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Solar Water Heaters

Example designs for Solar Hot Water Systems

By

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An example of designing several solar water heating projects comparing the costs of running the circulator pump with mains power or directly coupled to a photovoltaic solar panel.

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Abstract:

A general method for determining the financial viability of solar hot water systems is presented. The method, illustrated by two examples, one a house in Canada, the other a hotel in the United Arab Emirates, uses the free Canadian Government program *RETScreen* to determine the most economical number of solar thermal panels on the basis of payback time and cumulative cash flow. A free program, *CARF*, is used to calculate pressure drop in the system, which allows selection of an appropriate circulator pump size. Financial viability of conventional 115 VAC grid powered circulator pumps are then compared to payback time for direct coupled photovoltaic powered circulator pump systems.

For small systems that heat only hundreds of liters of water per day, as for a typical household, the most economic and reliable system is often an integrated DC motor-pump direct coupled to a photovoltaic panel. For larger systems that heat thousands of liters of water per day, a conventional electronic controller and an AC pump is generally the more economic option. Choosing the most economic circulator system can be done by using a payback time calculation program (retscreen.net) for each particular solar hot water installation. There is no single best circulator pump solution; indeed, the best solution may be no circulator pump at all, so a general method is presented here to compare economics of various solar hot water system circulator pump options.

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Part 1: Introduction

Why solar hot water?

Solar hot water, or solar thermal water systems, can save money and reduce pollution compared to conventional energy sources: a typical solar hot water system in Canada will reduce annual energy costs by 40 to 50 percent. Solar thermal systems are cheap and efficient compared to solar photovoltaic systems, as making sunlight into heat is easier than making sunlight into electricity. Typical new thermal absorption coatings absorb 98% of solar energy while commercial PV systems do well to change 15% of incoming solar into electricity (Wenham et al, 2006). Even when grid electrical power is available, solar hot water systems can pay for themselves in electrical energy savings. Moreover, many states have incentives to reduce pollution and greenhouse gases that solar water heating qualifies for. Solar water heating is a “green” consumer option that can save money (NRCan, 2003).

How solar water heating works

System overview

Most solar thermal water heating systems use collectors to absorb the suns energy and transfer that energy to water, or a working fluid such as glycol, which is then used to heat the water in a central tank. All solar hot water systems have a means of collecting the solar heat, storing the heat, delivering hot water and controlling operation. Some simple systems use basic physics-hot water rising-as the control. Cold locations need a means to protect the system from freezing. Often the collector units are on the roof, while the central water storage tank is in the building below. A pump circulates the working fluid between the tank and the thermal collectors when the collector fluid is warmer than the water in the central storage tank.

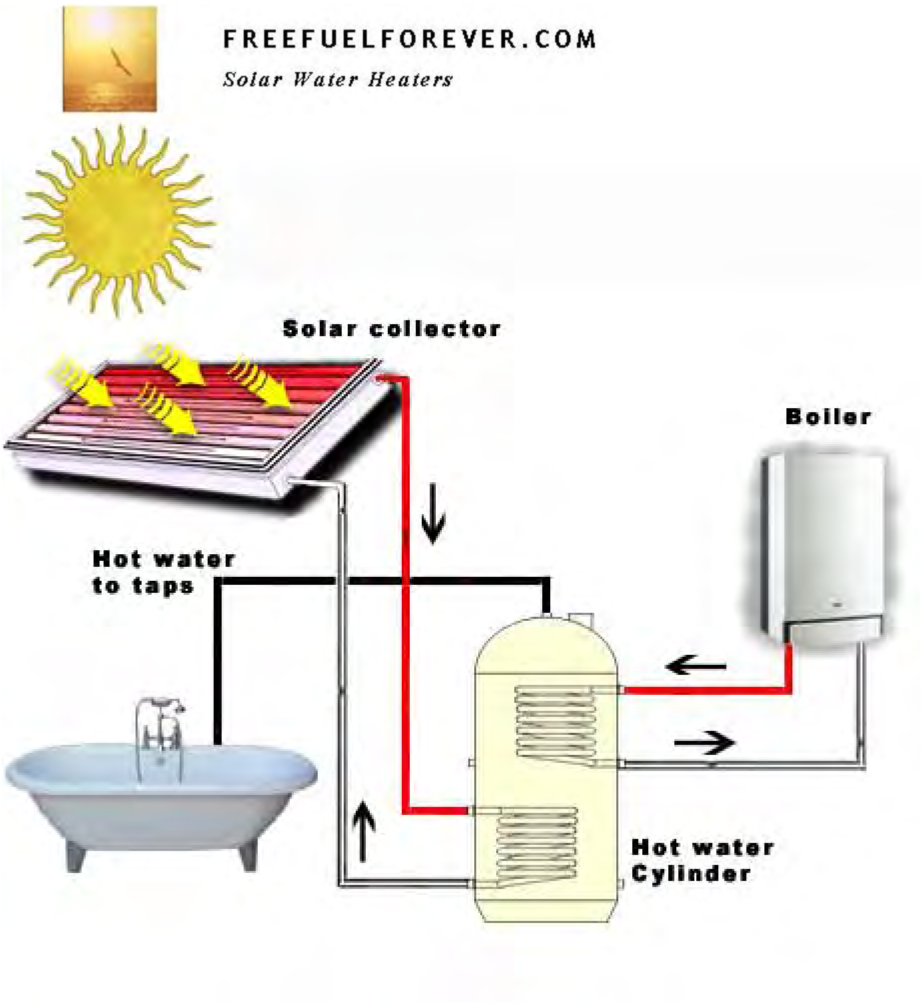

Figure 1: Typical solar hot water system with collector, tank, pump and heat exchanger.

When there is no sun, the insulated hot water cylinder stays warm for hours, even days if large and well insulated. If the hot water runs out or cools down because there is not enough sun to heat the water to the desired temperature, some other form of water boiler can be used-anything from a wood pellet fed boiler to an electric element on a thermostat. Fluid being circulated to the collector could be water. In warm climates, directly heating the water to be used means that the heat exchanger can be eliminated and the hot water in the collectors used directly. Cold climates require freeze protection for the collector, perhaps by draining back the collectors when temperatures are low (drain back systems, Appendix A, Figure 14).

Circulator Pump Control

When the sun is shining strongly, the water must be circulated more quickly to efficiently remove the maximum amount of heat from the thermal collectors, as larger temperature differences between the working fluid and the thermal collector absorbing surfaces mean more efficient heat transfer. If the temperature difference across a heat exchanger is large, then the rate of heat transfer is also large. But if the temperature difference is small, or zero, then no heat transfer will be able to take place. This could be the case at night, when the water in the central storage tank is warmer than the collector on the roof. In some kinds of collectors, such as flat-plate, the working fluid could actually be cooler than the water in the central storage tank, so that the solar collector turns into a heat radiator at night. In this case, circulating the water to the roof would cool the hot water tank and cost energy. Generally, temperature sensors and a control unit are used to ensure that the pump only runs when a positive heat gain can be made by circulating water to the solar collector. Temperature sensors and electronic controllers are historically the most problematic parts of a solar thermal system, mostly due to fouling of the temperature probes, software problems, and electrical disruptions to the controller (Beckman et al., 1994 and Duffie and Beckman, 1991).

Why Photovoltaics for the Pump?

Using photovoltaic cells to power the circulator pump for solar domestic hot water saves on system components, makes the system independent of grid power and makes the system simpler. A simpler system is usually a more reliable system, since there is less to break. Photovoltaic cells coupled to a solar circulator pump act as fast response sensors to solar energy, only running the pump when solar energy is available to heat the water. Electrical savings are realized exactly at peak air conditioning demand times, when the sun is shining. The electronic controller previously needed to turn the pump on and off can be eliminated (Figure 2). Properly matched to a pump, a direct coupled system will run whenever the sun is shining above a certain level; which is precisely the time that the solar thermal system will have energy to give to the central storage tank. A directly coupled DC centrifugal pump would dispense with the electronic controller, the temperature sensors and the dependence of the solar thermal system on any type of grid electricity. Besides being economic, this simplicity has been cited as a selling point with North American consumers (NAHB, 1998).

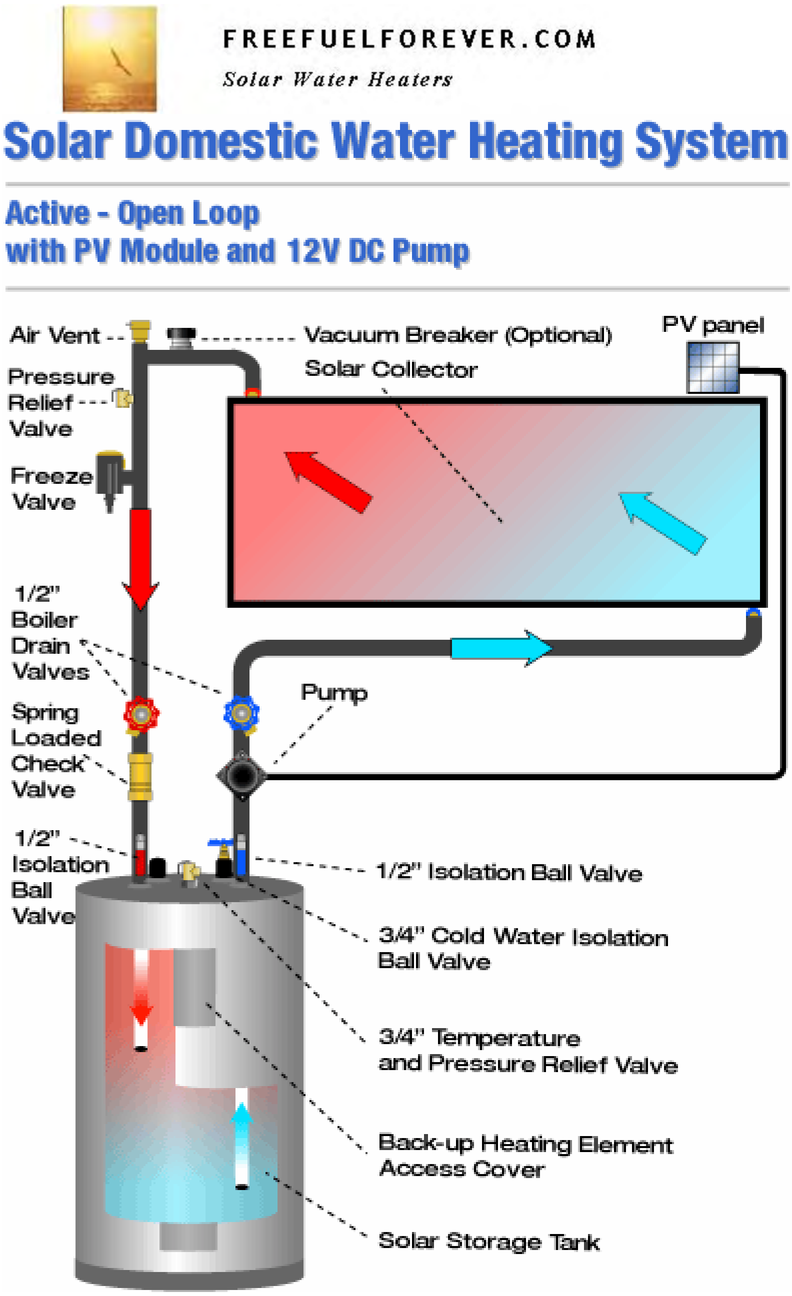

Figure 2: PV powered solar hot water system

Part 2: Method

Objective of Selection

The objective is to find a quick, technically simple, yet accurate method of selecting a solar hot water system that has the least number of years payback time. Payback of initial investment in energy savings can be used to show the consumer which system choice will save the most money, so payback time is the desired quantity. To determine if photovoltaic circulator pump installation is financially superior to a grid powered system, the cumulative cash flow over the system lifetime can be compared for the baseline case of an AC grid powered pump with controller.

Steps to be followed

The sequence of steps is:

1. Select a solar collector based on availability and cost for performance.
2. Estimate the most economic number of collector panels using *RETScreen*
3. Calculate pump size using the *CARF* program
4. Select circulator pump based on availability and cost for quality.
5. Recheck payback period for number of collectors using *RETScreen*
6. Check payback period using photovoltaic powered pump
7. Select most economic system

To compare costs for any particular installation, first the most economic number of solar hot water panels must be determined. Then, with a fixed number of solar hot water panels, pump power can be determined, allowing selection of a suitable pump and photovoltaic panel combination. The cumulative cash flows for both a photovoltaic circulator pump system and an AC pump on grid power can then be compared for a fixed number of solar hot water panels.

The iterative nature of this process is illustrated by the fact that the most economic number of panels depends on installed system cost, which depends on the cost of the pump and the solar PV panels. Fixing the number of solar hot water panels and then changing the pump from AC to DC could be a problem since:

(1) The number of solar water heater panels will determine the pump size and
(2) The optimum number of panels is dependent on system (and thus pump) cost.

The solution is to use a formula of $200 plus $25 per panel to determine an approximate pump cost, then with the most economic number of panels known, to select a pump for the head and flow rate required. If the pump selected is far from the original estimate of pump cost, then the process will have to be repeated. Likewise, changing the power source from AC to photovoltaic DC may change the optimum system size: the most economic PV solar system may have a different number of solar hot water panels from the most economic AC grid powered system because the pump and solar PV panel costs scale differently from AC pump costs with grid power. Luckily, pumps are available in only a series of step sizes, so one pump can be used for different numbers of panels. Thus, iteration is used, starting with the same number of solar hot water panels for both the AC and DC PV powered systems. Payback period for PV powered systems with more or less panels is then calculated to check that the most economic number of solar water panels is the same as for the AC powered system.

A typical small solar heater system for a 3 person house and a typical large solar heater system for a factory will be selected. Typical solar collectors being sold today will be used. Solar water heater system options for each will be surveyed, including AC and DC pumps powered by conventional and photovoltaic electricity. A recommended system will be suggested for the proposed locations.

Example Cases Selected

Two example cases are worked in this report to show the process of selecting and evaluating a solar water heater system configuration. A 3 bedroom house in Victoria, British Columbia, Canada, was selected as an example of a solar domestic service hot water application. A hotel located in Dubai, United Arab Emirates, was selected as an example of a larger scale commercial hot water system. The baseline case of AC powered conventional circulator pumps will be evaluated first to determine the most economic number of solar collector panels to use. The same number of panels, with the same balance of system, except powered by a PV powered circulator pump, will then be evaluated and compared on the basis of payback time.

Solar Thermal Collectors Selection

The Solar Rating and Certification Corporation (SRCC, 2007) publishes a directory of hundreds of common solar water heaters along with their efficiencies under standard flow rate and environmental conditions. With a price quote for a particular collector, the price per kW heating performance can be compared to other collectors, as explained in the freely downloadable SRCC directory (SRCC, 2007). Evacuated tubular collectors supplied by Tsinghua Solar Systems Beijing were selected for use in both installations. These16-tube collectors contain internal copper piping to withstand high pressures (Freefuelforever, 2007).

Direct versus Indirect:

A direct solar hot water system heats the water to be used directly in the collector. An indirect system heats some fluid in the collector and circulates that fluid to a heat exchanger in the storage tank. A direct system is inherently more efficient since there is no heat exchanger. Energy transfer rates between two mediums depend on the temperature difference between them. In other words, cold water is more effective at taking heat from the solar collector surface than lukewarm water returning from the heat exchanger. Eliminating the heat exchanger is a cost saving, but balanced against this are the limitations of a direct system, such as the need for freeze protection. Indirect systems can circulate propylene glycol for freeze protection, though glycol is less efficient than water as a heat transfer fluid (Baechler and Love, 2007). Indirect systems can be used for heating of any fluid in contact with the heat exchanger. Since neither example case requires freeze protection, the simpler and more efficient direct system (no heat exchanger) was selected.

Solar Thermal Collector Efficiency:

In order to calculate payback period for a solar system, the efficiency of the system and the cost must be known. The Solar Rating and Certification Corporation tests efficiency of solar water heater collectors under standard conditions of sun and water flow rate. A solar installer can use these published efficiency figures, so long as the circulator pump is matched to the ASHRAE standard test flow rate, which is 0.02 kg/s per m^2 of collector (SRCC, 2007). For a solar water system with a grid-powered AC pump, the cost of system equipment and electrical energy can be used with published collector efficiencies to obtain payback time. For a photovoltaic powered pump, the flow rate of the pump varies with the amount of sunshine, which raises the question of which efficiency value may be used in payback time calculations.

Flow rate versus solar thermal system efficiency:

Most researchers found an optimum flow rate for best efficiency of solar hot water systems because various components have conflicting reactions to flow rate changes. For example, the collector has higher efficiency with a higher flow rate, since more energy can be removed with more flow. Obviously at very high flow rates, the temperature rise through the collector will be close to zero and the energy required for the pump will be large. If circulator pump power is ignored and the storage tank is assumed fully mixed, in other words, with one temperature value for water in the tank, then the maximum flow rate is desired for best efficiency (Hollands and Brunger, 1992). Maximum flow rate would mean a large solar PV panel and increased mixing of the storage tank, which would destroy stratification. Water storage tank stratification means that the hot water rises to the top of the tank and is used first, while the collector is fed from the coldest water at the bottom of the tank. Cooler water inlet temperatures to the collector help more heat to be extracted and so increase collector efficiency per liter of flow.

Lower flow rates increase the efficiency of the storage tank, as less flow means less mixing of water, which allows thermal stratification. Solar PV panel size, circulator pump power and piping cost would be minimized at lower flow rates. Wuestling et al. (1985) showed an optimum flow rate to maximize Solar Direct Hot Water system efficiency that was approximately 20% of conventional flow rates recommended by collector manufacturers. Having a flow rate proportional to incident solar energy, in other words, speeding up the pump when there is more sun, yielded almost the same performance to the system operating at the constant, reduced flow rate. Fanny and Klein (1988) experimented with two Solar Direct Hot Water systems, one with tank stratification devices, and one without. Their conclusion was that efficiency was similar for high and low flow systems if tank stratification devices were used.

Heat exchanger efficiency is directly proportional to fluid flow rate on both sides of the exchanger. A heat exchanger would have best efficiency at maximum flow rate. Hirsch (1985) found that tank stratification at low flow rates was not as significant as the efficiency gains of the heat exchanger at higher flow rates. Overall conclusions were that efficiency is relatively constant as flow rate varies around standard but low flow rate installations have dramatic changes in performance. At high collector flow rates, system performance is more stable than at low flow rates. With a heat exchanger in the system using one efficiency value is not as good an approximation as with direct solar hot water systems.

The question of low flow rate efficiency may be irrelevant when applied to PV circulator pump systems, since as Cromer (1983) pointed out, pump starting torque means that direct-coupled PV pump systems are oversized when running at full speed, so the flow rate is likely to be at or above ASHRAE standard once running. The extra PV panel power needed for pump starting can be eliminated by use of a pump starter, or storage batteries, but Mertes and Carpenter (1985) recommended delaying pump starting below selected radiation levels, allowing the collector to heat the water longer at low light.

Replacement of a conventional AC circulator pump with a PV direct coupled DC motor was investigated by Chandra and Litka (1979), who empirically found a small improvement in solar system efficiency for the PV system. Miller and Hittle (1993) used a PV powered pump in an indirect system and found little difference in energy collected versus a conventional system. Loxsom and Durongkaveroj (1994) did a more detailed analysis of a PV Solar Direct Hot Water system, including a time varying flow rate profile. Their conclusions were similar: no significant change in efficiency, or small advantages for either solar or conventional pumping.

By assuming collector efficiency is insensitive to flow rate changes at or above ASHRAE standard, freely available efficiency measurements for hundreds of collectors may be used from such organizations as the SRCC (2007). One efficiency value, instead of a time dependent efficiency equation, greatly simplifies calculation of payback time, so standard ASHRAE flow rates will be used with tested efficiency figures.

Part 3: Modeling Payback Period

The RETScreen Program:

RETScreen is a free program is available from the Canadian government. The RETScreen Software is made of a series of Microsoft Excel worksheets and forms. The software can be used worldwide to evaluate the energy production and savings, costs, emission reductions, financial viability and risk for various types of **R**enewable-energy and **E**nergy-efficient **T**echnologies (RETs). In RETScreen, the software's capabilities have been expanded from renewable energy, cogeneration and district energy, to include a full array of financially viable clean power, heating and cooling technologies, and energy efficiency measures. For solar water heating, the payback period is calculated based on the system cost, the local climate and the demand of hot water. Inputs for the program are tabulated below, as they would appear in the program, which runs as an excel spreadsheet.

Source of RETScreen program inputs:

The daily hot water use and temperatures for a house in Victoria were taken from RETScreen (2007) example data on an actual house. Water supply temperature and daily usage rates were based on a formula that RETScreen has determined fits typical daily patterns. Heating required was taken from power invoices at the example house. Resource assessment, or the amount of sun available, was taken from the RETScreen climate database. Solar water heater data were obtained from test reports and modified for use in the RETScreen program as explained in Appendix C. Other input values were taken from suggested values for the location given in the RETScreen help section (Canmet Energy Technology Center, 2007).

Baseline-House-RETScreen data

Baseline case for solar water heating is taken to mean an AC powered circulator pump connected to the number of panels that give least number of years for equity payback. The house size system in Victoria used the following data input into the RETScreen Excel program.

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Solar Water Heaters

Load type		House	
Number of units	Occupant	3	
Occupancy rate	%	100%	
Daily hot water use - estimated	L/d	180	
Daily hot water use	L/d	180	180
Temperature	°C	65	65
Operating days per week	D	7	7

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Percent of month used

Supply temperature method		Formula	
Water temperature - minimum	°C	7.4	
Water temperature - maximum	°C	11.9	

	Unit	Base case	Proposed case
Heating	MWh	4.6	4.6

Resource assessment

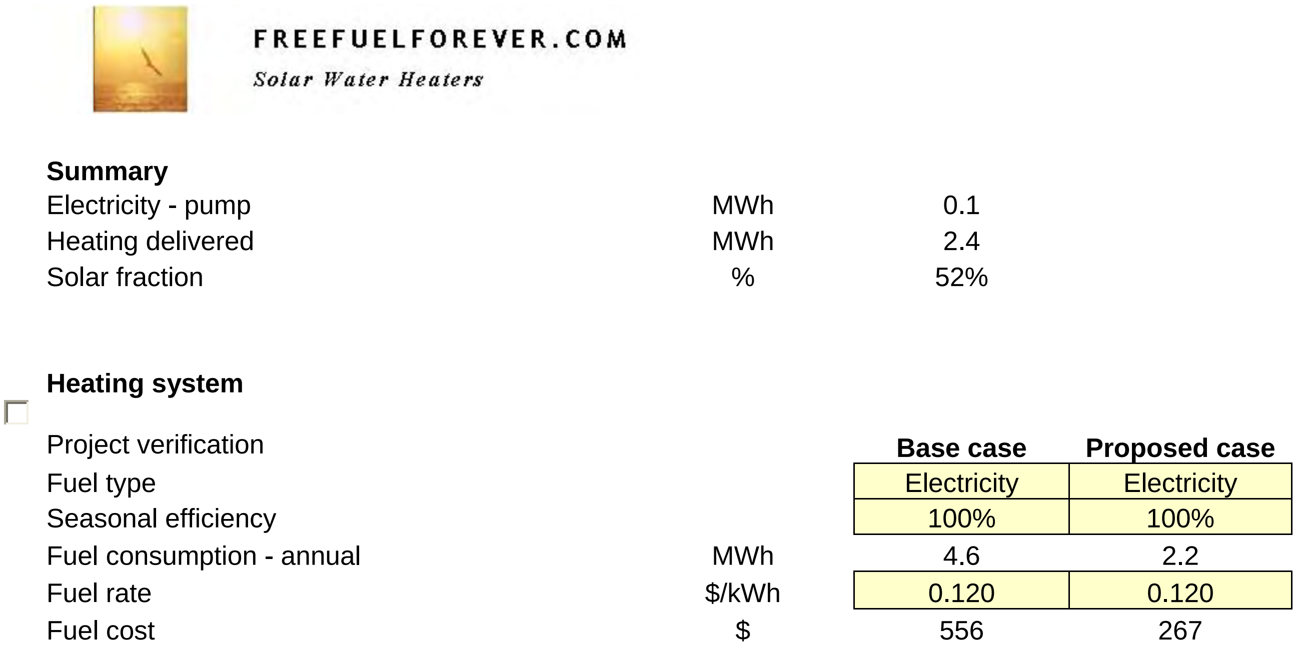
Solar tracking mode		Fixed	
Slope	°	45.0	
Azimuth	°	0.0	

Solar water heater

Type	Evacuated		
Manufacturer	Tsinghua		
Model	SLU1500/16		
Gross area per solar collector	m^2	1.62	
Aperture area per solar collector	m^2	1.33	
Fr (tau alpha) coefficient		0.57	
Fr UL coefficient	(W/m^2)/°C	1.11	
Temperature coefficient for Fr UL	W/(m - °C)^2	0.008	
Number of collectors		3	3
Solar collector area	m^2	4.86	
Capacity	kW	2.79	
Miscellaneous losses	%	3.0%	

Balance of system & miscellaneous

Storage		Yes	
Storage capacity / solar collector area	L/m^2	77	
Storage capacity	L	307.2	
Heat exchanger	yes/no	No	
Miscellaneous losses	%	5.0%	
Pump power / solar collector area	W/m^2	8.00	
Electricity rate	$/kWh	0.120	



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Summary

Electricity - pump	MWh	0.1
Heating delivered	MWh	2.4
Solar fraction	%	52%

Heating system

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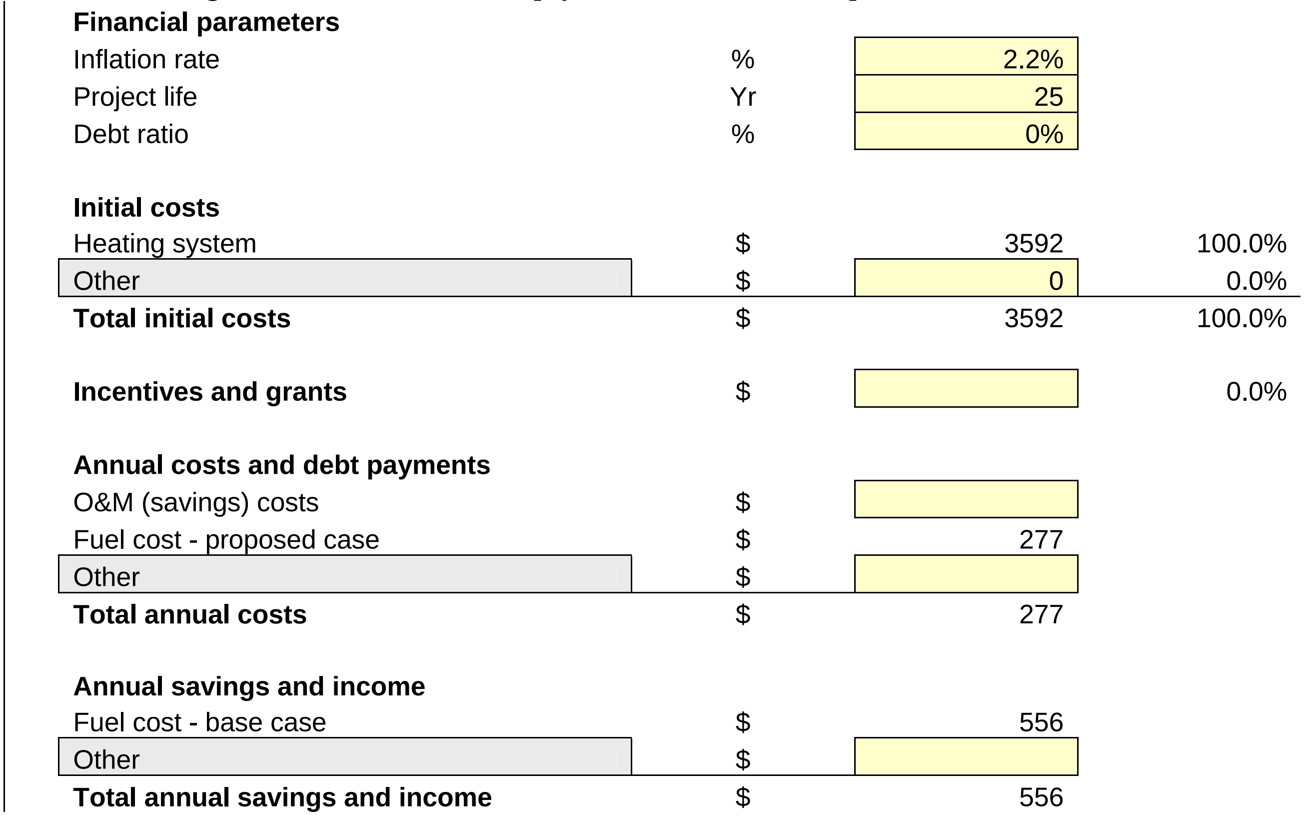
		Base case	Proposed case
Project verification			
Fuel type		Electricity	Electricity
Seasonal efficiency		100%	100%
Fuel consumption - annual	MWh	4.6	2.2
Fuel rate	$/kWh	0.120	0.120
Fuel cost	$	556	267

Figure 3: House Size System RETScreen Program inputs

Baseline Financial Results-House

Baseline financial results are for a house in Victoria with 3 solar collector panels and an AC circulator pump connected to grid power. Equity payback varied ±1 year for electricity prices of ±0.01 $/kW/hr.

Figure 4: House Baseline case payback time and financial parameters



Financial parameters			
Inflation rate	%	2.2%	
Project life	Yr	25	
Debt ratio	%	0%	
Initial costs			
Heating system	$	3592	100.0%
Other	$	0	0.0%
Total initial costs	$	3592	100.0%
Incentives and grants	$		0.0%
Annual costs and debt payments			
O&M (savings) costs	$		
Fuel cost - proposed case	$	277	
Other	$		
Total annual costs	$	277	
Annual savings and income			
Fuel cost - base case	$	556	
Other	$		
Total annual savings and income	$	556	

Financial viability		
Pre-tax IRR - assets	%	8.1%
Simple payback	Yr	13.1
Equity payback	Yr	11.4

Results from other locations in nearby Canadian provinces show that coastal British Columbia, Canada, is a relatively poor location for solar energy. An identical system was simulated for the locations below, changing only the climate database.

Figure 5: House system payback period, various locations

Location	Equity Payback, years
Vancouver, British Columbia, Canada	12.0
Victoria, British Columbia, Canada	11.4
Edmonton, Alberta, Canada	9.0
Saskatoon, Saskatchewan, Canada	8.4
Winnipeg, Manitoba, Canada	9.4
Sydney, NSW, Australia	9.3
Dubai, United Arab Emirates	9.3

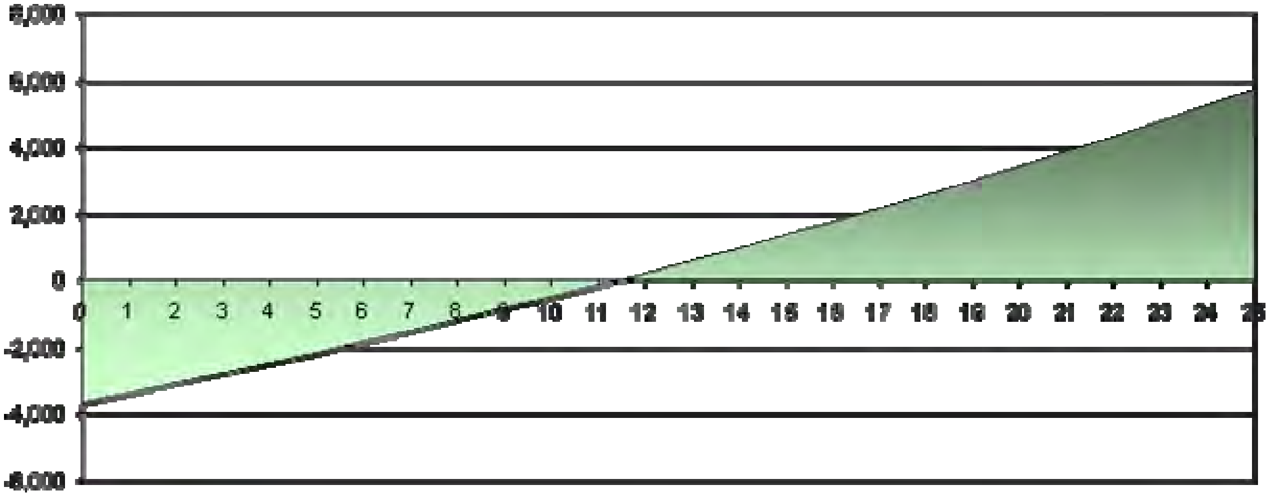


Figure 6: Cumulative $US cash flows vs. number of years, Baseline Canada house

After crossing the zero cumulative cost line, the system has paid for itself. Energy saved after this point is “free”.

Baseline-Hotel-RETScreen data

The Dubai hotel used exactly the same performance inputs as the Canada house, except for the climate and input water temperature changing for the location.

Baseline Financial Results-Hotel

Figure 7: Dubai hotel baseline solar payback and savings.

Initial costs		
Heating system	$	11,045
Other	$	0
Total initial costs	$	11,045
Incentives and grants	$	
Annual costs and debt payments		
O&M (savings) costs	$	
Fuel cost - proposed case	$	3,729
Other	$	
Total annual costs	$	3,729
Annual savings and income		
Fuel cost - base case	$	5,792
Other	$	
Total annual savings and income	$	5,792
Financial viability		
Pre-tax IRR - assets	%	21.0%
Simple payback	yr	5.4
Equity payback	yr	5.0

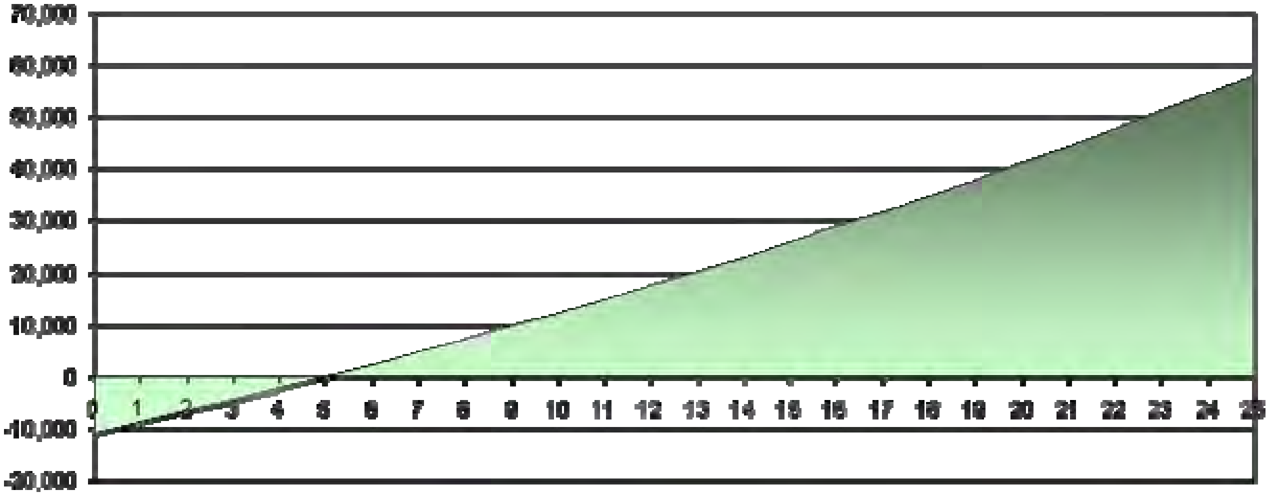


Figure 8: Cumulative $US Cash Flow vs number of years, Baseline Dubai hotel

The Dubai hotel system pays for itself in much less time than the Canada house, evidence of the much greater amount of sunshine available, even though input water temperature is higher.

Baseline case: Number of Collector Panels

For the house-size system, 3 SLU1500/12 collector panels were used. For the factory system, 10 SLU1500/16 panels were used. The number of panels was selected by using the RETScreen program for several different numbers of panels and selecting the shortest payback time based on a conventional AC circulator pump with mains power (see Appendix D). Since efficiency has been shown to be relatively insensitive to the selection of a mains power or PV powered circulator pump, the same number of hot water collector panels were used for both the PV powered and mains powered circulator pump systems. With the same number of solar thermal panels, the difference in payback period should be only due to the selection of either the PV system or the mains power. First, though, the size of the circulator pump must be determined.

Calculation of Circulator Pump Power

Manufacturers sell circulator pumps for direct coupling to solar water heater systems based on power output. The circulator pump power has to be found for each solar installation. Power will depend on how much fluid is being pumped and how much pressure is required. Pressure required will depend on the head, or equivalent change in elevation of the fluid. A key point to remember with circulator pump sizes is that sometimes there is no static head, which means water is being circulated back to the same level; there is no change in elevation. The power required of the circulator pump is to overcome frictional losses in the piping system. For this reason, circulator pumps are small compared to the pump sizes needed to supply the same volumes of water from a well. Although the equations to calculate fluid frictional losses are complex, finding the correct circulator pump size is a common problem and many online tools are available, such as the CARF Engineering Pressure Drop Calculator, available to download from www.freefuelforever.com/index_files/carf.exe

Dynamic head can be calculated by knowing the length of pipe, number and type of fittings, the flow rate and the roughness of the pipe. The effect of fittings and bends in the pipe may be approximated by adding an equivalent length to the total pipe used in the calculation. The equivalent length of pipe may be calculated from the Hazen-Williams Equation or the Darcy-Weisbach equation. Fluid frictional losses depend on flow rate, Reynolds number, friction factor, relative roughness, whether the flow is turbulent or laminar. The CARF Engineering Pressure drop calculator allows the selection of fittings and bends and shows the equivalent pipe length for each.

Inputs to the CARF Engineering Pressure Drop Calculator include the volume flow rate, liquid density, dynamic viscosity, the pipe inner diameter, pipe inner surface roughness, pipe length, elevation change and pressure drop for extra equipment such as the solar collector. The output of interest is the power loss in the fluid. Pump power multiplied by pump efficiency should be greater than the power loss in the fluid.

The power obtained will be an approximation. Input conditions will change with flow rate as more or less sunshine drives the pump and heats up the water. Pipe surface roughness will change with time (Appendix F). An exact figure for water pump size is not required since there are limited numbers of DC pumps on the market suitable for direct coupling to PV panels. To allow for degradation of the system with time, such as scale in the pipes increasing roughness and wearing of pump impellors, pump power will be calculated, then the next largest pump size to power required will be selected.

Pressure loss program inputs:

3 SLU1500-12 panels tested by Muller-Steinhagen (2005).

Volume flow rate: Standard test condition of 0.02 l/s per m^2 of collector
    Canada house: 0.02 l/s*3600s/hr*1.62m^2*3 panels = 350 l/hr
    Dubai hotel: 0.02 l/s*3600s/hr*1.62m^2*10 panels = 1166 l/hr
Density: 1000 kg/m^3 for 4°C water (less with warmer water, conservative pump size)
Dynamic viscosity: 1.7 milliPas @ 0°C (less with warmer water, conservative pump size)
Pipe inner diameter: ½ inch (12.7 mm), ¾ inch, (19.1 mm), 1 inch (25.4 mm), 2 inch (50.8 mm)
Pipe inner surface roughness: 0.2 mm typical old pipe (Appendix F)
Pipe length, from tank to collector and return: 30 meters
Elevation change: 0 m, circulator system
Pressure drop for extra equipment: solar collector, 12 mbar per panel at 300 l/hr (Muller-Steinhagen, 2005), round upwards
    Canada house: 0.05 bar
    Dubai hotel: 0.12 bar (collectors paralleled, so use 300l/hr figure)

Bends and Valves:
Canada house from Figure 2: PV powered solar hot water system
Ten 90 degree bends in the pipe
2 ball valves, 2 check valve, 2 gate valves
Dubai hotel: 4 times all of above, as collectors paralleled in sets of 3,4,3.

Pumped Head and Pump Size Results:

Given the conservative figures input into the pressure loss program (cool, dense, high viscosity water and scaled pipes), pumps should be oversized when running at full power. In evenings and mornings with less than full sun, circulation will be less with a PV driven system. The objective with the over sizing is to keep the flow rate within ±20% of standard flow rates so that tested efficiency values may reasonably be used. Greater flow rates help collector efficiency so slight over sizing is preferable to under sizing.

	Total Pressure Drop, kPa (inches H_20)	Pump Size (Cost, USD)
Canada house-½ inch pipe-350 l/hr (1.54 gpm)	48.64 kPa (195”)	
Canada house-¾ inch pipe 350 l/hr (1.54 gpm)	10.52 kPa (42”)	
Canada house-1 inch pipe 350 l/hr (1.54 gpm)	6.35 kPa (26”)	Laing D5 Solar 35 W ($250)
Dubai Hotel-½ inch pipe-1166 l/hr (5.13 gpm)	672.99 kPa (2704” H_20)	
Dubai Hotel-1 inch pipe-1166 l/hr (5.13 gpm)	30.18 kPa (121” H_20)	
Dubai Hotel-2 inch pipe-1166 l/hr (5.13 gpm)	12.58 kPa (51”=4.2 ft H_20)	1 Laing D5 Strong 55 W ($250)

Figure 9: Pumped head, pump size and cost for Canada house and Dubai hotel.

Pipe sizes are extremely important to keep circulator pump power low. Though fittings for the solar collectors and pumps are ½ inch or ¾ inch standard, it must be remembered that on larger systems such as the Dubai hotel, the collector panels are paralleled. A larger pipe is used for the total flow, with smaller pipes branching to the collectors. With series connected collectors, the flow rates become large to avoid fluid boiling, efficiency is less the last collectors due to super-heated fluid and pump cost becomes excessive. A one inch pipe is selected for the house example, while a two inch pipe is selected for the hotel example.

See Appendix E for the flow rate vs pumped head graphs for PV powered circulator pumps. 1 inch pipe is selected for the supply line, as the flow rate and pressure drop fit exactly below the pressure-flow curve of the most common PV-powered circulator pump. Of course, this is not a coincidence: the manufacturer made the pump this size because this power is typically what a solar hot water system needs. See Appendix E for DC circulator pump prices and sizes. Laing is the selected pump manufacturer due to price, correct size, inclusion of maximum power point tracking and original design for direct coupled PV applications. Due to a lack of quality alternatives for large DC pumps, two Laing pumps were needed for the hotel example.

Control of Solar Thermal Water Heaters

Differential Controller

An electronic differential controller is the most common of control options and works with two temperature sensors, one at the hottest point of the collector, the other at the bottom of the storage tank. When the collector temperature is 4-8° C greater than the tank, the controller starts the circulator pump. When the temperature difference is less than approximately 4°, the controller stops the pump. During the night, if the water in the solar thermal panels is approaching freezing, one possible means of freeze protection is to run the circulator pump and circulate some warmer water from the central storage tank to the collector on the roof. This feature can be programmed into most common electronic controllers, as well as other options such as alarms and telephone calls when problems arise. The THY controller from Tsinghua solar is selected as it comes packaged with the Tsinghua solar collectors already selected.

Photovoltaic Control

A photovoltaic module adjacent to, and in the plane of the solar thermal collector can supply DC power to a DC pump. Photovoltaic power is only available when the sun shines, which means solar energy is available to heat the water. A critical part of this application is matching the module and pump properly for optimal operation, which means starting, stopping and flow rates appropriate to the solar collector.

Timers, Manual Control, No Control

Timers and manual on/off control of the circulator pump are rarely used and not certified by the USA’s SRCC or Canada’s CSA, so are not recommended for use (Baechler and Love, 2007). No control of the pump, in other words, running the pump 24 hours a day, obviously would be wasting electricity and heat at night, wearing out the pump prematurely and not providing any change in circulation rate for fluctuating solar insolation. This would only make sense if the installation had serious efficiency problems to start with. For example, if electricity is used for heating, the heat generated by the pump is used, at least in winter. If the solar collector has freezing problems at night, then circulating some water would keep the pipes from freezing. However, this crude solution would waste electrical energy in summer and heat energy from the water in winter, so it is not considered. The case of no control by using a thermosiphon system, as shown in Appendix A, is ruled out by the consumers preference not to have a water tank on their roof for aesthetic or structural reasons.

Comparing Costs

The cost of the solar thermal collector panels is fixed, as is the balance of system excluding the circulator pump and power supply. Maintenance and depreciation is assumed equal for both the solar and grid power systems.

Figure 10: Fixed costs of solar thermal system installation.

Component	Cost (House, 3 Panels; Hotel 10 Panels)
Pipes	\$200+\$50 per solar hot water panel
Solar Panel, SLU1500/16 Tube	\$675 per solar hot water panel
Fittings, labor to install	\$100[1] per solar hot water panel
Installation labor, callout	\$500[2]
Fixed costs	\$3175 (House); \$8950 (Hotel)

The variables thus introduced to the RETScreen program are thus the costs of PV panels combined with DC pumps versus the cost of AC pumps and mains electricity. Costs were estimated as:

Figure 11: Installed solar water system cost, AC Power

Component	Cost (House, 3 Panels; Hotel 10 Panels)
Circulator Pump, Laing SMT-303, 115 VAC, 33 W	\$217 (House), electricity 0.12 \$/kWh
Circulator Pump, Laing SM 1212 115 VAC AC, 140 W	\$245 (Hotel), electricity 0.12 \$/kWh
Electronic controller	\$200
Fixed Costs	\$3175 (House); \$8950 (Hotel)
Total Installed Cost:	\$3592 (house); \$9395 (hotel)

Figure 12: Installed solar water system cost, DC Solar Power

Component	Cost (House, 3 Panels; Hotel 10 Panels)
Circulator Pump, Laing D5 Solar 35 W 12 VDC	\$250 (house, hotel[3])
Circulator Pump, Laing D5 Strong 55 W 24 VDC	\$250 (hotel)
Solar Photovoltaic Panel, 50 W, 12 V	\$250 (house, 1; hotel, 2)
Fixed Costs	\$3175 (House); \$8910 (Hotel)
Total Installed Cost	\$3675 (house); \$9700 (hotel)

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[1] Educated supervisor pay with expenses, same in Dubai and Canada.

[2] Labor cost in Dubai \$10 USD per day, per Indian Subcontinent employee, same total as house.

[3] Hotel requires two pumps, one D5 strong, one D5 solar.

See Appendix D for sources of pricing. In the RETScreen program, the only values changed between the PV case and the mains power case were the total system cost, to allow for the change to a DC pump and Solar Photovoltaic panels, and the cost of electricity for the circulator pump being set to 0. Total system cost for a photovoltaic direct coupled pump system does not include an electronic controller.

Payback Time and Cumulative Cash Flow Compared

System	Equity Payback, Years	Cumulative Cash Flow, Year 25, USD
House, Canada, Mains Power, AC pump	11.4	+$5,800
House, Canada, PV Power, DC pump	11.2	+$6,000
Hotel, Dubai, Mains Power, AC Pump	5.0	+$58,000
Hotel, Dubai, PV Power, DC Pump		

Part 4: Conclusions

Consumer Preferences

Consumers who purchase solar hot water systems want to save money on their energy bills and do no maintenance on their systems once installed. The most economic and reliable system possible for the consumer’s location is often a tank-on-roof pre heater system with no pump at all. National Association of Home Builders studies in the USA have shown that appearance of the solar heater is often even a greater determinant of consumer preference than cost, and most people still consider the tank on roof designs to be ugly, while panel only designs are more acceptable. Some North American consumers will purchase solar systems even if they cost more than conventional energy supplies, but most want to see purchase price payback within 5 years. (NAHB, 1998)

Large Systems

For larger systems, using thousands of liters of water per day, the economics of photovoltaic powered circulator systems are less favorable than small independent systems. Large installations almost certainly have electronic controllers for other system components, are on grid and need larger pumps. Modern electronic controllers for solar hot water systems are multifunction devices, so one controller can handle alarms, freeze protection, backup conventional heating, water distribution and water circulation. There is no cost saving from controller elimination, and photovoltaic power is almost certainly more expensive than grid electricity. Large AC electric motor pumps are much more widely available and cheaper than large DC motor pumps. If the only suitable motor for the circulator pump size is an AC motor, then photovoltaic panels would require an expensive inverter to power the motor.

Some solar hot water systems require no pump at all, such as the passive, thermosiphon system. If the solar hot water installation is simply a pre heater for an existing conventional hot water heating system, then no circulator pump or controllers are required at all. Cold water simply flows through the solar collector tank on its way to the existing hot water tank. No removal of the existing system is required, no electricity, pumps or controls at all are required. System reliability is extremely high while costs are low. Thus the simplest and cheapest system could be a passive system with no circulator pump. If the consumer can be convinced of the costs over the aesthetics, and the roof is strong enough, an integrated tank and collector is recommended. Solar Photovoltaic panels can still be considered for primary home power, or driving the pump from a well.

Most consumers do not like the sight of a solar heater with tank attached if it is in a visible location on their roof and not all roofs are strong enough to carry several hundred liters of water (NAHB, 1998). Also, some systems require water circulation, such as in floor heating, since health concerns preclude drinking the water that is circulated in heating pipes. Extremely large systems benefit from a central hot water storage tank insulated within the interior of a building, with less surface area per liter than many small tanks.

Appendix A: Solar Hot Water System Configurations

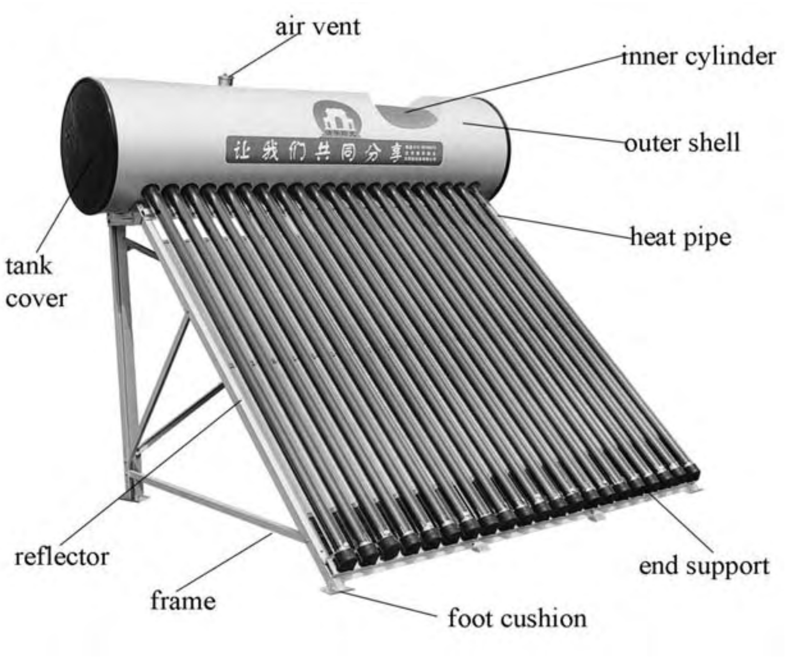

Figure 13: Solar Collector with integrated tank and heat pipes.

One of the simplest installation configurations is shown in Figure 13, where no controller, pump or heat exchanger is needed and freeze protection is provided by the use of heat pipes. To avoid having the tank on the roof, another alternative is Figure 14, which uses a heat exchanger and drain back tank.

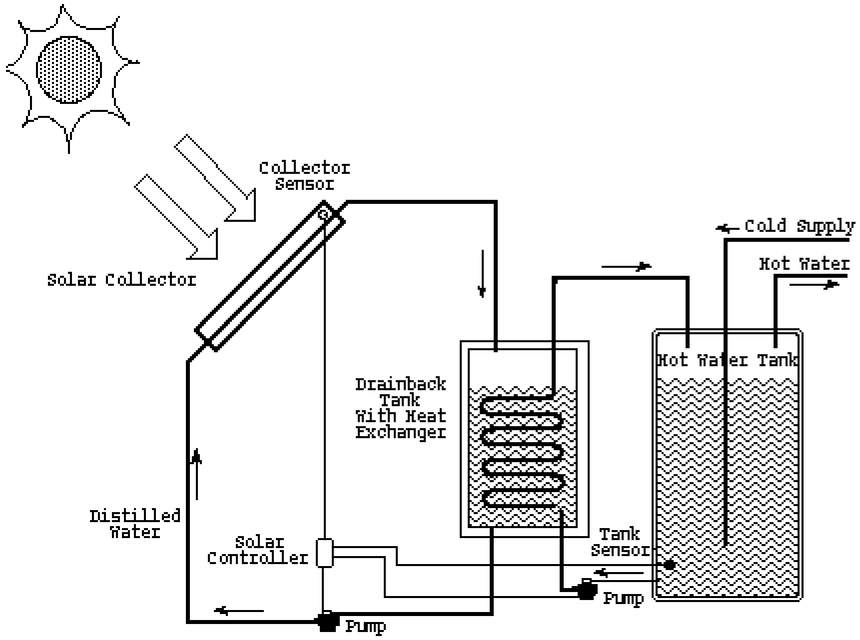

Figure 14: Solar Water Heater system with drainback and heat exchanger

Appendix B: Solar Data, Dubai and Victoria

Solar radiation data, and other climate data used in the RETScreen model, were obtained from the RETScreen database. Dubai, UAE, is obviously a much warmer and sunny place than Victoria, BC.

	Dubai, United Arab Emirates		**Victoria, BC, Canada**	
	Daily solar radiation - horizontal	**Daily solar radiation - tilted**	**Daily solar radiation - horizontal**	**Daily solar radiation - tilted**
Month	**kWh/m^2/d**	**kWh/m^2/d**	**kWh/m^2/d**	**kWh/m^2/d**
January	3.90	5.05	0.90	1.55
February	4.79	5.73	1.60	2.42
March	5.31	5.74	2.89	3.69
April	6.36	6.30	4.39	4.74
May	7.27	6.70	5.35	5.09
June	7.40	6.58	6.01	5.40
July	6.94	6.29	6.30	5.81
August	6.70	6.45	5.54	5.73
September	6.21	6.52	4.12	5.13
October	5.39	6.31	2.28	3.48
November	4.32	5.53	1.10	1.86
December	3.67	4.87	0.73	1.31
Annual	**5.69**	**6.01**	**3.44**	**3.86**

Appendix C: Modification of Test Report Values:

Efficiency measurements and data for the SLU1500/16 solar collector were obtained from tests of the solar collector (Muller-Steinhagen, 2005). The test report can be downloaded from www.freefuelforever.com/index_files/germantest.pdf . Some tested values are in a different format from that of the RETScreen program and thus require modification.

All the efficiency equations used by RETScreen are based on *gross area*, not aperture area. Typically, the performance of a glazed or evacuated solar collector is modeled by the following equation:

eta = Fr (tau alpha) - [Fr UL]*DT/G (1)

where:

eta is the collector efficiency [dimensionless]
Fr (tau alpha) is a parameter used to characterise the collector's optical efficiency [dimensionless] = 0.571 for SLU1500/16
Fr UL is a parameter used to characterise the collector's thermal losses =1.114 [(W/m^2)/°C] corrected for the SLU1500/16
DT is the temperature differential between the working fluid entering the collector and the outdoors [°C]
G is the global incident solar radiation on the collector [W/m^2]

The larger Fr (tau alpha) is, the more efficient the collector is at capturing the energy from solar radiation. The smaller Fr UL is, the better the collector is at retaining the captured energy instead of losing it through convection and conduction to the ambient air.

<u>Tsinghua Solar Collector Test Format:</u>

The German test laboratory also included a quadratic term in the efficiency equation:

eta = Fr (tau alpha) - [Fr UL]*DT/G - [Fr _UL-T]*DT^2/G

where Fr UL_T=0.008 [(W/m^2)/°C^2] is the temperature coefficient of Fr UL. As is usual in Europe, Muller-Steinhagen (2005) reports collector efficiency with a quadratic equations where DT is the temperature differential between the *average* collector temperature and the outdoors. All collector efficiency equation of that form in the RETScreen program database were converted to the *linear* form using the temperature differential between *inlet temperature* and the outdoors. To compensate for the European style of measurement, it is necessary to reduce collector efficiency by about 3%. This is done by increasing the *Miscellaneous losses* by 3%

Changing from Aperture to Gross Area:

RETScreen expects collector efficiencies *expressed in terms of gross area*. Tsinghua’s efficiency is expressed in terms of aperture area. The following conversion can be used:

eta_g = eta_a (Aa / Ag)

where eta_g is the efficiency based on gross area, eta_a is the efficiency based on aperture area, Ag is the gross area (1.62 m^2) and Aa is the aperture area (1.33 m^2). Muller-Steinhagen (2005) tested the SLU1500/16 at:

eta_a = 0.695 - 1.357 (DT/G) - 0.010 (DT^2/G)

The efficiency equation based on gross area is obtained by multiplying the coefficients of the equation above by 1.33 m^2/1.62 m^2, hence the efficiency equation based on gross area is:

eta_g = 0.571 – 1.114 (DT/G) - 0.008 (DT^2/G)
Fr (tau alpha) = 0.571
Fr UL = 1.114
Fr _UL = 0.008

These are the values entered in the RETScreen program.

Appendix D: Payback Period vs Number of Solar Hot Water Panels

Before comparing the photovoltaic powered pump and the AC powered circulator pump options, the most economic number of solar thermal panels must be determined. A greater number of panels require a larger pump to move the water through a larger distance of pipe. The baseline case is the convention AC powered circulator pump system. Efficiency data from test reports for the solar collectors was modified for input into the RETScreen program are explained in Appendix C. Storage tank cost was assumed equal to the electrically-heated tank required on a non-solar system. More panels require a larger pump, more pipes and more fittings, so increments were added for extra panels. For the purpose of determining the optimum number of panels only, $200+$25 per solar hot water panel was used as a cost for the circulator pump. Ordering in larger volumes will lower the unit cost of the solar hot water panels, and perhaps other system components, but compensating for this is the increased cost of larger pipes and longer wire runs.

Baseline House System Payback vs Panels

For the house-sized system located in Victoria, Canada, equity payback time as a function of number of panels is as follows:

Figure 15: House size system, payback time versus number of SLU1500/16 panels

Number of panels:	Equity Payback Time, Years
1	15.7
2	12.8
3	12.3
4	12.7
5	13.8

3 SLU1500/16 panels is thus the optimum number for the Victoria house example.

Baseline Hotel System Payback vs Panels

For the 70-unit hotel located in Dubai, United Arab Emirates, equity payback time as a function of number of solar collector panels is as follows:

Number of SLU1500/16 Collectors	Equity Payback, Years

4	5.4
6	5.1
8	5.0
10	5.0
12	5.0
14	5.1
16	5.1
18	5.2
20	5.3
25	5.5

Figure 16: Number of hotel solar collectors vs equity payback in years

Optimum payback of equity occurs when approximately 10 SLU1500/16 solar collectors are used with the parameters estimated.

Appendix E: Circulator Pump Flow and Head

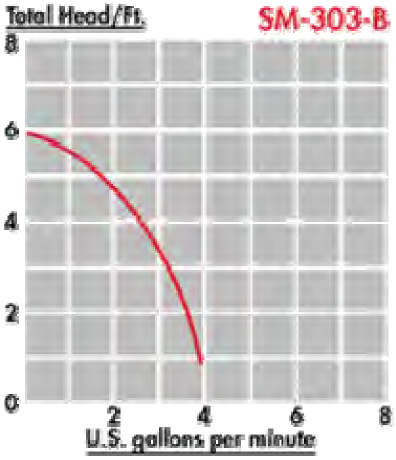

Figure 17: Laing 35 W 115 VAC circulator pump head vs. flow rate

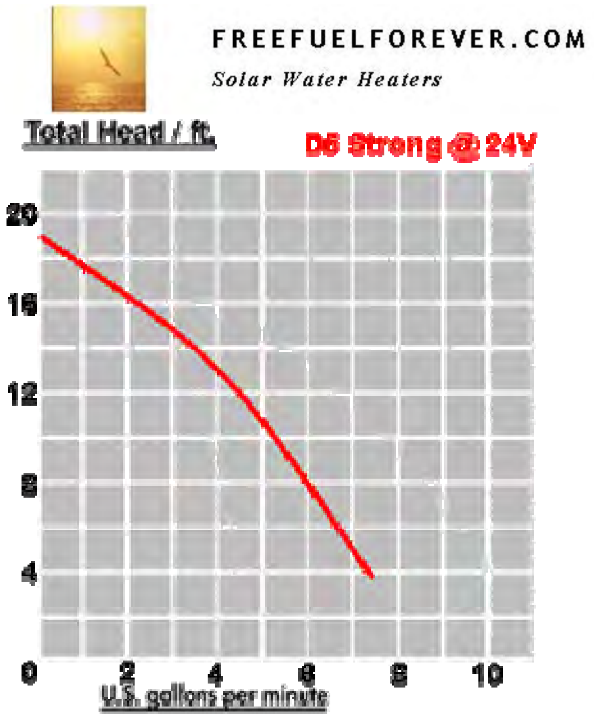

Figure 18: Laing D5 Strong 24 V 55 W pump curve

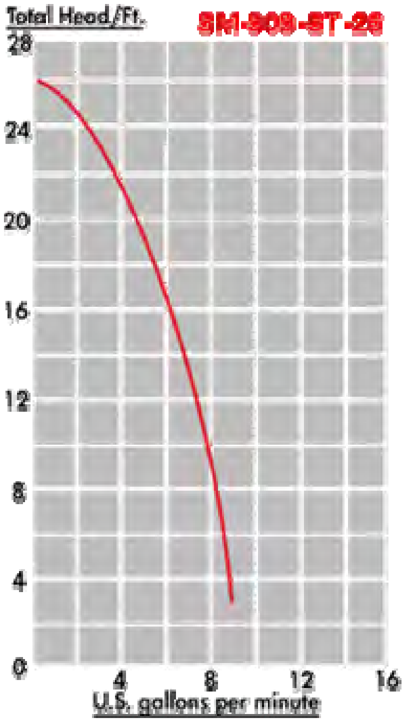

Figure 19: Laing 140 W 115 VAC circulator pump head vs flow rate

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Solar Water Heaters

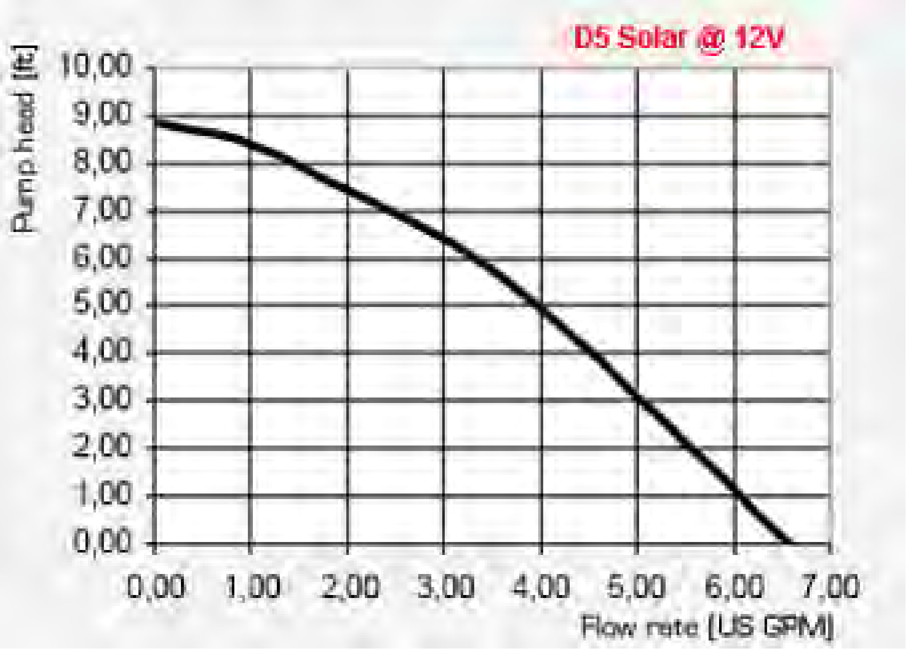

Figure 20: Laing D5 35 W 12 VDC Solar Pump head vs flow rate

0 2 4 6 8 10 12
Water head in feet vs US Gallons per minute flow rate

Appendix F: Pipe Inner Surface Roughness

Typical surface roughness

Material	Nature of Material	Roughness [mm]
Steel pipe	drawn, new	0.02 - 0.1
	welded, new	0.05 - 0.1
	galvanized, new	0.15
	used, cleaned	0.15 - 0.2
	lightly corroded	0.1 - 0.4
	severely corroded	0.4 - 3
	light scaling	1 - 1.5
	heavy scaling	1.5 - 4
	bitumed coated	0.05
cast - iron pipe	new	0.25 - 1
	corroded	1 - 2
	with scaling	1 - 4

From the www.the-engineering-page.com

Appendix G: Circulator Pump Prices:

From Northern Arizona Wind+Sun (2007), Laing (2007)

Pump Description	Power, maximum	Price USD
March 809 BR-HS-12 V Brushless circulator	1/25 HP, 50 W	$357
March 809 BR-HS-12 V Brushless circulator	1/100 HP	$323
Hartell Brushless DC MD-10-HEH	18 W	$348

Laing D5 090 B Ecocirc Bronze	35 W	$250
Laing D5 Strong	55 W	$250
El SID 5 PV Direct	5 W	$219
El SID 10 PV Direct	10 W	$220
El SID 20 PV Direct	20 W	$310
Ametek 10 Gallon Seal less pump, Brush motor 12 VDC	75 W	$145
Laing SMT-303 115 VAC	33 W	$217
Laing SM 1212 115 VAC	140 W	$245

Laing and El SID pumps are designed to be connected directly to PV panels. Laing uses Maximum Power Point tracking in the pump, so power varies with PV panel voltage.

Prices from manufacturer, or manufacturers’ dealer online. Ametek from Allied Electronics.

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