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A Techno-Economic Viability of a Residential Air Source Heat Pump Water Heater: Fort Bueafort, South Africa

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Abstracts

sThe utilization of an air source heat pump (ASHP) to retrofit geyser can significantly reduce electricity consumption for sanitary hot water production. Furthermore, optimal operation of the system based on ambient conditions and capacity of hot water usage would enhance both achievable performance and payback time. The study focus on using a data acquisition system to evaluate the performance of an efficiently installed ASHP water heater and hence determine the payback period of the system. Preliminary results depict that during the four months of performance monitoring of the system, the average month-day input energy, coefficient of performance and volume of hot water usage was 3.0 kWh, 260 L and 2.2 respectively. An average monthly energy saved of 125 KWh was achieved while the average ambient temperature and relative humidity of 24.6 oC and 64.2% were recorded for the entire time of operation of the system. Finally, using a multiple comparison test, it was demonstrated that no mean significant difference occurred in both the average week electrical energy and COP for each of the different months throughout the observations. The payback period of the ASHP unit was determined to be less than 6 years from a conservative approach method.

Keywords: Air source heat pump (ASHP); Sanitary hot water; Coefficient of performance (COP); Payback, multiple comparison test, Data acquisition system (DAS).

Introduction

The commonly applicable type of heat pump heaters employ for sanitary hot water heating are the air source and the geothermal or ground source systems. These systems operate on the principle of vapor compression refrigerant cycle. The geothermal air source heat pump water heater possesses a better techno-economic potential to an ASHP water heater by virtue of its relatively constant and higher COP [1, 2]. Both systems can be classified as a renewable energy device, as they all use a given form of renewable energy from their immediate surroundings where the evaporator is located during the vapor compression cycle. The ground source heat pump water heater extract waste heat from underground in the form of geothermal energy while ASHP water heater utilized the heat from the air as aero-thermal energy. The capital cost of ground source heat pump water heater is much higher as compared to an ASHP water heater. ASHP water heat is fast gaining maturity in the market as sanitary hot water production constitutes a significant percentage of monthly energy consumption in the residential sector worldwide. In South Africa, residential hot water heating can contribute to more than 50% of the monthly energy utilization [3]. A far-reaching research conducted to justify in terms of energy usage revealed that the hot water contribution in the domestic sector of South Africa is between 40% to 60% on an average monthly basis [4, 5]. It is worth mentioning that despite the daunting electrical energy consumed for hot water production, not all the thermal energy gained by the hot water is effectively utilized. There are always standby losses which are responsible for 20% to 30% of the total thermal energy gained by hot water contained in a storage tank [6]. Although, ASHP water heater coefficient of performance (COP) value can range from 2 to 4 [7, 8]; it is crucial to note that the system COP depends on the COP of the ASHP unit and the ambient climatic condition [9]. Clearly, the COP could be defined as the ratio of the useful thermal energy gained when water is heated to set point temperature and the electrical energy used by the system during the vapor compression refrigerant cycle. A salient and better understanding of refrigeration cycle of heat pump water heater was given by Ashdown *et al*. (2004) and Sinha and Dysarkar, (2008) [10, 11]. Moreover, the performance can be severely affected by standby losses. Heat pump water heaters also render an extra benefit of dehumidification and space cooling because they pull warm vapor from the air [12]. An efficiently installed residential ASHP water heater can guarantee an improvement on the system performance [13]. The study deal with an in depth performance monitoring of a residential split type ASHP water heater installed in a middle class home (compose of 2 adults and a child) in

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Fort Beaufort, found in the Eastern Cape province in South Africa. The sole purpose was to determine both the electrical energy saving from hot water production and payback period of the ASHP unit. The sanitary hot water set point temperature was 55 ºC. The ASHP water heater and the metering equipments were installed in the month of January (2013) while the data collected for the analysis was from 01 st January - 30 th April 2014.

Types of ASHP water heater

Residential ASHP water heaters in South Africa are divided into two categories, namely the integrated and the split type systems. The performance of the integrated system is better than that of the split type, albeit the latter is more stable [14]. In an integrated system, both the ASHP unit and the storage tank exist as a compact system. The condenser is usually immerse in the storage tank and act as the heat exchanger between the primary refrigerant in the close circuit of the heat pump and the water store in the storage tank. The heat dissipated from the refrigerant is absorbed by the water to raise the temperature to the set point. Figure 1 shows a typical integrated ASHP water heater.

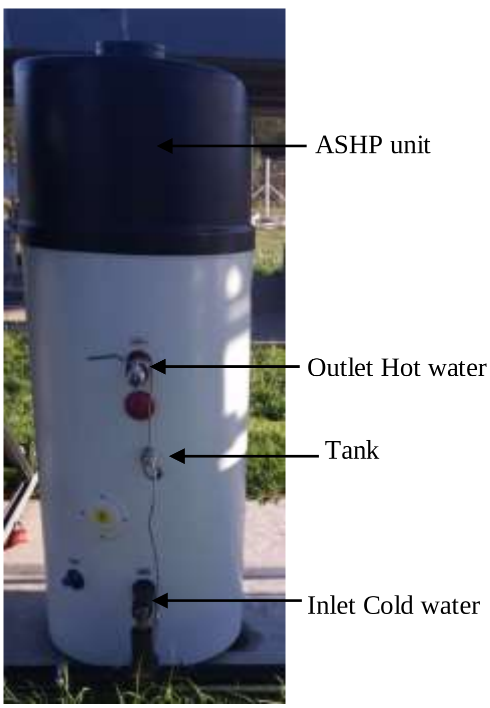

Figure 1: Shows an integrated ASHP water heater

Split type ASHP water heater is a retrofit system comprising of an ASHP unit and a storage tank connected by pipes. Split type system can either be a once pass or recirculation type. In a once pass type the inflowing water from the tank to the inlet of the ASHP unit is heated to hot water set point temperature before exiting via the outlet. This type of circulation is referred to as a single pass. A recirculation type is where there is continuous circulation of the water between the tank and the ASHP unit until the set point temperature of the water is attained. In a split type ASHP water heater the storage tank is usually above the ASHP unit and there are pipes connected from the inlet and outlet of the ASHP unit to the storage tank. More importantly, there is a water circulation pump connected via the ASHP inlet pipe and aid to provide sufficient pressure for the heated water to flow back to the tank. In addition to the water circulation pump, there exist other valuable components that make up the close circuit of the vapor compression cycle. These include the evaporator, compressor, condenser and the thermal expansion values. There are also a propeller axial fan, strainer, open and close valves. The connecting pipes are well insulated to prevent both reticulation and standby heat losses. Figure 2 shows a detail installation of a split type ASHP water heater.

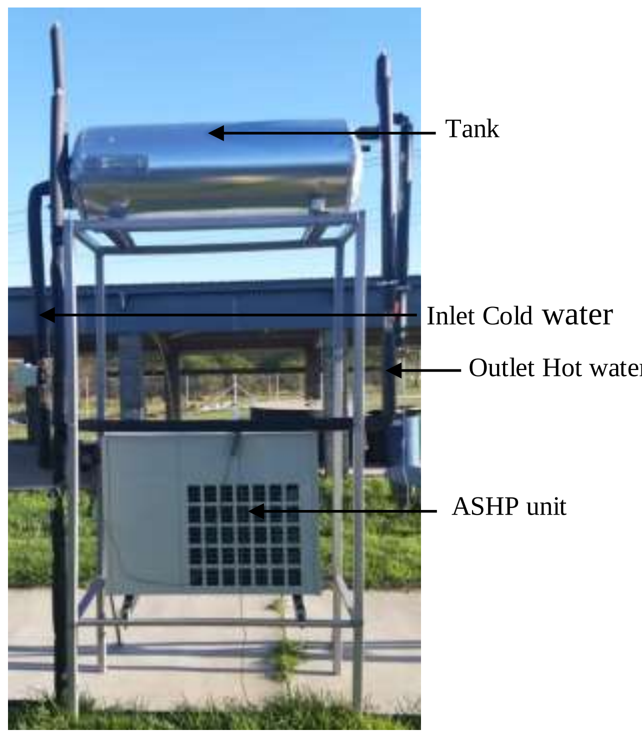

Figure 2: Shows a split type ASHP water heater

Methodology

The methodology is divided into two; sensors and traducers use in the building of the data acquisition system and the full schematic layout of the ASHP water heater including the enclosure housing the data acquisition system.

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Materials
Table 1 shows all the sensors use in the building of the data acquisition system to monitor the performance of the ASHP water heater. All the sensors and the data logger were purchased from a single manufacturer (Hobo Onset Corporation). The sensors and transducer were all classified as class A and each come with its calibration certificate.

Table 1: show the sensors and the quantity used

Sensors	Quantity
U30-NRC (15 channels) data logger	1
T-VER-E50B2 power and energy meter	1
T-MINOL 130 flow meter	2
12 bits S-TMB temperature sensor	6
12 bits S-THB ambient temp and rel hum sensor	1
S-UCD electronic input pulse adapter	2
S-UCC electronic input pulse adapter	6
Protective fuse (50 A)	2
Current transformer (50 A)	2
4.5 V DC battery using a 240 V AC input	1

The U30-NRC was a robust and reliable data logger containing 15 digital smart jack ports. These ports are used to connect the sensors to the data logger to ensure measurement obtained from a specific sensor was recorded and stored in the data logger. The battery was used to power the U30-NRC data logger. The free end of the black and white twisted pair cable of the input pulse adapter (S-UCD) was connected to the output cable of the flow meter and was not polarity sensitive while the smart jack end was connected to one of the U30-NRC data logger ports [15]. Each T-VER-E50B2 power and energy meter was connected with 3 S-UCC input pulse adapters from the Wh (active energy in watt hour), VARh (reactive energy in reactive volt-ampere hour) and Ah (current rating in ampere hour) ports to three ports in the logger via the smart jack ports [15]. 1 current transformer (CT) and 1 fuse were connected from the desired ports of the power meter (T-VER-E50B2) to the live cable powering the ASHP water heater and the water circulation pump. All the temperature sensors, the ambient temperature and relative humidity sensor were also connected to the U30-NRC data logger via the smart jack ports. The power meter was configured such that 1count equal 1 Wh and 1 VARh while 100 counts equal 1 Ah. The flow meters were configured such that 1 count equal 3.7854 liters [15]. The electronic input pulse adapters convert the analogue signal sense by the respective sensor to digital and hence eliminating errors in the measurement. The U30-NRC data logger was configured to log every five minute interval using the hoboware pro software which was also used to download the stored data obtained from the respective sensors for further analysis. It is important to note that due to the incorporation of the electronic input pulse adapter on the cable of the temperature sensors, flow and power meters, the data store was integral or average value for each logging interval (5 minutes). The figure 3 shows the schematic layout of the ASHP water heater and the enclosure accommodating the data acquisition system.

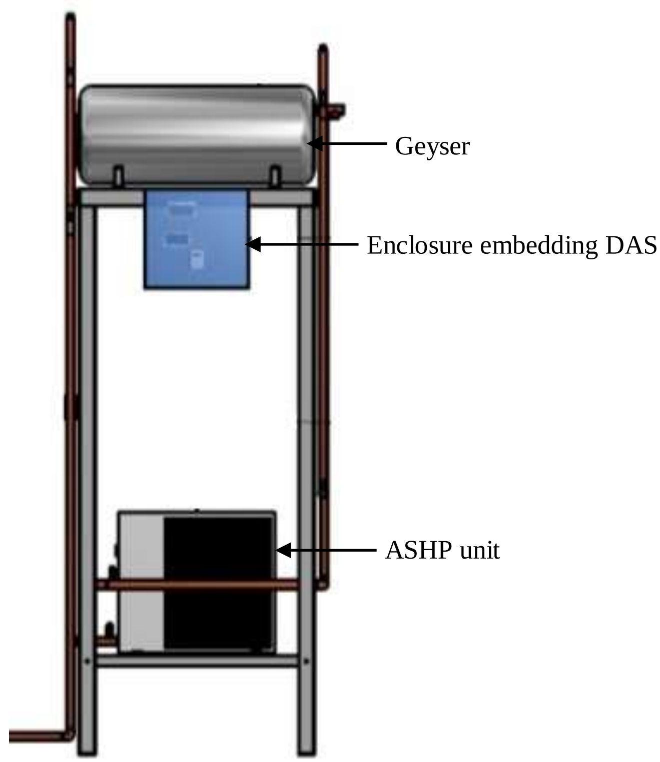

Figure 3: Shows the schematic diagram of the ASHP water heater and the enclosure housing DAS

Theory and calculations

The set of equations given in the equation 1- 5 shown below were used to calculate the active power (kW); electrical energy (kWh), thermal energy gained by hot water (kWh), the COP and the energy save (kWh).

$$E = \frac{Wh}{1000} \quad (1)$$

$$E = p \times t \quad (2)$$

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Where E = electrical energy in kWh and t = time in hour p = power in kW

$$Q = mc(T_o - T_i) \quad (3)$$

Where

Q = thermal energy gain in kWh, m = mass of heated water = volume of water in litres heated by ASHP, c = specific heat capacity of water = 4.2 kJ/kg^{o}C, T_0 = ASHP outlet water temperature while T_i = ASHP inlet water temperature.

The COP of the system is given by the empirical equation shown in equation 4.

$$COP = \frac{Q}{E} = \frac{\text{output useful thermal energy gain}}{\text{input electrical energy}} \quad (4)$$

The energy saves (ES) is the difference between E and Q during a vapor compression refrigerant cycle assuming electrical energy consume by the power circuit of the control panel is negligible when heat pump unit is not running.

$$ES = Q - E \quad (5)$$

Results and discussions

Average month-day comparative analysis of the ASHP water heater performance

Table 2 shows a detail analysis of the ASHP water heater performance for an average month-day over the monitoring duration (January-April 2014).

Table 2: Shows a comparative monthly analysis

Parameters	Jan	Feb	Mar	Apr
Volume drawn (L)	258	271	263	253
Electrical energy (kWh)	2.93	2.94	2.93	3.22
Mean COP	2.18	2.17	2.25	2.08
Average ambient temp(^{o}C)	25.3	24.2	26.0	22.7
Average Rel hum (%)	64.4	77.8	60.0	55.7
Average operating time(h)	2.27	2.08	2.23	2.73

Rel hum (relative humidity), temp (temperature)

It can be depicted that the hot water consumption based on the average month-day results were theoretically constants (slightly over 250 L). The systems COP on an average month-day were above 2 and in accordance with literature [16]. The COP is likely to increase with an increase in temperature as demonstrated in the month of March and January were COPs were both 2.93 and the average ambient temperature were 26.0 ^{o}C and 25.3 ^{o}C. Although there exist a negligible difference between the average ambient temperatures, the COPs have been constant since the average relative humidity which also influence COP was slightly higher for the month of January as could be observed on table 2. On the contrary, the system COP was minimal for the April average month-day since its average ambient temperature was low (22.7 ^{o}C). It can also be elucidated that the better the COP, the smaller the electrical energy consumption and operating time for the ASHP water heater. The average operating time per day during the entire monitoring duration was more than 120 minutes but less than 180 minutes. Figure 4 illustrates two subplots that presented the variation of electrical energy consumption and operating time against the average month-day as well as the capacity of hot water usage per average month-day. From a comparative analysis using the two subplots a noticeable increase in electrical energy consequently accompany an increase in the running time of the ASHP water heater. But an increase in the average daily electrical energy consumption might not lead to increase in the capacity of hot water drawn off, since not all drawn off leads to the running of the system and also the time taken for a specific heating cycle depends on the ambient temperature and relative humidity. The initial water temperature flowing into the ASHP inlet can also determine the electrical energy consumption.

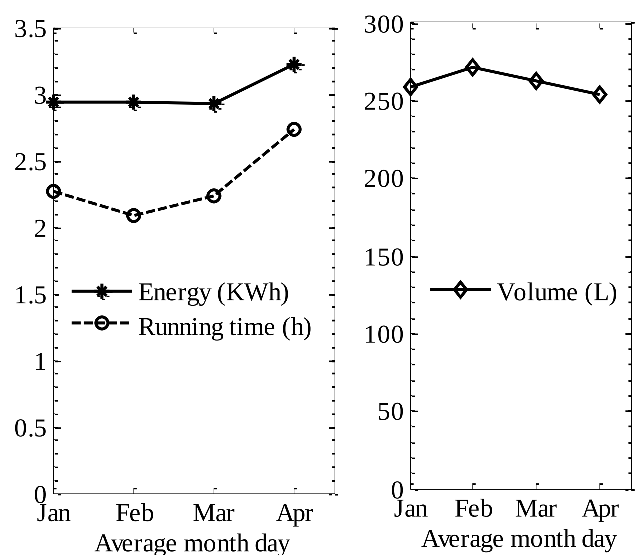

Figure 4: Variation of average heating up energy, time of operation and capacity of hot water usage (average month-day)

Monthly electrical energy consumption and thermal energy generated.

Figure 5 gives an illustration of the total electrical energy consume and the thermal energy gain for the four months (January-April). It can be deduced that the thermal

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energy gain by the storage tank were comparable (over 200 kWh) except for the month of February with less than 30 days. In a similar manner, the electrical energy consumption was about 75 kWh. It can therefore be delineated that on average per month the electrical energy saves owing to the retrofitting of the geyser with an ASHP unit is 125 kWh. This saving is true because geyser energy factor is very close to unity.

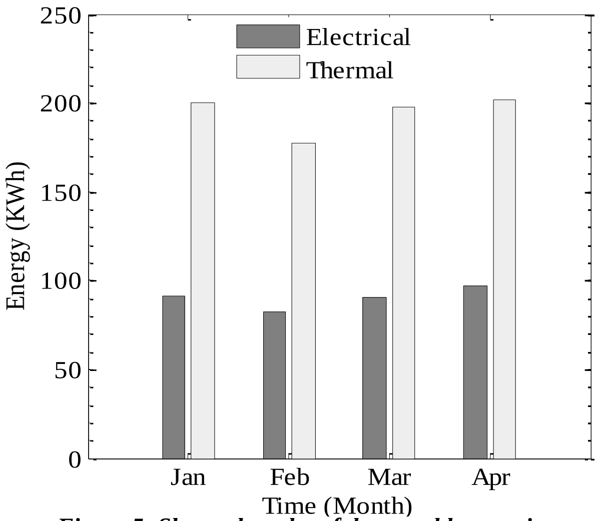

Figure 5: Show a bar plot of the monthly energies

Evaluation of bill for energy consumption

The figure 6 revealed that there is a huge cost saving despite the environmental benefits just be retrofitting geyser with ASHP. Judging from the energies results in figure 5 and using it to predict the projected costs for the monthly energy consumption for hot water production, there are adequate reasons to motivate for a massive rollout of ASHP water heater in the residential sector. Furthermore, translating the thermal energy gain for the respective months to electrical energy for the scenario were geyser (old technology) was use and using an Eskom flat rate per kWh (tariff structure) of 1.20 Rands, the total energy consumption costing for hot water production is over 250 Rands. On the other hand, by retrofitting the system with an ASHP, the monthly energy cost of hot water production by the ASHP water heater reduces to about 110 Rands. More generally, reporting on an average month cost saving for hot water production of 140 Rands and by assuming no increase in the Eskom tariff structure, the ASHP unit payback period can be estimated to be 5.4 years with the capital cost of the unit value at 9000 Rands. It is crucial at this junction to highlight that this payback duration can be far lower with some rebates or incentive from the Government to subsidies for the purchase of the system. And also in homes where there is huge demand for hot water usage.

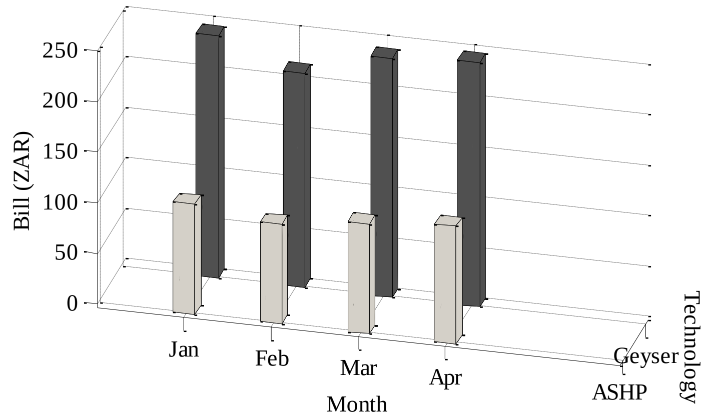

Figure 6: Energy use costing on both technologies

4.4. Simple economic life costing of the ASHP

The ASHP unit comes with a manufacturer warranty of 15 years and no maintenance cost over this duration. Hence, without loss of generality and from a conservative calculation with a payback time of 5.4 years, a net accumulated cost saving of 16,000 Rands can be accrued over the remaining 9.6 years before the unit reaches its lifespan. It is worthy, to categorically highlight the fact that this analysis has been done without considering any inflation rate as well as any increase in the electricity cost per unit of electrical energy consumption. Furthermore, with an increase in the tariff structure, the accumulated cost saving would significantly increase.

Multiple comparison tests for the COPs

A multiple comparison test was performed for the average month-day COP using the data for the four months monitoring period. This statistical test computes the mean COP of the ASHP water heater for specific month using the one way analysis of variance test and also checks for mean significant difference in the monthly COP through a visual plot [17]. The figure 7 shows the multiple comparison test of the COP for the respective monitoring months. It can be viewed from the simulation plots that the mean COP for each month was represented by a circle mark which is fixed on the respective line plot. The vertical broken lines reveal the upper and lower limit of the average COP for the whole week day in the month of January. Comparing the COP for the month of January to the other months, the simulation plots show no mean significant difference as the rest of the COP line plots overlapped with that for the month of January.

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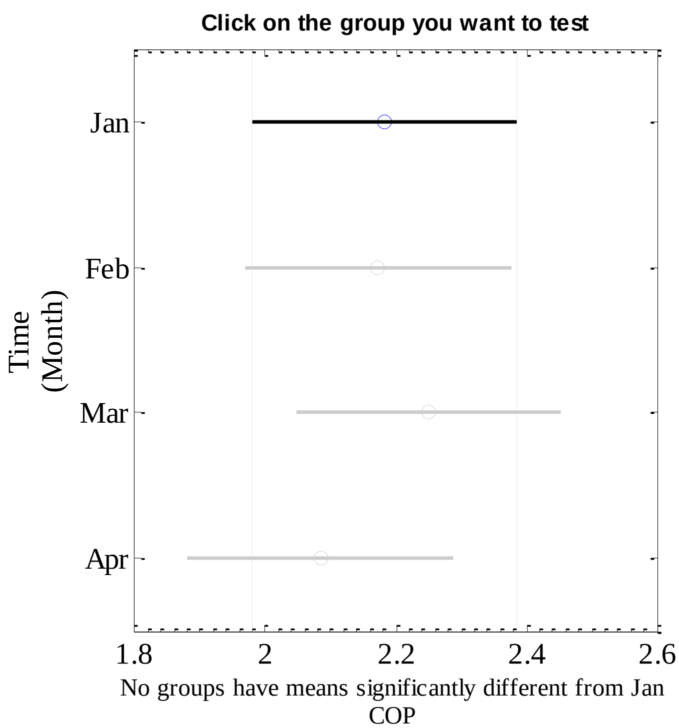

Figure 7: Multiple simulation plot of the week day COP

Conclusion

The following observable conclusions can be drawn from this study;

There was no mean significant difference in the system COP for each of the monitoring months. The energy saving potential of the ASPH water heater would even increase further with an increase in the capacity of hot water usage in conjunction of the system operational time coinciding with an increase in ambient temperature and relative humidity. A favorable increase in the fuel adjustment cost as well as progressive increase in the electricity tariff rate can also result in a payback time well below 5 years.

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