

ENERGY ANALYSIS AND SUSTAINABLE OPERATION OF A WATER PURIFICATION PROCESSING PLANT

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Abstract - A water purification processing plant which employs a reverse osmosis technology was investigated in order to determine means to efficiently utilize energy in the provision of portable drinking water. The operational parameters of the operating units of the plant such as the rated power, operating efficiency and temperature were used to conduct the energy performance analysis of the plant. Also, the horsepower of the electrical generator employed as a power supplement and the average annual operating hours were used for the greenhouse gas (GHG) emission and carbon dioxide equivalents (CO₂e) analysis. The average operating hours of the electrical generator is 1092 hr/yr. The overall input and output energy of the plant as well as the plant energy efficiency were determined as 200.39 and 165.08 MJ, and 82.38% respectively. The greenhouse gas (GHG) emission and carbon dioxide equivalents (CO₂e) of the generating set reduces from 115.258 to 14.407 tons/yr as the horsepower of the generator reduced from 110 kVA (184.32 hp) to 13.75 kVA (23.04 hp) accordingly. Employing solar energy for powering the pumps operation instead of conventional electricity and generators helps in mitigating the use of fossil fuel generator, and lessen operational cost, air pollution and emissions respectively.

Keywords - Water purification, Energy efficiency, Solar energy, Emissions

I. INTRODUCTION

Privately owned water processing plants are on a steady rise in the world. Aside from multinational corporations playing a key role in fresh water supply chain, global trade agreements and international development organizations, such as the International Monetary Fund (IMF) and the World Bank are increasingly promoting the privatization of fresh water supplies [1]. Inadequate access to fresh clean water continues to be a source of concern in many developing countries, both in the rural and urban areas. Reasons for this predicament are inadequate social infrastructure, such as electricity and water processing plants and accompanying water supply piping-network facilities. This persistent situation has led to thriving privately owned small and medium scale water processing plants in cities across developing countries in Sub-Saharan Africa. Some of the newly commissioned commercial water processing plants are beginning to employ the reverse osmosis technology to improve the quality of fresh drinking water. Like every energy dependent industry, it is essential for energy to be effectively and efficiently utilized in this emerging sector of the economy so that the proprietors of the industry would be able to operate sustainably and provide potable drinking water to the teeming masses at affordable prices.

Viable water processing industries in various countries is paramount to meeting the Millennium Development Goals, which includes reducing by half the proportion of people without access to safe drinking water and basic sanitation in the second decade of the 21st century. The World Health Organization (WHO) and the United Nations

Children's Fund (UNICEF) reported in 2012 that about 780 million people around the world lack access to clean drinking water [2]. Availability of fresh drinking water sources is regularly becoming an important issue, especially in regions with limited amount of water [3]. It was discovered that in China, close to 80% of major rivers are so degraded that they no longer support aquatic life, while 90% of the groundwater is contaminated, and less than 25% of the population of Pakistan has access to clean drinking water [4]. About half of the water in drinking water supply systems in the developing world is lost to leakage, illegal hookups, and vandalism [5]. Over 75 % of all diseases in developing countries are attributed to the consumption of polluted water or the lack of sanitary installation [6]. Accessibility to fresh clean water is required to interrupt the transmission of trachoma, the leading infectious cause of blindness worldwide [7]. Energyanalyses have been used by several researchers to analyze industrial plants and systems, such as, the performance of hybrid photovoltaic thermal air collector systems; malt drink production and fruit juice processing industries; system components of a steam power plant; and steam production and distribution system including alternatives to throttling and the single pressure steam production [8-12]. Energy balance is a means to quantitatively interpret a thermodynamic analysis based on the first law of thermodynamics. Energy efficiency is a useful decision making tools for thermodynamic processes. Energy analysis along with exergy studies usually helps to point to possible areas requiring improvement and enhanced performance of energy systems [13]. Most researches only studied the reverse osmosis system and units

directly involved in processing of the feed stream, and not the entire processing plant [14-16]. Subsequently, any industry involved in water purification processes must seek to improve the performance of the entire industrial-value chain in other areas of units' operations.

Previous studies on water purification processing plants only focused on the first and second law efficiencies analysis, and never really pay attention on alternative use of energy sources and possible implications on the environment and cost of operation. This study focuses on energy analysis of a reverse osmosis water purification plant in order to determine means to efficiently utilize energy in the provision of portable drinking water. Furthermore, to find ways of minimizing operational cost, air pollution and emissions respectively.

II. DESCRIPTION OF THE REVERSE OSMOSIS (RO) WATER PROCESSING PLANT

The study was conducted at university of Ilorin water processing factory located in Ilorin, Nigeria. The facility employs a reverse osmosis technology for water purification. There are eleven major operating units involved in the entire plant to produce clean water fit for drinking as shown in Fig. 1 and Table 1. The plant utilizes a submersible pump capable of operating optimally continuously for about 5-7 hours at a time. Aside of purifying the water, other processes undertaken by the plant in the post purification processes, include washing and blowing of water bottles, filling and capping, batch coding and packaging respectively. The machines used for the

post-water purification processes are included in Table 1. Raw bore-hole water is usually pumped from beneath the ground surface via a submersible pump, and stored in overhead tanks of 5000 liters' capacity each. The submersible pump was capable of delivering up to 5000 liters of water in 1.5 hours, which is at a rate of 3,333.33 liters/hour at peak operating conditions. Additives are added to the stored water before further processing in order to help disinfect the raw water. The water was passed through composites (sand composite and carbon composite). The sand composite helps in removing sand and stones in the water while the carbon composite helps to remove odor and also improve the appearance. The water was then passed through ultra-filters placed in the path of flow of the disinfected water. The water was then stored in treated tanks. The treated water was further passed through an ultra-filter. The entire process described above occurs outdoor.

The outdoor water was pumped from the treated tank to the reverse osmosis (RO) system via an ultra-filtration system. Clean water was then separated from salts and other contaminants which are either retained or rejected. The water leaving the RO system was further treated by an ultraviolet radiation ozonizer (UV-type ozone generator). The ozonation process involves ozone to form oxides with iron, manganese, and sulphur in the water to produce insoluble metal oxides or elemental sulphur particles which are then removed by post-filtration [17]. The clean purified water was stored in a storage tank, ready for packaging prior to consumption.

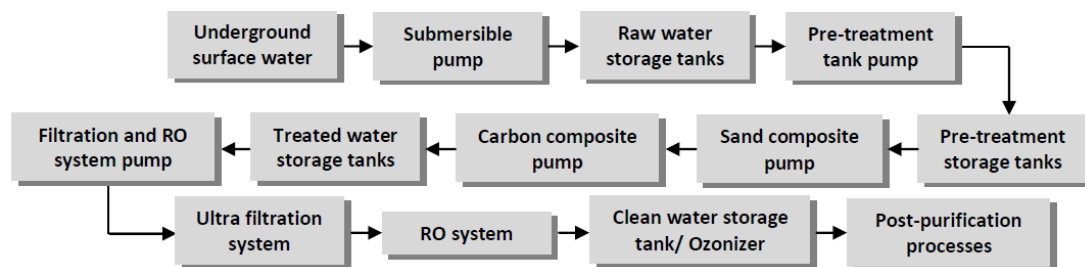


Fig. 1. Flow diagram for the reverse osmosis water processing plant.

III. METHOD

A. Data collection

Vital information required for conducting a detailed energy analysis of the plant were collected by direct investigation of the plant and inquisition of the plant

personnel and other secondary sources. The data included operating units; rated power; operating efficiency; operating temperatures; generator specification, etc. associated with the plant operation as presented in Tables 1 and 2 respectively.

Operating units	Rated power (kW)	Operating efficiency (%)	Average operating temperature (°C)
1. Submersible pump	0.75	80	60.00
2. Pre-treatment tank pump	0.75	80	75.00
3. Sand composite pump	0.75	80	75.00
4. Carbon composite pump	0.75	80	75.00
5. Filtration and RO system pump	1.50	80	75.00
6. RO system	1.50	90	25.00

7. Ozonizer	0.14	90	30.00
8. Washing and blowing machine	0.55	75	45.00
9. Filling and capping	0.75	80	65.00
10. Batch coding machine	1.00	90	40.00
11. Packaging machine/compressor	1.50	80	210.00

Table 1. Operational parameters of operating units of the plant.

Property specification	Value
Depth of well	55.05 m
Distance from well location to raw water storage tanks	51.21 m
Inlet pressure of RO system	0.25 MPa
Flow rate of RO system	1000 kg/h
Generator rating	110 kVA
Generator motor efficiency	80%
Generator load during operation	60-70%
Generator fuel	Diesel
Rate of fuel consumption	11.43 litres/h
Operation time	7 hours
Calorific value of diesel fuel	35.70 kJ/litre
Electrical power factor	0.80

Table 2. Some related data of the operating plant.

B. Analytical method

1. Energy analysis of operating units and the plant

The output power of each operating unit of the plant can be obtained from their respective operating or energy efficiency and rated power which is taken as the input power to the units as presented in Table 1. The output powers for the operating units were determined by:

$$\eta_{op} = \frac{P_{out}}{P_{in}} \quad (1)$$

where, η_{op} = operating efficiency, P_{out} = output power, and P_{in} = input power.

Subsequently, the input and output energy of each operating unit is expressed by Eqns. (2) and (3) as follows:

$$E_{in} = P_{in} \cdot t \cdot f \quad (2)$$

$$E_{out} = \eta_{op} \cdot P_{in} \cdot t \cdot f \quad (3)$$

where, t and f are the time in seconds and power factor respectively.

The energy efficiency of the plant can therefore be obtained by Eqn. (4):

$$\eta_{plant} = \frac{\sum E_{out}}{\sum E_{in}} \times 100\% \quad (4)$$

2. Energy transfer analysis of the plant generating set

The output power of the generating set was determined as follows:

$$\eta_{gen} = \frac{W_{out}}{W_{in}} \quad (5)$$

$$W_{in} = \frac{V \cdot I \cdot \sqrt{3} \cdot F \cdot L \cdot t}{1000} = \frac{kVA \cdot \sqrt{3} \cdot F \cdot L \cdot t}{1000} \text{ MJ/day} \quad (6)$$

where, η_{gen} is the generator motor efficiency; W_{in} and W_{out} are the inlet and output power in MJ/day of the generator; $V \cdot I$ is the product of voltage and current, which equals the kVA of the generator; F is the power factor; L is the generating load ($\approx 65\%$); and t in seconds is the operation time in seconds. Therefore, the efficiency of energy transferred to the plant from the generator is given by:

$$\eta_{gen-plant} = \frac{\sum E_{in}}{W_{out}} \quad (7)$$

3. Emission analysis of the plant generating set

The horsepower of the generating set can be determined as:

$$HP = \frac{kVA \times 1000}{746 \times \eta_{gen}} \quad (8)$$

Hence, by making use of the Engine Air Emissions Calculator for Small Business Environmental Assistance Program (SBEAP) [19], and the values of the generator horsepower and operating hours, the Potential to Emit and Actual Emissions Calculations were obtained.

IV. RESULTS AND DISCUSSION

A. Energetic performances of the processing plant

The operational parameters of operating units of the water purification processing plant presented in Table 2, namely: rated power, operating efficiency, operating temperature were used in conjunction with Eqns. (1) to (4) for the energy performance analysis of the plant. The energy input and output of 15.12 and 12.12 MJ were respectively obtained for the submersible pump, pre-treatment tank pump, sand composite pump, and the carbon composite pump. The equivalent values of the input and output energy

of these operating units was as a result of similarity in values of their rated power (0.75 kW) and operating efficiency (80%) accordingly. The highest input energy of 30.24 MJ was obtained for the filtration and RO system pump, RO system and packaging machine/compressor operating units due to the same values of their rated horse power (1.5 kW). The Ozonizer has the lowest input and output energy of 2.82 and 2.54 MJ because it possesses the lowest value of rated horsepower (0.14 kW). The overall input and output energy of the plant were determined as 200.39 and 165.08 MJ, and consequently the energy efficiency of the plant was obtained as 82.38%. The efficiency of energy transferred to the plant from the generator was determined as 10.01%. This implies that the capacity of generator required to supplement the energy requirement of the plant is only about 10% of the current capacity, that is, just 11 kVA generating set.

If about 15% of electrical energy is required for office operation and miscellaneous uses, then the actual capacity of supplementary generator required to run the entire plant and secondary energy demands would be 25% of current capacity or 27.5 kVA generating set. Furthermore, if a solar energy source is employed to power all the pumps of the plant and most of the office lightings and other accessories up to 50% of the initial 15%; the total energy input of the pumps to the total energy input of the plant would be 90.72 MJ: 200.39 MJ, that is 45.27%. Hence, employing a solar energy source can reduce the total energy of the plant facility by as much as 50%, leading to a required supplementary generator of only 13.75 kVA instead of the currently used 110 kVA, that is, 12.5% of the current capacity.

B. Emission and greenhouse gas generation of the processing plant

The emission and greenhouse gas generation of the processing plant was analyzed by mainly investigating the operation of the generating set employed as an auxiliary electricity power source to ensure continuous source of power to the plant when electricity outage is experienced from the national grid. Results of the greenhouse gas (GHG) emission and carbon dioxide equivalents (CO₂e) analysis of the generating set at average operating hours of 1092 hr/yr are presented in Tables 3 and 4. The generator rating of 110 kVA, equivalent to 184.32 hp accounted for the potential to emit and actual emissions of the pollutant shown in Tables 3 and 4. At the current usage, the generating set produces actual emissions of CO₂ (114.864 tons/yr), CH₄ (0.116 tons/yr) and N₂O (0.277 tons/yr) respectively; resulting in GHG total (CO₂e) of 115.258 tons/yr

It had been demonstrated in above analysis that the actual capacity of generating set for the entire plant facility is only 13.75 kVA instead of the currently used 110 kVA. Using the horsepower equivalent of 13.75 kVA (23.04 hp) and estimated operating hours of 1092 hr/yr, the reduced values of actual emissions are obtained as: CO₂ (14.358 tons/yr), CH₄ (0.015 tons/yr) and N₂O (0.035 tons/yr) respectively; resulting in GHG total (CO₂e) of 14.407 tons/yr This shows a reduced value in GHG total (CO₂e) of 12.5% of the initial of the initial 115.258 tons/yr In otherwise, the GHG total (CO₂e) have been mitigated by 87.5% when appropriate energy transfer efficiency and solar energy source was considered. Also the potential to emit was reduced from 924.593 to 115.574 tons/yr for the GHG total (CO₂e).

Pollutant	Emission Factor (lb/hp·hr)	Emission Rate (lb/hr)	Potential to Emit (tons/yr)	Actual Emissions (tons/yr)
PM	0.0022	0.406	1.776	0.221
PM10	0.0022	0.406	1.776	0.221
S0x	0.00205	0.378	1.655	0.206
N0x	0.031	5.714	25.027	3.120
VOC	0.002514	0.463	2.030	0.253
CO	0.00668	1.231	5.393	0.672
Lead	-	-	-	-

Table 3. Emission analysis of the generating set operation at an average of 1092 hr/yr

Pollutant	Global Warming Potential	Emission Factor (lb/ hp·hr)	Emission Rate (lb/hr)	Potential To Emit (ton/yr)	Actual Emissions (ton/yr)
CO ₂	1	1.14135	210.374	921.437	114.864
CH ₄	25	0.00004627	0.009	0.934	0.116
N ₂ O	298	0.00000924	0.002	2.223	0.277
GHG Total (CO ₂ e)				924.593	115.258

Table 4. Green House Gas (GHG) Emissions and (CO₂e) analysis.

CO₂e = carbon dioxide equivalents

V. CONCLUSION

The study involves the investigation of energy analysis of a water purification processing plant. The plant utilizes a supplementary energy source from a diesel generator to guarantee constant electricity supply whenever power outage is experienced from the national grid. The operating units with rated power of 0.75 kW and operating efficiency of 80% resulted in energy input and output of 15.12 and 12.12 MJ respectively. The overall input and output energy of the plant was obtained as 200.39 and 165.08 MJ, resulting in energy efficiency of the plant of 82.38%. The actual capacity of electrical generator required to supplement the energy requirement of the plant operation was determined to be only about 10% of the current capacity, that is, 11 kVA instead of 110 kVA. If solar energy is employed to power the pumps in the plant, and at the same time employing an optimum energy transfer from supplementary generating set to the plant facility (main plant, office equipment, etc.), a supplementary generator of only 13.75 kVA would be needed for the entire plant and other facilities instead of the currently used 110 kVA, which is just 12.5% of the current capacity. The use of an electrical generator is an issue of concern as far as a sustainable environment is concerned. Hence, it is necessary to find ways of mitigating the consequences of using a fossil fuel energy source. Furthermore, the greenhouse gas (GHG) emission and carbon dioxide equivalents (CO₂e) of the generating set at an average operating hours of 1092 hr/yr and generator rating of 110 kVA (184.32 hp), resulted in GHG total (CO₂e) of 115.258 tons/yr. The GHG total (CO₂e) was found to reduce to 14.407 tons/yr when the horsepower equivalent of 13.75 kVA (23.04 hp) generating set was considered to replace the current 110 kVA (184.32 hp) generator. Consequently, the study has shown that a sustainable environment could be enhanced by improving the energy transfer efficiency from energy sources to energy utility plants and by employing solar energy sources to replace fossil based energy sources for some of the plant operating units where possible. Also, overall energy efficiency of a plant can further be enhanced by a detailed energy and exergy analysis of individual operating units that makes up the plant in order to identify the machines with highest inefficiencies for possible redesign or technical replacement.

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