeper analysis on the fluid output temperature from the TRNSYS simulations. Outlet temperatures will be designated into three different temperature ranges to help categorize their potential applications. Thermal output temperatures below 40°C will be designated for preheating only. Fluid temperatures between 40-110°C will be designated as applicable for low-grade heating like domestic hot water and space heating. Although unlikely to occur with flat-panel PVT, temperatures above 110°C can be designated as useful for high direct heat demands and electricity generation. Data will be compared for different system sizes and hot water demands to determine which scenarios for demand profiles can be satisfied by a hybrid photovoltaic-thermal system.

Expected Outcomes

The expectation is that the flat-plate systems will provide DHW and other low-grade heating applications in Imperial (IMP) and Sacramento (SAC), California, perhaps supplying high-grade demands in the hottest months, and for optimized systems in Portland (PDX) and Salt Lake City (SLC). PDX and SLC should offer decent DHW applications during the summer months and beneficial preheating in the winter. The PVT systems are only expected to perform well in the summer for Riverton, Wyoming (WY), with only slight preheating in the winter.

Levelized Cost of Energy

The levelized cost of energy (LCOE) is a standard metric to measure the per unit cost of energy from a system over its lifetime. LCOE is likely the most important variable that will be determined in this research, at least from an investor perspective. Many industry decisions are made solely based on the bottom line. For this reason, there is significant need to categorize hybrid PVT systems by their LCOE for particular regions and applications. The prior two aims will help develop a proper levelized cost, because the climatic conditions and applications for use can have a significant impact.

Justification and Feasibility

As mentioned, the bottom line is often the most important number that investors see. In most cases, hybrid photovoltaic-thermal systems have shown both technical and economic feasibility. However, there are still certain instances where the systems do not offer any economic benefits and some where the system is not technically feasible to meet the electricity or heat demands. This imbalance of positive and negative economic benefits adds uncertainty into hybrid PVT systems. An analysis of the simple LCOE for different regions and applications will help to alleviate some of this uncertainty in situations where the technology would be beneficial as well as help solidify circumstances where PVT is not worthwhile to consider.

Review of Relevant Literature

The LCOE of the concentrating dish system discussed earlier was found to be less than that of a PV and battery system, with LCOEs of \$0.07-\$0.13/kWh [10]. The levelized cost of heat for the system, however, was found to be more than that of natural gas (\$0.07/kWh) but is still quite competitive, at \$0.09/kWh [10]. The present value of comprehensive energy price analysis for a flat-plate system in the Hunan Province, China, was found to be 0.293 CNY/kWh (\$0.043/kWh) with an assumed electricity cost growth rate of 3% and a base discount rate (capital cost reduction) of 10% [7]. Conventional CPVT and flat-plate technologies can only harvest electricity from PV and cogenerate low quality heat at best [24], whereas PVT with high-temp PV cells extends a number of possible applications, including electricity generation [9], and should certainly be investigated further. One of the greatest limitations to properly compare and contrast the different hybrid PVT solar systems is the wide variety of analysis methods used to determine value. In order to make worthwhile advancements in the implementation and commercialization of hybrid PVT technologies, a standard method of analysis needs to be established so investors can truly understand the potential economic and environmental benefits of adopting hybrid systems.

Research Design

The design of the levelized cost analysis will be heavily dependent on the data produced from the climate and heat demand analyses. Heat energy produced at temperatures below that which is required for low-grade heating applications will be considered applicable only for preheating purposes, but will be treated the same as thermal outlet temperatures in the range for low-grade heating applications, in which the energy produced will be calculated as an energy savings equal to the cost of the energy source being replaced. That savings will then be levelized, assuming a 3% annual cost of energy increase, and incorporated into the levelized cost of energy. Each system will be assumed to have a lifetime of 25 years, which is consistent with that of many commercial photovoltaic and concentrating solar systems. The LCOE will be determined for two scenarios for each system. The total energy produced by the solar collector will be categorized as the potential LCOE, while the energy that is actually utilized will determine the actual LCOE for that system setup. The equations for the levelized cost and savings are:

$$LCOE = \frac{C_{TOTAL}}{E_{TOTAL}} \quad , \qquad \textit{Equation 10}$$

$$C_{TOTAL} = C_0 + A_{OM} \cdot n \quad , \qquad \textit{Equation 11}$$

where LCOE is the levelized cost of energy in $/kWh, C_{TOTAL} is the total lifetime cost of the system, C_0 is the initial capital cost, A_{OM} is the annual cost of operations and maintenance, n is the lifetime of the system (25 years), and E_{TOTAL} is the total energy, both electrical and thermal, saved over the life of the system, measured in kWh.

Expected Outcomes

It is anticipated that that the lowest LCOE for the hybrid PVT systems will be for the highest hot water demands in the hottest climates and for systems that have balanced combinations of electricity and low-grade heating applications. It is expected that competitive levelized cost, comparable to standard PV, will be obtained in PDX and SLC for special applications and only for summer seasons, and PVT in WY will only offer a feasible LCOE for high summer hot water demands.

Previous Design Approaches

There are not many well-known approaches to solving similar problems or achieving the same goals as this project. Much of the research involved with hybrid photovoltaic-thermal systems focuses on case studies for specific devices or applications, and does not perform a sweeping analysis to generate guidelines for those interested in pursuing hybrid PVT installations or retrofits. For example, economic analysis of for an indoor/outdoor swimming pool and a university building in Naples, Italy, suggests that incentive policies are necessary to improve economic profitability of hybrid PVT systems for those applications [6,7]. However, hybrid PVT systems for DHW applications demonstrated excellent economic potential in China [7], Cyprus [6], Greece [12], and India [25]. Much of the analyses within the literature regarding heat production also disregards any benefits from the heat produced if it did not meet all demands, but it is important to consider energy savings from preheating. An analysis of how PVT systems will be able to meet specific heat demands, or at least offer a savings, for different climates will help investors identify the feasibility of hybrid PVT for their particular needs. Now that design approaches have been established, setup of the modeling and analysis proceeds.

IV. Modeling and Analysis

The inputs used in the TRNSYS simulation come from the weather data and load profiles, while the output data is measured from the solar collector, thermal storage tank, and auxiliary heater. Figure 8 shows the simulation to be modelled, which is an adaptive redesign of the existing solar domestic hot water (SDHW) template within TRNSYS. A more simplified diagram of the simulation setup is illustrated in Figure 9. The PVT outlet fluid can be passed through a heat exchanger before entering the tank, creating a closed loop and allowing an antifreeze mixture in the case of colder climates. Another option is a low-speed circulation loop for cold temperatures to prevent freezing. The method for preventing freezing in colder climates is variable depending on the user. Added electrical costs or heat losses from the desired method can be applied to the results of this research ad-hoc. For this reason, a heat exchanger is not used in the simulation, as all locations are tested with the same system to maintain consistency. Water that is not needed immediately can be stored in a thermal tank, which for the purposes of the simulation will be overly sized and have no heat losses. Finally, an auxiliary (tankless) heater brings the temperature up to a desired level.

A reference heat exchanger determines the energy required to heat the fluid without preheating to calculate energy savings. A reference PVT collector with no fluid (no heat gain or cooling) is also included to determine the average cell temperature and electrical outputs of a standard PV panel for comparison. The inputs and outputs for the PVT collector used in the simulations (Type 50d) can be seen in Figure 10, of which fluid temperature, energy gain, electrical output, and average cell temperature are key points of interest.

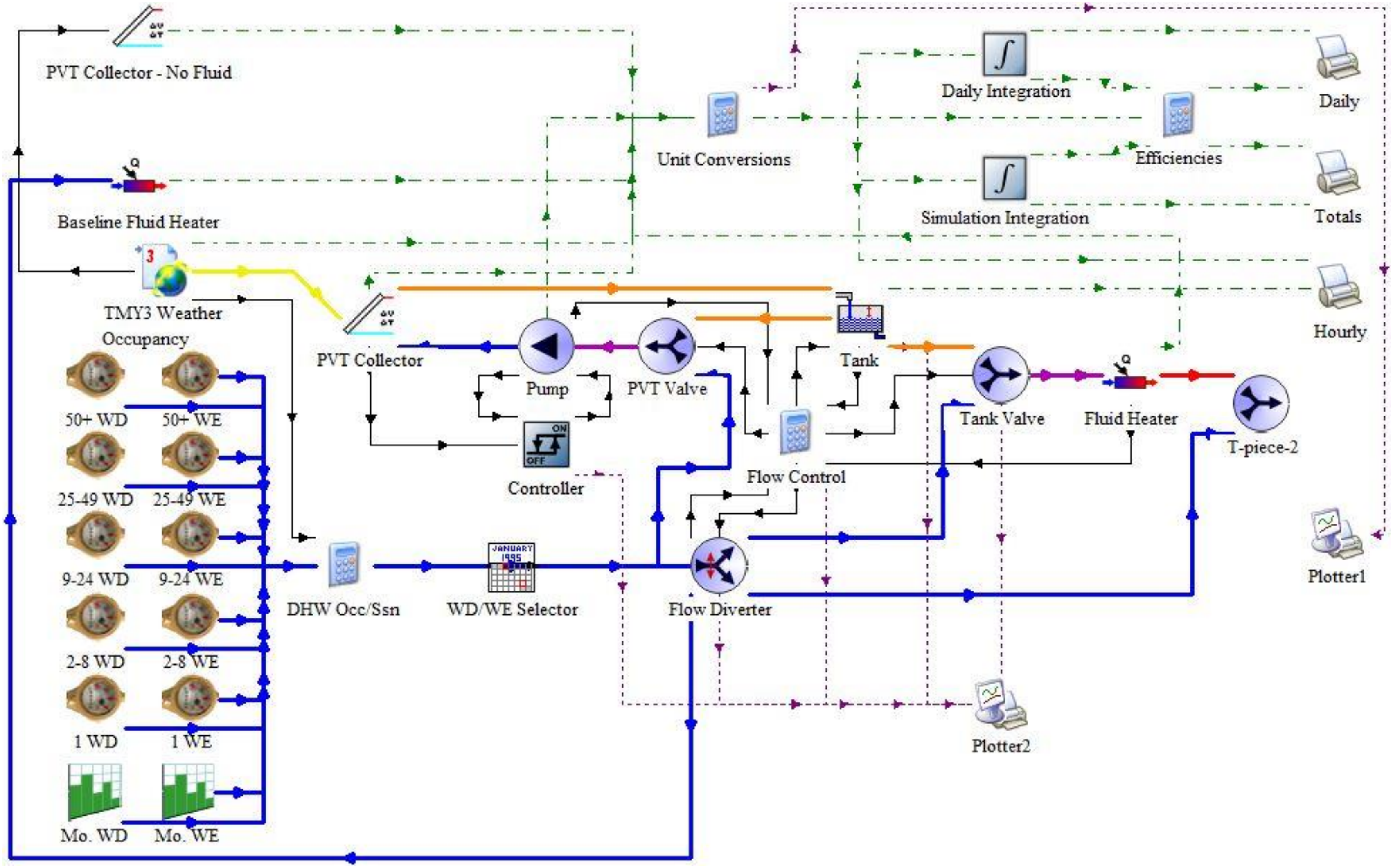


Figure 8. TRNSYS simulation model for residential DHW demand profiles.

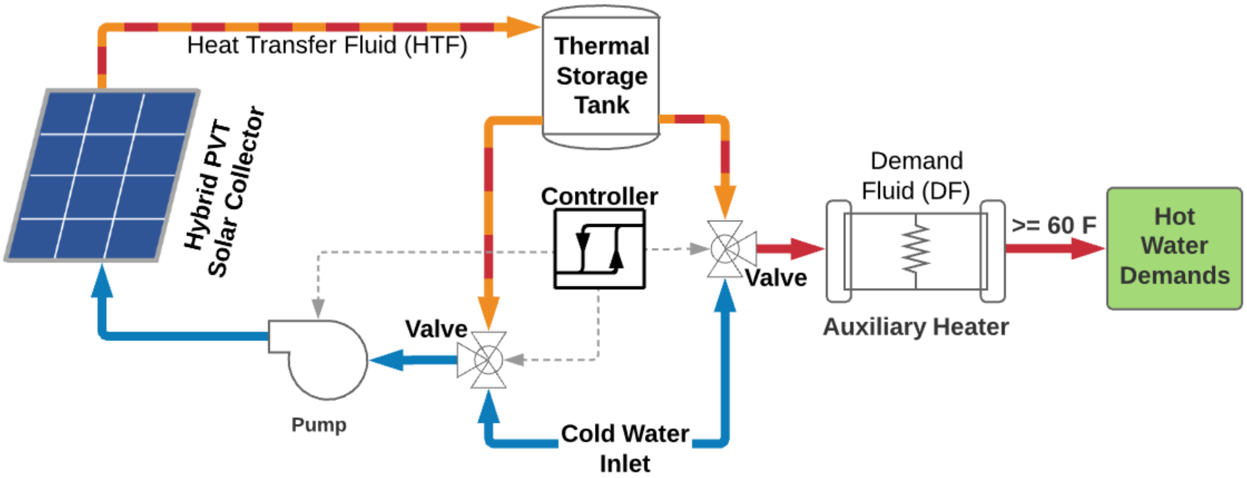
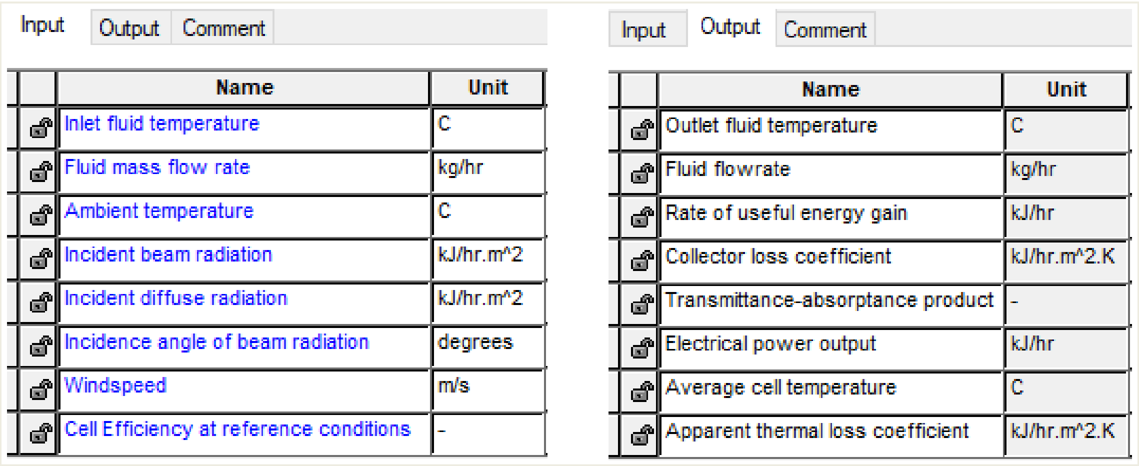


Figure 9. Simplified diagram of simulated PVT system.



Name	Unit
Inlet fluid temperature	C
Fluid mass flow rate	kg/hr
Ambient temperature	C
Incident beam radiation	kJ/hr.m^2
Incident diffuse radiation	kJ/hr.m^2
Incidence angle of beam radiation	degrees
Windspeed	m/s
Cell Efficiency at reference conditions	-

Name	Unit
Outlet fluid temperature	C
Fluid flowrate	kg/hr
Rate of useful energy gain	kJ/hr
Collector loss coefficient	kJ/hr.m^2.K
Transmittance-absorptance product	-
Electrical power output	kJ/hr
Average cell temperature	C
Apparent thermal loss coefficient	kJ/hr.m^2.K

Figure 10. Available inputs and outputs for the TRNSYS Type 50d hybrid solar collector.

Design Specifications and Constraints

Due to the myriad of variables that can affect the results of a hybrid photovoltaic-thermal system performance, certain specifications and constraints must be applied to maintain this research to a reasonable scope. Additionally, assumptions must be made for input temperatures, system sizes, tank size, hot water demand profiles, and flow rates. Some basic specifications and constraints are described in Table 1, while more detailed specifications and assumptions are discussed throughout this section. System simulations are categorized into residential and small commercial applications.

Table 1. Design Specifications, Constraints and Justifications

Specifications & Constraints	Justification
Unglazed flat-plate panel	Most common PV system on the market; easily adaptable.
Compared to standalone photovoltaic (PV) and thermal solar collectors (SC)	Most comparable to PV-only or SC-only systems due to their being the base design for the hybrid PVT collector.
Modules tested in series only	Parallel modules will produce same results assuming equal sun exposure and ambient temperatures.
$T_{out\_PVT} > T_{in\_PVT}$ = potential savings	Temperature increases to inlet of standard heating methods require less energy to reach desired output temperature.
Minimal heat energy wasted	Assuming water can be stored in lossless tank and used on demand; losses only due to full tank capacity.
No parasitic load for fluid pumps	Literature shows energy required for powering pumps is negligible compared to energy generated by the system.
T_{out} = 60°C (140° F) for Residential T_{out} = 80°C (176° F) for Commercial	60°C is a common setpoint temperature for residential DHW. 80°C is adequate for process loads beyond DHW.

Groundwater Temperatures

The temperature of groundwater fluctuates significantly throughout different regions of the United States unless drawn from deep wells. It is important to apply the proper groundwater temperatures for each location for accurate analysis of energy gained from the system. Inputting a colder inlet temperature than what realistically exists produces false results and superior simulated energy gains than what could be achieved in practice. Inlet temperatures for this work are extracted from a groundwater temperature map, courtesy of the Environmental Protection Agency (EPA) [31]. The map is shown with the tested locations designated in Figure 11. A more updated and accurate groundwater map can be found Chapter 10 of Mechanical and Electrical Equipment for Buildings [32], but is not necessary for the purposes of this research.

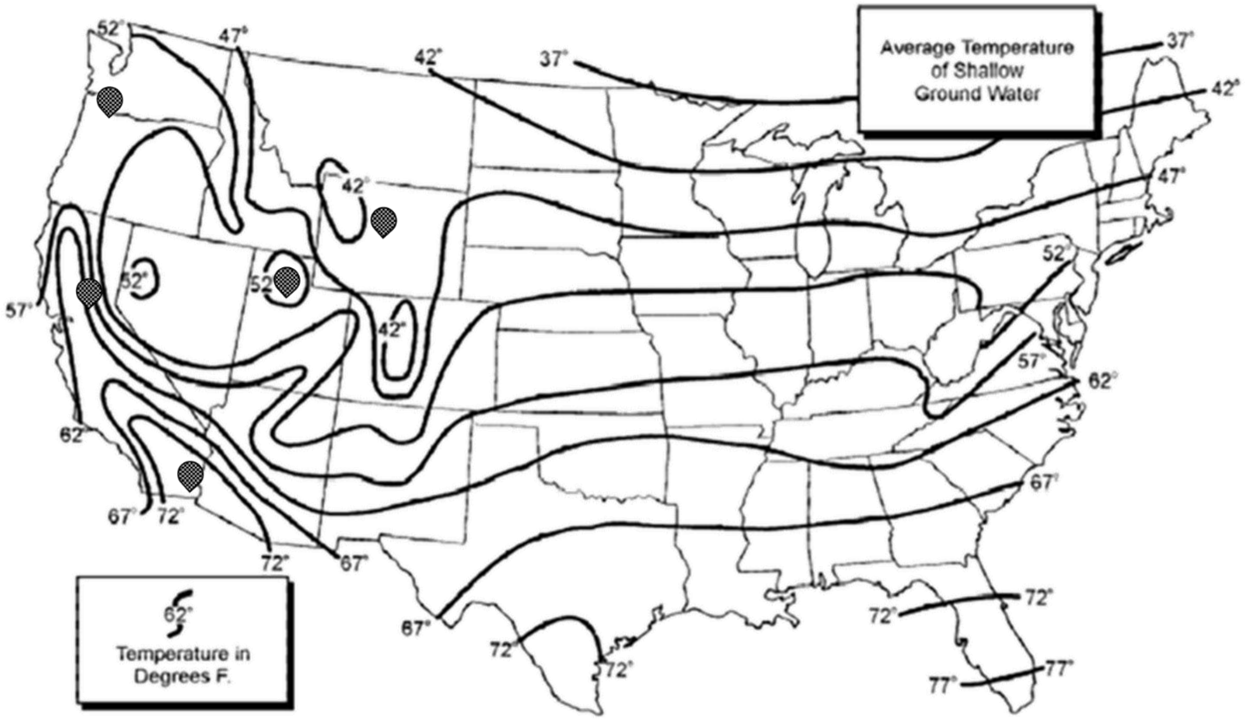


Figure 11. Groundwater temperature map, courtesy of the EPA, with simulated locations designated.

Commercial PVT Systems

The primary differences between the commercial and residential systems tested in this work are the system sizes and the hot water demand profiles, as a commercial PV installation would be much larger than that of residential.

System and Storage Tank Sizes

Five system sizes were chosen for commercial simulations based on the typical size of photovoltaic installations. Since this study focuses on small commercial and industrial systems, the maximum size tested for commercial applications is 200 kilowatts (kW), which matches the baseline commercial systems tested in NREL's PV system benchmarking. The solar cell efficiency used for commercial systems at nominal temperature (25°C) is 17.5%, as that was found to be the average efficiency for commercial panels in benchmarking [33]. System sizes were tested for 10 kW, 25 kW, 50 kW, 100 kW, and 200 kW. The physical sizes of the collectors were then determined by using data for the selected efficiency and standard PV panel sizes.

The standard size for commercial photovoltaic panels are 39” wide by 77” tall [34, 35], which is approximately 20.9 ft^2 (1.94 m^2) per panel. At an efficiency of 17.5%, the maximum power output from the panel is 339 watts (W), which is then rounded to 350 W for the simulation parameters. The number of panels required to achieve the total system size is determined, which is then multiplied by the area per panel to get the total collector area for the PVT system. The thermal storage tank size, for commercial applications, is based on the collector size and is set at one cubic meter (264 gal.) per kW of system size, capping at 100 m^3. These tank sizes were chosen somewhat arbitrarily for intentional oversizing to allow for proper sizing analysis of the tank based on hot water demands.

Hot Water Demand Profiles

The hot water demand profiles vary substantially from the residential to the commercial simulations. Residential load profiles are quite complicated, but the profiles for commercial demand are much more simplistic and assumed to be constant from seven o’clock in the morning to eleven o’clock at night (16 hours) every day of the year. Holidays were not accounted for, but the difference would be negligible, as there are approximately only eight US holidays per year. The tested flow rates for the demand fluid (DF) (i.e. at the tap) are dependent on the baseline flow rate of the heat transfer fluid (HTF) through the collectors. To simulate varying demands, four different DF flow rates are tested for each system size. The four DF flow rates for the hours of operation are scaling factors (0.25, 0.5, 1, and 2) multiplied by the HTF flow rate through the collector, which will be discussed in more detail. As highlighted in Table 1, the output temperature for the auxiliary heater is set to 80°C (176°F) for commercial applications.

Fluid Flow Rates

The optimum HTF flow rates of thermal solar collectors for hot water applications has been found to be in the range of 0.2 to 0.4 kg/min per square meter (m^2) of solar collector area, with the lower end of that window providing better results for high heat applications [36, 37]. For active solar space heating applications, a much higher flow rate has been established [32], as temperatures drastically higher than the human comfort zone are not desirable. The advantages of faster flow rates for space-heating applications, regarding hybrid PVT, would be lower cell temperatures and superior electrical efficiency with the trade-off of lower fluid output temperatures. For this research, however, a constant HTF flow rate of 0.2 kg/min/m^2 was chosen for commercial systems. The system specifications for commercial TRNSYS simulations are provided in Table 2. Residential systems have many similarities with commercial systems, but there are also some important distinctions.

Table 2. System specifications for commercial TRNSYS simulations.

kW	**# of Panels**	**Collector Area [m^2]**	**Tank Vol. [m^3]**	**Tank Vol. [gal]**	**HTF Flow [kg/h]**	**HTF Flow [kg/min]**	**HTF Flow [gal/min]**
10	29	56.2	10	2642	674	11.2	2.97
25	72	139.5	25	6604	1674	27.9	7.37
50	143	277.1	50	13209	3325	55.4	14.64
100	286	554.1	100	26417	6649	110.8	29.28
200	572	1108.2	100	26417	13298	221.6	58.55

Residential PVT Systems

The schematic design for residential applications, as seen in Figure 8, consists of all the same components as the commercial simulations except for those comprising the DF load profiles. Residential systems were sized and fluid flow rates determined through two different methods, which will be discussed in the applicable sections.

System and Storage Tank Sizes

The first method for sizing the residential systems arose from a somewhat erroneous assumption. While the results generated from this assumption are still valid, the systems tested are unlikely to be deployed in practical applications. As with the commercial systems, a variety of common system sizes were established, and the assumption was that all panels in the array would consist of hybrid PVT collectors. This resulted in a significant oversizing of the entire system compared to US Department of Energy guidelines for sizing solar water heaters [38]. Nevertheless, the resulting simulation data still provides some pertinent information for extreme scenarios. Four different system sizes were chosen based on a five-kilowatt average size for residential PV installations in the United States [33, 39] adjusting for different occupancy levels. The four systems sizes tested are 3 kW, 5 kW, 10 kW, and 20 kW.

The second method for sizing the residential PVT systems is based on the average flow rates of the DHW demand profiles and the occupancy of the building. The first method sized the PVT system to align with typical PV installation sizes and occupancies, whereas this second method sizes the PVT system to align with typical solar water heater sizes relative to occupancy. An optimum flow rate of 0.225 kg/min/m^2, established through model validation and discussed in Section V, was used to determine the correct system sizing. This second method applies a bottom-up approach in which the demand profiles determine the baseline HTF flow rate, which then governs the sizing of the system from the optimum flow rate. The four system sizes considered for this second method are 275 W, 550 W, 1100 W, and 2200 W, which consist of one, two, four, and eight hybrid PVT panels, respectively.

The standard size for residential photovoltaic panels are 39” wide by 65” tall [34, 35], which is approximately 17.6 ft^2 (1.64 m^2) per panel. At an efficiency of 16.2%, the maximum power output from the panel is 265 W, which is then rounded to 275 W to represent a realistic panel for the simulation parameters. For the first method, the number of panels required to achieve the total system size is determined then multiplied by the panel area to get the total collector area for the PVT system. For the second method, however, the total area is determined first, then the number of panels required to achieve that area is calculated. The thermal storage tank sizes, for residential applications, are based on the collector size and set at 0.4 m^3 (106 gal.) per kW (rounded to the nearest m^3), for the first method, and 1.0 m^3 per panel (275 W) for the second method. Akin to the commercial systems, the tank sizes were chosen rather arbitrarily for intentional oversizing to allow for proper tank sizing analysis based on DHW demands.

Domestic Hot Water Demand Profiles

The hot water demand profiles for residential applications are quite a bit more erratic that those of commercial applications. Due to the nature of the workaday world, residential DHW demands have drastic peaks in consumption in the mornings and evenings with periods of lull throughout the remainder of the day. It is also important to note that weekend behavior may vary slightly from weekday behavior, as residents are not going to and from work at the same times of day. Ahmed et. al [40] performed a study of DHW demands based on varying levels of occupancy in Finnish residential buildings, which produced results for hourly demand profiles for weekdays and weekends for each tier of occupancy. A baseload demand profile for each tier was established, then a multiplier is applied for each month of the year to account for the different seasons. The baseline DHW demand data derived from [40] is presented in Figure 12 and Figure 13 for weekday (WD) and weekend (WE) consumption, respectively, and the monthly multiplication factors are listed in . The average demand for WD and WE use is nearly the same, but the WE morning activity shifts later than that of the WD by approximately three hours. Ahmed et. al noted that demand rates in the United States are much higher than in Finland, which is corroborated by the American Society of Plumbing Engineers (ASPE) in their CEU 221 report [41]. A multiplication factor of 2.5 is applied to the derived baseline DHW demands to more accurately align with the average daily per-person demand for medium usage US households presented by the ASPE [41]. With the baseline profiles for weekdays and weekends established, the flow rates for each system setup can be computed. The auxiliary output temperature for residential systems is set to 60°C (140°F), as highlighted in Table 1.

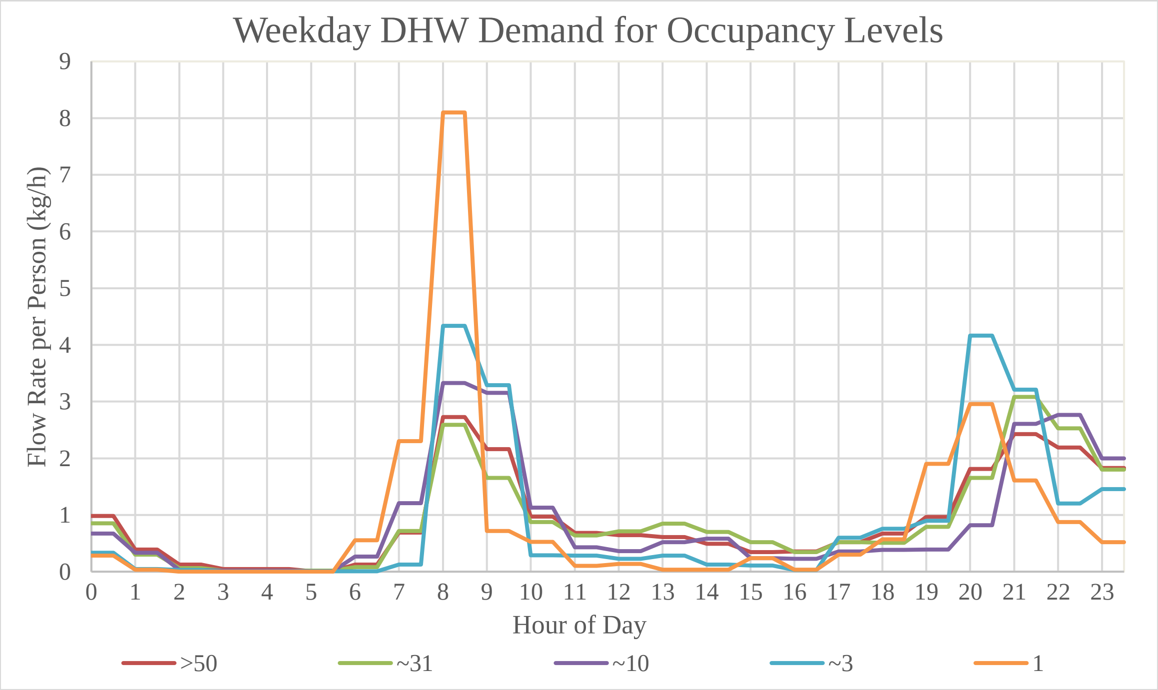


Figure 12. Weekday domestic hot water demands for varying occupancy levels derived from [40].

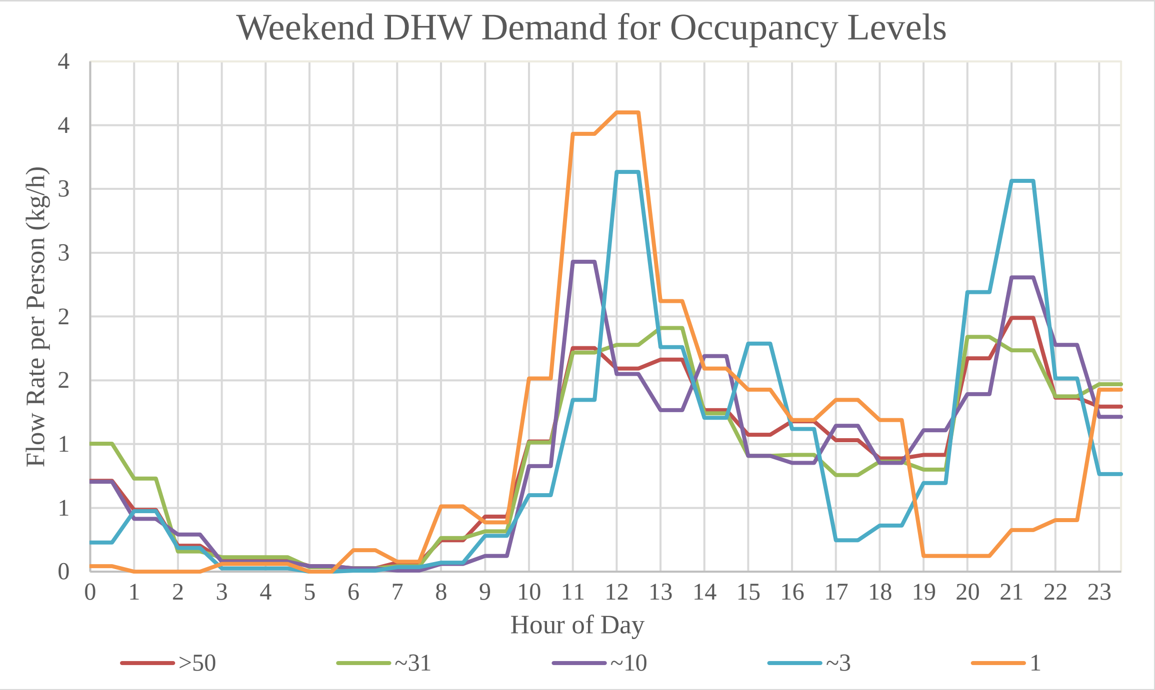


Figure 13. Weekend domestic hot water demands for varying occupancy levels derived from [40].

Fluid Flow Rates

Table 3. DHW Multiplication Factors [40]

Month	**Weekday**	**Weekend**
January	1.119	1.067
February	1.119	1.067
March	1.049	1.017
April	1.020	1.062
May	0.999	1.023
June	0.941	1.062
July	0.912	0.860
August	0.892	0.845
September	0.964	0.964
October	0.982	0.940
November	0.987	0.961
December	1.100	1.136

The flow rates for the two methods of residential system sizing are both based upon the DHW demand profiles. For the first method (oversized systems), the HTF flow rate varies with the DF flow rate. The average peak DF flow rate was determined to be approximately 3.5 kg/hour per person. That value was doubled and applied to each occupancy tested. For the first method, the speed of the pump is 7 kg/h (0.12 kg/min) per person.

For the second method, the HTF flow rates are still determined by the DHW demand but are based upon the average demand and do not change for every occupancy setting. The average demand for DHW was calculated to be approximately 0.90 kg/h per person. That value was multiplied by 2.5 to account for US consumption, then doubled to produce an HTF flow rate twice the average DF flow, which works out to approximately 4.5 kg/h (0.075 kg/min) per person. As discussed previously, this second method is a bottom-up system sizing process in which the size of the system is determined by the domestic hot water demands. The four system sizes were each calculated from the HTF flow rate for a central occupancy value (5, 10, 20, and 40 occupants). Two occupancy settings above and below each central occupancy value are simulated with the constant system size and HTF flow rate, only altering the demand fluid (DF) flow rate and testing five different DHW demands for each system. The various system sizes, occupancy levels, and heat transfer fluid flow rates simulated for residential system for each of the five locations are provided in Table 4.

Table 4. System specifications for residential system simulations.

Method 1											
Size [W]	**Occ**	**HTF [kg/h]**	**Size [W]**	**Occ**	**HTF [kg/h]**	**Size [W]**	**Occ**	**HTF [kg/h]**	**Size [W]**	**Occ**	**HTF [kg/h]**
3000	2	14	5000	2	14	10000	2	14	20000	5	35
	3	21		5	35		5	35		10	69
	5	35		10	69		10	69		20	139
	8	55		15	104		20	139		35	242
	12	83		20	139		30	208		50	346
Method 2											
Size [W]	**Occ**	**HTF [kg/h]**	**Size [W]**	**Occ**	**HTF [kg/h]**	**Size [W]**	**Occ**	**HTF [kg/h]**	**Size [W]**	**Occ**	**HTF [kg/h]**
275	2	22.5	550	3	45	1100	5	90	2200	10	180
	3			5			10			20	
	5			10			20			40	
	8			15			35			70	
	12			25			50			100	

Control Schemes

The control schemes used in this research, while not part of the scope of this work, were setup to prevent wasted energy, and are discussed in this section to offer the reader a deeper understanding of how the simulations behaved. Control methods are an extremely important variable in the operation and performance of all types of solar systems, specifically active solar thermal systems with a heat transfer fluid. While highest possible efficiency of the hybrid photovoltaic-thermal collectors may not be achieved, the control methods utilized in this research should help to optimize the percentage of the load satisfied by the PVT system, thus maximizing the economic benefits. As mentioned in Section I, the production of additional energy is useless if the energy is wasted. Referring to Figure 8, the four components of the system that require automated control are the pump, PVT valve, tank valve, and flow diverter.

Flow Diverter

The flow diverter is dependent upon the T-piece at the outlet of the fluid heater, which represents a user controlled outlet valve, such as a faucet. In the event of temperatures from the storage tank being higher than the auxiliary heater setpoints for the respective system type, the flow diverter (i.e. user) will send the necessary portion of cold water to mix with the hot water and produce the desired temperature. The control scheme for the flow diverter only exists in the simulation and would not be a physical component in practical applications, as the user would manually control said flow at the tap. The pump, PVT valve, and tank valve, however, would need to be physical components in a real system that would need to be controlled.

Collector Pump

The control methods for the PVT system components are simplistic and only digital output signals. The pump is single speed and operated through an ON/OFF controller that reads the temperature differential between the collector average cell temperature and inlet fluid temperature. The controller implements hysteresis, with a temperature deadband in which the control will not change states. The pump will always be on when the average cell temperature minus the inlet fluid temperature (ΔT) is at least 10°C (18°F), and it will always be off when ΔT is less than 5°C (9°F). From within the deadband (5°C ≤ ΔT ≤ 10°C), the pump will only change states if the temperature delta exits the deadband in the direction opposite of its current state of operation. This implements hysteresis, preventing the pump from rapidly toggling on and off when the ΔT fluctuates around the upper or lower threshold. The ΔT for the pump control is dependent on the source of the fluid sent to the collector, whether it be from the ground or recirculated from the tank.

Recirculation Valve

To avoid wasting energy produced, the PVT valve is setup to close the loop between the PVT collector and the thermal storage tank, recirculating the fluid from the tank back through the PVT collector in the event the tank is full. The loop will close whenever the tank is full, but flow will only continue if a 10+°C ΔT still persists between the average cell temperature and the mixed tank temperature, which becomes the new inlet temperature on such an occasion. The control for the PVT valve is crude but effective. If the tank is full, the valve closes the loop to recirculate fluid. Any time the tank is anything less than full, the PVT opens the loop to pull water from the ground source. The final component requiring control methods is the tank valve.

Auxiliary Heater Control Valve

The tank valve in Figure 8 functions in virtually the exact opposite way as the PVT valve. The tank valve controls whether the fluid entering the auxiliary heater is drawn from the ground source or from the thermal storage tank. The total amount of flow through the tank valve is determined by demand and the flow diverter (user), but the control scheme decides the source of said flow. Just like the PVT valve, the tank valve is either fully-open or fully-closed, meaning flow is drawn entirely from one source (input) or the other, but not both simultaneously. The tank valve is also dependent on the level of the tank, but is concerned with whether the tank is empty instead of full. If the storage tank is empty, the tank valve will draw its full flow from the ground source. If the tank is anything other than completely empty, however, demand flow will draw from the tank before entering the auxiliary heater, thus providing preheating savings.

It is important to note again that control methods are not within the scope of this research, and the preceding information was discussed strictly for the purposes of clarity and repeatability.

Economic Analysis

To ascertain the economic feasibility of each system tested, multiple forms of cost-benefit analysis are performed. A combination of simple and complex economic analysis is performed to provide a more encompassing report on the costs and benefits of hybrid photovoltaic-thermal systems.

Simple Economic Analysis

The levelized cost of energy is a standard measurement for the price of energy for a multitude of different sources. The LCOE for electrical energy produced will be considered in dollars per kilowatt-hour ($/kWh), whereas levelized cost of heat (LCOH) for heat energy produced will be accounted for with the assumption that the fuel replaced is natural gas. The LCOH will be converted into $/kWh for proper comparison. For replacement of natural gas, the LCOH will be calculated in dollars per therm ($/therm), where one therm is equal to 100,000 British thermal units (Btu). For total LCOE of the system, the LCOH will be converted to $/kWh, if necessary, and aggregated with the electrical LCOE.

In addition to how much the energy produced by the system will cost, it is also important to assess how long it will take to recover the investment capital. Calculations for levelized cost of energy will be accompanied by a simple payback period (SPP) analysis, shown below.

$$SPP = \frac{C_0}{A_S - A_{OM}} \quad . \qquad \textit{Equation 12}$$

where SPP is the time (in years) to recover system costs, C0 is the initial system cost, AS is the annual savings, and AOM is the annual O&M costs. The average prices of energy in the United States are $0.138/kWh for electricity and $1.024/therm for natural gas, according to the Bureau of Labor Statistics (BLS) [42]. These prices will be used to determine the potential and actual energy savings generated by each system tested.

There are numerous weaknesses inherent in an LCOE analysis, such as a lack of distinction between capital, marginal, and O&M costs, uncertainty in the assumptions used for analysis, and perhaps most importantly, the volatility of energy prices. An LCOE generally assumes one cost for energy during the entire lifecycle, perhaps with an inflation rate applied to account for annual increases, but energy prices can be volatile within short timeframes. A prime example is the seasonal effect, in which energy is generally more expensive during the summer months due to greater demands. As an industry standard, LCOE is used quite frequently, and it is used in this research for easier comparability. However, due to the weaknesses discussed, more complex methods of analysis are also performed, as to not rely solely on LCOE.

Complex Economic Analysis

LCOE and SPP analyses are both simplistic methods that do not account for the time value of money (TVoM). More complex analysis is often necessary to gain the confidence of financiers in the realistic benefits of a potential investment. Two of the most common economic analysis methods in most industries, which are performed for the systems in this research, are the net present value (NPV) and internal rate of return (IRR) of the proposed investment. The net present value will determine the value of the investment based on a specific interest rate for borrowed money. LCOE, NPV and IRR analyses will both be performed for different installation scenarios. For example, if building is new construction or the hot water heating system is already planned for replacement, the installation costs can be omitted from the analysis as a sunk cost that will be spent even if PVT is not installed. It is important to note that the entire installation cost is not omitted in this scenario, as the full cost of installing the PV array is still applied. The net present value is calculated as,

$$NPV = \left(A_S - A_{OM} \right) \cdot \frac{(1+i)^n - 1}{i(1+r)^n} - C_0 \qquad \textit{Equation 13}$$

where *AS* - *AOM* is the annual savings minus annual O&M costs, i is the inflation rate applied to the cost of energy, *r* is the interest rate on debt, n is the life of the system in years, and C_0 is the initial capital cost of the system. The method determines the future value of the annual savings of energy based on the inflation rate, which is set at 2.5% to align with NREL benchmarking [33]. That future value is then used to determine the effective annual savings relative to the interest rate on debt, which is then used to calculate the present value of the system. The interest rate for commercial systems is slightly lower than for residential systems, consistent with benchmarking [33]. All systems are assumed to have a lifecycle of 25 years, which is industry standard for photovoltaic panels and easily accomplished for solar collectors with proper maintenance.

The internal rate of return (IRR) analysis is an iterative process that repeatedly applies a new interest rate (*i*) to Equation 13 until it a NPV of zero is achieved. This method of analysis determines the maximum interest rate on loans acceptable to break even on the investment.

Capital, Operations and Maintenance Costs

Capital, operations and maintenance (O&M) costs for photovoltaic systems are well established, as the PV industry has significantly grown over the past few decades. The costs used in this analysis for the PV part of the hybrid PVT systems are coordinated with the pricing determined in the NREL PV benchmarking [33]. Thermal solar collector costs are not as well established in industry, though. The pricing used for the thermal aspect of the hybrid PVT systems is derived from multiple sources. The total cost to install residential solar water heating systems in the US, including all components, ranges from about $2000 to $5500 [43-45], and cost for flat-plate thermal collector panels of similar size to standard PV averages approximately $550 per panel [46-50]. O&M costs for solar thermal have been estimated at 1-3% of the installation cost per year [51-53]. The cost of installation for PV is a much smaller portion of the initial capital costs than for that of a solar collector system.

Cost and economies of scale are assumed based on pricing data available. Assumed costs for each system size are broken down in Table 5, in which the installation cost for PV is encompassed in the per unit price. The economic analyses of the systems tested do not include any incentives, as they are subject to change by region and bureaucratic processes. Immediate discount incentive amounts can simply be added to the NPV of the system.

Table 5. System cost breakdown used for economic analysis.

System Size [W]	**Standalone PV**		**Thermal Solar Collector**			**Hybrid PVT**			**TVoM**
	[$/W]	**[$/yr]**	**[$/W]**	**[$/Install]**	**[$/yr]**	**[$/W]**	**[$/Install]**	**[$/yr]**	**r**
275	$2.80	$6	$2.00	$1,500	$62	$4.80	$900	$64	4.8%
550	$2.80	$12	$2.00	$1,600	$81	$4.80	$960	$86	4.8%
1100	$2.80	$23	$2.00	$1,700	$117	$4.80	$1,020	$126	4.8%
2200	$2.80	$46	$2.00	$1,900	$189	$4.80	$1,140	$207	4.8%
3000	$2.80	$63	$1.80	$2,150	$227	$4.60	$1,290	$252	4.8%
5000	$2.80	$105	$1.65	$2,500	$323	$4.45	$1,500	$365	4.8%
10000	$2.66	$210	$1.57	$4,000	$590	$4.23	$2,400	$674	4.8%
20000	$2.54	$300	$1.49	$6,600	$728	$4.03	$3,960	$848	4.5%
25000	$2.51	$375	$1.41	$8,250	$872	$3.92	$4,950	$1,022	4.5%
50000	$2.30	$750	$1.34	$16,000	$1,664	$3.64	$9,600	$1,964	4.5%
100000	$2.03	$1,500	$1.28	$25,000	$3,053	$3.31	$15,000	$3,653	4.5%
200000	$1.85	$3,000	$1.21	$40,000	$5,652	$3.06	$24,000	$6,852	4.5%

V. Results and Discussion

For the five different locations, systems types, and various hot water demand profiles, 300 total simulations were performed. The detailed breakdown of the performance of each system tested can be found in Appendix A, while the breakdown of the economic analysis for each system can be found in Appendix B, in which the solar energy systems are analyzed both with the cost of installation and without the installation costs. The installation consists of a substantial portion of the cost of the system. However, in the event of a new construction or water heater replacement already planned, those costs would not be considered as additional capital investment above the cost of the panels, as that investment would need to be made whether choosing solar or not. The only difference in the cost would that to install a pipe from the solar collectors to the water heater system, which would amount to a negligible marginal cost when installation crews are already on-site installing solar panels and a new hot water heater system. To maintain confidence in the results of the simulation, the model setup for this research must be validated.

Validation of Model

The TRNSYS simulation software has been demonstrated in the past to accurately align with experimental results for solar domestic hot water systems [12, 54-57]. The variations between the experimentally validated systems and the simulations created for this research are scarce. In fact, the template is nearly identical with only a few components altered to offer flexibility for simulating numerous system sizes and DHW profiles. The only significant difference is that a combination solar storage tank with a heat exchanger and heating coil built-in, used in most of the experimentally validated systems, were separated into a storage tank and an auxiliary heater. Although the simulations in this research are setup using as much real-world data as possible, the fact that minor variations have been made from previously validated templates necessitates the future experimental validation of the system in this research. Such experimental validations are beyond the scope of this work, but will be necessary in the future to be fully confident in, and to calibrate the results of, the simulation models in this work.

Without experimental validation, it is imperative to verify the settings model for this research to ensure a reasonable system is being tested. Optimum HTF flow rates of thermal solar collectors for hot water applications have been found to be in the range of 0.2 to 0.4 kg/min/m^2 of solar collector area, with the lower end of that window providing better results for high heat applications [36, 37]. To verify the reasonableness of the model setup, a single PVT collector was tested with an area of one m^2, with a constant ambient temperature of 25°C, inlet of 15°C, and constant irradiance of 1000 W/m^2. The flow rate of the collector was gradually increased from 0.0-2.0 kg/min/m^2 to determine where optimum flow rates are for heat transfer and electrical efficiency. If the software behaves as expected, the optimum flow should range from 0.2-0.4 kg/min/m^2. Model verification was successful, as can be seen in Figure 14 and Figure 15.

The model verified that the optimum flow rate for the PVT collector is exactly in the range of 0.2-0.4 kg/min/m^2. The difference between the HTF and PV average temperatures flattens out at 0.225 kg/min/m^2, at which point 80% of total possible energy gains are achieved, while almost double that rate (0.43 kg/min/m^2) is required to attain 90% energy gains. The greatest temperature difference between the HTF and PV cells occurs at 0.06 kg/min/m^2.

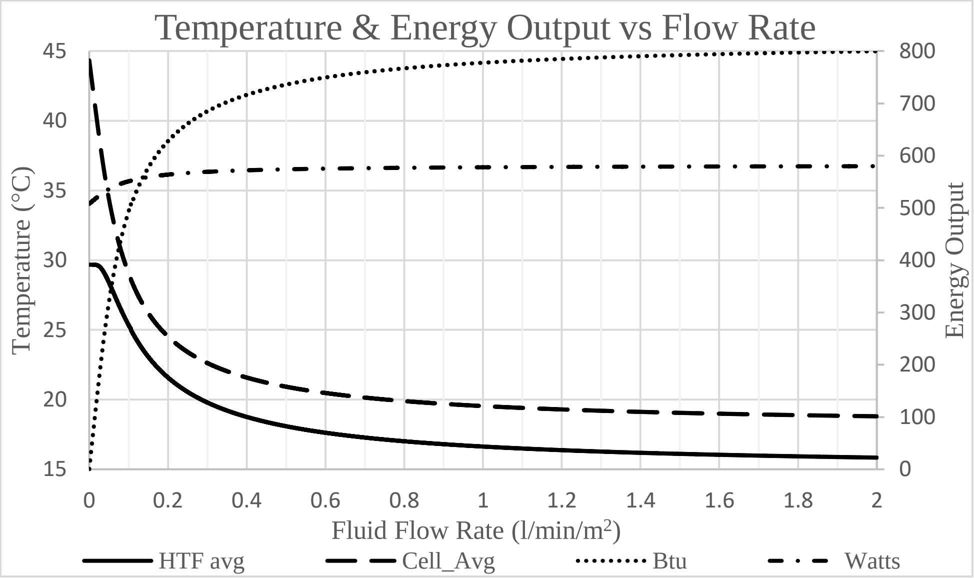


Figure 14. Temperature and energy output versus fluid flow rate.

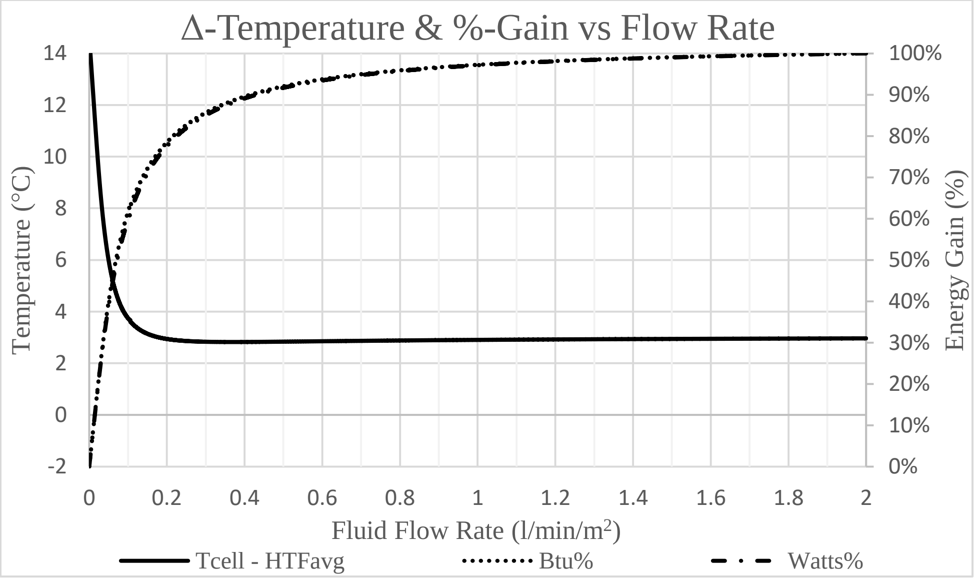


Figure 15. Percent of efficiency gains versus fluid flow rate.

In addition to verifying the optimization of the collector flow rates, a sensitivity analysis was performed by slightly altering various inputs and parameters in the simulation and post simulation analysis, assessing the results for drastic changes. A 275W (1 panel) system was selected for Sacramento, California, for three and five occupants for the sensitivity analysis. Small variations were made, independently, to the ambient temperature (+/- 2.5°C), solar irradiance (+/- 2%), groundwater temperature (+/- 1°C), temperature difference to activate the pump (+/- 2°C), and the cost of energy (+/- 2%). The IRR analysis gives an impression of interest rate sensitivity, indicating the amount the interest rate can fluctuate while remaining economically feasible, or what reduction is required to become feasible. The detailed results from the sensitivity analysis can be found in Appendix C. In reviewing the results of sensitivity, there were no significant changes resulting from small changes in the parameters. Systems that had a small base case NPV (+/- $100) did not experience drastic enough changes to alter the economics of the system from feasible to not feasible, or vice versa. The most sensitive data points are the flow rates through the PVT collector and the average demand flow rate relative to the collector flow. The combination of the micro-simulations, sensitivity studies, and similarities to models that have previously been experimentally validated offers some credence to the model designed in this research and validates that a reasonable model was chosen. This does not, however, eliminate the need for experimental validation of this research in the future.

Simulation Results

The performance and economic evaluation results vary quite dramatically between locations and system sizes. The temperature of the solar cells appears to be heavily dependent upon solar irradiance, despite the ambient temperature. Ambient temperature, however, serves as the baseline for cell temperature, as the cell temperature is never less than the ambient temperatures. As can be seen in Figure 16 – Figure 20, especially for Portland, Oregon and Riverton, Wyoming, there are noticeable drops in reference cell temperature when irradiance is decreased, such as on overcast days. Consistent data for each location that are independent of other variables are listed in Table 6.

It is important to note that the average values for temperatures, except for the temperature of the fluid in the tank, are calculated only during the hours of irradiance. The average volume of the storage tank is also determined by averaging the times when the tank is not empty. Temperatures outside irradiance hours or including the winter periods in which the tank is empty will provide skewed results for performance and system sizing. The cooling effect on the PV cells is quite significant, maintaining a delta of 20°C in winter and peaking at approximately 60°C during the summer months in all locations, even approaching 75°C in SLC.

The levelized cost of energy for solar collectors proved to be lower than that of PV systems, in most instances, and the levelized cost of energy for the hybrid photovoltaic-thermal system is lower than both the SC and PV independently. The relationship between the HTF flow rate and the total collector area is quite significant. In addition, the ratio of DF flow rates to HTF flow rates has a strong relationship to the average volume of the storage tank and the net present value per panel. Plots of these relationships and their respective equations are show in Figure 21 – Figure 23, and Equation 14 – Equation 16.

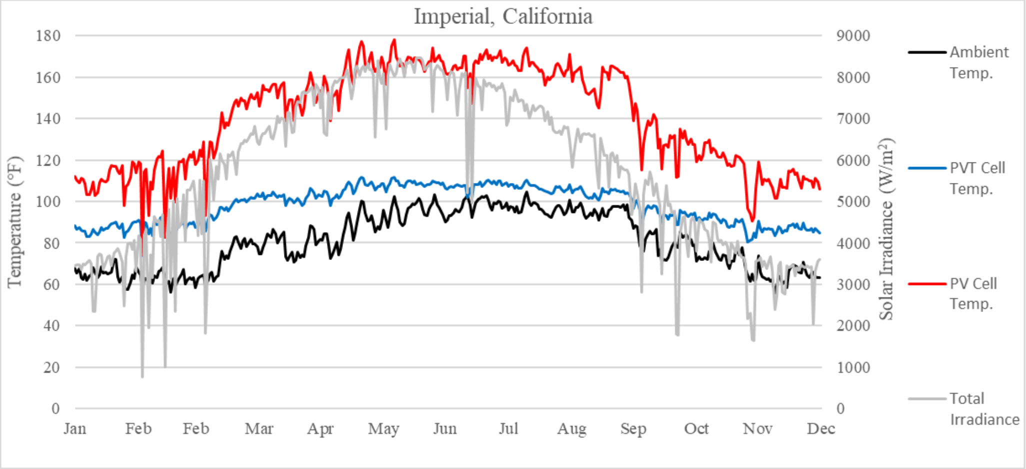


Figure 16. Daily average temperatures during irradiance for Imperial, California.

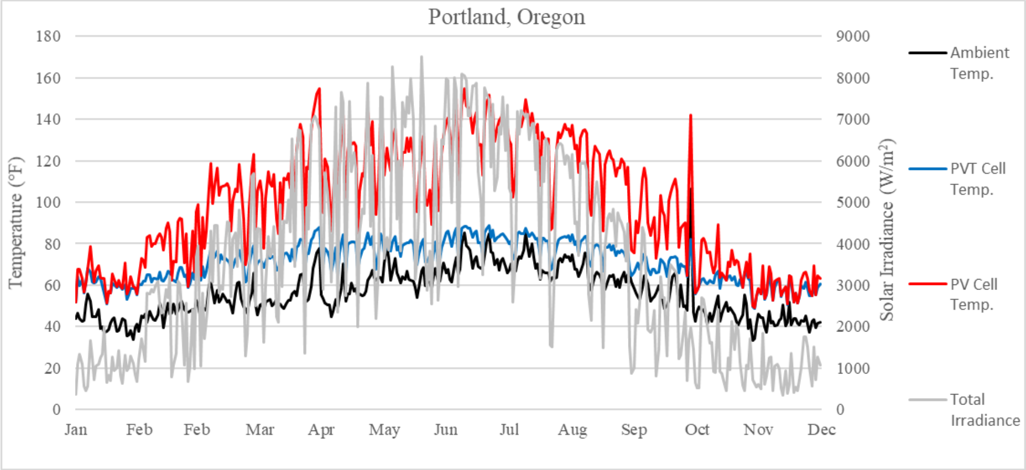


Figure 17. Daily average temperatures during irradiance for Portland, Oregon.

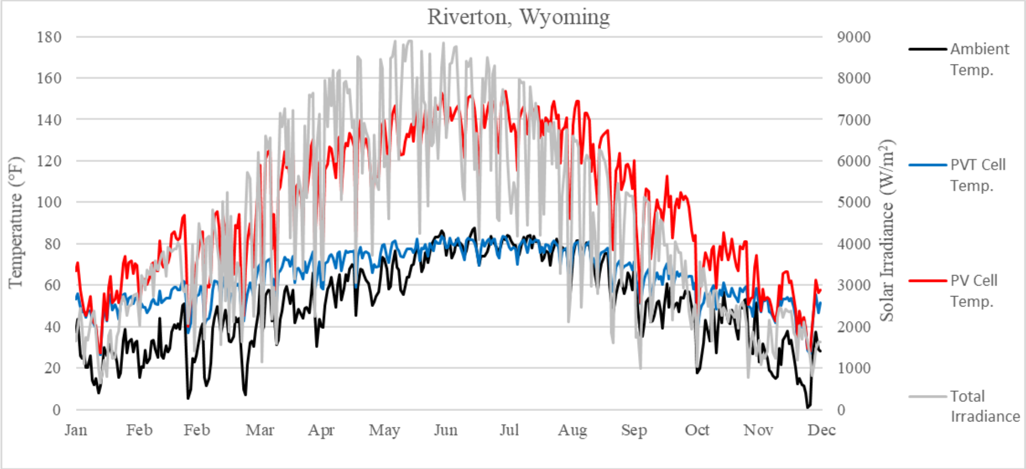


Figure 18. Daily average temperatures during irradiance for Riverton, Wyoming.

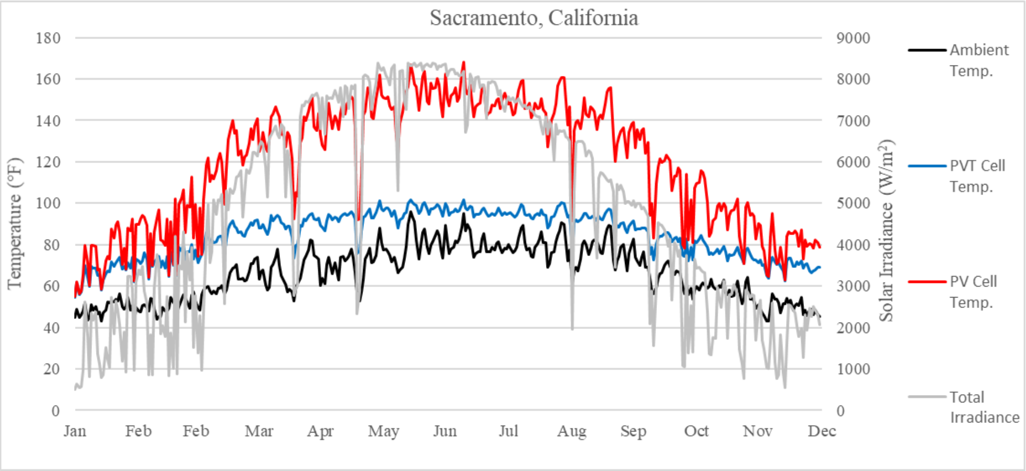


Figure 19. Daily average temperatures during irradiance for Sacramento, California.

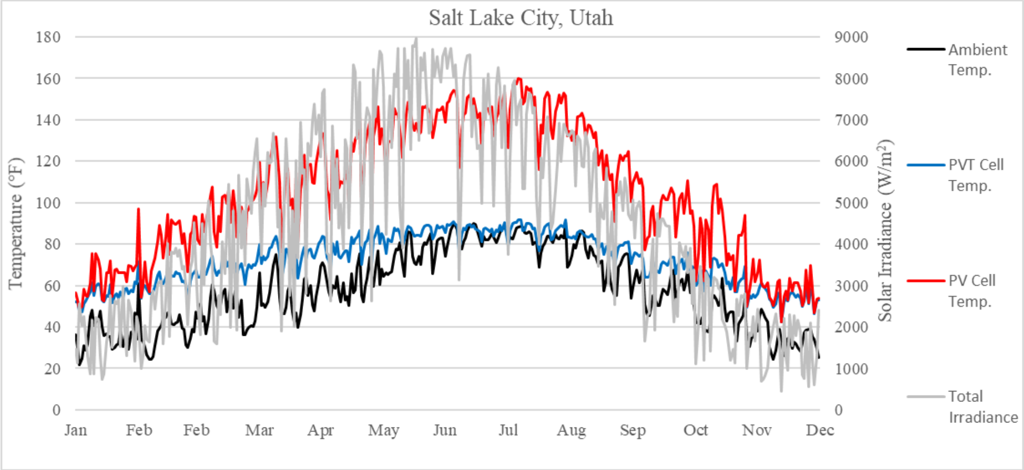


Figure 20. Daily average temperatures during irradiance for Salt Lake City, Utah.

Table 6. Simulation output data consistent for each location.

Loc.	Type	$T_{DB\text{-}AVG}$ [°C]	I_{TOTAL} [W/m^2]	I_{AVG} [W/m^2]	$T_{PV\text{-}AVG}$ [°C]	$T_{PV\text{-}MAX}$ [°C]	η_{PV}
IMP	Res	27.92	2093913	495.8	62.40	112.11	12.79%
IMP	Com	27.92	2093913	495.8	61.99	111.43	13.86%
PDX	Res	14.40	1303907	308.6	40.70	101.74	17.71%
PDX	Com	14.40	1303907	308.6	40.33	101.05	19.17%
WY	Res	12.01	1629377	384.3	40.36	100.03	15.70%
WY	Com	12.01	1629377	384.3	39.97	99.31	17.00%
SAC	Res	19.65	1792612	423.3	50.98	103.96	15.18%
SAC	Com	19.65	1792612	423.3	50.57	103.34	16.44%
SLC	Res	15.44	1641819	373.9	43.28	101.05	15.56%
SLC	Com	15.44	1641819	373.9	42.91	100.39	16.84%

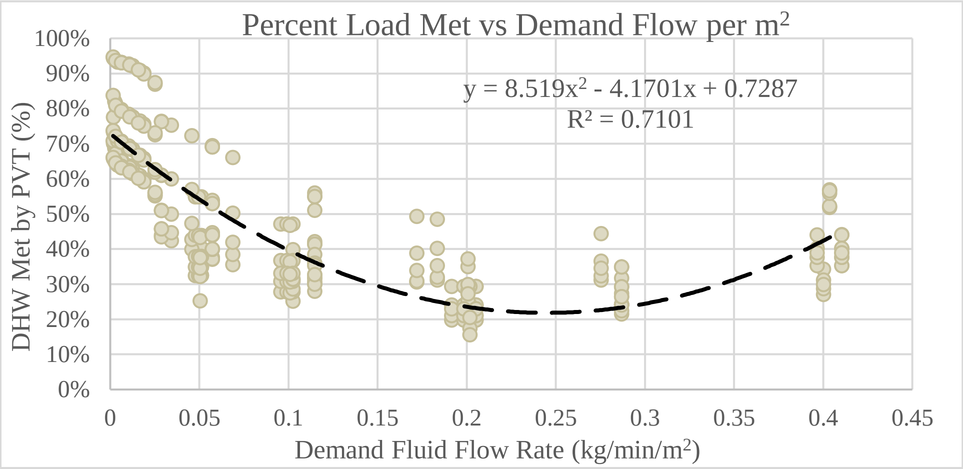


Figure 21. Load percentage met by PVT relative to demand flow.

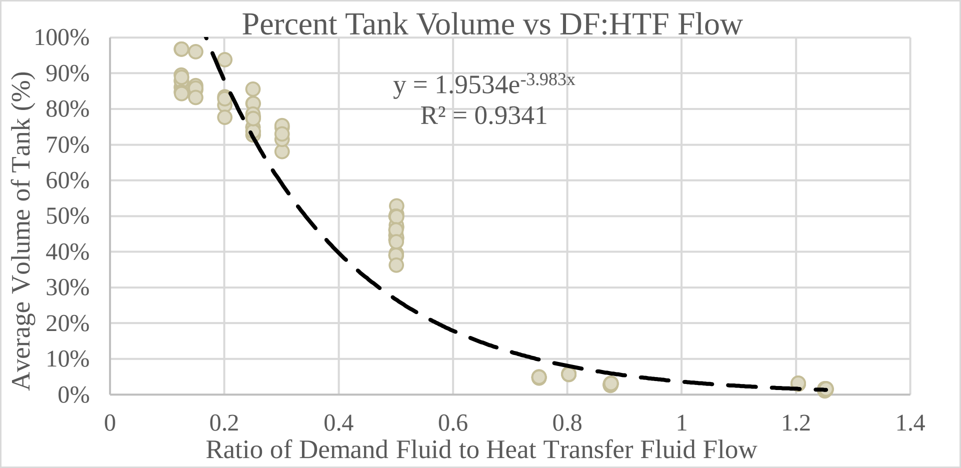


Figure 22. Average storage tank volume relative to ratio of demand to collector flow.

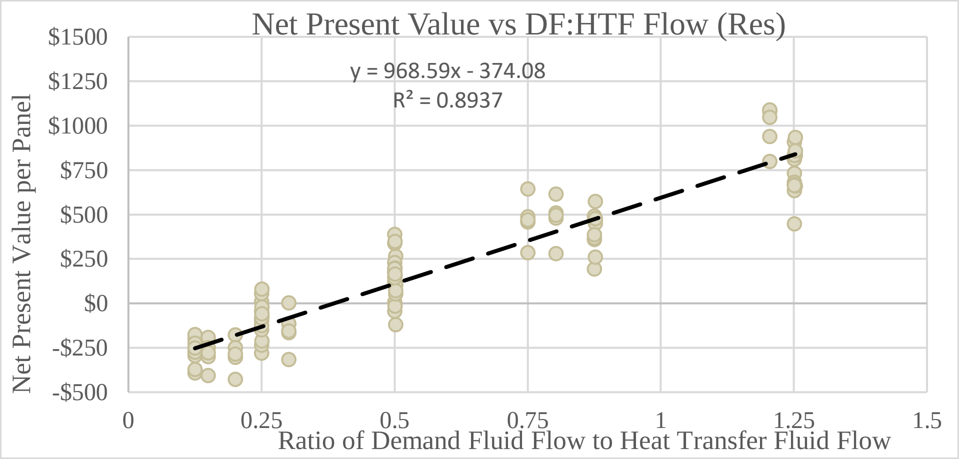


Figure 23. Net present value relative to ratio of demand to collector flow.

The equations for the trendlines in Figure 21 – Figure 23, can be used as rough guidelines to approximate size and economic benefits of hybrid PVT systems. The equations are as follows:

$$\%\mathrm{PVT} = 8.519\dot{m}^2 - 4.1701\dot{m} + 0.7287 \quad , \qquad \textit{Equation 14}$$

$$\%Vol_{AVG} = 1.9534 \cdot e^{-3.983x} \quad , \qquad \textit{Equation 15}$$

$$\mathrm{NPV}_{PANEL} = 968.59x - 374.08 \quad , \qquad \textit{Equation 16}$$

where %PVT is the percentage of the hot water heating load that is satisfied by the PVT system, $\dot{m}$ is the fluid mass flow rate in kg/min per square meter of solar collector, %VolAVG is the average volume of the storage tank during the hours it is not completely empty, NPVPANEL is the net present value of the system per panel (1.64m^2 for residential, 1.94m^2 for commercial), and x is the ratio of the demand fluid (DF) flow rate to the heat transfer fluid (HTF) flow rate. The coefficient of determination (R^2) is included with the trendlines to demonstrate how well the regression fits correlate to the real data. The coefficient of determination is calculated by summing the squared difference of the true y-value for a respective x (y[x]) from the value produced by the regression line (yreg[x]), then dividing that by the summed squares of the difference from the respective y-value (y[x]) and the average of all y-values (yavg[x]), such that

$$R^2 = 1 - \frac{\sum\left(y[x] - y_{reg}[x]\right)^2}{\sum\left(y[x] - y_{avg}[x]\right)^2} \quad . \qquad \textit{Equation 17}$$

With an R^2 value of approximately 0.9 associated to Equation 15 and Equation 16, the relationship is strong, and the equations can be trusted to produce general guidelines for economic feasibility. The lower R^2 value around 0.7 for Equation 14 suggests that, while there is still a decent correlation, the variance in the regression line is too great to trust the equations for much more than observing the trends. The sections on the plots in Figure 21 – Figure 23 showing clusters of dots that appear to form a vertical line is a result of the economic scaling of the systems. As the size of the system increased, there were DF:HTF flow rates that aligned across different system sizes, but the cheaper per unit marginal cost of installation and O&M for larger systems results in greater net present value, lower average storage tank volumes, and, in general, more of the DHW load profile being supplied by energy from the PVT collector.

Discussion

The data provided by the multitude of simulations performed can be used to determine a baseline scenario for specific regions and whether a hybrid PVT system is economically feasible. The systems are not always profitable, and sometimes may not be profitable when one would assume they would be. Following the information derived in this research can help a prospective hybrid PVT system owner determine if there will be any economic benefit to such a system. The systems can be profitable in any climate tested, so long as the demand flow rates are adequately higher than that of the collector flow rates. However, the system may still not be economically feasible, even in the hottest climates, if the system is not sized properly and energy is wasted. Although this research performed an overarching analysis and assessed numerous variables, there is still much future work to be done for hybrid photovoltaic-thermal systems.

Continued Research on Hybrid Photovoltaic-Thermal

Continuing the work of this research will be imperative to maximize the benefits of the simulations performed and solidify the data. The control systems are likely the most important variable to be modified for future simulations, as they were not part of the scope of this work. This research tested different system sizes and demand loads with some optimization of flow rates. The main focuses of this research were the size of the system and the demand flow rates. Future work should investigate the differences the control systems can make to optimize the performance of hybrid PVT systems. The temperature differential for the ON/OFF pump controller, for example, may make a significant difference in the functionality of the system if tuned properly. Optimum flow rates have been determined, but the optimum temperature differential is a topic of research that is heavily neglected.

The most important step to continuing this research would be to physically build a collector and system that incorporates the design of this research to test if the real-world adaptation of this theoretical hybrid PVT aligns with the modelling. Building the devices and assembling components would also help to generate a more accurate cost analysis of the system, as all the components would need to be sourced, so actual pricing could be applied to analysis. There are myriad of methods by which a physical hybrid PVT collector could be built, which could all result in slightly different performance. The design of the control scheme, however, will likely be the determining factor, assuming the demand flow is adequately setup and the flow of the heat transfer fluid is optimized. The more research performed in the realm of hybrid photovoltaic-thermal solar collectors and systems, the faster the technology will become adopted in industry, start degrading in price, and accelerate the drive toward clean, renewable energy.

VI. Conclusion

The objective of this research was to produce some general guidelines as to whether a hybrid PVT system may offer economic benefit over standard PV. Over 300 simulations were performed, including the sensitivity analysis, across five different climate zones with varying levels of solar irradiance. The systems were also tested for varying demand flow rates relative to the flow rate through the PVT collector. For almost all scenarios simulated, the levelized cost of energy was lower for hybrid PVT than standalone solar systems, suggesting that a hybrid PVT systems will almost always be more economically feasible than standalone photovoltaics or solar-thermal collectors.

The flow rate through the collector array was optimized via a preliminary micro-simulation for a PVT collector module, and sensitivity analysis showed that the system is fairly robust to small changes in solar irradiance, ambient temperature, groundwater temperature, the control pump temperature differential, and energy costs. The systems did, however, prove to be susceptible to large dips in solar radiation caused by cloud cover. With the data provided by the multitude of simulations, guidelines have been generated to show that with proper system sizing, a hybrid PVT collector system can offer many benefits.

Following the guidelines and using the equations derived in this research (Equation 14 – Equation 16) will help to eliminate some of the uncertainty surrounding hybrid photovoltaic-thermal technology. The overall rule of thumb to follow when attempting to size a hybrid PVT systems is to operate the system with an average demand flow rate that is greater than or equal to the flow rate through the collector. The average hot water demands are approximately 0.15

kg/min per person, and the optimum flow rate for the solar collector is approximately 0.25 kg/min/m^2. Once occupancy is known, the average demand flow rate can be determined, then a collector flow rate can be chosen that is less than the average demand flow (it is recommended to set to ≤ 75%), then determine the required collector area based on the optimum collector flow rate. For residential systems, a basic rule is that at least two occupants are required per panel for economic feasibility, with that number extending to three occupants for colder, darker climates. For commercial systems, demand flow rates are usually more accurately monitored, which should make sizing a hybrid PVT system easier than for residential use. An extremely rough approximation for the necessary tank size can be calculated using Equation 14, but the results would need further verification before making a solid commitment to those specifications, as the correlation for that particular equation is not strong enough to instill great confidence. More accurate analysis on the specifications of the desired systems are required to consider this model fully validated.

This research does, however, provide dependable data that can be used to assess a wide array of possibilities for the installation of a hybrid PVT system, depending on location, size, and hot water demands. Prior work regarding hybrid photovoltaic-thermal solar collectors focuses on singular systems to meet a specific need, with excessive emphasis on meeting the full hot water demands. The benefit if this research is an overarching analysis for hundreds of variations in system parameters that could affect the economic feasibility.

A wider range of climatic settings needs to be assessed in the future, as well, as this research only tested five locations within the United States. While the results of this work may not be task specific or applicable to niche scenarios, the metadata derived is useful for providing general guidelines. Much future work is still necessary, though, to truly validate, calibrate, and utilize the information derived in this research with impunity. Although the system has only minor alterations from previously validated models, those alterations could still be sufficient enough to cause erroneous results. For this reason, a physical build and experimental validation of this system is necessary in the future.

With further research into the subject, the performance of hybrid PVT systems and collectors can be optimized to provide a variety of benefits, namely cost savings and reductions in greenhouse gas emissions. Hybrid photovoltaic-thermal systems currently demonstrate that they offer greater benefits than standalone solar systems. The results of this work should provide some helpful guidelines for prospective investors to determine if a PVT system will be beneficial, or if adjustments need to be applied before economic feasibility can be achieved.

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Appendix A.1

Table 7. Performance analysis results for Imperial, California residential systems.

	Size	Occ/gpm	n_t	$Btu_{savings}$	$\%Btu_{PVT}$	$T_{HTF-Avg}$	$T_{HTF-Max}$	$T_{cell-Avg}$	$T_{cell-Max}$	n_e	ΔkWh	kWh_{PVT}	kWh_{PV}	$\%\Delta n$	$[kg/min/m^2]$	$T_{tank-Avg}$	$T_{tank-Max}$	V_{tank}	$\%V_{Max}$	$\%V_{Avg}$
Residential Method 1	3000	2	4.40%	3805125	93.26%	62.19	110.14	60.24	107.24	12.98%	91.4	4825.9	4734.5	1.44%	0.013	65.76	78.55	1.00	100.0%	88.99%
	3000	3	6.60%	5704383	93.12%	62.19	110.07	59.28	105.85	13.06%	128.9	4863.4	4734.5	2.08%	0.019	65.71	79.30	1.00	100.0%	90.69%
	3000	5	10.89%	9503963	92.69%	61.94	109.63	57.41	103.26	13.22%	201.2	4935.7	4734.5	3.31%	0.032	65.42	80.69	1.00	100.0%	91.93%
	3000	8	16.91%	15122620	90.87%	60.77	107.95	54.84	99.83	13.44%	301.6	5036.0	4734.5	5.02%	0.052	64.19	81.76	1.00	100.0%	90.37%
	3000	12	23.47%	22281581	86.98%	58.40	104.59	51.99	96.25	13.68%	413.5	5147.9	4734.5	6.92%	0.078	61.68	81.86	1.00	100.0%	86.21%
	5000	2	2.61%	3829254	93.96%	62.21	110.21	61.05	108.47	12.91%	103.8	8283.9	8180.1	0.90%	0.008	65.94	77.75	2.00	100.0%	85.18%
	5000	5	6.34%	9507746	93.18%	62.19	110.10	59.39	105.97	13.05%	215.4	8395.5	8180.1	2.00%	0.019	65.74	78.95	2.00	100.0%	90.09%
	5000	10	12.66%	18950770	92.24%	61.71	109.31	56.64	102.26	13.28%	397.7	8577.8	8180.1	3.82%	0.038	65.24	80.60	2.00	100.0%	89.71%
	5000	15	18.17%	28199027	90.15%	60.40	107.44	54.29	99.05	13.48%	556.1	8736.2	8180.1	5.39%	0.056	63.84	81.27	2.00	100.0%	89.59%
	5000	20	22.77%	37134736	87.43%	58.68	104.97	52.29	96.49	13.65%	693.5	8873.6	8180.1	6.72%	0.075	62.04	81.27	2.00	100.0%	87.74%
	10000	3	2.03%	5758460	94.37%	62.22	110.25	61.32	108.88	12.89%	168.1	16081.2	15913.1	0.72%	0.006	66.10	77.45	4.00	100.0%	83.31%
	10000	5	3.31%	9554434	93.68%	62.20	110.19	60.73	107.98	12.94%	243.2	16156.3	15913.1	1.11%	0.010	65.84	77.99	4.00	100.0%	86.68%
	10000	10	6.57%	18984644	93.08%	62.18	110.09	59.28	105.86	13.06%	430.8	16343.9	15913.1	2.07%	0.019	65.78	78.95	4.00	100.0%	88.00%
	10000	20	13.00%	37900444	92.19%	61.65	109.23	56.50	102.05	13.30%	793.6	16706.7	15913.1	3.92%	0.039	65.19	80.54	4.00	100.0%	89.61%
	10000	30	18.46%	56114988	89.91%	60.26	107.25	54.15	98.72	13.49%	1096.5	17009.6	15913.1	5.48%	0.058	63.69	80.99	4.00	100.0%	84.19%
	20000	5	1.72%	9613869	94.66%	62.23	110.27	61.46	109.11	12.87%	293.6	31699.0	31405.4	0.63%	0.005	66.23	77.24	8.00	100.0%	82.10%
	20000	10	3.36%	19089238	93.68%	62.19	110.19	60.70	107.95	12.94%	488.6	31894.0	31405.4	1.13%	0.010	65.93	77.99	8.00	100.0%	84.78%
	20000	20	6.66%	37976345	93.09%	62.18	110.09	59.24	105.80	13.06%	859.8	32265.2	31405.4	2.10%	0.020	65.78	78.95	8.00	100.0%	87.99%
	20000	35	11.46%	66215926	92.42%	61.85	109.54	57.15	102.86	13.24%	1392.0	32797.3	31405.4	3.48%	0.034	65.30	80.26	8.00	100.0%	85.21%
	20000	50	16.13%	94150856	91.05%	60.99	108.28	55.16	100.25	13.41%	1906.2	33311.5	31405.4	4.80%	0.049	64.40	80.62	8.00	100.0%	85.52%
Residential Method 2	275	2	39.44%	4241193	72.24%	48.57	85.88	45.13	83.07	14.27%	65.7	497.1	431.4	11.54%	0.229	50.87	65.80	1.00	100.0%	93.81%
	275	3	48.75%	5910398	66.13%	45.48	83.85	41.28	76.76	14.60%	83.9	515.3	431.4	14.13%	0.229	47.74	60.89	1.00	100.0%	74.79%
	275	5	57.79%	8343215	56.01%	42.43	78.43	37.50	70.70	14.93%	100.0	531.4	431.4	16.69%	0.229	44.56	57.40	1.00	100.0%	50.47%
	275	8	59.70%	11555806	48.49%	41.72	64.76	36.63	53.15	15.00%	101.9	533.2	431.4	17.25%	0.229	43.06	63.78	1.00	15.0%	5.92%
	275	12	59.70%	15860266	44.36%	41.72	64.76	36.63	53.15	15.00%	101.9	533.2	431.4	17.25%	0.229	40.94	64.72	1.00	10.0%	2.96%
	550	3	35.98%	6588641	75.25%	49.73	86.38	46.60	83.07	14.14%	118.7	978.8	860.1	10.55%	0.229	52.29	65.98	2.00	100.0%	96.03%
	550	5	44.54%	10340435	69.50%	46.85	84.36	43.01	77.75	14.45%	150.8	1010.9	860.1	12.96%	0.229	49.07	62.14	2.00	100.0%	85.54%
	550	10	58.20%	16382956	54.96%	42.26	75.69	37.32	69.32	14.94%	200.3	1060.4	860.1	16.81%	0.229	44.39	58.38	2.00	100.0%	44.63%
	550	15	59.74%	22029712	49.29%	41.68	64.66	36.61	53.11	15.00%	203.3	1063.4	860.1	17.26%	0.229	43.04	64.14	2.00	15.0%	4.78%
	550	25	59.74%	23648139	31.77%	41.68	64.66	36.61	53.11	15.00%	203.3	1063.4	860.1	17.26%	0.229	37.35	65.05	2.00	10.0%	1.29%
	1100	5	34.10%	11111638	76.39%	50.38	86.87	47.40	83.07	14.07%	225.2	1945.4	1720.2	10.01%	0.229	52.88	66.91	4.00	100.0%	96.74%
	1100	10	43.92%	20486217	69.07%	47.06	85.69	43.27	79.89	14.43%	296.0	2016.2	1720.2	12.79%	0.229	49.16	64.91	4.00	100.0%	81.48%
	1100	20	58.20%	32771805	54.97%	42.26	75.69	37.32	69.32	14.94%	400.6	2120.8	1720.2	16.81%	0.229	44.39	58.38	4.00	100.0%	44.63%
	1100	35	59.74%	36519239	35.04%	41.68	64.66	36.61	53.11	15.00%	406.5	2126.7	1720.2	17.26%	0.229	40.68	64.99	4.00	10.0%	2.78%
	1100	50	59.74%	51989364	34.93%	41.68	64.66	36.61	53.11	15.00%	406.5	2126.7	1720.2	17.26%	0.229	38.76	65.19	4.00	8.8%	1.62%
	2200	10	33.77%	22178653	76.26%	50.50	86.75	47.55	83.07	14.06%	446.3	3891.9	3445.6	9.91%	0.229	52.90	66.74	8.00	100.0%	96.78%
	2200	20	43.90%	40998446	69.12%	47.08	85.72	43.28	79.89	14.43%	592.6	4038.3	3445.6	12.78%	0.229	49.18	64.93	8.00	100.0%	81.48%
	2200	40	58.69%	60808502	51.03%	42.08	77.71	37.09	69.92	14.96%	804.7	4250.3	3445.6	16.95%	0.229	43.92	57.58	8.00	100.0%	39.53%
	2200	70	59.72%	77425356	37.16%	41.70	64.71	36.62	53.13	15.00%	814.0	4259.6	3445.6	17.25%	0.229	41.31	64.59	8.00	10.6%	3.06%
	2200	100	59.72%	104042235	34.95%	41.70	64.71	36.62	53.13	15.00%	814.0	4259.6	3445.6	17.25%	0.229	38.78	65.24	8.00	8.8%	1.62%

Appendix A.2

Table 8. Performance analysis results for Portland, Oregon residential systems.

	Size	Occ/gpm	n_t	$Btu_{savings}$	$\%Btu_{PVT}$	$T_{HTF-Avg}$	$T_{HTF-Max}$	$T_{cell-Avg}$	$T_{cell-Max}$	n_e	ΔkWh	kWh_{PVT}	kWh_{PV}	%Δn	$[kg/min/m^2]$	$T_{tank-Avg}$	$T_{tank-Max}$	V_{tank}	$\%V_{Max}$	$\%V_{Avg}$
Residential Method 1	3000	2	5.80%	4057735	66.17%	40.63	100.44	38.89	96.91	17.89%	64.7	3882.0	3817.3	1.02%	0.013	45.21	63.62	1.00	100.0%	77.76%
	3000	3	8.63%	5983755	65.10%	40.61	100.36	38.05	95.21	17.98%	93.2	3910.5	3817.3	1.51%	0.019	44.97	64.56	1.00	100.0%	78.31%
	3000	5	14.24%	9760984	63.74%	40.33	99.80	36.40	91.96	18.14%	149.2	3966.5	3817.3	2.45%	0.032	44.53	67.22	1.00	100.0%	78.59%
	3000	8	21.61%	14930011	60.88%	39.20	97.58	34.27	87.69	18.36%	222.9	4040.1	3817.3	3.67%	0.052	43.21	68.11	1.00	100.0%	77.34%
	3000	12	28.96%	20331836	55.17%	37.19	93.55	32.16	83.32	18.57%	298.8	4116.0	3817.3	4.88%	0.078	40.75	68.84	1.00	100.0%	75.18%
	5000	2	3.41%	4217119	68.71%	40.63	100.54	39.61	98.40	17.82%	69.9	6665.3	6595.4	0.61%	0.008	46.01	62.23	2.00	100.0%	75.37%
	5000	5	8.34%	10045205	65.55%	40.61	100.39	38.13	95.37	17.97%	155.8	6751.2	6595.4	1.46%	0.019	45.04	64.13	2.00	100.0%	78.24%
	5000	10	16.28%	19233160	62.75%	40.10	99.36	35.80	90.72	18.20%	293.2	6888.5	6595.4	2.79%	0.038	44.33	66.79	2.00	100.0%	77.42%
	5000	15	22.96%	27504584	59.75%	38.87	96.95	33.88	86.99	18.40%	408.9	7004.2	6595.4	3.90%	0.056	42.85	67.45	2.00	100.0%	77.44%
	5000	20	28.39%	34377614	55.96%	37.39	93.91	32.32	83.46	18.55%	505.9	7101.3	6595.4	4.78%	0.075	41.04	67.24	2.00	100.0%	76.52%
	10000	3	2.66%	6452617	70.05%	40.64	100.58	39.84	98.90	17.79%	110.1	12940.3	12830.2	0.49%	0.006	46.52	61.58	4.00	100.0%	74.82%
	10000	5	4.34%	10377219	67.66%	40.63	100.51	39.33	97.80	17.85%	168.1	12998.4	12830.2	0.78%	0.010	45.69	62.79	4.00	100.0%	76.46%
	10000	10	8.60%	19960704	65.10%	40.61	100.38	38.05	95.23	17.97%	312.5	13142.7	12830.2	1.50%	0.019	45.11	64.11	4.00	100.0%	76.99%
	10000	20	16.71%	38427443	62.68%	40.05	99.25	35.68	90.52	18.21%	584.8	13415.0	12830.2	2.86%	0.039	44.28	66.69	4.00	100.0%	77.40%
	10000	30	23.23%	54987854	59.77%	38.76	96.70	33.79	86.64	18.41%	801.5	13631.7	12830.2	3.94%	0.058	42.72	67.42	4.00	100.0%	75.71%
	20000	5	2.28%	10872746	70.80%	40.64	100.59	39.96	99.17	17.78%	189.7	25510.8	25321.1	0.42%	0.005	46.85	61.12	8.00	100.0%	74.79%
	20000	10	4.41%	20638836	67.26%	40.63	100.51	39.31	97.76	17.85%	336.0	25657.1	25321.1	0.79%	0.010	45.68	62.82	8.00	100.0%	75.14%
	20000	20	8.73%	39922678	65.10%	40.61	100.38	38.02	95.16	17.98%	625.0	25946.1	25321.1	1.52%	0.020	45.11	64.09	8.00	100.0%	76.96%
	20000	35	14.79%	67799607	63.26%	40.25	99.66	36.23	91.49	18.16%	1024.6	26345.7	25321.1	2.55%	0.034	44.55	66.31	8.00	100.0%	76.18%
	20000	50	20.36%	93612450	61.11%	39.41	98.00	34.62	88.44	18.32%	1391.3	26712.4	25321.1	3.46%	0.049	43.51	67.29	8.00	100.0%	76.11%
Residential Method 2	275	2	45.16%	3068924	39.94%	29.92	71.53	27.55	65.01	19.03%	44.7	392.5	347.8	7.47%	0.229	32.28	51.16	1.00	100.0%	81.09%
	275	3	52.23%	4095914	35.54%	28.28	69.76	25.57	64.03	19.23%	53.0	400.8	347.8	8.60%	0.229	30.30	47.30	1.00	100.0%	75.32%
	275	5	61.86%	5907574	30.75%	26.03	65.38	22.85	57.61	19.50%	63.0	410.8	347.8	10.12%	0.229	28.01	44.21	1.00	100.0%	46.93%
	275	8	63.61%	9592829	31.21%	25.61	51.58	22.33	41.00	19.55%	64.1	411.9	347.8	10.38%	0.229	27.07	49.79	1.00	15.0%	5.67%
	275	12	63.61%	14384685	31.19%	25.61	51.58	22.33	41.00	19.55%	64.1	411.9	347.8	10.38%	0.229	26.01	50.66	1.00	10.0%	3.00%
	550	3	41.41%	4885478	42.39%	30.78	72.09	28.61	67.45	18.92%	80.7	774.2	693.5	6.87%	0.229	33.32	50.90	2.00	100.0%	85.38%
	550	5	48.72%	7233092	37.66%	29.08	70.48	26.55	63.53	19.13%	97.5	790.9	693.5	8.03%	0.229	31.27	48.72	2.00	100.0%	77.76%
	550	10	62.32%	11564041	30.09%	25.90	65.32	22.72	58.04	19.51%	126.3	819.7	693.5	10.19%	0.229	27.89	47.75	2.00	100.0%	43.34%
	550	15	63.65%	17672989	30.65%	25.58	51.48	22.32	40.95	19.55%	127.9	821.4	693.5	10.39%	0.229	27.19	50.19	2.00	15.0%	4.79%
	550	25	63.65%	20657355	21.51%	25.58	51.48	22.32	40.95	19.55%	127.9	821.4	693.5	10.39%	0.229	23.87	51.04	2.00	7.5%	1.15%
	1100	5	40.22%	8437988	43.93%	31.07	72.03	28.95	67.52	18.89%	156.5	1543.4	1386.9	6.67%	0.229	33.77	51.55	4.00	100.0%	86.13%
	1100	10	48.98%	14255212	37.09%	29.02	70.55	26.48	64.44	19.14%	195.8	1582.7	1386.9	8.08%	0.229	31.16	48.91	4.00	100.0%	77.81%
	1100	20	62.32%	23128691	30.09%	25.90	65.32	22.72	58.04	19.51%	252.5	1639.5	1386.9	10.19%	0.229	27.89	47.75	4.00	100.0%	43.34%
	1100	35	63.65%	30065938	22.36%	25.58	51.48	22.32	40.95	19.55%	255.8	1642.7	1386.9	10.39%	0.229	25.85	50.55	4.00	10.0%	2.69%
	1100	50	63.65%	46395296	24.16%	25.58	51.48	22.32	40.95	19.55%	255.8	1642.7	1386.9	10.39%	0.229	24.76	51.15	4.00	7.5%	1.53%
	2200	10	40.30%	16722566	43.51%	31.05	72.12	28.93	67.52	18.89%	314.2	3092.3	2778.1	6.69%	0.229	33.77	51.31	8.00	100.0%	85.88%
	2200	20	48.95%	28564085	37.16%	29.04	70.59	26.49	64.44	19.14%	392.0	3170.1	2778.1	8.08%	0.229	31.18	48.94	8.00	100.0%	77.81%
	2200	40	62.70%	42970553	27.96%	25.82	66.13	22.60	58.08	19.52%	507.1	3285.3	2778.1	10.25%	0.229	27.66	46.21	8.00	100.0%	38.92%
	2200	70	63.63%	63330859	23.56%	25.59	51.53	22.33	40.97	19.55%	512.2	3290.3	2778.1	10.38%	0.229	26.16	50.60	8.00	10.6%	2.98%
	2200	100	63.63%	92862800	24.18%	25.59	51.53	22.33	40.97	19.55%	512.2	3290.3	2778.1	10.38%	0.229	24.78	51.20	8.00	8.1%	1.53%

Appendix A.3

Table 9. Performance analysis results for Riverton, Wyoming residential systems.

	Size	Occ/gpm	n_t	$Btu_{savings}$	$\%Btu_{PVT}$	$T_{HTF\text{-}Avg}$	$T_{HTF\text{-}Max}$	$T_{cell\text{-}Avg}$	$T_{cell\text{-}Max}$	n_e	ΔkWh	kWh_{PVT}	kWh_{PV}	%Δn	[kg/min/m^2]	$T_{tank\text{-}Avg}$	$T_{tank\text{-}Max}$	V_{tank}	$\%V_{Max}$	$\%V_{Avg}$
Residential Method 1	3000	2	5.56%	4327769	63.89%	40.35	99.06	38.47	94.87	15.87%	71.1	4371.1	4300.1	1.08%	0.013	41.41	59.32	1.00	100.0%	80.32%
	3000	3	8.29%	6431787	63.30%	40.34	99.03	37.57	92.90	15.95%	103.0	4403.1	4300.1	1.60%	0.019	41.21	60.40	1.00	100.0%	81.17%
	3000	5	13.64%	10580009	62.48%	40.07	98.30	35.80	89.58	16.11%	165.2	4465.3	4300.1	2.62%	0.032	40.83	61.74	1.00	100.0%	81.67%
	3000	8	20.69%	16281120	60.09%	38.89	95.83	33.47	85.48	16.32%	248.0	4548.0	4300.1	3.96%	0.052	39.61	62.85	1.00	100.0%	79.83%
	3000	12	26.99%	22554744	55.47%	36.74	91.75	31.21	81.24	16.53%	325.6	4625.6	4300.1	5.28%	0.078	37.69	63.66	1.00	100.0%	74.58%
	5000	2	3.27%	4411367	65.12%	40.36	99.02	39.25	96.63	15.80%	75.4	7504.9	7429.6	0.63%	0.008	41.95	57.44	2.00	100.0%	78.22%
	5000	5	8.01%	10770754	63.60%	40.34	99.03	37.65	93.08	15.95%	172.7	7602.3	7429.6	1.55%	0.019	41.28	59.84	2.00	100.0%	80.87%
	5000	10	15.01%	20852741	61.54%	39.81	97.76	35.27	88.38	16.16%	313.5	7743.1	7429.6	2.93%	0.038	40.75	61.82	2.00	100.0%	80.63%
	5000	15	21.21%	30086700	59.19%	38.55	95.22	33.19	84.64	16.35%	438.4	7868.0	7429.6	4.14%	0.056	39.53	62.37	2.00	100.0%	78.60%
	5000	20	26.34%	38048181	56.14%	36.98	92.17	31.44	81.55	16.51%	547.5	7977.1	7429.6	5.15%	0.075	37.99	62.72	2.00	100.0%	75.61%
	10000	3	2.55%	6676437	65.71%	40.38	99.00	39.51	97.17	15.78%	116.0	14569.1	14453.0	0.48%	0.006	42.24	56.49	4.00	100.0%	77.02%
	10000	5	4.16%	10968326	64.77%	40.36	99.03	38.95	95.95	15.83%	183.0	14636.0	14453.0	0.80%	0.010	41.76	58.10	4.00	100.0%	79.04%
	10000	10	7.89%	21407227	63.17%	40.30	99.02	37.65	92.93	15.95%	333.3	14786.3	14453.0	1.55%	0.019	41.35	60.07	4.00	100.0%	79.51%
	10000	20	15.39%	41676214	61.49%	39.75	97.62	35.14	88.14	16.17%	624.9	15077.9	14453.0	3.00%	0.039	40.71	61.77	4.00	100.0%	80.55%
	10000	30	21.58%	60106920	59.16%	38.43	94.97	33.08	84.25	16.36%	864.5	15317.5	14453.0	4.19%	0.058	39.33	62.33	4.00	100.0%	76.02%
	20000	5	2.18%	11190566	66.08%	40.39	98.98	39.65	97.45	15.77%	197.1	28720.9	28523.8	0.40%	0.005	42.44	56.07	8.00	100.0%	76.15%
	20000	10	4.07%	21877664	64.56%	40.32	99.03	38.93	95.91	15.83%	362.0	28885.8	28523.8	0.81%	0.010	41.84	58.14	8.00	100.0%	77.25%
	20000	20	7.99%	42811711	63.17%	40.30	99.02	37.61	92.86	15.95%	666.0	29189.8	28523.8	1.57%	0.020	41.35	60.06	8.00	100.0%	79.51%
	20000	35	13.67%	73437393	61.95%	39.95	98.13	35.72	89.07	16.12%	1097.4	29621.1	28523.8	2.67%	0.034	40.86	61.12	8.00	100.0%	78.71%
	20000	50	18.73%	101877101	60.18%	39.11	96.23	34.03	85.98	16.27%	1486.9	30010.6	28523.8	3.64%	0.049	40.02	61.89	8.00	100.0%	77.70%
Residential Method 2	275	2	42.31%	3620263	42.75%	28.32	72.42	25.52	65.91	17.05%	50.5	442.3	391.8	8.58%	0.229	30.29	50.37	1.00	100.0%	83.37%
	275	3	50.29%	4888747	38.49%	26.09	70.37	22.80	62.99	17.29%	62.2	454.0	391.8	10.13%	0.229	27.91	46.68	1.00	100.0%	68.05%
	275	5	59.59%	6914749	32.66%	23.47	66.07	19.63	58.10	17.59%	74.9	466.7	391.8	12.00%	0.229	25.15	40.13	1.00	100.0%	52.85%
	275	8	63.10%	10852831	32.04%	22.43	50.95	18.37	38.48	17.70%	77.9	469.7	391.8	12.73%	0.229	23.78	49.26	1.00	20.0%	5.80%
	275	12	63.10%	16468678	32.40%	22.43	50.95	18.37	38.48	17.70%	77.9	469.7	391.8	12.73%	0.229	22.42	50.74	1.00	10.0%	3.18%
	550	3	39.73%	5676271	44.69%	29.04	72.81	26.41	69.08	16.97%	94.0	875.1	781.2	8.09%	0.229	31.25	50.86	2.00	100.0%	86.51%
	550	5	46.81%	8450985	39.92%	27.05	70.88	23.98	66.61	17.19%	113.5	894.6	781.2	9.45%	0.229	28.88	47.88	2.00	100.0%	74.88%
	550	10	60.13%	13453151	31.76%	23.28	67.21	19.42	59.03	17.61%	150.5	931.7	781.2	12.13%	0.229	25.04	41.43	2.00	100.0%	49.97%
	550	15	63.12%	19661993	30.94%	22.40	50.84	18.35	38.43	17.70%	155.4	936.6	781.2	12.74%	0.229	23.88	50.05	2.00	17.5%	4.98%
	550	25	63.12%	23782132	22.47%	22.40	50.84	18.35	38.43	17.70%	155.4	936.6	781.2	12.74%	0.229	19.97	51.34	2.00	10.0%	1.33%
	1100	5	38.58%	9682875	45.74%	29.38	72.70	26.82	68.31	16.93%	182.7	1745.1	1562.4	7.85%	0.229	31.72	50.67	4.00	100.0%	87.87%
	1100	10	46.48%	16918828	39.94%	27.14	71.95	24.10	65.91	17.18%	224.7	1787.1	1562.4	9.38%	0.229	28.96	49.18	4.00	100.0%	72.73%
	1100	20	60.13%	26906310	31.76%	23.28	67.21	19.42	59.03	17.61%	301.0	1863.4	1562.4	12.13%	0.229	25.04	41.43	4.00	100.0%	49.97%
	1100	35	63.12%	33806128	22.82%	22.40	50.84	18.35	38.43	17.70%	310.8	1873.2	1562.4	12.74%	0.229	22.35	50.46	4.00	11.3%	3.03%
	1100	50	63.12%	51398657	24.29%	22.40	50.84	18.35	38.43	17.70%	310.8	1873.2	1562.4	12.74%	0.229	20.97	51.31	4.00	10.0%	1.71%
	2200	10	38.29%	19388108	45.77%	29.47	72.75	26.93	68.31	16.93%	362.9	3492.4	3129.5	7.79%	0.229	31.73	50.63	8.00	100.0%	87.78%
	2200	20	46.44%	33874776	39.98%	27.16	71.99	24.11	65.91	17.17%	449.5	3579.0	3129.5	9.37%	0.229	28.97	49.21	8.00	100.0%	72.74%
	2200	40	60.66%	50767368	29.98%	23.13	67.16	19.23	58.95	17.62%	605.0	3734.5	3129.5	12.22%	0.229	24.78	41.09	8.00	100.0%	47.45%
	2200	70	63.10%	74300974	25.08%	22.41	50.90	18.36	38.46	17.70%	622.4	3751.9	3129.5	12.74%	0.229	22.69	50.82	8.00	10.6%	3.22%
	2200	100	63.10%	102719604	24.27%	22.41	50.90	18.36	38.46	17.70%	622.4	3751.9	3129.5	12.74%	0.229	20.99	51.36	8.00	9.4%	1.71%

Appendix A.4

Table 10. Performance analysis results for Sacramento, California residential systems.

	Size	Occ/gpm	n_t	$Btu_{savings}$	$\%Btu_{PVT}$	$T_{HTF-Avg}$	$T_{HTF-Max}$	$T_{cell-Avg}$	$T_{cell-Max}$	n_e	ΔkWh	kWh_{PVT}	kWh_{PV}	$\%\Delta n$	$[kg/min/m^2]$	$T_{tank-Avg}$	$T_{tank-Max}$	V_{tank}	$\%V_{Max}$	$\%V_{Avg}$
Residential Method 1	3000	2	4.63%	4003776	80.18%	50.77	103.24	48.96	99.99	15.36%	82.9	4604.4	4521.5	1.20%	0.013	57.05	73.34	1.00	100.0%	78.65%
	3000	3	6.85%	5954939	79.46%	50.76	103.16	48.10	98.82	15.44%	116.4	4637.9	4521.5	1.71%	0.019	56.78	74.03	1.00	100.0%	77.54%
	3000	5	11.32%	9822787	78.37%	50.52	102.03	46.40	96.67	15.59%	182.6	4704.0	4521.5	2.73%	0.032	56.29	75.80	1.00	100.0%	76.59%
	3000	8	17.36%	15534878	76.51%	49.45	100.81	44.14	93.50	15.80%	272.4	4793.8	4521.5	4.07%	0.052	54.96	76.17	1.00	100.0%	75.48%
	3000	12	24.15%	22605880	72.55%	47.33	98.10	41.64	89.91	16.02%	377.0	4898.5	4521.5	5.55%	0.078	52.33	76.40	1.00	100.0%	73.39%
	5000	2	2.72%	4104698	82.08%	50.78	102.37	49.72	100.99	15.29%	92.7	7904.8	7812.1	0.75%	0.008	57.65	72.41	2.00	100.0%	78.06%
	5000	5	6.64%	9962910	79.78%	50.76	103.18	48.18	98.95	15.43%	195.8	8007.9	7812.1	1.67%	0.019	56.89	73.76	2.00	100.0%	78.20%
	5000	10	12.91%	19507489	77.63%	50.31	101.82	45.79	95.79	15.65%	355.9	8168.0	7812.1	3.09%	0.038	56.02	75.44	2.00	100.0%	76.39%
	5000	15	18.71%	28872288	75.53%	49.11	100.40	43.64	92.86	15.84%	506.8	8318.9	7812.1	4.37%	0.056	54.50	75.75	2.00	100.0%	75.25%
	5000	20	23.43%	37859918	73.12%	47.57	98.43	41.90	90.33	16.00%	632.7	8444.8	7812.1	5.40%	0.075	52.64	75.88	2.00	100.0%	74.06%
	10000	3	3.96%	6203992	77.56%	51.67	106.70	50.15	103.15	15.25%	107.0	15304.2	15197.2	0.49%	0.006	51.62	64.17	4.00	100.0%	82.21%
	10000	5	3.47%	10171806	81.39%	50.78	102.36	49.42	100.60	15.32%	218.8	15416.0	15197.2	0.93%	0.010	57.41	72.73	4.00	100.0%	78.59%
	10000	10	6.77%	19803494	79.28%	50.75	102.32	48.12	98.87	15.44%	388.4	15585.5	15197.2	1.70%	0.019	56.85	73.99	4.00	100.0%	77.04%
	10000	20	13.25%	39012612	77.58%	50.26	101.77	45.66	95.61	15.66%	709.6	15906.8	15197.2	3.17%	0.039	55.96	75.37	4.00	100.0%	76.39%
	10000	30	18.85%	57270091	75.01%	49.00	100.25	43.57	92.57	15.85%	989.5	16186.7	15197.2	4.41%	0.058	54.29	75.47	4.00	100.0%	73.88%
	20000	5	1.83%	10483664	83.80%	50.80	102.41	50.09	101.49	15.26%	259.0	30251.4	29992.4	0.53%	0.005	58.24	71.76	8.00	100.0%	76.30%
	20000	10	3.49%	20221536	80.90%	50.77	102.36	49.40	100.57	15.32%	436.2	30428.6	29992.4	0.94%	0.010	57.39	72.80	8.00	100.0%	77.83%
	20000	20	6.86%	39609117	79.28%	50.75	102.32	48.09	98.82	15.44%	775.4	30767.8	29992.4	1.72%	0.020	56.85	73.99	8.00	100.0%	77.01%
	20000	35	11.73%	68075543	77.67%	50.45	101.99	46.23	96.31	15.61%	1249.2	31241.6	29992.4	2.83%	0.034	56.16	75.08	8.00	100.0%	75.57%
	20000	50	16.48%	95926136	75.91%	49.65	101.06	44.46	93.92	15.77%	1717.0	31709.4	29992.4	3.88%	0.049	55.15	75.34	8.00	100.0%	74.70%
Residential Method 2	275	2	39.63%	3843800	57.01%	38.92	79.79	35.98	76.17	16.53%	57.8	469.8	412.0	8.88%	0.229	42.54	59.11	1.00	100.0%	77.71%
	275	3	46.68%	5084010	50.27%	36.90	77.60	33.48	70.96	16.75%	70.3	482.3	412.0	10.36%	0.229	39.97	55.00	1.00	100.0%	71.44%
	275	5	56.43%	7095694	42.09%	34.04	72.04	29.94	64.66	17.06%	84.4	496.4	412.0	12.41%	0.229	37.05	50.59	1.00	100.0%	43.85%
	275	8	57.63%	10845033	40.21%	33.67	59.33	29.48	47.75	17.10%	85.6	497.5	412.0	12.67%	0.229	35.86	58.15	1.00	15.0%	5.60%
	275	12	57.63%	14817162	36.61%	33.67	59.33	29.48	47.75	17.10%	85.6	497.5	412.0	12.67%	0.229	34.49	59.05	1.00	10.0%	2.90%
	550	3	35.85%	6063176	59.95%	40.00	79.97	37.35	75.03	16.41%	102.8	924.2	821.4	8.08%	0.229	43.70	59.98	2.00	100.0%	85.81%
	550	5	43.09%	9083481	53.89%	37.91	78.25	34.75	72.82	16.64%	127.7	949.1	821.4	9.61%	0.229	41.24	56.39	2.00	100.0%	74.91%
	550	10	56.86%	13967216	41.41%	33.89	68.66	29.78	62.08	17.08%	169.3	990.7	821.4	12.50%	0.229	36.93	53.32	2.00	100.0%	39.05%
	550	15	57.65%	19657771	38.85%	33.64	59.23	29.48	47.70	17.10%	170.7	992.1	821.4	12.68%	0.229	36.06	58.60	2.00	15.0%	4.63%
	550	25	57.65%	23025694	27.32%	33.64	59.23	29.48	47.70	17.10%	170.7	992.1	821.4	12.68%	0.229	31.55	59.19	2.00	10.0%	1.06%
	1100	5	34.48%	10281719	61.00%	40.40	80.10	37.85	78.56	16.36%	197.6	1840.4	1642.8	7.77%	0.229	44.14	59.78	4.00	100.0%	89.46%
	1100	10	43.38%	17851564	52.92%	37.83	78.28	34.64	72.82	16.65%	257.1	1899.9	1642.8	9.67%	0.229	41.09	56.44	4.00	100.0%	73.75%
	1100	20	56.86%	27934434	41.41%	33.89	68.66	29.78	62.08	17.08%	338.5	1981.3	1642.8	12.50%	0.229	36.93	53.32	4.00	100.0%	39.05%
	1100	35	57.65%	33104469	28.06%	33.64	59.23	29.48	47.70	17.10%	341.4	1984.2	1642.8	12.68%	0.229	34.25	58.94	4.00	10.0%	2.59%
	1100	50	57.65%	49399771	29.32%	33.64	59.23	29.48	47.70	17.10%	341.4	1984.2	1642.8	12.68%	0.229	32.72	59.31	4.00	8.8%	1.42%
	2200	10	34.43%	20603167	61.08%	40.42	80.24	37.86	75.03	16.36%	394.3	3684.9	3290.6	7.76%	0.229	44.19	60.09	8.00	100.0%	88.86%
	2200	20	43.32%	35725834	52.96%	37.85	78.32	34.66	72.82	16.65%	514.2	3804.8	3290.6	9.66%	0.229	41.11	56.47	8.00	100.0%	73.75%
	2200	40	57.07%	51868937	38.47%	33.84	67.61	29.70	61.49	17.08%	679.7	3970.3	3290.6	12.55%	0.229	36.60	52.70	8.00	100.0%	36.27%
	2200	70	57.64%	70475779	29.87%	33.66	59.28	29.48	47.72	17.10%	683.7	3974.3	3290.6	12.67%	0.229	34.66	58.99	8.00	10.0%	2.83%
	2200	100	57.64%	98737393	29.30%	33.66	59.28	29.48	47.72	17.10%	683.7	3974.3	3290.6	12.67%	0.229	32.74	59.36	8.00	8.8%	1.43%

Appendix A.5

Table 11. Performance analysis results for Salt Lake City, Utah residential systems.

	Size	Occ/gpm	n_t	$Btu_{savings}$	$\%Btu_{PVT}$	$T_{HTF\text{-}Avg}$	$T_{HTF\text{-}Max}$	$T_{cell\text{-}Avg}$	$T_{cell\text{-}Max}$	n_e	ΔkWh	kWh_{PVT}	kWh_{PV}	%Δn	[kg/min/m^2]	$T_{tank\text{-}Avg}$	$T_{tank\text{-}Max}$	V_{tank}	$\%V_{Max}$	$\%V_{Avg}$
Residential Method 1	3000	2	5.32%	4340224	70.83%	43.24	100.16	41.49	96.61	15.73%	72.3	4495.7	4423.4	1.08%	0.013	47.11	64.91	1.00	100.0%	79.60%
	3000	3	7.91%	6466401	70.38%	43.23	100.14	40.64	94.84	15.80%	104.4	4527.8	4423.4	1.59%	0.019	46.92	65.94	1.00	100.0%	79.91%
	3000	5	12.93%	10609242	69.34%	43.00	99.69	39.03	92.04	15.96%	166.2	4589.6	4423.4	2.56%	0.032	46.60	67.82	1.00	100.0%	80.13%
	3000	8	19.75%	16348773	66.75%	41.99	97.68	36.85	88.62	16.16%	250.4	4673.8	4423.4	3.87%	0.052	45.48	69.02	1.00	100.0%	79.25%
	3000	12	26.72%	22791371	61.93%	39.98	93.81	34.54	84.40	16.38%	339.7	4763.1	4423.4	5.28%	0.078	43.57	69.31	1.00	100.0%	75.12%
	5000	2	3.10%	4450139	72.55%	43.24	100.14	42.22	98.11	15.66%	77.2	7719.9	7642.7	0.64%	0.008	47.64	63.65	2.00	100.0%	78.78%
	5000	5	7.67%	10836117	70.75%	43.23	100.14	40.72	95.03	15.80%	175.0	7817.7	7642.7	1.54%	0.019	47.01	65.49	2.00	100.0%	79.66%
	5000	10	14.71%	20964827	68.46%	42.81	99.31	38.43	91.11	16.01%	326.5	7969.2	7642.7	2.92%	0.038	46.47	67.94	2.00	100.0%	79.16%
	5000	15	20.97%	30241784	65.78%	41.67	97.06	36.44	87.84	16.20%	459.9	8102.6	7642.7	4.11%	0.056	45.27	68.49	2.00	100.0%	78.42%
	5000	20	26.00%	38440694	62.66%	40.21	94.27	34.77	84.77	16.35%	571.0	8213.7	7642.7	5.12%	0.075	43.86	68.53	2.00	100.0%	76.60%
	10000	3	2.42%	6746271	73.28%	43.25	100.13	42.45	98.57	15.64%	121.0	14988.6	14867.6	0.50%	0.006	47.93	63.07	4.00	100.0%	78.03%
	10000	5	3.97%	11055463	72.13%	43.23	100.15	41.93	97.52	15.68%	187.2	15054.8	14867.6	0.82%	0.010	47.46	64.09	4.00	100.0%	79.06%
	10000	10	7.74%	21577729	70.42%	43.22	100.14	40.69	94.89	15.80%	344.9	15212.5	14867.6	1.56%	0.019	47.04	65.80	4.00	100.0%	78.77%
	10000	20	15.10%	41820991	68.27%	42.76	99.22	38.30	90.91	16.02%	651.3	15518.9	14867.6	2.99%	0.039	46.41	67.87	4.00	100.0%	79.15%
	10000	30	21.31%	60054005	65.39%	41.55	96.83	36.32	87.56	16.21%	904.5	15772.0	14867.6	4.19%	0.058	45.10	68.34	4.00	100.0%	77.45%
	20000	5	2.07%	11312499	73.70%	43.26	100.12	42.57	98.80	15.62%	206.8	29548.7	29341.9	0.43%	0.005	48.08	62.57	8.00	100.0%	77.28%
	20000	10	3.96%	22106922	72.08%	43.23	100.14	41.91	97.49	15.68%	372.4	29714.4	29341.9	0.82%	0.010	47.50	64.41	8.00	100.0%	77.51%
	20000	20	7.85%	43159235	70.43%	43.22	100.14	40.65	94.82	15.80%	689.5	30031.4	29341.9	1.58%	0.020	47.04	65.80	8.00	100.0%	78.77%
	20000	35	13.32%	73474029	68.60%	42.92	99.58	38.86	91.62	15.97%	1134.3	30476.2	29341.9	2.66%	0.034	46.51	67.08	8.00	100.0%	78.38%
	20000	50	18.31%	102136734	66.76%	42.17	98.09	37.26	88.97	16.12%	1541.3	30883.2	29341.9	3.62%	0.049	45.76	67.83	8.00	100.0%	78.18%
Residential Method 2	275	2	41.99%	3636147	47.32%	32.20	76.00	29.45	73.23	16.85%	51.3	454.3	403.0	8.33%	0.229	35.41	56.01	1.00	100.0%	82.88%
	275	3	50.23%	4831599	41.92%	30.11	73.59	26.85	66.26	17.09%	63.0	466.0	403.0	9.88%	0.229	33.11	51.33	1.00	100.0%	72.98%
	275	5	59.51%	6915623	36.00%	27.73	67.63	23.92	59.74	17.36%	76.0	479.0	403.0	11.61%	0.229	30.41	45.03	1.00	100.0%	49.79%
	275	8	62.45%	10841721	35.28%	26.89	55.46	22.90	42.99	17.45%	78.4	481.4	403.0	12.18%	0.229	29.07	52.12	1.00	15.0%	5.74%
	275	12	62.45%	15930068	34.54%	26.89	55.46	22.90	42.99	17.45%	78.4	481.4	403.0	12.18%	0.229	27.77	55.89	1.00	10.0%	3.15%
	550	3	38.63%	5756389	49.95%	33.06	75.52	30.53	73.23	16.75%	93.4	897.0	803.6	7.68%	0.229	36.42	55.24	2.00	100.0%	83.21%
	550	5	46.20%	8585418	44.70%	31.12	74.21	28.12	67.34	16.98%	113.9	917.5	803.6	9.12%	0.229	34.15	53.05	2.00	100.0%	78.55%
	550	10	60.14%	13587234	35.35%	27.54	70.42	23.70	62.04	17.38%	152.7	956.3	803.6	11.73%	0.229	30.31	45.31	2.00	100.0%	46.13%
	550	15	62.49%	19562319	33.93%	26.86	55.37	22.88	42.94	17.45%	156.4	960.0	803.6	12.19%	0.229	29.22	52.65	2.00	15.0%	4.89%
	550	25	62.49%	23154556	24.11%	26.86	55.37	22.88	42.94	17.45%	156.4	960.0	803.6	12.19%	0.229	25.01	55.44	2.00	10.0%	1.19%
	1100	5	37.93%	9805344	51.05%	33.24	75.87	30.76	73.23	16.73%	183.4	1790.5	1607.2	7.54%	0.229	36.85	55.80	4.00	100.0%	84.76%
	1100	10	46.54%	16897827	43.96%	31.03	74.68	28.01	67.47	16.99%	229.6	1836.7	1607.2	9.19%	0.229	34.05	53.05	4.00	100.0%	77.28%
	1100	20	60.14%	27174469	35.35%	27.54	70.42	23.70	62.04	17.38%	305.3	1912.5	1607.2	11.73%	0.229	30.31	45.31	4.00	100.0%	46.13%
	1100	35	62.49%	34202775	25.44%	26.86	55.37	22.88	42.94	17.45%	312.8	1920.0	1607.2	12.19%	0.229	27.57	53.81	4.00	10.0%	2.84%
	1100	50	62.49%	50725108	26.42%	26.86	55.37	22.88	42.94	17.45%	312.8	1920.0	1607.2	12.19%	0.229	26.13	55.47	4.00	8.8%	1.57%
	2200	10	37.58%	19583478	50.95%	33.33	75.98	30.86	73.23	16.72%	363.3	3582.6	3219.3	7.47%	0.229	36.90	55.93	8.00	100.0%	84.26%
	2200	20	46.51%	33825152	44.00%	31.05	74.72	28.02	67.50	16.99%	459.5	3678.7	3219.3	9.18%	0.229	34.07	53.08	8.00	100.0%	77.28%
	2200	40	60.53%	50303719	32.74%	27.44	70.18	23.57	61.71	17.39%	613.4	3832.7	3219.3	11.81%	0.229	30.04	46.79	8.00	100.0%	42.82%
	2200	70	62.47%	73335701	27.28%	26.88	55.41	22.89	42.96	17.45%	626.3	3845.5	3219.3	12.18%	0.229	27.93	53.66	8.00	10.6%	3.07%
	2200	100	62.47%	101502607	26.43%	26.88	55.41	22.89	42.96	17.45%	626.3	3845.5	3219.3	12.18%	0.229	26.15	55.52	8.00	8.8%	1.57%

Appendix A.6

Table 12. Performance analysis results for Imperial, California and Portland, Oregon commercial systems.

	Size	Occ/gpm	n_t	$Btu_{savings}$	$\%Btu_{PVT}$	$T_{HTF-Avg}$	$T_{HTF-Max}$	$T_{cell-Avg}$	$T_{cell-Max}$	n_e	ΔkWh	kWh_{PVT}	kWh_{PV}	$\%\Delta n$	[kg/min/m^2]	$T_{tank-Avg}$	$T_{tank-Max}$	V_{tank}	$\%V_{Max}$	$\%V_{Avg}$
Imperial, California	10000	0.75	42.61%	85665394	40.31%	47.83	109.25	43.42	109.25	15.57%	2709.3	18734.3	16025.0	12.34%	0.200	45.40	57.98	10.00	100.0%	93.31%
	10000	1.5	56.95%	169280812	39.83%	43.20	68.51	37.31	55.00	16.14%	3596.5	19621.5	16025.0	16.43%	0.200	45.32	55.02	10.00	100.0%	72.56%
	10000	3	56.96%	249949575	29.41%	43.20	68.51	37.31	55.00	16.14%	3596.5	19621.5	16025.0	16.43%	0.200	39.00	66.56	10.00	10.0%	4.36%
	10000	6	56.96%	749571221	44.09%	43.20	68.51	37.31	55.00	16.14%	3596.5	19621.5	16025.0	16.43%	0.200	36.98	68.97	10.00	8.0%	1.18%
	25000	1.75	31.59%	289674634	54.89%	51.30	88.73	47.98	84.36	15.15%	4790.6	44567.9	39777.3	9.28%	0.200	53.85	70.36	25.00	100.0%	93.54%
	25000	3.5	42.89%	497763352	47.16%	47.67	87.42	43.19	82.60	15.59%	6611.5	46388.8	39777.3	12.51%	0.200	49.68	68.04	25.00	100.0%	72.22%
	25000	7	56.96%	620559105	29.40%	43.19	68.49	37.31	54.99	16.14%	8929.0	48706.3	39777.3	16.43%	0.200	38.99	66.54	25.00	10.0%	4.33%
	25000	15	56.96%	1861119343	44.08%	43.19	68.49	37.31	54.99	16.14%	8929.0	48706.3	39777.3	16.43%	0.200	36.99	68.95	25.00	7.6%	1.17%
	50000	3.75	31.59%	575375610	54.89%	51.30	88.74	47.97	84.36	15.15%	9513.4	88526.2	79012.8	9.28%	0.200	53.85	70.33	50.00	100.0%	93.58%
	50000	7.5	42.89%	988753530	47.16%	47.67	87.43	43.19	82.60	15.59%	13130.2	92143.0	79012.8	12.51%	0.200	49.68	68.01	50.00	100.0%	72.25%
	50000	15	56.96%	1232640072	29.40%	43.19	68.49	37.31	54.99	16.14%	17736.0	96748.8	79012.8	16.43%	0.200	38.99	66.54	50.00	10.0%	4.30%
	50000	29	56.96%	3696721931	44.08%	43.19	68.49	37.31	54.99	16.14%	17736.0	96748.8	79012.8	16.43%	0.200	36.99	68.95	50.00	7.6%	1.17%
	100000	7.25	31.59%	1150563560	54.89%	51.30	88.74	47.97	84.36	15.15%	19023.6	177020.7	157997.1	9.28%	0.200	53.85	70.33	100.00	99.9%	93.58%
	100000	14.5	42.89%	1977168175	47.16%	47.67	87.42	43.19	82.60	15.59%	26256.0	184253.1	157997.1	12.51%	0.200	49.68	68.01	100.00	99.9%	72.25%
	100000	29	56.96%	2464861896	29.40%	43.19	68.49	37.31	54.99	16.14%	35465.9	193463.0	157997.1	16.43%	0.200	38.99	66.54	100.00	10.1%	4.30%
	100000	59	56.96%	9539503530	56.88%	43.19	68.49	37.31	54.99	16.14%	35465.9	193463.0	157997.1	16.43%	0.200	36.95	68.95	100.00	7.6%	0.71%
	200000	14.75	74.68%	1057378521	25.23%	37.35	62.80	30.02	47.99	16.77%	86107.4	402101.6	315994.3	21.01%	0.200	35.93	50.04	100.00	99.9%	92.06%
	200000	29.5	43.33%	3918365006	46.73%	47.53	87.17	43.01	82.74	15.61%	53254.4	369248.7	315994.3	12.64%	0.200	49.43	71.65	100.00	99.9%	66.65%
	200000	59	56.96%	4929574606	29.39%	43.19	68.49	37.31	54.99	16.14%	70931.7	386926.0	315994.3	16.43%	0.200	38.96	66.57	100.00	20.0%	8.50%
	200000	117	56.96%	6402449602	34.27%	43.19	68.49	37.31	54.99	16.14%	70931.7	386926.0	315994.3	16.43%	0.200	36.94	68.94	100.00	15.1%	2.23%
Portland, Oregon	10000	0.75	37.53%	82213571	32.52%	31.67	75.38	29.28	74.41	20.37%	1332.5	14248.1	12915.6	6.29%	0.200	34.32	58.32	10.00	100.0%	83.90%
	10000	1.5	56.17%	127079919	25.13%	27.54	74.53	24.00	67.75	20.95%	2064.3	14979.9	12915.6	9.28%	0.200	29.69	55.25	10.00	100.0%	70.09%
	10000	3	61.13%	199844524	19.76%	26.46	55.36	22.62	43.09	21.09%	2271.0	15186.6	12915.6	10.00%	0.200	24.27	53.40	10.00	10.0%	2.75%
	10000	6	61.13%	714359251	35.32%	26.46	55.36	22.62	43.09	21.09%	2271.0	15186.6	12915.6	10.00%	0.200	23.39	55.68	10.00	8.0%	0.99%
	25000	1.75	37.55%	204102532	32.51%	31.67	75.36	29.27	74.41	20.37%	3309.8	35369.0	32059.3	6.29%	0.200	34.32	58.26	25.00	100.0%	83.93%
	25000	3.5	47.36%	349235546	27.81%	29.49	74.50	26.49	67.72	20.68%	4280.4	36339.7	32059.3	7.88%	0.200	31.59	55.70	25.00	100.0%	69.81%
	25000	7	61.13%	496187367	19.76%	26.46	55.34	22.62	43.08	21.09%	5637.8	37697.1	32059.3	10.00%	0.200	24.27	53.38	25.00	10.0%	2.73%
	25000	15	61.13%	1774074679	35.32%	26.46	55.34	22.62	43.08	21.09%	5637.8	37697.1	32059.3	10.00%	0.200	23.38	55.66	25.00	7.6%	0.99%
	50000	3.75	37.57%	405332147	32.50%	31.67	75.35	29.27	74.41	20.38%	6575.9	70257.7	63681.9	6.29%	0.200	34.32	58.21	50.00	100.0%	83.98%
	50000	7.5	47.36%	693712055	27.81%	29.49	74.49	26.49	67.70	20.68%	8502.0	72183.8	63681.9	7.88%	0.200	31.59	55.66	50.00	100.0%	69.83%
	50000	15	61.13%	985591178	19.76%	26.46	55.34	22.62	43.08	21.09%	11198.7	74880.5	63681.9	10.00%	0.200	24.27	53.38	50.00	10.0%	2.72%
	50000	29	61.13%	3523812913	35.32%	26.46	55.34	22.62	43.08	21.09%	11198.7	74880.5	63681.9	10.00%	0.200	23.38	55.66	50.00	7.6%	0.98%
	100000	7.25	37.57%	810531760	32.50%	31.67	75.35	29.27	74.41	20.38%	13149.6	140490.3	127340.7	6.29%	0.200	34.32	58.21	100.00	99.9%	83.98%
	100000	14.5	47.36%	1387181309	27.81%	29.49	74.49	26.49	67.69	20.68%	17001.1	144341.9	127340.7	7.88%	0.200	31.59	55.66	100.00	99.9%	69.83%
	100000	29	61.13%	1970853208	19.76%	26.46	55.34	22.62	43.08	21.09%	22393.5	149734.2	127340.7	10.00%	0.200	24.27	53.38	100.00	10.1%	2.72%
	100000	59	61.13%	9694882312	51.90%	26.46	55.34	22.62	43.08	21.09%	22393.5	149734.2	127340.7	10.00%	0.200	23.35	55.66	100.00	7.6%	0.49%
	200000	14.75	37.34%	1605778912	32.19%	31.71	76.86	29.33	75.32	20.37%	26173.2	280854.7	254681.5	6.28%	0.200	34.12	62.85	100.00	99.9%	80.54%
	200000	29.5	47.42%	2751802667	27.59%	29.47	76.21	26.46	75.32	20.68%	33953.2	288634.7	254681.5	7.89%	0.200	31.40	61.16	100.00	99.9%	65.85%
	200000	59	61.13%	3254503312	17.42%	26.46	55.34	22.62	43.08	21.09%	44786.9	299468.4	254681.5	10.00%	0.200	24.24	53.40	100.00	20.0%	5.33%
	200000	117	61.13%	5057023701	27.07%	26.46	55.34	22.62	43.08	21.09%	44786.9	299468.4	254681.5	10.00%	0.200	23.34	55.66	100.00	15.1%	1.86%

Appendix A.7

Table 13. Performance analysis results for Riverton, Wyoming and Sacramento, California commercial systems.

	Size	Occ/gpm	n_t	$Btu_{savings}$	$\%Btu_{PVT}$	$T_{HTF\text{-}Avg}$	$T_{HTF\text{-}Max}$	$T_{cell\text{-}Avg}$	$T_{cell\text{-}Max}$	n_e	ΔkWh	kWh_{PVT}	kWh_{PV}	$\%\Delta n$	$[kg/min/m^2]$	$T_{tank\text{-}Avg}$	$T_{tank\text{-}Max}$	V_{tank}	$\%V_{Max}$	$\%V_{Avg}$
Riverton, Wyoming	10000	0.75	36.05%	94509933	34.86%	30.14	76.41	27.26	70.32	18.25%	1563.7	16113.5	14549.8	7.35%	0.200	32.11	56.45	10.00	100.0%	86.06%
	10000	1.5	49.93%	155242031	28.63%	26.44	75.12	22.50	70.32	18.71%	2224.0	16773.8	14549.8	10.03%	0.200	27.86	55.03	10.00	100.0%	66.81%
	10000	3	60.60%	228736225	21.09%	23.60	54.96	18.87	40.64	19.07%	2753.4	17303.2	14549.8	12.18%	0.200	20.88	53.15	10.00	41.0%	5.08%
	10000	6	60.60%	816212551	37.63%	23.60	54.96	18.87	40.64	19.07%	2753.4	17303.2	14549.8	12.18%	0.200	19.63	55.17	10.00	19.0%	1.21%
	25000	1.75	36.07%	234914454	34.89%	30.13	76.39	27.24	70.32	18.25%	3884.7	40000.2	36115.6	7.36%	0.200	32.12	56.41	25.00	100.0%	86.09%
	25000	3.5	43.59%	414633447	30.79%	28.11	75.09	24.65	70.32	18.50%	4751.1	40866.6	36115.6	8.80%	0.200	29.51	54.98	25.00	100.0%	66.68%
	25000	7	60.60%	567429414	21.07%	23.60	54.94	18.86	40.63	19.07%	6835.9	42951.5	36115.6	12.18%	0.200	20.87	53.13	25.00	40.4%	5.04%
	25000	15	60.60%	2026877077	37.63%	23.60	54.94	18.86	40.63	19.07%	6835.9	42951.5	36115.6	12.18%	0.200	19.63	55.15	25.00	19.2%	1.20%
	50000	3.75	36.06%	466577967	34.88%	30.13	76.38	27.25	70.32	18.25%	7713.3	79452.6	71739.2	7.36%	0.200	32.12	56.37	50.00	100.0%	86.11%
	50000	7.5	43.61%	823462171	30.78%	28.10	75.08	24.64	70.32	18.50%	9441.0	81180.3	71739.2	8.81%	0.200	29.51	54.95	50.00	100.0%	66.72%
	50000	15	60.60%	1127103770	21.07%	23.60	54.94	18.86	40.63	19.07%	13578.5	85317.7	71739.2	12.18%	0.200	20.87	53.13	50.00	40.0%	5.01%
	50000	29	60.60%	4025950440	37.63%	23.60	54.94	18.86	40.63	19.07%	13578.5	85317.7	71739.2	12.18%	0.200	19.63	55.16	50.00	19.2%	1.20%
	100000	7.25	36.06%	933003337	34.88%	30.13	76.38	27.25	70.32	18.25%	15424.2	158876.8	143452.6	7.36%	0.200	32.12	56.37	100.00	99.9%	86.11%
	100000	14.5	43.61%	1646652166	30.78%	28.10	75.08	24.64	70.32	18.50%	18878.9	162331.5	143452.6	8.81%	0.200	29.51	54.94	100.00	99.9%	66.72%
	100000	29	60.60%	2253828077	21.07%	23.60	54.94	18.86	40.63	19.07%	27152.3	170604.9	143452.6	12.18%	0.200	20.87	53.13	100.00	40.0%	5.01%
	100000	59	60.60%	9759563315	52.24%	23.60	54.94	18.86	40.63	19.07%	27152.3	170604.9	143452.6	12.18%	0.200	19.60	55.15	100.00	19.2%	0.69%
	200000	14.75	35.95%	1848820358	34.56%	30.15	76.93	27.28	75.59	18.25%	30685.4	317590.6	286905.2	7.34%	0.200	31.78	60.98	100.00	99.9%	82.03%
	200000	29.5	43.40%	3273085878	30.59%	28.13	76.01	24.69	71.76	18.49%	37450.6	324355.7	286905.2	8.77%	0.200	29.29	60.50	100.00	99.9%	65.81%
	200000	59	60.60%	2907743063	15.56%	23.60	54.94	18.86	40.63	19.07%	54304.6	341209.7	286905.2	12.18%	0.200	20.85	53.15	100.00	79.9%	9.92%
	200000	117	60.60%	5359508473	28.69%	23.60	54.94	18.86	40.63	19.07%	54304.6	341209.7	286905.2	12.18%	0.200	19.59	55.07	100.00	38.3%	2.29%
Sacramento, California	10000	0.75	32.01%	101298802	43.89%	41.12	83.31	38.26	81.23	17.63%	1683.7	16986.3	15302.6	7.28%	0.200	44.93	65.57	10.00	100.0%	81.99%
	10000	1.5	55.08%	144837546	31.38%	34.79	63.10	29.94	49.72	18.43%	3024.7	18327.3	15302.6	12.13%	0.200	37.89	50.13	10.00	100.0%	71.36%
	10000	3	55.08%	222248312	24.07%	34.79	63.10	29.94	49.72	18.43%	3024.7	18327.3	15302.6	12.13%	0.200	32.05	60.91	10.00	10.0%	2.50%
	10000	6	55.08%	742784927	40.23%	34.79	63.10	29.94	49.72	18.43%	3024.7	18327.3	15302.6	12.13%	0.200	30.92	63.03	10.00	8.0%	0.95%
	25000	1.75	32.03%	251670461	43.90%	41.12	83.29	38.25	81.23	17.63%	4182.0	42166.3	37984.3	7.28%	0.200	44.93	65.52	25.00	100.0%	82.02%
	25000	3.5	42.42%	421810859	36.79%	38.26	81.91	34.49	77.52	18.00%	5752.8	43737.1	37984.3	9.51%	0.200	41.41	63.67	25.00	100.0%	70.99%
	25000	7	55.09%	552167369	24.08%	34.79	63.09	29.94	49.71	18.43%	7509.2	45493.5	37984.3	12.13%	0.200	32.04	60.89	25.00	10.0%	2.48%
	25000	15	55.09%	1844564541	40.22%	34.79	63.09	29.94	49.71	18.43%	7509.2	45493.5	37984.3	12.13%	0.200	30.91	63.01	25.00	7.6%	0.95%
	50000	3.75	32.03%	499732457	43.89%	41.12	83.28	38.25	81.23	17.64%	8307.7	83758.9	75451.2	7.29%	0.200	44.93	65.48	50.00	100.0%	82.04%
	50000	7.5	42.43%	837830982	36.79%	38.25	81.90	34.49	77.52	18.00%	11429.5	86880.7	75451.2	9.51%	0.200	41.41	63.63	50.00	100.0%	71.01%
	50000	15	55.09%	1096788863	24.08%	34.79	63.09	29.94	49.71	18.43%	14915.9	90367.1	75451.2	12.13%	0.200	32.05	60.89	50.00	10.0%	2.47%
	50000	29	55.09%	3663829090	40.22%	34.79	63.09	29.94	49.71	18.43%	14915.9	90367.1	75451.2	12.13%	0.200	30.91	63.01	50.00	7.6%	0.94%
	100000	7.25	32.03%	999301900	43.89%	41.12	83.28	38.25	81.23	17.64%	16612.8	167487.9	150875.2	7.29%	0.200	44.93	65.48	100.00	99.9%	82.04%
	100000	14.5	42.43%	1675372252	36.79%	38.25	81.90	34.49	77.52	18.00%	22855.2	173730.3	150875.2	9.51%	0.200	41.41	63.63	100.00	99.9%	71.01%
	100000	29	55.09%	2193208224	24.08%	34.79	63.09	29.94	49.71	18.43%	29826.6	180701.8	150875.2	12.13%	0.200	32.05	60.89	100.00	10.1%	2.47%
	100000	59	55.09%	10175416740	55.86%	34.79	63.09	29.94	49.71	18.43%	29826.6	180701.8	150875.2	12.13%	0.200	30.88	63.01	100.00	7.6%	0.50%
	200000	14.75	31.72%	1974165297	43.35%	41.22	84.03	38.38	81.84	17.62%	33039.1	334789.4	301750.3	7.21%	0.200	44.70	70.03	100.00	99.9%	80.10%
	200000	29.5	42.43%	3313736721	36.38%	38.26	82.44	34.49	81.23	18.00%	45518.0	347268.4	301750.3	9.50%	0.200	41.20	67.37	100.00	99.9%	66.02%
	200000	59	55.09%	4386129054	24.08%	34.79	63.09	29.94	49.71	18.43%	59653.3	361403.6	301750.3	12.13%	0.200	32.01	60.90	100.00	20.0%	4.83%
	200000	117	55.09%	5831810170	31.22%	34.79	63.09	29.94	49.71	18.43%	59653.3	361403.6	301750.3	12.13%	0.200	30.86	63.04	100.00	15.1%	1.78%

Appendix A.8

Table 14. Performance analysis results for Salt Lake City, Utah commercial systems.

	Size	**Occ/gpm**	**n_t**	**$Btu_{savings}$**	**$\%Btu_{PVT}$**	**$T_{HTF-Avg}$**	**$T_{HTF-Max}$**	**$T_{cell-Avg}$**	**$T_{cell-Max}$**	**n_e**	**ΔkWh**	**kWh_{PVT}**	**kWh_{PV}**	**$\%\Delta n$**	**[kg/min/m^2]**	**$T_{tank-Avg}$**	**$T_{tank-Max}$**	**V_{tank}**	**$\%V_{Max}$**	**$\%V_{Avg}$**
Salt Lake City, Utah	10000	0.75	34.67%	95730075	37.87%	34.09	79.12	31.35	73.34	18.01%	1545.3	16512.6	14967.3	6.94%	0.200	37.44	61.07	10.00	100.0%	84.17%
	10000	1.5	48.66%	159182650	31.48%	30.69	78.32	26.88	73.34	18.47%	2202.0	17169.3	14967.3	9.64%	0.200	33.53	59.54	10.00	100.0%	70.08%
	10000	3	59.85%	232478820	22.99%	27.95	59.21	23.31	44.92	18.81%	2769.5	17736.8	14967.3	11.66%	0.200	25.48	57.30	10.00	14.0%	3.20%
	10000	6	59.85%	786984143	38.91%	27.95	59.21	23.31	44.92	18.81%	2769.5	17736.8	14967.3	11.66%	0.200	24.49	59.87	10.00	11.0%	1.03%
	25000	1.75	34.68%	237786617	37.87%	34.09	79.10	31.35	73.34	18.01%	3837.1	40989.1	37151.9	6.94%	0.200	37.44	61.03	25.00	100.0%	84.20%
	25000	3.5	44.05%	415367976	33.08%	31.80	78.30	28.34	73.34	18.32%	4913.3	42065.2	37151.9	8.74%	0.200	34.65	59.49	25.00	100.0%	69.87%
	25000	7	59.86%	577206483	22.98%	27.95	59.19	23.31	44.91	18.81%	6875.7	44027.6	37151.9	11.66%	0.200	25.47	57.28	25.00	13.6%	3.18%
	25000	15	59.86%	1954425872	38.91%	27.95	59.19	23.31	44.91	18.81%	6875.7	44027.6	37151.9	11.66%	0.200	24.48	59.85	25.00	10.8%	1.03%
	50000	3.75	34.65%	472520711	37.89%	34.10	79.10	31.36	73.34	18.01%	7617.0	81414.8	73797.9	6.93%	0.200	37.44	61.00	50.00	100.0%	84.22%
	50000	7.5	44.05%	825060930	33.08%	31.80	78.30	28.34	73.34	18.32%	9759.5	83557.3	73797.9	8.74%	0.200	34.65	59.46	50.00	100.0%	69.89%
	50000	15	59.86%	1146522383	22.98%	27.95	59.19	23.31	44.91	18.81%	13657.5	87455.3	73797.9	11.66%	0.200	25.47	57.29	50.00	13.4%	3.16%
	50000	29	59.86%	3882041377	38.91%	27.95	59.19	23.31	44.91	18.81%	13657.5	87455.3	73797.9	11.66%	0.200	24.48	59.85	50.00	11.0%	1.02%
	100000	7.25	34.65%	944873360	37.89%	34.10	79.10	31.36	73.34	18.01%	15231.5	162800.5	147569.1	6.93%	0.200	37.44	61.00	100.00	99.9%	84.22%
	100000	14.5	44.05%	1649835735	33.08%	31.80	78.30	28.34	73.34	18.32%	19515.7	167084.8	147569.1	8.74%	0.200	34.65	59.46	100.00	99.9%	69.89%
	100000	29	59.86%	2292660541	22.98%	27.95	59.19	23.31	44.91	18.81%	27310.3	174879.4	147569.1	11.66%	0.200	25.47	57.28	100.00	13.4%	3.16%
	100000	59	59.86%	10567410435	56.57%	27.95	59.19	23.31	44.91	18.81%	27310.3	174879.4	147569.1	11.66%	0.200	24.45	59.84	100.00	10.9%	0.53%
	200000	14.75	35.05%	1872383371	37.54%	33.98	80.96	31.21	80.96	18.03%	30662.8	325801.0	295138.2	7.02%	0.200	37.14	65.24	100.00	99.9%	81.29%
	200000	29.5	44.22%	3271634446	32.80%	31.75	79.17	28.28	73.51	18.32%	39199.9	334338.1	295138.2	8.76%	0.200	34.42	63.87	100.00	99.9%	65.55%
	200000	59	59.86%	3831737948	20.51%	27.95	59.19	23.31	44.91	18.81%	54620.6	349758.8	295138.2	11.66%	0.200	25.45	57.37	100.00	26.7%	6.21%
	200000	117	59.86%	5583781289	29.89%	27.95	59.19	23.31	44.91	18.81%	54620.6	349758.8	295138.2	11.66%	0.200	24.45	59.97	100.00	21.7%	1.94%

Appendix B.1

Table 15. Economic analysis results for Imperial, California.

Size	Occ/ gpm	PV				SC w/ Install				SC w/o Install				PVT w/ Install				PVT w/o Install			
		NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs
3000	2	2,154	3.57	0.071	14.2	7,322	#NUM!	0.229	0.0	5,172	#NUM!	0.152	0.0	5,713	1.68	0.072	22.0	4,423	2.20	0.064	19.4
	3	2,154	3.57	0.071	14.2	7,116	#NUM!	0.153	0.0	4,966	#NUM!	0.101	0.0	5,507	1.84	0.066	21.0	4,217	2.36	0.058	18.4
	5	2,154	3.57	0.071	14.2	6,705	#NUM!	0.092	0.0	4,555	#NUM!	0.061	0.0	5,095	2.15	0.056	19.1	3,805	2.67	0.049	16.8
	8	2,154	3.57	0.071	14.2	6,096	-7.46	0.058	0.0	3,946	-5.93	0.038	0.0	4,487	2.56	0.045	17.0	3,197	3.09	0.040	14.9
	12	2,154	3.57	0.071	14.2	5,320	-2.46	0.039	93.6	3,170	-0.85	0.026	62.1	3,711	3.04	0.037	14.9	2,421	3.57	0.032	13.1
5000	2	3,168	3.73	0.068	13.7	10,648	#NUM!	0.325	0.0	8,148	#NUM!	0.236	0.0	8,199	2.07	0.072	19.6	6,699	2.45	0.066	17.9
	5	3,168	3.73	0.068	13.7	10,033	#NUM!	0.131	0.0	7,533	#NUM!	0.095	0.0	7,584	2.35	0.061	18.1	6,084	2.73	0.055	16.5
	10	3,168	3.73	0.068	13.7	9,010	-11.96	0.066	0.0	6,510	-10.83	0.048	0.0	6,561	2.77	0.048	16.0	5,061	3.15	0.044	14.6
	15	3,168	3.73	0.068	13.7	8,008	-3.64	0.044	150.2	5,508	-2.40	0.032	109.1	5,559	3.15	0.040	14.4	4,059	3.53	0.036	13.1
	20	3,168	3.73	0.068	13.7	7,040	-1.21	0.034	59.9	4,540	0.07	0.024	43.5	4,591	3.49	0.034	13.2	3,091	3.87	0.031	12.0
10000	3	5,589	3.82	0.067	13.0	19,316	#NUM!	0.390	0.0	15,316	#NUM!	0.295	0.0	14,545	2.26	0.071	18.6	12,145	2.58	0.066	17.2
	5	5,589	3.82	0.067	13.0	18,904	#NUM!	0.235	0.0	14,904	#NUM!	0.178	0.0	14,134	2.35	0.067	18.1	11,734	2.68	0.062	16.7
	10	5,589	3.82	0.067	13.0	17,883	#NUM!	0.118	0.0	13,883	#NUM!	0.090	0.0	13,112	2.59	0.058	16.9	10,712	2.91	0.053	15.6
	20	5,589	3.82	0.067	13.0	15,834	-8.05	0.059	0.0	11,834	-7.02	0.045	0.0	11,063	3.02	0.046	15.0	8,663	3.34	0.042	13.8
	30	5,589	3.82	0.067	13.0	13,860	-2.66	0.040	100.6	9,860	-1.57	0.030	76.1	9,090	3.39	0.038	13.5	6,690	3.72	0.035	12.5
20000	5	4,953	4.07	0.065	12.6	32,313	#NUM!	0.426	0.0	25,713	#NUM!	0.333	0.0	16,025	3.20	0.069	15.9	12,065	3.48	0.065	14.8
	10	4,953	4.07	0.065	12.6	31,210	#NUM!	0.215	0.0	24,610	#NUM!	0.167	0.0	14,922	3.30	0.064	15.4	10,962	3.59	0.059	14.4
	20	4,953	4.07	0.065	12.6	29,012	-8.76	0.108	0.0	22,412	-7.85	0.084	0.0	12,724	3.50	0.055	14.5	8,764	3.79	0.051	13.5
	35	4,953	4.07	0.065	12.6	25,726	-3.32	0.062	131.6	19,126	-2.35	0.048	102.7	9,438	3.78	0.046	13.3	5,478	4.07	0.043	12.4
	50	4,953	4.07	0.065	12.6	22,475	-1.11	0.044	58.4	15,875	-0.13	0.034	45.6	6,187	4.04	0.039	12.3	2,227	4.33	0.037	11.5
275	2	201	3.54	0.071	14.3	1,855	-8.91	0.062	0.0	355	-3.15	0.013	0.0	1,079	0.99	0.041	33.7	179	3.86	0.020	16.7
	3	201	3.54	0.071	14.3	1,674	-3.58	0.044	152.7	174	2.52	0.010	32.9	898	1.91	0.032	24.6	2	4.81	0.016	12.2
	5	201	3.54	0.071	14.3	1,411	-0.66	0.031	51.1	89	5.62	0.007	11.0	634	2.98	0.024	17.9	266	5.90	0.012	8.9
	8	201	3.54	0.071	14.3	1,063	1.45	0.023	27.2	437	7.87	0.005	5.9	286	4.07	0.018	13.4	614	7.03	0.009	6.7
	12	201	3.54	0.071	14.3	596	3.25	0.016	16.7	904	9.78	0.004	3.6	180	5.20	0.014	10.1	1,080	8.19	0.007	5.0
550	3	406	3.52	0.072	14.4	2,230	-5.24	0.050	374.9	630	-1.07	0.017	127.6	1,346	2.00	0.038	21.9	386	3.78	0.024	14.2
	5	406	3.52	0.072	14.4	1,823	-0.88	0.032	54.0	223	3.49	0.011	18.4	940	3.05	0.027	16.3	20	4.85	0.018	10.6
	10	406	3.52	0.072	14.4	1,169	2.08	0.020	22.7	431	6.58	0.007	7.7	285	4.34	0.019	11.6	675	6.16	0.012	7.5
	15	406	3.52	0.072	14.4	557	3.71	0.015	14.7	1,043	8.28	0.005	5.0	327	5.27	0.015	9.3	1,287	7.11	0.009	6.0
	25	406	3.52	0.072	14.4	382	4.08	0.014	13.4	1,218	8.67	0.005	4.6	502	5.51	0.014	8.8	1,462	7.35	0.009	5.7
1100	5	813	3.52	0.072	14.4	2,855	-2.92	0.041	112.5	1,155	-0.13	0.020	55.4	1,815	2.70	0.035	16.8	795	3.74	0.027	13.0
	10	813	3.52	0.072	14.4	1,839	1.51	0.022	26.6	139	4.43	0.011	13.1	800	4.00	0.023	12.1	220	5.05	0.018	9.4
	20	813	3.52	0.072	14.4	509	4.11	0.014	13.3	1,191	7.10	0.007	6.6	531	5.26	0.016	8.8	1,551	6.33	0.012	6.8
	35	813	3.52	0.072	14.4	103	4.67	0.013	11.6	1,597	7.68	0.006	5.7	937	5.59	0.014	8.2	1,957	6.66	0.011	6.4
	50	813	3.52	0.072	14.4	1,573	6.43	0.009	7.5	3,273	9.48	0.004	3.7	2,613	6.71	0.011	6.4	3,633	7.80	0.008	5.0
2200	10	1,618	3.53	0.072	14.3	3,898	-0.85	0.032	53.5	1,998	0.97	0.020	34.0	2,547	3.26	0.032	14.0	1,407	3.88	0.027	12.0
	20	1,618	3.53	0.072	14.3	1,859	2.96	0.017	17.9	41	4.85	0.011	11.4	509	4.53	0.021	10.3	631	5.16	0.018	8.8
	40	1,618	3.53	0.072	14.3	287	5.03	0.012	10.6	2,187	6.95	0.007	6.7	1,637	5.56	0.015	8.0	2,777	6.19	0.013	6.9
	70	1,618	3.53	0.072	14.3	2,087	6.22	0.009	7.8	3,987	8.17	0.006	5.0	3,438	6.27	0.012	6.8	4,578	6.91	0.011	5.9
	100	1,618	3.53	0.072	14.3	4,971	7.65	0.007	5.6	6,871	9.63	0.004	3.5	6,321	7.22	0.009	5.6	7,461	7.86	0.008	4.8
10000	0.75	5,426	3.85	0.066	12.9	10,659	0.52	0.026	35.3	6,659	1.64	0.020	26.7	5,725	3.97	0.029	11.0	3,325	4.30	0.027	10.2
	1.5	5,426	3.85	0.066	12.9	1,601	4.37	0.013	12.4	2,399	5.54	0.010	9.4	3,333	5.22	0.018	8.2	5,733	5.55	0.017	7.6
	3	5,426	3.85	0.066	12.9	7,138	6.32	0.009	7.7	11,138	7.51	0.007	5.8	12,072	6.16	0.014	6.8	14,472	6.50	0.013	6.2
	6	5,426	3.85	0.066	12.9	61,263	11.51	0.003	2.3	65,263	12.76	0.002	1.7	66,197	9.64	0.005	3.2	68,597	9.98	0.005	3.0
25000	1.75	4,625	4.18	0.063	12.3	7,424	3.57	0.017	15.3	826	4.62	0.014	11.9	14,215	5.24	0.023	8.9	19,165	5.54	0.021	8.3
	3.5	4,625	4.18	0.063	12.3	16,794	6.08	0.010	8.1	25,044	7.16	0.008	6.3	38,432	6.27	0.015	6.9	43,382	6.57	0.014	6.5
	7	4,625	4.18	0.063	12.3	31,085	7.08	0.008	6.4	39,335	8.17	0.006	4.9	52,723	6.78	0.013	6.0	57,673	7.08	0.012	5.6
	15	4,625	4.18	0.063	12.3	175,463	12.07	0.003	2.0	183,713	13.21	0.002	1.6	197,101	10.09	0.005	3.0	202,051	10.40	0.005	2.8
50000	3.75	401	4.51	0.058	11.3	10,924	3.79	0.017	14.4	5,076	4.88	0.013	11.1	39,090	5.56	0.021	8.3	48,690	5.87	0.020	7.7
	7.5	401	4.51	0.058	11.3	37,186	6.30	0.010	7.7	53,186	7.41	0.007	5.9	87,200	6.59	0.014	6.4	96,800	6.90	0.013	6.0
	15	401	4.51	0.058	11.3	65,570	7.30	0.008	6.0	81,570	8.42	0.006	4.7	115,583	7.10	0.012	5.6	125,183	7.41	0.011	5.2
	29	401	4.51	0.058	11.3	352,342	12.29	0.003	1.9	368,342	13.47	0.002	1.5	402,356	10.40	0.005	2.8	411,956	10.73	0.004	2.6
100000	7.25	27,757	5.04	0.051	10.0	6,873	4.27	0.015	12.8	18,127	5.19	0.012	10.3	110,749	6.08	0.019	7.4	125,749	6.35	0.018	6.9
	14.5	27,757	5.04	0.051	10.0	89,328	6.76	0.009	6.9	114,328	7.70	0.007	5.5	206,950	7.10	0.013	5.7	221,950	7.38	0.012	5.4
	29	27,757	5.04	0.051	10.0	146,086	7.76	0.007	5.4	171,086	8.71	0.006	4.3	263,708	7.61	0.011	5.0	278,708	7.89	0.010	4.7
	59	27,757	5.04	0.051	10.0	969,440	13.93	0.002	1.3	994,440	14.94	0.001	1.1	1,087,062	11.85	0.003	2.0	1,102,062	12.13	0.003	1.9
200000	14.75	91,514	5.43	0.047	9.1	133,813	0.93	0.030	31.3	93,813	1.71	0.025	25.9	123,661	5.53	0.025	7.3	147,661	5.77	0.024	6.9
	29.5	91,514	5.43	0.047	9.1	199,151	7.13	0.008	6.3	239,151	7.95	0.007	5.2	456,626	7.50	0.012	5.2	480,626	7.74	0.011	4.9
	59	91,514	5.43	0.047	9.1	316,837	8.18	0.006	4.9	356,837	9.00	0.005	4.1	574,311	8.03	0.010	4.5	598,311	8.27	0.009	4.3
	117	91,514	5.43	0.047	9.1	488,251	9.36	0.005	3.7	528,251	10.20	0.004	3.1	745,726	8.70	0.008	3.9	769,726	8.94	0.007	3.7

Appendix B.2

Table 16. Economic analysis results for Portland, Oregon.

Size	Occ/ gpm	PV				SC w/ Install				SC w/o Install				PVT w/ Install				PVT w/o Install			
		NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs
3000	2	3,494	2.57	0.088	18.1	7,295	#NUM!	0.215	0.0	5,145	#NUM!	0.142	0.0	7,024	0.46	0.085	29.8	5,734	0.97	0.075	26.2
	3	3,494	2.57	0.088	18.1	7,086	#NUM!	0.146	0.0	4,936	#NUM!	0.096	0.0	6,816	0.68	0.076	28.0	5,526	1.19	0.067	24.6
	5	3,494	2.57	0.088	18.1	6,677	#NUM!	0.089	0.0	4,527	#NUM!	0.059	0.0	6,407	1.08	0.063	25.0	5,117	1.59	0.055	22.0
	8	3,494	2.57	0.088	18.1	6,117	-7.75	0.058	0.0	3,967	-6.22	0.039	0.0	5,847	1.57	0.051	21.8	4,557	2.09	0.045	19.2
	12	3,494	2.57	0.088	18.1	5,532	-3.33	0.043	132.4	3,382	-1.72	0.028	87.8	5,261	2.02	0.043	19.2	3,971	2.55	0.038	16.9
5000	2	5,482	2.74	0.085	17.4	10,606	#NUM!	0.295	0.0	8,106	#NUM!	0.214	0.0	10,471	0.85	0.086	26.2	8,971	1.23	0.078	23.9
	5	5,482	2.74	0.085	17.4	9,975	#NUM!	0.124	0.0	7,475	#NUM!	0.090	0.0	9,840	1.23	0.070	23.6	8,340	1.60	0.064	21.5
	10	5,482	2.74	0.085	17.4	8,979	-11.14	0.065	0.0	6,479	-9.99	0.047	0.0	8,844	1.76	0.054	20.4	7,344	2.14	0.049	18.6
	15	5,482	2.74	0.085	17.4	8,083	-3.91	0.045	170.1	5,583	-2.67	0.033	123.5	7,948	2.18	0.045	18.2	6,448	2.56	0.041	16.6
	20	5,482	2.74	0.085	17.4	7,339	-1.82	0.036	73.6	4,839	-0.55	0.026	53.4	7,204	2.51	0.040	16.7	5,704	2.89	0.036	15.2
10000	3	10,090	2.82	0.083	16.4	19,240	#NUM!	0.348	0.0	15,240	#NUM!	0.264	0.0	18,971	1.04	0.085	24.9	16,571	1.36	0.079	23.0
	5	10,090	2.82	0.083	16.4	18,815	#NUM!	0.216	0.0	14,815	#NUM!	0.164	0.0	18,546	1.18	0.079	24.0	16,146	1.50	0.073	22.2
	10	10,090	2.82	0.083	16.4	17,777	#NUM!	0.113	0.0	13,777	#NUM!	0.085	0.0	17,508	1.48	0.067	22.0	15,108	1.80	0.062	20.3
	20	10,090	2.82	0.083	16.4	15,776	-7.73	0.058	0.0	11,776	-6.70	0.044	0.0	15,507	2.02	0.051	19.0	13,107	2.34	0.047	17.6
	30	10,090	2.82	0.083	16.4	13,982	-2.85	0.041	108.2	9,982	-1.76	0.031	81.9	13,713	2.45	0.043	17.0	11,313	2.77	0.039	15.7
20000	5	14,496	3.11	0.080	15.9	32,167	#NUM!	0.377	0.0	25,567	#NUM!	0.294	0.0	25,421	2.20	0.083	20.5	21,461	2.48	0.078	19.1
	10	14,496	3.11	0.080	15.9	31,030	#NUM!	0.199	0.0	24,430	#NUM!	0.155	0.0	24,285	2.34	0.075	19.7	20,325	2.62	0.070	18.4
	20	14,496	3.11	0.080	15.9	28,786	-8.02	0.103	0.0	22,186	-7.10	0.080	0.0	22,040	2.59	0.063	18.2	18,080	2.87	0.059	17.0
	35	14,496	3.11	0.080	15.9	25,541	-3.16	0.060	122.9	18,941	-2.19	0.047	95.9	18,796	2.93	0.052	16.5	14,836	3.21	0.048	15.4
	50	14,496	3.11	0.080	15.9	22,537	-1.15	0.044	59.0	15,937	-0.16	0.034	46.1	15,792	3.22	0.044	15.2	11,832	3.51	0.041	14.2
275	2	323	2.54	0.089	18.2	1,982	#NUM!	0.085	0.0	482	#NUM!	0.018	0.0	1,328	-0.74	0.055	67.2	428	2.08	0.027	33.4
	3	323	2.54	0.089	18.2	1,871	-10.07	0.064	0.0	371	-4.38	0.014	0.0	1,216	0.12	0.045	46.7	316	2.97	0.022	23.2
	5	323	2.54	0.089	18.2	1,675	-3.58	0.044	153.1	175	2.52	0.010	33.0	1,020	1.31	0.033	30.7	120	4.19	0.017	15.2
	8	323	2.54	0.089	18.2	1,275	0.29	0.027	38.1	225	6.64	0.006	8.2	621	3.03	0.022	18.6	279	5.95	0.011	9.2
	12	323	2.54	0.089	18.2	756	2.71	0.018	19.3	744	9.21	0.004	4.2	102	4.55	0.015	12.3	798	7.53	0.008	6.1
550	3	650	2.53	0.089	18.3	2,414	-15.59	0.068	0.0	814	-11.86	0.023	0.0	1,774	0.50	0.050	34.7	814	2.26	0.032	22.5
	5	650	2.53	0.089	18.3	2,160	-4.08	0.046	185.6	560	0.15	0.016	63.1	1,520	1.45	0.038	26.0	560	3.22	0.024	16.9
	10	650	2.53	0.089	18.3	1,691	-0.09	0.029	42.2	91	4.31	0.010	14.4	1,050	2.79	0.026	17.8	90	4.58	0.017	11.6
	15	650	2.53	0.089	18.3	1,029	2.51	0.019	20.2	571	7.03	0.006	6.9	389	4.16	0.018	12.6	571	5.98	0.012	8.2
	25	650	2.53	0.089	18.3	706	3.37	0.016	16.1	894	7.92	0.005	5.5	65	4.70	0.016	11.1	895	6.53	0.010	7.2
1100	5	1,300	2.53	0.089	18.3	3,145	-6.28	0.054	1392.9	1,445	-3.58	0.027	686.1	2,591	1.35	0.045	24.1	1,571	2.38	0.035	18.7
	10	1,300	2.53	0.089	18.3	2,515	-0.86	0.032	54.1	815	1.99	0.016	26.6	1,961	2.47	0.032	18.0	941	3.52	0.025	13.9
	20	1,300	2.53	0.089	18.3	1,553	2.22	0.020	21.9	147	5.16	0.010	10.8	1,000	3.77	0.022	12.9	20	4.82	0.017	10.0
	35	1,300	2.53	0.089	18.3	802	3.66	0.015	15.0	898	6.64	0.007	7.4	248	4.57	0.017	10.8	772	5.63	0.014	8.4
	50	1,300	2.53	0.089	18.3	967	5.87	0.010	8.6	2,667	8.91	0.005	4.2	1,521	6.01	0.012	7.7	2,541	7.09	0.009	6.0
2200	10	2,593	2.53	0.089	18.3	4,489	-3.22	0.042	126.1	2,589	-1.44	0.027	80.0	4,113	1.94	0.041	19.4	2,973	2.55	0.036	16.7
	20	2,593	2.53	0.089	18.3	3,206	0.86	0.025	32.0	1,306	2.71	0.016	20.3	2,830	3.05	0.029	14.8	1,690	3.67	0.025	12.8
	40	2,593	2.53	0.089	18.3	1,645	3.22	0.017	16.8	255	5.11	0.010	10.6	1,270	4.10	0.021	11.4	130	4.72	0.018	9.9
	70	2,593	2.53	0.089	18.3	561	5.23	0.011	10.0	2,461	7.16	0.007	6.4	936	5.25	0.015	8.9	2,076	5.88	0.013	7.6
	100	2,593	2.53	0.089	18.3	3,760	7.11	0.008	6.3	5,660	9.07	0.005	4.0	4,135	6.52	0.011	6.7	5,275	7.16	0.009	5.8
10000	0.75	9,966	2.85	0.082	16.3	11,033	0.25	0.027	38.2	7,033	1.37	0.021	28.9	10,639	3.10	0.033	14.2	8,239	3.42	0.031	13.1
	1.5	9,966	2.85	0.082	16.3	6,173	2.85	0.018	18.5	2,173	4.00	0.013	14.0	5,778	3.96	0.024	11.4	3,378	4.29	0.022	10.5
	3	9,966	2.85	0.082	16.3	1,710	5.22	0.011	10.1	5,710	6.39	0.009	7.6	2,104	5.07	0.017	8.9	4,504	5.40	0.016	8.2
	6	9,966	2.85	0.082	16.3	57,449	11.29	0.003	2.4	61,449	12.54	0.002	1.8	57,843	9.25	0.006	3.6	60,243	9.59	0.005	3.3
25000	1.75	16,730	3.21	0.078	15.5	17,383	1.88	0.025	24.1	9,133	2.91	0.019	18.7	7,850	4.03	0.031	12.1	2,900	4.32	0.029	11.3
	3.5	16,730	3.21	0.078	15.5	492	4.44	0.014	12.2	7,758	5.51	0.011	9.5	9,041	4.99	0.021	9.5	13,991	5.28	0.020	8.9
	7	16,730	3.21	0.078	15.5	16,610	6.06	0.010	8.2	24,860	7.14	0.008	6.3	26,144	5.78	0.016	7.8	31,094	6.07	0.015	7.3
	15	16,730	3.21	0.078	15.5	165,332	11.85	0.003	2.1	173,582	12.99	0.002	1.6	174,865	9.71	0.005	3.3	179,815	10.02	0.005	3.1
50000	3.75	23,644	3.54	0.072	14.3	30,713	2.11	0.024	22.6	14,713	3.18	0.018	17.4	4,745	4.35	0.029	11.2	4,855	4.66	0.027	10.4
	7.5	23,644	3.54	0.072	14.3	2,849	4.67	0.014	11.6	18,849	5.76	0.011	8.9	28,817	5.30	0.020	8.9	38,417	5.61	0.018	8.2
	15	23,644	3.54	0.072	14.3	36,818	6.28	0.010	7.7	52,818	7.39	0.007	6.0	62,786	6.10	0.015	7.3	72,386	6.41	0.014	6.8
	29	23,644	3.54	0.072	14.3	332,219	12.07	0.003	2.0	348,219	13.24	0.002	1.5	358,187	10.03	0.005	3.0	367,787	10.35	0.005	2.8
100000	7.25	20,325	4.06	0.064	12.6	46,446	2.60	0.021	19.7	21,446	3.51	0.017	15.8	23,094	4.88	0.026	9.9	38,094	5.15	0.024	9.3
	14.5	20,325	4.06	0.064	12.6	20,665	5.13	0.012	10.3	45,665	6.07	0.010	8.2	90,205	5.83	0.018	7.8	105,205	6.10	0.017	7.4
	29	20,325	4.06	0.064	12.6	88,593	6.74	0.009	6.9	113,593	7.69	0.007	5.5	158,133	6.61	0.013	6.5	173,133	6.89	0.013	6.1
	59	20,325	4.06	0.064	12.6	987,524	14.00	0.002	1.3	1,012,524	15.01	0.001	1.0	1,057,063	11.75	0.003	2.1	1,072,063	12.03	0.003	2.0
200000	14.75	4,650	4.45	0.058	11.5	69,990	3.00	0.020	17.8	29,990	3.79	0.016	14.7	91,320	5.28	0.024	9.0	115,320	5.52	0.022	8.5
	29.5	4,650	4.45	0.058	11.5	63,385	5.52	0.011	9.3	103,385	6.33	0.009	7.7	224,696	6.22	0.016	7.1	248,696	6.46	0.015	6.8
	59	4,650	4.45	0.058	11.5	121,890	6.29	0.010	7.7	161,890	7.10	0.008	6.4	283,201	6.58	0.014	6.5	307,201	6.82	0.013	6.1
	117	4,650	4.45	0.058	11.5	331,669	8.29	0.006	4.8	371,669	9.12	0.005	3.9	492,980	7.67	0.010	5.1	516,980	7.91	0.009	4.8

Appendix B.3

Table 17. Economic analysis results for Riverton, Wyoming.

Size	Occ/ gpm	PV				SC w/ Install				SC w/o Install				PVT w/ Install				PVT w/o Install			
		NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs
3000	2	2,789	3.12	0.078	15.8	7,265	#NUM!	0.201	0.0	5,115	#NUM!	0.133	0.0	6,290	1.18	0.076	24.9	5,000	1.70	0.067	22.0
	3	2,789	3.12	0.078	15.8	7,037	#NUM!	0.135	0.0	4,887	#NUM!	0.090	0.0	6,062	1.38	0.068	23.5	4,772	1.90	0.060	20.7
	5	2,789	3.12	0.078	15.8	6,588	#NUM!	0.082	0.0	4,438	#NUM!	0.055	0.0	5,613	1.75	0.057	21.2	4,323	2.28	0.050	18.6
	8	2,789	3.12	0.078	15.8	5,970	-6.10	0.053	949.6	3,820	-4.54	0.035	629.6	4,995	2.22	0.046	18.6	3,705	2.74	0.041	16.4
	12	2,789	3.12	0.078	15.8	5,291	-2.35	0.039	89.9	3,141	-0.74	0.026	59.6	4,316	2.67	0.038	16.5	3,026	3.20	0.034	14.5
5000	2	4,264	3.29	0.075	15.2	10,585	#NUM!	0.282	0.0	8,085	#NUM!	0.205	0.0	9,232	1.56	0.077	22.2	7,732	1.94	0.070	20.2
	5	4,264	3.29	0.075	15.2	9,896	#NUM!	0.116	0.0	7,396	#NUM!	0.084	0.0	8,543	1.91	0.063	20.1	7,043	2.28	0.058	18.3
	10	4,264	3.29	0.075	15.2	8,804	-8.31	0.060	0.0	6,304	-7.13	0.043	0.0	7,451	2.40	0.049	17.6	5,951	2.78	0.045	16.0
	15	4,264	3.29	0.075	15.2	7,804	-2.99	0.041	114.0	5,304	-1.74	0.030	82.7	6,451	2.81	0.041	15.7	4,951	3.20	0.037	14.4
	20	4,264	3.29	0.075	15.2	6,941	-1.02	0.033	56.5	4,441	0.25	0.024	41.0	5,588	3.14	0.035	14.4	4,088	3.52	0.032	13.2
10000	3	7,721	3.37	0.074	14.4	19,216	#NUM!	0.336	0.0	15,216	#NUM!	0.255	0.0	16,577	1.74	0.077	21.1	14,177	2.06	0.071	19.5
	5	7,721	3.37	0.074	14.4	18,751	#NUM!	0.205	0.0	14,751	#NUM!	0.155	0.0	16,113	1.87	0.071	20.4	13,713	2.19	0.066	18.8
	10	7,721	3.37	0.074	14.4	17,620	#NUM!	0.105	0.0	13,620	#NUM!	0.079	0.0	14,982	2.15	0.060	18.8	12,582	2.47	0.056	17.4
	20	7,721	3.37	0.074	14.4	15,424	-6.18	0.054	1044.0	11,424	-5.13	0.041	790.3	12,786	2.66	0.046	16.4	10,386	2.98	0.043	15.2
	30	7,721	3.37	0.074	14.4	13,428	-2.06	0.037	80.5	9,428	-0.96	0.028	60.9	10,789	3.07	0.038	14.7	8,389	3.40	0.036	13.6
20000	5	9,472	3.64	0.071	14.0	32,130	#NUM!	0.366	0.0	25,530	#NUM!	0.286	0.0	20,361	2.77	0.075	17.8	16,401	3.05	0.070	16.6
	10	9,472	3.64	0.071	14.0	30,886	#NUM!	0.187	0.0	24,286	#NUM!	0.146	0.0	19,117	2.90	0.068	17.1	15,157	3.18	0.063	15.9
	20	9,472	3.64	0.071	14.0	28,450	-7.13	0.096	0.0	21,850	-6.20	0.075	0.0	16,681	3.14	0.057	15.9	12,721	3.42	0.053	14.9
	35	9,472	3.64	0.071	14.0	24,885	-2.63	0.056	99.4	18,285	-1.65	0.044	77.6	13,117	3.47	0.047	14.5	9,157	3.75	0.044	13.5
	50	9,472	3.64	0.071	14.0	21,576	-0.67	0.040	50.6	14,976	0.32	0.031	39.5	9,807	3.75	0.040	13.4	5,847	4.04	0.037	12.5
275	2	259	3.09	0.079	15.9	1,922	#NUM!	0.072	0.0	422	#NUM!	0.016	0.0	1,204	0.21	0.048	45.7	304	3.06	0.024	22.7
	3	259	3.09	0.079	15.9	1,785	-5.96	0.053	928.1	285	-0.01	0.012	200.2	1,066	1.06	0.038	33.3	166	3.93	0.019	16.5
	5	259	3.09	0.079	15.9	1,565	-2.12	0.038	83.9	65	4.08	0.008	18.1	847	2.14	0.029	23.4	53	5.05	0.014	11.6
	8	259	3.09	0.079	15.9	1,139	1.07	0.024	30.3	361	7.47	0.005	6.5	420	3.68	0.020	15.3	480	6.63	0.010	7.6
	12	259	3.09	0.079	15.9	530	3.45	0.016	15.9	970	9.99	0.003	3.4	188	5.22	0.013	10.2	1,088	8.21	0.007	5.1
550	3	522	3.08	0.079	16.0	2,328	-7.88	0.058	0.0	728	-3.82	0.020	0.0	1,560	1.31	0.043	27.1	600	3.08	0.028	17.6
	5	522	3.08	0.079	16.0	2,028	-2.52	0.039	95.0	428	1.78	0.013	32.3	1,260	2.24	0.032	20.7	300	4.03	0.021	13.4
	10	522	3.08	0.079	16.0	1,486	0.90	0.025	31.6	114	5.34	0.008	10.7	718	3.53	0.022	14.5	242	5.34	0.015	9.4
	15	522	3.08	0.079	16.0	813	3.10	0.017	17.3	787	7.64	0.006	5.9	45	4.73	0.016	10.8	915	6.56	0.011	7.0
	25	522	3.08	0.079	16.0	367	4.11	0.014	13.3	1,233	8.70	0.005	4.5	401	5.38	0.014	9.3	1,361	7.21	0.009	6.0
1100	5	1,043	3.08	0.079	16.0	3,010	-4.36	0.047	221.1	1,310	-1.62	0.023	108.9	2,200	2.08	0.040	19.9	1,180	3.12	0.031	15.4
	10	1,043	3.08	0.079	16.0	2,226	0.32	0.027	37.5	526	3.20	0.013	18.5	1,416	3.26	0.027	14.7	396	4.30	0.021	11.4
	20	1,043	3.08	0.079	16.0	1,144	3.06	0.017	17.5	556	6.02	0.008	8.6	334	4.48	0.019	10.8	686	5.54	0.015	8.4
	35	1,043	3.08	0.079	16.0	397	4.27	0.014	12.8	1,303	7.27	0.007	6.3	413	5.16	0.016	9.2	1,433	6.23	0.012	7.2
	50	1,043	3.08	0.079	16.0	1,509	6.37	0.009	7.6	3,209	9.43	0.004	3.7	2,319	6.54	0.011	6.8	3,339	7.62	0.008	5.3
2200	10	2,080	3.09	0.079	16.0	4,200	-1.89	0.037	75.9	2,300	-0.09	0.023	48.2	3,311	2.67	0.036	16.3	2,171	3.28	0.031	14.0
	20	2,080	3.09	0.079	16.0	2,631	1.89	0.021	24.0	731	3.76	0.013	15.2	1,742	3.81	0.024	12.4	602	4.43	0.021	10.6
	40	2,080	3.09	0.079	16.0	801	4.10	0.014	13.3	1,099	6.01	0.009	8.5	88	4.84	0.018	9.6	1,228	5.47	0.015	8.2
	70	2,080	3.09	0.079	16.0	1,749	6.02	0.010	8.2	3,649	7.97	0.006	5.2	2,637	5.97	0.013	7.5	3,777	6.60	0.011	6.4
	100	2,080	3.09	0.079	16.0	4,828	7.59	0.007	5.6	6,728	9.56	0.004	3.6	5,716	7.03	0.010	5.9	6,856	7.67	0.008	5.1
10000	0.75	7,580	3.40	0.073	14.3	9,701	1.13	0.024	29.6	5,701	2.27	0.018	22.4	6,921	3.77	0.029	12.1	4,521	4.10	0.027	11.2
	1.5	7,580	3.40	0.073	14.3	3,122	3.92	0.014	14.0	878	5.09	0.011	10.6	342	4.75	0.020	9.5	2,058	5.09	0.019	8.8
	3	7,580	3.40	0.073	14.3	4,840	5.89	0.010	8.5	8,840	7.07	0.007	6.5	7,620	5.71	0.015	7.6	10,020	6.04	0.014	7.1
	6	7,580	3.40	0.073	14.3	68,483	11.91	0.003	2.1	72,483	13.16	0.002	1.6	71,263	9.86	0.005	3.1	73,663	10.20	0.005	2.9
25000	1.75	10,368	3.75	0.069	13.6	13,797	2.56	0.021	20.0	5,547	3.61	0.017	15.5	2,098	4.62	0.027	10.4	7,048	4.91	0.025	9.7
	3.5	10,368	3.75	0.069	13.6	7,119	5.24	0.012	10.0	15,369	6.31	0.009	7.8	23,014	5.64	0.018	8.2	27,964	5.94	0.017	7.6
	7	10,368	3.75	0.069	13.6	24,902	6.68	0.009	7.0	33,152	7.76	0.007	5.5	40,797	6.36	0.014	6.8	45,747	6.66	0.013	6.3
	15	10,368	3.75	0.069	13.6	194,754	12.46	0.002	1.8	203,004	13.61	0.002	1.4	210,649	10.31	0.005	2.9	215,599	10.61	0.004	2.7
50000	3.75	11,007	4.08	0.064	12.6	23,585	2.79	0.020	18.8	7,585	3.87	0.016	14.5	15,020	4.94	0.025	9.7	24,620	5.24	0.023	9.0
	7.5	11,007	4.08	0.064	12.6	17,949	5.46	0.012	9.5	33,949	6.56	0.009	7.3	56,555	5.96	0.017	7.6	66,155	6.27	0.016	7.1
	15	11,007	4.08	0.064	12.6	53,287	6.89	0.008	6.7	69,287	8.01	0.007	5.1	91,893	6.68	0.013	6.3	101,493	6.99	0.012	5.9
	29	11,007	4.08	0.064	12.6	390,658	12.68	0.002	1.7	406,658	13.86	0.002	1.3	429,264	10.62	0.004	2.7	438,864	10.94	0.004	2.5
100000	7.25	4,945	4.60	0.057	11.1	32,193	3.28	0.018	16.5	7,193	4.19	0.015	13.2	62,617	5.46	0.023	8.6	77,617	5.73	0.021	8.1
	14.5	4,945	4.60	0.057	11.1	50,862	5.92	0.010	8.4	75,862	6.86	0.008	6.8	145,672	6.48	0.015	6.7	160,672	6.75	0.014	6.3
	29	4,945	4.60	0.057	11.1	121,526	7.35	0.008	6.0	146,526	8.30	0.006	4.8	216,336	7.19	0.012	5.6	231,336	7.47	0.011	5.2
	59	4,945	4.60	0.057	11.1	995,051	14.03	0.002	1.3	1,020,051	15.04	0.001	1.0	1,089,861	11.86	0.003	2.0	1,104,861	12.14	0.003	1.9
200000	14.75	45,891	4.99	0.052	10.1	41,705	3.67	0.017	14.9	1,705	4.46	0.014	12.3	170,146	5.86	0.021	7.8	194,146	6.10	0.020	7.4
	29.5	45,891	4.99	0.052	10.1	124,053	6.31	0.010	7.7	164,053	7.13	0.008	6.3	335,903	6.88	0.014	6.1	359,903	7.12	0.013	5.8
	59	45,891	4.99	0.052	10.1	81,534	5.77	0.011	8.8	121,534	6.58	0.009	7.2	293,385	6.64	0.015	6.3	317,385	6.88	0.014	5.9
	117	45,891	4.99	0.052	10.1	366,873	8.56	0.006	4.5	406,873	9.39	0.005	3.7	578,723	8.04	0.009	4.6	602,723	8.28	0.009	4.4

Appendix B.4

Table 18. Economic analysis results for Sacramento, California.

Size	Occ/ gpm	PV				SC w/ Install				SC w/o Install				PVT w/ Install				PVT w/o Install			
		NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs
3000	2	2,465	3.35	0.074	15.0	7,300	#NUM!	0.217	0.0	5,150	#NUM!	0.144	0.0	6,002	1.44	0.075	23.4	4,712	1.95	0.066	20.6
	3	2,465	3.35	0.074	15.0	7,089	#NUM!	0.146	0.0	4,939	#NUM!	0.097	0.0	5,791	1.61	0.067	22.2	4,501	2.13	0.059	19.5
	5	2,465	3.35	0.074	15.0	6,670	#NUM!	0.089	0.0	4,520	#NUM!	0.059	0.0	5,372	1.94	0.057	20.2	4,082	2.46	0.050	17.7
	8	2,465	3.35	0.074	15.0	6,051	-6.92	0.056	0.0	3,901	-5.38	0.037	0.0	4,753	2.39	0.046	17.8	3,463	2.91	0.041	15.7
	12	2,465	3.35	0.074	15.0	5,285	-2.33	0.039	89.3	3,135	-0.72	0.026	59.2	3,987	2.88	0.037	15.6	2,697	3.40	0.033	13.7
5000	2	3,706	3.52	0.072	14.4	10,618	#NUM!	0.303	0.0	8,118	#NUM!	0.220	0.0	8,707	1.83	0.075	20.8	7,207	2.20	0.068	18.9
	5	3,706	3.52	0.072	14.4	9,984	#NUM!	0.125	0.0	7,484	#NUM!	0.091	0.0	8,072	2.13	0.062	19.0	6,572	2.51	0.057	17.4
	10	3,706	3.52	0.072	14.4	8,950	-10.49	0.064	0.0	6,450	-9.33	0.046	0.0	7,038	2.58	0.049	16.8	5,538	2.96	0.045	15.3
	15	3,706	3.52	0.072	14.4	7,935	-3.40	0.043	134.9	5,435	-2.15	0.031	98.0	6,024	2.98	0.040	15.0	4,524	3.36	0.037	13.7
	20	3,706	3.52	0.072	14.4	6,962	-1.06	0.033	57.2	4,462	0.21	0.024	41.5	5,050	3.33	0.035	13.7	3,550	3.71	0.032	12.5
10000	3	6,635	3.60	0.070	13.7	19,267	#NUM!	0.362	0.0	15,267	#NUM!	0.274	0.0	15,542	2.01	0.074	19.8	13,142	2.33	0.068	18.3
	5	6,635	3.60	0.070	13.7	18,837	#NUM!	0.221	0.0	14,837	#NUM!	0.167	0.0	15,112	2.12	0.069	19.2	12,712	2.44	0.064	17.7
	10	6,635	3.60	0.070	13.7	17,794	#NUM!	0.113	0.0	13,794	#NUM!	0.086	0.0	14,069	2.37	0.059	17.8	11,669	2.69	0.055	16.5
	20	6,635	3.60	0.070	13.7	15,713	-7.40	0.058	0.0	11,713	-6.36	0.044	0.0	11,988	2.83	0.046	15.7	9,588	3.15	0.043	14.5
	30	6,635	3.60	0.070	13.7	13,735	-2.48	0.039	93.8	9,735	-1.38	0.030	71.0	10,010	3.22	0.038	14.1	7,610	3.55	0.036	13.1
20000	5	7,169	3.87	0.068	13.2	32,212	#NUM!	0.391	0.0	25,612	#NUM!	0.305	0.0	18,140	2.99	0.072	16.7	14,180	3.28	0.067	15.6
	10	7,169	3.87	0.068	13.2	31,079	#NUM!	0.203	0.0	24,479	#NUM!	0.158	0.0	17,007	3.11	0.066	16.2	13,047	3.39	0.061	15.1
	20	7,169	3.87	0.068	13.2	28,822	-8.13	0.103	0.0	22,222	-7.21	0.081	0.0	14,750	3.32	0.056	15.2	10,790	3.60	0.053	14.2
	35	7,169	3.87	0.068	13.2	25,509	-3.13	0.060	121.5	18,909	-2.16	0.047	94.8	11,437	3.61	0.047	13.9	7,477	3.90	0.043	13.0
	50	7,169	3.87	0.068	13.2	22,268	-1.01	0.043	56.4	15,668	-0.02	0.033	44.0	8,196	3.88	0.040	12.9	4,236	4.17	0.037	12.0
275	2	230	3.33	0.075	15.1	1,898	-13.82	0.068	0.0	398	-8.36	0.015	0.0	1,150	0.56	0.045	39.5	250	3.42	0.022	19.6
	3	230	3.33	0.075	15.1	1,764	-5.38	0.051	471.0	264	0.61	0.011	101.6	1,016	1.34	0.036	30.0	116	4.22	0.018	14.9
	5	230	3.33	0.075	15.1	1,546	-1.90	0.037	77.6	46	4.31	0.008	16.7	798	2.35	0.028	21.7	102	5.26	0.014	10.8
	8	230	3.33	0.075	15.1	1,140	1.07	0.024	30.3	360	7.47	0.005	6.5	391	3.77	0.019	14.8	509	6.72	0.010	7.3
	12	230	3.33	0.075	15.1	709	2.88	0.018	18.4	791	9.38	0.004	4.0	39	4.89	0.015	11.1	939	7.87	0.007	5.5
550	3	463	3.31	0.075	15.1	2,287	-6.54	0.055	2231.1	687	-2.42	0.019	759.0	1,460	1.65	0.040	24.5	500	3.42	0.026	15.9
	5	463	3.31	0.075	15.1	1,959	-1.89	0.036	75.7	359	2.43	0.012	25.8	1,132	2.58	0.030	18.7	172	4.37	0.020	12.2
	10	463	3.31	0.075	15.1	1,430	1.13	0.024	29.6	170	5.59	0.008	10.1	603	3.76	0.022	13.6	357	5.57	0.014	8.8
	15	463	3.31	0.075	15.1	814	3.10	0.017	17.3	786	7.64	0.006	5.9	13	4.82	0.016	10.5	973	6.65	0.011	6.8
	25	463	3.31	0.075	15.1	449	3.95	0.014	13.9	1,151	8.53	0.005	4.7	378	5.34	0.014	9.3	1,338	7.18	0.009	6.0
1100	5	926	3.31	0.075	15.1	2,945	-3.69	0.044	157.4	1,245	-0.93	0.022	77.5	2,018	2.38	0.038	18.3	998	3.42	0.029	14.2
	10	926	3.31	0.075	15.1	2,125	0.67	0.026	33.9	425	3.56	0.013	16.7	1,198	3.53	0.026	13.6	178	4.58	0.020	10.6
	20	926	3.31	0.075	15.1	1,033	3.27	0.016	16.6	667	6.23	0.008	8.2	106	4.70	0.018	10.2	914	5.77	0.014	7.9
	35	926	3.31	0.075	15.1	473	4.16	0.014	13.1	1,227	7.16	0.007	6.5	454	5.20	0.016	9.1	1,474	6.27	0.012	7.1
	50	926	3.31	0.075	15.1	1,293	6.18	0.009	7.9	2,993	9.23	0.005	3.9	2,220	6.47	0.011	6.8	3,240	7.56	0.009	5.3
2200	10	1,845	3.32	0.075	15.1	4,068	-1.40	0.034	64.2	2,168	0.41	0.022	40.8	2,944	2.96	0.034	15.1	1,804	3.58	0.029	13.0
	20	1,845	3.32	0.075	15.1	2,430	2.19	0.020	22.0	530	4.07	0.013	14.0	1,306	4.08	0.023	11.5	166	4.70	0.020	9.9
	40	1,845	3.32	0.075	15.1	681	4.21	0.014	13.0	1,219	6.13	0.009	8.2	443	5.02	0.017	9.1	1,583	5.65	0.015	7.8
	70	1,845	3.32	0.075	15.1	1,335	5.76	0.010	8.8	3,235	7.70	0.006	5.6	2,458	5.90	0.013	7.5	3,598	6.53	0.012	6.5
	100	1,845	3.32	0.075	15.1	4,396	7.40	0.007	5.9	6,296	9.37	0.005	3.7	5,520	6.97	0.010	5.9	6,660	7.61	0.009	5.1
10000	0.75	6,481	3.64	0.070	13.6	8,965	1.55	0.022	26.3	4,965	2.69	0.017	19.9	5,086	4.07	0.027	11.3	2,686	4.40	0.025	10.4
	1.5	6,481	3.64	0.070	13.6	4,249	3.56	0.016	15.4	249	4.72	0.012	11.6	370	4.75	0.021	9.2	2,030	5.08	0.019	8.5
	3	6,481	3.64	0.070	13.6	4,137	5.74	0.010	8.8	8,137	6.93	0.008	6.7	8,016	5.75	0.015	7.5	10,416	6.08	0.014	6.9
	6	6,481	3.64	0.070	13.6	60,528	11.47	0.003	2.3	64,528	12.72	0.002	1.7	64,407	9.55	0.005	3.3	66,807	9.90	0.005	3.1
25000	1.75	7,437	3.97	0.066	12.9	11,847	2.90	0.020	18.3	3,597	3.94	0.016	14.2	6,979	4.88	0.025	9.8	11,929	5.17	0.024	9.1
	3.5	7,437	3.97	0.066	12.9	7,954	5.32	0.012	9.8	16,204	6.39	0.009	7.6	26,781	5.81	0.018	7.8	31,731	6.10	0.016	7.2
	7	7,437	3.97	0.066	12.9	23,125	6.55	0.009	7.2	31,375	7.63	0.007	5.6	41,952	6.40	0.014	6.7	46,902	6.70	0.013	6.2
	15	7,437	3.97	0.066	12.9	173,536	12.03	0.003	2.0	181,786	13.17	0.002	1.6	192,362	10.01	0.005	3.0	197,312	10.32	0.005	2.8
50000	3.75	5,185	4.31	0.061	11.9	19,727	3.12	0.019	17.2	3,727	4.20	0.015	13.3	24,701	5.20	0.024	9.1	34,301	5.51	0.022	8.5
	7.5	5,185	4.31	0.061	11.9	19,621	5.54	0.011	9.3	35,621	6.64	0.009	7.2	64,049	6.12	0.016	7.2	73,649	6.43	0.015	6.7
	15	5,185	4.31	0.061	11.9	49,759	6.77	0.009	6.9	65,759	7.89	0.007	5.3	94,187	6.72	0.013	6.2	103,787	7.03	0.012	5.8
	29	5,185	4.31	0.061	11.9	348,514	12.25	0.003	1.9	364,514	13.42	0.002	1.5	392,942	10.33	0.005	2.8	402,542	10.65	0.004	2.6
100000	7.25	16,587	4.83	0.054	10.5	24,477	3.60	0.017	15.2	523	4.52	0.014	12.2	81,975	5.72	0.021	8.1	96,975	5.99	0.020	7.6
	14.5	16,587	4.83	0.054	10.5	54,205	6.00	0.010	8.3	79,205	6.94	0.008	6.6	160,657	6.64	0.015	6.4	175,657	6.91	0.014	6.0
	29	16,587	4.83	0.054	10.5	114,471	7.23	0.008	6.1	139,471	8.18	0.006	4.9	220,923	7.24	0.012	5.5	235,923	7.51	0.011	5.2
	59	16,587	4.83	0.054	10.5	1,043,449	14.23	0.002	1.2	1,068,449	15.24	0.001	1.0	1,149,900	12.05	0.003	1.9	1,164,900	12.34	0.003	1.8
200000	14.75	69,174	5.22	0.049	9.6	27,117	3.98	0.016	13.8	12,883	4.77	0.013	11.4	208,017	6.12	0.019	7.3	232,017	6.35	0.018	6.9
	29.5	69,174	5.22	0.049	9.6	128,784	6.37	0.010	7.6	168,784	7.18	0.008	6.3	363,918	7.03	0.013	5.8	387,918	7.27	0.013	5.5
	59	69,174	5.22	0.049	9.6	253,590	7.65	0.007	5.6	293,590	8.47	0.006	4.6	488,724	7.65	0.011	5.0	512,724	7.89	0.010	4.7
	117	69,174	5.22	0.049	9.6	421,840	8.94	0.005	4.1	461,840	9.77	0.004	3.4	656,974	8.36	0.009	4.3	680,974	8.60	0.008	4.1

Appendix B.5

Table 19. Economic analysis results for Salt Lake City, Utah.

		PV				SC w/ Install				SC w/o Install				PVT w/ Install				PVT w/o Install			
Size	Occ/ gpm	NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs	NPV ($)	IRR %	LCOE $/kWh	SPP yrs
3000	2	2,609	3.25	0.076	15.3	7,264	#NUM!	0.201	0.0	5,114	#NUM!	0.133	0.0	6,109	1.34	0.075	24.0	4,819	1.86	0.066	21.1
	3	2,609	3.25	0.076	15.3	7,034	#NUM!	0.135	0.0	4,884	#NUM!	0.089	0.0	5,879	1.54	0.067	22.7	4,589	2.06	0.059	19.9
	5	2,609	3.25	0.076	15.3	6,585	#NUM!	0.082	0.0	4,435	#NUM!	0.054	0.0	5,430	1.90	0.056	20.5	4,140	2.42	0.049	18.0
	8	2,609	3.25	0.076	15.3	5,963	-6.03	0.053	860.8	3,813	-4.48	0.035	570.7	4,808	2.35	0.045	18.0	3,518	2.87	0.040	15.9
	12	2,609	3.25	0.076	15.3	5,265	-2.26	0.038	86.9	3,115	-0.64	0.025	57.6	4,110	2.80	0.038	16.0	2,820	3.33	0.033	14.0
5000	2	3,953	3.42	0.073	14.7	10,581	#NUM!	0.280	0.0	8,081	#NUM!	0.203	0.0	8,917	1.72	0.075	21.3	7,417	2.10	0.069	19.5
	5	3,953	3.42	0.073	14.7	9,889	#NUM!	0.115	0.0	7,389	#NUM!	0.083	0.0	8,225	2.06	0.062	19.4	6,725	2.44	0.056	17.7
	10	3,953	3.42	0.073	14.7	8,792	-8.18	0.059	0.0	6,292	-6.99	0.043	0.0	7,128	2.54	0.048	17.0	5,628	2.92	0.044	15.5
	15	3,953	3.42	0.073	14.7	7,787	-2.94	0.041	111.7	5,287	-1.69	0.030	81.1	6,123	2.94	0.040	15.3	4,623	3.32	0.036	13.9
	20	3,953	3.42	0.073	14.7	6,899	-0.95	0.032	55.1	4,399	0.33	0.024	40.0	5,234	3.27	0.035	14.0	3,734	3.65	0.032	12.8
10000	3	7,116	3.50	0.072	14.0	19,209	#NUM!	0.333	0.0	15,209	#NUM!	0.252	0.0	15,965	1.90	0.075	20.3	13,565	2.23	0.069	18.8
	5	7,116	3.50	0.072	14.0	18,742	#NUM!	0.203	0.0	14,742	#NUM!	0.154	0.0	15,498	2.02	0.069	19.7	13,098	2.34	0.064	18.2
	10	7,116	3.50	0.072	14.0	17,602	#NUM!	0.104	0.0	13,602	#NUM!	0.079	0.0	14,358	2.30	0.059	18.2	11,958	2.62	0.054	16.8
	20	7,116	3.50	0.072	14.0	15,409	-6.12	0.054	954.3	11,409	-5.07	0.041	722.4	12,165	2.79	0.046	15.9	9,765	3.11	0.042	14.7
	30	7,116	3.50	0.072	14.0	13,434	-2.07	0.037	80.7	9,434	-0.97	0.028	61.1	10,190	3.19	0.038	14.3	7,790	3.51	0.035	13.2
20000	5	8,189	3.77	0.069	13.5	32,116	#NUM!	0.362	0.0	25,516	#NUM!	0.283	0.0	19,064	2.90	0.073	17.2	15,104	3.19	0.068	16.0
	10	8,189	3.77	0.069	13.5	30,859	#NUM!	0.185	0.0	24,259	#NUM!	0.145	0.0	17,807	3.03	0.066	16.5	13,847	3.31	0.062	15.4
	20	8,189	3.77	0.069	13.5	28,409	-7.03	0.095	0.0	21,809	-6.11	0.074	0.0	15,357	3.26	0.056	15.4	11,397	3.55	0.052	14.4
	35	8,189	3.77	0.069	13.5	24,881	-2.62	0.056	99.3	18,281	-1.65	0.044	77.5	11,829	3.58	0.046	14.1	7,869	3.86	0.043	13.1
	50	8,189	3.77	0.069	13.5	21,545	-0.65	0.040	50.4	14,945	0.34	0.031	39.3	8,493	3.86	0.039	13.0	4,533	4.15	0.037	12.1
275	2	243	3.22	0.076	15.4	1,921	#NUM!	0.072	0.0	421	#NUM!	0.015	0.0	1,185	0.33	0.047	43.7	285	3.18	0.023	21.7
	3	243	3.22	0.076	15.4	1,791	-6.14	0.054	1296.1	291	-0.20	0.012	279.6	1,056	1.12	0.038	32.6	156	3.99	0.019	16.2
	5	243	3.22	0.076	15.4	1,565	-2.11	0.038	83.8	65	4.08	0.008	18.1	830	2.21	0.029	22.9	70	5.12	0.014	11.4
	8	243	3.22	0.076	15.4	1,140	1.07	0.024	30.3	360	7.46	0.005	6.5	405	3.73	0.020	15.1	495	6.68	0.010	7.5
	12	243	3.22	0.076	15.4	589	3.27	0.016	16.6	911	9.80	0.004	3.6	146	5.13	0.014	10.5	1,046	8.12	0.007	5.2
550	3	489	3.21	0.077	15.5	2,320	-7.56	0.057	0.0	720	-3.49	0.020	0.0	1,519	1.45	0.042	26.1	559	3.23	0.027	16.9
	5	489	3.21	0.077	15.5	2,013	-2.38	0.039	90.1	413	1.93	0.013	30.7	1,212	2.37	0.032	20.0	252	4.16	0.021	13.0
	10	489	3.21	0.077	15.5	1,471	0.96	0.024	31.0	129	5.41	0.008	10.6	670	3.63	0.022	14.2	290	5.44	0.014	9.2
	15	489	3.21	0.077	15.5	824	3.07	0.017	17.4	776	7.62	0.006	5.9	23	4.76	0.016	10.7	937	6.59	0.011	7.0
	25	489	3.21	0.077	15.5	435	3.97	0.014	13.8	1,165	8.56	0.005	4.7	366	5.33	0.014	9.4	1,326	7.17	0.009	6.1
1100	5	978	3.21	0.077	15.5	2,997	-4.22	0.047	204.2	1,297	-1.46	0.023	100.6	2,122	2.21	0.039	19.2	1,102	3.25	0.030	14.9
	10	978	3.21	0.077	15.5	2,228	0.31	0.027	37.6	528	3.19	0.013	18.5	1,353	3.34	0.027	14.4	333	4.39	0.021	11.2
	20	978	3.21	0.077	15.5	1,115	3.12	0.017	17.2	585	6.08	0.008	8.5	240	4.57	0.018	10.6	780	5.64	0.014	8.2
	35	978	3.21	0.077	15.5	354	4.33	0.013	12.6	1,346	7.33	0.007	6.2	521	5.25	0.015	9.0	1,541	6.32	0.012	7.0
	50	978	3.21	0.077	15.5	1,436	6.31	0.009	7.7	3,136	9.36	0.004	3.8	2,311	6.53	0.011	6.8	3,331	7.61	0.008	5.3
2200	10	1,344	3.22	0.070	15.5	2,122	-1.81	0.000	73.7	2,122	0.00	0.000	46.8	6,821	2.79	0.000	15.8	6,821	3.41	0.000	13.6
	20	1,949	3.22	0.077	15.5	2,636	1.88	0.021	24.0	736	3.75	0.013	15.3	1,616	3.89	0.024	12.1	476	4.51	0.021	10.4
	40	1,949	3.22	0.077	15.5	851	4.05	0.014	13.5	1,049	5.96	0.009	8.6	169	4.89	0.018	9.5	1,309	5.51	0.015	8.2
	70	1,949	3.22	0.077	15.5	1,644	5.96	0.010	8.4	3,544	7.90	0.006	5.3	2,664	5.98	0.013	7.4	3,804	6.62	0.011	6.4
	100	1,949	3.22	0.077	15.5	4,696	7.53	0.007	5.7	6,596	9.51	0.004	3.6	5,715	7.03	0.010	5.9	6,855	7.67	0.008	5.1
10000	0.75	6,970	3.53	0.071	13.9	9,569	1.21	0.023	28.9	5,569	2.35	0.018	21.9	6,179	3.89	0.028	11.8	3,779	4.22	0.026	10.9
	1.5	6,970	3.53	0.071	13.9	2,695	4.05	0.014	13.5	1,305	5.22	0.011	10.2	695	4.89	0.020	9.3	3,095	5.22	0.018	8.6
	3	6,970	3.53	0.071	13.9	5,246	5.97	0.010	8.4	9,246	7.15	0.007	6.3	8,635	5.81	0.015	7.5	11,035	6.15	0.014	6.9
	6	6,970	3.53	0.071	13.9	65,316	11.74	0.003	2.2	69,316	12.99	0.002	1.6	68,706	9.75	0.005	3.2	71,106	10.09	0.005	3.0
25000	1.75	8,742	3.87	0.068	13.2	13,462	2.62	0.021	19.6	5,212	3.67	0.016	15.3	4,058	4.72	0.027	10.2	9,008	5.02	0.025	9.5
	3.5	8,742	3.87	0.068	13.2	7,205	5.25	0.012	10.0	15,455	6.32	0.009	7.8	24,725	5.72	0.018	8.0	29,675	6.01	0.017	7.5
	7	8,742	3.87	0.068	13.2	26,040	6.75	0.009	6.9	34,290	7.84	0.007	5.4	43,560	6.46	0.014	6.6	48,510	6.76	0.013	6.2
	15	8,742	3.87	0.068	13.2	186,322	12.30	0.003	1.9	194,572	13.44	0.002	1.5	203,842	10.20	0.005	2.9	208,792	10.51	0.004	2.7
50000	3.75	7,778	4.21	0.062	12.2	22,894	2.86	0.020	18.5	6,894	3.93	0.016	14.2	18,941	5.05	0.025	9.5	28,541	5.35	0.023	8.8
	7.5	7,778	4.21	0.062	12.2	18,135	5.47	0.012	9.5	34,135	6.57	0.009	7.3	59,970	6.04	0.017	7.5	69,570	6.35	0.016	6.9
	15	7,778	4.21	0.062	12.2	55,547	6.97	0.008	6.5	71,547	8.09	0.006	5.0	97,382	6.78	0.013	6.2	106,982	7.09	0.012	5.7
	29	7,778	4.21	0.062	12.2	373,910	12.52	0.002	1.8	389,910	13.69	0.002	1.4	415,744	10.51	0.004	2.7	425,344	10.84	0.004	2.5
100000	7.25	11,402	4.73	0.055	10.8	30,811	3.34	0.018	16.2	5,811	4.25	0.015	13.0	70,455	5.57	0.022	8.4	85,455	5.84	0.021	7.9
	14.5	11,402	4.73	0.055	10.8	51,233	5.93	0.010	8.4	76,233	6.87	0.008	6.8	152,499	6.55	0.015	6.6	167,499	6.83	0.014	6.2
	29	11,402	4.73	0.055	10.8	126,046	7.43	0.008	5.9	151,046	8.38	0.006	4.7	227,312	7.29	0.011	5.5	242,312	7.57	0.011	5.1
	59	11,402	4.73	0.055	10.8	1,089,069	14.40	0.002	1.2	1,114,069	15.42	0.001	1.0	1,190,336	12.18	0.003	1.9	1,205,336	12.47	0.003	1.8
200000	14.75	58,803	5.12	0.050	9.8	38,962	3.73	0.017	14.7	1,038	4.52	0.014	12.1	185,801	5.97	0.020	7.6	209,801	6.21	0.019	7.2
	29.5	58,803	5.12	0.050	9.8	123,884	6.31	0.010	7.7	163,884	7.13	0.008	6.3	348,647	6.95	0.014	6.0	372,647	7.19	0.013	5.7
	59	58,803	5.12	0.050	9.8	189,069	7.03	0.008	6.4	229,069	7.85	0.007	5.3	413,833	7.29	0.012	5.4	437,833	7.53	0.011	5.1
	117	58,803	5.12	0.050	9.8	392,974	8.74	0.006	4.3	432,974	9.57	0.005	3.5	617,737	8.21	0.009	4.5	641,737	8.45	0.008	4.2

Appendix C.1

Table 20. Sensitivity results for three occupants

Sensitivity	Change	n_t	$Btu_{savings}$	$\%Btu_{PVT}$	$T_{HTF\text{-}Avg}$	$T_{HTF\text{-}Max}$	$T_{cell\text{-}Avg}$	$T_{cell\text{-}Max}$	n_e	ΔkWh	kWh_{PVT}	kWh_{PV}	$\%\Delta n$	[kg/min/m^2]	$T_{tank\text{-}Avg}$	$T_{tank\text{-}Max}$	V_{tank}	$\%V_{Max}$	$\%V_{Avg}$
Base	-	46.68%	5084010	50.27%	36.90	77.60	33.48	70.96	16.75%	70.3	482.3	412.0	10.36%	0.229	39.97	55.00	1.00	100.00%	71.44%
Ambient	-2.5°	44.55%	4808962	47.55%	34.92	76.78	31.65	69.57	21.27%	76.3	488.3	412.0	6.09%	0.229	38.96	53.74	1.00	100.00%	71.86%
Ambient	+2.5°	49.54%	5343249	52.83%	38.36	80.58	34.73	73.01	20.89%	68.5	480.4	412.0	5.71%	0.229	40.91	56.53	1.00	100.00%	71.70%
Ground	-1°	47.73%	5183575	50.09%	36.57	77.34	33.07	70.25	16.79%	71.4	483.3	412.0	1.61%	0.229	39.38	54.54	1.00	100.00%	71.83%
Ground	+1°	45.70%	4969898	50.31%	37.21	77.90	33.85	70.95	16.72%	69.4	481.4	412.0	1.54%	0.229	40.55	55.56	1.00	100.00%	71.54%
ΔT-Pump	-2°	46.76%	5107467	50.50%	36.88	77.65	33.45	70.96	16.75%	70.6	482.6	412.0	1.57%	0.229	40.00	55.11	1.00	100.00%	71.02%
ΔT-Pump	+2°	46.54%	5069966	50.13%	36.94	77.60	33.52	70.58	16.75%	70.1	482.0	412.0	1.57%	0.229	39.96	55.01	1.00	100.00%	71.41%
Solar	-2%	46.14%	4989333	49.33%	36.29	77.76	32.90	70.50	20.66%	63.8	475.7	412.0	5.48%	0.229	39.55	54.49	1.00	100.00%	71.67%
Solar	+2%	47.79%	5166624	51.08%	37.02	79.62	33.51	72.10	21.43%	80.5	492.5	412.0	6.25%	0.229	40.29	55.68	1.00	100.00%	71.77%
Energy$	-2%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Energy$	+2%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Sensitivity	Change	NPV_{PV}	IRR%	$LCOE_{PV}$	SPP	NPV_{SC+}	IRR%	$LCOE_{SC+}$	SPP	NPV_{SC}	IRR%	$LCOE_{SC}$	SPP	NPV_{PVT+}	IRR%	$LCOE_{PVT+}$	SPP	NPV_{PVT}	IRR%	$LCOE_{PVT}$	SPP
Base	-	$230	3.33	$0.089	15.1	$1,764	-5.38	$0.084	471.0	$264	0.61	$0.043	101.6	$1,016	1.34	$0.066	30.0	$116	4.22	$0.048	14.9
Ambient	-2.5°	$230	3.33	$0.089	15.1	$1,794	-6.22	$0.088	1537.7	$294	-0.29	$0.046	331.7	$1,045	1.18	$0.069	31.0	$145	4.05	$0.050	15.4
Ambient	+2.5°	$230	3.33	$0.089	15.1	$1,736	-4.72	$0.080	284.8	$236	1.31	$0.041	61.4	$987	1.48	$0.064	28.8	$87	4.37	$0.046	14.3
Ground	-1°	$230	3.33	$0.089	15.1	$1,753	-5.11	$0.082	376.5	$253	0.89	$0.042	81.2	$1,005	1.39	$0.065	29.4	$105	4.27	$0.047	14.6
Ground	+1°	$230	3.33	$0.089	15.1	$1,776	-5.71	$0.085	661.4	$276	0.26	$0.044	142.6	$1,028	1.27	$0.067	30.6	$128	4.15	$0.049	15.2
ΔT-Pump	-2°	$230	3.33	$0.089	15.1	$1,761	-5.31	$0.083	444.7	$261	0.68	$0.043	95.9	$1,013	1.35	$0.066	29.8	$113	4.23	$0.048	14.8
ΔT-Pump	+2°	$230	3.33	$0.089	15.1	$1,765	-5.42	$0.084	488.3	$265	0.57	$0.043	105.3	$1,017	1.33	$0.066	30.1	$117	4.21	$0.048	14.9
Solar	-2%	$230	3.33	$0.089	15.1	$1,774	-5.65	$0.085	618.8	$274	0.32	$0.044	133.5	$1,026	1.28	$0.067	30.9	$126	4.16	$0.049	15.4
Solar	+2%	$230	3.33	$0.089	15.1	$1,755	-5.16	$0.082	389.8	$255	0.85	$0.043	84.1	$1,007	1.38	$0.065	28.9	$107	4.26	$0.047	14.3
Energy$	-2%	$242	3.23	$0.089	15.4	$1,775	-5.67	$0.084	633.5	$275	0.30	$0.043	136.6	$1,039	1.27	$0.066	31.2	$139	4.09	$0.048	15.5
Energy$	+2%	$218	3.42	$0.089	14.7	$1,753	-5.11	$0.084	374.9	$253	0.90	$0.043	80.9	$992	1.34	$0.066	28.8	$92	4.34	$0.048	14.9

Appendix C.2

Table 21. Sensitivity results for five occupants.

Sensitivity	Change	n_t	$Btu_{savings}$	$\%Btu_{PVT}$	$T_{HTF\text{-}Avg}$	$T_{HTF\text{-}Max}$	$T_{cell\text{-}Avg}$	$T_{cell\text{-}Max}$	n_e	ΔkWh	kWh_{PVT}	kWh_{PV}	%Δn	[kg/min/m^2]	$T_{tank\text{-}Avg}$	$T_{tank\text{-}Max}$	V_{tank}	$\%V_{Max}$	$\%V_{Avg}$
Base	-	56.43%	7095694	42.09%	34.04	72.04	29.94	64.66	17.06%	84.4	496.4	412.0	12.41%	0.229	37.05	50.59	1.00	100.00%	43.85%
Ambient	-2.5°	53.62%	6664222	39.53%	32.35	63.33	28.44	58.84	21.61%	90.1	502.1	412.0	6.43%	0.229	36.20	49.71	1.00	100.00%	40.70%
Ambient	+2.5°	60.44%	7435545	44.11%	35.22	74.11	30.84	66.47	21.30%	84.9	496.9	412.0	6.12%	0.229	37.74	51.23	1.00	100.00%	47.72%
Ground	-1°	57.99%	7253838	42.05%	33.54	71.89	29.34	64.47	17.12%	86.3	498.2	412.0	1.94%	0.229	36.36	50.06	1.00	100.00%	45.66%
Ground	+1°	54.98%	6864184	41.69%	34.50	70.48	30.50	63.33	17.01%	82.8	494.7	412.0	1.83%	0.229	37.73	51.24	1.00	100.00%	42.89%
ΔT-Pump	-2°	56.30%	7210500	42.78%	34.09	72.10	30.00	64.73	17.06%	84.4	496.4	412.0	1.88%	0.229	37.09	50.59	1.00	100.00%	43.18%
ΔT-Pump	+2°	56.43%	6998325	41.52%	34.04	72.06	29.94	64.69	17.06%	84.4	496.4	412.0	1.88%	0.229	37.07	50.59	1.00	100.00%	44.45%
Solar	-2%	55.98%	6947964	41.22%	33.47	68.17	29.40	61.89	21.03%	78.4	490.4	412.0	5.85%	0.229	36.68	49.44	1.00	100.00%	42.43%
Solar	+2%	58.17%	7154986	42.45%	34.06	69.75	29.83	63.29	21.83%	96.5	508.5	412.0	6.65%	0.229	37.29	50.62	1.00	100.00%	43.49%
Energy$	-2%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Energy$	+2%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Sensitivity	Change	NPV_{PV}	IRR%	$LCOE_{PV}$	SPP	NPV_{SC+}	IRR%	$LCOE_{SC+}$	SPP	NPV_{SC}	IRR%	$LCOE_{SC}$	SPP	NPV_{PVT+}	IRR%	$LCOE_{PVT+}$	SPP	NPV_{PVT}	IRR%	$LCOE_{PVT}$	SPP
Base	-	$230	3.33	$0.089	15.1	$1,546	-1.90	$0.060	77.6	$46	4.31	$0.031	16.7	$798	2.35	$0.051	21.7	$102	5.26	$0.037	10.8
Ambient	-2.5°	$230	3.33	$0.089	15.1	$1,593	-2.43	$0.064	94.5	$93	3.74	$0.033	20.4	$844	2.15	$0.053	22.8	$56	5.06	$0.038	11.3
Ambient	+2.5°	$230	3.33	$0.089	15.1	$1,509	-1.52	$0.057	68.0	$9	4.71	$0.030	14.7	$761	2.50	$0.049	20.8	$139	5.41	$0.035	10.3
Ground	-1°	$230	3.33	$0.089	15.1	$1,529	-1.72	$0.059	72.8	$29	4.50	$0.030	15.7	$780	2.42	$0.050	21.3	$120	5.33	$0.036	10.6
Ground	+1°	$230	3.33	$0.089	15.1	$1,571	-2.18	$0.062	85.8	$71	4.01	$0.032	18.5	$823	2.25	$0.052	22.5	$77	5.15	$0.038	11.1
ΔT-Pump	-2°	$230	3.33	$0.089	15.1	$1,533	-1.77	$0.059	74.0	$33	4.45	$0.031	16.0	$785	2.40	$0.050	21.4	$115	5.31	$0.036	10.6
ΔT-Pump	+2°	$230	3.33	$0.089	15.1	$1,556	-2.01	$0.061	80.8	$56	4.19	$0.031	17.4	$808	2.31	$0.051	22.0	$92	5.21	$0.037	10.9
Solar	-2%	$230	3.33	$0.089	15.1	$1,562	-2.08	$0.061	82.6	$62	4.12	$0.032	17.8	$814	2.28	$0.052	22.4	$86	5.19	$0.037	11.1
Solar	+2%	$230	3.33	$0.089	15.1	$1,539	-1.83	$0.059	75.7	$39	4.38	$0.031	16.3	$791	2.38	$0.050	21.2	$109	5.29	$0.036	10.5
Energy$	-2%	$242	3.23	$0.089	15.4	$1,561	-2.07	$0.060	82.4	$61	4.13	$0.031	17.8	$825	2.30	$0.051	22.5	$75	5.14	$0.037	11.2
Energy$	+2%	$218	3.42	$0.089	14.7	$1,530	-1.74	$0.060	73.2	$30	4.48	$0.031	15.8	$770	2.35	$0.051	21.0	$130	5.37	$0.037	10.8