MECHANICAL ENGINEERING | RESEARCH ARTICLE

Design and monitoring of a hybrid energy system: performance analysis and modelling

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Abstract: The utilization of a hybrid energy system (combined solar water heater (SWH) and an air source heat pump (ASHP) water heater) can result in over 80% reduction in the electrical energy consumed as the system is capable to operate with an energy factor of above 4.0. A major challenge is to develop credible methodology or mathematical model to predict energy savings. The research focused on the design and installation of a hybrid energy system and a data acquisition system to monitor its performance. The average weekday volume of hot water consumed, thermal energy gained by water in the tank of the air source heat pump (ASHP) water heater, electrical energy consumed, and the COP were 225.03 L, 5.25 kWh, 1.52 kWh, and 3.50. The average weekday global solar radiation, ambient temperature, solar fraction of the solar water heater (SWH) and the energy factor of the hybrid energy system were 579.67 W/m², 23.58°C, 0.52, and 4.02, respectively. A multiple linear regression model was developed to predict the energy factor of the

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PUBLIC INTEREST STATEMENT

Hot water heating is predominantly achieved by the utilization of inefficient electric geysers and contributes to significant energy consumed in the residential sector. It is very paramount to retrofit the existing electric geyser with a hybrid solar-assisted heat pump system as a measure to reduce both the demand and energy consumption due to hot water heating by more than 80%. A huge challenge is encountered in the adaptation of an international standard to accurately model the hybrid energy system to ensure it predicts the energy factor with high confidence level. The research sought to develop a credible method and multiple linear regression models coupled with a multiple 2D surface simulation plot to predict the energy factor and demonstrate the variation of each predictor to the output. A robust and cost-efficient data acquisition system was built to collect the relevant data needed to achieve the research objectives.
hybrid energy system. Both the modelled and validated results showed very good determination coefficients of 0.952 and 0.935, with the trained and validated dataset. Hence, by employing both multiple linear regression model and a multiple 2D contour plot simulation, the energy factor and the variation of the input parameters can be accurately determined. The developed model can help homeowners, energy service companies, and policy makers to appreciate and confidently support the rollout of the technology for sanitary water heating.

**Subjects:** Mechanical Engineering; Heating Ventilation & Air Conditioning; Power & Energy; Clean Tech

**Keywords:** Hybrid solar water heater and air source heat pump water heater; solar fraction; coefficient of performance; energy factor; data acquisition system; multiple linear regression model

1. **Introduction**

Globally, sanitary water heating is among the services responsible for daunting energy consumption in the residential sector and is predominantly achieved by the use of inefficient geysers. The electrical energy consumed due to water heating can be reduced by the utilisation of solar water heaters or air source heat pump water heaters. The energy saving due to hot water heating can be further improved with the implementation of a hybrid energy system (combine solar water heater and an air source heat pump water heater).

South Africa electricity supply utility (Eskom) embarked on the integrated demand management programme to achieve demand and energy consumption reduction (Eskom IDM, 2011). The sanitary hot water heating in the domestic sector of South Africa was targeted at achieving demand and energy reduction by the rollout of the solar water heaters and the air source heat pump water heaters (Eskom report, 2011). An electrical energy saving ranging from 30% to 50% can be achieved by retrofitting an electric geyser with a solar water heater (Hossain et al., 2011). The energy saving due to hot water heating may range from 50% to 70% when an electric geyser is replaced with an air source heat pump unit (Bodzin, 1997; Levins, 1982). Tangwe and co-authors designed and built a data acquisition system that monitors both the electrical and thermal performance of an air source heat pump water heater and showed that the average COP was between 2 and 4 (Tangwe et al., 2016).

The critical performance parameters of the solar assisted heat pump were COP and collector efficiencies and are strongly related to the collector operating temperature (Buker & Riffat, 2016). Research conducted on the performance of the direct expansion solar-assisted heat pump water heaters is concentrated on both the energy and exergy analyses (Howlader et al., 2008). The COP of a solar-assisted heat pump system varies with the evaporator and condenser temperatures and is sensitive to the availability of irradiance and the hot water set point temperature.

Hong and Yang (2010) recommended the evaporator temperature to be maintained in the range of 5–10°C above the ambient temperature from a well-matching collector size and heat pumping capacity from the compressor (Hong & Yang, 2010). The utilization of variable speed compressor to keep the temperature level constant can enhance the COP of a direct expansion solar assisted heat pump system (Hadorn, 2015). However, according to Huang et al. (2005), operating at higher evaporation temperature can lead to a higher compressor discharge temperature that may exceed the operating range (Huang et al., 2005). Exergetic analysis of solar assisted heat pump water heaters has been conducted by a good number of researchers with the results confirming the highest exergy loss occurring at the compressor while the least is at the expansion valve (Frank et al., 2010). Nuntaphan et al. (2009) conducted research on the thermal performance of an indirect expansion solar assisted air source heat pump system with a solar collector designed
from corrugated metal roofing and copper tubes attached beneath. The COP of the system was in the range of 2.5 to 5.0 while the payback period was 2.3 years.

Chow et al. (2010) proposed a direct expansion solar assisted ASHP water heater using a variable speed reciprocating compressor, immersed condenser coil, tube in plate heat exchanger, and capillary tube for the production of hot water with high efficiency. The average annual COP of the direct expansion heat pump system was 6.46 and outperform that of the conventional heat pump system.

Sikhonza et al. (2019) executed a study on the design and performance monitoring of a hybrid solar assisted ASHP water heater in King Williams Town in South Africa. The preliminary results show that the average weekday energy factor of the hybrid system was 3.45 and the average solar fraction as well as the COP were 0.72 and 2.83, respectively. Li et al. (2007) designed and analysed the performance of a direct expansion solar assisted heat pump water heater in Shanghai, China during the spring season. The results revealed that a maximum COP of 6.61 was attained when 150 L of water was heated from 13.4 to 50.5°C over a duration of 90 minutes while the average ambient temperature was 20.6°C. The authors also demonstrated that the seasonal average of the COP and the collector efficiency were 5.25 and 1.08, respectively.

Wang et al. (2012) developed an innovative hybrid solar ground source heat pump system (HSGSHPS) for the purpose of heating and cooling of space loads. The authors implemented a controlled strategy method that resulted in significant energy savings. Furthermore, a credible model was built and used to predict the system performance in the past 25 years. Kong et al. (2018a) designed and built a direct-expansion solar-assisted heat pump for sanitary water heating. The performance was analyzed under a typical summer condition. Xu et al. (2019) constructed a cascade heat pump for the production of high-temperature water in cold climate. They determined that the COP was 1.69 under an extreme ambient temperature of –21°C. The cascade heat pump operating power varies from 11.32 to 18.93 kW while the supply water temperature was 75°C. Kong et al. (2018b), designed and built a variable capacity direct expansion solar assisted heat pump and conducted a series of experiments to monitor the autumn and winter thermal performance.

Ran et al. (2020) designed an efficient integrated solar–air source heat pump that operated on thermosiphon phenomenon and their results revealed that the system was more efficient than their counterpart conventional system with a payback period ranging from 2.7 to 4.4 years for typical cities. T. Long et al. (2020) conducted a study on the performance and optimization of the key design parameters of a solar assisted solar heat pump (SASHP) in Tibetan climatic conditions. They observed that the SASHP operated with a high efficiency for most of the heating cycles with an average COP of 1.95 and a maximum COP of 2.68.

Kuang et al. (2003) proposed a simple and cost-efficient solar-assisted heat pump water heater with a flat plate collector and demonstrated that the system had a favourable thermal performance for the full year (2000–2001) in North China. They concluded that any proper design of the hybrid system should take into consideration the storage tank, operating condition, payback period and climate change mitigation. Fang et al. (2010) performed an experimental analysis of the operational performance of a photovoltaic-thermal system for the purpose of space conditioning. They depicted that the mean efficiency increases by more than 10.4% and could attain 23.8%, when compared to that of conventional air conditioner. J. Long et al. (2021) conducted thermal performance analyses of different hybrid solar hot water and air source heat pump for both hot water and space heating using the TRNSYS software. They depicted that the proposed systems can save very high energy in buildings. Esen et al. (2017) designed and conducted experiments to assess the performance of a slinky horizontal- and vertical-type ground source heat pump water heaters. They determined that the COP of both the horizontal ground source heat pump unit and the horizontal ground source heat pump water heater were 3.55 and 2.88 while for the vertical system the COPs were 2.91 and 2.34, respectively. They also modelled the performance of the systems using the adaptive neural fuzzy inference (ANFIS) and artificial neural network (ANN)
models and showed that the ANFIS model outperformed the ANN model. Chen and Yang (2012) proposed an optimization approach for the ratio of the collector area and group loop length for a multi-functional solar-assisted ground coupled heat pump. They further conducted a full thermal and economic analysis of the proposed system. Qu et al. (2016) recommended a solar photovoltaic-thermal integrated dual-source heat pump (DSHP) water heater in the water-to-water and air-to-water modes. They proved that the electrical conversion efficiency of such system can increase by 10.3% in the city of Shanghai in China. Michopoulos et al. (2013) reported the seasonal energy efficiency ratio of a ground source heat pump system over 8 years period to vary between 4.5–5.5 and 3.6–4.5, in the heating and cooling mode. Youssef et al. (2017) designed an indirect solar assisted heat pump system and conducted a series of experiments with the system with and without a phase change material tank. The results demonstrated that the hybrid system with the phase change material tank performed better than that without changing material tank. Kim et al. (2013) employed simulation methods to prove that the hybrid solar geothermal CO2 heat pump system exhibits significant improvement in the system performance and is very reliable.

2. Objectives of the study
The main assumptions of the study were:

i. To design and build an energy-efficient hybrid energy system (combine SWH and ASHP water heater) for sanitary hot water heating that can be used in the residence of a middle- to high-income family.

ii. To determine the solar fraction (SF) of the SWH and the COP of the ASHP water heater of the hybrid energy system use in sanitary hot water heating during the monitoring period.

iii. To calculate the overall EF of the hybrid energy system during the performance monitoring period.

iv. To develop and validate the multiple linear regression model used to predict the EF of the hybrid energy system (the selected predictors were volume of hot water consumed, ambient temperature and global solar radiation as the input parameters).

3. Assumptions of the study
The primary assumptions of the study include:

i. The distribution of the water temperature in the storage tanks of the hybrid energy system was uniform (no thermal stratification in the tanks).

ii. The impact of the solar contribution to the performance of the hybrid energy system out of the interval (09:00–18:00) was neglected throughout the monitoring period.

iii. The EF of the hybrid energy system was solely from the COP of the ASHP water heater between the interval (0–8:30) and (18:30–23:30), throughout the days of the performance monitoring.

iv. The analyses were performed only on the weekdays as the hot water consumption profile per day from the occupants (middle- and working-class family) were identified to be similar throughout the weekdays.

4. Experimental site
The experimental setup was built in King Williams Town on the residence with physical address; 69A Kings Road, Fort Hill, Post code 5601. King Williams Town is located in the Buffalo municipality in the Eastern Cape province in South Africa. King Williams Town is remarkably known to be situated on the bank of the Buffalo River and is about 50 km west of East London from the Kings Road as shown in Figure 1. East London is the administrative capital of the Eastern Cape province. The latitude and longitude associated with the research facility were S –32°46’0” and E 27°28’59”.

Additionally, King Williams Town experiences an average annual-month-day ambient temperature ranging from 17.0 to 23.0°C with the minimum average month-day value of 17.0°C,
recorded in July and the maximum average month-day was 23°C corresponding to January, as shown in Figure 2. In addition, the average month-day global solar radiation varies between 3.45 and 6.70 kW/m²/day with an annual average of 5.73 kW/m²/day. The ambient temperature and global solar radiation in King Williams town strongly favoured the implementation of a hybrid solar and air source heat pump system for sanitary hot water heating.

Figure 3 shows the duration of the average month-day sunrise and sunset time over a full year (2020). The figure depicted that the average month-day sunrise time was 05:00 and the average month-day sunset time was 19:00, resulting in an average duration of global solar isolation of 12 h. The minimum and maximum duration of average month-day global solar availability were 9.83 and 14.25 h and occurred in the month of June (winter month) and December (summer month), respectively. The duration of the solar availability per day for all the months in the year provides an excellent potential for significant energy saving due to hot water heating with a hybrid solar air source heat pump water heater.

5. Theory and calculation
The surface area of the evacuated tube solar collector (A) is the area covered by the solar evacuated tubes. The total area is the product of the length (L), the diameter (D) and the number of tubes (n) of the SWH. The length was 1800 mm and the diameter was 58 mm while the number of tubes (n) was 24. The total area of the of tubes (A) is given by Equation 1.

\[ A = nLD \]  

(1)

The solar energy falling or incidence on the evacuated tubes of the SWH is given by Equation 2.

\[ E_{sol} = IAT \]  

(2)
where $T =$ time taken from 09:00 to 18:00 in h, $I =$ Average irradiance over period $T$ in W/m$^2$, $A =$ Total area of evacuated tubes and $E_{sol} =$ Solar energy incident on the collectors in kWh.

The thermal energy gain by water in the preheated 200 L solar tank is given by Equation 3.

$$Q_{SWH} = m_1 c (T_0 - T_i)$$

where $Q_{SWH} =$ Thermal energy gained by the water stored in solar tank in kWh, $m_1 =$ Mass of preheated water in kg, $c =$ Specific heat capacity of water in kJ/kg$^\circ$C, $T_0 =$ Average final temperature of stored water in preheated solar tank in $^\circ$C, and $T_i =$ Average initial temperature of stored water in preheated solar tank in $^\circ$C,
The solar fraction is the ratio of the thermal energy gained by the water in the solar storage tank of the SWH to the solar energy incidence in the evacuated tubes and is given by Equation 4.

\[ SF = \frac{Q_{SWH}}{E_{sol}} \]  

(4)

where \( SF \) = Solar fraction.

The coefficient of performance (COP) of the ASHP water heater in the hybrid energy system is given by Equation 5.

\[ COP = \frac{m_2 c(T_{o,HP} - T_{i,HP})}{P_t} \]  

(5)

where \( m_2 = \) Mass of heated water by ASHP unit from the retrofitted geyser in kg, \( T_{o,HP} = \) Outlet temperature of water at the ASHP unit in °C, \( T_{i,HP} = \) Inlet temperature of water at the ASHP unit in °C, \( t = \) Duration of the vapour compression refrigeration cycle in h, \( P = \) Average power consumed by the air source heat pump in kW, \( COP = \) Coefficient of performance.

The electrical energy consumed by the heat pump water heater in the hybrid solar assisted ASHP system is given by Equation 6.

\[ E = P t \]  

(6)

The energy factor per day of the hybrid energy system is given by Equation 7.

\[ EF = COP + SF \]  

(7)

where \( EF = \) Energy factor of the hybrid energy system

The energy factor per day of the hybrid energy system is given by Equation 7.

\[ EF = \text{Average COP + SF} \]  

(7)

The multiple linear regression model to predict the energy factor using the input factors (volume of hot water consumed, ambient temperature and global solar irradiance) is given by Equation 8.

\[ EF = \gamma_0 + \gamma_1 V + \gamma_2 T_{amb} + \gamma_3 I \]  

(8)

where \( EF = \) Energy factor, \( V = \) Volume of hot water consumed in L, \( T_{amb} = \) Ambient temperature in °C, \( I = \) Global solar radiation in W/m². \( \gamma_0 = \) Forcing constant, \( \gamma_1 = \) Scaling constant of the volume of hot water consumed in L⁻¹, \( \gamma_2 = \) Scaling constant of the ambient temperature in (°C)⁻¹ and \( \gamma_3 = \) Scaling constant of the global solar radiation in (W/m²)⁻¹.

The uncertainties derived from the calculations, as a result of the error measurements from the set of independent variables, is given by Equation 9.

\[ w_r = \left[ w_1 \left( \frac{\partial R}{\partial X_1} \right)^2 + w_2 \left( \frac{\partial R}{\partial X_2} \right)^2 + \ldots + w_n \left( \frac{\partial R}{\partial X_n} \right)^2 \right] \]  

(9)

where \( R = \) The given function; \( w_r = \) total uncertainty; \( X_1, X_2, \ldots, X_n = \) Independent variables and \( w_1, w_2, \ldots, w_n = \) Uncertainty in the independent variables.
6. Materials and methods

The list of materials used in the study is presented in Table 1. Table 1 shows the hot water devices, sensors, transducers and data loggers used in the study.

6.1. Experimental setup

Figures 4 and Figures 5 show the schematic diagram and the actual installed hybrid energy system (combine solar water heater and an air source heat pump water heater). The experiment was designed and implemented in a typical residential user (middle-income families with five adults). Figure 4 shows the hybrid energy system and the sensors used in the study. The performance monitoring period of the hybrid energy system was during the summer period (February—March 2019).

Figure 5 shows the installed hybrid energy system known as a hybrid solar water heater and air source heat pump water heater and the data acquisition system on the roof of the experimental facility.

6.2. Methods

The methods of the study are broken down into five procedures as follows:

i The design and performance monitoring of the hybrid energy system for sanitary hot water heating in a middle-income family.

ii The determination of the COP of the ASHP water heater in the hybrid energy system during the summer season.

| Table 1. Materials used in the experimental setup |
|--------------------------------------------------|
| **Items** | **Devices and sensors** | **Quantity** |
| 1 | Evacuated tubes solar water heater | 1 |
| 2 | 200 L pre-heated hot water storage tank | 1 |
| 3 | 1.2 kW input split type air source heat pump | 1 |
| 4 | 150 L hot water storage tank with set point temperature of 55°C | 1 |
| 5 | TVER-E50B2 power meters | 1 |
| 6 | T-Minol 130 flow meters | 3 |
| 7 | 12 bits S-TMB temperature sensors | 12 |
| 8 | 12 bits S-THB ambient temperature and relative humidity sensor | 1 |
| 9 | Solar radiation shield | 1 |
| 10 | Anemometer (S-WSB- Wind Speed Smart Sensor) | 1 |
| 11 | RXW-LIB-868-Silicon pyranometer | 1 |
| 12 | S-UCC electronic input pulse adapter | 13 |
| 13 | U30-NRC 15 channels hobo data loggers | 2 |
| 14 | 4.5 V DC battery | 2 |
| 15 | Waterproof enclosure | 1 |
| 16 | Mixing control temperature valve | 2 |
| 17 | Hoboware pro software | 1 |
Figure 4. Schematic of the installed hybrid energy system and the data acquisition system.

Figure 5. Installed hybrid energy system and the data acquisition system.
iii The determination of the SF of the SWH in the hybrid energy system during the summer season.
iv The evaluation of the EF of the hybrid energy system during the summer period.
v The development and validation of a multiple linear regression model to predict the EF of the hybrid energy system based on the trained and test dataset.

6.3. Description of installed sensors on the designed hybrid energy system
The installed hot water devices and the sensors are shown in Figure 4. A 200 L solar water heater was connected in series with a 1.2 kW input split type ASHP, with a 150 L high pressure geyser (geyser’s element of 3 kW disabled). The hybrid energy system formed a hybrid solar assisted ASHP water heater, with the SWH acting as the pre-heater and the pre-heated water was stored in the 200 L tank. The hybrid energy system was installed on the roof of the building. The makeup cold water from the mains was fed into the inlet of the 200 L storage tank via a copper pipe. A flow meter (V1) and a temperature sensor (T1) were installed on the copper pipe. A temperature sensor (T2) was installed at the proximity to the copper pipe feeding the mains water into the 200 L tank. A copper pipe was connected from the outlet of the 200 L tank to a water flow control valve and temperature mixing (FCV1) that was set at 55°C. A connecting copper pipe carrying the mains cold water was installed with a flow control and temperature mixing valve (FCV2). The FCV2 provides a bypassed cold water require to adjust hot water temperature from the solar tank, if the temperature have exceeded the 55°C. A temperature sensor (T3) was connected at the outlet of the 200 L storage tank just after the FCV1 on the copper pipe leading into the inlet of the ASHP unit. Temperature sensor (T4) and flow meter (V2) were installed at the closed location of the inlet of the ASHP unit. Temperature sensor (T5) was connected at a close range to the outlet of the ASHP unit. A water circulation pump was installed in line with the copper pipe connected to the inlet of the ASHP unit by the manufacturer and was embedded in the ASHP unit. This helps to direct the flow of pre-heated water from the 150 L retrofitted geyser into the condenser of the ASHP unit. Temperature sensors were installed at specific locations on the refrigerant closed loop circuit of the ASHP unit. Temperature sensors (T6 and T7), were installed at the inlet and outlet ends of the evaporator. Furthermore, temperature sensors (T8 and T9), were installed at the inlet and outlet of the condenser. A copper pipe was connected from the outlet of the 150 L retrofitted geyser into the building. The copper pipe was supplying the outlet hot water demanded by the occupants in the building. Temperature sensor (T10) was installed at a proximity to the outlet of the retrofitted 150 L geyser. A flow meter (V3) was installed in the inlet of the heat exchanger of the SWH and measured the volume of preheated water during the thermosyphon process. Temperature sensors (T11 and T12) were installed at the inlet and outlet of the heat exchanger of the SWH. A power meter (E) was installed on the mains electrical cable powering the ASHP water heater. A pyranometer (I) was installed on the SWH. An anemometer (WS) and an ambient temperature and relative humidity sensor (AT/RH) were installed in the vicinity of the hybrid solar assisted ASHP water heater. The flow meters (V1, V2 & V3), pyranometer, anemometer and the power meter (E) were connected to one of the hobo U30 remote communication data logger. The temperature sensors (T1-T12) were connected to a second hobo remote communication data logger. Each of the hobo remote communication data loggers can accommodate up to 15 logging channels. The ambient temperature and relative humidity sensor, as well as the temperature sensors (T1-T12), anemometer, pyranometer were connected to both hobo U30 remote communication data loggers and integrated with electronic input pulse adapters. All the sensors and transducers were logged at 5 minute intervals as per the configuration with the hoboware pro software (Onset Corporation, 2013). The ambient temperature and relative humidity sensor were protected by a solar radiation shield. The three flow meters were enclosed by waterproof enclosures. The data loggers were accommodated by a waterproof enclosure, which was mounted in the vicinity of the building. The metering data from the sensors were stored in the U30 remote communication data loggers and were downloaded from the loggers for analysis.
7. Error analysis

The type A uncertainties were based on the statistical means and standard deviations from the recorded measurements and are shown in Table 2. In addition, the type B uncertainties are determined with reference to the accuracy of the sensors or the derived uncertainty by exploiting Equation 9 in the derivation of the uncertainty of the prescribed quantity. The combined uncertainties of the prescribed measurements are provided in Table 2.

8. Results and discussion

8.1. Typical weekday performance of the hybrid energy system

The results were analyzed on three intervals on a daily basis (the first period was from 0 to 08:30, the second period was from 09:00 to 18:00 and the third period was from 18:30 to 23:30) from the 4th–8th of February 2019. During the first and third periods in each day, only the performance of the ASHP water heater was contributing to the EF of the hybrid energy system. This could be accounted by the fact the impact of solar radiation was practically negligible during these intervals. Alternatively, for the second period of each day, the EF of the hybrid energy system was achieved from the combined performance of the SWH and the ASHP water heater. During this interval, the solar radiation availability is guaranteed that favoured the operation of the SWH and the prevailing ambient condition usually enhanced the performance of ASHP water heater.

8.1.1. Typical weekday performance of the ASHP water heater in the hybrid energy system

Table 3 shows the volume of hot water consumed, the COP, the electrical energy consumed and the thermal energy gained by the ASHP water heater in the hybrid energy system for the weekdays. The results revealed that the average volume of hot water consumed, the electrical energy consumed, the thermal energy gained and the COP of the ASHP water heater in the first period was 105 L, 0.98 kWh, 3.47 kWh and 3.62, respectively. In the second period, the volume of hot water consumed, the electrical energy consumed, thermal energy gained by the ASHP water heater and the COP were 91.60 L, 0.37 kWh, 1.07 kWh and 2.78. Lastly, in the third period, the volume of hot water consumed, the electrical energy consumed, thermal energy gained by the ASHP water heater and the COP were 42.04 L, 0.38 kWh, 1.49 kWh and 3.89, respectively. The greatest volume of hot water and maximum electrical energy consumed occurred during the first period of the operation of the hybrid energy system. The average weekday performance in relation to the

| Table 2. Uncertainties of the measured and derived quantities |
|-------------------------------------------------------------|
| **Quantity** | **Type A uncertainty** | **Type B uncertainty** | **Combined uncertainty** |
|-----------------|----------------------|----------------------|----------------------|
| Ambient temperature (°C) | ±0.200                | ±0.120                | ±0.233                |
| Relative humidity (%) | ±0.250                | ±0.140                | ±0.286                |
| Water flow rates measurements (L/min) | ±0.010                | ±0.006                | ±0.012                |
| Power consumed by integrated type ASHP system (kW) | ±0.120                | ±0.003                | ±0.120                |
| Power consumed by split type ASHP system (kW) | ±0.130                | ±0.003                | ±0.130                |
| Water and refrigerant temperatures measurements (°C) | ±0.250                | ±0.120                | ±0.277                |
| Global solar radiation measurements (W/m²) | ±10.00                | ±4.350                | ±10.905               |
| Electrical energy consumed (kWh) | ±0.130                | ±0.025                | ±0.132                |
| Thermal energy gained (kWh) | ±0.190                | ±0.042                | ±0.195                |
| COPs | ±0.260                | ±0.203                | ±0.330                |
| Solar fraction | ±0.060                | ±0.020                | ±0.080                |
| Energy factor | ±0.320                | ±0.223                | ±0.390                |
Table 3. Week days performance of the ASHP water heater in the hybrid system

| Day | Period      | V/L | E/kWh | Q/kWh | COP  |
|-----|-------------|-----|-------|-------|------|
| 1   | 00:00-08:30 | 82.59 | 1.02 | 4.06 | 3.97 |
|     | 09:00-18:00 | 90.10 | 0.63 | 2.07 | 3.25 |
|     | 18:30-23:30 | 78.83 | 0.63 | 2.65 | 4.20 |
| 2   | 00:00-08:30 | 108.87 | 0.83 | 2.40 | 2.92 |
|     | 09:00-18:00 | 90.10 | 0.40 | 1.05 | 2.64 |
|     | 18:30-23:30 | 26.28 | 0.53 | 1.73 | 3.30 |
| 3   | 00:00-08:30 | 82.59 | 0.79 | 2.99 | 3.77 |
|     | 09:00-18:00 | 131.39 | 0.14 | 0.35 | 2.49 |
|     | 18:30-23:30 | 11.26 | 0.10 | 0.36 | 3.53 |
| 4   | 00:00-08:30 | 138.90 | 0.61 | 2.59 | 4.21 |
|     | 09:00-18:00 | 86.34 | 0.39 | 1.22 | 3.05 |
|     | 18:30-23:30 | 48.80 | 0.12 | 0.52 | 4.41 |
| 5   | 00:00-08:30 | 112.62 | 1.62 | 5.24 | 3.24 |
|     | 09:00-18:00 | 60.06 | 0.27 | 0.66 | 2.49 |
|     | 18:30-23:30 | 45.05 | 0.54 | 2.13 | 3.98 |

V = Volume of hot water consumed, E = Electrical consumed, Q = Thermal energy gained, COP = Coefficient of performance

...volume of hot water consumed, the electrical energy consumed, the thermal energy gained and the COP were 238.75 L, 1.73 kWh, 6.02 kWh and 3.43, respectively. The weekday performance of the ASHP water heater in the hybrid energy system depicted the heat pump unit operated in all the periods and with 1 unit of input energy capable to produce more than 3 units of useful thermal energy.

8.1.2. Week days performance of the SWH in the hybrid energy system

Table 4 shows the average water temperatures at the inlet and outlet of the 200 L tank of the SWH, the solar thermal energy gained, the average solar energy incidence on the evacuated tubes and the efficiency of the SWH in the hybrid energy system during the second period of the weekdays. It was depicted that the average water temperature at the inlet of the solar storage tank range from 26.5°C to 34.46°C and the mean was 28.70°C. The average water temperature at the outlet of the solar storage tank varies between 48.77 and 63.24°C and the mean was 55.13°C. The total area of the evacuated tubes of the SWH was 2.51 m², and the duration of the harnessed solar incident radiation was 9 h per day. The average global irradiance ranges from 417–685 W/m² and the mean was 527.99 W/m². The weekdays solar energy gained was between 9.41 and 15.45 kWh while the average was 11.90 kWh. The weekdays thermal energy gained by the collector of the SWH was between 4.85 and 7.65 kWh and the average was 6.17 kWh. The collector efficiency of the SWH was between 46.72 and 54.22% and the average was 51.90%. It can be deduced that during the second period for the weekdays, the solar collectors of the SWH are capable to convert more than 50% of the incidence solar energy into useful thermal energy stored in the preheated solar storage tank.

8.1.3. Comparison of the typical weekday and the average month-day performances of the hybrid energy system

Figure 6 shows the electrical energy consumed, the thermal energy gained and the COP for a typical weekday (7 February 2019) and the average month-day (February 2019). It can be depicted that the typical weekday electrical energy consumed, the thermal energy gained and the COP of the ASHP water heater was 1.98 kWh, 6.90 kWh and 3.47 and the total volume of hot water consumed was 230.0 L. The average month-day electrical energy consumed and the
thermal energy gained by the ASHP water heater was 1.50 kWh and 5.25 kWh, while the average volume of hot water consumed and the COP were 225.035 L and 3.50. The results show that despite the minimal differences in the electrical consumed and thermal energy gained for both the typical weekday and average month-day, there was insignificant disparity in their COP and volume of hot water consumed.

Figure 7 shows the solar energy gained, the thermal energy gained and the solar fraction of the SWH of the hybrid energy system for a typical weekday and an average month-day. The solar energy gained, the thermal energy gained by SWH and the solar fraction were 13.07 kWh, 6.86 kWh and 0.51 for the typical weekday and for the average month-day the values were 11.90 kWh, 6.73 kWh and 0.52, respectively. Hence, the results justified that the SWH performance exhibited a fairly constant efficiency during the months of February.
8.2. Multiple linear regression model of the EF of the hybrid energy system

The weekdays dataset of the month of February 2019 were used in the development and training of the multiple linear regression model of the EF of the hybrid energy system. Table 5 shows sample weekdays and their determined critical quantities and span the entire 22 weekdays of the month. It was depicted that the minimum weekday volume of hot water consumed was greater than 200 L while the minimum COP was more than 3.0. Alternatively, the average solar energy fraction was above 0.50 and the minimum EF was above 4.0. The average weekday global solar radiation ranges from 417.40 to 649.00 W/m² while the average weekdays ambient temperature was between 22.41 and 25.74°C.

Table 6, shows the derived forcing and scaling constants of the input parameters (volume of hot water consumed, ambient temperature and global solar radiation) to correlate the output (energy

Table 5. Performance parameters for sample week days of February 2019

| Day  | V/L  | E/kWh | Q/kWh | COP  | Tamb/C | I/W/m² | Q_SWH/kWh | E_Col/kWh | λ%  | EF  |
|------|------|-------|-------|------|--------|--------|-----------|-----------|------|-----|
| 1    | 251.52 | 2.29  | 8.79  | 3.84  | 25.74  | 530.36 | 5.59      | 11.96     | 0.47 | 4.30 |
| 3    | 225.24 | 1.03  | 3.69  | 3.57  | 24.04  | 427.19 | 5.22      | 9.63      | 0.54 | 4.12 |
| 5    | 217.73 | 2.42  | 8.05  | 3.32  | 22.41  | 417.40 | 4.86      | 9.41      | 0.52 | 3.84 |
| 7    | 230.00 | 1.99  | 6.90  | 3.47  | 23.38  | 592.00 | 6.86      | 13.35     | 0.51 | 3.98 |
| 9    | 228.00 | 1.12  | 3.96  | 3.53  | 23.75  | 613.00 | 7.09      | 13.82     | 0.51 | 4.04 |
| 11   | 226.00 | 1.42  | 4.97  | 3.50  | 23.57  | 594.00 | 6.89      | 13.39     | 0.51 | 4.01 |
| 13   | 216.00 | 1.27  | 4.47  | 3.51  | 23.65  | 649.00 | 7.49      | 14.64     | 0.51 | 4.02 |
| 15   | 224.00 | 1.72  | 5.99  | 3.48  | 23.45  | 561.00 | 6.53      | 12.65     | 0.51 | 4.00 |
| 19   | 224.00 | 1.33  | 4.66  | 3.51  | 23.62  | 584.00 | 6.78      | 13.17     | 0.51 | 4.02 |
| 21   | 226.00 | 1.52  | 5.30  | 3.49  | 23.53  | 643.00 | 7.42      | 14.50     | 0.51 | 4.01 |

V = Volume of hot water consumed, E = Electrical energy consumed by ASHP, Q = Thermal energy gain by water in the tank of the ASHP water heater, COP = Coefficient of performance of the ASHP water heater, Tamb = Ambient temperature, I = Global solar radiation, Q_SWH = Thermal energy gained by water in the preheated tank of the SWH, λ = Solar fraction, EF = Energy factor.
The scaling constant for the volume of hot water consumed was $-0.001 \text{ L}^{-1}$. The negative scaling constant, insinuate that there is an inverse relationship between the volume of hot water consumed and the energy factor. The very small magnitude of the scaling constant implies the contribution to the energy factor is very small as compared to the influenced due to ambient temperature and can be depicted in Figure 10. The scaling constant for the global solar radiation was $-2.52 \times 10^{-5} \text{ (W/m}^2\text{)}^{-1}$. The negative scaling constant revealed an inverse correlation exist between the global solar radiation and the energy factor. The very small magnitude of the scaling constant, which was much smaller than the scaling factor of the volume of hot water consumed, lead to a negligible contribution to the energy factor as shown in Figure 10. The scaling constant for the ambient temperature was $0.149 \text{ (°C)}^{-1}$ and the positive value shows a direct linear relation with the energy factor. The contribution from the ambient temperature was contributing the most to the energy factor.

Figure 8 shows the calculated dataset and the modelled line of the energy factor of the hybrid energy system over the 22 weekdays in the month of February 2019. The actual dataset and the modelled line gave negligible deviation with a very good determination coefficient of 0.952 and a very small root mean square error of 0.0293. Therefore, the modelled was accurately predicting the actual energy factor of the hybrid energy system.

Figure 9 shows the simultaneous multiple 2D surface linear plots of each of the input parameters to the energy factor. The 2D contour plots represent the linear variation of each predictor

Figure 8. Calculated dataset and the modelled line of energy factors of the hybrid energy system.

| Table 6. Forcing and scaling constants of the multiple linear regression model |
|---------------------------------|--------|----------------|-----------------|----------------|
| Input parameter                | Symbol | Scaling symbol | Scaling value   | Output          |
| Forcing parameter             | $\gamma_0$ | $y_0$        | 0.7532          | Energy factor $\Delta F$ |
| Volume of hot water consumed  | $V$     | $y_1$        | $-0.0010$       |                 |
| Ambient temperature           | $T_{amb}$ | $y_2$        | 0.1486          |                 |
| Global solar radiation        | $I$     | $y_3$        | $-2.25 \times 10^{-5}$ |                 |
to the energy factor with the rest held constant. The red dash lines represent the 95% confidence bound for each predictor. The green line between the red dash lines represented the gradient of the energy factor to the specific predictor. It can be depicted that the volume of hot water demonstrated an inverse correlation to the energy factor and the gradient (green line) corresponded to its scaling factor (−0.0010) derived from the multiple linear regression model. The ambient temperature varies in a direct linear correlation to the energy factor and the slope (0.1486) was equivalent to it scaling factor derived from the multiple linear regression model. The changed in global solar radiation confirmed an inverse relationship was exhibited with the energy factor. But, because of the very small value of the slope, the line (green line) was practically horizontal. Therefore, the scaling constants from the multiple linear regression model were in strong agreement with the slopes (gradients) of each of the predictors to the energy factor in the multiple 2D contour plots.

8.3. Validation of the multiple linear regression model of the energy factor

Weekdays processed data for the month of March 2019 were used to validate the derived multiple linear regression model. A sample of 10 out of the 23 weekdays were used for both the input and output dataset in March 2019 and is presented in Table 7. The validated input dataset (volume of hot water consumed, ambient temperature and global solar radiation) and the output data (energy factor) contain dataset the cover the full range of the data of the month of March. The average weekdays volume of hot water consumed ranges from 214 to 260 L, while the ambient temperature and global solar radiation ranges from 22°C to 26°C and 485 to 610 W/m², respectively. The average weekday energy factor was in the range of 3.75 to 4.22.
Figure 10 shows the weights ranking of the predictors according to the importance to the energy factor using the relieff test. The weights of contribution to the energy factor to the volume of hot water consumed, the ambient temperature and the global irradiance was 0.2697, 0.3190 and 0.1139, respectively. All the predictors are depicted to be primary factors with the percentage of contribution by the ambient temperature, the volume of hot water consumed and the global irradiance as 45.06, 38.10 and 16.84%, respectively. Hence, the predictor with the maximum percentage of the contribution was the ambient temperature while the global irradiance was contributing the least.

Table 7. Sample of week days and the input and output parameters use in validation

| March 2019 | V/L    | Tamb /°C | I/W/m² | EF    |
|------------|--------|----------|--------|-------|
| Day 1      | 225.03 | 23.62    | 579.67 | 4.017 |
| Day 3      | 214.36 | 21.96    | 453.95 | 3.784 |
| Day 5      | 224.25 | 22.76    | 486.5  | 3.892 |
| Day 8      | 239.79 | 23.79    | 531.89 | 4.028 |
| Day 10     | 245.47 | 24.17    | 536.17 | 4.079 |
| Day 14     | 259.77 | 25.23    | 609.81 | 4.221 |
| Day 15     | 256.34 | 24.8     | 628.65 | 4.159 |
| Day 18     | 223.65 | 22.28    | 519.89 | 3.821 |
| Day 19     | 213.76 | 21.88    | 489.92 | 3.774 |
| Day 21     | 237.78 | 23.51    | 482.21 | 3.9991|

V = Volume of hot water consumed, Tamb = Ambient temperature, I = Global solar radiation, Q_{SWH} = Thermal energy gained by water in the preheated tank of the SWH, EF = Energy factor.

Figure 10. Evaluation and validation of the developed modelled of energy factor.
9. Conclusion
The annual ambient temperature (20.75°C), global solar radiation (5.7 kW/m²/day) and duration of the solar isolation availability (12 h) were favourable for the potential installation of the hybrid energy system (hybrid SWH and ASHP water heater) in King Williams town. The ambient weather conditions in King Williams Town, exceeded the minimum threshold acceptable ambient temperature (4°C), global solar irradiance (3.0 kW/m²/day) and solar isolation availability of 7–9 h that guaranteed a good performance of solar heat pump water heaters (Nuntaphan et al., 2009; Xu et al., 2019). A reliable and robust data acquisition system was designed and built to monitor the performance of the hybrid energy system. The design of the hybrid energy system and the acquisition system was first of its kind to be implemented in South Africa. It was depicted that the average weekday volume of hot water consumed, thermal energy gained by water in the tank of the ASHP water heater, electrical energy consumed and the COP were 225.03 L, 5.25 kWh, 1.52 kWh and 3.50. The average weekday global solar radiation, ambient temperature, solar fraction of the SWH and the energy factor of the hybrid energy system were 579.67 W/m², 23.58°C, 0.52 and 4.02, respectively. The results from the findings confirmed the hybrid energy system was operating with an excellent performance throughout the monitoring period. The multiple linear regression model was developed and used in modelling and validation of the energy factor of the installed hybrid energy system. The mathematical model gave a high level of accuracy (over 90% confidence level) with the determination coefficients of more than 0.93 for both the trained and validated dataset. Hence, without loss of generality the mathematical model is acceptable for the prediction of the energy factor of the hybrid energy system in other locations and during the summer season as the inputs ambient conditions cover a sufficient range for the season under consideration. The modelled scaling constants and the multiple 2D contour plots showed that the ambient temperature was contributing the most to the energy factor with a direct linear correlation. The established model can be used to predict the energy factor of the hybrid energy system with the same specification in different regions across the globe with 95% confidence level.

Figure 11, shows the validated dataset of the EF and the predicted dataset of the EF of the 23 weekdays in March 2019. The model is capable of predicting the desired output with sufficient accuracy. The determination coefficient and the root mean square error of the validated data on the EF and the developed output from the modelled were 0.935 and 0.0651. The good determination
coefficient value that was greater than 0.900 and the very small root mean square error that was
closed to 0.00, confirmed that the developed mathematical modelled can be accepted for the
prediction of the EF using the summer data. Therefore, the developed multiple linear regression
model gave very good predictions based on the modelled and validated dataset with over 90% confidence level and no exclusive outliers were depicted between the dataset and modelled line.

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Author contributions
S. Tangwe was responsible for conceptualization, drafting and provision of technical input in a bid to add value to the manuscript. M. Sikhonza was responsible for the installation, collection and analysis of the data as well as led the writing the manuscript.

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References
Bodzin, S. 1997. Air-to-water heat pumps for the home. Home Energy Journal, 14(4).
Buker, M. S., & Riffat, S. B. (2016). Solar assisted heat pump systems for low temperature water heating applications: A systematic review. Renewable and Sustainable Energy Reviews, 55, 399–413. https://doi.org/10.1016/j.rser.2015.10.157
Chen, X., & Yang, H. (2012). Performance analysis of a proposed solar assisted ground coupled heat pump system. Applied Energy, 97, 888–896. https://doi.org/10.1016/j.apenergy.2011.11.073
Chow, T. T., Pei, G., Fong, K. F., Lin, Z., Chan, A. L. S., & He, M. (2010). Modeling and application of direct-expansion solar-assisted heat pump for water heating in subtropical Hong Kong. Applied Energy, 87 (2), 643–649. https://doi.org/10.1016/j.apenergy.2009.05.036
Esen, H., Esen, M., & Ozsakal, O. (2017). Modelling and experimental performance analysis of solar-assisted ground source heat pump system. Journal of Experimental & Theoretical Artificial Intelligence, 29 (1), 1–17. https://doi.org/10.1080/0952813X.2015.1056242
Eskom IDM. 2011. Solar water heating rebate programme. Eskom annual report s.n.
Eskom report. (2011). Residential heat pump rebate programme. Energy efficiency measurement & verification practices (pp. 127–135).
Fang, G., Hu, H., & Liu, X. (2010). Experimental investigation on the photovoltaic-thermal solar heat pump air-conditioning system on water-heating mode. Experimental Thermal and Fluid Science, 34(8), 736–743. https://doi.org/10.1016/j.expthermfsuci.2010.01.002
Frank, E., Haller, M., Herkel, S., & Ruschenburg, J., 2010. Systematic classification of combined solar thermal and heat pump systems. In Proc. of the EuroSun 2010 Conference, Graz, Austria.
Hadar, J. C. (ed.). (2015). Solar and heat pump systems for residential buildings. John Wiley & Sons.
Hawelka, M. N. A., Rahman, S. M. A., & Jahangeer, K. A. (2008). Performance of evaporator-collector and air collector in solar assisted heat pump dryer. Energy Conversion and Management, 49(6), 1612–1619. https://doi.org/10.1016/j.enconman.2007.12.001
Hong, L., & Yang, H. (2010). Study on performance of solar assisted air source heat pump systems for hot water production in Hong Kong. Applied Energy, 87(9), 2818–2825. https://doi.org/10.1016/j.apenergy.2009.06.023
Hossain, M. S., Saidur, R., Fayaz, H., Rahim, N. A., Islam, M. R., Ahamed, J. U., & Rahman, M. M. (2011). Review on solar water heater collector and thermal energy performance of circulating pipe. Renewable and Sustainable Energy Reviews, 15(8), 3801–3812. https://doi.org/10.1016/j.rser.2011.06.008
Huang, B. J., Lee, J. P., & Chyng, J. P. (2009). Heat-pipe enhanced solar-assisted heat pump water heater. Solar Energy, 78(3), 375–381. https://doi.org/10.1016/j.solener.2004.08.009
Kim, W., Choi, J., & Cho, H. (2013). Performance analysis of hybrid solar-geothermal CO2 heat pump system for residential heating. Renewable Energy, 50, 596–604. https://doi.org/10.1016/j.renene.2012.07.020
Kong, X., Sun, P., Dong, S., Jiang, K., & Li, Y. (2018a). Experimental performance analysis of a direct-expansion solar-assisted heat pump water heater with r134a in summer. International Journal of Refrigeration, 91, 12–19. https://doi.org/10.1016/j.ijrefrig.2018.06.021
Kong, X., Sun, P., Li, Y., Jiang, K., & Dong, S. (2018b). Experimental studies of a variable capacity direct-expansion solar-assisted heat pump water heater in autumn and winter conditions. Solar Energy, 170, 352–357. https://doi.org/10.1016/j.solener.2018.05.081
Kuang, Y. H., Wong, R. Z., & Yu, L. Q. (2003). Experimental study on solar assisted heat pump system for heat supply. Energy Conversion and Management, 44(7), 1089–1098. https://doi.org/10.1016/S0196-8904(02)00110-3
Levins, W. P. (1983). Estimated seasonal performance of a heat pump water heater including effects of climate and in-house location (No. ONR/CON-81). Oak Ridge National Lab.
Li, Y. W., Wang, R. Z., Wu, J. Y., & Xu, Y. X. (2007). Experimental performance analysis on a direct-expansion solar-assisted heat pump water heater. Applied Thermal Engineering, 27(17–18), 2858–2868. https://doi.org/10.1016/j.applthermaleng.2006.08.007
Long, J., Xiao, K., Zhong, H., Lu, H., & Yonggo, A. (2021). Study on energy-saving operation of a combined heating system of solar hot water and air source heat pump. Energy Conversion and Management,
Tangwe, S., & Sikhonza, M., 2021. Efficient solar-assisted air source heat pump system: A case study in a cold environment. Energy and Buildings, 229, 113624. https://doi.org/10.1016/j.enbuild.2020.113624

Long, T., Qiao, Z., Wang, M., Li, Y., Lu, J., Li, W., Zeng, L., & Huang, S., (2020). Performance analysis and optimization of a solar-air source heat pump heating system in Tibet, China. Energy and Buildings, 220, 110084. https://doi.org/10.1016/j.enbuild.2020.110084

Michopoulos, A., Zachariadis, T., & Kyriakis, N. (2013). Operation characteristics and experience of a ground source heat pump system with a vertical ground heat exchanger. Energy, 51, 349–357. https://doi.org/10.1016/j.energy.2012.11.042

Nuntaphan, A., Chansena, C., & Kiatririroat, T. (2009). Performance analysis of solar water heater combined with heat pump using refrigerant mixture. Applied Energy, 86(5), 748–756. https://doi.org/10.1016/j.apenergy.2008.05.014

Qu, M., Chen, J., Nie, L., Li, F., Yu, Q., & Wang, T. (2016). Experimental study on the operating characteristics of a novel photovoltaic/thermal integrated dual-source heat pump water heating system. Applied Thermal Engineering, 94, 819–826. https://doi.org/10.1016/j.applthermaleng.2015.10.126

Ran, S., Lyu, W., Li, X., Xu, W., & Wang, B. (2020). A solar-air source heat pump with thermostiphon to efficiently utilize solar energy. Journal of Building Engineering, 31, 101330. https://doi.org/10.1016/j.jobe.2020.101330

Sikhonza, M., Tangwe, S., & Simon, M., 2019, March. An efficient design of a data acquisition system to monitor the operating performance of a hybrid solar assisted air source heat pump water heater. In 2019 International Conference on the Domestic use of Energy (DUE) (pp. 126–132). IEEE.

Wang, E., Fung, A. S., Qi, C., & Leong, W. H. (2012). Performance prediction of a hybrid solar ground-source heat pump system. Energy and Buildings, 47, 600–611. https://doi.org/10.1016/j.enbuild.2011.12.035

Xu, Y., Huang, Y., Jiang, N., Song, M., Xie, X., & Xu, X. (2019). Experimental and theoretical study on an air-source heat pump water heater for northern China in cold winter: Effects of environment temperature and switch of operating modes. Energy and Buildings, 191, 164–173. https://doi.org/10.1016/j.enbuild.2019.03.028

Youssef, W., Ge, Y. T., & Tassou, S. A. (2017). Effects of latent heat storage and controls on stability and performance of a solar assisted heat pump system for domestic hot water production. Solar Energy, 150, 394–407. https://doi.org/10.1016/j.solener.2017.04.065
