MODELING OF PHOTOVOLTAIC, SOLAR THERMAL, AND PHOTOVOLTAIC/THERMAL DOMESTIC HOT WATER SYSTEMS

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ABSTRACT

Solar heating of potable water has traditionally been accomplished through the use of thermal solar panels. With the recent increases in availability and lower cost of PV panels, the potential of coupling PV solar arrays to electrically heated domestic hot water (DHW) tanks has been considered. This paper attempts to compare the performance of a traditional solar thermal DHW system to a PV-solar-electric DHW system. To accomplish this, a detailed TRNSYS (Klein, 2006) simulation of various solar hot water systems was configured and simulations were performed for a 250L load in Toronto, ON and Vancouver, BC. In addition, a system utilizing combined PV/Thermal solar collectors was compared. It was shown that when considering both capital costs and operational costs, a PV-DHW system is not yet viable for either region, while the solar thermal and PV/T systems are much more competitive.

INTRODUCTION

In order to reduce Canadian dependency on fossil fuels, solar panels have received an increased amount of attention. One of the easiest ways to implement solar technology into the average Canadian household is via the hot water storage tank. Meeting hot water loads accounted for 20.2% of energy demand in Canada in 2012 (Natural Resources Canada, N.D.).

A common design for a Solar Domestic Hot Water (SDHW) system in Canada uses a flat plate solar thermal collector to absorb solar radiation and convert it to thermal energy. The heat is then transferred to a hot water tank via a heat exchanger. A back up heater is often integrated into the tank to provide heat during times of low solar availability (Fig 1). A standard solar thermal collector absorbs solar energy with a maximum efficiency of roughly 70% (Jaisankar, Ananth, Thulasi, Jayasuthakar, & Sheeba, 2011). This converted energy is transferred to the working fluid, typically water. To prevent freezing, the water in the collector loop is mixed with propylene glycol to create a 50% mixture. This reduces both the freezing point and the specific heat of the liquid, limiting the performance. The heat is transferred from the working fluid to the potable water, drawn from the bottom of the tank, via a heat exchanger. The tank loop deposits the heated water into the middle of the tank using a dip-tube. This, combined with an auxiliary heater for the top portion of the tank, creates stratification. Stratification is a process in which cold water near the bottom of a tank is heated (e.g., by a solar collector) and re-enters the tank at a higher position. This forms a temperature difference between the top of the tank and the bottom of the tank. For the same average temperature as a mixed tank, a hotter top and colder bottom exists. The result increases solar collector efficiency as the coldest water is sent to the collectors to be heated, and the hottest water is drawn off the top of the tank when needed to meet a load.

A recent development in the SDHW industry is the implementation of PV panels in DHW systems (PV-DHW). Hot water heating occurs via a resistance heater immersed in the storage tank and powered solely by PV. The PV modules are most often connected via a DC-AC inverter to be compatible with conventional hot water tanks. The conversion of solar energy to electricity in PV modules typically occurs at efficiencies below 20%. Consequently, PV-DHW systems were previously considered cost-prohibitive due to the size and cost of the PV array required. From 1998 to 2005, the cost of PV decreased by an average of $0.40 per W/year due to non-module cost reductions (e.g., inverters, labour). This decline in costs was especially beneficial for PV arrays generating less than 5 kW, which is the typical energy range for a DHW system (Wiser, Barbos, & Peterman, 2009). The International Energy Agency's Technology Roadmap similarly states that the cost of PV systems is now a third of the cost associated with similar systems 6 years ago. The Roadmap also predicted that PV will generate 16% of global power by 2050 (International Energy Agency, 2014).

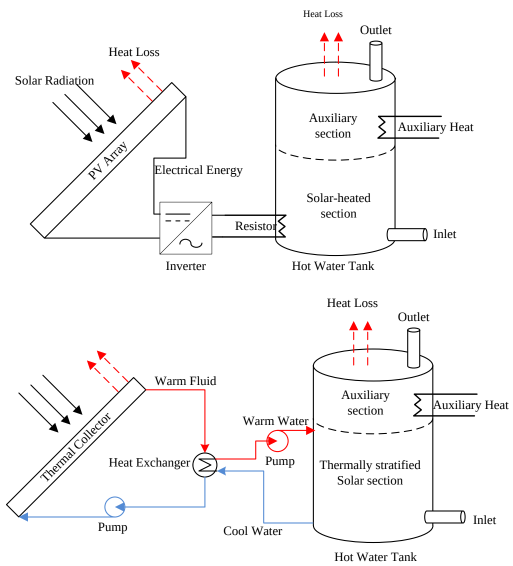

Fig 1. Simplified layout of the DHW systems. (a) PV configuration, (b) solar thermal configuration

A relatively new method of gathering solar energy uses Photovoltaic/Thermal (PV/T) collectors, which combine the cells of a PV system with the absorber plate and heat extraction of a solar thermal collector. It has been shown that while mounting the PV cells on the absorber plate may reduce the individual electrical and thermal efficiencies, the combined energy gain per unit area is usually greater than or equal to what the collectors could provide individually. While great attention has been given to both air and liquid-based systems, liquid systems are preferable due the lower radiation-related temperature fluctuations within the collector (Daghigh, Ruslan, & Sopian, 2011).

As of this study, few analyses have been conducted on PV-DHW systems. As a result, this paper focuses on the development a numerical model to determine if such a system is viable. A comparative analysis of PV, solar thermal, and PV/T domestic hot water systems was conducted using TRNSYS 17. Parameters such as hot water load and collector area were varied in order to compare their effects on performance. Each configuration was simulated for two Canadian cities over the course of one year using three minute time steps.

SIMULATIONS

The simulations for the systems described above were created in TRNSYS, a computer program which allows for entire systems to be simulated accurately under defined climatic conditions (Klein, 2006). TRNSYS is a versatile programming environment, allowing for flexibility in the modeling of complex systems consisting on many components. Numerical models for individual components are called "TYPES" and are usually coded in FORTRAN. These TYPES can be modified if necessary, and the graphical interface allows for easy addition, connection, or removal of various components to create a simulation of an entire system. This makes it ideal for design optimization as different systems can be compared and contrasted. An additional advantage is model parameters, input forcing functions (e.g., weather and load data) and outputs (e.g., results) can be selected to mimic existing experimental results, allowing for model validation.

For this study, the simulations were run for year-long periods based on weather data imported from Typical Meteorological Year (TMY) data files provided with TRNSYS. Simulation time steps were set to three minutes, as this value was found to meet the convergence criterion without excessive computational time duration. Specifications for the PV modules were taken from TrinaSolar's TSM-180D module (Trina Solar Ltd, 2006), and the solar thermal collector specifications were taken from the SOL+20 flat plate solar thermal collector manufactured by Dimas (Dimas Solar Thermal Industry, 2013). For an effective comparison, the various properties of these panels were combined for the PV/T design. This was accomplished by combining the properties of both the PV and solar thermal systems into one TRNSYS module (e.g., thermal coefficient for losses from the back and edges, temperature coefficient of PV cells, etc.); this represents a best-case scenario, as PV cells typically

Table 1. TRNSYS TYPES used in the system models

TYPE Number	Description
1	Solar Thermal Collector
2	Temperature Controller
3	Pump
14	Forcing Function
31	Pipe
48	Inverter
50	PV/T Collector
91	Heat Exchanger
94	PV Array
534	Hot Water Tank
1226	Heating Element

have higher emissivity values, resulting in a higher heat loss rate from a PV/T collector compared to the solar thermal collector.

Built-in TRNSYS and TESS TYPES were used for the simulations. In-depth descriptions of the TYPES can be found in the TRNSYS and TESS documentation (Klein, 2006) (Thermal Energy Systems Specialists, 2012). Weather conditions were generated from a TMY data file for Toronto and Vancouver. A list of components is provided in Table 1.

For TYPE 534, used as the hot water tank, a nodal convergence analysis determined that 20 nodes provided comparable results to the next largest node configuration for the 1.5 m tall, 270 L tank modelled. A daily hot water draw of 250 L was chosen to represent a typical operation of the system. This draw was distributed over 24 hours according to a designated profile provided in the CSA F379-M1982 standard (Canadian Standards Association, 1982). The auxiliary heater was placed such that the top 25% of the tank's water was heated. Auxiliary heat was provided by an electrical heater immersed in the tank, with a set point of 50 ± 1°C (this is considered the hot water set point for the tank) and a safety limit temperature of 80°C. Heat transfer and heat loss for both the auxiliary and solar-heated portions of the tank is calculated for each node at each timestep. For simulations taking heat from the solar thermal array, the heat exchanger water loop used a tank entry point placed in the node below the auxiliary element. The PV system had an additional aquastat; set to maintain a set point of 79 ± 1°C, (with a safety temperature of 80°C) in the node with the PV powered resistance heater. For practical considerations, this hard limit was chosen for safety considerations concerning temperature and pressure within the tank. This also prevented any scenario occurring in which a phase change (i.e., boiling) would be expected as TYPES used were unable to compute property changes in water near its boiling point.

For simulations using fluid loops (which in the present work, are closed-loop systems), a differential temperature controller (TYPE 2) was implemented to prevent hysteresis; the temperature of the fluid exiting the collector was the upper input temperature, and the fluid at the bottom of the tank was the lower input temperature, with the dead band between the two inputs set to 3°C. A mechanical pump was used to circulate the fluid through piping in the collector loop. The pipe before and after the collector was 10 m in length, with a 0.95 cm inner diameter, and a heat loss coefficient value of 0.55 W/K. A pump was also used in the tank loop, circulating water from the tank to the heat exchanger and back, but it was assumed that the pipe losses were insignificant. Each pump was set to a constant speed of 1 L/min, and was controlled by the differential temperature controller to only activate when a 3°C temperature difference was seen between the collector array outlet temperature and the bottom of the hot water tank. This low flow rate was specified to promote stratification within the storage tank.

For the PV/T simulation, electrical energy was provided directly to the grid, instead of the hot water tank. All calculations involving the electrical energy delivered by this system account for losses associated with a typical DC-AC inverter. The solar collectors were modeled with one layer of glazing.

The heat exchanger model used to transfer the heat from the collector loop to the potable water assumed a counter-flow configuration with a constant effectiveness of 0.85. The efficiency of the electrical inverter in the PV system was assumed constant at a value of 0.90.

ANALYSIS

The primary method of comparison for the simulations was comparing the solar fraction. Solar fraction is defined as:

$$f = \frac{Q_{solar} - Q_{losses}}{Q_{load}} = 1 - \frac{Q_{aux}}{Q_{load}} \tag{1}$$

The energy generated, required, and delivered by each system was measured in kWh, and has been tabulated in annual values. The operating cost for each system was calculated by multiplying the combined auxiliary heat energy and pump energy (defined as Q_{aux}) by the Ontario residential electricity rate, which when evaluated as a time-based average is currently \$0.1515/kWh (Ontario Energy Board, 2015).

In addition to the solar fraction, solar component comparisons were made using electrical/thermal/total efficiency, exergy efficiency, and Primary Energy Savings (PES) efficiency as defined in Table 2. These values are typically used in literature to quantify energy efficiency, and were recommended by the International Energy Agency's Task 35 to properly evaluate performance of PV/T systems (Zondag, 2009).

Task 35 recommended using PES because it accounts for the amount of fossil fuel saved by the system, arguing that this was the main purpose of renewable energy systems.

Table 2: Equations for performance evaluation of collectors

Evaluation Method	Equation	
Total Efficiency	$\eta_o = \eta_e + \eta_{th}$	(2)
Exergy Efficiency	$\xi_o = \eta_c \eta_{th} + \eta_e$	(3)
PES Efficiency	$E_f = \frac{\eta_e}{\eta_{power}} + \eta_{th}$	(4)

For the exergy efficiency, the Carnot efficiency, η_c, is described by:

$$\eta_c = \left(1 - \frac{293\text{K}}{293\text{K} + (T_{wm} - T_a)}\right) \quad (5)$$

where η_e is the efficiency of PV cells, η_{th} is the efficiency of thermal components, T_a is ambient temperature surrounding the collector, T_{wm} is the temperature of the working medium (which is in case was assumed to be the collector outlet temperature), and η_{power} is the efficiency of local power plants. Task 35 indicates this value is 39% for OECD countries, which is equivalent to the IEA's efficiency value for fossil fuel plant energy efficiency (Taylor, Lavagne d'Ortigue, Trudeau, & Francoeur, 2009).

RESULTS AND DISCUSSION

The purpose of SDHW systems is to have a large portion of the hot water load met by the solar components. The PV/T system was configured to provide the best performance based on combined thermal and electrical energy. The results of this analysis were mixed; with some of the performance criteria favouring the solar thermal system (Fig.'s 3, 4) others favour the PV/T system. This was expected for the exergy and total efficiency calculations, since the solar thermal (only) collectors typically collect more thermal energy than the PV/T collector. However the PES efficiencies, solar fraction values and operating costs, both monthly and annual, favoured the PV/T system as expected.

Two different sizes of solar arrays were simulated for the PV system. It is well-known that the efficiency of a PV system is significantly less than that of a solar thermal or PV/T collector. Typically the efficiency of a PV collector is approximately half that of a solar thermal system. This was confirmed from the simulation results that showed that when the PV area was double the size of the solar thermal and PV/T system, a similar solar fraction was achieved. It is important to recognize that thermal and electrical efficiencies are not synonymous, due to higher exergy value associated with electricity over thermal energy. Accounting for this, other performance indices were explored.

The simulations were conducted for Toronto, ON in an effort to compare the performance of the three systems studied. In all three cases a collector array size of 6.75 m^2 was assumed. Annual solar fractions for PV, solar thermal, and PV/T systems were 29%, 65%, and 74% respectively (Table 3). The solar fraction for the PV system was notably lower than the other two. This was primarily due to the lower efficiency of the PV array (16%); however, the solar fraction was negatively impacted by mixing in the tank caused by the resistance heater.

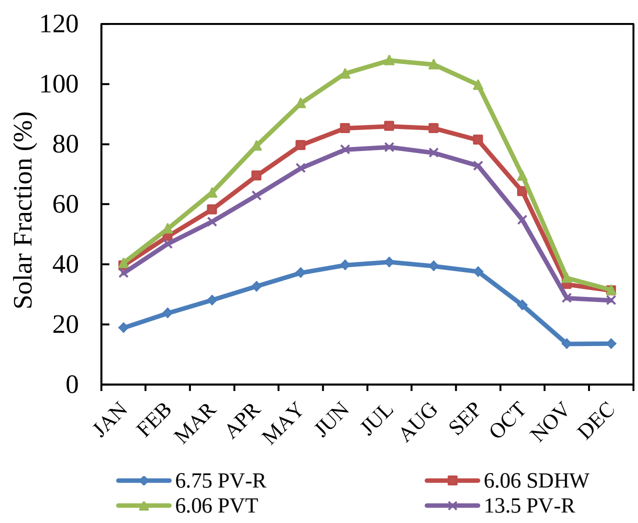

Fig 2. Simulated monthly solar fraction for Toronto

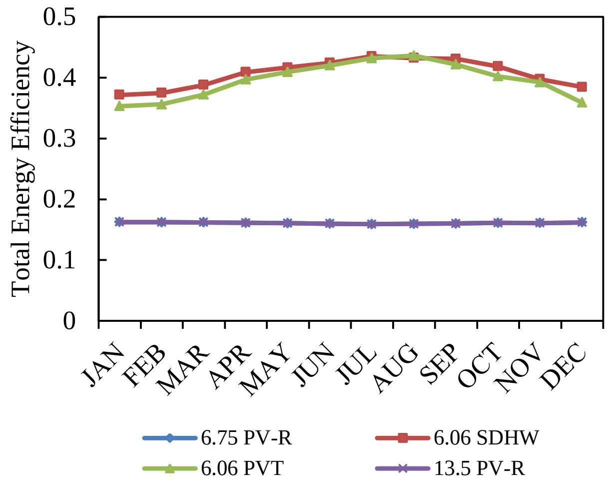

Fig 3. Monthly total energy efficiencies for Toronto

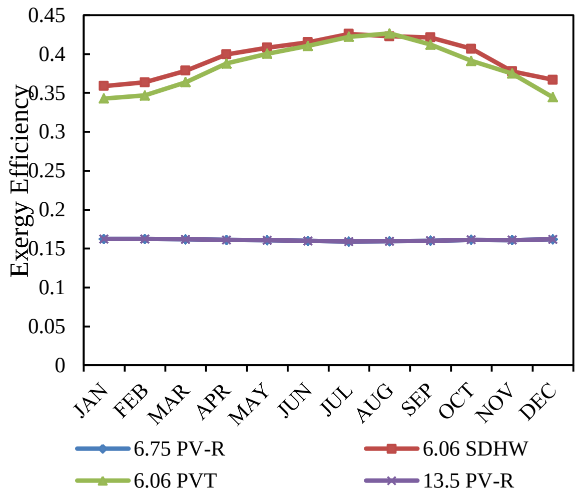

Fig 4. Monthly exergy efficiencies for Toronto

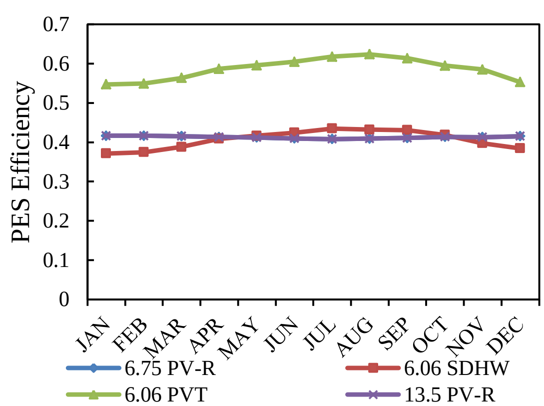

Fig 5. Monthly PES efficiencies for Toronto

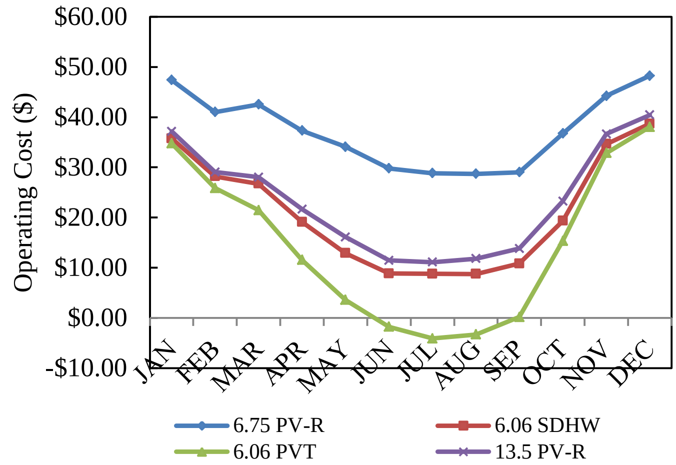

Fig 6. Monthly operating costs for Toronto

On a component level, the solar thermal system outperformed the other designs in total efficiency and exergy efficiency. However, the PES efficiency of the PV/T collector surpassed that of the solar thermal collector by approximately 18%. As expected, the efficiency values for the two PV resistance systems were the same (and therefore are superimposed for certain performance plots) but lower than the solar thermal and PV/T simulations. The average, maximum, and minimum of these values are provided in Table 3.

When comparing energy provided directly to the hot water tank, it was expected that the PV/T solar fraction would be lower than that of the solar thermal system since the available thermal energy was reduced by the presence of the PV panels (48% compared to 65%) that converted a portion of the incident solar irradiance to electricity rather that heat. In this case, electrical energy provided by the PV/T system is not included in this calculation. However when the electrical energy was used to offset the energy from the auxiliary heater, the annual PV/T solar fraction increased from 48% to 73%. In the summer season, the solar fraction of the PV/T system was above 100%, indicating more energy than was needed to meet the hot water load was provided from solar sources. In some jurisdictions, excess electrical energy could be sold back to the grid. Table 4 provides the energy outputs of the systems. The solar thermal and PV/T systems were found to provide similar energy outputs.

Seasonal averages of solar fraction were also calculated. The summer averages for the 6.75 m^2 PV, solar thermal, and PV/T systems were 40.0%, 85.5%, and 105.9% respectively. For the winter, the solar fractions were 18.7%, 40.1%, and 41.3% respectively. It was evident that the presence of PV cells in the PV/T system increases the solar fraction such that a negative operating cost can be achieved in warmer months.

For comparative purposes, a similar analysis was made using climate conditions and pricing for Vancouver, BC. The annual solar fractions for the 6.75 m^2 PV, solar thermal, and PV/T systems were 28%, 64%, and 74% respectively. These are nearly identical to the Toronto solar fractions; however, there was a difference in the seasonal distribution of solar fraction. Summer solar factions were 45.3%, 88.5%, and 112.5%, and the winter solar fractions were 12.4%, 31.7%, and 33.8%. In the winter case, the lower solar radiation levels in Vancouver were a significant contributor to the decreased solar fraction. A significant difference in operating cost was predicted for the two locations. Specifically, for the 6.75 m^2 PV, solar thermal, and PV/T systems, the annual operating costs were $222.99, $127.63, and $83.35 compared to $447.84, $252.44, and $174.33 respectively for Toronto. This is because of the lower utility rate assumed for Vancouver, which is $0.0797/kWh (BC Hydro, 2015).

The operating cost of each system reflects the performance of each system; confirming that the PV/T operating cost is the lowest of the simulated systems. The capital cost of a typical solar thermal system was reported to be $3,500 (Boone, 2010), and the capital cost for the simulated PV system at 6.75m^2 was assumed $4,076, using the lowest CanSIA reported average price for grid-connected systems in 2013 (i.e., $2.80/W) (Luukkonen, et al., 2013). Recent trends have seen significant reductions in PV costs with market prices for PV modules dropping to below $0.80 per peak watt. Consequently it is difficult at this time to predict current installed costs for PV-only DHW systems. Similarly, combined PV/T systems have not yet been introduced to the market and are therefore difficult to assess based on capital cost. Assuming installation costs are similar, the PV/T system would seem to offer advantages when roof space is limited. This system also has the highest PES efficiency and solar fraction.

Table 3: Average Energy Efficiency, Exergy Efficiency, and PES Efficiency values for twelve months in Toronto

Simulation	Energy Efficiency			Exergy Efficiency			PES Efficiency		
	avg	max	min	avg	max	min	avg	max	min
PV Resistance	16.1%	16.2%	15.9%	16.1%	16.2%	15.9%	41.3%	41.6%	40.8%
Solar Thermal	40.7%	43.5%	37.2%	39.5%	42.6%	35.9%	40.7%	43.5%	37.2%
PV/T	39.6%	43.6%	35.3%	38.5%	42.6%	34.3%	58.6%	62.4%	54.7%

Table 4. Annual system performance values

Simulation	System Specifications		Performance Indices						
System	Collector Area (m^2)	Hot Water Load (L)	Q_{elec} (kWh)	Q_{therm} (kWh)	Q_{aux} (kWh)	Q_{solar} (kWh)	Q_{load} (kWh)	Solar Fraction (%)	Op. Cost ($/year)
PV Resistance	6.75	250	1456	0	2956	1456	4156	29	447.84
PV Resistance	13.5	250	2911	0	1851	2911	4337	57	280.44
Solar Thermal	6.06	250	0	3617	1666	3617	4661	64	252.44
PV/T	6.06	250	1094	2473	1151	3568	4253	73	174.33

CONCLUSIONS

A PV-Resistance, solar thermal, and PV/T system were modeled using built-in components in TRNSYS. Actual solar components were simulated to find the system with highest performance.

When comparing systems with similar collector areas, The PV/T system gives the highest solar fraction and PES efficiency, while maintaining a similar energy output to that of the solar thermal system. The PV/T operation costs are also the lowest of any system.

Two significant limitations of the PV Resistance system are the lower efficiency of the modules and the relatively mixed nature (i.e., un-stratified) of the hot water tank. When the PV area is doubled, the system performs similarly to the PV/T and solar thermal simulations. However, even the base PV configuration is currently cost-prohibitive. Therefore, it is recommended that experimental research be conducted on PV-DHW systems to improve performance

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