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Solar Thermal Sterilization: A TRNSYS Performance Analysis

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Abstract

Most industrial processes require heat in the temperature range from (60-260)°C (Kalogirou, 2002b). – representing an application which could potentially be met with locally derived solar heat (Li et al., 2016). The authors believe this is a promising, but critically under-developed field, so this paper employs TRNSYS software (Klein, 2012) to conduct a comparative annual parametric study of four different solar thermal collectors for a sterilization application. Several cases were investigated using different load profiles, control methods, tank configurations, and two solar resource locations in Sydney and Alice Springs. Sterilization process requires steam to be delivered at a temperature from 132°C-135°C (Patel, 2003). To meet this demand, a solar collector must provide 180°C Oil to a steam generator. Our results indicate that a small, but significant, fraction of industrial demand can indeed be met with solar heat coming from the rooftop of the building. Solar contribution up to 53% has been acheived using the TVP collector, stratified tank-differential controller strategy. However, an economic analysis reveals that the system must be carefully designed in order to have any chance at achieving an economic payback (without subsidies).

1. Introduction

Sterilization is a process for eliminating any form of microbial life in a product to prevent diseases caused by viruses and bacteria. Sterilization is applied to a wide range of consumer products in biomedical and food industries. Plastic, glass, and metal packaging and tools must be sterilized during production at the factory. Chemical or physical methods may be used. While chemical methods are used in many processes, physical methods using saturated steam, dry heat, or hot water are more commonly used due to their superior economics (Case medical, 2016). Saturated steam at a temperature from 132°C-135°C in particular, has been proven to be successful in many applications (Patel, 2003).

Solar thermal energy can be used to supply some portion of the thermal energy for these types of sterilization loads. However, using transient solar energy resources for such a sensitive application requires a smart control strategy to ensure that energy supply meets the load requirements in terms of steam temperature, pressure, exposure time and other variables accompanying this process.

Research has been conducted into using solar thermal collectors for industrial heating applications such as distillation, agricultural processing, drying, and the textiles industry (Norton, 2012; Norton et al., 1999; Mekhilef et al., 2011). These studies range from local kW-scale systems to large MW-scale systems, and they have been analysed over a wide range of output temperatures and system designs (Kalogirou, 2002b). Some papers outlined low-temperature steam production, but these focused on the collector design and performance analysis rather than a systems analysis (Kalogirou, 1996). In addition, there is a critical lack of investigations for a key industrial heat market – sterilization processes.

A brief overview of the literature available in solar driven industrial heat applications is presented. (Kalogirou, 2002b) has analyzed the performance of the flat plate collector (FPC), advanced flat-plate (AFP), compound parabolic collector (CPC), evacuated tube collector (ETC) and a parabolic trough collector (PTC) for several heat applications at a temperature from 60°C - 240°C using the Mediterranean climate. He concluded that fuel price and solar system capital cost are the dominant factors for solar system viability. (Kalogirou, 2002a) has also analyzed the performance of a parabolic trough collector (PTC) for 85°C hot water production in Nicosia, Cyprus and found that the solar system is more economically viable for industrial processes that have higher energy consumption. (Proctor et al., 1977) have analyzed a commercial collector for the food industry in Melbourne, Australia that requires heat from 40°C - 90°C and found that the solar heat system viability decreases when the process required temperature increase. (Norton, 2012) has analyzed a double glazed collector for several processes including the Brewing process in Neuwirth, Austria and found that the thermal stratification can maintain a good outlet discharge temperature from the solar tank when a storage system is used. (Frein et al., 2014) have analyzed a flat plate solar collector in Benetton Tunisia for 60°C drying process and investigated the heat recovery potential in the system. He found that there are several methods to recover the heat after supplying the process which contribute to a significant energy savings. (Arabkoohsar et al., 2016) have analyzed an evacuated tube collector for 130°C compressed air energy storage system in Natal city, Brazil and found that the stratified tank can result in more accurate simulation results. (Kalogirou et al., 1997) have studied the performance of a parabolic trough collector (PTC) for steam generation because of its good efficiency at higher temperatures and found that the collector and thermal losses are higher than the collector output. The available literature did not investigate or compared several collectors, control methods and tank configurations for low temperature steam generation processes.

To overcome the present lack of investigation into solar-driven sterilization systems, this paper provides a comprehensive solar system design comparison that considers the variables that could affect or improve the output of the solar system. In particular, we investigated various solar collector types, control methods, and storage tank configurations, to determine the optimal solar systems for this low-temperature steam application.

2. Method

The annual performance of four different solar collectors was compared using TRNSYS software for a sterilization process that requires steam at 134°C outlet temperature. The collector output was maintained at 180°C to drive a heat recovery steam generator (HRSG). A comparison was done for six different transient load profiles. Two tank configurations were also modelled along with two controller methods. Finally, all (4x6x2x2 = 96) systems were compared for two Australian locations, Sydney and Alice Springs (96x2 = 192).

3. Development of the TRNSYS model

TRNSYS software has several advantages over the simple analysis methods. It has a wide range of pre-defined components or ’types‘ which are flexible and/or easy to modify. The system can also be reconfigured rapidly to suit different assumptions or system requirements.

The process for simulating any system is to construct all the components together and connect them in a way to achieve the desired system, as shown in Figure 1. Outputs are easily plotted in the system‘s information flow diagram. Calculated outputs such as the solar fraction, efficiency, useful energy output can be obtained over a whole year or any specific period.

Each component consists of inputs, outputs and operational parameters. The outputs are calculated based on the mathematical description of each component. After connecting all the components together, the input file is constructed consisting of the weather data, the components used in the system and their information. The solar thermal collector transfers the absorbed energy to the heat transfer fluid. Although there is a small portion of energy loss to the environment via the piping, the rest is transferred to the storage tank. The amount of transferred energy directly depends on the flow rate which is controlled by the solar loop pump. Energy is transferred to the load after passing through the tee piece which mixes the incoming fluid with the low temperature recovered fluid if the temperature is higher than the application required set point temperature. This fluid then passes through the gas-boosted auxiliary heater which adds heat to the fluid if required. Table 1 and Figure 1 summarize the input parameters and information flow used in this study, including locations, annual load profiles, and other system variables.

Table 1. System studied locations and variables

	Annual load	Tank type		Control strategy	
Sydney 33.8^0	1668 GJ, for the 6 load distributions (shown in Figure 3)	Stratified tank	mixed tank	on/off controller	Iterative Controller
Alice Springs 23.7^0	1668 GJ, for the 6 load distributions (shown in Figure 3)	Stratified tank	mixed tank	on/off controller	Iterative Controller

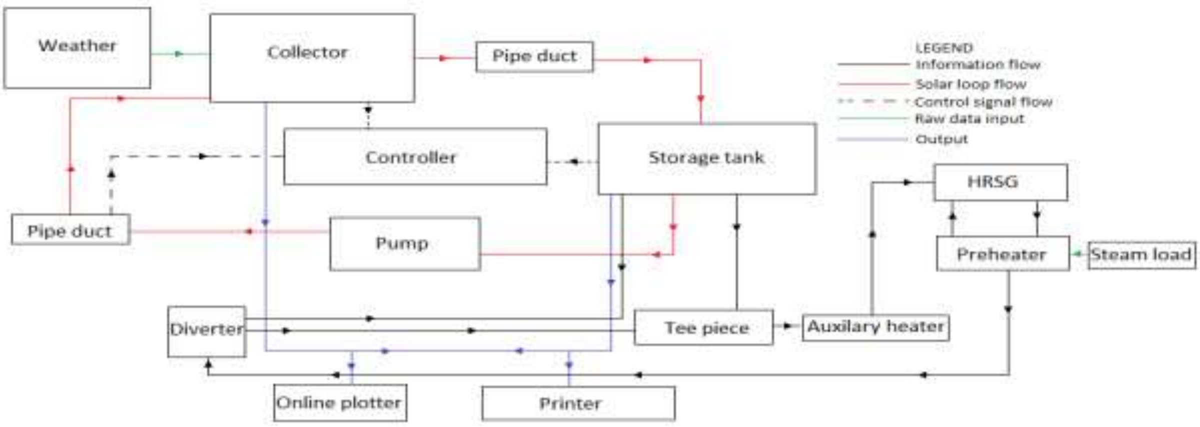

Figure 1. TRNSYS flow diagram for solar sterilization process

3.1. System Analysis

The sterilization process requires 134°C saturated steam at the outlet of the HRSG and the required enthalpy is 2,745 kJ/kg. The HRSG receives solar-heated oil at 180°C, and if the oil temperature was less, it is preheated to achieve the desired temperature by the gas boosted auxiliary heater. To evaluate the performance of each system, the annual solar fraction was evaluated.

$$Fsol = \frac{Q_{Load}-Q_{aux}}{Q_{Load}} \quad \textbf{(Kalogirou, 2002b)}$$

Total load of 1668GJ was given from the real load requirements and was adopted for the other assumed load profile cases.

3.2. System validation

In practical systems or even in the theoretical models it is impossible to get a perfect system. Therefore, a tolerance of 2% was allowed. The system was validated against its energy balance, for each component the energy should balance and the whole system should also achieve a < 2% tolerance in its energy balance. Figure 2 presents the system gains, losses and the tolerance. It is clear that the tolerance is less than 1% in all months which means that it is a good model.

There are only moderate differences in the auxiliary heater on/off cycling between the assumed load cases. It is assumed that there are no losses from the auxiliary heater because the relative differences resulting from heat loss due to cycling can be neglected.

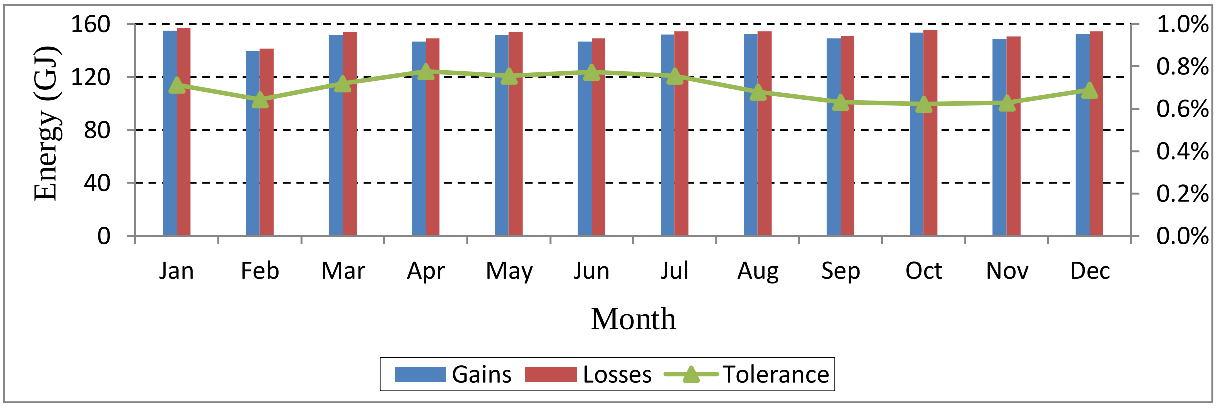

Figure 2. System energy balance results

4. Systems comparison conditions

To analyze the solar system of Figure 1, it is necessary to maintain the same total load in all cases. However, the timing of the load is expected to vary depending on the production schedule for different factories. Figure 3 shows the weekly load variations assumed in this study.

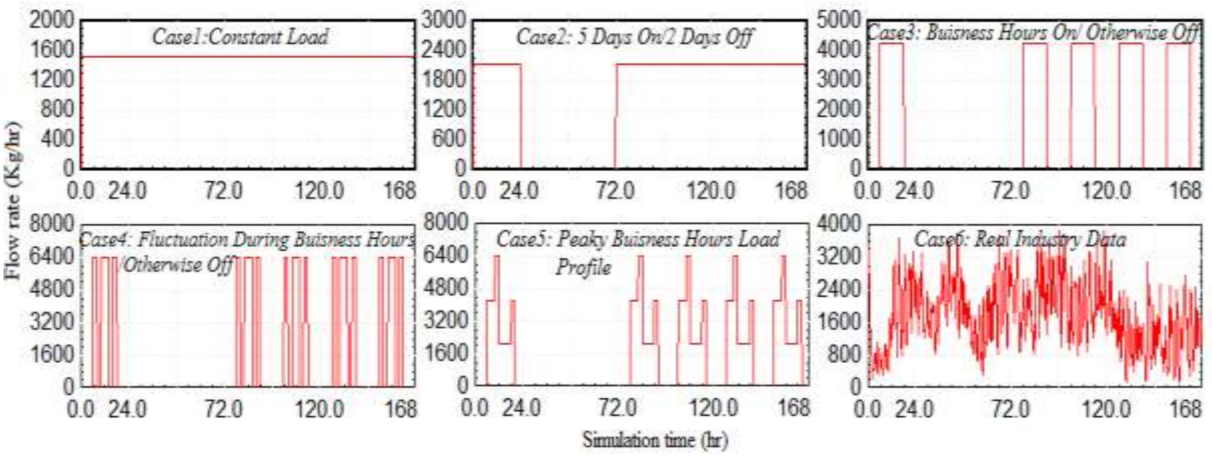

Figure 3. Load profiles weekly distribution for the same annual load consumption

The weekly consumption was assumed to be 12 tonnes (624 tonnes of steam per year) which are equivalent to 1668 GJ/year (463.3 MWh/year).

4.1. Solar thermal collectors

Four different collectors were used in this study. A UNSW-developed solar thermal collector, the Micro Urban Solar Integrated Concentrator (MUSIC) (Li et al., 2014), an Apricus evacuated tube collector ETC-30 (Apricus solar Ltd, 2015), a NEP polytrough 1800 parabolic trough collector (PTC) (Institute for Solar Technology, 2012), and an evacuated flat plate collector – the TVP MT v3.11 (TVP solar, 2013). The efficiency curve constants for each of these collectors are given in Table 2.

Table 2. Studied collectors specifications

	F´$\tau\alpha$ product	c1 (W/m^{2}K)	c2 (W/m^{2}K^2)	c5 (kJ/m^{2}K)	IAM	Stagnate temp(°C)
TVP	0.759	0.508	0.007	------------	Manf-specif **	~320
PTC	0.689	0.36	0.0011	7.80	Manf-specif **	~600
ETC	0.687	1.505	0.011	------------	Manf-specif **	~230
MUSIC	0.8	0.639	0.004	7.80	Exp-test*	~400

*Non-published experimental data, test ** Manufacturer specification. Where c1- c6 are the collector efficiency coefficients. Note that c3,c4 and c6 are zeros for all the collectors.

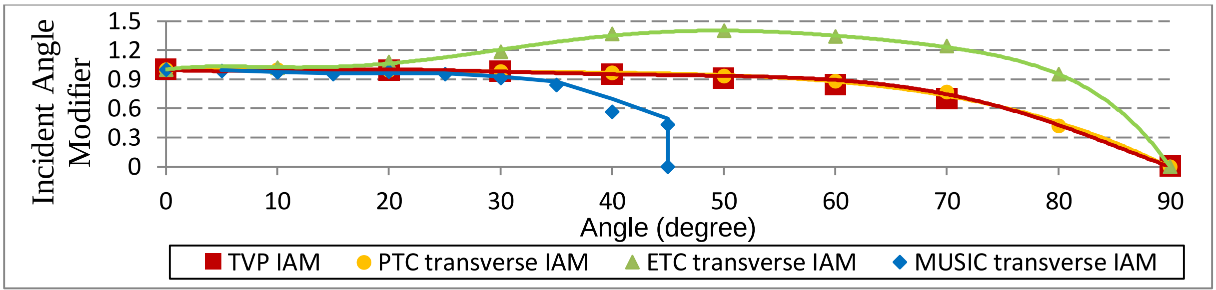

Figure 4. Various collectors transverse IAM with the TVP IAM

Figure 4 shows the incident angle modifier (IAM) for the proposed collectors. The TVP collector has a 1st order incident angle modifier while the other collectors have biaxial incident angle modifiers. Hence, the TVP IAM was plotted with the transverse component for the other collectors. The graph shows how the optical efficiency changes with incident angle variation and how the diffuse component increases the ETC IAM above 1. Figure 5 shows how these performance curves translate into an *annual* efficiency as a function of the output temperature in Sydney. The TVP and ETC Collectors benefit from being able to utilize the diffuse portion of the spectrum (~20-30% of the annual solar resource, even for a relatively clear location). It should also be noted that although the PTC has a relatively low instantaneous efficiency, its rotational tracking gives it good *annual* efficiency as compared to collectors with no external tracking. Overall, the vacuum packaged flat plate collector is expected to have the best annual performance for the temperature range of interest.

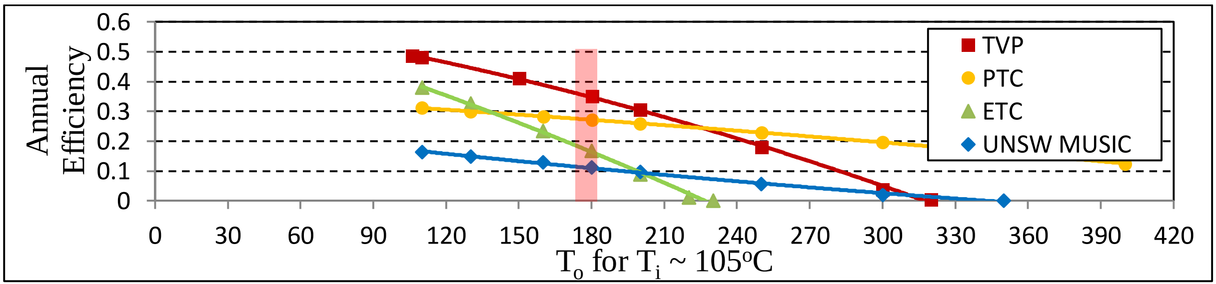

Figure 5. Annual collector efficiency comparison in Sydney

4.2. Solar loop control

A pump is used to control the fluid flow between the collector and the tank. It is clear that there is an optimum flow rate depending on the solar resource and demand profile which achieves the highest energy transfer from the collector with minimal energy loss (Prasanna et al., 2011).

4.2.1. On/ Off controller

One of the possible controllers in the solar loop is the on/off controller. It can be set to be 'on' when the difference between the outlet and the inlet temperature becomes higher than 10°C and 'off' when the difference between the outlet and the inlet temperature becomes less than 2°C (the solar ouput has been maximized using these settings). Thus, with this strategy, the collector operates whenever useful heat is delivered above the inlet temperature until the collector reaches its stagnation temperature. Since the tank desired temperature can float to be as high as possible using this control strategy, the tank output can exceed the desired temperature and then it will be mixed with the diverter makeup fluid to be reduced to 180°C at the outlet to meet the desired HRSG inlet temperature.

4.2.2. Iterative Controller

Unlike the on/off controller, an iterative controller uses a variable speed pump flow rate to seamlessly achieve the best flow rate between zero and it's maximum to get the desired outlet temperature of 180°C by sending a proportional signal. In this type of system design, the pump rating is not as critical, but it must be set to a reasonably high value to ensure good system performance.

4.3. Optimum tank size

System performance was studied for a thermal collector array area of 250 m^2. The system must be designed such that the pump rate flow rate and tank volume optimize the system performance. In this analysis, the tank volume was simply varied until the optimum solar fraction was reached and then the pump flow rate was modified to reach the optimum point. Iteration between the tank size and the pump flow rate should yield the best combination of the system performance.

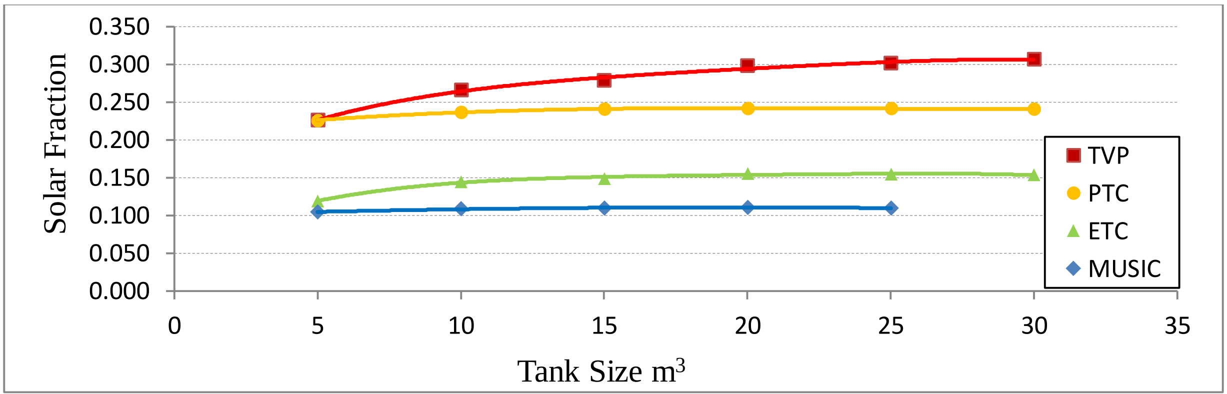

Figure 6. Collector tank size with solar fraction variation using iterative controller

Figure 6 shows that all the collectors have a good performance at 20 m^3 tank size using the iterative controller, and hence further simulations were done using 20 m^3 tank. A summary of the systems used in the next section is shown in Table 3 and Table 4.

Table 3. Control method-Collector area-tank volume combination

	on/off Controller	Iterative Controller
Pump flow rate (kg/hr)	2000	Any high reasonable flow (i.e 20000 kg/hr)
Tank size	15 m^3	20 m^3
Collector area	250 m^2	250 m^2

Table 4. Collectors mounting angles and direction

	Mounting angle	Direction
Sydney	33°	facing north
Alice Springs	23°	facing north

5. Results and discussion

The results are divided into three sections. The performance of the system in Sydney, the performance of the system in Alice Springs, and a collector area optimization for a specific system configuration. These results reveal better performance in Alice Springs as expected and that a stratified tank with an on/off controller result in the best solar system output. The heat transfer fluid in the on/off controller operates at variable temperatures however the iterative controller changes the fluid flow rate to reach 180°C and thus the on/off controller give better performance than the iterative controller.

5.1. Sydney weather

Table 5 shows the solar fraction for four collector types and various load profiles operation in Sydney. Each cell consists of the solar fraction for the on/off and iterative controllers respectively.

Table 5. Sydney-on/off / iterative controller solar fraction with stratified and totally mixed tanks

	Stratified Tank				**Totally mixed tank**			
Collector Type →: *Load Type* ↓	UNSW - MUSIC	ETC	PTC	TVP	UNS WMU SIC	ETC	PTC	TVP
Load case1	0.131/ 0.110	0.218/ 0.156	0.263/ 0.242	**0.352/ 0.298**	0.115/ 0.102	0.180/ 0.135	0.232/ 0.229	**0.279/ 0.286**
Load case2	0.129/ 0.109	0.225/ 0.147	0.253/ 0.236	**0.326/ 0.286**	0.113/ 0.101	0.173/ 0.131	0.226/ 0.225	**0.266/ 0.276**
Load case3	0.128/ 0.110	0.224/ 0.147	0.254/ 0.238	**0.326/ 0.286**	0.115/ 0.102	0.178/ 0.133	0.230/ 0.227	**0.273/ 0.279**
Load case4	0.128/ 0.108	0.224/ 0.147	0.253/ 0.238	**0.326/ 0.287**	0.115/ 0.102	0.178/ 0.134	0.229/ 0.228	**0.273/ 0.278**
Load case5	0.128/ 0.109	0.223/ 0.145	0.253/ 0.238	**0.325/ 0.287**	0.113/ 0.101	0.176/ 0.133	0.227/ 0.225	**0.269/ 0.278**
Load case6	0.129/ 0.110	0.233/ 0.152	0.257/ 0.239	**0.334/ 0.292**	0.115/ 0.102	0.178/ 0.134	0.229/ 0.227	**0.270/ 0.280**
Average	0.129/ 0.109	0.225/ 0.149	0.256/ 0.239	**0.330/ 0.289**	0.114/ 0.101	0.177/ 0.133	0.229/ 0.227	**0.272/ 0.279**
Standerd deviation	0.0012/ 0.001	0.005/ 0.004	0.004/ 0.002	0.01/ 0.005	0.001/ 0.001	0.002/ 0.001	0.002/ 0.002	0.005/ 0.003

The TVP collector has the highest average solar fraction between the proposed load profiles, however, the MUSIC collector has the lowest deviation among the different profiles. It is also clear that the average output is higher when using the stratified tank.

The on/off controller results in a higher output for each of the collectors and both tank configurations. However, the iterative controller provided precise control at the specified temperature (180°C). Although the load distribution has a negligible effect on the system performance, it has a significant effect on the system if the load is low and requires a low flow rate. It is also apparent that the TVP has the best output for all cases. Based on these results it is recommended that the on/ off controller be selected for this application since it maintains higher temperatures in the tank.

5.2. Alice Springs weather

Table 6 shows the solar fraction for four collector types and various load profiles operation in Alice Springs. Each cell consists of the solar fraction for the on/off and iterative controllers respectively.

The PTC shows better performance than the TVP collector in Alice Springs using the on/off controller-mixed tank case configuration where the radiation beam component is higher and the TVP waste some energy by heating the mixed tank fluid content.

Table 6: Alice Springs- on/off / iterative controller solar fraction with stratified and totally mixed tanks

	Stratified Tank				**Totally mixed tank**			
Collector Type →: *Load Type* ↓	UNSW-MUSIC	ETC	PTC	TVP	UNSW-MUSIC	ETC	PTC	TVP
Load case1	0.256/ 0.231	0.406/ 0.353	0.473/ 0.454	**0.530/ 0.496**	0.216/ 0.214	0.293/ 0.300	**0.413/** 0.427	0.414/ **0.474**
Load case2	0.245/ 0.225	0.362/ 0.325	0.447/ 0.436	**0.482/ 0.471**	0.208/ 0.210	0.275/ 0.286	**0.397/** 0.413	0.388/ **0.447**
Load case3	0.245/ 0.228	0.362/ 0.327	0.450/ 0.439	**0.484/ 0.478**	0.212/ 0.212	0.284/ 0.289	**0.404/** 0.418	0.398/ **0.453**
Load case4	0.245/ 0.228	0.362/ 0.326	0.449/ 0.440	**0.482/ 0.477**	0.209/ 0.211	0.284/ 0.292	**0.403/** 0.419	0.396/ **0.453**
Load case5	0.245/ 0.225	0.361/ 0.326	0.449/ 0.439	**0.482/ 0.477**	0.208/ 0.210	0.279/ 0.288	**0.398/** 0.414	0.391/ **0.449**
Load case6	0.246/ 0.226	0.375/ 0.332	0.446/ 0.432	**0.487/ 0.468**	0.210/ 0.211	0.279/ 0.289	**0.396/** 0.411	0.391/ **0.447**
Average	0.247/ 0.227	0.371/ 0.332	0.452/ 0.440	**0.491/ 0.478**	0.211/ 0.211	0.282/ 0.291	**0.402/** 0.417	0.396/ **0.454**
Standerd deviation	0.004/ 0.002	0.018/ 0.011	0.010/ 0.006	0.019/ 0.010	0.003/ 0.002	0.006/ 0.005	0.006/ 0.006	0.009/ 0.010

If the application requires a specific outlet temperature of 180°C, the iterative controller works best with the TVP collector relative to the PTC collector since it achieves higher average solar fractions. Additionally, the PTC has a lower deviation from the average for each of the proposed load profiles.

Figure 5 and Table 5 - Table 6 corroborate the fact that of the collectors studied for this application, a vacuum packaged flat plate collector has the best annual performance (efficiency and solar fraction).

5.2.1. Economic analysis

Economic analysis reveals that the system must be carefully designed in order to have any chance at achieving an economic payback (without subsidies). To justify the impact of system design on the payback time, the TVP system in Alice Springs is considered as an example.

The TVP collector price is AUD 547/m^2. Total system cost was assumed to be 1.5 of the solar collector array capital cost. Gas price in Australia was assumed to be 19 AUD/GJ based on (Shirazi et al., 2016), however, since the gas price is not stable, a parametric study analysis can be conducted.

Table 7. Simple payback time analysis for the TVP collector in Sydney and Alice Springs

Controller	Tank type	SF_SYD	PPT_SYD (years)	SF_AS	PPT_AS (years)
on/ off	Stratified	0.352	18.43	0.530	12.24
Iterative	Stratified	0.298	21.77	0.496	13.08
Iterative	Mixed	0.286	22.69	0.474	13.69
on/ off	Mixed	0.279	23.26	0.414	15.67

Table 7 shows that the controller - tank combinations can result in a >3 years variation in the payback time.

6. Collector area optimization

A collector area analysis was also conducted to determine how this would affect the system performance. It was found that the collectors might overtake one another regarding the solar fraction as the total collector area changes. Figure 7 shows that the ETC collector has equal or better performance than the PTC array at an area of below 500 m^2. The PTC collector, on the other hand, has equal or better performance than the TVP collector for an array size greater than 2,000 m^2. As the array area increases and the tank size is fixed, the tank frequently becomes fully charged in the summer months for both the ETC and the TVP collectors. In this case, temperatures operate close to their stagnation temperature and even reach the stagnation temperature many times in the summer for high aperture area. However, the PTC has a very high stagnation temperature compared to the others, enabling it to maintain better performance for a large collector area.

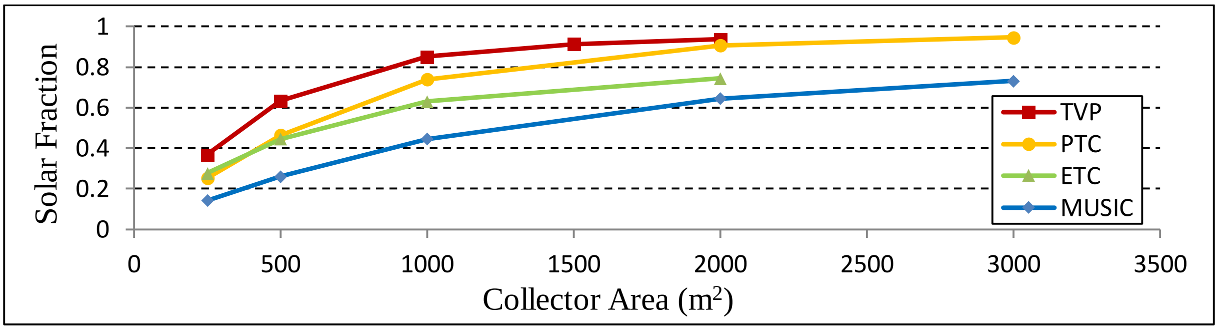

Figure 7: Solar fraction variation with collector area using on/off controller at 10,000 Kg/hr rated flow rate and 50 m^3 tank volume

The previous optimization just focused on minimizing the auxiliary heater usage, but this is not the whole story as it neglects the detailed economics of these choices. There are many other factors that affect the system feasibility, such as the life cycle savings (LCS) and the payback time (PBT). Collector area can be optimized to get the highest solar fraction. However, this may decrease the system LCS and increase the PBT, making the system non-viable economically. Further work is required to optimize the system and analyze these aspects. On technical performance and capital cost alone, the TVP system with the simple on/off controller is recommended.

7. Conclusion

Overall, the findings of this study imply that the load profile does not have a significant effect on the collector performance if the annual demand is much larger (> 3X) than the collector's supply. Since the TVP collector has the highest *annual* efficiency at 180°C, it out-performs the other collector technologies. Additionally, a stratified tank was found to perform better than the mixed tank due to better usage of high-temperature oil, rather than destroying the available energy via mixing. A simple on/off control mechanism also provides a better annual performance than a variable flow rate. Ultimately, these findings indicate that solar thermal systems must be carefully designed to achieve feasiblity.

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