

Analysis of energy efficiency and energy consumption costs: a case study for regional wastewater treatment plant in Malaysia

Nor Azuana Ramli and Mohd Fairuz Abdul Hamid

ABSTRACT

The objective of this study is to analyze the possibilities of increasing energy efficiency in the central region wastewater treatment plant by focusing on two aspects: biogas production and prediction of energy production. The analysis is based on one of the biggest central region wastewater treatment plants in Malaysia. After studying the energy efficiency, which consists of optimization of energy consumption and enhancing gas generation, the prediction of power consumption is performed using an autoregressive integrated moving average (ARIMA) model. The prediction results are compared with the linear regression method. Comparison shows that even though the total cost of savings is greater by using linear regression, the prediction through ARIMA is more accurate and has smaller root mean square error. The implementation of these two aspects managed to increase energy efficiency by 10% of energy recovery that could further reduce electricity cost and reduction of sludge cake disposal off site. The study recommends other aspects, such as modification in setting up the frequency of variable speed drive for aerators and blowers and optimizing number of feeds into train unit processes within aeration tanks in increasing energy efficiency.

Key words | ARIMA, energy efficiency, energy optimization, energy production cost, wastewater treatment process

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INTRODUCTION

The United Nations stated that the current world population is expected to increase to 11.2 billion by the year 2100. This is a great challenge to water supply providers to provide people with access to clean water. In fact, access to clean and safe water is already a daunting task with the seven billion current population, with the ratio to (not) getting clean water being 1:10. One solution to this problem is to find another source of clean water. Wastewater treatment is a process to convert wastewater into an effluent that can be returned to the water cycle with minimal environmental issues. One cubic meter of

regional wastewater contains sufficient water supply for 5–10 people per day.

Electricity is the major significant cost contributed to the total cost operational expenditure (OPEX). Malaysia's Indah Water Konsortium reported ([Indah Water Konsortium Sdn Bhd \(IWK\) 2010](#)) electricity cost was RM 152.50 mil in 2010 and the figure could be seen to increase since 2007. Electricity cost also is the highest contribution of total regional wastewater treatment plant expenses, followed by parts and contractor costs, other operating expenses, salary-related overheads and office rental and premises. Electricity cost is expected to increase over the years as the number of plot ratio and density of developments within regional wastewater treatment plant keeps increasing more than is allowable in urban areas to connect to the

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existing sewer line. According to the energy expenses record available from 2003 until 2010, data indicated that the energy consumption started to rise from 2006. The quantum of the energy increased is formidable, with an increase from 17.3% in 2006, which peaked in 2008 with a 26.5% increase in energy cost. The annual electricity cost for the regional wastewater treatment plant is approximately RM 2.3 million which is the highest among all the cost elements in operating the plant. Therefore, the improvement of energy efficiency is needed in order to reduce the electricity cost, and hence decrease total cost OPEX.

Many studies have shown the enormous potential of increasing energy efficiency (Shi 2011). A general example is the Strass wastewater treatment plant in Austria, which has reached 108% of energy recovery through increasing energy efficiency (Wett 2007). Usually, energy management and optimization work across an entire wastewater treatment system in order to achieve energy efficiency. For example, aerators and blowers in the aeration tanks consume high energy components in actual operation but, at the same time, afford opportunities to tap a new potential for the cost reduction of electricity. Schneider Electric is a company in the United States that provides software to solve energy optimization problems for wastewater treatment; however, it is costly and therefore we have done our own analysis. In this study, improvement of energy efficiency is based on two aspects: first, to increase energy generation via increasing biogas production and electricity recovery by application of new combined heat and power generation systems; and second, to analyze the cost of operating a wastewater plant and predicting the energy usage. The autoregressive integrated moving average (ARIMA) is selected as our methodology in order to predict the energy usage and the prediction will be compared with linear regression.

In this paper, electricity consumption and generation are focused upon. In order to reach up to 10% energy efficiencies in the regional wastewater treatment plant, electricity generation within the range of 0.25 kWh/m³ to 0.40 kWh/m³ has to be achieved. Specifically, the paper is organized as follows. First, there is a brief explanation on the energy efficiency of the regional wastewater treatment plant including a baseline investigation. Then, the roadmap to high energy efficiency, which includes the two aspects that were mentioned earlier, is described. Next, the overall

results of energy efficiency and cost saving are presented before we end with a conclusion of our analysis and discussion about the potential for future research.

BASELINE INVESTIGATION

Since energy consumption and generation are the focus of this study, it is necessary to determine the main cause of the energy usage. By using a fishbone diagram, which is also known as the Ishikawa diagram, Figure 1 shows five main factors that contribute to the increase of energy usage. The first factor is the environment, where energy usage increases when the blower house becomes dirty. The energy usage also increases when extra aerators are used and the operation is run without properly setting up the frequency of the variable frequency drive (VFD) for blowers. Insufficient training of staff is a major human factor effect, which probably causes an increase of energy since the staff have designed the parameters wrongly. Ultimately, the majority of the causes of energy usage relate to machines, where the problems are triggered by aerators and blowers.

Calculation of energy usage by all the equipment is carried out after the analysis on the causes of the increase of energy usage is done. The calculation is based on the design of operating hours multiplied by the power rating of the equipment.

$$\text{Operating Hours Daily (h)} \times \text{Power Rating (kW)} = \text{kWh} \quad (1)$$

Table 1 shows the electricity consumption of the individual units.

Data from Table 1 indicate that the blower and aerator are two units that consumed the highest amount of electricity. However, lower energy consumption can be achieved through various approaches, and for aerator and blower some proposed actions that can be done in order to reduce energy consumption are given in Table 2.

In order to reach a higher percentage of energy efficiency in the regional wastewater treatment plant, proposed optimization measures alone are insufficient. Hence, we need other methods to help achieve electricity generation within the range of 0.25 to 0.40 kWh/m³, and these are discussed in the next section.

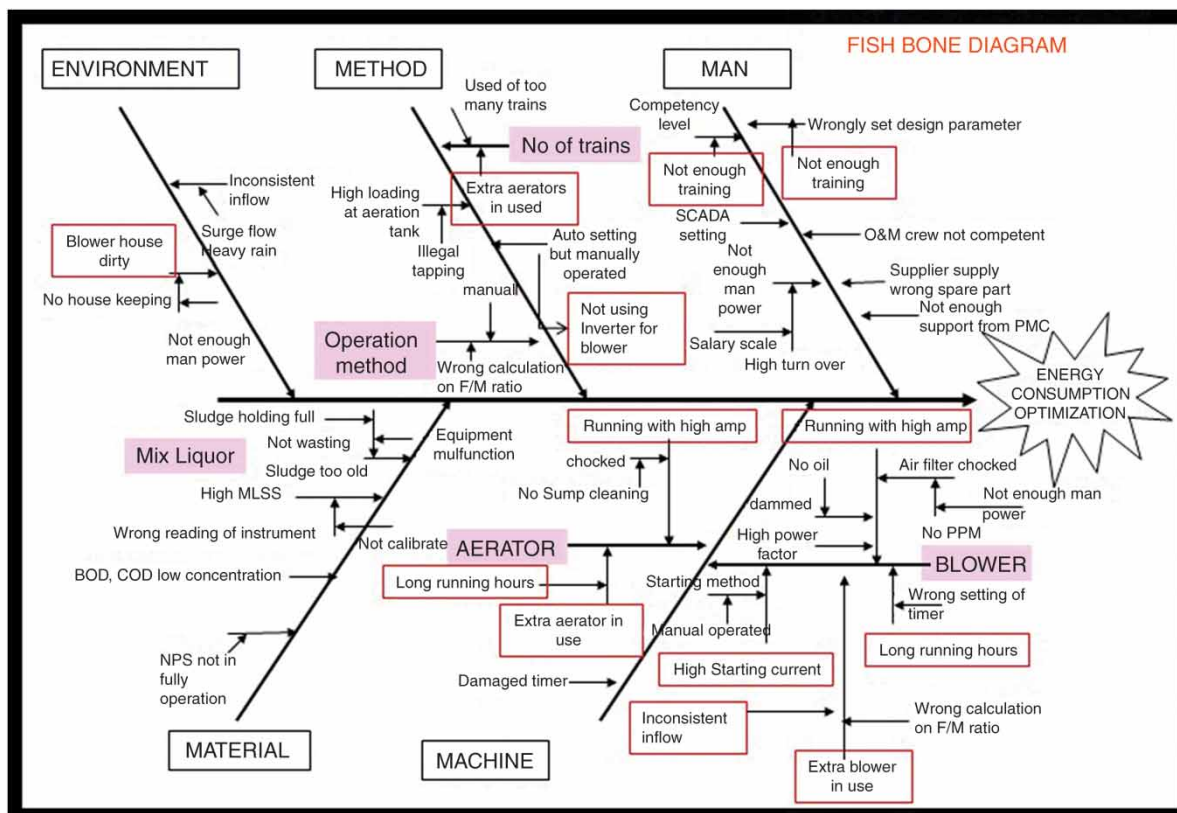


Figure 1 | Fishbone diagram used to find causes for the increase of energy usage.

Table 1 | Evaluation of equipment electrical consumption by design

No.	Unit/Equipment name	Electricity consumption, kWh/day	Percentage of energy consumption, %
1	Blower	9,061.29	0.44
2	Aerator	5,616.74	0.27
3	Return sludge pump	1,949.13	0.09
4	Auto. feed water supply unit	1,831.94	0.09
5	No. 3 anoxic tank mixer	766.11	0.04
6	Digested sludge mixer	484.35	0.02
7	No. 1 anoxic tank mixer	383.13	0.02
8	Secondary clarifier sludge collector	272.20	0.01
9	Sludge feed pump for dewatering	204.39	0.01
10	Sludge cake conveyor	179.76	0.01

ENERGY EFFICIENCY IN REGIONAL WASTEWATER TREATMENT PLANT

Energy efficiency is defined as the ratio of electricity generated to the electricity needed to operate the wastewater treatment plant

(Shi 2011). In this study, we defined energy efficiency as improvement of the system to reduce energy usage but at the same time maintaining full compliance with Environmental Quality Act (EQA) 2009 requirements and the effluent discharge standards. Reducing electricity consumption of the regional wastewater

Table 2 | Proposed optimization measures

No.	High energy consumption equipment	Proposed action
1	Submersible aerators	Optimize the feed into each treatment train thus reducing the number of trains in operation from 6 to 4 This, in turn, will reduce the number of aerators operating daily from 12 to 8
2	Blowers	Existing blowers are previously running on manual operation using soft starter at 50 Hz To supply and install VFDs at 40 Hz of the blower unit To control the blower operation automatically by delay timer

treatment plant can be carried out through improvement of both the hardware such as mechanical equipment and software such as process and operation (Metcalf & Eddy 2003). Through mechanical equipment and operation, there are many parameters that can be controlled such as sludge characteristics, sludge volume, and operation cycle. There is much related equipment as well to be operated by the digestion facility. Some of these parameters are observed and laboratory sample results used to determine gas production volume. In this section, steps on increasing biogas production will be discussed first before we proceed with the analytical analysis.

Enhancing electricity generation from biogas

A previous study by the Massachusetts Department of Environmental Protection demonstrated that many things can be done at the anaerobic digestion (AD) in order to save energy and one of them is by producing more biogas (Wong 2011). Three steps need to be performed in order to increase biogas production. First, is to increase the solid concentration of the activated sludge from the primary clarifier tank (PCT). The main objective of pre-concentrating is to retain a maximum amount of chemical oxygen demand (COD) in wastewater and transfer waste sludge to anaerobic digesters for higher biogas production and reduce oxygen demand at the biological process (aeration tank). Next is to reduce the volume of waste sludge from the secondary clarifier tank (SCT) to the thickened sludge holding tank (TSHT). Finally,

is to produce higher concentration at gravity thickener. To start, the solid concentration from the PCT to the anaerobic digester tank is measured and obtained from the calculation. This process is also known as developing mass and balance for optimal process selection and all the calculations are done using Microsoft Excel, as shown in Figure 2.

The existing wastewater treatment plant has to operate and be maintained to produce absolute effluent quality that complies to Standard B under the provisions of the EQA 2009. Standards have been established for the quality of effluent discharged from treatment plant to river. These absolute standards take the form of acceptable upper limits for various influent characteristic parameters defined by EQA 2009. Effluents from the treatment plant are regularly sampled and tested in laboratories to ensure that the standards are still met even after optimization has been applied.

The major indices that are measured consist of biochemical oxygen demand (BOD), suspended solids (SS), COD, oil and grease, ammoniacal nitrogen, nitrate nitrogen, and total phosphorus. The actual results from sampling showed there are some improvements in performance of the effluent standards after optimization, as shown in Table 3. Further efforts are needed to improve sampling of the dewatering process and digested sludge storage tank while maintaining full compliance with EQA 2009 requirements. After the PCT, the gravity thickener should produce solid concentrations up to approximately 2.3% based on sampling observation. Subsequently, the TSHT should increase the volume of the PCT with sludge and at the same time reduce the SCT. By increasing the waste sludge from the PCT, the organic loading to the aeration tank will be reduced proportionally and result in less sludge waste in the SCT.

Reduction of sludge cake volume sewage is important to minimize impacts to the environment and reduce the operation costs. Sludge produced from the treatment process is usually in liquid form, which typically contains 0.25 to 4.0% of solids, depending on the type of treatment process. It also contains grease, fats, organic and inorganic chemicals. High concentrations of certain components will determine the type of sludge treatment process to be used. Sludge should be thickened, stabilized, conditioned and dewatered before it is finally disposed of, following the requirement stipulated by the Department of the Environment. The dried sludge must attain a minimum of 20% dry solid content before off-site disposal.

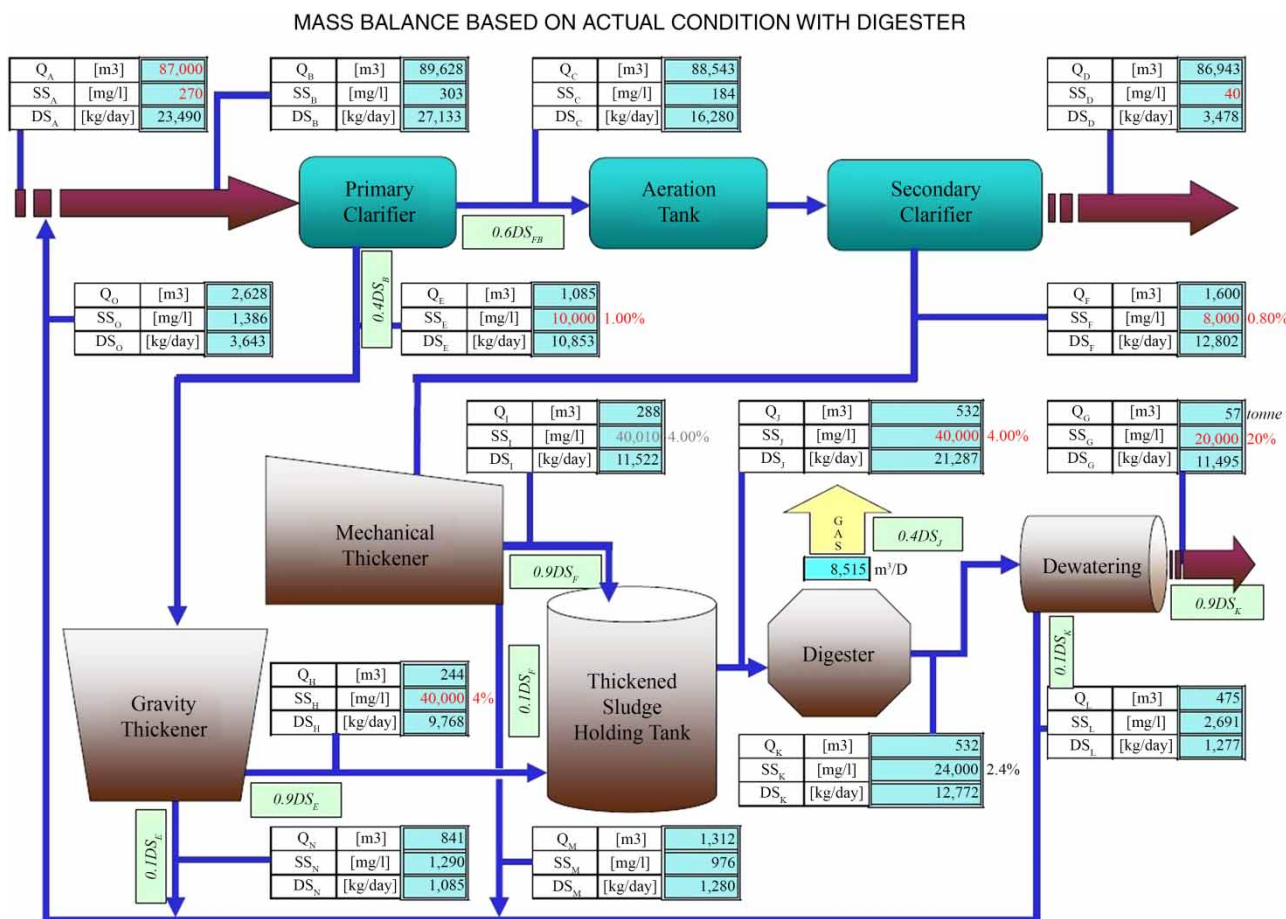


Figure 2 | Developing mass and balance for optimal process selection.

Table 3 | Characteristics of influent and effluent standards for the main parameters

Items	Influent sewage		Effluent Standard B	
	Absolute	Actual sampling	Absolute	Actual sampling
BOD	250	120–180 mg/L	50	2–2.5 mg/L
SS	300	180–220 mg/L	100	2–4 mg/L
Total nitrogen	50	28–33 mg/L	50	5–12 mg/L

Additional sampling and testing, mainly on the solid content, are performed for verification purposes. Reliable key parameters and data are adopted in verification of the value reported (for example, sludge retention time (SRT) of the activated sludge process used to check flow and solid concentrations of waste activated sludge; volatile suspended solid destruction, biogas production and composition of anaerobic digesters used to check solids concentrations entering and

existing the digester; dewatering cake composition used to check TSS after digesters and flow of dewatering concentrate). Table 4 shows the production of sludge cake before, and our target after developing mass and balance for process selection.

A part of the above process, solids' treatment process, plays an important role too as it is closely related to electricity recovery in the regional wastewater treatment plant. The design and operation of the PCT and activated sludge process

Table 4 | Reduction and saving of sludge cake production volume

Sludge cake yard	Production of sludge cake	
	Before	Target
Reduction of volume (ton/day)	57	41
Saving sludge disposal and transportation (%)		39
(RM/annual)		438,000

have a direct impact on the amount of sludge sent to anaerobic digesters for better enhancement of biogas. The amount of primary sludge depends on the removal efficiency of the primary clarifiers, which varies from 40 to 60% for TSS removal. Enhanced precipitation is employed in enhancing preliminary treatment (EPT) aimed to increase the amount of primary solid from PCT and sending it to anaerobic digesters to increase biogas production, also to reduce oxygen demand and biomass produced in the secondary biological process (aeration tank).

Similar to the EPT process, the primary goal of this type of fast activated sludge process is a diversion of more organics from the liquid stream to the solid stream to increase energy recovery. This type of activated sludge process has the features of short SRT and hydraulics retention time. AD involves bacterial decomposition of the bio-solid organic constituents in the absence of oxygen. Besides solids, the products of AD include water and biogas composed of methane, carbon dioxide, hydrogen sulfide, and other minor gases with methane as the major component.

Appropriate optimal design process control and efficient operation of the anaerobic digester involves employing proper feeding patterns, SRT, mixing and recycling. The ratio of primary and secondary sludge is an influencing factor as well. Also, the thicker the sludge from the primary clarifier and secondary clarifier, the more biogas is produced, as indicated by the correlation between gas production and COD/BOD mass loading. Increasing TSS concentration of the sludge through thickening may be beneficial for greater biogas production. Hence, the sludge treatment process will be configured to operate efficiently, thus reducing the active power of the respective equipment at the biomass process (aeration tank).

Energy consumption, energy generation and cost analysis

The performance indicator (PI) used in this study is the cubic meter of sewage treated per day. As such, the energy units will be measured in kWh/m³ sewage treated per day. The current energy performance indicator (EnPI) before the analysis was 0.44 kWh/m³. The target and expected reduction is about 10%. Thus, it is expected that the EnPI after the analysis is 0.40 kWh/m³ or less. Based on an average flow of 1.3 million m³/month of flow, the reduction in electrical energy usage is $1,300,000 \times (0.44 - 0.40) = 52,000$ kWh and the estimated

saving is $52,000 \times \text{RM } 0.337/\text{kWh} = \text{RM } 17,524/\text{month}$. As the plant equipment and processes do not have any sub-meters and the regional wastewater treatment plant does not possess any electrical meter for monitoring at that time, the only way to verify the savings is through electricity bills. The usage and cost from the electricity bills is evaluated for at least six months before and after the analysis.

Prediction of energy consumption by using ARIMA

ARIMA method is selected to be applied in our analysis because it allows deeper understanding of the data and can be used to predict future points in the series. Before embarking on the cycle, the first step to take is to examine the time plot of the data and to judge whether it is stationary or not. Many time series are nonstationary and the ARIMA model supports the type of nonstationarity by simple differencing. In fact, one or two levels of differencing are frequently enough to reduce a time series. The three parameters in the ARIMA model are the number of differencing, d , the number of autoregressive, p , and the number of moving average, q . A general model of ARIMA is written in the form:

$$x_t = A + \varphi_1 x_{t-1} + \varphi_2 x_{t-2} + \cdots + \varphi_p x_{t-p} + b_t - \theta_1 b_{t-1} - \theta_2 b_{t-2} - \cdots - \theta_q b_{t-q} \quad (2)$$

where t is the periodic time, x_t is the numerical value of an observation, φ_i for $i = 1, 2, \dots, p$ are the autoregressive parameters, θ_j for $j = 1, 2, \dots, q$ are the moving average parameters and b_t is the shock element at time t .

In this analysis, the active power (kWh) will be the forecasted variable. The following procedure is used to model an ARIMA, where by using Time Series Modeler in the SPSS software, we can get the best ARIMA model. From SPSS, the best ARIMA model that should be used based on our data is ARIMA (0,1,0). This model allows prediction for energy consumption to be obtained and these results can be used as guidelines for energy efficiency.

RESULTS AND DISCUSSION

The results from our analysis are separated into two parts: enhancement of biogas production and predicting the energy

Table 5 | Digester performance before and after CIP phase 1

Item	Before CIP (2013)	After CIP (phase 1–2014)	Design
Bio-gas generation (m ³ /day)	876.55	1,307.29	9,000
Feed sludge volume (m ³ /day)	353.69	481.31	600
Feed sludge density (%)	0.6	0.94	4
Hydraulic retention time (day)	31.88	28.59	30
Temperature (°C)	31	30	31
pH	6.54	6.77	6.7–7
Digester operation (unit)	3	3	4

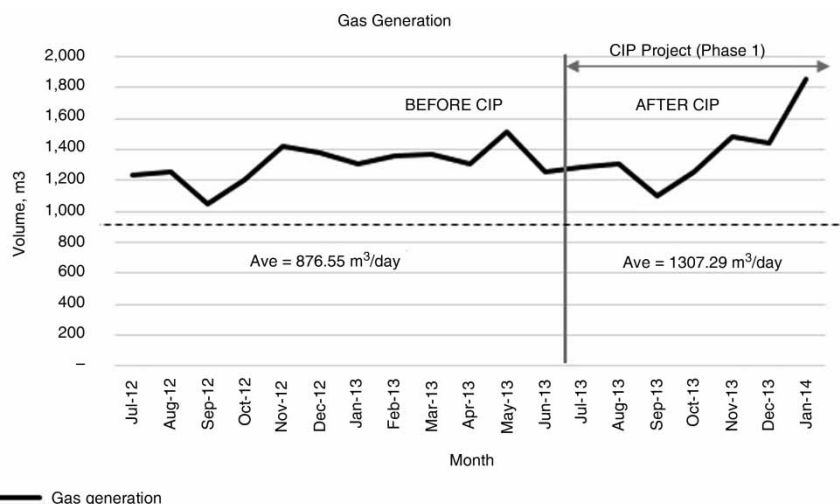
consumption. After implementing three steps, which we called continuous improvement project (CIP), we obtained results to show the increase of biogas that can help to reduce active power for equipment in the aeration tank. First, by increasing TSS concentration of the sludge through thickening, the volume of gas generation has been increased from 876.55 m³/day (which is around 9.7% of the design) to 1,307.29 m³/day (14.5% of the design), as shown in Table 5 and Figure 3. In Figure 3, the solid line indicates average of volume gas generation before CIP while the dashed dotted line is the actual monthly gas production taken from the regional wastewater treatment plant after on-site process alteration. The results also show improvements in terms of pH, which is closer to the design, and the hydraulic retention time is shorter than before.

Table 6 | Digester performance and improvement of the volume of biogas generation

Item	Before CIP	After CIP (phase 1)	Ultimate CIP (phase 2)
Bio-gas generation (m ³ /day)	876.55	1,307.29	1,850.07
Feed sludge volume (m ³ /day)	353.69	481.31	612.24
Feed sludge density (%)	0.6	0.94	1.30
Hydraulic retention time (day)	31.88	28.59	30.33
Temperature (°C)	31	30	31
pH	6.54	6.77	6.75
Digester operation (unit)	3	3	4
Sludge cake generation (ton/day)	40–60	30–40	30–40

The first stage of the CIP (2013) project has achieved the target to increase biogas generation from an average 876.55 to 1,307.29 m³/day, shown in Table 6. The second stage of the CIP (2014) project has achieved the target to maintain and optimize biogas generation. To date, biogas generation has maintained an average of 1,850.07 m³/day.

By using ARIMA, prediction on the energy consumption can be obtained and the results are plotted with actual values and prediction by using linear regression, as shown in Figure 4. Based on the graph, we can see that ARIMA has a better prediction which is close to actual values compared to linear regression. In addition, ARIMA produced less error than

**Figure 3** | Enhancing gas generation under CIP.

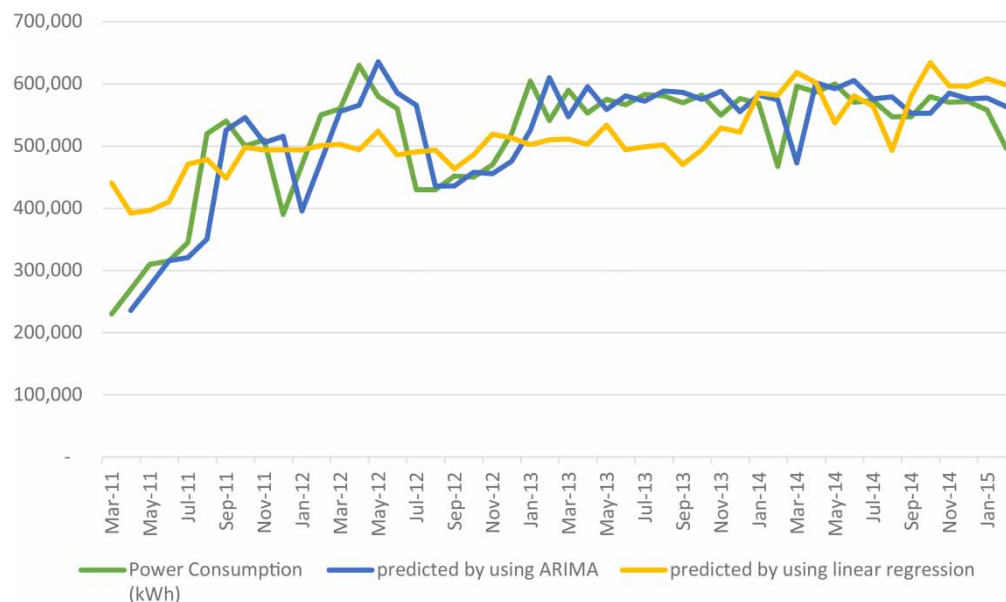


Figure 4 | Results on prediction power consumption with difference between prediction using ARIMA and linear regression and actual value.

linear regression with root mean square error 55,598.591 and 67,505.649, respectively. By using ARIMA prediction results, the differences between actual and prediction energy consumption are calculated, followed by cumulative summation of the differences and, finally, the amount of costs from energy consumption that can be saved (RM 36723.61) is obtained. By increasing biogas production and using prediction analysis to save energy consumption, the results showed that the EnPI can be reduced from 0.44 to 0.39 kWh/m³, which corresponded to the objective of this study.

CONCLUSION

Electricity cost is one of the major expenses in operating wastewater treatment. In order to reduce the cost, energy efficiency needs to be implemented. By using a fishbone diagram and calculation of the energy usage by all equipment, we found that most of the energy consumption is by blowers and aerators. To optimize the energy consumption, several actions are taken, such as a proposal on optimization measures for both aerators and blowers, as well as predictions on energy consumption by using ARIMA and increases in biogas production. From the results obtained through the ARIMA

model, the EnPI can be reduced from 0.44 to 0.39 kWh/m³ and the amount of production cost that can be saved is RM 36723.61. To sum up, the objective of this study is achieved without compromising the main purpose of the regional wastewater treatment plant which is to treat sewage while complying with the EQA, Environmental Quality (Sewage) Regulations 2009. To obtain more accurate prediction results, methodologies from machine learning can be applied for future study.

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