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Operating cost reduction by electricity profiling and demand management

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Abstract

Like many other industries, water utilities use a high amount of electricity to operate water and wastewater treatment plants and incur a large percentage of their operating cost as electricity bills. This study investigates the electricity usage profile of a water utility and employs demand management strategies for cost reduction. Two cost reduction strategies are verified in this research – (i) fixed price contract, and (ii) electricity time-of-use shifting. An illustrative case study has been presented with two years of interval data from eight selected sites of an Australian/Victorian water utility. The study results suggest that by employing the demand management strategies, up to 22% cost reduction could be achieved from annual electricity bills. The study recognizes that the solution could be customized for each individual site based on the site-specific electricity usage profile.

Key words: demand management, economic efficiency index (EEI), electricity price, electricity profiling

Highlights

- Operating cost savings for water utilities.
- Electricity profiling and demand management for water and wastewater treatment plants.
- Load shifting and price fixing may reduce electricity bills for water utilities.

INTRODUCTION

The aim of this research is to identify periods of high electricity consumption for a water utility and to achieve an economically beneficial overall electricity tariff. Electricity profiling enables large energy users to understand the electricity usage patterns. Once the electricity usage patterns are recognized, demand management strategies could be implemented to operate water treatment plants (WTP) and wastewater treatment plants (WWTP) to a time when electricity prices are low. Thereby the operational flexibility of the WTPs and WWTPs are the key for operating cost reduction by reducing electricity bills (Póvoa *et al.* 2017; Tadokoro *et al.* 2019).

As the electricity price varies depending on the peak and off-peak usage of the electricity grid, the savings will mostly depend on the flexibility of shifting usage of WTPs and WWTPs; that is, reducing peak-consumption and increasing off-peak consumption. Therefore, shifting electricity consumption and implementing electricity demand management depends on several different factors, such as the type of loads on site, electricity pricing (spot or fixed prices) and any renewable energy or generators

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on site (Mohammadzade Negharchi *et al.* 2016; Azimi & Rocher 2017; Wibowo & Chang 2020). There are several existing ways to shift electricity consumption; as such, this research is primarily focused on (i) load management, and (ii) demand response.

Load management

The de-regulated energy markets across the globe have resulted in prices that vary with respect to time. The variation is ultimately dependent on the supply and demand in the electricity market. There are two types of electricity prices: wholesale and retail. Wholesale prices are also known as spot prices as they fluctuate on a real-time basis while taking into consideration the electricity demand at a time. Retail prices, however, are fixed for the consumer and generally divided into two sets of time: peak and off-peak, where peak time reflects the hours where the demand is high and off-peak where demand is low. This is known as *time-of-use* tariffs. Load management becomes particularly important in reducing the energy bills as one can dictate usage based on the price at a given time. Water utilities would benefit immensely with the use of clever load management strategies (Loureiro *et al.* 2015).

A way to manage loads would be to shift consumption from peak time to off-peak time. Financial incentives offered from electricity retailers can influence the customer's load and thereby, their electricity bill. The utilization of off-peak electricity results in the improvement of the *power system load factor* and this can help the customer's electricity retailers to further incentivise them (Ram 1995). Exploring these incentives can significantly aid water utilities as they can reduce their electricity retail price when shifting their load to an off-peak time, thereby reducing peak time consumption.

Another technique that manages load is implementing a load forecasting technique and shifting loads to off-peak periods (McRae *et al.* 2004). A load forecasting system uses historical data and predicts when the loads will be at the maximum and at what time this will occur. This information can then be used to shift loads in a way that avoids turning off the load completely. At times where loads cannot be shifted to off-peak times, customers are forced to run high-consumption electrical equipment during peak time. Some industries are charged for the *MVAh* consumed; that is, the apparent power during peak time (Li *et al.* 2013). This forces customers to look towards power factor correction to reduce the apparent power. In an instance where motors are the primary loads, capacitive compensators attached to the motors can reduce the reactive power consumption, resulting in a better power factor and hence reduced electricity prices (Simpson 2005).

Demand response

As mentioned earlier, electricity pricing works in two ways: retail and wholesale prices. Wholesale prices are set based on the demand at that time as well as historical demand at that time, and hence are known as spot pricing (Li *et al.* 2013). This makes load management difficult for consumers that buy electricity on a wholesale basis, as the fluctuations are hard to predict. Consumers that are billed based on spot price may choose demand management, as the retail price is often too high for the demand they require; hence the gamble is taken with spot pricing (Palensky & Dietrich 2011). Demand response is essentially responding to the electricity demand at a given time by changing the demand of the consumer. This research will be particularly useful for such water utilities, which buy electricity on a wholesale basis.

An effective way of demand response is to solve a finite-horizon Markov decision process (MDP). A load that consumes electricity requires a set total amount of electricity over a period and therefore can shift the energy usage in time, as mentioned earlier with load management. This becomes crucial

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to profit maximisation as a demand response strategy can be obtained by solving a finite-horizon MDP problem, which requires extremely high computational complexity due to continuous state and action spaces. To tackle the high computational complexity, one can solve a dual approximate approach that transforms the MDP problem into a linear programming problem by exploiting the threshold structure of the optimal solution. Then, a row-generation-based solution algorithm is proposed to solve the problem efficiently (Wang *et al.* 2018).

METHODOLOGY/PROCESS

This study investigates the electricity usage profile of a water utility and employs demand management strategies for cost reduction. Figure 1 presents the conceptual framework of the research methodology.

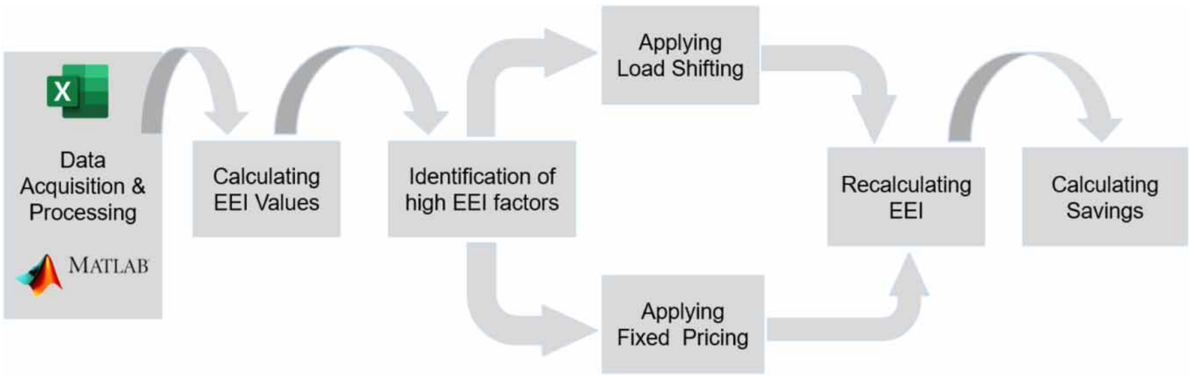

Figure 1 | Conceptual framework of the research methodology.

The following approach has been implemented in this study: the interval data from the individual site and the wholesale electricity price data from the system operator have been collected. To explore the economic operation of a site, an economic index has been calculated by dividing the 'Volume Weighted Average' cost of electricity at a site by the 'Time Weighted Average' cost of the wholesale market. The resulting indicator can be called the Economic Efficiency Index (EEI), as presented below.

$$\left(\text{EEI} = \frac{\text{Volume Weighted Average Price of Electricity (/MWh)}}{\text{Time Weighted Average Price of Electricity (/MWh)}}\right) \quad (1)$$

The EEI is a measure that reflects whether an individual site is operating economically or there is some scope for improvement. An EEI value greater than 1 means a site may be exposed to higher cost and a cost reduction strategy could be applied.

Understanding current electricity consumption patterns for a water utility is the key consideration to reduce the price they pay for electricity; as such, the focal point of this research is to develop an index as well as visual representations of the data provided.

Data acquisition

There are two types of data used throughout this project: (i) electricity price data, and (ii) electricity consumption data. Electricity spot price data from April 2017 – March 2019 was gathered from AEMO (Australian Energy Market Operator). This data is essentially the price of electricity for every 30 minutes, in $/MWh. This price fluctuates depending on the supply and demand of electricity

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for that given time. As the AEMO spot price data provides the price for every 30-minute interval, it is essential to collect the water utility's 30-minute interval data so that it is in line with the spot prices.

Calculating EEI

Energy Efficiency Index (EEI) is an index used by industries that purchase electricity on the wholesale market to gauge their electricity consumption against the price they pay for their electricity. This is formulated as a measure for industries to track their consumption patterns and is used throughout this report to establish the efficiency patterns.

Electricity spot prices in the AEMO (Australian Energy Market Operators) are published for each 30-minute time interval period and the average electricity price over a specified time can be calculated by taking the average of the 30-minute interval prices. This is called the Time Weight Average Price (TWAP) and reflects the market average spot price of electricity in the AEMO. The Volume Weighted Average Price (VWAP) is calculated by multiplying each 30-minute interval of MWh consumption by its spot price and then totalling this amount for 3 months. It is then divided by the total MWh consumption in 3 months.

EEI is simply defined as the ratio of VWAP and the TWAP, as shown in Equation (1). The value of the EEI can be greater than 1, equal to 1 and less than 1. For EEI values greater than 1, the average price paid for electricity is higher than the market average price and the electricity consumption is skewed towards more expensive time periods. For EEI values equal to 1, the average price paid for electricity is equal to the market average spot price, and the electricity usage profile is relatively flat and consistent with the market. For EEI values less than 1, the average price paid for electricity is lower than the market average price, and the electricity use profile is optimised towards less expensive time periods. EEI can be used as a powerful indicator to measure and track the electricity profile of a WTP and WWTP site relative to the electricity pricing in the electricity market.

Table 1 presents the EEI for 20 water and wastewater treatment plants for 8 quarters over 2017 to 2019. It can be seen from Table 1 that the value of EEI is higher than 1 for many WTP and WWTP sites and for multiple quarters. Thus, all these sites that have EEI higher than 1 are running inefficiently; that is, paying electricity bills more than the market average price. Hence, the consumption of these WTPs and WWTPs could be managed better to reduce the electricity bills. It is important to note that the higher the EEI for a particular WTP and WWTP site is, the more the site consumption is during the system peak hours, and thus the more inefficient the site is!

Representing heatmaps

Heatmaps are produced to closely examine the consumption patterns of a WTP and WWTP site and the time when it is consuming greater amounts of electricity. The heatmaps generated for this project essentially have 24 points on the horizontal axis which depict the 24 '1 hour' blocks throughout the day and 7 points on the vertical axis showing the days of the week, thereby giving 168 blocks in a heatmap. Each block shows the average kWh consumption for that hour (of a day) and day (of the week). As it is a heatmap, a darker region means that on average, the electricity consumed by that site at that time is high. Figure 2 is an example of the type of heatmap developed for this project.

Figure 2 reveals that the price of electricity varies in the range of 60–120 $/MWh on average during 2018 in Victoria, Australia. It can also be seen from Figure 2 that the price of electricity is high during the morning between 7AM to 9AM and in the evening between 6PM to 8PM. Thus, there are two peak periods in the electricity market, where the average price of electricity is significantly higher than some other times of the day. It can be observed from Figure 1 that the average price of electricity is low during 1AM to 6AM, thus this is the off-peak period. Thereby, the electricity bills can be

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Table 1 | Energy efficiency index (EEI) of 20 water sites for 8 quarters in 2017–19

	Meter ID 1	Meter ID 2	Meter ID 3	Meter ID 4	Meter ID 5	Meter ID 6	Meter ID 7	Meter ID 8	Meter ID 9	Meter ID 10	Meter ID 11	Meter ID 12	Meter ID 13	Meter ID 14	Meter ID 15	Meter ID 16	Meter ID 17	Meter ID 18	Meter ID 19	Meter ID 20
2017	1.02	1.04	1.02	1.02	1.00	–	1.00	1.00	1.00	1.00	1.01	0.97	1.00	1.04	1.00	1.00	1.03	1.01	1.02	1.00
2017	1.04	1.48	1.49	1.42	1.32	–	1.59	1.48	1.49	1.46	1.03	0.88	1.01	1.02	1.00	0.99	1.00	1.04	1.02	0.99
2017	1.04	1.08	0.99	1.01	1.03	–	1.10	0.97	1.03	1.00	1.06	0.95	1.02	1.03	1.00	1.00	1.02	1.03	1.05	1.00
2018	1.17	1.29	0.81	0.96	1.07	–	1.43	0.99	1.06	1.01	1.09	0.83	1.06	1.03	1.01	1.00	1.01	1.10	1.09	1.01
2018	0.99	1.00	1.04	0.98	1.01	–	1.12	1.01	1.02	1.01	1.11	0.93	1.00	1.08	1.02	0.97	1.06	0.99	1.00	0.98
2018	1.13	1.06	1.01	1.03	1.07	-	1.09	0.99	1.03	1.00	1.00	0.88	0.98	1.07	1.01	0.73	1.03	1.05	1.02	1.00
2018	1.00	1.10	1.04	1.03	1.03	1.05	1.07	0.99	1.02	1.01	1.01	0.99	1.00	1.04	1.00	0.98	1.02	1.02	1.09	0.98
2019	0.93	1.12	0.66	1.03	0.95	0.99	1.49	0.96	1.08	0.99	1.09	1.27	1.15	1.06	0.90	0.78	1.04	1.19	1.20	0.91

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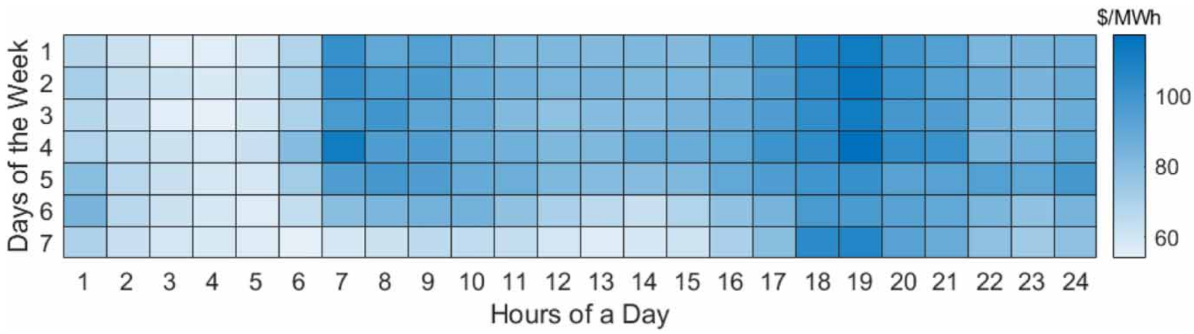

Figure 2 | Example of heatmap: average Australian (Victoria state) electricity price in 2018.

reduced if the electricity consumption of WTPs and WWTPs could be shifted from peak (7AM to 9AM and 6PM to 8 PM) hours to off-peak (1AM to 6AM) hours.

There is another cost reduction philosophy that can be mentioned here; that is, contract pricing or fixed pricing. In such a case, large electricity customers (e.g. water utilities) enter into contracts with electricity system operators (or retailers) to buy electricity at a fixed price. These contracts ensure a fixed electricity price for the contract period, which is 3 months in our simulated scenario. This type of contract reduces the customer's exposure to high spot prices.

Load shifting and price fixing

The two main solutions that have been employed in this study to reduce the price of electricity are 'load shifting' and 'price fixing'. Load shifting is essentially reducing the consumption of a WTP and WWTP site during peak times on a given day and increasing the consumption during the off-peak time, thereby shifting the load. It was determined that the 'peak time' would be defined to be between 7AM – 9AM and 6PM – 8PM; as such, 'off-peak' time is defined as 1AM – 6AM. Load shifting is performed by taking a certain percentage of the consumption during peak time and adding that value to the off-peak time. To implement this strategy for a WTP and WWTP, the flexibility of the electricity demand for that site needs to be evaluated. There might be some critical equipment operating during peak time, which may not be shiftable.

The 'price fixing' approach 'keeps the electricity price the same as contracted'; that is, paid by the end-user, as opposed to buying from the wholesale market where the price fluctuates every 30 minutes. The price that is considered fixed in this study is the 2-year wholesale market average, 102 $/MWh.

Calculating savings and recalculating EEI

Initial costs of running each analysed meter over a 2-year period were calculated first by multiplying half-hourly meter power consumption data (in MWh) with half-hourly electricity prices ($/MWh); then adding all half-hourly costs over the 2-year period together to obtain a total cost amount for running a meter for 2 years. Table 2 presents the energy efficiency index (EEI) of 8 selected sites for 2 years in 2017–19.

Table 2 | Energy efficiency index (EEI) of 8 selected water sites for 2 years in 2017–19

Meter No.	ID 1	ID 2	ID 3	ID 4	ID 5	ID 6	ID 7	ID 8
Initial EEI	1.25	1.14	1.12	1.03	1.09	1.06	1.06	1.10

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Further, to calculate savings after performing either load shifting or price fixing procedures, new load data has been obtained after load shifting. Then the total cost has been calculated for new demand data. These new costs were subtracted from the original costs that were previously calculated, leaving a savings amount in dollars for a 2-yearly period of analysed meter operation.

Moreover, EEI values have been recalculated after the load shifting operation. By observing cost savings and reductions in EEI values, it has been concluded that shifting electricity consumption and price contracts may provide financial benefits.

RESULTS/OUTCOMES

EEI for 20 meters for 8 quarters

Table 1 presents the EEI for 8 quarters from April 2017 – April 2019 of 20 sites of the water utility. This was done as the water utility pay their bills on a quarterly basis – hence observing which quarters result in a high EEI is beneficial for the water utilities to decide their strategy.

As can be seen in Table 1, the majority of the quarters for these meters contain an EEI over 1. This essentially means that they are paying above the price of electricity, which is above the market average. Upon noticing that this occurs frequently, it became imperative to reduce the electricity bills.

EEI for selected meters for 2 years

Calculating the EEI for 2 years as opposed to every quarter may facilitate a large-scale overview of the electricity consumption patterns over 2 years. Further, 8 meters with high EEI values have been selected among 52 sites. The EEI values for the selected 8 meters over 2 years data has been shown in Table 2.

Heatmap of wholesale price

For strengthening the analysis, it is important to attain a visual representation of the wholesale price of electricity. Figure 2 shows the heatmap for the wholesale price of electricity for 2018. The raw data was gathered from AEMO (Australian Energy Market Operator) and it provides an overview of the fluctuations of price depending on the day (of the week) and hour (of a day).

It can be noted that the darker regions of the heatmap lie between 7AM – 9AM and 6PM - 8 PM. This reflects the daily routine of the household energy usage patterns, where the darker regions and lighter regions occurs respectively when people wake up (7AM – 9AM) and when they have dinner and go to bed (6PM - 8 PM). Further, it is evident that days 6 and 7, which are Saturday and Sunday, respectively, are lighter in colour, indicating that the price of electricity reduces over the weekend.

Since the wholesale electricity price is dependent on supply and demand, it is useful for industries to avoid consumption during the peak times. Conversely it would be highly useful to consume electricity during off-peak time as it is evidently less expensive. Although the price difference is not a large amount, over time the cumulative effects are enormous, therefore it is important for water utilities to know when they consume their electricity.

Implementation of solution #1 (load shifting)

Based on Figure 2, it was established that the peak times where electricity prices are more expensive lie between 7AM – 9AM, and between 6PM – 8PM. The off-peak hours for electricity usage are 1AM – 6AM. Therefore, the electricity consumption has been shifted from peak time (7AM - 9AM,

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6PM – 8PM) to off-peak time (1AM – 6AM) in steps of 5% from 5% up to 20%. This is done to essentially consume more electricity when the price of electricity is cheaper.

Figure 3 presents the heatmaps of load shifting operation, such as (a) original load, (b) 5% shift, (c) 10% shift, (d) 15% shift, and (e) 20% shift of peak load to off-peak hours. As presented in Figure 3(a)

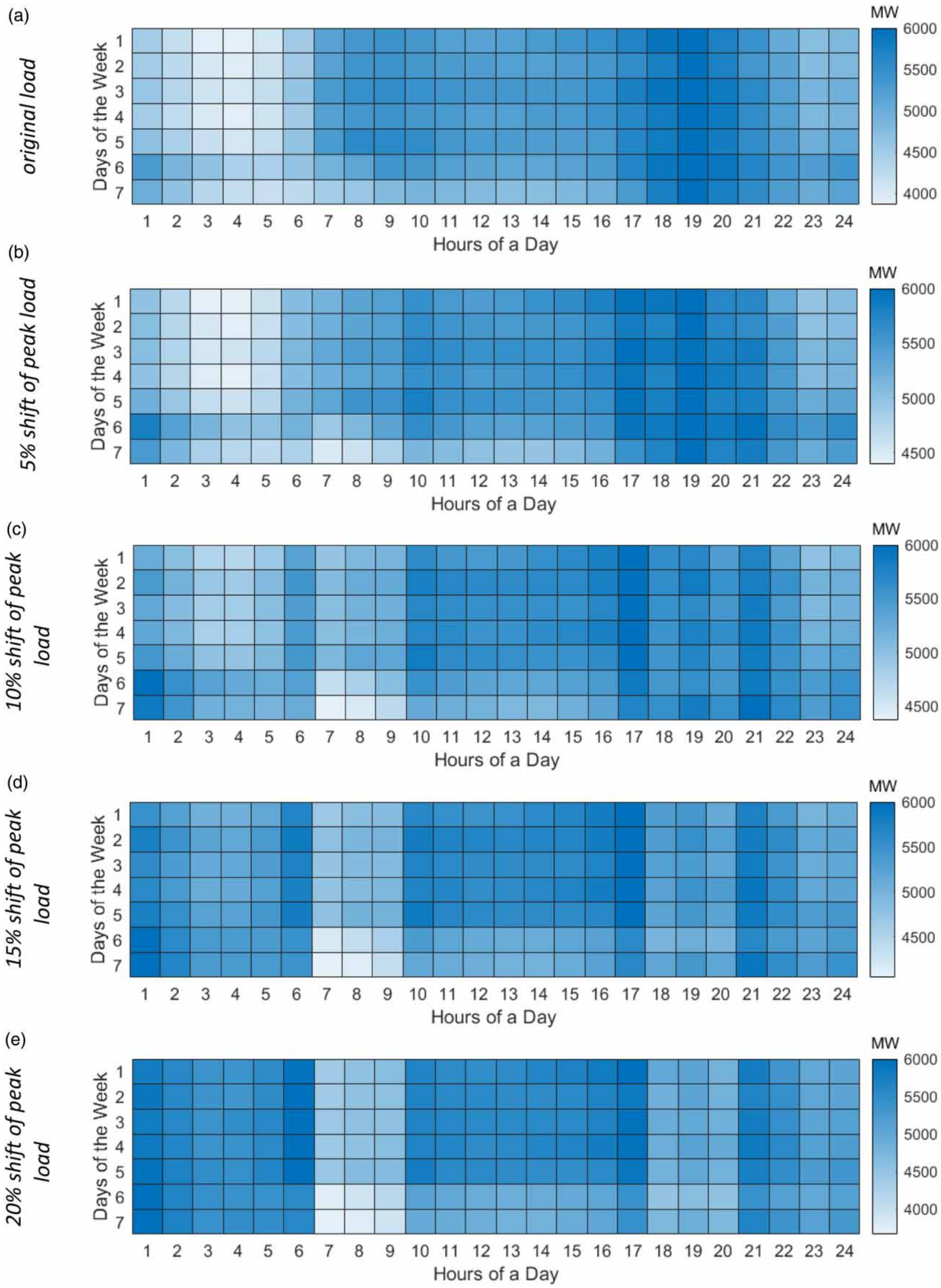

Figure 3 | Heatmaps showing load shifting operation: (a) original load, (b) 5% shift, (c) 10% shift, (d) 15% shift, and (e) 20% shift of peak load (7AM - 9AM in the morning and 6PM - 8PM in the evening) to off-peak (1AM – 6AM) hours.

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original load scenario, shows the electricity consumption of a WTP and WWTP. As the electricity price is higher between 7AM – 9AM and between 6PM – 8PM, and the electricity price is low during 1AM – 6AM, electricity consumption has been shifted from peak hours to off-peak hours, by 5, 10, 15, and 20%, in Figure 3(b)–3(e), respectively. Consequently, due to the load shifting operation, system peak hours 7AM – 9AM and 6PM – 8PM become lighter and off-peak hours 1AM – 6 AM become darker. This is done to reduce consumption at a higher electricity price and increasing consumption during a lower electricity price.

Implementation of solution #2 (price fixing)

Solution 2 revolves around attempting to replicate a scenario where an agreed fixed electricity rate would be payed to the electricity retailer by the water utility, under contract terms. In this case, average electricity price is considered as the contract price, which corresponds to the average electricity price from two years Australian (Victoria state) market price. This is done to avoid any conflict with the non-disclosure agreement, as the contract electricity price is confidential business information.

Once the fixed averaged electricity price is decided, the EEI has been calculated for a fixed price scenario. For a fixed price scenario, all EEI values have been reduced to 1, which is expected because by fixing the electricity price at the two-yearly average, the volume weighted electricity price was now equal to the time-weighted electricity price, due to the elimination of price fluctuations over the analysed data period.

The total costs for running each meter both before and after the price fixing had been applied over the 2-year period of given data. It has been observed that the fixed price contract can ensure savings across all meters. This finding validates the use of this technique as an alternative option to load shifting, as no rescheduling of usage time would be required.

Savings, improvement in EEI, and overall savings

Tables 3–5 demonstrate the impact of load shifting and price fixing operation on savings in AUD, savings in percentage, and reduction in EEI, respectively. The load shifting amount has been considered as 5%, 10%, 15%, and 20%. The actual amount of flexible or shiftable load may vary depending on the WTP and WWTP sites. When observing the results in Tables 3–5, there was a direct correlation between the highest EEI value reductions and cost savings. It can also be noted that fixing electricity prices could be an effective method of cost saving for some WTPs and WWTPs.

It can be observed from Table 3 that load shifting may bring cost savings proportional to the amount of load shifted. Hence, the cost savings increase proportionately from 5% to 20% cases. However, the amount of shiftable load may be different in reality for different sites. Also, the amount of savings is

Table 3 | Savings in AUD in 2 years from 8 selected water and wastewater treatment plants in 2017–19

Meter No.	Original cost	5% Shift savings	10% Shift savings	15% Shift savings	20% Shift savings	Fixed price savings
Meter ID 1	$133,505	$7,178	$14,356	$21,533	$28,711	$27,014
Meter ID 2	$42,500	$1,179	$2,359	$3,538	$4,717	$5,381
Meter ID 3	$104,162	$3,935	$7,869	$11,804	$15,738	$11,441
Meter ID 4	$47,799	$333	$665	$998	$1,330	$1,641
Meter ID 5	$19,960	$233	$465	$698	$930	$1,760
Meter ID 6	$48,693	$555	$1,109	$1,664	$2,218	$3,113
Meter ID 7	$19,847	$343	$687	$1,030	$1,373	$1,147
Meter ID 8	$71,410	$2,617	$5,235	$7,852	$10,469	$6,874

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Table 4 | Savings in % in 2 years from 8 selected water and wastewater treatment plants in 2017–19

Meter No.	Original cost	5% Shift savings	10% Shift savings	15% Shift savings	20% Shift savings	Fixed price savings
Meter ID 1	$133,505	5.40%	10.81%	16.21%	21.61%	20.23%
Meter ID 2	$42,500	2.83%	5.65%	8.48%	11.30%	12.66%
Meter ID 3	$104,162	3.82%	7.63%	11.45%	15.27%	10.98%
Meter ID 4	$47,799	0.73%	1.46%	2.20%	2.93%	3.43%
Meter ID 5	$19,960	1.20%	2.39%	3.59%	4.79%	8.82%
Meter ID 6	$48,693	1.18%	2.35%	3.53%	4.70%	6.39%
Meter ID 7	$19,847	1.77%	3.54%	5.31%	7.08%	5.78%
Meter ID 8	$71,410	3.70%	7.39%	11.09%	14.79%	9.63%

Table 5 | Improvement in EEI due to load shifting and price fixing from 8 selected water and wastewater treatment plants in 2017–19

Meter No.	Original EEI	5% Shift EEI	10% Shift EEI	15% Shift EEI	20% Shift EEI	Fixed Price EEI
Meter ID 1	1.25	1.19	1.13	1.07	0.98	1.00
Meter ID 2	1.15	1.12	1.08	1.05	1.02	1.00
Meter ID 3	1.12	1.08	1.04	1.00	0.95	1.00
Meter ID 4	1.04	1.03	1.02	1.01	1.01	1.00
Meter ID 5	1.10	1.08	1.06	1.05	1.05	1.00
Meter ID 6	1.07	1.05	1.04	1.03	1.02	1.00
Meter ID 7	1.06	1.04	1.02	1.01	0.99	1.00
Meter ID 8	1.11	1.07	1.02	0.98	0.94	1.00

different for different sites depending on the total consumption and consumption patterns. The same trend is evident in Table 4 for percentage cost savings (which is obvious) and Table 5 for EEI.

As shown in Table 5, some EEI values are unable to be reduced below 1 even with up to 20% load shifting applied. This occurred because the power consumption data for these meters (IDs:2,4,5,6) appeared to have a very scattered daily load profile, indicating that there were no identifiable daily power consumption trends. A predictable daily profile allows significant cost cuts to be achieved by precisely manipulating its profile with load shifting. With the daily load profiles being so unpredictable, it was very difficult to perform accurate load shifting for better load management. As a result, the most saving achieved in these situations may come from the fixed price method.

CONCLUSIONS

This research presents electricity cost reduction by electricity profiling and demand management. Both demand shifting and fixed price contract may result in the reduction of EEI values and electricity costs. Fixed price contracts can bring EEI down to 1, whereas demand shifting may take that to below 1 (and save more). The solution will be dependent on the amount of controllable demand of the individual WTP and WWTP site. Based on the consumption patterns, individual sites may require a customized solution approach.

The EEI has been calculated for 8 WTPs and WWTPs, by using Equation (1). Sites with high EEI values have been chosen to implement EEI reduction approaches, which are (i) option 1: fixed price contract, and (ii) option 2: time-of-use shifting. It has been found that the example site may save more than 20% of its annual electricity bill by (option 1) signing a fixed price market contract. On the other

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hand, it may save 22% of its annual electricity bill by (option 2) shifting 20% of its peak demand from peak period to off-peak demand; that is, the late-night period.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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