HIGH-EFFICIENCY RESIDENTIAL SOLAR POOL HEATING SYSTEMS

Jianzhou Zhao, Jose I. Bilbao and Alistair B. Sproul

School of Photovoltaic and Renewable Energy Engineering, UNSW, Sydney (Australia)

Abstract

This paper investigates the operation of a typical residential solar pool heating system under an optimal, low flow scenario. A high-efficiency pump was retrofitted to an existing residential solar pool heating system (with a pool area of 48 m^2 and a solar collector area of 30 m^2). The system originally used a single-speed pump (Business as Usual scenario) with a mass flow rate of 0.07 $kg\ s^{-1}\ m^{-2}$ as recommended by the Australian Standard AS 3634. For the low flow scenario (0.016 $kg\ s^{-1}\ m^{-2}$) a longer operation time (one hour/day on average) or for a new system, a larger collector area (+17%) is required to achieve an equivalent pool thermal performance to the BAU system. However, under the low flow scenario, retrofit scenario, a reduction in pump energy of 75% was achieved, together with a four-times increase in the system coefficient of performance (COP), reaching a value of 64. This high-efficiency solar pool heating pump retrofit can achieve a payback time of 2.4 years if the single-speed pump is replaced at the end of its life.

Keywords: solar pool heating; pump sizing; high-efficiency hydraulic systems

1. Introduction

The match between the heat demand and the availability of solar energy makes solar heating systems a perfect option for outdoor swimming pools (IEA, 2012; Ramos et al., 2017). Currently, swimming pool heating represents the world's second most widely used application of solar heating systems (Wang and Ge, 2016) and it is mainly achieved using unglazed solar collectors.

Australia and the USA are the two biggest residential swimming pool markets in the world (Weiss and Spörk-Dür, 2018). While the USA has more residential pools (~10 million) (APSP, 2013), Australia holds the highest per capita ownership of residential pools (McIntyre, 2014). In both counties, around one-third of the residential swimming pools are heated (Wilkenfeld, 2009; EIA, 2013; Woolcott Research and Engagement, 2016). As for swimming pool filtering, pool heating is also an energy-intensive activity. The total energy consumption for heating all residential swimming pools in Australia (including solar, heat pump and gas pool heating) was estimated as 1250 GWh per year (Wilkenfeld, 2009), which corresponds to 1.09 Mt CO_2-e of GHG emissions (DEE, 2018). Solar pool heating is more energy-efficient and environmentally friendly than the other two common options (Ausgrid, 2015); consequently, high-efficiency solar pool heating systems are the focus of this study, in particular, low flow systems using a systemic optimization approach.

The operation of typical residential solar pool heating systems under lower flow conditions was first investigated by Cunio and Sproul (2012). The authors reported that it was feasible to run a solar pool heating system at a low water flow rate (0.02 $kg\ s^{-1}\ m^{-2}$). Although the solar collector's thermal efficiency was reduced by approximately 15%, due to the reduced energy use of the pumping system, the system COP (i.e., energy ratio of the heat output of the solar thermal collector to pump energy) increased significantly. Zhao et al. (2018) validated a residential solar pool heating system model with experimental data, and found that over the whole swimming season, the optimal mass flow rate per unit collector area (from the whole system perspective) was 0.016 $kg\ s^{-1}\ m^{-2}$. For this optimal flow rate, in comparison to the Business as Usual (BAU) scenario (~0.08 $kgs^{-1}m^{-2}$), the pumping energy was reduced by 60% and a COP of 25 was obtained, which was 2.5 times that of the BAU scenario. It is important to note that the multi-speed pump used in Zhao et al. (2018)'s work, was oversized, i.e., the pump generated 2 – 10 m of pressure above the optimal pressure required, than required under the default low, medium and high speeds, which limited the extent of the pump energy savings achieved. As such, this study builds on the previous work and explores the technical opportunities of operating a typical residential solar pool heating system under the optimal, low flow rate using a high-efficiency pump. This was done in order to investigate if greater energy savings and further improvement of the COP could be achieved.

doi:10.18086/swc.2019.09.02 Available at http://proceedings.ises.org

2. Experimental system and high-efficiency pump retrofit

An open loop, residential solar pool heating system located in Sydney, Australia, was selected as the testbed for this study (see Fig. 1). The solar pool heating system is independent of the pool filtering system and has a single-speed water pump which circulates the pool water through a Heliocol HC38 solar thermal collector via 40 mm pressure pipes. The unglazed solar thermal collector is made of UV stabilized polypropylene tubes, which are connected in parallel.

Fig. 1 Overview of the residential solar pool heating system.

The collector is mounted on the roof of the adjacent residence and a vacuum relief valve is located at the highest point of the collector (Fig. 2). The vacuum relief valve opens automatically under negative pressures (when the pump is off) to allow the water in the system to safely drain out. A throttle valve was fitted downstream of the vacuum relief valve and before the pool return (between point 2 and 3 in Fig. 2), which was adjusted to increase the pressure at the location of the vacuum relief valve and keep it closed during the pump operation (Zhao et al., 2018).

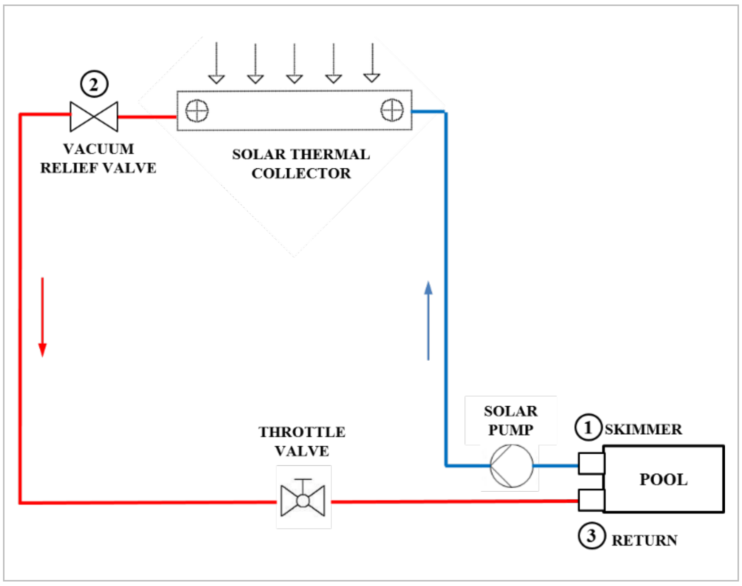

Fig. 2 Schematic layout of the residential solar pool heating system.

A high-efficiency pump retrofit was proposed to replace the existing single-speed solar pool heating pump, which had been operating for around 15 years. The new pump was sized based on the optimal, low flow scenario (i.e. a mass flow of 0.016 kg s^{-1} m^{-2}) along with the parameters of the existing solar pool heating system shown in Table 1. It is important to note, the solar collector to pool surface area ratio (A_c/A_{pool}) is 63%, which is similar to the recommended value by the Australian Standard AS 3634 (2013) for Sydney weather conditions.

Table 1: Parameters of the existing solar pool heating system

Parameters	**Values**
Swimming pool surface area	48 m^2
Swimming pool volume	64 m^3
Solar thermal collector area	30 m^2
Water mass flow rate per unit collector area	0.016 kg s^{-1} m^{-2}
The height of the vacuum relief valve above the pool water level (*H*)	3.5 m
PVC pipe diameter	0.04 m
Length of PVC pipe from the pool to the vacuum relief valve (estimated)	20 m
Estimated number of 90° bends	20
Number of pool skimmers (water inlets to the pump)	1
Surface roughness - PVC pipe (The Engineering ToolBox, 2017)	7.0e-6 m

Under the optimal, low flow scenario, it is important to ensure the vacuum relief valve stays closed (Zhao et al., 2018). The minimum pump pressure required to keep the vacuum relief valve closed at all times is given by Eqn.1 (Zhao et al., 2018):

$$\Delta P_{pump} > \Delta P_{pool\_vac} + \rho_w g H + \frac{1}{2}\rho_w V_{av}^2 \qquad (1)$$

where ΔP_{pump} is the pump pressure, ΔP_{pool_vac} is the pressure loss from the pool skimmer (point 1 in Fig. 2) to the vacuum relief valve (point 2 in Fig. 2), V_{av} is the average velocity of the water in the pipe at the location of the vacuum relief valve, and *H* is the height of the vacuum relief valve above the pool water level. Note that $\Delta P_{pool_vac}$was calculated using the Darcy–Weisbach equation and the pressure loss coefficients for various pipe components (i.e., pipe inlets, bends) (Cengel and Cimbala, 2010).

Fig. 3 presents the calculated pump pressures required for the solar pool heating system to operate properly (i.e., the vacuum relief valve remains closed) for flow rates between zero to the BAU mass flow rate of 0.07 kg s^{-1} m^{-2}. Note that the pump pressure includes a 15% safety margin as suggested by Joey Sarver et al. (2018) and 10 kPa extra pressure to overcome the spring force of the vacuum relief valve as reported by Zhao (2018). With the required pump pressure, an appropriate water pump was sized to meet the pressure and flow requirements while selecting a pump with high efficiency. A three-speed Grundfos water pump (model: UPS 25–80 N 180) was found to be suitable and its pressure and power use at the high speed are shown in Fig. 3. As seen, the pump can generate 6.7 m of pressure at the optimal, low mass flow of 0.016 kg s^{-1} m^{-2}, which is higher than the required pump pressure head (5.6 m) calculated as per Eqn.1. Also note that the pump has a stainless-steel housing, which is corrosion resistant against the chlorinated pool water. Another Grundfos water pump (model: UPML AUTO 15-105 130) also meets the flow rate and pressure requirements and uses less power (102 W). However, it is not an appropriate option since its cast iron housing would be corroded by the pool water over time.

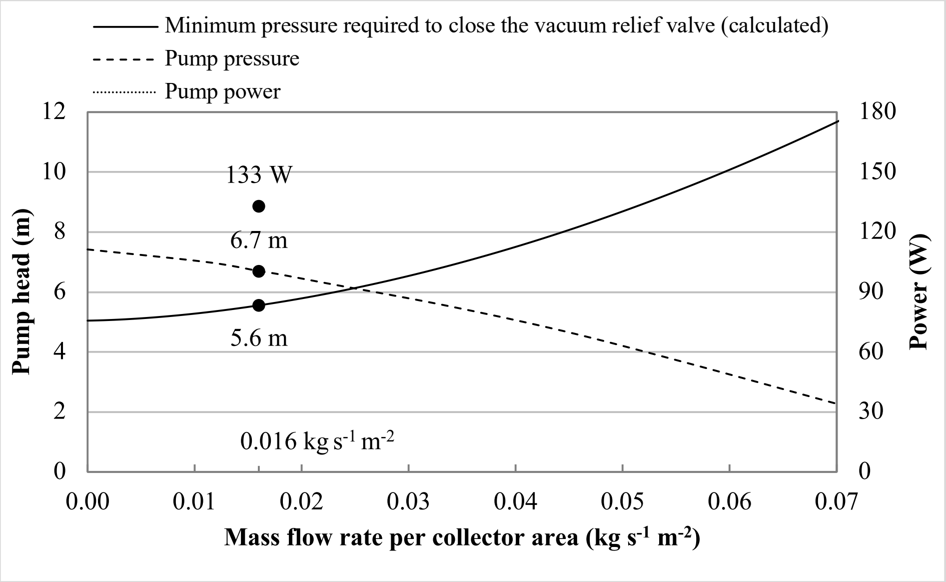

Fig. 3 Minimum pump pressure required (with 15% margin) and characteristics of Grundfos UPS 25-80 N 180 water pump at high speed.

Fig. 4a shows the retrofitted Grundfos UPS 25–80 N 180 pump in the solar pool heating system under test. To assist the start-up/priming of the pump, a small tank was installed prior to the pump inlet as a self-priming reservoir (Mackay, 2004). Fig. 4b shows the throttle valve (PVC ball valve) installed on the vertical pipework downstream from the solar thermal collector, which was partially closed to keep the vacuum relief valve closed.

Fig. 4 a) High-efficiency pump retrofit and b) Throttle valve (partially closed) on the downstream of the solar thermal collector.

3. Operating the system under the optimal, low flow scenario – extending the pump run time

When operating the high-efficiency pump at high speed with the throttle valve fully open, air bubbles were observed in the pool, near the water return from the solar collector (point 3 in Fig. 2). This was an indication that the vacuum relief valve on the top of the solar collector was open due to insufficient pressure produced by the pump. To close the vacuum relief valve and prevent air entering into the pool heating circuit, the throttle valve on the downstream of the solar collector had to be partially closed – about 45 degrees clockwise from the fully open position (see Fig. 4b). The pump power and the water mass flow were measured as 142 W and 0.016 kg s^{-1} m^{-2} respectively.

To compare the system performance under the optimal, low flow scenario (0.016 kg s^{-1} m^{-2}) and the BAU scenario (0.07 kg s^{-1} m^{-2}) over the whole swimming season, TRNSYS simulations were performed using an experimentally validated residential solar pool heating system model (Zhao et al., 2018). The following parameters and assumptions were used in the simulations:

- TMY2 weather data of the Sydney climate was used and the simulation period was the whole swimming season in Sydney (October to March);
- The initial pool water temperature was set as the local mean ambient temperature of September, which was obtained from the Australian Government Bureau of Meteorology (BOM, 2019);
- The solar pool collector was assumed not to be shaded.
- The pool water temperature between 10 am to 7 pm was considered, as this is the period when the pool is most likely to be used (Ruiz and Martínez, 2010);
- The pool water usually has a salt level of 4000 ppm (0.4%) (Khouzam, 2008) and the associated impact on the specific heat of pool water is negligible (Qu, 2016). Therefore, the specific heat of the pool water was assumed as a constant of 4190 J kg^{-1} K^{-1};
- A default pump control strategy (ΔT_H = 8°C; ΔT_L = 4°C) was used (Dontek, 2018), so the pump switches ON when the collector surface temperature is 8°C above the pool water temperature, and the pump switches OFF when the collector surface temperature minus the pool water temperature is below 4°C;
- The daily system COP was calculated as the energy ratio of the average daily heat output of the solar thermal collector delivered to the pool, over the average daily electrical energy used by the pump:

$$COP = \frac{Q_u}{W_{pump}} \tag{2}$$

- The pump power was measured by a Power-Mate power meter (accuracy of ±2.0%) and the water flow rate was measured by a Dynaflox DMTFH ultrasonic flow meter (accuracy of ±1.0%);
- The grid electricity price used was 0.253 AU$/kWh (Energy Australia, 2019) with a 3% increase per year (Kai, 2017). The discount rate assumed was 5% (Drury et al., 2011).

Table 2 presents the simulation results of operating the residential solar pool heating system under the optimal and BAU flow rate scenarios over the whole swimming season in Sydney, Australia. For the optimal, low flow scenario, the average daily pumping energy over the whole swimming season is 0.7 kWh/day (with annual costs of AU$32). This represents more than a 75% reduction in comparison to the BAU scenario. On the other hand, both scenarios deliver a similar amount of heat to the pool, so the significant pumping energy reduction under the optimal, low flow scenario leads to a noticeable increase of the COP to 64. This result is more than four times higher than the BAU scenario. In addition, this present result is a further improvement on the COP of 25 reported previously which utilized a multi-speed pump (Zhao et al., 2018).

Table 2: Simulation results of operating the solar pool heating system under the BAU and optimal flow rate scenarios over the whole swimming season in Sydney, Australia (default pump control strategy of ΔT_H = 8°C; ΔT_L = 4°C).

Operating scenario	Mass flow rate (kg $s^{-1}m^{-2}$)	Pump power (kW)	Avg pump run time (hr/day)	Avg pump energy (kWh/day)	Avg collector heat output to the pool (kWh/day)	COP	Annual costs	Swimming period (days)
BAU flow	0.070	0.795	3.7	3.0	46	15	AU$137	105
Optimal flow	0.016	0.142	4.8	0.7	45	64	AU$32	104

Based on a fixed electricity tariff (Energy Australia, 2019), the annual cost savings obtained under the optimal, low flow scenario is AU$105 per year. The Grundfos UPS 25–80 N 180 water pump costs around AU$650 to install and thus the discounted payback period for this high-efficiency solar pool heating system retrofit is approximately 6.7 years. This is similar to the average life expectancy of a typical pool pump (7 years) as reported by DEE (2016) but Grundfos (2019) suggested their pump would last for around 10 to 20 years. If the high-efficiency pump was purchased as a replacement of an existing single-speed pump at the end of its life (e.g. Davey Whisper 750 pump costs around $AU400), then the simple payback period would be only 2.4 years. This is less than the average pool pump lifetime, making it an ideal energy-saving option for pool owners.

Furthermore, it is worth investigating the thermal performance of the open-air swimming pool under the two operating scenarios. The pool thermal performance was evaluated using the swimming period, which represents the total number of days with the average water temperature of the pool stays above a certain temperature. In this study, the minimum acceptable pool water temperature was chosen as 26°C (Higgs, 1984; Dongellini et al., 2015). Operating a solar pool heating system at a lower mass flow rate, reduces the thermal efficiency of the solar collector (13% absolute efficiency drop from the BAU to the optimal flow scenario), so a longer run time is needed to achieve a similar pool thermal performance. For the system under investigation, the average daily run time for the optimal, low flow scenario is around one hour per day longer than the BAU scenario over the whole swimming season (see Table 2). This provides a similar amount of heat delivered to the pool (on average 45 kWh/day) as the BAU scenario (on average 46 kWh/day) and a similar swimming period (104 days) in comparison to BAU scenario (105 days).

4. Operating the system under the optimal, low flow scenario – increasing the collector area

Running the solar pool heating system for longer hours is an option for existing solar pool heating systems. However, for new systems, pool owners will have the option to install a larger collector. As such, this study also investigates the option of increasing the area of the solar thermal collector to overcome the lower thermal performance under low flow conditions.

To simulate the same run time for both scenarios, an adjusted control strategy was also investiagted. As reported by Bilbao (2012), the pump control strategy with a smaller 'switch off' band (ΔT_L = 0.5°C) ran the pump for about the same period at both the low and high mass flow rates, and a similar thermal yield was obtained. Therefore, the adjusted pump control strategy adopted for this simulation consists of a 'switch off' band (ΔT_L) of 0.5°C. The 'switch on' band (ΔT_H) remained the same as the default value of 8°C recommended by the manufacturer of the solar pump controller (Dontek, 2018). Hence, the pump will switch ON when the collector surface temperature is more than 8°C above the pool water temperature and switch OFF when the collector surface temperature minus the pool water temperature, is lower than 0.5°C , as opposed to the 4°C used in the previous simulation. Simulation results are presented in Table 3 for a solar collector with an area of 30 m^2 for both scenarios.

Table 3. Simulation results of operating the solar pool heating system under the BAU and optimal flow scenarios over the whole swimming season in Sydney, Australia (adjusted pump control strategy of ΔT_H = 8°C; ΔT_L = 0.5°C) for the same collector area of 30 m^2.

Operating scenario	Mass flow rate (kg s^{-1}m^{-2})	Pump power (kW)	Avg pump run time (hr/day)	Avg pump energy (kWh/day)	Avg collector heat output to the pool (kWh/day)	COP	Annual costs	Swimming period (days)
BAU flow	0.070	0.795	6.3	5.0	66	13	AU$231	135
Optimal flow	0.016	0.142	6.6	0.9	52	55	AU$43	119

As seen in Table 3, because of the smaller ‘switch off’ band, the adjusted control strategy runs the solar heating pump longer, delivering more heat to the swimming pool in comparison to the default pump control strategy. Thus, longer swimming periods were achieved by the solar pool heating system. However, the adjusted control extends the pump running period towards the late afternoon, when weather conditions like solar irradiance and ambient temperature are likely to decrease, resulting in the solar thermal collector working less efficiently than the default control operated system. According to Table 2 and Table 3, for the optimal, low flow scenario, the pump with the adjusted control strategy consumes about 30% more electricity than that with the default control (0.9 versus 0.7 kWh/day), but it only delivers 15% extra heat to the swimming pool (52 versus 45 kWh/day) and thus, the COP decreases from 64 to 55.

Furthermore, with the adjusted pump control strategy applied, the optimal, low flow scenario runs for a similar period of time as the BAU scenario; and given that the thermal efficiency of the solar pool collector is 13% (absolute) less than the BAU (0.07 kg s^{-1} m^{-2}), the optimal, low flow scenario, therefore, delivered less heat to the pool (52 kWh/day vs 66 kWh/day). Consequently, despite the excellent pumping energy reduction of 80%, the associated swimming period of the optimal, low flow scenario falls 16 days short of the BAU scenario over the whole swimming season, indicating a compromised pool thermal comfort for the users.

As the pool thermal performance is reduced under the optimal, low flow scenario without extending the pump run time, further investigations were made looking at increasing the collector area of such a high-efficiency solar pool heating system. This has the potential to compensate for the heat loss and aims to achieve a similar pool thermal performance as the BAU scenario. In an additional simulation, the ratio of the collector area to the pool surface area (A_c/A_{pool}) was varied from the original value of 63% to the value of 100% (collector area equal to the pool surface area) in steps of 1%. The system was set to operate at the optimal, low flow scenario (0.016 kg s^{-1} m^{-2}) using the adjusted pump control strategy. All the other system parameters remained the same.

Fig. 5 shows the modelled pool thermal performance, characterized by the swimming periods for various collector to pool area ratios (A_c/A_{pool}) over the swimming season. It can be seen that the average daily pump run time decreases gradually as the collector area increases, as the same amount of thermal energy can be delivered by the solar thermal collector in less time.

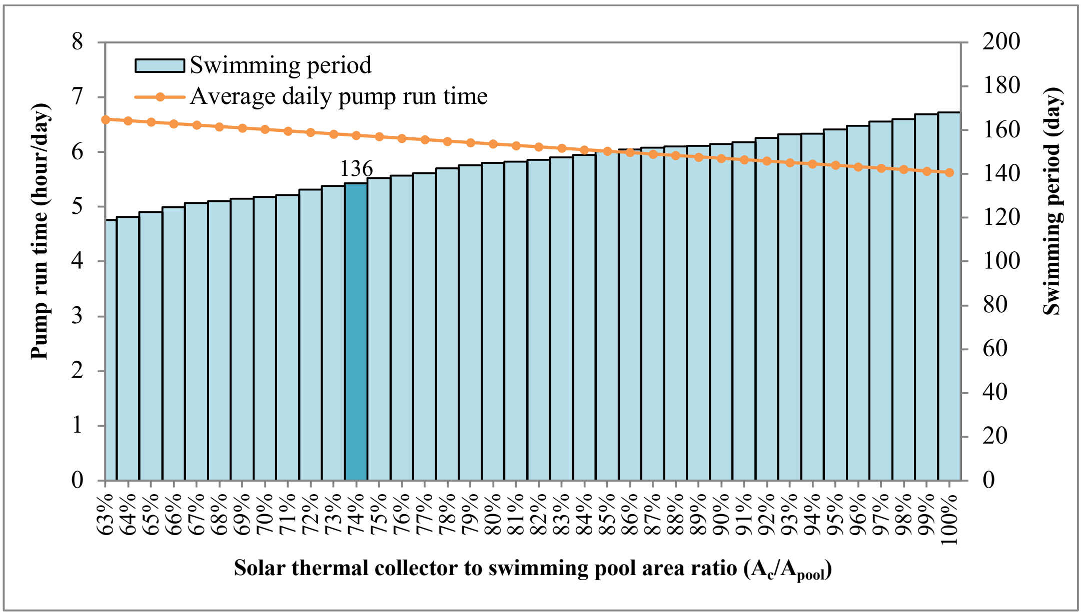

Fig. 5 Swimming period and average daily pump run time for the solar pool heating system operating under the optimal low flow scenario (0.016 kg s^{-1} m^{-2}) over the whole swimming season in Sydney, Australia (adjusted pump control strategy of ΔT_H = 8°C; ΔT_L = 0.5°C) for a range of collector areas.

Note from Fig. 5, that at a collector to pool area ratio (A_c/A_{pool}) of 74%, the pool thermal performance matches the BAU scenario (see Table 3), with a similar swimming period of 136 days over the whole swimming season. This implies that for the same pump run time (6.3 hours/day) as the BAU scenario, increasing the solar collector area by 17% from the original case (A_c/A_{pool} of 63%), can compensate for the lower thermal energy produced when operating the solar pool heating system under low flow conditions.

Since the average pump run time decreases marginally when A_c/A_{pool} increases from 63% to 74%, the pump energy consumption remains at 80% lower than the BAU scenario. Assuming the solar collector costs $130 per square meter including installation costs (Heliocol, 2017), the extra expense for the larger solar collector is around AU$680. Taking into account the additional cost of a high-efficiency pump over a regular single-speed pump, the new high-efficiency system (with a larger collector area) has a payback time of 5.3 years, assuming the same flat rate electricity tariff of $0.253/kWh This is still less than the average life expectancy of typical pool pumps (7 years) (DEE, 2016) and less than the typical lifetime of solar thermal systems (20 years) (Kalogirou and Tripanagnostopoulos, 2006).

5. Conclusions

This study investigated the operation of a typical residential solar pool heating system under an optimal, low flow scenario (mass flow rate of 0.016 kg s^{-1} m^{-2}), using a high-efficiency water pump. Based on the work published by Zhao et al. (2018), a three-speed Grundfos UPS 25–80 N 180 water pump was chosen and retrofitted to the existing solar pool heating system. With the throttle valve (downstream from the solar thermal collector) partially closed, the pump was able to operate under the optimal, low flow conditions using only 142 W of pump power.

According to the simulation over the whole swimming season in Sydney, Australia, the optimal, low flow scenario operated one hour longer per day than the BAU scenario (mass flow rate of 0.07 kg s^{-1} m^{-2}) so as to compensate for the lower thermal performance due to the lower flow rate. Both scenarios achieved a similar swimming period of around 105 days over the swimming season. Despite the longer run time, the low flow scenario achieved significant pump energy savings of 75%, whilst the COP increased about four times from 15 to 64 when compared to the BAU scenario. If such a high-efficiency pump is retrofitted to replace the existing (conventional) pump at its end of life, or alternatively when installed in new systems, then it would take 2.4 years to pay pack the additional cost of the high-efficiency pump.

Without extending the pump run time, it is also feasible to recover the reduced heat output under the optimal, low flow scenario by increasing the solar thermal collector area (e.g. for new systems). The long-term simulation showed that with a 17% increase in the collector area (an A_c/A_{pool} of 63%), the optimal scenario achieved almost the same pump run time and heat output as the BAU scenario, providing the same pool thermal performance (i.e., swimming period) over the whole swimming season. In this case, around 80% of the pump energy was saved and it would take around 5.3 years to pay back the additional costs for the larger collector and the high-efficiency pump. Note that the energy saving could be futher improved if a water pump with a higher pump/motor efficiency was developed (the selected pump has a pump/motor efficiency of 26%). Therefore, it is useful in future study to investigate the technical opportunities for designing a high efficiency as well as a cost-effective pump solution.

The high-efficiency solar pool heating system investigated in this study presents significant potential energy savings and GHG reductions in countries with high swimming pool density (e.g., Australia and the USA). Assuming all residential solar pool heating systems in Australia were retrofitted with the high-efficiency pumps and achieve a 75% reduction of the solar pool heating pump energy use reported by Ausgrid (2015), then approximately 300 GWh of electricity could be saved per year. This accounts for 24% of the total pool heating energy in the Australian residential sector and corresponds to around 0.3 Mt CO_2-e of GHG emissions.

6. Acknowledgements

This research is funded by the CRC for Low Carbon Living Ltd supported by the Cooperative Research Centre program, an Australian Government initiative. The authors would like to thank Mr Brian Copeland for providing his swimming pool as the test site for this study.

7. References

APSP, 2013. U.S. Swimming Pool and Hot Tub Market 2013. Association of Pool and Spa Professionals (APSP). Available: http://apsp.org/resources/research/industry-statistics.aspx, [Accessed February 3rd 2019].

Ausgrid, 2015. Pool & Spa Guide - Swimming pool efficiency. Available: https://www.ausgrid.com.au/-/media/Files/Customer-Services/Homes/Energy-Efficiency/Ausgrid-Swimming-Pool-brochure-2015.pdf, [Accessed January 29th 2018].

Bilbao, J. I. 2012. Photovoltaic thermal water Systems - modelling and design considerations for residential applications in different climates and demand conditions. Ph.D. Thesis, University of New South Wales.

BOM, 2019. Terrey Hills, New South Wales - Daily Weather Observations. Available: http://www.bom.gov.au/climate/dwo/IDCJDW2154.latest.shtml, [Accessed June 15th 2019].

Cengel, Y. A., Cimbala, J. M., 2010. Fluid mechanics: fundamentals and applications, Boston, McGraw-Hill Higher Education.

DEE, 2016. Consultation Regulation Impact Statement - Swimming Pool Pumps. Proposed Energy Labelling and Minimum Energy Performance Standards. Department of the Environment and Energy, Commonwealth of Australia.

DEE, 2018. National Greenhouse Accounts Factors. Department of the Environment and Energy, Commonwealth of Australia.

Dongellini, M., Falcioni, S., Martelli, A., Morini, G. L., 2015. Dynamic simulation of outdoor swimming pool solar heating. Energy Procedia, 81, *1-10.*

Dontek, 2018. Aquasun 3 Instruction Manual. Dontek Electronics Pty Ltd, 19 Melrich Road Bayswater, VIC 3153, Australia. Available: http://dontek.com.au/wp-content/uploads/2014/10/Aquasun-3-Instruction_rAD.pdf, [Accessed April 12th 2018].

Drury, E., Denholm, P., Margolis, R., 2011. Impact of Different Economic Performance Metrics on the Perceived Value of Solar Photovoltaics. National Renewable Energy Laboratory (NREL), Golden, CO.

EIA, 2013. Residential Energy Consumption Survey (RECS) data. April 2013 ed. U.S. Energy Information Administration (EIA), 1000 Independence Ave., SW, Washington, DC 20585.

Energy Australia, 2019. EnergyAustralia - Residential Electricity Plan. Available: https://www.energymadeeasy.gov.au/offer/902165?utm_source=EnergyAustralia&utm_campaign=bpi-retailer&utm_medium=retailer&postcode=2088, [Accessed July 10th 2019].

Grundfos, 2019. Life cycle cost equation for pumping systems. GRUNDFOS, Poul Due Jensens Vej 7, DK-8850 Bjerringbro, Denmark. Available: https://www.grundfos.com/service-support/encyclopedia-search/life-cycle-cost-equationforpumpingsystems.html, [Accessed July 11th 2019].

Higgs, J., 1984. The Solar Heating of Public and Institutional Pools. Victorian Solar Energy Council, March 1984.

IEA, 2012. Technology Roadmap: Solar Heating and Cooling. International Energy Agency (IEA), 31-35 rue de la Fédération, 75739 Paris Cedex 15, France.

Joey Sarver, Blake Finkenauer, Y.A. Liu, 2018. Pump Sizing and Selection Made Easy. Virginia Tech University. Available: https://www.chemengonline.com/pump-sizing-selection-made-easy/?pagenum=1, [Accessed February 18th 2019].

Kai, S., 2017. Energy prices—the story behind rising costs. Parliament of Australia. Available: http://www.aph.gov.au/About_Parliament/Parliamentary_Departments/Parliamentary_Library/pub *s/BriefingBook44p/EnergyPrices, [Accessed September 28th 2017].*

Kalogirou, S. A., Tripanagnostopoulos, Y., 2006. Hybrid PV/T solar systems for domestic hot water and electricity production. Energy Conversion and Management, 47, **3368-3382.**

Khouzam, K. Y., Electrolysis of salt water for chlorine production by photovoltaic power. Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, 2008. IEEE, 1-8.

Mackay, R. C., 2004. The practical pumping handbook, Elsevier.

McIntyre, T., 2014. Swimming pools add value to homes, as long as they tick the boxes. DailyTelegraph. Available: https://www.news.com.au/finance/real-estate/swimming-pools-add-value-to-homes-as-long-as-they-tick-the-boxes/news-story/d5087b361066bf28a63cea6086fab722 [Accessed Jan 21st 2019].

Qu, L., 2016. Investigating the Relationship between Salinity and Specific Heat Capacity. Toowong,Queensland,Australia: Queensland Academy for Science, Mathematics and Technology (QASMT).

Ramos, A., Guarracino, I., Mellor, A., Lvarez, D., Childs, P., Ekins-Daukes, N., Markides, C., 2017. Solar-Thermal and Hybrid Photovoltaic-Thermal Systems for Renewable Heating. Imperial College London Grantham Institute, Briefing paper.

Ruiz, E., Martínez, P. J., 2010. Analysis of an open-air swimming pool solar heating system by using an experimentally validated TRNSYS model. Solar Energy, 84, 116-123.

Standards Australia, 2013. AS 3634-1989 (R2013) - Solar heating systems for swimming pools Standards Australia, SAI Global.

The Engineering ToolBox, 2017. Ventilation Ducts - Roughness & Surface Coefficients. Available: https://www.engineeringtoolbox.com/surface-roughness-ventilation-ducts-d_209.html, [Accessed January 5th 2018].

Wang, R., Ge, T., 2016. Advances in Solar Heating and Cooling, Woodhead Publishing.

Weiss, W., Spörk-Dür, M., 2018. Solar heat worldwide. Global Market Development and Trends in 2017, Detailed Market Figures 2016. AEE - Institute for Sustainable Technologies (INTEC) and IEA Solar Heating and Cooling (SHC) Programme, Supported by the Austrian Ministry for Transport, Innovation and Technology.

Wilkenfeld, G., 2009. Swimming pools and electric space heating, prepared for the Australian Building Codes Board. Energy Policy and Planning Consultants.

Woolcott Research and Engagement, 2016. Pool Pumps: An Investigation of Swimming Pool Pumps in Australian and New Zealand, A research report prepared for the Department of the Environment and Energy. Commonwealth of Australia.

Zhao, J. 2018. Whole system energy and cost optimization of residential swimming pool pumping systems. Ph.D. Thesis, University of New South Wales.

Zhao, J., Bilbao, J. I., Spooner, E. D., Sproul, A. B., 2018. Experimental study of a solar pool heating system under lower flow and low pump speed conditions. Renewable Energy, 119, 320-335.