Energy Management Methodology for Sustainable Water Development and Servicing, Considering the POET Based Concept

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Abstract. This paper aims at analysing the energy management activities for commercial bulk water development and servicing in South Africa. The energy efficiency, in terms of performance, operation, equipment and technology (POET), is reviewed. The sustainability of a general energy management program is discussed within this POET framework. As an application of this discussion to the commercial bulk water development scenario, the POET efficiency of an energy system is a measure of energy efficiency, which is determined by external but deterministic system indicators, such as production period, energy sources, environmental impact and technical indicators, amongst others. The case study concludes that the POET, based framework does not only cover all major energy management activities, but further identifies energy efficiency improvement opportunities.

1. Introduction
Increasing water costs of the municipality have provoked a need for the review of work carried out in the demand side management of the bulk sustainable water development energy systems, for commercial purposes. The treatment of water for human, animal and plant consumption, is a typical energy-intensive process [1]. The flowchart below, shows the different stages involving potable water harvesting [2, 3].
Figure 1 shows the flow cycle diagram of raw water development stages, from harvesting through the purification and utilization. Securing water levels throughout the general cycle, is one of the most challenging technological issues for water supply. The common mechanism, that has over the years been adopted to achieve this milestone, is by installing electrical pumps at various stages in the operation of the water processing/distribution system and optimizing the consumer water usage, minimizing water retention times.

The high operation cost is a common challenge for an urban water treatment plant. Ideally, energy is needed to transfer water from one place to another, the use of electrical pumps to pump water from one stage to another and the supposed water losses either through leakages or evaporation, may constitute the reason for a high consumption rate [4]. This research will underline a concept known as “POET” to achieve a reduction of these constraints to enable a sustainable water harvesting system.

POET forms a rigorous framework for energy management [5]. In POET, energy efficiency is summarized to have the following four components: performance efficiency (P), operation efficiency (O), equipment efficiency (E) and technology efficiency (T). Technology efficiency is a measure of the ratio of useful work performed in energy conversion. These include processing, transmission and usage; mindful of the limitation due to natural laws. Equipment efficiency is a measure of the energy output of isolated individual energy equipment, with respect to the given technological design specifications. Operation efficiency is evaluated, by considering the appropriate coordination of various system components. Performance efficiency of an energy system is a measure of energy efficiency, which is determined by external, but deterministic system indicators such as production, cost, energy sources, environmental impact and technical indicators, amongst others [6]. In other to appropriately coordinate the four main pillars that liaise with the POET concept, in association with water harvesting/treatment, it is imperative to look at the various research that involved the water harvesting/treatment system. The following section presents the literature in water harvesting energy management, Section 3 analyzes the POET based energy efficiency method in their various categories, Section 4 provides a case study analysis on POET base energy efficiency in water generation processes, while Section 5 presents an objective conclusion.
2. Literature in water harvesting energy management

The literature regarding energy management, in terms of the water harvesting/treatment field, specifically energy efficiency, POET based characteristics. Wanjiru and Xia looked at energy and water optimization of typical systems, such as rooftop harvesting systems. Their research is based on the capturing of rainfall water for garden irrigation [7, 8]. Zhanbo et al. analyzed and compared the energy storage devices that aid in producing the most efficient output, in terms of their differed coordination [9]. Matsubayashi et al. work on the energy management systems that provide information on energy serving recommended equipment. The theory is archived by calculating and comparing the power consumption estimate base on the various equipment information [10]. Sallem et al. presented an intelligent algorithm, based on the fuzzy rules that make a decision on the interconnection, an instants of photovoltaic installation components. The result shows an improved operating time for more than 5/hours [11]. These works are fundamentally within the category of energy efficiency, however, the adopted approach and vision are not systematically cascaded to obtain a common goal; thus, they are a challenge to interpret. In view of the above challenge, this paper aims at developing the systematic water developmental energy efficiency mechanism for water catchment purposes. However, it recognized the established research framework; specifically, the developed POET (Performance, Operation, Equipment, Technology) energy management framework [5].

3. POET based energy efficiency method

3.1. Performance efficiency

Performance efficiency of the water treatment energy system, is a measure of energy efficiency determined by external deterministic system indicators. The performance efficiency, in this case, will focus on the environmental impact, effect of evaporation in water transformation and technical indicators [6].

3.1.1. Environmental impact relating evaporation.

This is known as the spontaneous escape of high energy molecules from the liquid surface into vapor state [12, 13]. Figure 2 shows the process of vaporization that occurs on the surface molecules in water.

Evaporation occurs below its boiling point. Evaporation, known as a surface phenomenon, occurs because the molecules at the bottom of the liquid have a stronger force of attraction, as opposed to that at the surface of the liquid. When the surface molecules absorb heat, they gain a slight amount of energy from the surrounding atmosphere. This molecule increases the kinetic energy to such a level that it overcomes the force of attraction and escapes as gas [12]. The various factors that influence the rate at which evaporation occurs, are shown in Table 1 below.
### Table 1. Factors affecting the rate of evaporation [14. 15].

| Factors                  | Influence on evaporation                                                                                                                                 |
|--------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|
| Force of attraction      | A greater force of attraction will result in a less rate of evaporation.                                                                                   |
| Temperature              | An increase in temperature, resulting in increased kinetic energy of molecules and more surface molecules overcome the force of attraction, thereby escape out as gas. (temperature is proportional to the kinetic energy of the molecules) |
| Surface area             | Less surface area, fewer molecules escape as gas and more surface area result in more evaporation.                                                        |
| Wind                     | More wind speed results in more molecules escape from surface area and a greater rate of evaporation.                                                     |
| Humidity                 | Humidity is defined as the amount of water vapor in the air. So, as the increase of the humidity in the atmosphere, the amount of water vapor in the atmosphere increase. Therefore, resulting in a lesser rate of evaporation. |
| Nature of liquid         | This relates to the viscosity and density of fluids. While viscosity is the thickness or thinness of fluid, density refers to the space between its particles. However, both properties are affected by temperature, which affects the rate of evaporation. |

The above factors depend on geothermal conditions, which in most cases are influenced naturally. However, the surface area may be controlled in the case of water processing systems.

#### 3.1.2 Environmental impact relating to reservoir and transmission pipe leakages.

According to the 2018 global water report, a number of residents who receive piped water complained that the water was highly contaminated, had a bad smell, unusual color and visible particles [16]. This could be as a result of the old, rusty pipes that often break and water gets polluted before reaching the taps. Due to the high leakage in the water channels, treated water is, at times, re-contaminated before it reaches the users. The water sector reported that merely 76% of treated water in fact, reaches the consumer, a level considered unacceptable by the regulator [16]. Likewise, water may be contaminated as a result of pipe bursts [17] that occur exceedingly frequently.

#### 3.2. Operation efficiency

Operation impact, in this case, relates to the time at which pumping should take place, which is informed by various factors, such as the electricity tariff structure of the locality, as well as the water demand alteration (load flow diagram).

In South Africa, just as in many other countries, electricity cost varies with the time of use of the day, alongside the period of the year. Electricity time of use (TOU) tariffs, TOU pricing tariffs used by South African electrical utility (Eskom), has been elaborated in Table 2, according to the various pricing structures [18]. The Gentlex TOU tariff scheme is used for customers who consume energy supplied by Eskom, as well as independent energy producers that sell to Eskom. Table 2 shows the Eskom Genflex TOU tariffs for high-demand and low-demand seasons. During the study, a ratio of 1:14 is used to define the market price of USS against ZAR. The contracted ratio, assuming that the selling price is 65% of the utility price, was used.

### Table 2. Eskom Genflex TOU tariffs and seasonal periods [18].

| TOU Periods       | Low- demand Season | Period range | High- demand Season | Period range |
|-------------------|---------------------|--------------|---------------------|--------------|
| Peak Periods      | US$0.07/kWh         | 07:00-10:00  | US$0.21/kWh         | 06:00-09:00  |
|                   |                     | 18:00-20:00  |                     | 17:00-19:00  |
| Standard periods  | US$0.05/kWh         | 06:00-07:00  | US$0.06/kWh         | 09:00-17:00  |
|                   |                     | 10:00-18:00  |                     | 19:00-22:00  |
| Off-peak periods  | US$0.03/kWh         | 20:00-22:00  | US$0.035/kWh        | 22:00-06:00  |
|                   |                     | 22:00-06:00  |                     |              |
Table 2 above, provides the tariff structure and grading used by the energy utility company in South Africa (Eskom). The tariffs are divided based on two seasons, alongside the periods of the day. It is observed that using electricity during the peak period will cost more, as opposed to the off-peak periods, whereas the high-demand season will charge more than the low-demand season. In the case of water supply, load flow describes (or informs) the evolution of the changes in water demand in a specific period (or time). It is critical to evaluate the system capability to adequately supply the load while staying within appropriate energy consumption range.

3.3. Equipment efficiency

In this category, measuring of the energy out of the different individual output equipment and their unique technological design, is an emphasis on the utility pump. The overall operating principle of a water pump system may be seen towards the application of “Boyle's law”, that elaborates on the relationship by using the following quantities: pressure, volume and temperature [19]. Electrical pumps are known by their ability to effect a change of movement in fluid, solid and gas. Pumps systems technology has grown over time, from the manual actuator, to various forms of energy controllers [20, 21]. Table 3 shows the various categories of pump groups, their principle of operation, mechanisms of pumping, possible multiple stages, the advantages and disadvantages.

Table 3. Pump grouping, operating mechanism, advantages and disadvantages.

| Pump group          | Operation types | Pumping mechanisms | Multiple Stages possibilities | Advantages                                                                 | Disadvantages                                      |
|---------------------|-----------------|--------------------|-------------------------------|---------------------------------------------------------------------------|---------------------------------------------------|
| Positive displacement pumps | Reciprocating    | Piston [22]        | Yes                           | - Performance at low speeds.                                               | - Pulsed output.                                  |
|                     |                 |                    |                               | - May achieve greater pressures at low flow-rates.                        | - Higher sheer on pumping stroke.                  |
|                     |                 |                    |                               | - No internal leakage                                                      | - Cannot dry run.                                  |
|                     |                 |                    |                               | Smaller hydraulic shock pressure spikes.                                   | - Not efficient with particulates.                 |
|                     |                 |                    |                               | - Long service interval.                                                  |                                                   |
|                     |                 |                    |                               | - High accuracy.                                                           |                                                   |
|                     | Plunger [23]    | Yes                |                               | - High reliability.                                                       | - Slow speed operation.                           |
|                     |                 |                    |                               | - Easily controlled by stroke adjustment or variable speed.               | - Lower flow rates.                               |
|                     | Diaphragm [24]  | Yes                |                               | - May develop high pressure in a single stage.                            | - Costly in large size.                           |
|                     | External Gear [25] | Yes              |                               | - Self priming.                                                           | - Non-constant flow.                             |
|                     |                 |                    |                               | - Variable speed and pressure.                                            | - Vibration.                                      |
|                     |                 |                    |                               | - Handle slurries and solids.                                             | - Inlet pressure limitations.                     |
|                     |                 |                    |                               | - High viscosity handling.                                                | - Acceleration head.                              |
|                     |                 |                    |                               | - High suction life capacities.                                           |                                                   |
|                     | Internal Gear [26] | Yes              |                               | - High speed.                                                             | - Bushings wear in liquid areas.                   |
|                     |                 |                    |                               | - High pressure.                                                          | - Fixed end clearances.                           |
|                     |                 |                    |                               | - Quiet operation.                                                        |                                                   |
|                     |                 |                    |                               | - Variety of build material operations Complete rotary motion.            |                                                   |
|                     |                 |                    |                               | - Easily control speed.                                                   |                                                   |
|                     |                 |                    |                               | - Easily control direction.                                               |                                                   |
|                     | Rotary          | External Gear [25] | Yes                           | - Smooth/pulseless flow.                                                  | - Higher cost.                                     |
|                     |                 | Internal Gear [26] | No                            | - Slightly more horsepower for size.                                      | - Limited size range.                             |
                                           |                    |                                 |                              |                                                    | - Low to moderate pressure ratings.               |
                                           |                    |                                 |                              |                                                    | - Few sources of manufacture.                     |
| Type                        | Yes/No | Benefits                                                                                      | Drawbacks                                                                                             |
|-----------------------------|--------|----------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|
| **Lobe** [27]               | Yes    | - Ability to handle medium sized solid particles in the pumping fluid                        | - Low pressure.                                                                                       |
|                             |        | - No metal-to-metal contact                                                                  | - External gears.                                                                                     |
|                             |        | - Long term dry run (with lubrication to seals)                                             | - Reduced lift with thin liquids                                                                      |
|                             |        | - Non-pulsating discharge                                                                    |                                                                                                       |
| **Vane** [28]               | Yes    | - Low viscosity fluids at high pressures.                                                   | - Complexity.                                                                                         |
|                             |        | - Dry run for short periods.                                                                | - Unsuitability for high pressure.                                                                   |
|                             |        | - Develops a good vacuum.                                                                  | - Does not run high viscosity fluids.                                                                 |
| **Peristaltic** [29]        | Yes    | - Good flow ranges.                                                                       | - Tubing is a consumable.                                                                            |
|                             |        | - Liquid contained in tubing suction lift.                                                  | - Flowrate and pressure limited by tubing.                                                           |
|                             |        | - Dry running.                                                                             |                                                                                                       |
|                             |        | - Good chemical compatibility.                                                             |                                                                                                       |
| **Screw/Progressive cavity** [30] | Yes | - Metering accuracy.                                                                      | - Larger number of moving parts.                                                                      |
|                             |        | - Higher viscosity liquids.                                                                 | - High maintenance.                                                                                    |
|                             |        | - Volumetric efficiency (lower power and more flow).                                      | - Larger footprint.                                                                                   |
|                             |        | - Low shear.                                                                              |                                                                                                       |
| **Radial flow** [31]        | Yes    | - No leakages in fluid.                                                                    | - Energy loss because of coupling.                                                                    |
|                             |        | - Last longer.                                                                             | - Chances of coupling slips due to intense loads.                                                    |
|                             |        | - Less maintenance.                                                                       | - Low flow may lead to overheating of the pump.                                                      |
|                             |        | - Pump and motor are apart from each other so no heat transfer is possible.                  |                                                                                                       |
|                             |        | - Less friction.                                                                           |                                                                                                       |
| **Axial flow** [32]         | Yes    | - Wide range of pressure, flow & capacities                                               | - Not well-suited for high-pressure applications.                                                     |
|                             |        | - Fewer moving parts.                                                                     | - Do not handle high-viscosity fluids well.                                                           |
|                             |        | - No excess pressure build-up                                                              | - No suction lift capabilities                                                                        |
|                             |        | - Produce high flow rates necessary for industrial applications                            |                                                                                                       |
| **Mixed flow** (part radial, part axial) [33] | Yes | - Initial and maintenance cost are comparatively low                                       | - Requires priming.                                                                                  |
|                             |        | - Their size is compact and may be installed in limited space                              | - For higher head, efficiency is low.                                                                  |
|                             |        | - Their mechanism is simple.                                                                | - The discharge pipe has to be provided with check valve, to avoid the backflow when the pump suddenly stops due to power failure. |
|                             |        | - Less skilled labour is required for its operation and repairs.                            | - Discharge varies with the head of water.                                                           |
|                             |        | - May be operated with high speed electric motors, or gas engines and steam turbines      | - Their ordinary suction lift is limited (about 6m or so).                                           |
|                             |        | - Discharge is steady and non-pulsating                                                    |                                                                                                       |
|                             |        | - May be used for pumping water containing silt, sand etc.                                 |                                                                                                       |
|                             |        | - Durable and safe against pressure.                                                       |                                                                                                       |

A Positive displacement pump causes fluid movement, by trapping a fixed amount of the fluid and providing a certain force, in the form of kinetic energy that trapped volume into a discharge pipe (or discharge system). On another hand, dynamic pumps produce additional kinetic energy to the same flow at a given speed (RPM), regardless of the discharge pressure [34].

3.4. Technological efficiency
Modern technology in energy resources edifies on how important and affordable renewable energy could be in our daily life [35]. However, the many challenges involving the renewable sources warrant a different approach towards its application. Hence, the introduction of the hybrid system in pump-stations for the pumping of water is of viable significance. Figure 3 shows a hybrid system configuration of simple renewable energy sources. Hybrid energy systems are practices in energy generation and supply systems, where the various forms of electrical energy generation systems are merged together, to obtain an optimized, effective and less costly output power supply, at a particular time of use [36, 37].

Figure 3. Hybrid system layout.

The proposed hybrid system is composed of the main grid alternating current (AC) supply, a photovoltaic (PV) system, a micro-hydrokinetic (MHK) turbine generator, a battery storage system, an inverter, a charge controller, as well as an AC load, as shown in Figure 3. The power flow of the proposed PV–MHK–Battery and the grid system, is shown in Figure 1. The load energy requirement is principally covered by the PV and MHK units. When there is sufficient energy to supply the load directly from the PV and MHK units, the surplus of generated energy is used to charge the battery. However, when there is insufficient energy to supply the load (water pumps) directly from the PV and MHK units, the excess energy is provided from the battery. Supposing the PV unit, MHK unit and the battery are not sufficient to the load energy requirement, the main grid supply is turned on as a last resort, to balance the shortage of energy required by the load.

4. POET analyses

This section analyses and highlights the key areas of emphasis, in terms of water and energy efficiency, regarding sustainable water development and servicing. It stretches the preferred approach, in terms of energy reliability and managing efficiency, drawing from the POET concept:

- The overall observation in terms of performance efficiency reviewed that, evaporation is a result of a number of factors listed in Table 1 above. However, solely the surface area could be considered as a variable that could be controlled, whereas the others are dependent on the natural hemisphere. The study recommends that future construction of a water reservoir or treatment plant should be constructed in a semi-conical shape. This should further reduce the rate of wind speed to the water surface.
- A water transmission pipe should be replaced on or before it reaches the determinate lifecycle. Furthermore, a method of backwash should be adopted, in other to clean the
contaminated water area, immediately after performing maintenance or replacement on a brooking pip.

- According to the tariff structure in Table 2 and based on the operating efficiency, it is recommended that pumps should be operated during the off-peak periods, since the cost of electrical energy is relatively more affordable. In addition, during the peak periods, the pumps may be switch off for cooling and maintenance.

- Equipment efficiency endorses the optimal equipment selected for a given task. In the case of a commercial bulk water development and focusing on the various pumps listed in Table 3, care should be given to the following factors when selecting a pump: pumping mechanism, the possible number of stages, advantages of the pump, as well as the energy consumption.

- A holistic view is added in Section 3.4, relating to Figure 3 on the best possible hybrid model that will produce an optimal energy management performance, in the event of a water harvesting and purification system.

5. Conclusions
Water harvesting and treatment are considered in an intensive survey mechanism. The POET energy management framework has put forward corresponding saving proposals, at various stages of the process. The classification of the energy management concept is realized, based on the four pillars of the POET concept. Energy consumption efficiency of water harvesting and treatment plan is enveloped under the performance, operation, equipment and technological operation of its processes. The submitted case shows that the POET based energy management method has an efficient coordinated energy saving capability. It may effectively obtain the energy-saving opportunities of the water treatment processes and laid a foundation for a future project in the area of water harvesting.

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