Analytical evaluation of energylosses of an air source heat pump water heater : A retrofit type

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ABSTRACT

Air source heat pump (ASHP) water heater is a renewable and energy efficient device used for sanitary hot water production. The system comprises of two major blocks (storage tank and heat pump) connected by pipes or tubing. These blocks can either be compact as in the integrated model or split as in the retro-fit model. ASHP water heater efficiency is primarily governed by its coefficient of performance usually more than 200 % and also depends on the circumstances and climatic conditions under which the system is operating. In this paper, the analysis of energy losses was performed using SIRAC residential split type heat pump of 1.2 kW input power and 240 V single phase as per manufacturer's specification to retrofit a 200 litres high pressure kwikhot storage tank without hot water being drawn off for the entire monitoring period. Likewise to experimentally determine the losses a data acquisition system (DAS) was designed and built to measure ambient temperature, relative humidity, outlet hot water temperature of the storage tank, in let cold water and outlet hot water temperatures of the ASHP. Two flow meters were also installed on the inlet cold water pipe of ASHP and on the outlet hot water pipe of storage tank. In addition, electrical power of ASHP was also measured. The results showed that heat gain to compensate stand by losses could range from 1.8 kWh to 2.1 kWh with the corresponding electrical energy (EE) used by ASHP ranged from 0.55 kWh to 0.66 kWh. The stand by losses depend primarily on volume of water heated (V), ambient temperature (T_a) and relative humidity (RH) while influence of the temperature difference between the hot water and cold water from the outlet and inlet pipes of the ASHP (T_h-T_c) is secondary. Finally, we also determined the energy consumed by the power electronic board of ASHP to be approximately 0.10 kWh.

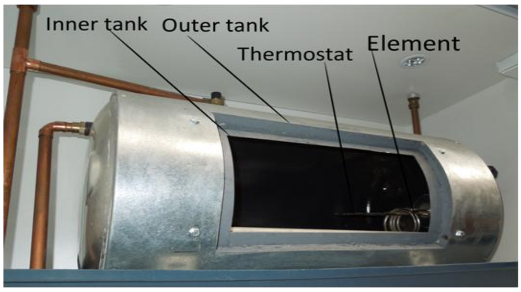
KEYWORDS: *Air source heat pump (ASHP); Coefficient of performance; Renewable energy device*

1.0. INTRODUCTION

It is worth mentioning that despite the daunting electrical energy consumed for hot water generation, not all the thermal energy gained by the hot water is effectively utilized. There are always stand by losses which is responsible for 20% to 30% of the total thermal energy gained by hot water contained in a storage tank [Van Tonder et al., 2001; Delport, 2005].Although, ASHP water heater coefficient of performance (COP) value can range from 2 to 4 [Levins 1982; Bodzin, 1997]; it is crucial to note that the COP depends on primary (volume of hot water heated, hot water set point temperature and cold water temperature) and secondary factors (ambient temperature and relative humidity). Clearly, the COP could be defined as the ratio of useful thermal energy gained when water is heated to set point temperature and the electrical energy used by the system during the vapour 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 & Dysarkar, (2008). Moreover, the performance can be severely affected by stand by losses [Morrison et al., 2004]. Heat pump water heaters also render an extra benefits of dehumidification and space cooling because they pull warm vapour from the air (Baxter et al., 2005).

1.1. Brief description of the installation of a split type ASHP water heater.

Figure 1 and 2 shows the essential components of the system. It comprises of a 400 kPa , 200L high pressure geyser with it 4 kW element disabled, so that it now serves as a hot water storage tank and also an ASHP unit rated 1.2 kW. These primary components are connected by copper pipes incorporating water circulation pump, non return gate valve and a mechanical close and open valve to complete the closed circuit.This system was installed in a middle income home in Fort Beaufort, located in the Eastern Cape province of South Africa.



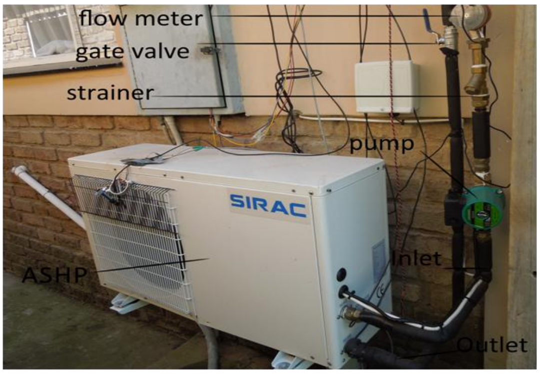


Figure 1: The geyser to be used as storage tank.   Figure 2:Illustration of the installed ASPH unit.

2.0. Description of the meters and sensors used in the experimental setup

ASPH water heater was set to produce hot water at 55°C with a temperature differential of 5°C. This implied ASHP unit would start the vapour compression refrigerant cycle once hot water inside the storage tank was 5°C or more below the set point temperature. The system was allowed to operate in an uninterrupted mode and without any hot water drawn in to the main building from the 18 th December 2012 to 01 st January 2013. The performance and energy losses of the system was evaluated for eight consecutive days within the experimental duration. 12 bits S-TMB temperature sensors incorporating electronic input pulse adapters were used to measure cold water temperature in to the inlet and hot water temperature from the outlet of the ASHP unit. 12 bits S-THB ambient temperature and relative humidity was also used to measure ambient temperature and the relative humidity. The T-Minol 130 flow meters were installed at the cold water inlet pipe in to ASHP and hot water outlet pipe from the storage tank to measure the water flow rates of the respective unit. A T-VER-B50B2 power and energy meter was also used to measure the power factor and energy consumption by the ASHP water heater. All these meters and sensors are housed by hobo U30-NRC data logger.

3.0. Methodology

The methodology is divided into two; the data acquisition architectural design and the full schematic lay out of the ASHP water heater including the meters installation and the data logger. The losses are experimentally determined for each of the 24 hours period.

3.1. Data acquisition system

Figure 3 below shows the data acquisition system designed and built for this study. All analogue signals sensed by their respective sensors and transducers were converted to digital signals by the pulse input adapters integrated with their connecting cables. The data were stored in hobo U30-NRC data logger and could only be downloaded for further analysis using the hoboware pro software.

Figure 3: Shows the data acquisition system designed and built for the research

3.2. Full schematic of the complete set up

Figure 4 below shows the complete setup for the study. This schematic was designed using the simulink library of MATLAB.In the schematic in figure 6 all sensors (temperatures and relative humidity sensors) are represented by f(u). The following labels are used for this sensors; temperature sensors (TS) , ambient temperature (T_a) and relative humidity RH. The transducers mainly the flow meter and current transformer (CT) are also represented by f(u). In the setup ,three TS , two flow meters and one ambient temperature and relative humidity sensor (RH and T_a) were installed and their reading recorded were stored in the U30 logger. The power meter T-VER E50B2 measured the real energy (Wh), reactive energy (VARh) and the current hour (Ah) of the ASHP water heater and was also stored in the logger as counts. The flow rate was also measured in counts and 1 count equal to 3.7854 L/min. The data logger was configured to log every 1 minute throughout the duration of the experiment.

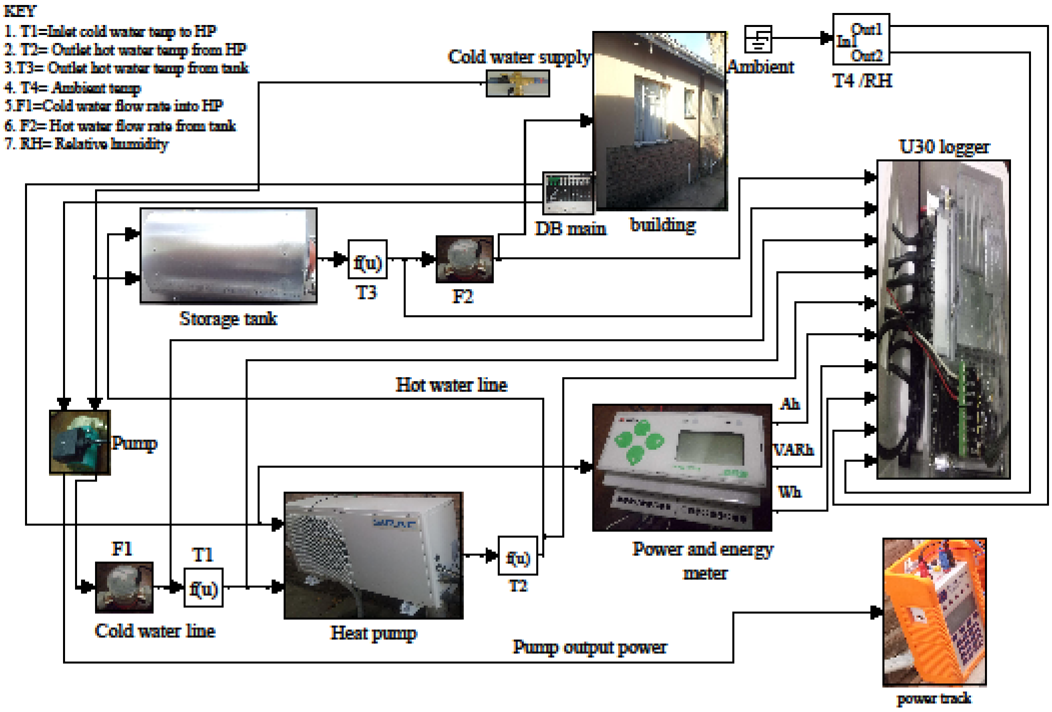


Figure 4: Shows the full schematic architectural layout used in the study.

4.0. Calculations

The set of equations given in the equation 1-4 shown below were used to calculate the active power (kW) , electrical energy (kWh) and the thermal energy gained by hot water (kWh) respectively.

$$p = \frac{Wh}{1000} \tag{1}$$

where p = power in kW

$$E_e = p \times t \tag{2}$$

where E_e = electrical energy in kWh and t = time in hour

$$E_t = mc(T_h - T_c) \quad \Rightarrow E_t = Vm(T2 - T1) \tag{3}$$

where Et = thermal energy gain in kWh, m = V = volume of water in litres heated by ASHP, c = specific heat capacity of water = 4.2 kJ/kg°C, T_h = T2 =hot water temperature while T_c = T1 = cold water temperature.

It is important to note that 1 pulse represent 1Wh and 1 VARh but 100 Ah as per the configuration setting in the power meter.

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

$$COP = \frac{E_t}{E_e} = \frac{\text{output useful thermal energy gain}}{\text{input electrical energy}} \tag{4}$$

5.0 Results and Discussions

5.1. A comparative analysis of the performance and energy losses

Table 1 below shows a detail analysis of the ASHP water heater coefficient of performance, energy factor, stand by losses and conditions under which the following results were achieved. It is worth to note that for each run, the first row shows the condition for which water was heated to set point temperature before monitoring the heat losses for 24 hours. In each of the runs over 24 hours duration the ASHP unit only comes on once. This interval was shown on the second row of each runs. It can be depicted that the average power of the system in each run were almost equal both when water was heated before the start of observation and when heated owing to stand by losses during monitoring period. The COP in all the heating mode ranged from 2.95 to 3.4. This is in accordance with the studies of Levins [1982] and Bodwins [1997]. The stand by heat losses also ranged from 1.8 kWh to 2.1 kWh. It can be shown that in all cases the average COP was greater than the energy factor (EF) of the system which ranged from 2.60 to 2.95. This could be accounted for by the electrical energy consumed by the power electronic circuit integrated in to the ASHP water heater.(0.09 kWh-0.1 kWh). Finally without loss of generality, the stand by loss in the system was approximately equal to heat gain to heat up water to set temperature before monitoring the losses for 24 hours ± 0.08 in kWh.

Table1: A comparison analysis of the system performance and energy losses of the 8 consecutive days

period	Heat up time HH:MM	[1]P_{av} kW	[2]E_eT kWh	[3]E_tT kWh	[4]**COP**	[5]V L	[6]Tc °C	[7]Th °C	[8]Ta °C	[9]RH %	[10]E_e**D** kWh	[11]EF
1 run,19-20	05:54-06:27	1.44	0.62	1.97	3.15	204	30.1	53.9	18.7	94.8	0.72	2.76
	00:32-01:04	1.49	0.62	2.03	3.28	223	28.9	54.0	20.7	84.6	0.71	2.88
2 run,21-22	10:08-10:39	1.46	0.56	1.87	3.34	208	34.6	55.0	26.2	70.8	0.66	2.85
	06:39-07:10	1.48	0.57	1.82	3.20	208	31.3	54.6	23.8	80.6	0.65	2.79
3 run,23-24	03:14-03:47	1.46	0.63	1.95	3.10	227	31.3	53.8	19.5	83.7	0.71	2.76
	01:02-01:32	1.50	0.55	1.82	3.32	204	32.9	54.1	21.9	88.3	0.63	2.88
4 run,24-25	20:20-20:52	1.47	0.59	1.97	3.35	211	25.5	54.3	21.1	93.7	0.66	2.99
	13:36-14:08	1.49	0.59	1.85	3.10	215	30.9	54.6	24.6	66.0	0.68	2.73
5 run,26-27	06:54-07:26	1.47	0.58	1.89	3.23	219	35.7	54.3	20.4	94.7	0.70	2.78
	01:48-02:12	1.48	0.61	1.92	3.12	227	34.3	53.6	18.1	94.7	0.73	2.65
6 run,27-28	23:05-23:38	1.45	0.63	1.87	2.95	223	28.0	53.9	21.9	62.9	0.7	2.67
	19:36-20:08	1.44	0.60	1.88	3.13	211	23.9	53.7	21.7	69.6	0.66	2.87
7 run,29-30	16:20-16:42	1.56	0.47	1.49	3.19	162	38.9	55.9	33.8	41.5	0.51	2.94
	11:11-11:38	1.55	0.52	1.66	3.19	185	34.2	55.4	29.4	49.6	0.58	2.84
8 run,31-01	08:11-08:44	1.43	0.62	2.03	3.30	227	31.2	53.6	19.1	96.1	0.71	2.86
	01:50-02:25	1.46	0.66	2.14	3.25	234	28.9	52.9	16.4	98.7	0.76	2.80

[1] [1]Average power, [2]Total electrical energy used , [3]Total thermal energy gain , [4] Average COP , [5]Total volume of water heated,[6]Initial cold water temperature,[7]Final hot water temperature, [8]Average ambient temperature ,[9]Average relative humidity, [10]Total electrical energy use in a complete 24 hours and [11]Energy factor

5.2 Profile of electrical energy used and heat loss for a day

The figure 5 below shows the profiles of electrical energy used by the ASHP water heater and the thermal energy gain by hot water for the 5 th run (06:54 ,26 December 2012 - 07:26, 27 December 2012). From Figure 7, the profiles of electrical and thermal energy for the 5 th run is divided into four zones; A, B, C and D. Zone A was where the water is first heated to set point temperature (reference heating up cycle). It can be clearly seen that the total energy of zone A was equal to that of zone C. Hence heat losses in the zone B was equal to heat gain in zone C. In zones B and D, no thermal energy was gained by water as ASHP was in an off mode but energy was consumed by system micro controller unit and equal to 0.044 kWh.The subplot labeled A, B, C and D clearly illustrates the electrical and thermal energy involved in the respective zones. It can also be observed that in the zones A and C where water was heated up by ASHP unit, the unit usually runs for about 5 minutes before continuous heating up of water begins. In the zones B and D the system was not heating up water, thus, no thermal energy was gained but electrical energy was consumed as the micro controller never turned off provided the entire system was not shut down from the main switch.

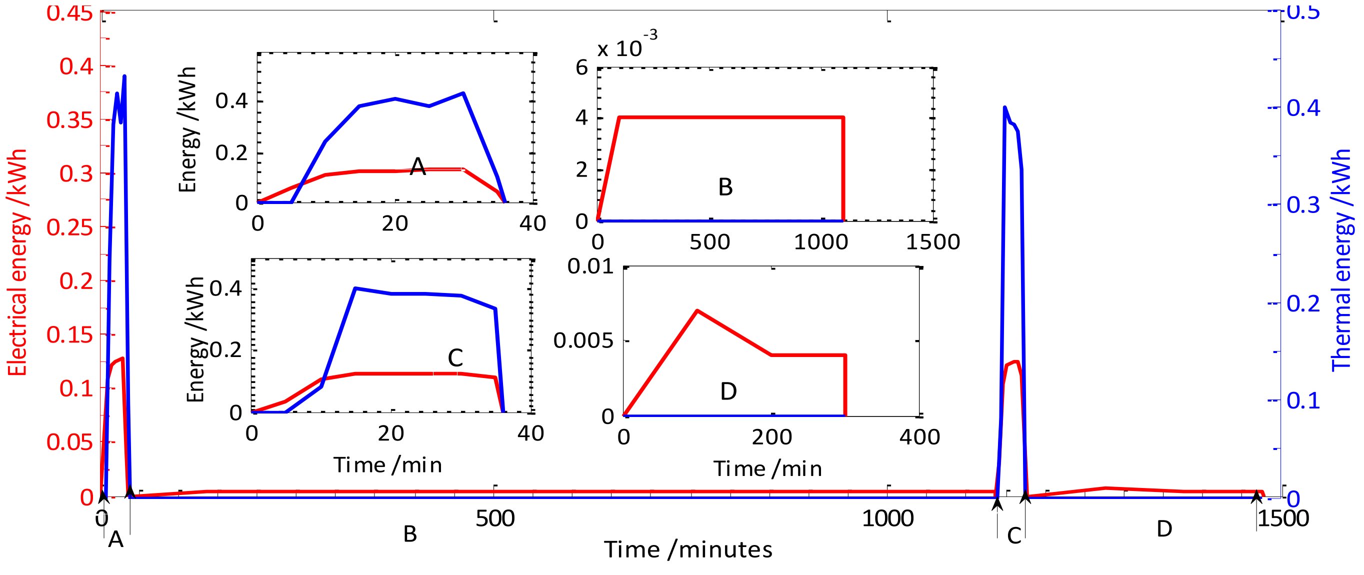


Figure 5: The energy profiles for the 5 th run experiment.

5.3. Temperatures , relative humidity and flow variation

The figure 6 below shows temperature, relative humidity and flow variation of the system in the 5 th run whose energy profiles were shown in figure 5 above. The blue, red, green and cyan lines represent the relaive humidity, hot water temperature from the outlet of ASHP, cold water temperature in to the inlet of the ASHP and the ambient temperature, respectively. The black line represent the volume of water heated and is on the opposite y axis. From figure 6 it can de deduced that at the start up of the hot water heating process which is occurring in zone A, temperature of standing cold and hot water at the respective inlet and outlet pipes of ASHP was equivalent to the ambient temperature (approximately 20^{o}C). This heat up process lasted for about 33 minutes before hot water could attain set point temperature and both the outlet hot water and inlet cold water temperatures were 54^{o}C and 46^{o}C while the relative humidity was about 95 % and the volume of water heated was about 224 L. It can also be observed that once hot water inside the tank attained the set temperature, the rate of temperature drops in both pipes exhibited an exponential decay until they reached an equilibrium temperature with the ambient. This took place in the very early phase of the zone B and in the later phase of zone B temperature changes on both pipes are greatly affected by fluctuation in ambient temperature and relative humidity. As a final point, once the hot water inside the tank went below the 5^{o}C differential, the ASHP water heater began the heat up process again where both cold and hot water in the inlet and outlet pipes for the ASHP began to rise. This occurred in zone C . The heat gain in zone C can be reasonably equated to the heat loss in zone B . The heat loss in zone D is very small since the losses was only taking place within the small volume of water inside the pipes and does not result in switching on the ASHP. It can be noted that at zone C , the peak is where the ASHP unit was again turned off and the hot water ,cold water and ambient temperatures were 46^{o}C, 54^{o}C, and 18.1^{o}C while relative humidity was 95 % and volume of water heated was 230L. It can be noticed that the circle region shows an abnormality in the cold and hot water temperatures inside the pipes. This sudden rise of temperature is owing to increase in ambient temperature and was maximum where ambient temperature was at its peak (28^{o}C at about 14:30 on 26 December 2012).

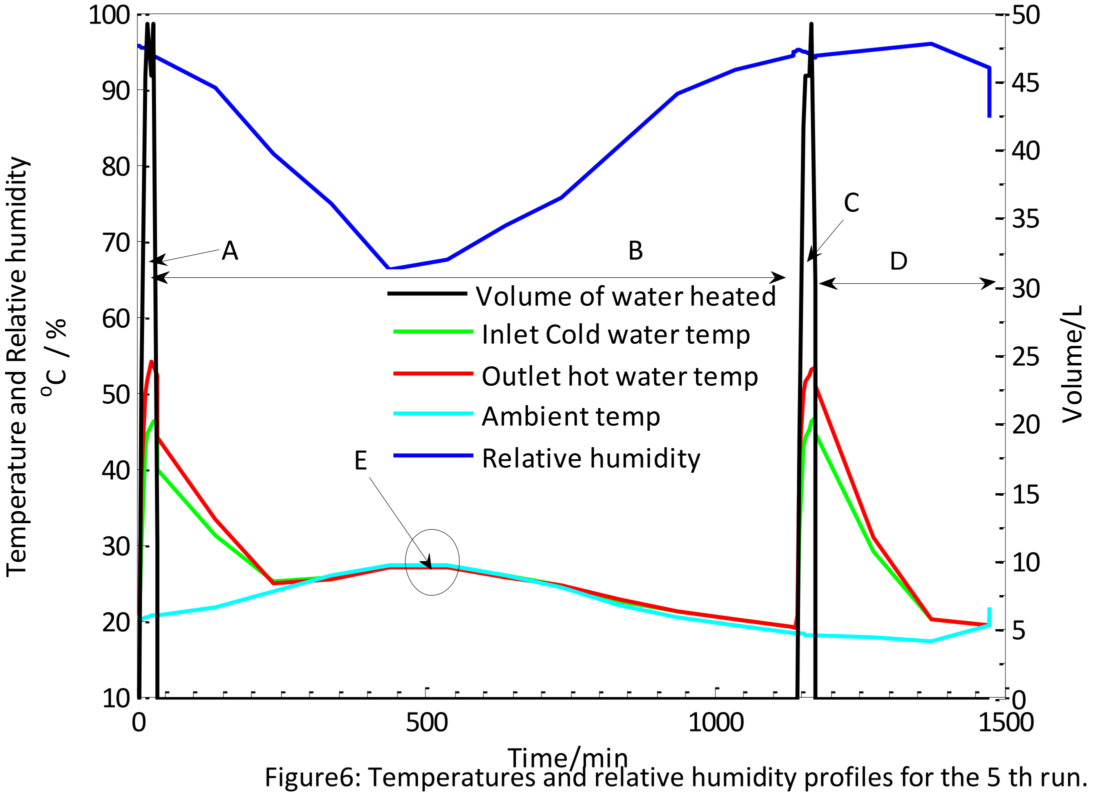


Figure6: Temperatures and relative humidity profiles for the 5 th run.

5.4 Determination of input predictors contributing to heat gain to compensate stand by losses

The four input variables; volume of water heated (V), difference in the hot and cold water temperature inside the inlet and outlet pipes of ASHP (T_h-T_c) , ambient temperature (T_a) and relative humidity (RH) values obtained for specific heat gain to compensate stand by losses were used to rank their importance to the output response (heat loss) using the statistical function (reliefF) in the MATLAB statistics tool. The results showed that the volume of water heated was the most significant followed by ambient temperature and relative humidity. These three predictors were determined to be primary factors while the difference in hot and cold water temperature was secondary. The contribution by weight to the heat gain to compensate for stand by losses for the four predictors were 0.2045, 0.1853 , 0.1309 and-0.0661 as shown figure 7 below.

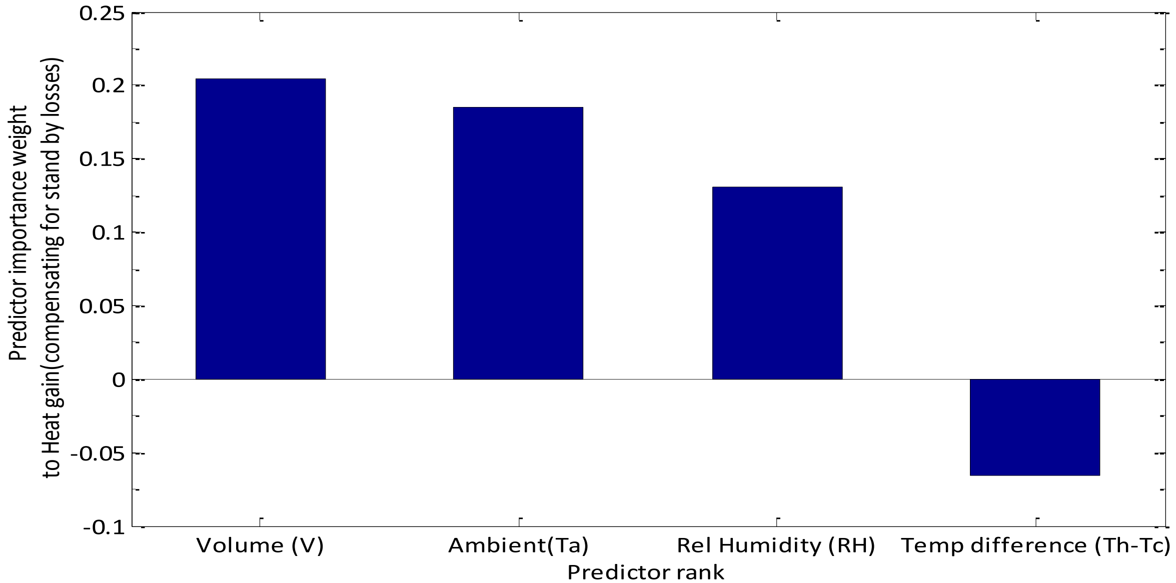


Figure 7: Shows the predictors weight ranking of importance to stand by losses.

6.0 Conclusion

The following observable conclusions can be drawn from this study;Despite the average stand by losses of 1.9 kWh which is in agreement with the South African Board standard (SABS) for measurement and verification rating for the storage tank only, 0.6 kWh of electrical energy was used by the ASHP due to its average COP of more than 3. In addition, considering the electrical energy and average COP of the second row of each run in table 1 ,the stand by losses is simply approximately the product of these two quantities. Finally, stand by losses depends primarily on volume of water heated by ASHP, ambient temperature and relative humidity.

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