Solar thermal technologies for domestic hot water applications: An energy and economic investigation for the Australian climate

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Abstract

By displacing the current heavy use of electricity and gas for domestic hot water applications, solar thermal technologies have significant potential to reduce Australia's fossil fuel emissions. Solar thermal systems prevalent in the current Australian market include a mixture of flat plate and evacuated tube collector types applied in either active or passive style circulation systems. The performance of these systems can vary significantly depending on a number of factors including; the characteristics of the solar collector, storage tank size, hot water load and usage, and climate. As all these factors can vary considerably, particularly the Australian climate, the optimal configuration (considering both performance and economics) of a solar hot water system can also be expected to vary substantially. The purpose of this study is to examine the performance of common solar thermal system designs operating in four climate zones of Australia (Rockhampton, Alice Springs, Sydney, and Melbourne) operating under the load of a four person detached dwelling. A total of six solar hot water systems were designed and simulated using the commercial software package POLYSUN operating in the four Australian climate zones mentioned.

The results showed that solar fractions and payback periods can vary considerably, ranging from 58 to 100 per cent and between 3.8 and 10.1 years respectively. It was found, in this work that, although the evacuated tube collector generally operates with a marginally higher annual thermal efficiency over the selective surface flat plate collector, the overall performance of a system comprising of two selective surface collectors, is greater than a 30 tube evacuated tube system due to its larger absorber area despite taking less roof area. Due to the ratio of absorber to gross collector area, the selective surface flat plate collector was shown, in this study, to yield a higher thermal output per unit area of roof over the evacuated collector making it an ideal choice for domestic hot water projects where roofing area is limited relative to the thermal load. Furthermore, for the regions of high solar irradiance in Australia (Rockhampton and Alice Springs) the cheaper, lower performance flat plate collector was found in this study to operate with very high solar fractions while lowering the stagnation temperature over the selective surface flat plate and evacuated tube collector alternatives and is therefore the preferred solution.

Keywords: solar, thermal, flat plate, evacuated tube, domestic hot water, simulation

1. Introduction

Net energy consumption is increasing steadily in Australia due to a combination of factors including population growth and an increase in living standards (Bush, Harris et al. 1997). A significant portion of the energy consumed within the Australian residential sector is the energy required in meeting domestic hot water needs. Here, Australia is heavily dependent on the use of electric and gas fuelled water heaters responsible for approximately 24% of residential sector greenhouse gas emissions (Ferrari, Guthrie et al. 2012). Solar water heaters have been shown in a number of previous studies to make significant reductions in conventional energy (i.e. electricity and gas) use (Czarnecki 1958, Czarnecki and Read 1978, Morrison, Tran et al. 1984, Crawford 2001, Lloyd 2001, Vieira, Beal et al. 2014) while also demonstrating energy pay back periods of less than two years in some studies (Crawford and Treloar 2004, Hernandez and Kenny 2012).

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In order to increase the penetration of solar hot water heaters into the hot water market and reduce greenhouse emissions, a number of incentives have been provided at both state and federal levels resulting in strong growth within the Australian solar hot water industry, particularly within the new housing market such as the Small-Scale Renewable Energy Scheme (CER 2015). In the southern state of Victoria, new homes now require the installation of either a solar hot water system or rainwater tank. This programme alone has resulted in an increase adoption of solar water heaters from approximately 5% in 2004 to over 70% in 2011 (Ferrari, Guthrie et al. 2012).

Although Australia has recently experienced an uptake in the penetration of solar hot water heaters, it is approximated that energy efficient hot water heaters (i.e. solar and heat pump water heaters) constitute only 13% of total current installed water heaters (Shrapnel 2010). With the total number of water heaters sold in Australia to be approximately 700,000 units annually, the future market for solar thermal installations is large, particularly considering the rapid increase in utility costs that is occurring in Australia.

Solar thermal collectors can efficiently convert incident solar energy directly into useful thermal energy. This energy can be utilised by a household and significantly reduce the usage of the traditional fossil fuel powered energy sources.

1.1 Solar hot water systems and components

The typical domestic hot water solar thermal system comprises of the following major components (Kalogirou 2009):

1. Solar thermal collectors
2. Storage tank
3. Energy transfer system
4. Method of providing auxiliary boosting

The principal component of the solar thermal hot water system is the collector. The solar thermal collector is a unique heat exchanger which consists of an absorber, the component which absorbs incident electromagnetic energy radiated from the sun and converts this energy to useful thermal energy via an absorption process. Thermal energy is then transferred to the transport medium (typically water or a water/glycol mixture) which is circulated within the absorber. Thermodynamically, the design of a solar thermal collector aims to maximise the absorption of solar radiation and the heat transfer from the absorber to the transport medium, while minimising heat losses to the environment. A number of collector designs currently exist to achieve these engineering goals, with the stationary non-concentrating type flat plate collector and evacuated tube collector predominant in the Australian solar hot water market.

The typical design of a flat plate collector is shown in Fig 1 with major components forming the assembly identified. Incident solar radiation is attenuated through the glazing, generally high transmission low iron glass, onto the absorber surface. The absorber is made from a material of high thermal conductivity such as steel, aluminium, or copper and coated to increase its absorptivity. As a result of the impinging solar radiation being absorbed the temperature of the absorber will increase. The majority of this energy is then transferred to the transport medium (e.g. water) that is flowing within a series of fluid risers that are placed in thermal contact with the absorber via convection heat transfer.

Analysing the performance of a solar collector can be simplified to highlight the influence of the most important materials. The optical efficiency (η_0) of a solar collector is dependent on the properties of the absorber and glazing. The absorber is a function of two dominant properties: the absorptance of the absorber coating and the collector efficiency factor (*F'*) as shown by Eq. (1) (Frei and Brunold 2000).

$$\eta_o = F'(\alpha\tau)_e \tag{1}$$

Where α is the absorptance, τ is the transmission of the glazing, F' is the collector efficiency factor, and $(\alpha\tau)_e$ is the effective absorption-transmittance product. The efficiency of a collector while in operation is calculated using Eq. (2).

$$\eta = F'(\alpha\tau)_e - F'U_L\left(\frac{T_m - T_a}{G_t}\right) \tag{2}$$

Where U_L is the overall heat loss coefficient, T_m is the mean collector temperature, T_a is the ambient temperature and G_t is the solar insolation on the collector plane.

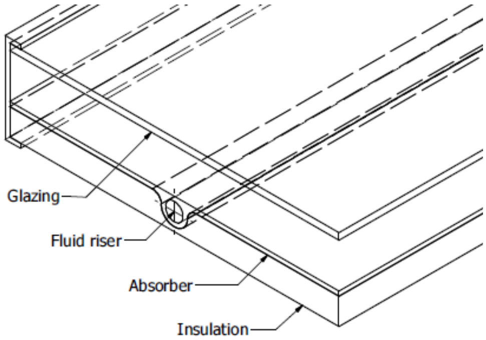

Fig 1: Typical components of a flat plate collector.

Examining Eq. (2), we can see that the thermal efficiency of a solar thermal collector is reduced by the heat loss term which is a factor of the temperature difference between the mean collector temperature (T_m) and the ambient temperature (T_a). As the mean absorber temperature rises above ambient, heat losses will inevitably occur via radiation, convection, and conduction modes reducing the thermal efficiency, and therefore yield of the collector. The characteristic performance of a solar thermal collector is typically expressed using Eq. (3) below.

$$\eta_{th} = a_1 - a_2\frac{(\bar{T} - T_a)}{G_t} - a_3\frac{(\bar{T} - T_a)^2}{G_t} \tag{3}$$

Where a_1, a_2, and a_3 are the collector performance characteristics determined by a laboratory to the local relevant test standard. It is of course ideal to maximise collector efficiency for the range of operating temperatures a solar collector will operate within which is dependent on the application (e.g. domestic hot water or industrial process heat application). For domestic hot water applications, this can range up to 70 degrees C, where a standard flat plate collector can experience significant heat losses reducing the useful energy gained by the transport medium. To minimise this loss, a number of strategies may be employed. One successful method which has been shown in previous studies (Jung 1988, Eisenhammer, Mahr et al. 1997, Schüler, Geng et al. 2000, Roberts 2013) to significantly improve the thermal performance of a collector is the use of spectrally selective absorber coatings onto the absorber substrate. By applying a spectrally selective coating onto the absorber, absorption (α) and emittance (ε) values can be altered and optimised such that thermal radiation losses can be reduced. Heat loss via convection may also be retarded by the evacuation of the air between the absorber and outer glazing reducing heat loss. This is the key feature of the evacuated tube collector (Gao, Fan et al. 2014). By creating a vacuum envelope, the thermal efficiency of the evacuated tube collector is less influenced by ambient conditions (temperature and wind) allowing higher collector operational temperatures.

The performance of a solar hot water system however, is not only dependent on the collector but the design of the whole system. Thermal energy collected from the collector must be stored in a thermally insulated container so that it can be later used by the household. The characteristics of the storage tank (size, heat loss, location of plumbing ports, etc.) will directly influence the collector and the quantity of hot water available to the household. A tank that is undersized for a given collector, application, and climate will lower the efficiency of the collector (due to an elevated mean collector temperature) and increase the likelihood of stagnation and the associated risks. An oversized tank on the other hand will increase the cost of the system and have a detrimental impact on the cost/performance ratio and excessive heat loss.

The manner in which energy is transferred between the collector and tank will have a significant influence on the performance of the system. This can be performed either by active or passive means. An active system is where an electrically driven circulator is used in conjunction with a controller to pump fluid around the collector loop. Alternatively, the passive or thermosiphon system works of the principle of natural convection and flow induced by a density differential and therefore does not need a pump or controller. Of these two methods, the active system will operate with the higher fluid velocity which will improve the heat transfer from the absorber to the transport medium, improving the thermal efficiency of the collector. The passive/thermosiphon system however will operate with reduced electricity consumption and potentially lower annual operational cost.

Finally, when designing a solar hot water system, a means to provide additional heating powered by conventional fuels (e.g. electricity/gas) is generally incorporated to ensure thermal loads are met during periods of insufficient radiation. A number of methods currently exist to achieve this with in-tank electric boosting and in-line continuous gas boosting methods the dominant methods in Australia. The in-tank electric boosting method is where an electric element is immersed in the tank and controlled via a thermostat. Although simple and cheap, a significant pitfall with this method is the addition of energy directly to the fluid being circulated through the collectors. As this will elevate the mean operating temperature of the collector, it will also reduce its operational efficiency. To avoid this issue, a gas booster can be placed between the outlet of the storage tank and the hot water supply line making an ‘in-line’ configuration. This way, energy is only added to the fluid when required and will not adversely affect the collector performance.

The combination of collector, tank, circulation method, and auxiliary boosting method will all contribute to the performance and cost of a solar hot water system. The optimal configuration will be dependent on a number of factors including the thermal load, installation parameters, and climate.

1.2 Aims of this study

It was discussed in the previous section that a number of collector types and system configurations are typically employed in Australia. When one considers the vast size of Australia, and consequently the vast differences in climate across the continent, the optimal configuration of solar thermal system components can also be expected to vary considerably when both thermodynamics and economics are taken into account.

The aim of this study is to conduct a computational study to determine the thermal performance of a number of solar hot water systems for a typical four-person household in Australia. This study will be limited to stationary, non-concentrating type collectors (i.e. flat plate and evacuated tube collectors only) that are boosted via an in-line continuous gas booster as discussed previously in Section 1.1. One area of focus for this study will be to compare performance and economic metrics between the flat plate and evacuated tube collectors. An emphasis will therefore be placed in this study to examine this specific issue further.

2.0 Method

A computational approach was applied in this work as it has now become common practice to incorporate simulations for the design of a solar thermal systems. Doing so allows the performance to be approximated for a specified system operating under transient environmental conditions. Computer simulations allow a number of system design parameters such as the characteristics of the collector, how it is orientated (azimuth and inclination), climate data, thermal loads, etc. to be varied so that their influence on output can be quantified and then examined and optimised. Although experimental work is the preferred method of acquiring data from an engineered system, it is often not practical and feasible considering time and costs. Such is the case for this study as we wish to investigate a number of system designs operating in different climate zones.

A number of sophisticated off-the-shelf computer simulation programmes for carrying out solar simulations are currently available such as TRNSYS (TRNSYS), T*SOL (T*SOL), and POLYSUN (POLYSUN). POLYSUN software package is used in this study and has also been applied successfully in previous studies (Kalogirou 2009, Bornatico, Pfeiffer et al. 2012, Carbonell, Haller et al. 2014). The accuracy of any computer simulation however, is not only dependent on the software package used but also by the quality of the simulation setup and the input of realistic parameters by the user and the consideration of system uncertainties (Dominguez-Munoz, Cejudo

Lopez et al. 2012). Details of the solar thermal systems and the parameters for the simulation are provided in the next section.

2.1 Simulation setup

In total, six solar thermal domestic hot water systems were investigated in this work operating under four climate zones of Australia. Details of each system configuration are provided in Tab 1. With regards to the types of solar thermal collectors investigated, high and low performance flat plate collectors as well as an evacuated tube type collector were examined in this work. All systems were coupled with a 300 litre storage tank with a daily draw-off of 200 litres per day at 50° Celsius, sufficient for a family dwelling of 4 people (50 litres/person). The energy draw-off pattern shown in Figure 3 was defined and assumed for all simulation studies conducted. All systems were auxiliary boosted via the in-line continuous gas boosted methodology discussed previously in Section 1.1.4. The gas booster chosen in this study was a generic 25kW natural gas fired type operating with a thermal efficiency (η_{th}) of 80 per cent.

The performance characteristics for each of the three solar thermal collectors are provided in
Tab 2 below. In all simulations carried out, it was assumed that the collectors were orientated directly north and tilted at 25 degrees in accordance with the Australian standards relevant to the simulation of solar thermal systems (2008). All storage tanks (both active and thermosiphon) were 300 litres in storage capacity, fabricated from stainless steel and insulated with rigid polyurethane (PU). Additionally, piping length between the storage tank and collectors was fixed at 10m for all active systems with loose glass fibre\mineral wool type insulation (ρ = 250 kg/m^3 and k_{th} = 0.045 W/m.k) 20mm in thickness. For active systems, piping length between collectors and tank was fixed at 10m.

Tab 1: Details of the six solar thermal system configurations investigated in this work.

System	Type	Collector	Tank	Auxiliary booster
1	Active	2 x High performance flat plate	300L	25kW in-line gas booster
2	Active	2 x Low performance flat plate	300L	25kW in-line gas booster
3	Thermosiphon	2 x High performance flat plate	300L	25kW in-line gas booster
4	Thermosiphon	2 x Low performance flat plate	300L	25kW in-line gas booster
5	Active	1 x 30 Tube evacuated tube	300L	25kW in-line gas booster
6	Thermosiphon	1 x 30 Tube evacuated tube	300L	25kW in-line gas booster

Tab 2: Performance characteristics of each of the collectors investigated in this work.

Parameter	High performance flat plate (x1)	Low performance collector (x1)	Evacuated collector x 30 tube
$A_{absorber}$ (m^2)	1.62	1.87	2.84
A_{gross} (m^2)	1.8	2.01	4.4
η_0	0.785	0.687	0.71
a_1 (W/m^2/k)	3.35	5.761	1.65
a_2 (W/m^2/k^2)	0.012	0.014	0.008
T_{stag} (°C)	203	124	228

As previously stated, one of the key factors under investigation in this work is the influence of weather on system behaviour. Given the vast size of Australia, four climate zones have been identified in the Australian Standards (2008) to standardise the performance assessment of solar energy systems across the country. These four zones are shown in Fig 2 below. For each climate zone, the meteorological data is taken from a single city. These are Rockhampton, Alice Springs, Sydney, and Melbourne for Zones 1, 2, 3, and 4 highlighted in Fig 2 respectively.

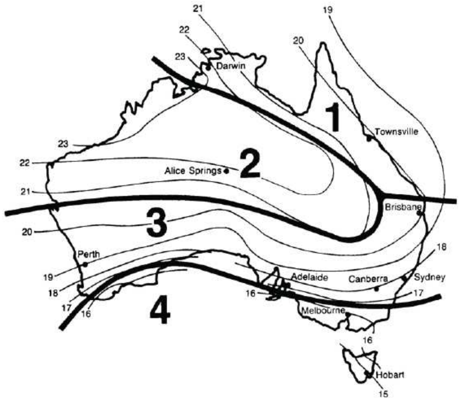

Fig 2: A map of Australia identifying the four climate zones used for simulation studies (2008).

With regard to thermal loading on the hot water system, user profiles will, of course, change considerably based on consumer preferences and seasonal variation. In this work, we will use the thermal load profile specified in the Australian standards (2008). This profile, shown in Fig 3, consists of morning and evening peaks with some usage shouldering the lunch time periods.

In summary, six solar thermal systems (see Tab 1) operating under four weather climates were investigated in this work. Results are presented in the next section.

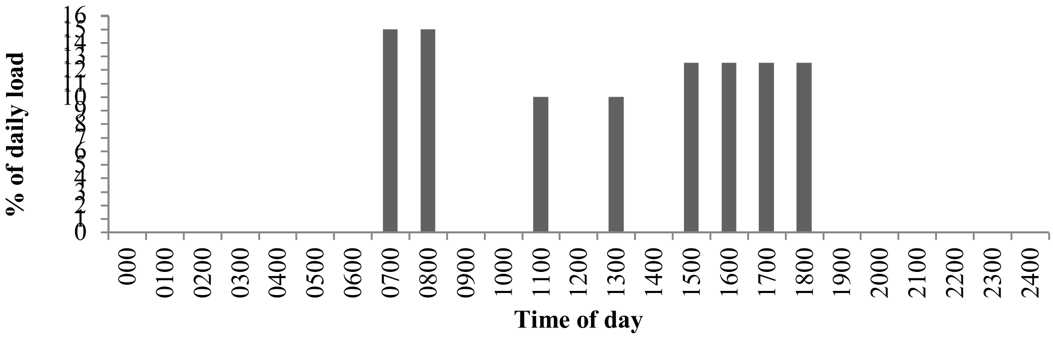

Fig 3: Thermal load profile for all solar hot water systems studied in this work (2008).

3.0 Results and Discussion

The results with respect to energy and economics are presented in this section.

3.1 Energy analysis

Quantitative annual energy results are provided in Tables A.1 to A.6 for Systems 1 through to 6 respectively. The following key performance metrics were taken from the POLYSUN generated results in order to evaluate the overall performance of the systems studied:

a) E_{tot} – the total annual energy that must be purchased by the consumer to operate the booster and if applicable, auxiliary equipment (kWh).
b) *Solar fraction* (S_f) – The POLYSUN total solar fraction is determined by equation Eq. (4).

$$S_f = \frac{Q_{sol}}{Q_{sol} + Q_{aux}} \tag{4}$$

Where Q_{sol} is the collector field yield (kWh) and Q_{aux} is the energy required by the auxiliary booster (kWh).
c) Collector field yield (Q_{sol}) – the total annual energy delivered by the collectors to the loop (kWh).

d) Specific collector field yield – The quotient of the annual collector field yield (Q_{sol}) and the gross collector area (kWh/m^2/year).
e) Collector efficiency ($\eta_{th,col}$) – the quotient of the annual collector field yield ($Qsol$) and the annual global irradiation incident on the collector aperture area.

From the data presented in Tables A.1 to A.6, a number of key findings can be extracted:

1. Comparing System 1 and System 5 we see that the evacuated tube collectors operate with a slightly higher thermal efficiency. However, solar fractions are higher for the flat plate system due to the larger absorber area of the two flat plate collectors resulting in greater collector field yield (Q_{sol}) and reduced auxiliary energy consumption.
2. The specific collector field yield for the high performance flat plate collector system is higher than the evacuated tube collector. This is explained by comparing the ratio of absorber to gross collector areas for both collectors. The flat plate collector has a ratio of A_{abs}/A_{gross} = 0.9 while the evacuated tube collector is 0.65.
3. For Zones 1 and 2, regions of Australia with high solar irradiance, the lower performing flat plate collector is a good choice as high solar fractions can be obtained in both active and thermosiphon systems while reducing the stagnation temperature.
4. Thermosiphon systems operate the minimum E_{tot} values due to the passive or natural circulation of fluid.
5. The difference in solar contribution from a solar hot water system is heavily influenced on its installed location in Australia.

Qualitatively examining the tabulated data presented in Appendix A specifically for Zone 3 (Sydney) we can visually compare the behaviour of each system for a single climate. Fig 4 compares the specific collector field yield and collector efficiencies between all six systems. From this figure we observe that an active system coupled with the high performance flat plate collectors (System 1) offers the maximum specific yield (Q_{sol}/A_{gross}) despite operating with a collector efficiency value slightly lower than the evacuated tube collector (System 5). This result which was similarly found in other work (Budihardjo and Morrison 2009), can be explained by comparing the collector characteristics, specifically the collector area values provided in
Tab 2. The ratios of absorber to gross collector areas are 0.9 and 0.65 for the high performance flat plate and evacuated tube collectors respectively. As the flat plate collector has a much higher ratio of absorber to gross collector area, it is able to compensate for its slightly lower thermal efficiency. This is again highlighted in Fig 5 which plots solar fraction and collector efficiency for each system for weather zone 3. The active system with high performance collectors offers the maximum solar fraction, greater than the 30 tube evacuated tube system. The system with the greatest solar fraction will require the least amount of purchased energy and potentially operate with the lowest annual running cost.

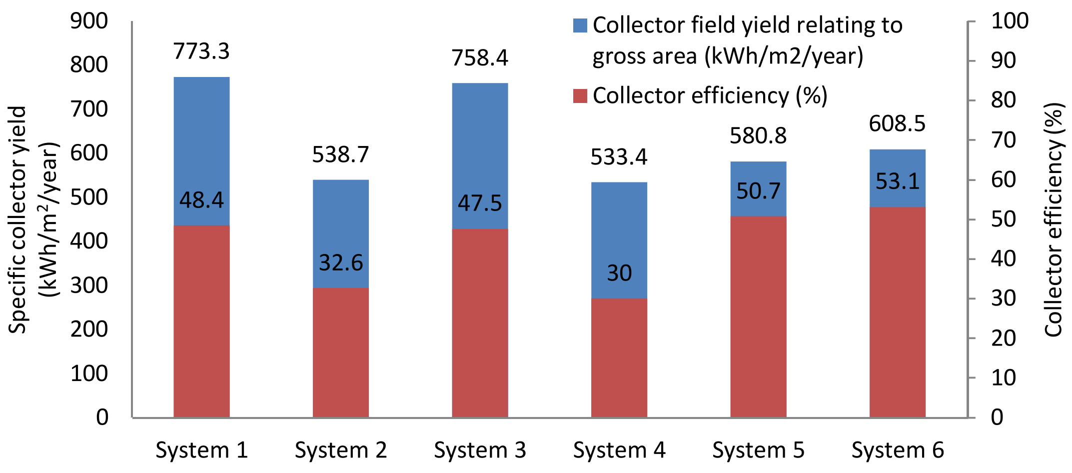

Fig 4: Comparing specific collector output and thermal efficiencies for all systems in climate Zone 3.

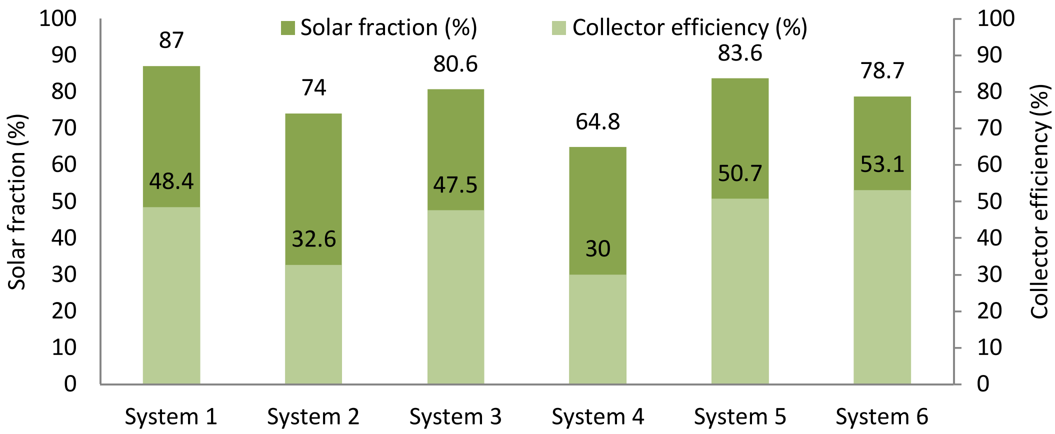

Fig 5: Comparing solar fractions and collector efficiencies for all systems in climate Zone 3.

3.2 Economic analysis

An economic analysis of the results was also conducted where the annual energy savings and return on investment (ROI) for each system and weather zone were calculated. System costs for each of the six solar hot water systems used for this step of the analysis are summarised in Tab 3. These figures were determined in consultation with Solimpeks Australia, one of Australia's distributors of solar thermal systems. Installation costs were also included to consider the differences in installing active and passive type solar thermal systems into the analysis. These figures were obtained from Australian Plumbing & Gas Australia Pty Ltd.

Tab 3: Approximate pricing for all six systems investigated in this work including installation. All prices are in Australian dollars.

	System					
	1	2	3	4	5	6
TOTAL (AUD)	$4,210.00	$4,190.00	$3,560.00	$3,540.00	$4,650.00	$4,000.00

Results for the average annual energy savings and ROI are presented in Fig 5 and Fig 6 respectively. Examining these two figures we can extract the following key results:

1. The thermosiphon system comprising of high performance flat plate system offers the maximum annual energy savings and fastest return on investment for all four weather climates investigated followed by a thermosiphon system coupled with an evacuated tube collector.
2. For all active type systems studied, the high performance flat plate collector system offered the greatest energy savings and fastest payback period.
3. A large variation in ROI values was calculated ranging from 3.8 to 10.1 years for the systems studied under the largely varying Australian climate.

The favourable payback period of the flat plate collector system over the evacuated tube system found in this study is supported by the experimental work carried out in a previous study (Chow, Dong et al. 2011). The results of this study highlight the importance of considering the system's holistic performance in its installed location and intended use as opposed to the thermal efficiency of the collector alone. However, under certain circumstances the evacuated tube collector may be the better choice particularly for applications which require higher fluid temperatures (> 70 degrees C) such as industrial process heat applications.

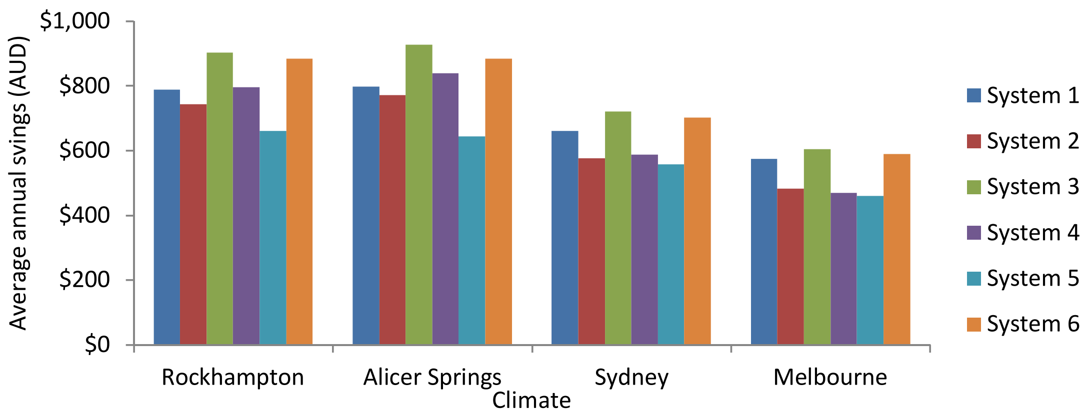

Fig 6: Average annual energy savings for each system in each of the four weather climates investigated.

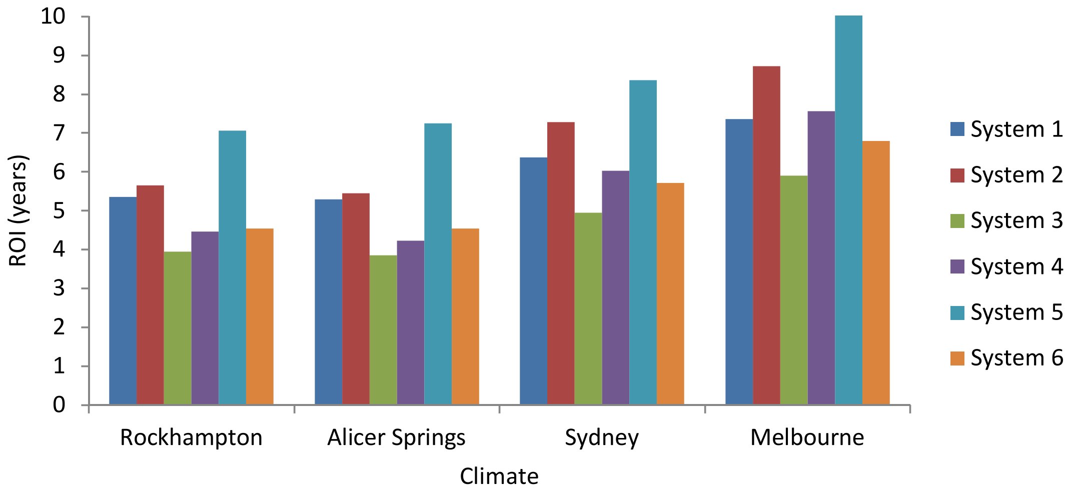

Fig 7: Payback periods for all systems investigated for all four climates in Australia.

4. Conclusions and recommendations

In this study, a number of computational simulations have been carried out on typical solar thermal systems typically deployed in Australia for domestic hot water purposes. Three collector types were investigated including high and low performing flat plate collectors and evacuated tube collectors which were integrated into both active and passive systems. From this work we can make the following conclusions:

1. The high performance flat plate collector operates with a slightly lower thermal efficiency in comparison to the evacuated tube collector, but contributes greater thermal yield per unit area of roof due to its comparatively higher absorber area.
2. The high performance flat plate collector offers the greatest thermal yield per unit area of roof of all collectors studied.
3. For Zones 1 and 2 of Australia, the low performance flat plate collector is a good choice based on its ability to operate with high solar fractions and its reduced cost and operational safety concern which arise from excessively stagnation temperatures.
4. A large variation in payback periods was found in this study highlighting the importance of system design for solar hot water applications in Australia.
5. Thermosiphon systems offer the fastest payback periods due to the lower capital and operational costs despite operating with reduced collector efficiency.

It is common in the solar thermal industry to emphasise the thermal performance of solar thermal collectors as a single component, but other considerations should be taken into account. The results from this study support the claim that the evacuated tube collector do indeed operate with a higher thermal efficiency over the flat plate collector, however, it is important to assess the performance of the overall system, not just one component forming it. This study has shown for all four weather profiles studied (Rockhampton, Alice Springs, Sydney, and Melbourne) the cheaper high performance flat plate collector operates with a greater solar fraction over the evacuated tube collector and offers the household a faster payback period and lower cost of energy. Furthermore, the high stagnation temperature of evacuated tube collector should always be considered when proposing this technology. With stagnation temperatures over 220°C achievable with the evacuated tube collector, this can stress component materials and create safety concerns for the user.

Appendix A. Results tables

Tab A.1: Energy results for System 1 (active system with 2 x high performance flat plate collectors).

	Zone 1	Zone 2	Zone 3	Zone 4
	Rockhampton	**Alice Springs**	**Sydney**	**Melbourne**
E_{tot} **(kWh)**	672.4	629.4	1173	1522.6
S_f, **Solar fraction (%)**	100	100	87	79.9
Q_{sol}, **Collector field yield (kWh)**	3247	3617.3	2783.8	2776.6
Specific collector field yield (kWh/m²/year)	901.9	1004.8	773.3	771.3
$\eta_{th,col}$, **Collector efficiency (%)**	47	46.3	48.4	49.7

Tab A.2: Energy results for System 2 (active system with 2 x low performance flat plate collectors).

	Zone 1	Zone 2	Zone 3	Zone 4
	Rockhampton	**Alice Springs**	**Sydney**	**Melbourne**
E_{tot} **(kWh)**	845.6	737.2	1509	1888.6
S_f, **Solar fraction (%)**	92.8	96.6	74	67.2
Q_{sol}, **Collector field yield (kWh)**	2589	2954.4	2165.7	2187.1
Specific collector field yield (kWh/m²/year)	644	734.9	538.7	544
$\eta_{th,col}$, **Collector efficiency (%)**	32.4	32.7	32.6	33.9

Tab A.3: Energy results for System 3 (thermosiphon system with 2 x high performance flat plate collectors).

	Zone 1	Zone 2	Zone 3	Zone 4
	Rockhampton	**Alice Springs**	**Sydney**	**Melbourne**
E_{tot} **(kWh)**	214.7	114.9	937.8	1397.8
S_f, **Solar fraction (%)**	97.5	100	80.6	72.8
Q_{sol}, **Collector field yield (kWh)**	3267.7	3712	2730.4	2717
Specific collector field yield (kWh/m²/year)	907.7	1031.1	758.4	754.7
$\eta_{th,col}$, **Collector efficiency (%)**	47.3	47.5	47.5	48.6

Tab A.4: Energy results for System 4 (thermosiphon system with 2 x low performance flat plate collectors).

	Zone 1	Zone 2	Zone 3	Zone 4
	Rockhampton	**Alice Springs**	**Sydney**	**Melbourne**
E_{tot} **(kWh)**	639.2	464.6	1465.7	1938.5

S_f, Solar fraction (%)	85.1	91	64.8	58.3
Q_{sol}, Collector field yield (kWh)	2463.7	2912	1994.9	2026
Specific collector field yield (kWh/m^2/year)	612.9	724.4	533.4	541.7
$\eta_{th,col}$, Collector efficiency (%)	30.9	32.3	30	31.4

Tab A.5: Energy results for System 5 (active system with 1 x 30 tube evacuated tube collector).

	Zone 1	Zone 2	Zone 3	Zone 4
	Rockhampton	Alice Springs	Sydney	Melbourne
E_{tot} (kWh)	1177.9	1245.3	1586	1973.5
S_f, Solar fraction (%)	97.8	99.3	83.6	75
Q_{sol}, Collector field yield (kWh)	2973.8	3249.5	2555.7	2503.8
Specific collector field yield (kWh/m^2/year)	675.9	738.5	580.8	569
$\eta_{th,col}$, Collector efficiency (%)	49.1	47.4	50.7	51.1

Tab A.6: Energy results for System 6 (active system with 1 x 30 tube evacuated tube collector).

	Zone 1	Zone 2	Zone 3	Zone 4
	Rockhampton	Alice Springs	Sydney	Melbourne
E_{tot} (kWh)	290.2	290.2	1015.5	1459.2
S_f, Solar fraction (%)	95.5	95.5	78.7	71
Q_{sol}, Collector field yield (kWh)	3159.8	3159.8	2677.5	2619
Specific collector field yield (kWh/m^2/year)	718.1	718.1	608.5	595.4
$\eta_{th,col}$, Collector efficiency (%)	52.1	52.1	53.1	53.5

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