A COMPARATIVE ANALYSIS OF WATER PASTEURIZATION USING PHOTOVOLTAICS, SOLAR THERMAL, AND PV/T SYSTEMS

A Thesis
By
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Abstract

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Clean drinking water is a finite resource that may prove to be the most valuable resource in the years to come. To provide safe drinking water, numerous purification methods have been researched. These methods can be paired with renewable energy systems to sustainably purify water. This research provides a comparative analysis of the ability of photovoltaic (PV), solar thermal (ST) and photovoltaic / thermal (PV/T) hybrid systems to pasteurize water for three different locations. All of the energy gain produced by each system will be transferred into heat energy to pasteurize the water within a storage tank. Water storage volume was optimized using TRNOPT software for a range of array sizes of each system. The results show that the ST and PV/T systems are able to pasteurize 63% and 53% more water than the PV system, respectively. By using this research, system designers and consumers can more accurately gauge how much pasteurized water each system can produce before purchasing and installing, and aid in choosing an optimal system for their location.

Acknowledgments

I would like to thank my committee members for their ongoing support throughout this research. I would like to give a special thanks to Brian Raichle, without whom, this research would not have been possible. Thank you to Appalachian State University for supplying me with the resources needed to complete this research. Thank you to my family and friends who have supported me on this journey.

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Introduction

Clean drinking water is a finite resource that may prove to be the most valuable resource worldwide in the years to come. This makes uncontaminated drinking water one of the most vital resources on the planet. Although humans are aware of this necessity, still one in four people out of the global population do not have access to safe drinking water, while unsafe water is responsible for 1.2 million deaths each year (Ritchie & Roser, 2021). It is critical that information and technology that aids in producing clean water advances and becomes reliable and accessible to the world's population.

To provide safe drinking water, numerous purification methods have been researched. Examples of these include solar pasteurization, reverse osmosis, nanotechnology and chemical treatments. This paper will summarize each of these treatment options, with a focus on solar pasteurization. Three different systems will be modeled and tank size optimized. The system types that will be analyzed are solar thermal (ST), photovoltaic (PV) and photovoltaic thermal hybrid (PV/T).

There has been a great deal of research regarding different water purification methods, as well as in-depth studies for each of the systems I will be analyzing. No studies have been found that compare the ability of these systems to pasteurize water. This research will provide a comparison of these systems and optimized design parameters based on collector area of the systems and tank volume. These systems will be modeled and analyzed using TRNSYS software. To compare the annual output of pasteurized water among the three systems, each TRNSYS system model will be simulated using the TMY3 files for Chattanooga, TN, Madison, WI and Yosemite, CA.

Literature Review

Water Purification Techniques

There are a variety of different techniques that can be used to clean water. Depending on the resources available, some techniques may be more reliable than others. These resources include temperature and solar irradiance in a particular area, water contamination levels, and available technology. The following sections will review membrane separation technology, chemical treatments, and pasteurization. Each of these techniques offers its own advantages and will be discussed in subsequent sections.

Membrane Separation

Membrane separation technology is a broad term that includes reverse osmosis, nanofiltration, and desalination. Membrane separation technology is one of the most cost-effective and widely applied technologies for water purification (Yang et al., 2019). These technologies are usually classified by the size of the pores in the membranes that are used.

The primary membrane technologies that will be reviewed in more depth are reverse osmosis and nanofiltration.

Reverse osmosis (RO) is a water purification process that uses permeable or semi-permeable membranes to remove unwanted contaminants from water (Malaeb & Ayoub, 2011). These membranes have the smallest pores out of any of the other membrane-based water purification methods. RO is a pressure driven process which purifies water on the molecular level (Joyce et al., 2001). The efficiency of this process depends largely on membrane and feed water properties. RO is preferred because it is the least energy intensive water purification process (Malaeb & Ayoub, 2011).

Nanotechnology is the controlled manipulation of matter at size scales of less than 100 nanometers. For use in water purification, special membranes with tiny pores are applied to moving water. As the water passes through them, the contaminants are caught in the membranes and freshwater is produced. Nanotechnology-based water purification processes are new and use nano membranes to efficiently capture contaminants found in water. These membranes span only a few nanometers, making the pores in the membrane smaller than ultrafiltration membranes (Kunduru et al., 2017). The pores present in nanotechnology membranes are slightly larger than those used in RO.

An important application of membrane separation techniques is desalination. Desalination is used to remove salt or other components in sea water or brackish water. This process removes minerals, specifically salt, from water. This technique is energy intensive and site specific. The primary techniques that are used are thermal distillation and membrane distillation. Thermal desalination can be performed by a PV/T system. This allows for higher electrical production by the PV panel, while simultaneously desalinating seawater. The heat absorbed from the panel resulted in an 8% increase in electricity production, while reducing the temperature of the solar cell by 15 °C (Wang et al., 2021).

Chemical

Chlorine disinfection is an efficient method for disinfecting water from bacteria and viruses and has been the most largely utilized water treatment disinfectant due to several appealing characteristics (Weiner, 2012). Iodine has been widely used as a water disinfectant, due to its simplicity and cost effectiveness (Backer & Hollowell, 2000). Chlorine can take on a variety of forms to be administered to water for disinfection, from a gaseous state to liquids. A drawback of using chlorine to disinfect water comes from the source of the chlorine. For example, chlorine gas has been found to be contaminated with carbon tetrachloride; hypochlorite that is stored for a long time gradually breaks down to give chlorate; and hypochlorite generated electrolytically from seawater or brine with a high bromide content can have high concentrations of bromate (Thompson, 2007).

Pasteurization

Thermal sterilization of liquids (e.g., water and milk) is termed "pasteurization" after Louis Pasteur, who first articulated the fundamental germ basis of infectious diseases in the 19th century (Burch & Thomas, 1998). This process can be used to kill harmful pathogens in water so that it is safer to drink.

There is a correlation between time and temperatures needed to kill common pathogens: higher temperature requires less time. A commonly accepted method of pasteurization that kill most pathogens is to heat the liquid to 65 °C for 5 min. Studies show that heating river water to temperatures of 65 °C eliminates Salmonella typhimurium, Streptococcus faecalis and Escherichia coli (Jorgensen et al., 1998).

Water can be pasteurized in a variety of ways, including by using solar thermal technologies. Solar box cookers and thermal collectors with reflectors can be used to achieve pasteurization temperatures (Al-Soud et al., 2010; Ciochetti & Metcalf, 1984; Safapour & Metcalf, 1999). Another very simple way of pasteurizing water is by placing water into polyethylene bags and exposing them to the sun. When exposed to 996.2 W/m^2 of radiation for at least thirty min at > 60 °C, the diarrheal pathogens in the water are inactivated, and the water is safe to drink (Zaman et al., 2019).

A slightly more complex way to pasteurize water would be to use solar thermal collectors of various types. These can range in complexity depending on the technology and materials used in them. A low-cost semi-permanent collector device was designed to pasteurize water in Bangladesh. The most important factors to achieve safe drinking water are solar radiation and time. One model showed that the lowest required solar radiation is 390 W/m^2 for 11 L to reach drinking water criteria, at an air temperature of 25 °C (Lundgren, 2014).

A continuous flow, density driven passive solar water pasteurization system is more complex, but also provides higher yields of potable water. A solar water pasteurization system with a total collector area of 0.45 m^2, an operating temperature of 80 °C, and a holding time of 30 sec can produce 80 - 90 kg of treated water on a sunny day (Duff & Hodgson, 2004).

An even more complex system is the PV/T system. An experimental study was done which proved that PV/T systems can pasteurize batches of water. The experimental result revealed that a batch of water of 10 L can easily reach 65 °C using a PV/T system (Kamaleswaran et al., 2016).

A downside of pasteurization is its inability to kill bacterial spores. This means that pasteurization does not truly sterilize the water, but it does make it much safer to drink than if no purification technique was applied (Helmenstine, 2019).

PV Technology

Photovoltaics is the conversion of light into DC electricity via the photovoltaic effect. Photovoltaics has advanced a great deal since its first observation when Edmond Becquerel discovered the photovoltaic effect in 1839. Since then, there has been great progress in improving and redesigning this technology. Research and experiments with various design configurations and materials for PV cells have been studied worldwide and are now able to consistently produce monocrystalline cells with efficiencies from 16% to 22% (Benda & Černá, 2020).

PV modules can be used in integrative systems, linked with water purification techniques. Using the electricity generated from PV modules, a resistive heating coil can be powered to heat water to temperatures required for pasteurization (Dev et al., 2016). This electricity produced by the PV module can similarly be used to power high pressure pumps that are used in RO (Joyce et al., 2001).

Monocrystalline cells are the most common types of cells and have the highest efficiency among commercially available cells. More advanced PV cells are multi-junction cells. These cells have multiple layers that are tuned to individual wavelengths of light, allowing for higher overall efficiency (Ghoneim et al., 2018).

Solar Thermal Technology

Another method of water purification is by using continuous flow solar thermal collectors to pasteurize water. Multiple studies have shown that solar thermal collectors provide sufficient thermal energy gain to heat the water used by the system to adequate temperature that can deactivate bacteria, viruses, and diarrheal pathogens. These studies concluded that solar thermal disinfection systems destroyed 99% of bacterial coliforms in less than thirty minutes at temperatures above 65 °C (Abraham et al., 2015; Burch & Thomas, 1998; Caslake et al., 2004; Duff & Hodgson, 2004; Zaman et al., 2019).

Natural circulation solar thermal systems provide a way to purify water and require no electricity to power pumps or heaters. This system design is simple and easy to build and operate, while being able to purify water using only heat energy from the sun (Manfrida et al., 2017).

PV/T Technology

A PV/T collector incorporates a thermal collector system to the back of a PV module. This increases the efficiency of the PV module by lowering the cell temperature, which increases the total electrical output. PV cell electrical power output is inversely proportional to the temperature of the cells. As the temperature of the module increases, the power of the module decreases (Hengel et al., 2020; Khordehgah et al., 2019). The heat energy from the PV module can be absorbed into the water or heat exchanger fluid from the tubing of the thermal collector, cooling the module, and heating water (Dev et al., 2016; Kamaleswaran et al., 2016; Kumar et al., 2015).

The thermal performance of PV/T systems using different glazing material and flow techniques has been compared. Parallel flow design PV/T systems achieve 3% higher thermal efficiencies at various flow rates and solar radiation levels than direct flow designs (Sultan & Tso, 2018).

The most recent studies of PV/T performance introduce a water based nanofluid (NF) containing magnetite nano additives as coolants. PV/T systems that integrate nanofluid have the best thermal performances and the lowest entropy generation rates (Shahsavar, 2021).

PV/T systems can be used to pasteurize water, while generating electricity from the solar resource. The combination of a solar thermal collector and a PV module increases PV module efficiency and utilizes otherwise wasted heat energy. The heat energy in addition to generated electric energy is used to heat the fluid inside the system to pasteurization temperatures, and if sustained for adequate lengths of time then a PV/T collector can be effective at deactivating harmful pathogens and viruses. This system can be used to pasteurize water or milk (Akmese et al., 2021; Kamaleswaran et al., 2016).

Knowledge Gap

Through all the research that has been reviewed, none of the articles offered a comparison of the ability of the three systems to pasteurize water. My research fills this gap in knowledge by offering a comparative analysis of each system's ability to pasteurize water.

Methodology

In this research, I compare the amount of water pasteurized by PV, ST, and PV/T systems in three different cities. The cities chosen were Chattanooga, Tennessee, Madison, Wisconsin and Yosemite, California. I describe TRNSYS models which compare the annual amount of water pasteurized in gallons. All of the energy collected by each system will be transferred into heat energy to pasteurize water. These systems will be optimized using TRNOPT software. The optimization method used is parametric on mesh (POM). Water storage tank volume will be optimized for a range of collector array sizes for each system.

TRNSYS Modeling

TRNSYS modeling software was used for modeling of the three system configurations: a PV array, solar thermal collector, and PV/T hybrid system. Each configuration was modeled at three locations: Chattanooga, Tennessee, Madison, Wisconsin and Yosemite, California. The parameters and inputs to the model components were left as default unless otherwise noted. The variations from the default TRNSYS parameters and inputs are the specifications for my chosen systems and are noted in Table 1 (PV module), Table 2 (solar thermal collector), Table 3 (PV/T module), Table 4 (storage tank), Table 5 (differential controller), and Table 6 (solar circulating pump). The solar resource is from TMY3 files. The tanks in the ST and PVT models will assume zero heat loss for simplicity and contain 20 horizontal tank nodes as shown in Table 2, which provides negligible difference in pasteurized water compared to 10 nodes. The solar differential controller used in the ST and PV/T systems will have a turn-on differential temperature of 5 °C and a turn-off differential temperature of 2 °C.

Table 1

TRNSYS Type 190a PV Collector Parameters

	Name	Value	Unit
1	MPPT mode	1	-
2	Module I_{SC}	11.68	A
3	Module V_{OC}	41.0	V
4	Reference cell temp	25.0	C
5	Reference irradiance	1000.0	W/m^2
6	Module V_{MPPT}	40.6	V
7	Module I_{MPPT}	10.87	A
8	I_{SC} temp coefficient	0.067	A/K
9	V_{OC} temp coefficient	-0.239	V/K
10	Num of series cells	66	
11	NOC cell temp	46	C
12	Module area	1	m^2
13	Num modules in series	*Coll_Area*	*variable*
14	Num modules in parallel	1	-

Table 2

TRNSYS Type 73 ST Collector Parameters

	Name	Value	Unit
1	Number in Series	1	
2	Collector area	*Coll_Area*	*variable*
3	Fluid specific heat	4.187	kJ/kg/K
4	Collector fin efficiency	0.9	-
5	Bottom edge loss coeff	3.0	kJ/hr/m^2/K
6	Absorber plate emittance	0.9	-
7	Absorber plate absorption	0.9	-
8	Num of covers	1	-
9	Cover index of refraction	1.526	-

Table 3

TRNSYS Type 50d PV/T Collector Parameters

	Name	Value	Unit
1	Mode	4	-
2	Collector area	*Coll_Area*	*variable*
3	Collector efficiency factor	0.9	-
4	Fluid thermal capacitance	4.187	kJ/kg/K
5	Collector plate absorptance	0.9	-
6	Num of glass covers	1	-
7	Collector plate emittance	0.9	-
8	Bottom and edge loss coeff	3.0	kJ/hr/m^2/K
9	Collector slope	36.0	degrees
10	Extinction coeff thickness product	0.0028	-
11	Cell efficiency temp coeff	-0.0003	1/K
12	Reference cell temp	26.0	C
13	Packing factor	0.96	

Table 4

TRNSYS Type 534 Storage Tank Parameters

	Name	Value	Unit
1	LU for data file	-1	-
2	Num of tank nodes	20	-
3	Num of ports	2	-
4	Num of immersed heat exchangers	0	-
5	Num of miscellaneous heat flows	1	-
6	Tank volume	*Tank_Vol*	*variable*
7	Tank height	60.0	in
8	Tank fluid	0	-
9	Fluid specific heat	4.187	kJ/kg/K
10	Fluid density	1000.0	kg/m^3
11	Fluid thermal conductivity	0.598	W/m/K

Table 5

TRNSYS Type 911 Differential Controller Parameters

	Name	Value	Unit
1	Upper Input temp T_H	20.0	C
2	Lower Input temp T_L	10.0	C
3	Monitoring temp T_{IN}	20.0	C
4	High limit cut out	100.0	C
5	Upper dead band dT	5.0	C
6	Lower dead band dT	2.0	C
7	Lock-out control signal	0.0	-

Table 6

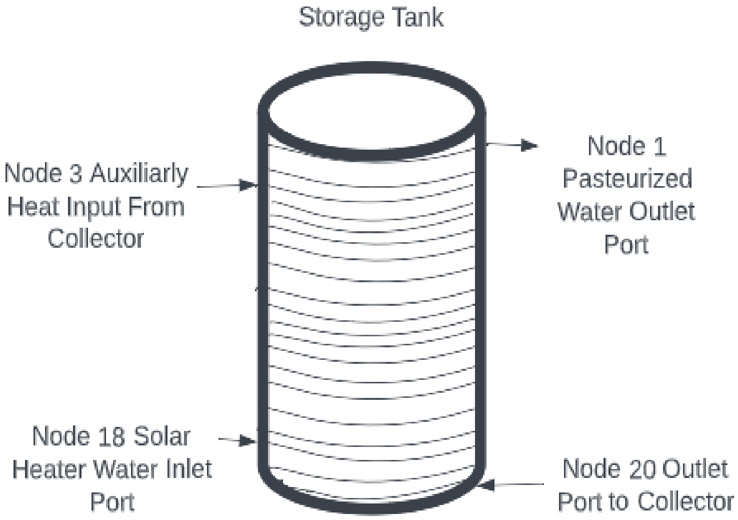
TRNSYS Type 114 Solar Circulating Pump Parameters

	Name	Value	Unit
1	Rated flow rate	62.0	kg/hr
2	Fluid specific heat	4.187	kJ/kg/K
3	Rated power	745.6	W
4	Motor heat loss fraction	0.0	-

The ST, PV, and PV/T total collector areas considered will be 1 - 4 m^2, and the array tilt angle will be the correlating latitude for the location. The models produce data on electrical output for the PV array and PV/T systems, and heat energy transferred for the ST and PV/T systems. Electrical energy will be converted to thermal energy using a resistive heating coil located within the tank at tank node 3, near the top of the tank as shown in Figure 1, for the PV and PV/T systems. The ST and PV/T systems are direct. The comparative analysis will provide the final amount of pasteurized water produced by each of the three configurations.

Figure 1

Storage Tank Schematic



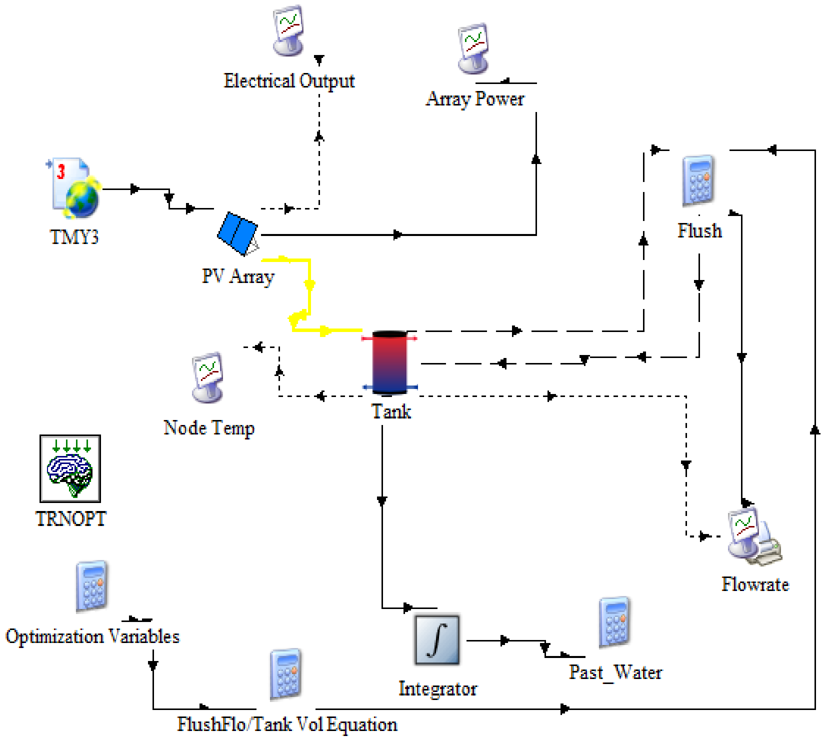
Pasteurized water, that is, water that has been held at pasteurization temperature for a sufficient length of time, must be removed from the tank to avoid wasteful overheating and to mimic a practical usage pattern. In these models, when the top tank node (1/20 of the tank volume) reaches 68 °C for one time step (7.5 min), a volume of water equal to a node volume will leave the tank from the top tank node 1 and will be replaced with an equal volume of ground temperature (20 °C) water entering the bottom tank node 20 before the next time step, as shown in Figure 1. A temperature of 68 °C was chosen to provide a safety margin above 65 °C, which is the accepted pasteurization temperature. This represents the flushing function that was implemented into the models. Flushing events will be counted to determine the volume of pasteurized water.

PV/Electrical Performance

The analysis of the PV array is focused on daily electrical output. This electrical output will be converted into heat energy to pasteurize water. The components in this model include the Type 15 weather component to read the solar resource TMY3 file, Type 190a PV panel, and the Type 534-NoHX tank. The PV Type 190a model is based on the calculation method presented by De Soto. (De Soto et al., 2006) The Type 190a output Array Power at Maximum Power Point is linked to the Type 534 Auxiliary Heat Input in tank node 3. The flushing function, as described in the TRNSYS Modeling section, was implemented and the amount of potable water produced will be quantified by counting node “flushes”. Figure 2 shows the model layout and connections between components.

Figure 2

Photovoltaic TRNSYS Model

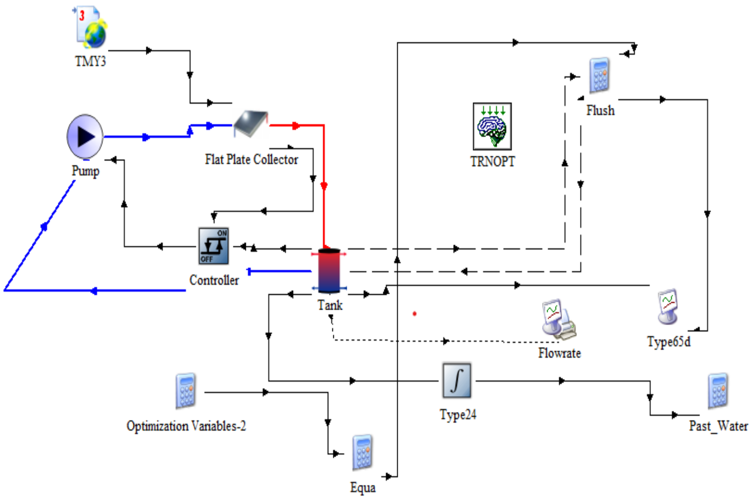


Solar Thermal Performance

The ST system is a direct system that uses solar energy to heat the water within the collector that is circulated from the water storage tank. The components used in this model are the Type 15 weather component to read the solar resource TMY3 file, a flat plate solar collector Type 73 which uses the Hottel-Whillier (Soto et al., 2006) steady-state model for evaluating the thermal performance, the Type 114 circulating pump, the Type 911 differential controller, and the Type 534-NoHX tank. The inlet for the solar heated water is tank node 18 and the outlet to the collector is at tank node 20 as shown in Figure 1. The pump controls the circulation through the collector. The pump is controlled by the differential controller, which turns the pump on when the turn-on differential temperature is met, and off when the turn-off differential temperature is met. The output pasteurized water will be determined by summing flush events and reported in gallons per year. Figure 3 shows the overall layout and connections between components.

Figure 3

Solar Thermal TRNSYS Model



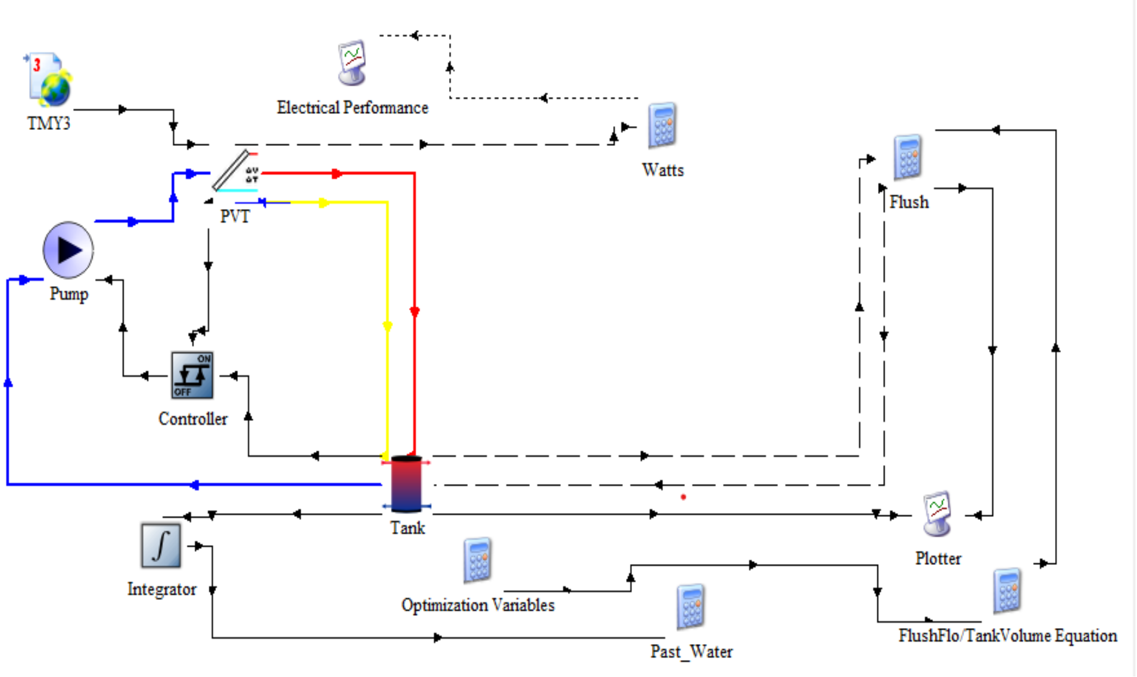
PV/T Performance

The PV/T collector provides useful heat gain from the solar thermal collector and the PV electrical power output transferred to the resistive heating coil. The components that are used include the Type 50d P-V Thermal Collector, the Type 534-NoHX tank, the Type 114 circulating pump, and the Type 911 differential controller.

The water inside the thermal collector portion of this component will be heated by the solar resource and pumped to the storage tank. The solar thermal collector part of the PV/T operates identically as described in the ST section. The PV part of the PV/T collector operates identically as described in the PV section. The total amount of pasteurized water exported by the system will be calculated by counting flushing events and recorded in gallons per year. Figure 4 shows the overall layout and the connection between components.

Figure 4

PV/T TRNSYS Model



Run Time

All three of these models will be simulated in TRNSYS using a time step of 7.5 minutes. This was intentional, because when water is heated to the flushing temperature and held there for one time step the water is pasteurized. Each simulation will run for 8,760 hours, comprising yearly data. A TRNOPT optimizing component has been implemented into each of the systems. This optimizing component optimizes using the selected parametric on mesh method. Other methods were tested and provided identical results. This component was used to optimize tank size for a range of total array area.

Results

Optimized Storage

The objective of this study is to compare the amount of pasteurized water produced by PV, ST, and PVT systems at three locations for a range of collector areas. To provide a fair comparison, the water storage volume was optimized individually for each system at each collector area.

The optimized tank size is the volume that was required to achieve maximum water pasteurization. Results are presented in Table 7. Optimum tank size varied from system to system for each of the cities. The PV system required a lower tank volume than the ST and PV/T systems for each location when the collector area was 2 - 4 m^2, but required a larger tank size when the collector area was 1 m^2. The ST system required a larger tank volume than the PV/T system in Chattanooga and Madison, while the PV/T system required a larger tank volume in Yosemite. The optimized tank volume for the PV, ST, and PV/T systems across all locations and collector areas ranged from 53-208 gallons, 95-126 gallons, and 80-120 gallons respectively.

Table 7

Optimized Storage in Gallons for Chattanooga, Madison, and Yosemite

Area (m^2)	Chattanooga			Madison			Yosemite		
	PV	ST	PVT	PV	ST	PVT	PV	ST	PVT
1	68	95	89	53	97	80	74	98	97
2	111	108	72	115	101	82	135	101	101
3	134	113	89	139	109	84	173	104	119
4	197	115	115	170	126	114	208	119	120

Pasteurized Water Production

Table 8 show the amount of pasteurized water by each system, relative to collector size, in each city. Overall, the PV system produced the lowest amount of pasteurized water and pasteurized water to collector area ratio. This was true for each of the cities where the system was implemented. The ST and PV/T system performed similarly in production and ratio. For smaller collectors (1 - 3 m^2), the ST system produced higher amounts of pasteurized water than the PV/T system. However, the PV/T system produced a higher amount of pasteurized water when the collector size was 4 m^2.

Table 8

Pasteurized Water Production in Gallons for Chattanooga, Madison, and Yosemite

Area (m^2)	Chattanooga			Madison			Yosemite		
	PV	ST	PVT	PV	ST	PVT	PV	ST	PVT
1	2921	5881	5070	2597	4915	4046	3593	7390	6708
2	5843	9368	8835	5196	7804	7182	7188	12134	11661
3	8755	12984	12777	7793	10795	10472	10780	17026	16898
4	11680	16684	16921	10387	13894	13885	14365	22018	22360

Pasteurized Water Per Collector Area

The amount of pasteurized water per area of the collector (gal/m^2) was calculated by dividing the total amount of pasteurized water produced by the collector area. The same trend that was shown in the pasteurized water production results presented in Table 9.

Table 9

Pasteurized Water Produced per Collector Area in Gallons/m^2 for Chattanooga, Madison, and Yosemite

Area (m^2)	Chattanooga			Madison			Yosemite		
	PV	ST	PVT	PV	ST	PVT	PV	ST	PVT
1	2921	5881	5070	2597	4915	4046	3593	7390	6708
2	2922	4684	4418	2598	3902	3591	3594	6067	5831
3	2918	4328	4259	2598	3598	3491	3593	5675	5633
4	2920	4171	4230	2597	3474	3471	3591	5505	5590

Relative Pasteurized Water by System

To provide a simple comparison between the systems, pasteurized production relative to PV (being the lowest production) was calculated. Based on the 10 below, the results show that the relative pasteurized water production of ST and PVT was highest when the collector area is lowest.

Table 10

Relative Pasteurized Water Produced in Gallons by System for Chattanooga, Madison, and Yosemite

Area (m^2)	Chattanooga			Madison			Yosemite		
	PV	ST	PVT	PV	ST	PVT	PV	ST	PVT
1	100%	201%	174%	100%	189%	156%	100%	206%	187%
2	100%	160%	151%	100%	150%	138%	100%	169%	162%
3	100%	148%	146%	100%	139%	134%	100%	158%	157%
4	100%	143%	145%	100%	134%	134%	100%	153%	156%

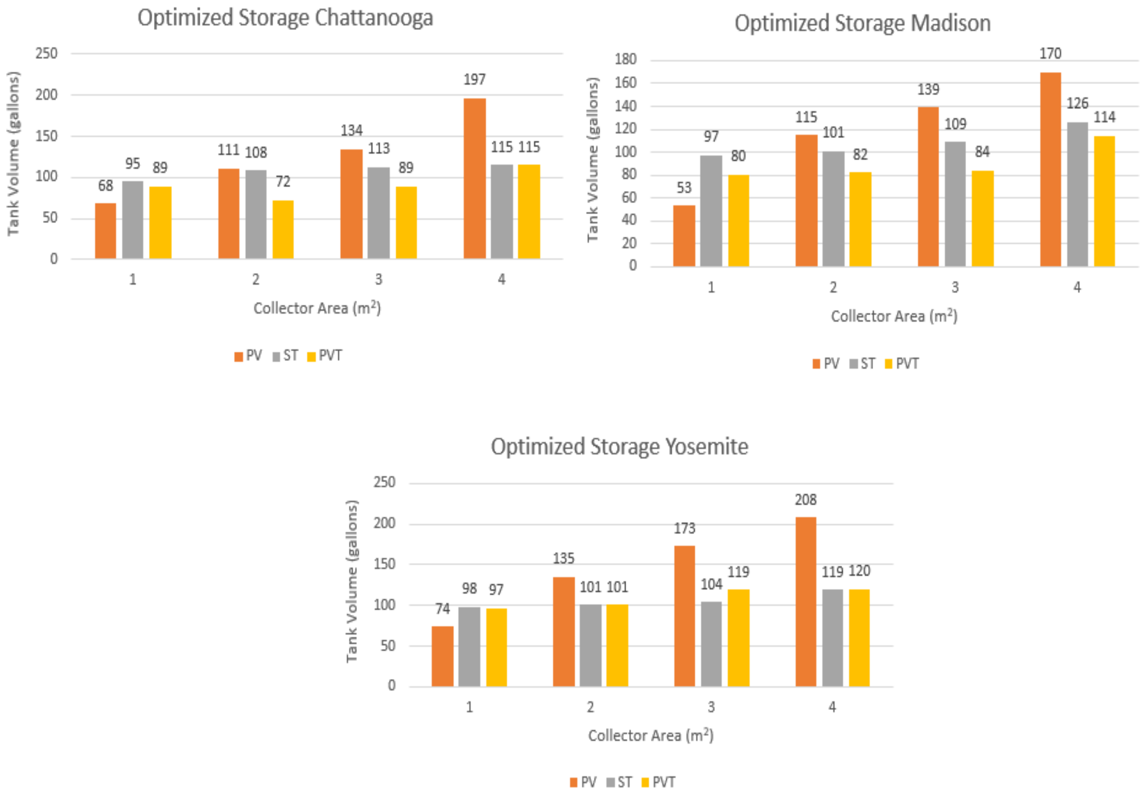
Discussion/Conclusions

Optimized Storage

Figure 5 shows each system accompanied by their optimized tank volume related to collector area.

Figure 5

Optimized Storage for Collector Areas 1 m^2 – 4 m^2 in Chattanooga, Madison, and Yosemite



Results of the optimized storage show that the PV system requires much larger tank volumes as the collector area rises, while the ST and PV/T systems require smaller incremental increases in tank volume when increasing the collector area. This is true for the systems at each location.

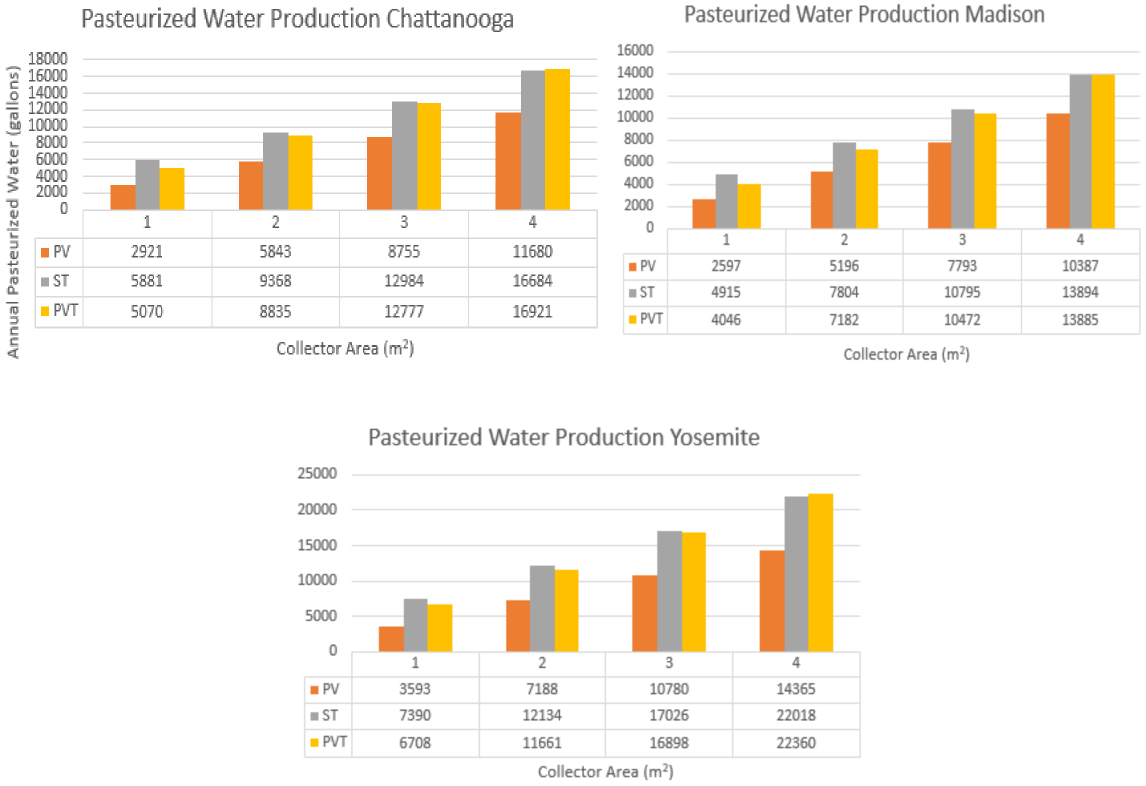
It is important to note here that typical residential water heaters are sized between 40 and 120 gallons. However, it is crucial for each system to be on a level playing field by optimizing them individually. Due to this, the optimized storage results in tank volumes that are not commercially available.

Pasteurized Water Production

Figure 6 below represent the annual amount of pasteurized water produced by each system in each location.

Figure 6

Pasteurized Water Production for Collector Areas 1 m^2 – 4 m^2 in Chattanooga, Madison, and Yosemite



A common trend that can be seen by the pasteurized water production is that when there is an increase in collector area, there is a correlated increase in pasteurized water production. This can be seen in each system regardless of the location. It is interesting to see in Figure 12 the ST system outperforms the PV/T system at all collector areas except for the 4 m^2 array. This may be because the optimum collector area for the PV/T system is higher than the ST. The PV system produces about half of the pasteurized water than the ST and PV/T system when the collector area is 1 m^2, but produces higher amounts of pasteurized water as the collector area is increased.

Pasteurized Water Per Collector Area

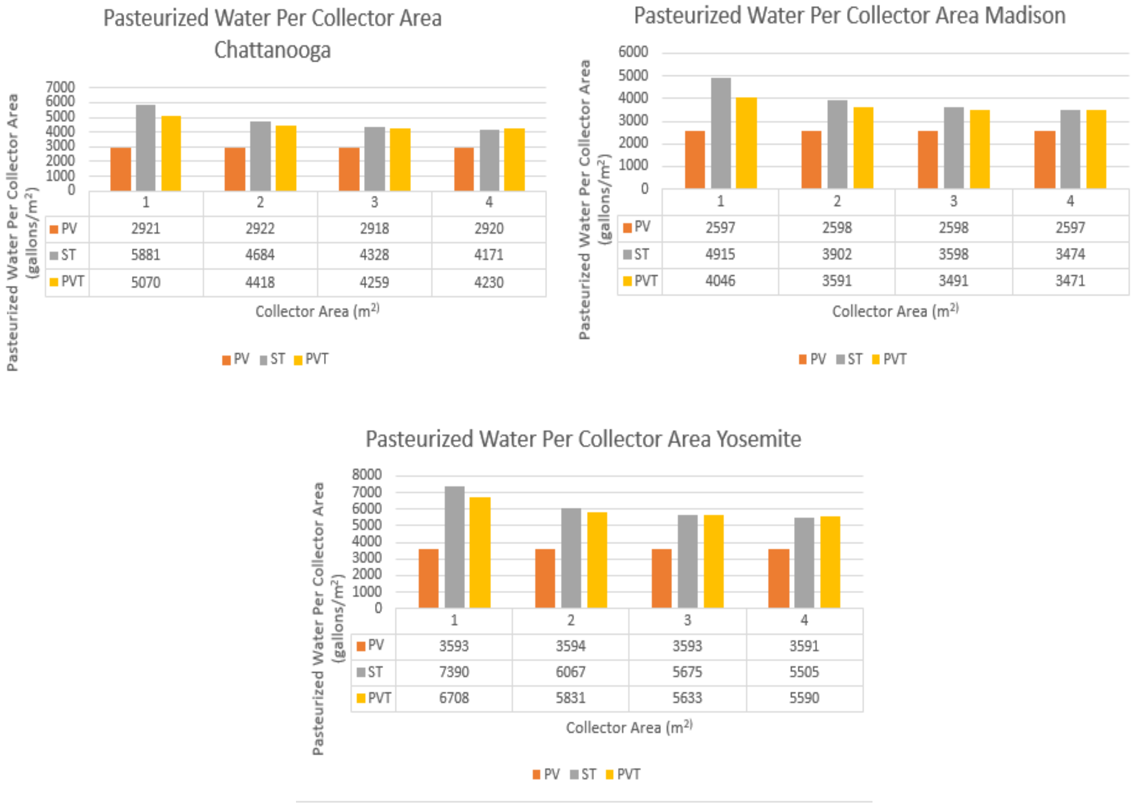
Figure 7 below shows the amount of pasteurized water per collector area. The trend of pasteurized water per collector area is diminishing returns for the ST and PV/T systems. This shows that there is less incremental pasteurized water production as the collector area is increased. The PV does not show this trend but shows constant returns when the collector area is increased. This should be taken into consideration when sizing the system.

Relative Pasteurized Water by System

Due to the PV system producing the least amount of pasteurized water throughout this study, it was used as the baseline when comparing systems. The results found in Figure 8 shows that the ST system produces 63% more pasteurized water than the PV system when averaged over all locations and array sizes. The PV/T system on average produced 53% more pasteurized water than the PV system.

Figure 7

Pasteurized Water Production per Collector Area for Collector Areas 1 m^2 – 4 m^2 in Chattanooga, Madison, and Yosemite



Pasteurized Water Per Collector Area Chattanooga

	1	2	3	4
PV	2921	2922	2918	2920
ST	5881	4684	4328	4171
PVT	5070	4418	4259	4230

Pasteurized Water Per Collector Area Madison

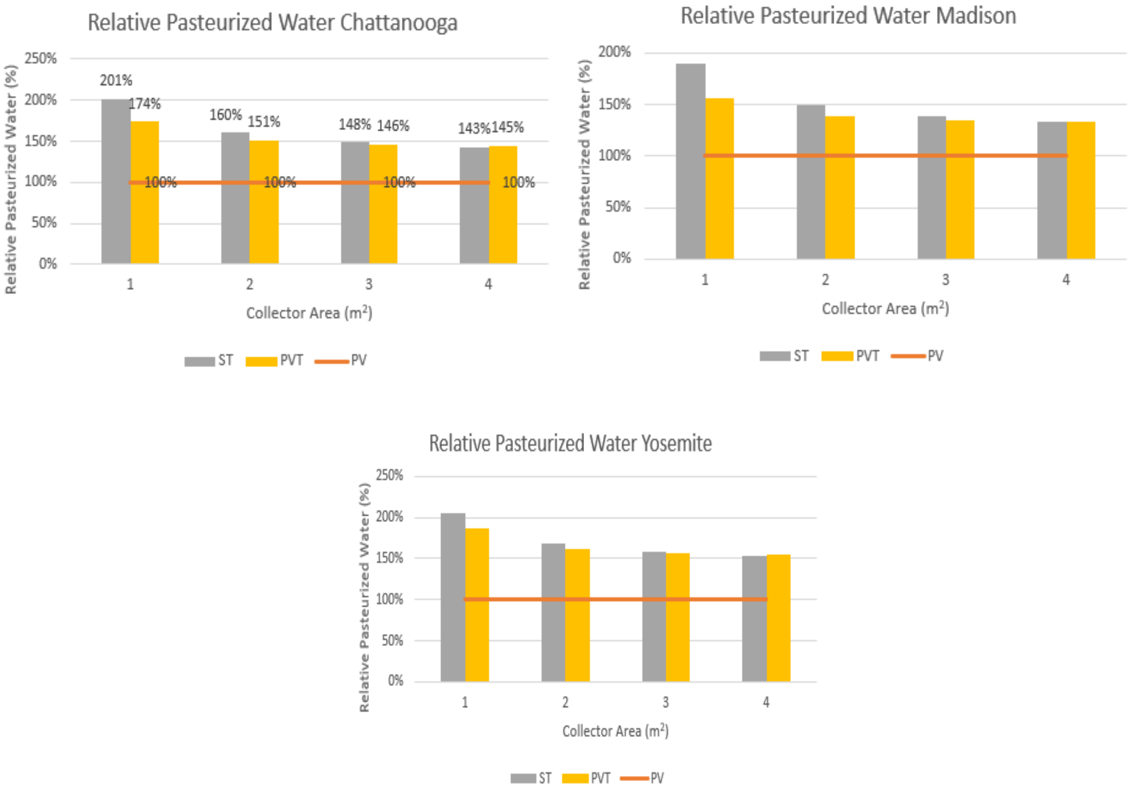
	1	2	3	4
PV	2597	2598	2598	2597
ST	4915	3902	3598	3474
PVT	4046	3591	3491	3471

Pasteurized Water Per Collector Area Yosemite

	1	2	3	4
PV	3593	3594	3593	3591
ST	7390	6067	5675	5505
PVT	6708	5831	5633	5590

Figure 8

Relative Pasteurized Water Production by System for Chattanooga, Madison, and Yosemite



Summary

In this study, PV, ST and PV/T systems were modeled and compared by their ability to produce pasteurized water. The tank volume of the systems was optimized based upon the collector area. There is no research that compares the three systems described and their ability to pasteurize water. This research provides a comparative analysis of the systems by these measurements and concludes that choosing a ST or PV/T system would be advantageous over a PV system. The ST and PV/T systems are able to pasteurize 63% and 53% more water than the PV system, respectively. By using this research, system designers and consumers can more accurately gauge how much pasteurized water a particular system can produce before purchasing and installing, as well as aid in choosing an optimal system for their location. These models can use any TMY3 weather file to model system performance at any location chosen. The models are scalable and will work for commercial and industrial sized projects.

Limitations

Not all of the system parameters can be optimized by TRNOPT. Examples of this are the location of the ports, location of the heating elements within the tank, and the circulating pump flow. Another limitation is my ability to create equivalent models. The PV ST and PV/T components in TRNSYS do not require the same parameters and inputs. All models were made to be as equal as they could with the parameters that were given.

Suggestions for Future Studies

For future studies, scaling up these models should be considered. Using larger ranges of collector area and tank size would allow for these systems to be implemented on commercial or industrial scales. Another recommendation is to use models for every climate zone to see how the systems performance differentiates across different climates.

Including a heat exchanger between flushed pasteurized water and incoming make-up water may have a positive effect on the overall efficiency of the systems. Location of the electric heating element in the tank and tank inlet and outlet ports may affect system performance. Including a heat exchanger between flushed pasteurized water and incoming make-up water may have a positive effect on the overall production of the systems. The net effect of circulating tank water on PV production from a PV/T panel should me studied, specifically investigating the potential for heating the collector with hot tank water.

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Vita

Patrick Kelly was born and raised in Wilmington, North Carolina. Growing up close to the beach, he enjoyed surfing, swimming and being by the water. Because of this, he is very passionate about clean water and technologies that support or produce clean water. He attended Appalachian State University in pursuit of sustainable technology. He received his bachelor's degree in Sustainable Technology, before moving on to pursuing a masters in Appropriate Technology. He plans to pursue higher education outside of the United States where he hopes to get a doctorate in the field.