ABSTRACT
It is well understood that a typical solar domestic hot water system can greatly reduce the reliance on electrical or fossil fuel consumption. The system may be further improved by including a heat pump as part of the design. In theory, a heat pump would result in colder fluid temperatures entering the collector giving higher collector efficiency and longer operation periods. One indirect-style solar assisted heat pump (i-SAHP) design was modeled using the TRNSYS software and compared to both a traditional solar domestic hot water system and an electric water heating system. All of the models had the same load profile and delivered the domestic hot water at a constant temperature. This insured that each system delivered the same amount of energy for the entire modeling period and allowed the projected benefits of the heat pump on the electrical energy consumption to be compared with the other two models.

It was found that the electrical consumption and operating cost were the lowest with the i-SAHP system examined in this study. More i-SAHP configurations need to be examined to determine which one works best for various locations.

Keywords: Solar water heater, heat pump, TRNSYS

INTRODUCTION
Solar energy can be used to assist in domestic air and water heating in order to greatly reduce the reliance on electrical or fossil fuel consumption. Implementation of a heat pump into the solar thermal system can also help to further improve the performance because it potentially offsets the electric loads to the heat pump rather than an auxiliary heater. This is a more efficient use of the electricity. There are two main types of heat pump assisted solar systems that have been studied in the past which include direct expansion solar assisted heat pump (DX-SAHP) and indirect solar assisted heat pump systems (i-SAHP).

DX-SAHP systems use the solar collector as one potential evaporator for the heat pump (Chaturvedi et al. 1998, Kuang et al. 2003). Therefore, the refrigerant is passed through a throttling valve just before entering the collector in order to drop its pressure to allow it to evaporate when it collects the solar energy. The refrigerant leaves the collector as a vapour and passes through the compressor causing it to become a superheated vapour. This high temperature and pressure vapour then flows through the condenser heat exchanger where it transfers energy into the domestic water tank. The solar panel is usually only one of two or more sources utilized by the system as the evaporator. For example, many systems also use an air source heat exchanger when there isn’t sufficient solar energy (National University of Singapore 2008). styled-SAHP systems are not the focus of the present work in this study.

For the i-SAHP systems, there are many possible configurations (Bridgeman et al. 2008, Chandrashekar et al. 1982, Kuang et al. 2003). Unlike the DX-SAHP systems, the solar collector does not act as the evaporator for the heat pump process, but rather the heat pump is integrated into the design as a closed unit. The heat pump is beneficial to the system because it will increase the collector efficiency by sending colder fluid to the collector inlet. This will also allow the system to run for longer periods during the days as well as extend the operation season. The solar collector benefits the heat pump as well by delivering warmer fluid to the evaporator of the heat pump which will result in a higher coefficient of performance (COP) (Bridgeman et al., 2008). Therefore, the heat pump and collector work very well together to help improve the overall performance of the system. An example of an indirect solar assisted heat pump system is one very similar to the traditional solar assisted water heater studied here except the external heat exchanger connecting the collector to the domestic tank is replaced with a heat pump (Bridgeman et al. 2008). In another series of studies, the indirect solar assisted heat pump systems were utilized for space and domestic water heating (Chandrashekar et al. 1982), which shows the versatility that is possible with the i-SAHP systems. One i-SAHP system is presented in this study.
SYSTEM DESCRIPTIONS

To quantify the benefits of a dual tank indirect solar assisted heat pump system, two standard systems were modeled in comparison; a domestic water tank with one 2 kW heater as the only heat source, and a generic solar hot water system. These systems were modeled using the TRNSYS software (REF).

The systems were set up to allow for a common basis of comparison. The domestic tank in each system was modeled as a 350 liters plug-flow stratified tank with a loss coefficient of 3 kJ/hr.m².k and the fluid was given a specific heat of 4.19 kJ/kg.K to simulate water. The same load profile was applied to all of the models and they all delivered water at 55°C. This ensured that all of the systems were supplying the same amount of energy over the one year simulation period. Four fifteen-minute water draws per day at a rate of 300 kg/hr were used to simulate a typical low flow shower at 6 a.m., 8 a.m., 8 p.m., and 10 p.m. during the simulation period of a year. Although this consistency of water draw each day was not necessarily realistic, it was sufficient to observe and compare the performance of each system.

A tempering valve was used in each system to help ensure that water was delivered at a set point temperature of 55°C. If the temperature of the water in the domestic tank was above 55°C, then the tempering valve mixed a portion of the cold 10°C mains water with the hot water from the domestic tank to cool it to the set point temperature. The layout of a tempering valve is shown in Figure 1. Whenever there was a hot water draw, mains water at 10°C replaces that volume used to the bottom of the tank. The tank was stratified, which means that there were temperature sections throughout the tank due to density differences. The hotter fluid rises to the top, while the colder water remains at the bottom. Therefore, the hot water draws were taken from the top of the tank and the cold was replaced at the bottom. Also, in the solar assisted systems, cold water was taken from the bottom of the tank and delivered to the heat exchanger connected to the collector where it gained solar energy and returned to the tank at a higher temperature. A variable inlet was used so that the water entering the tank from the collector loop did so an appropriate temperature node to help keep the tank stratified. If a water draw occurred when the domestic tank was below the delivery temperature, then there was a 2 kW safety electric heater after the tempering valve to ensure that the water was delivered at 55°C. This heater is also shown in Figure 1 and was included in each model.

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The TRNSYS models for the solar assisted systems require a weather file to complete the simulation. This file is connected to the collector in the TRNSYS software and provides the solar radiation detail along with outdoor temperature and other key elements throughout the year for calculating the solar effects on the system in a specific location. In both solar assisted cases examined, the weather data for Toronto, Ontario is used.

System 1: Electric Heating

The base system used an electric heater in the domestic water tank to provide all of the energy needed to meet the load requirements. The domestic tank used in the TRNSYS simulation of this system contained one 2 kW electric heater located in the top half of the tank. The set point temperature for the auxiliary heater to turn on was 55°C with a dead-band temperature of 5°C. Therefore the heater would turn on when the water that was at the height of the thermostat fell to 50°C and would remain on until the set point temperature was reached. The schematic and TRNSYS system layout are shown in Figure 1.
System 2: Traditional Solar Domestic Water Heater

For the traditional solar domestic water heater, a solar loop was added to the electric system configuration. This system required a collector, circulating pumps, a heat exchanger, and piping in addition to the other equipment used in System 1. The schematic and TRNSYS layout for the traditional solar domestic water heater are shown in Figure 2.

Due to the climate examined, a glycol solution was circulated through the collector loop to ensure that the fluid did not freeze during operation in the winter months. Therefore, a heat exchanger was necessary for transferring the energy collected in the collector by the glycol to the water in the domestic tank. To implement this into TRNSYS, a specific heat of 3.29 kJ/kg.K was used for the fluid flowing through the collector loop to simulate a 50%-50% glycol-water mixture (Engineering Toolbox, ?). The two loops on the left side of the
schematic shown in Figure 2 represent the glycol loop and water loop, and they pass through the heat exchanger as mentioned above.

A 4 m² second order incidence angle modifier flat plat collector was used in this system and in the indirect heat pump system to follow. Based on a second order quadratic function, TRNSYS calculated the incidence angle modifier continuously throughout the simulation in order to determine the amount of useful solar energy that was obtained at an instant in time. The default values given by the TRNSYS software were used for the coefficients of the quadratic equation as well as for the other efficiency values.

The pumps used circulated the glycol mixture and water at a flow rate of 100 kg/hr. While operating, the pump consumed 60 kJ/hr of energy and always operated at 100% power. The units were kept in the same form that they were entered into TRNSYS for clarity purposes.

The heat exchanger was a counter flow type with an overall heat transfer coefficient of 3000 kJ/hr.K. This resulted in a heat exchanger effectiveness between the glycol and water mixture of approximately 0.9.

The system did not run continuously because there was only solar energy when the sun was up, and even then the radiation was not always high enough for the system to gain energy. Therefore, system controls had to be implemented to ensure that the pumps were running only when there was sufficient energy to be collected. If the pumps were on during the night, for example, the system would have actually lost energy to the outdoor environment if the water was hotter than the outdoor air and used additional electrical pump power to circulate the fluid as well. Therefore the controls were very important to ensure the maximum energy gain from the addition of the solar loop. A differential controller for temperature was used in TRNSYS to control the system. It read in the temperature of the cold water at the bottom of the domestic tank and the outlet temperature of the solar collector to determine if there was energy to be collected. If the temperature of the glycol mixture at the collector outlet was 5°C or more above the temperature of the water at the bottom of the tank, then the pumps were turned on to collect this solar energy. The system would continue to run until the temperature difference condition was no longer satisfied. This would occur if the tank was charged or in situations when there was no energy to be collected. The controller also monitored the temperature of the water at the top of the tank to ensure that it did not get too hot by using a high temperature cut-off of 90°C. If this temperature was reached during operation, the pumps stopped so that the water in the domestic tank did not reach its boiling temperature.

Unlike the electric heater system, the temperatures in the domestic tank were allowed to get much higher than the required delivery temperature of 55°C. Therefore, it was expected that the tempering valve would be used much more in this case. The reason that the tank temperature was allowed to go above 55°C was because if there was solar energy to be collected, it would take advantage of that and store it in the domestic water tank. This thermal storage would allow the tank to meet higher load demands during times when there was no solar energy to be collected to recharge the tank, and would greatly reduce the usage of the electrical backup heaters.

**System 3: Dual Tank Indirect Heat Pump Assisted Solar Domestic Water Heater**

To attempt to further improve the performance of the traditional solar water heater system discussed above, a heat pump was implemented into the design and the performance was investigated. There are many different ways that a heat pump can be inserted into the system, but the configuration that was investigated here was a dual tank i-SAHP. The schematic and TRNSYS system layout are shown in Figure 3.
This system builds on the traditional solar water heater by adding a second tank and a heat pump to connect the two tanks. The tank that was connected to the solar loop was no longer the domestic hot water tank, but rather a large 500 liter float tank for thermal storage. This tank was connected to the domestic water tank via a heat pump and heat exchanger by-pass to transfer energy to the domestic tank. The idea was to allow the large tank to float in temperature while the domestic tank is kept close to the delivery temperature. The float tank will fluctuate in temperature because the collected solar energy will heat it, while the heat pump will cool it in order to heat the domestic tank. However, these two processes may or may not be occurring at the same time depending on the current situation. These two reverse effects work well together because the cooling caused by the heat pump potentially allows for more solar collection due to the colder fluid circulating in the solar loop. Also, the heat gained from the collector gave the float tank energy to transfer to the domestic tank to ensure that the delivery temperature was satisfied. For simplicity, the schematic shown in Figure 3 contains an internal heat exchanger in the float tank for the glycol loop. However, looking at the TRNSYS layout in Figure 3, the simulation was still run with an external heat exchanger just like System 2.

The heat pump used in the TRNSYS model required an external file to create a profile to determine the power consumption and energy transfer characteristics of the heat pump. The profile created for this system used three inlet load temperatures and seven inlet source temperatures to generate a table that determined what the power consumption and energy transfer rates would be for all the combinations of these values. Anything in between was found using linear interpolation between the data provided. The three inlet load temperatures (from domestic tank) were: 10°C, 35°C, and 60°C, and the seven inlet source temperatures (from float tank) were: -10°C, 10°C, 30°C, 50°C, 60°C, 60.1°C, and 80°C. The heat pump model reads in the input load and source temperatures that enter the heat pump and then used the data in the external file to determine the power consumption and the energy transfer for that case. Knowing the energy transfer rate, mass flow rate, and input temperatures, the outlet load and source temperatures were calculated and used in the simulation.

There were times when only a heat exchanger was necessary to transfer energy from the float tank to the domestic tank. This occurred in situations when the float tank was above the 60°C set point temperature of the domestic tank. The actual system would have a heat exchanger path to by-pass the heat pump in these cases. This by-pass is shown in the schematic in Figure 3. Therefore, in the case when only the heat exchanger was required, the heat pump would be shut off and the pumps circulating the water through the heat exchanger
would turn on. This was modeled in TRNSYS by hard-coding this effect into the external heat pump file so that the output characteristics represent a heat exchanger whenever applicable. Once the top section of the float tank (inlet source) was at or above this set point then the system used the heat exchanger by-pass to transfer the energy to the domestic tank. The 60°C and 60.1°C inlet source temperatures, used in creating the external file, model this switch from the heat pump to the heat exchanger and vice-versa. This was done by providing heat pump characteristics at 60°C and below in the external file and then dropping the power consumption and heat transfer rate at 60.1°C and above to simulate heat exchanger characteristics. A graph is shown in Figure 4 for an inlet load temperature of 10°C that gives the power consumption and energy transfer rates used in the external file at the various inlet source temperatures.

![Graph showing heat pump model](attachment:image.png)

**Figure 4: Heat Pump Model (For load temperature of 10°C)**

The other two load temperatures had their own set of values for power consumption and energy transfer rate that was similar to the one shown in Figure 4. The power consumption was decreased because only pump power was required for transferring the energy in the heat exchanger by-pass, where as the heat pump required a larger amount of power to operate the compressor. However, the greatest change was in the energy transfer because the benefits of the heat pump were no longer present. It should be noted that the values used for power consumption and energy transfer are preliminary values and were not based on a specific heat pump. The purpose was to try and model a variable capacity heat pump that used scroll compressor technology to increase the efficiency of the system.

The controls were very important to insure that the dual tank system was running efficiently, and there are two separate loops that needed to be controlled. The solar loop was controlled exactly the same way as in the traditional solar water heater. Therefore, when the outlet temperature of the collector was 5°C hotter than the water at the bottom of the float tank, there was energy to be collected so the pumps in the solar loop were turned on. This collected energy was stored in the float tank. The second loop to control was the heat pump which was used to supply energy to the domestic water tank to keep it at a temperature close to 60°C. The same type of controller was used for the heat pump but was utilized in a different fashion. The temperature at the top of the domestic tank was read by the controller as the lower input temperature and the set point temperature of 60°C was entered into the controller as the upper input temperature. The controller compared the temperature at the top of the tank to the 60°C set point and used a dead band temperature of 3°C. This means that the heat pump loop turned on when the top of the tank fell to or below 57°C and stayed on until it was heated to 60°C. This tight temperature range was used to ensure that the domestic water tank was always charged and able to meet various water draws.

RESULTS AND DISCUSSION
The three systems were assembled and run using the TRNSYS software (TRNSYS, 2006). Figure 5 shows the electrical usage and solar energy collected comparison between the three systems obtained from the simulation results.

The dual tank system used the least amount of electrical energy and gained the most solar energy. So with the addition of the heat pump, more energy was being collected due to the increased collector efficiency and the increased run times. Although the system was running longer, it used less electrical energy because the solar energy collected greatly reduced the energy required from the auxiliary heaters to meet the hot water draws throughout the simulation period. The four water draws that the systems were experiencing daily during the simulation period did not necessarily represent a typical draw profile of an actual application so the trend was more important here rather than the actual kilojoules of energy.

The electrical usage of each system directly correlated to the annual projected operating cost of the system. Therefore, the dual tank indirect heat pump assisted solar water heater had the lowest operating cost when compared to the other two systems. According to Ontario Hydro, the electricity rate in 2009 was approximately $0.075 per kilowatt-hour (Ontario Hydro). Using this value and the total electrical energy consumption for each system, the annual operating costs were projected for the three systems and are shown in Figure 6.
Although the operating cost of the heat pump assisted system was lower when compared to the standard electrical and solar water heaters, this will not be seen immediately due to an increased start up cost. The more components that are added to the system, the higher the start up cost will be. This must be taken into consideration when making the final decision on what system the user chooses, but was not covered in this study. However, comparing the dual tank system to the traditional solar system, the only additional equipment required was a heat pump, large storage tank, and extra piping. It will also be important to consider the projected change in the cost of energy over the period of use. Depending on the hot water usage of the application, the payback period will vary dramatically and will therefore be case specific to each user.

CONCLUSIONS

The dual tank indirect heat pump system proved to be the most energy efficient and had the lowest annual operating cost of the three models analyzed. Therefore, the simulation results of this system agreed with previous studies that there is potential for the use of heat pumps to assist solar domestic water heating systems to increase their performance. There are, however, many places in the system that the heat pump can be introduced and deciding where to put it and what size of heat pump to use are not trivial decisions. Depending on the geographical location, the weather that the system will experience will have a huge impact on the way that the system will function and what is required. The next step of this project will be to examine a couple more indirect heat pump assisted configurations and compare them to the dual tank system presented here. Then, all of the indirect heat pump assisted systems should be simulated with weather files from various locations to see what configuration works better in what environments. Therefore, simulation of these systems will be very important in the continuing development of implementing these indirect heat pump assisted systems.

REFERENCE