The Impact of an Air to Water Heat Pump in the Residence of a University Campus

Stephen Tangwe and Kusakana Kanzumba
Central University of Technology, Free State, P/SAK X20539, Bloemfontein, 9301, South Africa
Email: lstephen@cut.ac.za; kkusakana@cut.ac.za

***Abstract*—The implementation of an energy efficiency intervention in the students' residence of the university campus may lead to a reduction in the energy consumed and electricity cost. The study focused on retrofitting a 1000 L, 12 kW boiler, with a 4.0 kW Air Source Heat Pump (ASHP) unit. A data acquisition system was built and deployed, to monitor the baseline performance of the electric boiler and the actual performance of the installed ASHP water heater (which was used to retrofit the electric boiler during the assessment period). The results show an annual electrical energy saving of 34805.94 kWh and load factor reduction of 0.124 due to the replacement of the electric boiler with the ASHP unit. The payback period of the ASHP system was 1.7 years, using the method of net present value of money. Wilcoxon rank sum test was employed to compare both the daily volume of water and energy consumed by the electric boiler and the ASHP water heater to test if their difference was of any significance. We concluded that, there exists a significant difference in the average daily energy consumed by the boiler and the ASHP water heater in both summer and winter season with the utilization of the Wilcoxon rank sum test. We could conclude that, a rollout of the ASHP units to retrofit the existing electric boiler in the students' residence in the University campus is economically viable and calls for such an intervention is imperative.**

***Index Terms*—Load factor, Energy saving, Tariff hike, Air source heat pump, Electric boiler, Net present value payback period, Wilcoxon rank sum test**

I. INTRODUCTION

Heat pump technology (e.g., air source heat pump, ground source heat pump, and solar-assisted heat pump) is both a renewable and an energy efficient technology for both sanitary hot water and space heating [1], [2]. Extensive studies by a group of researchers in the United Kingdom have resulted in the finding that, air-source and geothermal heat pump water heaters can be employed in wider applications [3]. Hot water production is the fourth largest energy consumer in the commercial building sector following space heating, air conditioning and lighting [4]. The South Africa available commercial supply networks of natural gas are very limited as opposed to the European countries and United States [5]. The use of the inefficient resistance element, such as an electric boiler for water heating is predominant in the commercial sector of South Africa. An electric boiler is an inefficient sanitary hot water device, having the capacity of a storage tank above 500 L and the hot water heating is primarily achieved by a heating element [5]. Energy factor of an electric geyser is less than 1 and is due to the input electrical energy supplied which is often greater than the output thermal energy gained by the stored water [5]. Hence, by replacing the electric boiler with Air Source Heat Pump (ASHP) water heater can lead to significant power and energy reduction in the commercial sector. Research conducted on the techno-economic analysis of the ASHP water heater in the commercial sector based on limited experimental data, proved that the technology is viable with a simple payback period of 12.5 months and an internal rate of return of 98%. Zhang *et al*. [6] conducted a techno-economic analysis of ASHP with reference to space heating in Northern China and compared its viability to traditional heating methods that included coal-fired cogeneration, large coal-fired boiler heating, regional coal-fired boiler heating, wall hanging gas boiler heating and direct electric heating. They concluded that other than the coal-fired cogeneration mode, the ASHP demonstrated better energy consumption and economic efficiency than the rest of the technologies. In addition, Alshehri *et al*. [7] performed a techno-economic analysis between ground and air source heat pumps in the hot, dry climate and depicted that the total annual cost of the energy consumed by the ASHP system was more than that of ground heat pump water heater (a 34.6% increase). The authors demonstrated that the ASHP water heater possessed a greater efficiency of the operation cost in the long term to the ground source heat pump water heater. The authors further noted that due to the large installation cost of ground source heat pump water heater, the market penetration of this technology is unfavorable in the hot, dry climate. First degree audits were conducted in the major cities (Johannesburg and Cape Town) in South Africa to assess the economic viability of commercial ASHP water heaters over electric resistance heaters in large residential units and hospitals for sanitary hot water heating [8]. The findings showed that ASHP water heater is an economic viable technology, with an efficiency that could be enhanced via correct sizing and optimization of the operation. They further showed that the performance of an ASHP water heater was better in the coastal region as opposed to the inland region.

Manuscript received September 25, 2021; revised October 27, 2021; accepted November 3, 2021.

Corresponding author: Stephen Tangwe (email: lstephen@cut.ac.za).

Despite the energy and the cost saving of heat pump water heaters, it only contributes to 16% of the total number of commercial facilities in South Africa [9]. This is partly attributed to the poor integration and optimization of the ASHP unit during installation. And this can account to an increase in the life-cycle cost of the technology. Rebates stimulus for renewable energy and energy efficient technologies have accelerated the penetration of heat pump water heaters and other energy efficiency programs in the residential and commercial sectors [10]. Accordingly, sanitary hot water production in the university's residence may achieve more energy savings by retrofitting the existing electric boilers with ASHP units. The ASHP water heater is capable of utilizing one unit of input electrical energy and provide two to four units of useful output thermal energy during the vapor compression refrigeration cycle [11], [12]. The special characteristic of the ASHP water heater, associated with the exemplary performance is known as the coefficient of performance [13]. In addition to the energy saving, an ASHP water heater may reduce the power consumption during hot water heating, by more than 50% via retrofitting of the existing electric boiler. The Coefficient of Performance (COP) of an ASHP water heater is governed by the design of the components associated with the close loop circuit of the heat pump unit, the thermo-physical properties of the refrigerant utilized in the heat pump and the ambient conditions [14]. Precisely, the COP of an ASHP water heater depends strongly on the ambient temperature, with respect to other weather parameters (relative humidity, wind speed) [15]. Generally, the COP of heat pump systems depends on a number of factors, however, the temperature of the evaporator is considered as a critical factor [16]. The energy saving due to retrofitting of the electric boiler with an ASHP unit, depends on the volume of hot water consumption. The energy saving in the winter months is usually higher than the corresponding saving in the summer months, as hot water demand is more during the winter period [17]. The authors' also modelled the COP of an ASHP water heater with the ambient temperature, hot water set point temperature, wet and dry bulb temperatures as the predictors. Fu *et al*. [18] conducted a dynamic model of an air-to-water dual-mode heat pump of a screw type compressor with four-step capacities. The authors developed dynamic outputs with their models by adding compressor capacity in a step-wise approach and showed that the modelled results were in agreement with the experimental measurements. W. Wang *et al*. [19] developed a model predictive control to forecast the operation performance of transcritical CO_2 air source heat pump water heater. Also, Techarungpaisan *et al*. [20] developed a steady state simulation model to predict the performance of a small split type air conditioner with integrated water heater and experimentally validated their results. It is imperative to mention that unlike the solar water heater, the ASHP water heaters may operate throughout the year, with an annual COP greater than 2, in any region of South Africa [21]. The commercial ASHP water heaters possess a better COP relative to the residential ASHP water heaters on account of the type of compressor, condenser and expansion valve used. The capital cost of an ASHP water heater is particularly higher, in contrast to that of an electric storage hot water heater and despite the high capital cost of the ASHP water heater, the payback period is economically favorable [22]. Experimental research conducted in South Africa demonstrated that both the split and integrated types of residential ASHP water heaters are viable technologies for sanitary hot water heating [23]. Eskom's rollout the residential ASHP water heaters, to replace the inefficient geysers, as an integrated demand management intervention in order to reduce both the demand and the energy consumption. The Eskom's residential ASHP water heaters rebate scheme served as a part of the solution to reduce demand constraints on the national grid [24]. Nevertheless, the rebate program of the residential ASHP water heaters was discontinued at the end of 2015 because of the lack of funding to sustain the scheme, even though, the techno-economic performance was very good [23]. This study sought to demonstrate via experimental monitoring the technical performance and economic viability of a 4 kW input ASHP unit, used to retrofit a 12 kW electric boiler installed in a postgraduate female residence with 70 students at the Central University of Technology, Free State in South Africa. Additionally, to develop, test and validate, robust linear models that correlated the daily volume of hot water consumed with the electrical energy consumed for the electric boiler and the ASHP water heater. The electric boiler was monitored for a period of 12 months ranging from January to December 2016 before being replaced by the ASHP water heater. The ASHP water heater was monitored for a similar duration, but from January to December 2017. It is worth mentioning that, the winter season in South Africa span from May, June, July and August while the summer season includes the months of January, February, March, April, September, October, November and December, with reference to an annual cycle.

A. Objectives

To execute the study, the following specific objectives were investigated:

- To determine the reduction in the annual power and energy consumption after retrofitting the electric boiler with an ASHP unit.
- To develop linear regression models to correlate the daily volume of hot water consumed with the daily electrical energy consumed by the electric boiler and the ASHP water heater, in the summer and the winter periods.
- To test for the existence of any significant difference in the average daily volume and energy consumed by the electric boiler and the ASHP water heater, both in the summer and winter seasons.
- To justify the benefit of the ASHP water heater via the excellent techno-economic performance.

II. Theory and Calculations

The electrical energy consumed by the electric boiler or the ASHP water heater, is the product of the electrical power consumed and the time used during the heating period, as given by

$$E = Pt \tag{1}$$

where E is the electrical energy consumed in kWh, P is the electrical power consumed in kW, t is the time taken in h.

The thermal energy gained by the stored water in the storage tank connected to ASHP unit, is the product of the mass of water heated, the specific heat capacity of water and the temperature difference between the temperature of the water at the outlet and the inlet of the ASHP unit, during the heating cycle, as shown in Equation 2.

$$Q = mc\left(T_2 - T_1\right) \tag{2}$$

where Q is the thermal energy gained in kWh, m is the mass of water heated by the ASHP unit during the heating cycle in kg, c is the specific heat capacity of water in kJ/kg°C, T_2 is the temperature of water at the outlet of the ASHP unit in °C, and T_1 is the temperature of water at the inlet of the ASHP unit in °C

The COP of the ASHP water heater is the ratio of the useful output thermal energy gained by the stored water to the input electrical energy consumed during the vapour compression refrigeration cycle, presented as

$$\mathrm{COP} = Q/E \tag{3}$$

where COP is the coefficient of performance.

The load factor of the electric boiler or the ASHP water heater is the ratio of the energy consumed over a 24 h period to the product of the maximum power and the period (24 h), as given by

$$\mathrm{LF} = \frac{E \text{ over 24h}}{P_{\max}} \tag{4}$$

where LF is the load factor and $P_{\max}$ is the maximum power consumed in half-hourly intervals over a 24 h period in hour (h).

The determination coefficient (R^2) is the square of the correlation coefficient between the actual outputs (y_j) and the modelled output ($\hat{y}$), given as

$$R^2 = 1 - \frac{\sum_{1}^{n}\left(y_j - \hat{y}_j\right)^2}{\sum_{1}^{n}\left(y_j - \bar{y}_j\right)^2} \tag{5}$$

where $\bar{y}_j$ is the mean of the actual output data.

The root mean square error (RMSE) between the actual outputs (y_j) and the model output ($\hat{y}_j$) is given as

$$\mathrm{RMSE} = \sqrt{\left(\frac{1}{n}\sum_{1}^{n}\left(y_j - \hat{y}_j\right)^2\right)} \tag{6}$$

where j=1, 2, ···, n.

The derived linear models of the daily volume of hot water consumed and the electrical energy consumed by the electric boiler and the ASHP water heater is given as

$$E = A + BV \tag{7}$$

where E is the daily electrical energy consumed by the hot water heating devices in kWh, V is the daily volume of hot water consumed from the hot water heating devices in L, A is the forcing constant in kWh, and B is the scaling constant in /L.

The uncertainties obtained from the calculation are as a result of the error measurements from the set of independent variables and is given as

$$W_r = \left[\left[W_1 \frac{\partial R}{\partial X_1}\right]^2 + \left[W_2 \frac{\partial R}{\partial X_2}\right]^2 + \cdots + \left[W_n \frac{\partial R}{\partial X_n}\right]^2\right] \tag{8}$$

where R is the given function, W_r is the total uncertainty, X_1, X_2, ···, X_n are the independent variables, and W_1, W_2, ···, W_n are the uncertainty in the independent variables.

The simple payback period of a technology, is the ratio of the capital cost and the product of the annual energy saving and tariff rate. The simple payback period (SPB), may be expressed as

$$\mathrm{SPB} = \frac{\text{Capital cost}}{\text{Annual energysaving} \times \text{tariff}} \tag{9}$$

where SPB is the simple payback period.

The capital cost of a technology takes into consideration both the upfront cost and the maintenance costs. The maintenance costs of an ASHP water heater include the cost of replacing the water filter and the capacitor, as well as the disposal cost, at the end of the lifespan of the product (15 years).

The net present value (NPV) of money incorporates the concept that the value of money today is worth more than the value in the future. The NPV is influenced by factors such as inflation and interest rates and both have an adverse impact on money with respect to time. The net present value (NPV) of money with an annual hike in tariff rate (r%), and the future value (FV) for a number of years (n) is given as

$$\mathrm{NPV} = \frac{\mathrm{FV}}{\left(1 + r\right)^n} \tag{10}$$

It may be accepted without doubt, that a technology is regarded to be economically viable provided the payback period is significantly lower than its stipulated lifespan as prescribed by the manufacturer.

The electrical energy saving is defined from a conservative approach, as the difference between the electrical energy consumed by the electric boiler and the electrical energy consumed by the ASHP water heater on identical months. This was substantiated by showing that the volume of the average daily hot water consumed by the students had negligible variation (the percentage difference was 0.01).

A. Wilcoxon Algorithms

For a two-sided test of medians, with unequal sample sizes, the test statistic that rank sum returns, is the rank sum of the first sample. It should be noted that p = rank sum (x, y), gives the p-value of a two-sided Wilcoxon rank sum test. Furthermore, rank sum test examines the null hypothesis that the data in x and y, are samples from continuous distributions with equal medians, against the alternative that they are not. The test assumes that the two samples are independent, and x and y may have different lengths. In addition, $[p, h]$ = rank sum (x, y), gives a logical value indicating the test decision (h). The result $h = 1$, indicates a rejection of the null hypothesis and $h = 0$, indicates a failure to reject the null hypothesis, at 5% significance level.

III. Materials and Methods

A. Materials

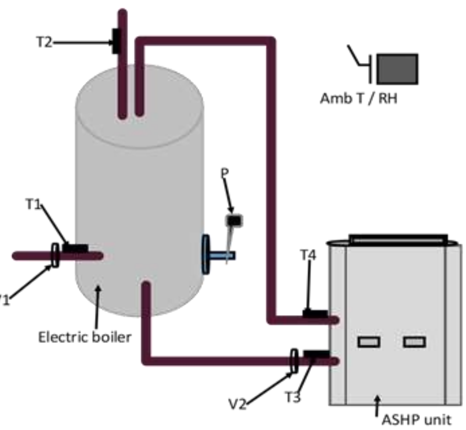
The list of hot water devices, sensors and transducers used in the study, is shown in Table I.

TABLE I. HOT WATER DEVICES, SENSORS AND TRANSDUCERS USED IN THE EXPERIMENT

Item	Material	Quantity
1	Power meter	1
2	Flow meters	2
3	Temperature sensors	5
4	Ambient temperature and relative humidity sensor	1
5	12 kW, 1000 L electric boiler	1
6	4.0 kW input ASHP unit	1
7	Water filter	1
8	Data logger	1
9	Waterproof enclosure	1
10	Power meter	1

B. Experimental Setup

Fig. 1, shows the schematic diagram of the ASHP unit retrofitting the electric boiler. The electric boiler was retrofitted with the ASHP unit and the sensors were inserted at various locations on the hot water heating systems.



T_1=Temperature sensor installed at the inlet of makeup water to the boiler, T_2=Temperature sensor installed at the outlet of the hot water from the boiler, V_1=Flow meter installed at the inlet of makeup water to the boiler, V_2=Flow meter installed at the inlet of the ASHP unit, T_3=Temperature sensor installed at the inlet of the ASHP unit, T_4=Temperature sensor installed at the outlet of the ASHP unit and Amb T/ RH = Ambient temperature and relative humidity sensor.

Fig. 1. Installed AWHP and the metering sensors.

A temperature sensor (T_1) was inserted by drilling at the inlet of the makeup cold water pipe of the electric boiler, which fed the main cold water into the storage tank containing a heating element. The temperature sensor (T_1) measured the temperature of the makeup cold water. A temperature sensor (T_2) was inserted by drilling at the outlet pipes of the hot water storage tank and measured the temperature of the hot water supplied to the residence. Another temperature sensor (T_3) was inserted by drilling at the inlet pipe of the ASHP unit, feeding the inlet of the ASHP unit with water from the storage tank. Also, a temperature sensor (T_4) was inserted by drilling at the outlet pipe of the ASHP unit, which allowed the heated water to exit the outlet of the ASHP unit into the storage tanks. All the installed water temperature sensors were adequately sealed to prevent water leakage from the drilled holes on the designated locations on the copper pipes. A flow meter (V_2) was installed on the pipe leading into the inlet of the ASHP unit and measured the volume of hot water heated by the ASHP unit, during the vapor compression refrigeration cycles. A second flow meter (V_1) was installed on the inlet pipe that was supplying the makeup cold water into the storage tank and measured the volume of hot water consumed by the students in the residence. Moreover, a power meter was installed on the electrical supply line, powering either the 12 kW electric boiler or the 4.0 kW input ASHP unit, thus measured the power consumed by either of the heating devices. An ambient temperature and relative humidity sensor (Tamb/RH) was installed in the vicinity of the hot water system and measured the ambient temperature and relative humidity. All the sensors and transducers were connected to a data logger (U30-NRC hobo logger), which was configured to log in 5 minute intervals throughout the monitoring period (that is when the hot water production was achieved by the electric boiler before the implementation of energy efficiency intervention and when the ASHP unit was used for hot water heating after the boiler's resistive element was disabled).

All the sensors and transducers were properly insulated to avoid signal interference from external sources. The monitoring period of the baseline performance with the electric boiler was from January to December 2016. The performance assessment period was from January to December 2017, and the ASHP water heater was used to provide hot water to the residence.

IV. Results and Discussion Establishment of a Correlation between the Daily Energy and Volume of Hot Water Consumed

Correlations between the daily electrical energy and volume of hot water consumed by the electric boiler and the ASHP water heater, were determined for both the summer and winter periods.

A. Correlation of Energy and Volume of Hot Water Consumed during the Summer Period

A dataset of over 120 daily volumes of hot water and electrical energy consumed by each of the hot water heating devices spanning the entire summer months (all the eight months of 2016 for the electric boiler and the same months of 2017 for ASHP water) were used in the development, testing and validation of the models. The dataset was randomly divided such that 70% of it (trained dataset), was used in the building and testing of the linear models that correlated the daily volume of hot water consumed with the electrical energy consumed. The remaining 30% (test dataset) of the dataset were used in the validation of the models derived for the electric boiler and the ASHP water heater. Fig. 2, shows samples of the daily volume of hot water consumed and the equivalent electrical energy used by both the electric boiler and the ASHP water heater. It is demonstrated that the electrical energy consumed increased with a corresponding increase in the volume of hot water consumed. Both modelled equations have positive gradients of 0.157 and 0.025 kWh/L, for the electric boiler and the ASHP water heater, respectively. The determination coefficients (R^2) and root mean square error (RMSE) of the modelled and measured electrical energy consumed of the electric boiler and the ASHP water heater were 0.989 and 2.650, and 0.953 and 1.148, respectively. The exceptional (R^2), suggested that the modelled equations derived for the electric boiler and the ASHP water heater were of high accuracies and the modelled outputs mimic the measured outputs. Hence, based on the trained dataset, the mathematical models perfectly predict the daily electrical energy consumed by the electric boiler and the ASHP water heater, with the volume of hot water consumed serving as the input parameter.

Table II, assembles information on the forcing and scaling constants of the linear models that correlate the daily volume of hot water consumed with the daily electrical energy consumed. The forcing constant is a lump arbitrary constant, that takes into consideration other input parameters not included in the mathematical models. The forcing constants assist in subjecting the models to accurately predict the measured output. The forcing constant (A) of the electric boiler and the ASHP water heater was -113.7 and 0.319 kWh, respectively, while the scaling constant (B) was 0.157 and 0.025 kWh/L, respectively.

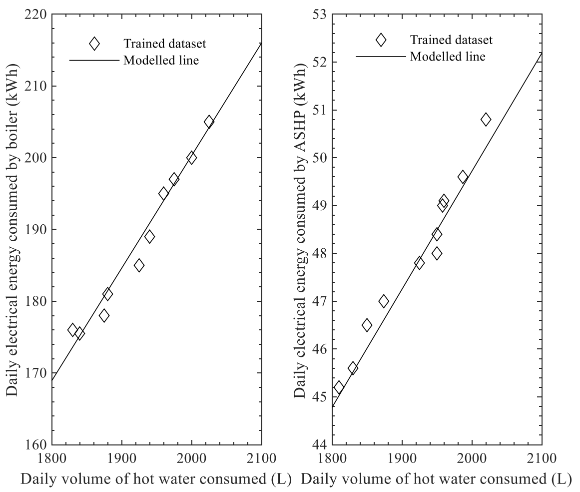


Fig. 2. Modelled and train dataset of daily volume and electrical energy consumed in summer.

TABLE II. THE FORCING AND SCALING CONSTANTS OF THE MATHEMATICAL MODELS IN THE SUMMER PERIOD

Input parameter	Volume consumed by Electric boiler (V_b)	Volume consumed by ASHP (V_a)
Forcing Constants	A= -113.7	A=0.319
Scaling constants	B= 0.157	B= 0.025
Output parameter	Electrical energy consumed (E_b)	Electrical energy consumed (E_a)
Mathematic model	E_b =-101.92 + 0.157 V_b	E_a=0.319+0.025V_a

E_b = Daily electric energy consumed by electric boiler, E_a= Daily electric energy consumed by ASHP water heater, V_b= Daily volume of hot water consumed by electric boiler, V_a= Daily volume of hot water consumed by ASHP water heater

Fig. 3 shows the sample test dataset and the modelled line used in the validation of the developed linear models for the electric boiler and the ASHP water heater. The model validations of the electric boiler and the ASHP water heater showed excellent prediction with R^2 and RMSE of 0.973 and 6.524 for the electric boiler and 0.942 and 0.438 for the ASHP water heater.

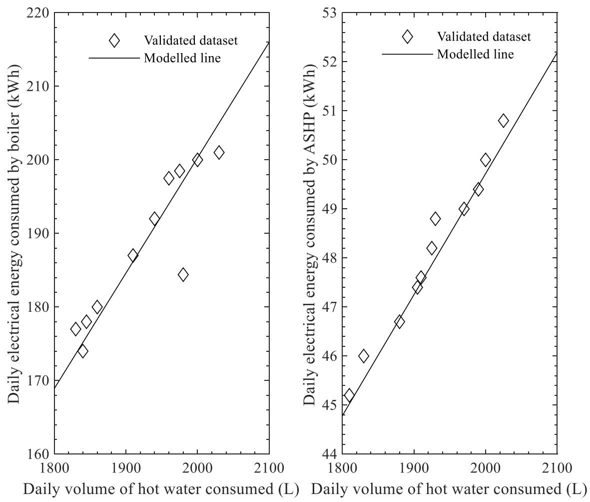


Fig. 3. Modelled and validation dataset of daily volume and electrical energy consumed in summer.

B. Correlation of Energy and Volume of Hot Water Consumed during the Winter Period

A dataset of over 80 daily volumes of hot water and electrical energy consumed by each of the hot water heating devices that transverse the whole winter months (all the four months of 2016 for the electric boiler and the same months of 2017 for ASHP water) were used in the building and validation of the models. A similar methodology to that employed during the summer season was performed. In view of that, the dataset was randomly divided and 70% were used as the trained data in the building and testing of the linear models that related the daily volume of hot water consumed with the electrical energy consumed. The remaining 30% of the dataset were used as the test data in the validation of the models derived for the electric boiler and the ASHP water heater. Fig. 4, illustrates samples of the trained dataset of the daily volume of hot water consumed and the equivalent electrical energy used by both the electric boiler and the ASHP water heater.

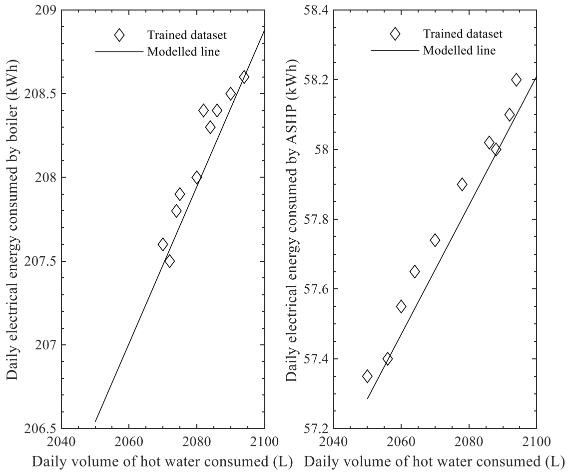


Fig. 4. Modelled and train dataset of daily volume and electrical energy consumed in winter.

TABLE III. THE FORCING AND SCALING CONSTANTS OF THE MATHEMATICAL MODELS IN THE WINTER PERIOD

Input parameter	Volume consumed by Electric boiler (V_b)	Volume consumed by ASHP (V_a)
Forcing Constants	A= -110.6	A=19.36
Scaling constants	B = 0.0468	B= 0.0185
Output parameter	Electrical energy consumed (E_b)	Electrical energy consumed (E_a)
Mathematic model	E_b =110.6 +0.0468V_b	E_a =19.36 + 0.0185V_a

E_b = Daily electric energy consumed by electric boiler, E_a = Daily electric energy consumed by ASHP water heater, V_b = Daily volume of hot water consumed by electric boiler, V_a = Daily volume of hot water consumed by ASHP water heater

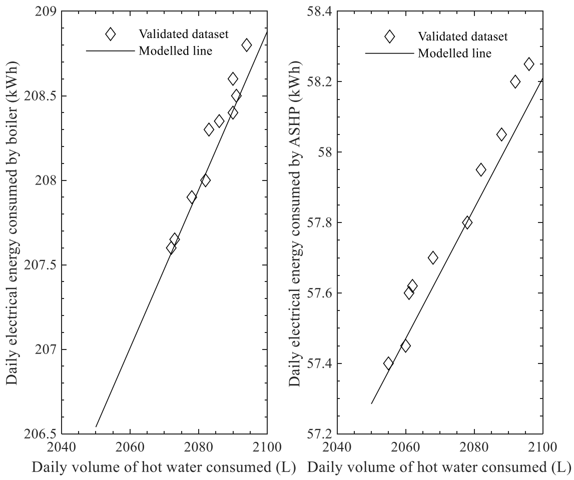


Fig. 5. Modelled and validation dataset of daily volume and electrical energy consumed in winter.

The R^2 and RMSE of the modelled and measured electrical energy of the electric boiler and the ASHP water heater were 0.940 and 0.295, and 0.982 and 0.093, respectively. The very good R^2 and small RMSE, revealed that the modelled equations derived for the electric boiler and the ASHP water heater had good accuracies between the predicted and the measured outputs. Therefore, with reference to the trained dataset, the mathematical models showed acceptable prediction of the electrical energy consumed by the electric boiler and the ASHP water heater, where the input parameter was the volume of hot water consumed.

Table III shows the forcing and scaling constants of the linear models of the daily electrical energy consumed in relation to the volume of hot water consumed. The forcing constant (A) of the electric boiler and the ASHP water heater was 110.60 and 19.36 kWh, while the scaling constant (B) was 0.0468 and 0.0185 kWh/L, respectively.

Fig. 5 represents the sample test dataset used as the validation dataset and the modelled line of the electric boiler and the ASHP water heater. The validations of the derived models of the electric boiler and the ASHP water heater gave a very good prediction with R^2 and RMSE of 0.945 and 0.338 for the electric boiler and also, 0.987 and 0.178 for the ASHP water heater.

C. Comparison of the Volume and Energy Consumed Using Wilcoxon Rank Sum Test

The Wilcoxon rank sum test of the daily volume of hot water consumed by the electric boiler and the ASHP water heater showed a p-value of 0.470 and the logical value of the test decision (h) was 0 for summer and the p-value was 2.33×10^{-2} while the logical value was 1 for winter at the 5% significance level. Therefore, the large p-value for summer confirmed that no significant difference exists between the two groups of the daily volume of hot water consumed, during the summer period. However, the h=0, indicated a failure to reject the null hypothesis test at the 5% significance level based on the logical decision. The very small p-value (less than 0.05) shows there existed a significant difference between the two groups of the daily volume of hot water consumed, during the winter period. The logical value of the test decision (h) was 1 and revealed a rejection of the null hypothesis test at the 5% significance level. On the contrary, the comparison of the daily electrical energy consumed by the electric boiler and the ASHP water heater during the summer period, showed that a significant difference exists between the two groups with a p-value of 3.09×10^{-9} while for winter the p-value was 0.0286. The logical value of the test decision (h) was 1 in both seasons and hence, rejected the null hypothesis of the groups originating from a continuous distribution, with equal medians.

D. Monthly Electrical Energy Saving due to Retrofitting of the Boiler with the ASHP Unit

Fig. 6 shows the monthly electrical energy consumed by the electric boiler and the ASHP water heater, as well as the determined COP.

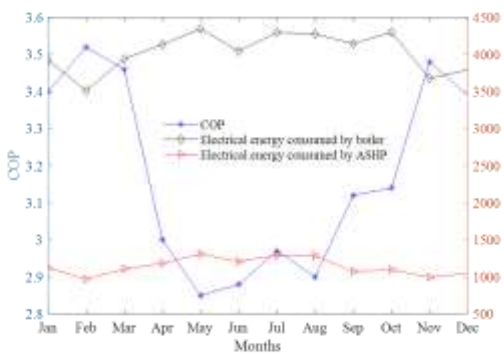


Fig. 6. Monthly performance of hot water devices during monitoring period.

It is depicted from the figure, that for each of the months, the electrical energy consumed by the electric boiler was approximately three times that of the ASHP water heater. This further indicated that the ASHP water heater is an energy efficient device for sanitary hot water heating, with an average annual COP of 3.18. The total electrical energy consumed by the electric boiler (January to December 2016) was 48390.58 kWh, while the ASHP water heater (January to December 2017), was 13703.23 kWh. It was determined that the average daily hot water consumed by the electric boiler and the ASHP water heater was 1865.25 L and 1847.88 L, respectively, over the monitoring period. The difference in the average daily volume of hot water consumed was 0.01%, which is practically negligible. Hence, the annual energy saving due to the retrofitting of the electric boiler with the ASHP unit, was 34687.35 kWh. This demonstrated that the ASHP water heater performed with an excellent COP, throughout the year. A substantial monthly electrical energy saving was achieved by the implementation of the ASHP unit to retrofit the electric boiler.

E. Techno-Economic Cost Analysis of the Installed ASHP System

The techno-economic life cost analysis of the ASHP system, envisages the viability of the technology on the basis of the payback period (PB), using the net present value of money (NPV). The NPV of money is of a higher value than the future value of money (FV). This may be accounted by inflation and an increase in the interest rate on the capital cost. The incurred cost of the ASHP system included the capital cost of the ASHP unit, the water filter and the maintenance cost of replacing the bags of sand used by the water filter, as well as the cost of installation and disposal of the ASHP system. The capital cost of the ASHP unit, the water filter and the installation of the ASHP system was R 80000.00. The cost of maintenance was R 1000.00, which was the cost, incurred for the replacement of the water filter, and will be implemented every four years, throughout the lifespan of the ASHP system. The disposal cost was R 2000.00 and will be incurred at the end of the lifespan of the ASHP system. Hence, the total cost incurred for the entire lifespan (15 years) of the ASHP system, will be R 85000.00. The Eskom's initial tariff was R 1.50/kWh and the annual percentage of tariff hike was assumed as 15%. The annual cost saving in terms of the future value of money, is the product of the annual energy saving and Eskom's tariff with the rates of tariff hike included. The annual cost saving, with reference to the net present value of money (NPV), is a combination of the annual cost saving of the future value of money (FV), with the annual rate of return (r), taken into consideration. The relation of the net present value of money (NPV), express in terms of the future value of money (FV), the annual rate of return (r) and the number of years (n) is provided in Equation 6. The annual rate of return (r) was considered as 6.5% in the techno-economic cost analysis. Table IV, provides the breakdown of the life cost economic analysis of the ASHP water system. The annual energy saving due to the retrofitting of the electric boiler, with the ASHP system was 34805.94 kWh. The future value and the net present value of the annual cost savings are as shown in Table IV. The payback period of the ASHP system was determined to be 1.7 years. The total net present value cost saving at the end of the lifespan (2031) of the ASHP system, will be R 1 239 590.77.

TABLE IV: TECHNO-ECONOMIC LIFE COST ANALYSIS OF THE ASHP SYSTEM

Year	No of year	Savings kWh	Tariff 15%	FV/ R	NPV/ R	Incur cost/R
2016	0					80000
2017	1	34805.94	1.50	52208.92	49022.46	0
2018	2	34805.94	1.73	60040.25	52935.05	0
2019	3	34805.94	1.98	69046.29	57159.91	0
2020	4	34805.94	2.28	79403.23	61721.97	1000
2021	5	34805.94	2.62	91313.72	66648.13	0
2022	6	34805.94	3.02	105010.78	71967.47	0
2023	7	34805.94	3.47	120762.39	77711.35	0
2024	8	34805.94	3.99	138876.75	83913.67	1000
2025	9	34805.94	4.59	159708.27	90611.00	0
2026	10	34805.94	5.28	183664.51	97842.86	0
2027	11	34805.94	6.07	211214.18	105651.92	0
2028	12	34805.94	6.98	242896.31	114084.23	1000
2029	13	34805.94	8.03	279330.76	123189.55	0
2030	14	34805.94	9.23	321230.37	133021.58	0
2031	15	34805.94	10.61	369414.93	143638.32	2000

R=South Africa rand, FV= Future value, PV=Present value

V. CONCLUSION

It can be concluded that, by simply retrofitting the electric boiler with the ASHP unit in the students' residence at the University campus, a significant demand and electrical energy reduction was realized. The power consumption of the installed ASHP unit was almost three times lower, than that of the inefficient electric boiler. The implementation of the ASHP unit as an energy efficient technology was accompanied by a reduction of the load factor. The Wilcoxon rank sum test was employed to show that a significant difference exists between the electrical energy consumed by the ASHP water heater and the electric boiler, in both the summer and winter seasons, respectively. Nonetheless, the logical values of the decision test showed a rejection of the null hypothesis test for the two groups to be continuous and having equal medians in terms of their daily electrical energy consumed for both the summer and winter seasons. The derived and validated models of the electric boiler and the ASHP water heater demonstrated excellent accuracies between the modelled and measured outputs with acceptable determination coefficients and root mean square errors. The average annual COP and the net present value payback period of the ASHP system were 3.18 and 1.7 years. The payback period may be further reduced, provided the hot water consumption by the students in the residence increased and the tariff rates continue to increase. Finally, the operating performance of the ASHP water heater demonstrated that the ASHP system can efficiently save electrical energy during the summer and the winter seasons. It is imperative to rollout this technology as a smart and energy efficiency measure for sanitary hot water heating in the residences of the University Campus.

Conflict of Interest

All authors declared no conflict of interest in the paper.

Author Contributions

Dr. Stephen Tangwe was responsible of conceptualization, drafting and development of the manuscript. Prof. K Kusakana provide technical input and conduct technical restructuring and proofreading of the manuscript.

Acknowledgment

We acknowledged the Centre for Sustainable SMART Cities, Central University of Technology, in Free State, South Africa for the financial supports.

References

[1] S. Ran, X. Li, W. Xu, and B. Wang, "A solar-air hybrid source heat pump for space heating and domestic hot water," *Solar Energy*, vol. 199, pp. 347-359, Mar. 2020.

[2] S. D'Arpa, I. Petrosillo, V. Uricchio, G. Zurlini, G. Colangelo, and G. Starace, "Heating requirements in greenhouses farming in South of Italy: Evaluation of ground source heat pump utilization," *Energy Efficiency*, vol. 9, pp. 1065–1085, Nov. 2015.

[3] A. S. Gaur, D. Z. Fitiwi, and J. Curtis, "Heat pumps and our low-carbon future: A comprehensive review," *Energy Research & Social Science*, vol. 71, Jan. 2021.

[4] A. Hepbasli and Y. Kalinci, "A review of heat pump water heating systems," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 7, pp. 1211-1229, Sept. 2009.

[5] R. Rankin, P. G. Rousseau, and M. Van Eldik, "Demand side management for commercial buildings using an inline heat pump water heating methodology," *Energy Conversion and Management*, vol. 45, no. 10, pp. 1553-1563, Jun. 2004.

[6] Q. Zhang, L. Zhang, J. Nie, and Y. Li, "Techno-economic analysis of air source heat pump applied for space heating in northern China," *Applied Energy*, vol. 207, pp. 533-542, Dec. 2017.

[7] F. Alshehri, S. Beck, D. Ingham, L. Ma, and M. Pourkashanian, "Techno-economic analysis of ground and air source heat pumps in hot dry climates," *Journal of Building Engineering*, vol. 26, pp. 100825-100945, Nov. 2019.

[8] J. P. Meyer and G. P. Greyvenstein, "Hot water for large residential units, hospitals and laundries with heat pumps in South Africa: A techno-economic analysis," *Energy Conversion and Management*, vol. 33, no. 2, pp. 135-143, Feb. 1992.

[9] P. G. Rousseau and G. P. Greyvenstein, "Enhancing the impact of heat pump water heaters in the South African," *Energy*, vol. 25, no. 1, pp. 51-70, Jan. 2000.

[10] A. S. Vieira, R. A. Stewart, and C. D. Beal, "Air source heat pump water heaters in residential buildings in Australia: Identification of key performance parameters," *Energy and Buildings*, vol. 91, pp. 148-162, Mar. 2015.

[11] H. Willem, Y. Lin, and A. Lekov, "Review of energy efficiency and system performance of residential heat pump water heaters," *Energy and Buildings*, vol. 143 pp. 191-201, May 2017.

[12] E. Osterman, and U. Stritih, "Review on compression heat pump systems with thermal energy storage for heating and cooling of buildings," *Journal of Energy Storage*, vol. 39, Jul. 2021.

[13] S. Tangwe, M. Simon, and E. Meyer, "Mathematical modeling and simulation application to visualize the performance of retrofit heat pump water heater under first hour heating rating," *Renewable Energy*, vol. 72, pp. 203-211, Dec. 2014.

[14] M. Mohanraj, Y. Belyayev, S. Jayaraj, and A. Kaltayev, "Research and developments on solar assisted compression heat pump systems–A comprehensive review (Part A: Modeling and modifications)," *Renewable and Sustainable Energy Reviews*, vol. 83, pp. 90-123, Mar. 2018.

[15] J. Vivian, E. Prataviera, F. Cunsolo, and M. Pau, "Demand side management of a pool of air source heat pumps for space heating and domestic hot water production in a residential district," *Energy Conversion and Management*, vol. 225, pp. 1134 -1157, Dec. 2020.

[16] K. Sezen, A. D. Tuncer, A. O. Akyuz, and A. Gungor, "Effects of ambient conditions on solar assisted heat pump systems: A review," *Science of the Total Environment*, vol. 778, pp. 1463-1482, Jul. 2021.

[17] G. L. Morrison, T. Anderson, and M. Behnia, "Seasonal performance rating of heat pump water heaters," *Solar Energy*, vol. 76, no. 3, pp. 147-152, Mar. 2004.

[18] L. Fu, D. Ding, and C. Zhang, "Dynamic simulation of air-to-water dual-mode heat pump with screw compressor," *Applied Thermal Engineering*, vol. 23, no. 13, pp. 1629-1645, Sept. 2003.

[19] W. Wang, Z. Zhao, Q. Zhou, Y. Qiao, and F. Cao, "Model predictive control for the operation of a transcritical CO_2 air source heat pump water heater," *Applied Energy*, vol. 300, pp. 11720-11739, Oct. 2021.

[20] P. Techarungpaisan, S. Theerakulpisut, and S. Priprem, "Modeling of a split type air conditioner with integrated water heater," *Energy Conversion and Management*, vol. 48, no. 4, pp. 1222-1237, Apr. 2007.

[21] P. A. Hohne, K. Kusakana, and B. P. Numbi, "A review of water heating technologies: An application to the South African context," *Energy Reports*, vol. 5, pp. 1-19, Nov. 2019.

[22] G. Martinopoulos, K. T. Papakostas, and A. M. Papadopoulos, "Comparative analysis of various heating systems for residential buildings in Mediterranean climate," *Energy and Buildings*, vol. 124, pp. 79-87, Jul. 2016.

[23] S. L. Tangwe and M. Simon, "Quantification of the viability of residential air source heat pump water heaters as potential replacement for geysers in South Africa," *Journal of Engineering, Design and Technology*, vol. 17, no. 2, pp. 456-470, Jan. 2019.

[24] M. Sikhonza, S. Tangwe, and M. Simon, "Energy management opportunities exploration in a residential air source heat pump water heater," in *Prof. 28th Int. SAUPEC/RobMech/PRASA Conf.*, Stellenbosch, 2020, pp. 1-6.

Stephen Tangwe (Ph.D., CEng, MIMECHE, CMVP) is a postdoctoral research fellow at the department of Electrical, Electronic and Computer Engineering, faculty of Engineering Built Environment and Information Technology, Central University of Technology. He is a Chartered Engineer and a Member of the Institution of Mechanical Engineers (CEng MIMechE) and also a CMVP and an energy expert. He holds a Ph.D. degree in Engineering from the University of Sunderland in the United Kingdom. He is a seasoned author and reviewer in accredited peer review Journals.

K. Kusakana (D.Tech., Pr.Eng., and CEM) is a NRF rated researcher. His research interests are power and energy systems, energy management, renewable and alternative energies. He is currently a Professor and Head of the Electrical, Electronic and Computer Engineering Department at CUT. He is a seasoned Author and reviewer in a series of DHET accredited peer review journals and conference proceedings with high impact factors.