Whole System Design of an Energy Efficient Residential Pool System

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Abstract

The impact of low-speed filtration on the performance of salt water chlorinators, pool cleaners, and the pool water quality, based on experimental and modelled data, is investigated. Results show that a typical salt water chlorinator and pressure pool cleaner do not work well for flow rates of less than 1 litre s^{-1} and 1.3 litre s^{-1} respectively. With the implementation of a robotic pool cleaner, energy savings of more than 70% can be obtained by operating the filtration system at around 1 litre s^{-1} with a correctly adjusted chlorinator setting. This does not compromise the system performance and achieves a largely improved water quality. Furthermore, it is shown that a small photovoltaic system can provide nearly all the energy required by such energy efficient pool system. This PV powered pool filtration system achieves a discounted payback period (DPP) of 5.4 years in comparison to the grid supplied pool filtration system (the Business as Usual (BAU) scenario).

Keywords: low-speed pumping; pool chlorinator; pool cleaner; high-efficiency pool filtration.

1. Introduction

With the rapid growth of residential energy consumption and peak electricity demand, it is important to investigate the energy saving potential in households and so achieve higher energy efficiency. Studies have shown that households with a swimming pool have higher energy demand than households with no pools (Elnakat et al., 2015; Fan et al., 2015). The savings in pump energy used for solar pool heating was previously investigated by the authors and the results showed that operating the system at a lower flow rate reduced the pumping energy by 60%, without materially affecting the pool thermal performance (Zhao et al., 2018). This paper will investigate how to improve the energy efficiency of the pool filtration system by evaluating the performance of the whole system. Such system could achieve significant savings in energy and cost, which therefore enables its energy load to be supplied by a typical photovoltaic system.

2. Background

Presently, there are approximately 1.1 million residential pools in Australia (DEE, 2016) and the total annual electricity demand is estimated be 2100 GWh per year (EES, 2008). This corresponds to approximately 2 million tonnes of carbon emissions per year (DEE, 2017). Operating the pool filtration system under low flow conditions have been recognized as an energy efficiency retrofit by the industry and many swimming pool have adopted this measure (DOE, 2018). Further, numerous studies have investigated the operation of pool filtration under low pump speed (Springer and Rohe, 1996; Sproul, 2005; Cunio and Sproul, 2008; Hameiri et al., 2009) with reported savings of as much as 80%. In addition, the use of a small photovoltaic system to power the low-energy pumping system was examined by Sproul (2005) and the system achieved a 14 year payback period.

Although it is clear that significant amounts of energy could be saved by operating the pool filtration system under low flow conditions, the impacts on other system components such as the salt water chlorinators and the pool cleaners have not been widely reported. In addition to this, the associated effects on pool water quality yet have not been quantitatively examined. According to a recent report prepared for the Department of the Environment and Energy (DEE) of the Commonwealth of Australia, the most common type of Australian pool is a salt water pool (60%) which relies on a chlorinator for sanitation (Woolcott Research and Engagement, 2016). The electrolysis process in the salt water chlorinator has been studied by Khouzam

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(2008); this process produces two gases, hydrogen gas and chlorine gas. The hydrogen gas is not soluble in water and therefore gets carried out of the chlorinator by the water flow, into the pool, and eventually into the environment. On the other hand, the chlorine gas, which is highly soluble in water, reacts with water to produce the hypochlorous acid (HOCl). The hypochlorous acid is known as free chlorine, which is an effective disinfectant in the pool. As in most cases, the same pump is used to both filter and chlorinate the water. One possible problem of operating the standard salt water chlorinators at low flow rate is that as the water flow reduces, the hydrogen gas produced accumulates in the chlorinator instead of being flushed out into the pool. Typically, chlorinators are designed to detect this dangerous situation and will switch off the chlorinator and the pump. Hence under these conditions, the pool sanitation deteriorates.

Additionally, a pressure pool cleaner powered by the filtration pump is also susceptible to low water flow operation, as the flow through the cleaners is shared with the pool skimmers or returns. Thus, to fulfill the cleaning task, the pump needs to run at a high speed for a certain period of time, which limits the extent to which the pool filtration can be completed at low flow rate using high-efficiency pumps.

Thus, it is the aim of this study to estimate the energy savings of the pool filtration system by taking the whole system into consideration. In particular, the low flow operation of the salt water chlorinator and the pressure pool cleaner are investigated to examine potential efficiency gains. To the authors' knowledge, there is no information available regarding the minimum operating flow rate of the chlorinator as well as its energy usage. Furthermore, energy efficient operating scenarios are proposed and the feasibility of utilising a PV system is analyzed.

3. Experimental system

Experiments were carried out on an existing domestic pool filtration system in Sydney Australia (Figure 1). The system has an eight-star variable speed water pump (Viron eVo P280), a controller, a salt water chlorinator (Hurlcon VX11T), an oversized cartridge filter (Viron CL400), and a pressure pool cleaner (Polaris 360) operated by the filtration pump. During the experiment key system parameters were monitored, which included the electrical power of the pump and chlorinator; water flow rates through the pump and the pressure pool cleaner; the pressure drop across the pump and the filter. A manually adjustable 3-way valve is located at the discharge of the chlorinator, which can change the proportion of water flow into the cleaner.

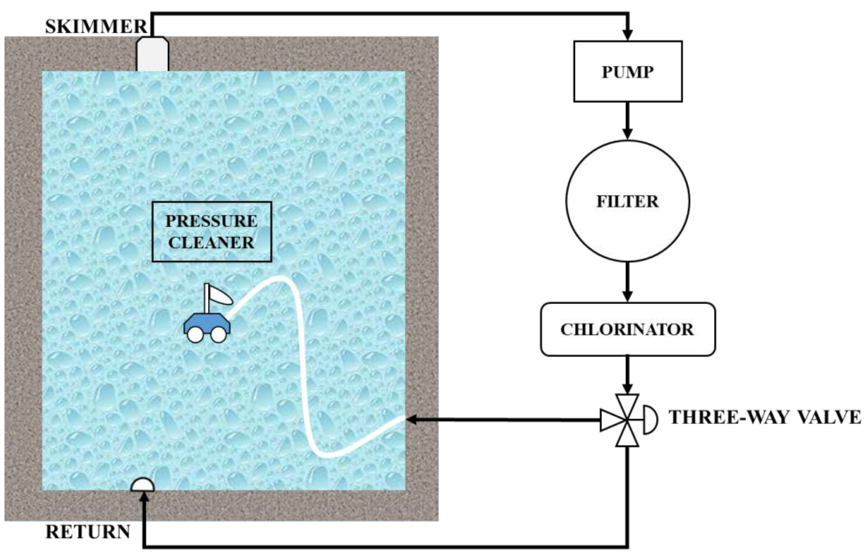


Figure 1: Pool filtration system layout.

The controller coupled to the pump was used to set the operating schedule as well as the pump speed so that the system performance could be investigated under multiple operating scenarios, with different pump speeds and running times. The details of the operating scenarios are presented in Table 2. A robotic cleaner (Zodiac, 2017) was also retrofitted to replace the existing pressure cleaner in order to evaluate further energy saving opportunities.

Under each operating scenario, the water quality and cleaning effectiveness were examined qualitatively and quantitatively according to the requirements as per the Australian Standard AS3633 (1989) and NSW Government (2013) (Table 1). Based on the measured water quality, the chlorinator setting was adjusted manually using the controller until an acceptable water condition was obtained. Notice that as the pool water quality is affected by pool chemical levels as well as ambient factors including solar irradiance, the location of the pool, and its surroundings (Khouzam, 2008), the scenarios were varied out during the summer period to minimize variations due to the ambient weather conditions. Specifically, each scenario was carried out for 5 consecutive days with similar weather conditions (sunny and warm) and the daily water quality check was performed at 9 am.

Table 1: Recommended pool water chemical concentrations (Standards Australia, 1989; NSW Government, 2013).

<table>
<tr><th>Parameters</th><th colspan="2">Recommended range</th></tr>
<tr><td rowspan="2">Free chlorine (ppm[1])</td><td>Pool temperature < 26°C</td><td>> 2</td></tr>
<tr><td>Pool temperature ≥ 26°C</td><td>> 3</td></tr>
<tr><td>pH</td><td colspan="2">7 – 7.8 (Optimum: 7.2 – 7.6)</td></tr>
<tr><td>Total alkalinity (ppm)</td><td colspan="2">60 – 200</td></tr>
<tr><td>Isocyanuric acid (ppm)</td><td colspan="2">30 – 50</td></tr>
<tr><td>Calcium hardness (ppm)</td><td colspan="2">0 – 500</td></tr>
<tr><td>Total dissolved solids (ppm)</td><td colspan="2">1000 – 2000</td></tr>
<tr><td>Turbidity</td><td colspan="2">0.5 (NTU[2])</td></tr>
</table>

4. Operating the whole pool filtration system at low flow

In order to assess the energy savings of running the variable speed pump at low speed, the comparison was made to the standard single speed pump investigated by Cunio and Sproul (2008). The Hurlcon 1500 W single speed pump was assumed to operate the same pool filtration system. The system operating point was obtained by overlaying the pump working curve with the measured system curve of the existing filtration system. The operating point was approximately 4.3 litre s^{-1} at a head of 18.5 m. For such a single speed pump to fully turnover the pool once every day as required by the Australian Standard AS3633 (1989), the daily pump energy is 3.6 kWh/day. This is comparable to the data reported by DEE (2016), which stated that "*Australian households with a pool use on average 1352 kWh per year (3.7 kWh/day) powering pool pumps used for filtration.*".

Figure 2 shows the daily required pump running time calculated based on one pool turnover and the measured pump efficiency (pump efficiency was calculated as the ratio of measured hydraulic and electrical power). Also shown is the daily pump energy savings in comparison to the single speed filtration by operating the variable speed pump over its flow rate range. Note that the daily energy consumption of the variable speed filtration was calculated based on the measured power usage and the required running time at each flow rate. As can be seen, lowering the flow rate leads to a significant increase in the daily running time while the pump efficiency decreases drastically. However, even at the minimum flow rate, one pool turnover can still be accomplished within 24 hours.

[1] Parts per million. One ppm is equivalent to 1 milligram of something per litre of water (mg/l).
[2] Nephelometric Turbidity Units.

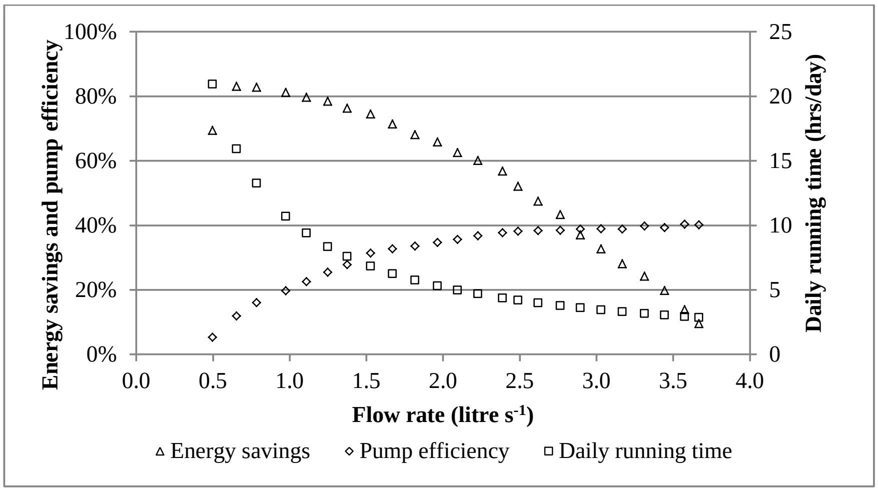


Figure 2: Pump energy savings in comparison to the BAU case, daily running time and measured pump efficiency.

Notice that even if the pump efficiency reduces by half, by operating the variable speed pump at a flow rate between 0.7 litre s^{-1} to 1 litre s^{-1}, pump energy savings of over 80% can still be obtained. This amount of pump energy savings matches the finding reported by Sproul (2005) and Cunio and Sproul (2008). However, the 80% energy savings were only contributed by the pool filtration pump, it is essential to adopt the whole system approach by taking other main system components into consideration, e.g. the pool chlorinator and the cleaner as shown in Figure 1.

Figure 3 shows the pressure drop across various system components. It can be seen that more than half of the total system pressure drop is due to the pipe and fittings. These include components that cause large pressure drop like the pool “eyeballs” (water inlet fittings), bends and tee pieces, and the three-way valve. It is also interesting to see that for flow rates below 1.7 litre s^{-1} (pump speed of less than or equal to the default low speed), the pressure drop across the oversized cartridge filter is very small and therefore can be neglected. This confirms that oversizing the pool filter could reduce the overall pressure loss and achieve a better energy efficiency (NRDC, 2013). In addition, the existing pressure pool cleaner accounts for noticeable pressure loss, which is about one-third of the total system pressure. In comparison to the filtration system without the pressure pool cleaner, this reduces the flow rate under a specific pump speed and leads to a longer daily filtration period to change over the same amount of water. Though the pump uses lower power, the daily energy is more.

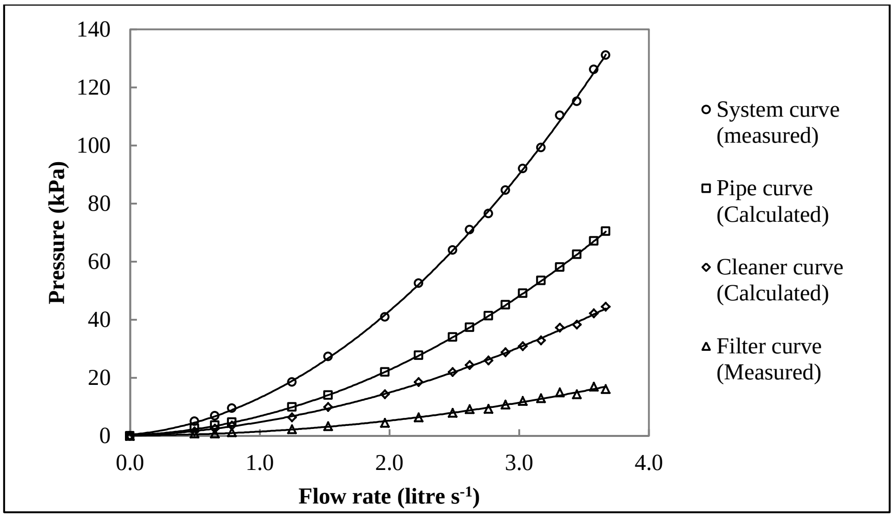


Figure 3: Pressure drop across the pool filtration system components.

By operating the pool filtration system under various scenarios, the energy savings achieved at low flow conditions can be examined along with the associated effects on key system components. Table 2 shows the experimental results obtained by operating the whole pool filtration system under 7 scenarios. Also shown is the chlorinator setting for maintaining an acceptable pool water quality as per the Australian Standard AS3633 (1989) for all scenarios. The Business as Usual (BAU) scenario is also presented, in which the variable speed pump was running at the highest speed and the chlorinator was at the highest setting. Notice that for scenario G, the pressure pool cleaner was disconnected and a robotic pool cleaner was used. Under this scenario, all flow was diverted through the pool returns by adjusting the three-way valve.

Table 2: Experimental results of the whole pool filtration system operating under different scenarios.

Scenarios	**A**	**B**	**C**	**D**	**E**	**F (BAU)**	**G**
Pump speed (RPM)	900	950	1150	1450	2075	2850	750
Cleaner type	Pressure cleaner						Robotic cleaner
Filtration time (hrs/day)	14 (11 for one turnover)	10	8	6	4	4 (2.8 for one turnover)	10
Schedule	5am – 7pm	7am – 5pm	8am – 4pm	9am – 3pm	10am – 2pm	10am – 2pm	7am – 5pm Robotic cleaner (11 am – 12 pm)
Flow rate (litre s^{-1})	0.97	1.03	1.30	1.73	2.58	3.67	1.07
Chlorinator working?	N	Y					
Chlorinator setting (out of 8)	N/A	3	4	5	8	8	3
Proportion of flow through pool returns	0%	0%	0%	24%	50%	65%	100%
Water chemistry	Poor	Good					
Water turbidity	3.2	0.82	0.45	0.41	0.43	0.4	0.24
Skimmer effectiveness and water clarity	Poor			Ok for small and lightly polluted pools.	Good		Perfect
Manual clean?	Y						N
Pool filtration system load (pump + chlorinator) (kW)				0.29	0.62	1.36	0.12 (before 11 am and after 13 pm) 0.19 (11 am to 13 pm)
Daily energy usage (kWh/day)				1.8	2.6	5.5	1.5

The pool chlorinator stopped working when the flow rate dropped below 1 litre s^{-1} due to insufficient flow and hydrogen accumulation. Hence under scenario A (flow rate of 0.97 litre s^{-1}), the pool water condition was heavily compromised – an unbalanced water chemical level and a turbidity of 3.2 NTU that was more than 6 times the recommended value of 0.5 shown in Table 1. This implies that 80% of savings of pump energy is actually not practical at a flow rate between 0.7 litre s^{-1} to 1 litre s^{-1}. This is due to the hydrogen accumulation in the salt water chlorinator, which is shut down under such circumstances.

In terms of the pressure pool cleaner, the operating flow rate for achieving the proper wheel rotations (28 – 32 RPM) was approximately 1.3 litre s^{-1} (Polaris, 2017). As seen from Table 2, under scenario A and B (flow rates of less than 1.3 litre s^{-1}), even if all flow was diverted into the pressure cleaner, its motion was still constricted and debris accumulated in the pool. By contrast, with proper adjustments of the existing three-way valve to meet the recommended flow range of the pressure cleaner, it was feasible to operate the pressure cleaner under scenario C to F. However for scenario C, the skimmer effects were heavily compromised since all flow was passed through the pressure cleaner. As a result, debris accumulated on the pool surface and this affected the pool clarity. The situation may get worse for heavily polluted areas.

From the whole of system performance perspective, it is more acceptable to operate the pool under scenario D (pump speed of 1450 RPM), where the three-way valve was adjusted to divert most of the flow (76%) through the pressure cleaner while still allowing some (24%) to allow the normal pool returns (“eyeballs”). This enabled the skimmer box and the pressure cleaner to be effective while running at the same time, therefore obtaining an appropriate pool condition. Notice that under scenario D, occasional manual cleaning was still needed to pick up the debris on the pool surface, especially during windy days.

After the robotic pool cleaner was retrofitted to replace the existing pressure cleaner, a significant improvement of pool cleanliness was observed (Figure 4). With the 4WD system, the robotic cleaner was able to climb on the pool steps and walls easily and perform cleaning without losing traction. In addition, since the water flow through the main pump was no longer needed to supply the pressure cleaner, all water flow was diverted via the normal pool returns and this allowed the skimmer box to operate more effectively. As a result, no manual work was required under this scenario to catch debris on pool surface nor to sweep the steps.

a) **b)**

Figure 4: Conditions of pool steps when the filtration system was operating under a) BAU scenario with a pressure cleaner, b) scenario G with a robotic cleaner (both with no manual cleaning) after a 24-hour period.

Apart from the improved water clarity, it was also encouraging to see that the robotic cleaner was highly energy efficient and additional energy savings were obtained. Figure 5 shows the measured daily energy usage of the whole system operating under different scenarios. Notice that under these scenarios, all the system components were experimentally examined to work appropriately and the water quality was checked as acceptable.

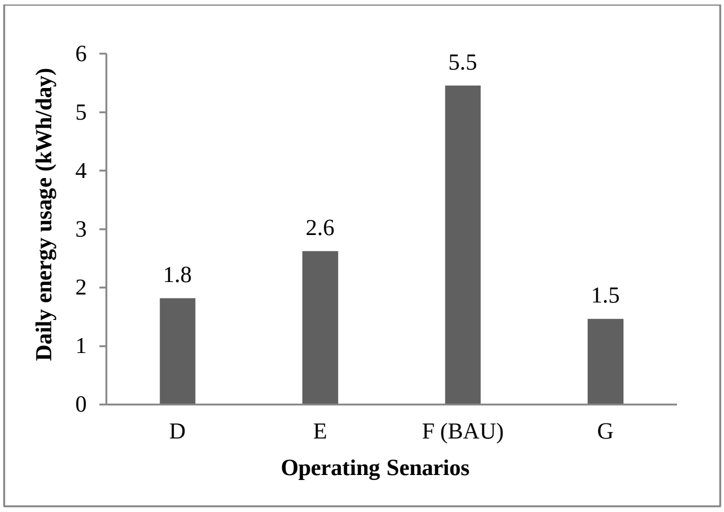


Figure 5: Measured daily energy usage of the whole pool filtration system operating under various scenarios.

For all scenarios with the pressure pool cleaner in use, the whole filtration system operating under scenario D consumed the least daily energy of 1.8 kWh/day. With a robotic cleaner in use (scenario G), the daily energy usage of the whole system was reduced to around 1.5 kWh/day. This is less than 30% of the BAU scenario (energy use of 5.5 kWh/day).

Assuming the pool filtration system is running year-round to maintain the pool conditions, the simple payback period of the whole system under the proposed energy efficient scenarios was calculated. Considering a variable speed pump (AU$1,500 including installation) as a retrofit option to the existing pool filtration system, operating the whole system at the minimum flow as required by the pressure cleaner (scenario D) has a simple payback period of approximately 3.4 years based on the electricity price of 0.323 AU$/kWh (Energy Australia, 2017). This is less than the average pool pump lifetime of approximately 7 years (DEE, 2016), making it an ideal energy saving option for pool owners. For the energy efficient scenario G where a robotic cleaner is retrofitted, it takes around 6.5 years to pay back the total capital cost of the variable speed pump and the robotic pool cleaner. This is nearly double the payback of scenario D since the robotic pool cleaner costs about the same as the variable speed pump (AU$1,550). If low-cost robotic pool cleaners were developed, operating a variable speed pump at the lowest flow that suits the chlorinator (scenario G) would obtain a lower payback and therefore become a better solution considering its superior cleaning quality as demonstrated above.

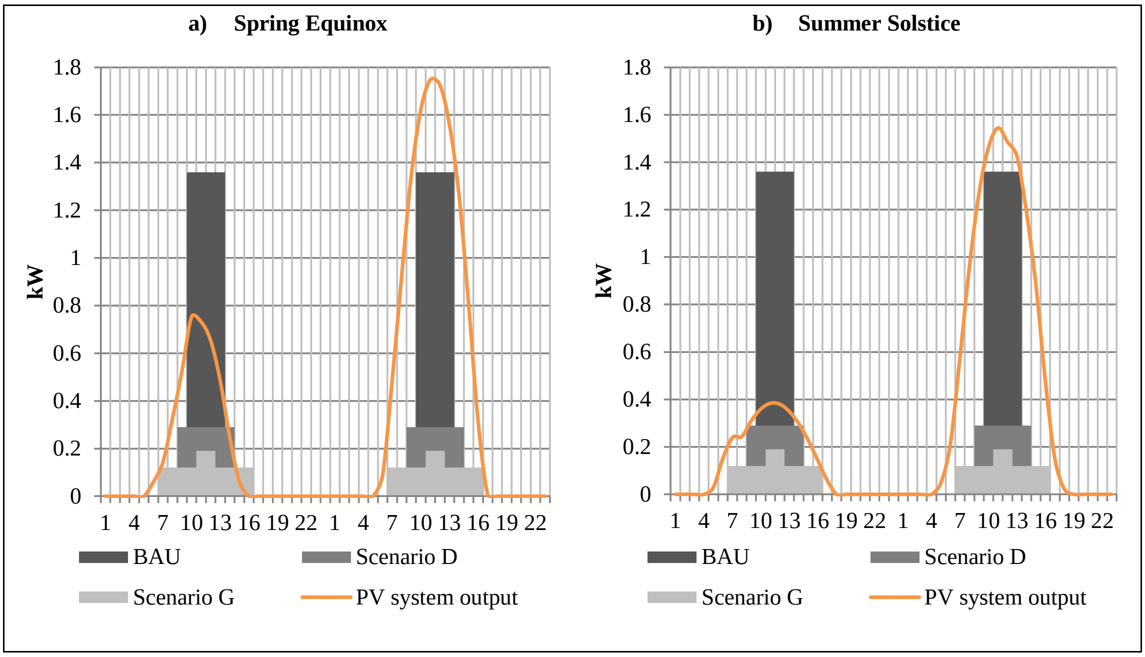
5. PV operated swimming pool filtration system

Previous results showed that operating the pool filtration system under energy efficient scenarios (D & G) achieves significant energy savings and acceptable paybacks in comparison to the BAU scenario. It is also interesting to investigate the feasibility of running the whole system from a PV array. The simulation was carried out using NREL’s System Advisor Model (SAM) (NREL, 2017a) and the PV system was sized based on the BAU high-speed operation of the pool filtration system (scenario F in Table 2) in Sydney. The filtration system was assumed to operate year-round and the PV array was assumed to be connected to the grid. The key assumptions and parameters are shown in Table 3.

Table 3: Assumptions and parameters of the PV system sized based on the BAU scenario (F).

Nameplate capacity	2 kW
Array orientation	North
Array tilt	34°
PV module	Suntech Power STP250-20/Wd
Number of PV modules	8
Modules per string	8
Strings in parallel	1
Inverter	Solar Power: YS-2000TL 277V
Shading loss	0%
Soiling loss	5%
DC power loss	3%
AC loss	1%
Total module area	13 m^2

Figure 6 shows the power generated by the PV system at three different dates near to the: a) Spring (Autumn) Equinox, b) Summer Solstice, and c) Winter Solstice. Notice that two days around each date are presented to demonstrate the system performance under i) cloudy and ii) clear weather conditions. Also shown is the pool filtration system loads under BAU scenario, scenario D, and scenario G. The associated daily operating schedules and the energy loads are presented in Table 2.



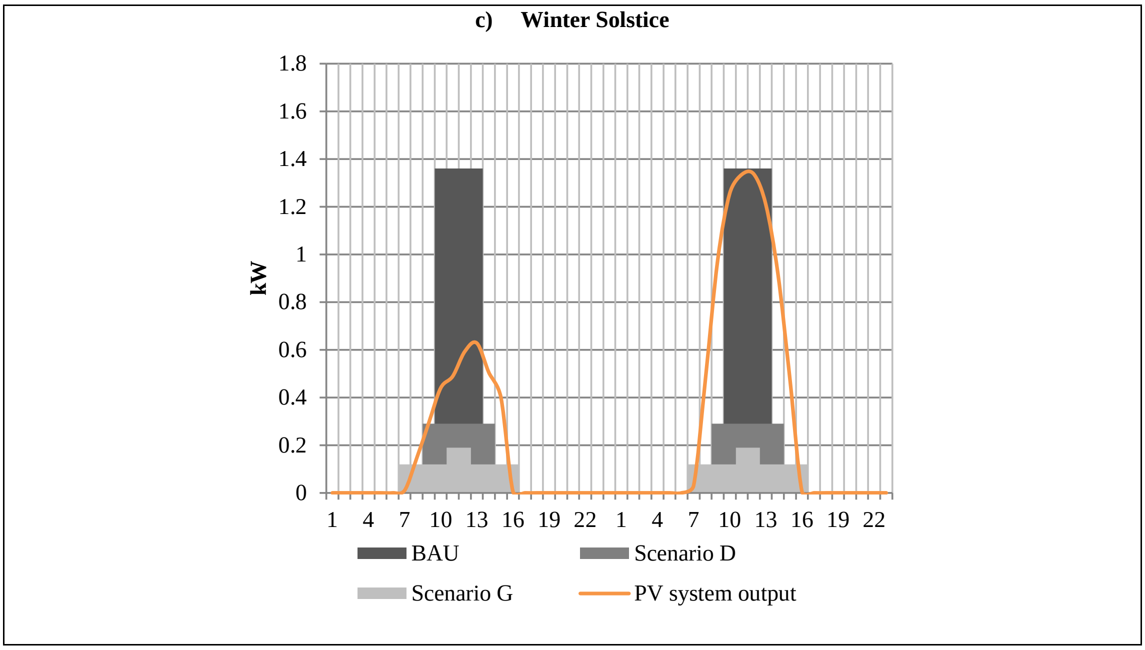


Figure 6: PV system output and pool load under scenario D, G, and BAU for different sun positions in the southern hemisphere (left: cloudy day; right: clear day).

It is clear from Figure 6 that on cloudy days, a majority of the pool load under the BAU scenario cannot be met by the PV system due to the significant decrease in the power generated. As seen from the SAM simulation results shown in Table 4, 423 kWh of electricity must be supplied annually by the grid under the BAU scenario and this leads to a PV fraction of only 45% (proportion of period where the pool filtration system load is completely covered by the PV system). By contrast, the same PV system is more likely to power the pool filtration system operating under energy efficient scenarios (D & G) even with bad weather. In both of these cases, only a small amount of electricity is sourced from the grid while the pool load can be fully supplied by the PV system for more than 90% of the total operating period (Table 4).

Table 4: SAM simulation results of the pool filtration system operating under BAU scenario (both grid and PV powered), scenario D, and scenario G.

	BAU+Grid	**BAU+PV**	**Scenario D (PV+Variable speed pump+Pressure cleaner)**	**Scenario G (PV+Variable speed pump+Robotic cleaner)**
PV system output (kWh/yr)	0	3017		
Excess PV output (kWh/yr)	0	1,454	2,391	2,547
Electricity from grid (kWh/yr)	1,986	423	9	19
Period with full load covered by PV (hrs/yr)	0	651	2,083	3,399
PV fraction	0	45%	95%	93%

Based on the results shown in Table 4, the net present values (NPV) and the discounted payback periods for the PV powered pool filtration systems were calculated relative to the BAU case: single speed pump, pressure cleaner, and grid-supplied system (BAU+Grid). The following parameters and assumptions were made for the calculations:

- Cost of system components:
  - Single speed pump: AU$ 775 (DEE, 2016).
  - Pressure pool cleaner: AU$ 720 (supplier).
  - Variable speed pump: AU$ 1,500 (supplier).
  - Robotic pool cleaner: AU$ 1,550 (supplier).
  - PV system: AU$ 5,868 (NREL, 2017a).
- The lifetime of both pool cleaners are assumed the same as that of a typical pool pump, therefore all need to be replaced every 7 years (DEE, 2016).
- All the PV electricity generated is assumed to be self-consumed by the household.
- The discount rate is 5% (Drury et al., 2011).
- The grid electricity price is 0.323 AU$/kWh (including GST) (Energy Australia, 2017)
- The grid electricity price is assumed to increase by 3% each year (Kai, 2017).
- The typical PV lifetime is 25 years (NREL, 2017b).

Table 5: Capital costs, net present values (NPV), and discounted payback periods (DPP) for PV powered pool filtration systems compared to BAU grid supplied system.

	BAU+Grid (Grid+Single speed pump+Pressure cleaner)	**BAU+PV** (PV+Single speed pump+Pressure cleaner)	**Scenario D** (PV+Variable speed pump+Pressure cleaner)	**Scenario G** (PV+Variable speed pump+Robotic cleaner)
Capital costs	AU$ 1,495	AU$ 7,363	AU$ 8,088	AU$ 8,918
NPV (relative to BAU+Grid)	AU$ 0	AU$ 13,288	AU$ 19,465	AU$ 17,649
DPP (years)		6.5	5.0	5.4

From Table 5, it can be seen that although the more efficient options have high upfront costs, the discounted payback periods for the two PV powered energy efficient systems (scenario D & G) are very attractive. In terms of scenario D, it has the highest NPV difference relative to the BAU grid supplied system and thus it is the most cost-effective solution. The whole system cost can be paid back in just 5 years, which is the shortest amongst three PV powered system considered. As for scenario G, due to the additional costs of the robotic pool cleaner and more electricity is purchased from the grid (Table 4), it needs around 5 months more for the whole system to pay back in comparison to scenario D. Nevertheless, it starts generating profits 1 year earlier than the BAU PV powered system (BAU+PV) and the discounted payback period is less than a quarter of the standard lifetime of a PV system. Considering that better pool quality and simpler pool maintenance can be achieved under scenario G, it is also an appropriate energy efficiency design of a residential pool filtration system.

6. Conclusion

The study presents for the first time the results of a typical residential pool filtration system operating under various scenarios. The water flow rate was varied under different scenarios and the pool chlorinator was adjusted accordingly to deliver different chlorine production rates. For lower flow rates and longer running times, the rate of chorine production was reduced in comparison to the high flow rate operation. The pool water was also tested to ensure that the key water chemistry such as free chlorine and pH levels met the Australian Standard AS3633 (1989) for all flow rates considered in this paper.

Experimental results revealed that over 80% of the pump energy could be saved by operating a variable speed pump at flow rates of less than 1 litre s^{-1}. However, at such flow rates, the salt water chlorinator and the pressure pool cleaner were identified not working properly and this led to unsatisfactory pool water conditions. For the pool filtration system considered in this study (with the pressure pool cleaner in use), it is more appropriate and energy efficient to operate the whole system at a flow rate of 1.7 litre s^{-1} with a properly adjusted chlorinator setting (scenario D). The associated energy use is 1.8 kWh/day, which is approximately 33% of the energy use of the BAU scenario. In addition, the energy use reduces to 1.5 kWh/day with a robotic cleaner and the pool cleanliness is also substantially improved. For these energy efficient pool filtration systems, its load can be supplied by a small PV system. With no export of the PV electricity, it takes around 5 years and 5.4 years respectively for scenario D (pressure pool cleaner in use) and scenario G (robotic cleaner in use) to payback the initial investment (both refer to the discounted payback period with the replacement of pool system components taken into consideration). These discounted payback periods are less than 25% of the PV system lifetime.

Approximately 70% of the swimming pools in Australia are operated by single speed pumps (DEE, 2016). If all of these pools were retrofitted to the energy efficient scenarios considered in this study, total energy savings of more than 1000 GWh and carbon reductions of nearly 1 million tonnes could be obtained annually (DEE, 2017). Further, if all the low energy pool filtration systems were powered by PV systems where possible, total peak demand reductions of approximately 1 GW could be realized in Australia.

Except during periods of experimentation, the pool under study was operated under low flow conditions for approximately two swimming seasons. During this time water quality tests were undertaken, and readings were always in the acceptable range to maintain healthy swimming conditions as per the Australian Standard AS3633 (1989). In all circumstances, the filtration flow rates and pump run times were set so that the full volume of pool water was filtered once per day, as required by the Australian Standard AS3633 (1989). We would propose that provided this methodology was adhered to and that pool chemistry levels were maintained, the findings of this study should be generally applicable to different pool sizes, climates, and pool usage. However further studies of different pools would be useful to further verify the approach used in this paper.

7. Acknowledgements

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