AN INVESTIGATION INTO THE ENERGY SAVINGS AND ECONOMIC VIABILITY OF HEAT PUMP WATER HEATERS APPLIED IN THE RESIDENTIAL AND COMMERCIAL SECTORS – A COMPARISON WITH SOLAR WATER HEATING SYSTEMS

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Introduction

Due to recent and on-going power supply problems experienced in South Africa, regulatory bodies have announced the use of a power ration scheme. This will result in the different markets sectors required to reduce energy consumption by a predetermined percentage, for instance 10% for the residential sector and 20% for the hospitality industry. This will be done in the hope of improving the stability of the electricity supply. While this is being put forward as a short term solution of a couple of months, it is evident that long term solutions should be implemented to ensure a reliable electricity supply for the next few years.

The main challenge confronting us is how to reduce the energy consumption with a sustainable demand side management effort. The temporary shut down of all mining operations during January 2008 is a clear example of non-sustainable demand side management where a reduction in production has a negative impact on the country's economy. The same is applicable for all other industrial and commercial business and even the residential sector. Reducing energy consumption by means of reducing for example manufacturing output, service levels in the hospitality industry, or quality of life at home, to name but a few, is not the most effective way to achieve a sustainable reduction in energy consumption as it has negative effects like harming our economy and living standards.

The only way to achieve a sustainable energy consumption reduction will involve the implementation of energy efficient programs in all sectors. These programs typically aim at installing energy efficient devices that consume less energy whilst, most importantly, still provide the same service levels. An example of this is the installation of Compact

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Fluorescent Lights where the electrical energy consumption are significantly reduced compared to conventional incandescent light bulbs, whilst still maintaining acceptable illumination levels.

In the field of sanitary water heating ESKOM identified solar water heaters as the energy efficient technology it wants to support and thus implemented a subsidy scheme to promote a full scale country wide implementation thereof. However, solar energy is not always the optimum solution. In this paper solar water heaters will be compared to another energy efficient technology called heat pump water heaters by doing an economic comparison.

Solar water heaters

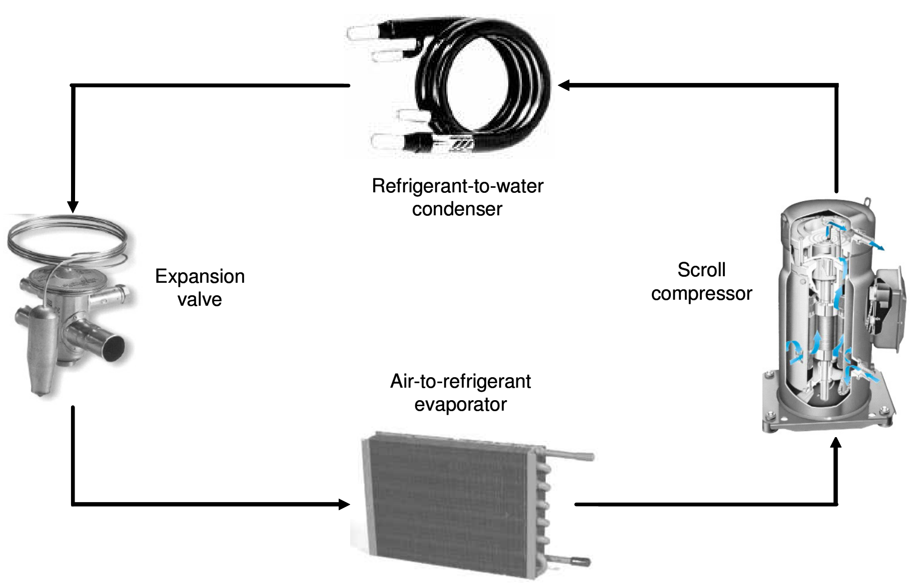
During the past few months ESKOM has given significant focus to solar water heating to mainly solve the problem of electricity consumption in the residential sector. Over the past few years solar heating has been improved significantly through research to provide a low maintenance solution mainly aimed at the residential market. This concept has several benefits, but also disadvantages:

- The main benefit of solar water heating is a total reduction in electricity cost that is normally incurred by electrical resistance heating of sanitary water as found in conventional geysers. The cost of water heating typically contributes to between 30% and 50% of a household's electricity cost. It can therefore save a significant fraction of the typical household's electrical bill.
- Unfortunately the disadvantage of the concept is the high capital cost of acquiring and installing such a unit. This cost coupled with the relatively low electricity cost in South Africa (compared to developed countries), means that the economic returns are poor resulting in typical payback periods for solar water heaters of more than 8 years.
- ESKOM has however embarked on a subsidy program for solar water heaters. Unfortunately the subsidy only reduces the capital cost of the unit and installation cost by 20-30%. The cost incurred by home owners is therefore still very high, and typical payback periods are still in excess of 6 years. (Please refer to the ESKOM DSM website [2] that boasts a calculator to show the typical installation costs, cost savings and payback periods).
- While the solar heating panel can typically heat 100% of the water requirements in summer, it can only heat a fraction of the hot water requirements in winter, due to i) lower solar irradiance in winter, and ii) higher hot water consumption in winter. Solar water heaters will therefore save a high fraction of energy required for water heating, but not 100% annually.

Heat pump water heaters

There is another energy-efficient water heating concept that has proven itself highly successful; known as a heat pump. Until now this success was mainly achieved in the commercial building market (hotels, hospitals, university residences, etc.) [4].

A heat pump is essentially a vapour compression cycle, similar to an air conditioning unit. However, instead of the cycle being used for air cooling purposes with the associated heat as a by-product, a heat pump utilizes the heat generated in the cycle to heat water.



In brief; energy is extracted from the ambient air using a finned-coil heat exchanger, also known as an evaporator, using a refrigerant at low pressure and temperature as the working fluid inside the tubes. This refrigerant is then compressed to a high pressure and temperature by an electrically driven compressor. The high pressure refrigerant is then circulated through a refrigerant-to-water heat exchanger, also known as a condenser. Here energy is exchanged with water, at a lower temperature, thus heating the water to temperatures in the region of 60°C. The refrigerant leaving the condenser is then expanded back to a low pressure by using an expansion valve before it enters the evaporator to start the cycle once more.

This is a continuous process, and the only electrical energy used is to drive i) the compressor, ii) a pump to circulate water through the refrigerant-to-water condenser, and iii) fan power to cycle air through the finned air-to-refrigerant evaporator.

This cycle typically consumes 1 unit of electrical energy for every 3 units of heating produced; i.e. only $33kWh_{electrical}$ is used to produce $100kWh_{thermal}$. Therefore on average two thirds (67%) of the electrical energy consumption can be saved compared to conventional electrical resistance heating.

As with solar heating, heat pumps also have several benefits and disadvantages:

- Heat pumps can, as mentioned already, save up to 67% of the energy required to heat water. With water heating by conventional geysers contributing 30-50% of a typical household electricity cost, it means that a heat pump can save 20-33% of the cost. This is more than what is currently required from the power ration scheme for the residential sector (10%) or the hospitality industry (20%).

- Heat pumps are relatively easy to install. All that a heat pump requires is a free air arrangement resulting in it usually being an outside installation. Heat pumps are built to be weather proof and comply with the SANS IP ratings for outdoor electrical installations.
- At large centralized water heating installations typically found at commercial buildings such as hotels and hospitals, heat pumps are relatively easy to install. For example, to provide 25000 litres of sanitary hot water at 60ºC per day a heating capacity of typically 100kW would be required. This can be achieved by installing 2 x $50kW_{thermal}$ heat pumps. These heat pumps can be installed on a hotel premises near the current water heating plant, taking up a space of approximately $10m^2$. This is opposed to a solar heating installation where 25000 litres of hot water at 60ºC per day would require solar panels covering approximately $267m^2$ based on an average solar radiation value of $4.8kWh/m^2$ per day.
- Heat pump installations, whilst more expensive than a conventional electrical resistance heater, are much less expensive than solar water heating installations. This will be shown in this article. In addition, ESKOM has launched a subsidy program for heat pumps, with this subsidy typically representing a 40-50% reduction in project cost. The economic returns on a large centralized heat pump installation, aided by the ESKOM subsidy, result in competitive payback periods of between 2 and 3.5 years. Payback periods in the residential sector vary between 2 and 4 years. The variance in payback periods is a function of several factors including levels of usage and the ease of installation.
- The only disadvantage of heat pumps is that it is still dependant on an electricity supply if compared to some solar water heaters that can be operated completely independent. However, while South Africa is unfortunately experiencing rolling blackouts, the electrical supply is sufficient for most of the day. The availability of electricity should at least stay this way, or even improve once energy efficiency programs start to show results. It will therefore not be an issue to have an energy efficient device that is still dependant on an electrical supply as is the case with lighting.

In the next section case studies will be discussed to compare and evaluate the two energy efficient solutions mentioned in this paper.

Case studies

Several arguments for and against the use of either heat pumps or solar water heaters have been made in the previous section. This section provides simulated case studies for both residential and commercial building sanitary hot water facilities. Comparisons are made between conventional electrical resistance heaters, heat pumps and solar water heaters in the residential sector, and between ASHRAE standard electrical systems and heat pumps in the commercial building sector. Data for solar water heating was obtained from the comprehensive website created by ESKOM DSM [2]. Data for heat pump systems and conventional electrical heating systems is obtained from previous studies ([4], [5], [7], [8], [9], [11]). Detailed comparisons will be made for the Johannesburg region in Gauteng.

Case study assumptions.

For purposes of comparison, the following assumptions are made allowing the three concepts to be evaluated on equal terms.

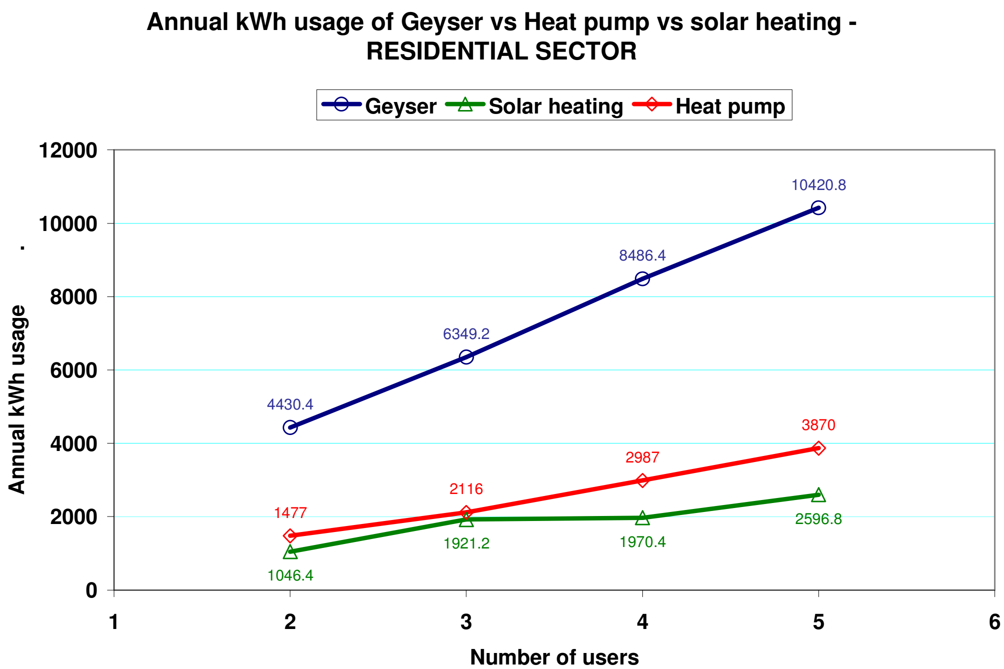
- Average inlet water temperature for Johannesburg is 14ºC.
- Average solar radiation values are: 1750kWh/m² annually for Johannesburg.
- Hot water is stored at 60ºC in an insulated vessel with heat loss characteristics as typically found in the industry: $Q_{loss,daily} = 0.125 \times Q_{max,vessel}$, where $Q_{max.vessel}$ represents hot water stored at 60°C.
- For the residential sector the vessel configuration found in most homes will be used as is to store hot water generated by the heat pump. Solar water heaters will however have their own storage vessels installed.
- In commercial buildings the existing hot water storage vessels will be used together with heat pumps.

Case study 1: Residential sector

In this specific case study the three heating methods will be evaluated on residential level. The results will be shown for houses having 2, 3, 4 and 5 persons using the sanitary hot water facilities. Typical hot water consumption patterns and figures have been obtained from a study by Meyer [6]. Consumption varies between 75 litre at 60°C per person in summer and 110 litre at 60°C per person in winter. Several other studies have used these figures in hot water system design and evaluation ([5], [9], [10]).

- The conventional geyser found in most homes is usually either a
  - 3kW, 150 litre unit (2-3 people) or a
  - 4kW, 200 litre unit (4-5 people).
- The proposed heat pump unit for both vessel sizes is $2.4kW_{thermal}$, using $0.8kW_{electrical}$.
- The solar heating system varies as follows:
  - 150 litre, 1.89m² collector span (2 people)
  - 200 litre, 2.45m² collector span (3-4 people)
  - 300 litre, 4.52m² collector span (5 people)

The systems as specified are provided as inputs to a simulation program [8]. The simulation program performs a first law conservation of energy analysis, and takes into account the annual distribution of hot water consumption and daily consumption profile as proposed by Meyer [6]. Results for annual energy consumption and electricity costs are shown below.

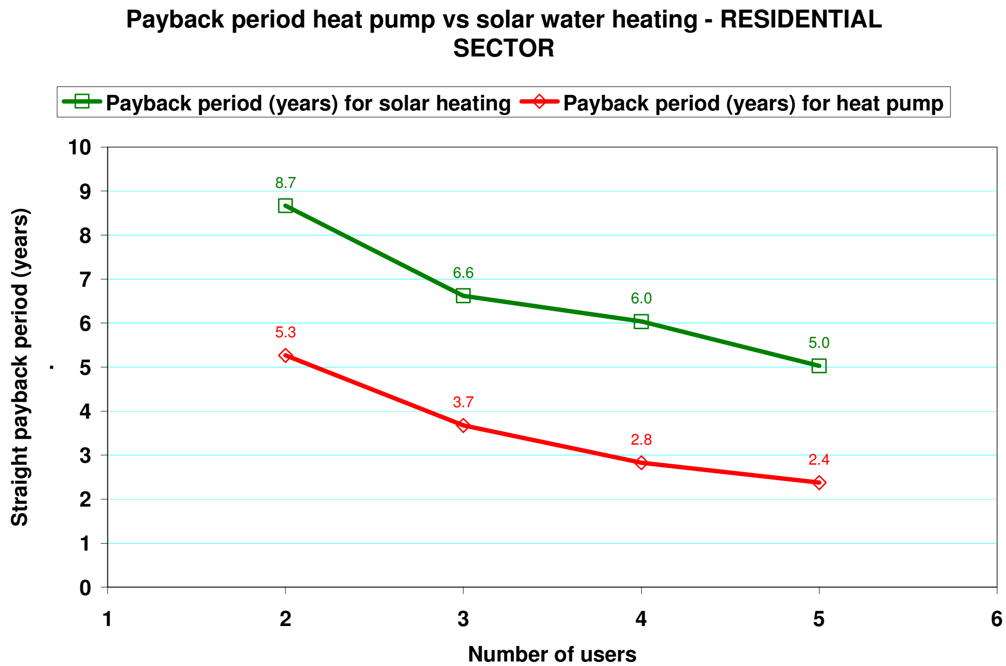


The above figure shows the annual electricity consumption per heating method. It can be seen that both the heat pump and solar water heater provide significant savings over the conventional electrical resistance geyser heater. Furthermore solar water heating saves a higher fraction of energy compared to a heat pump. This is due to the heat pump still consuming electricity to drive the cycle, amounting to about 33% of the electricity consumed by an electrical resistance heater. However, the solar water heater system also uses electricity in the form of backup electrical heating to assist i) during the night time when solar energy is not available, and ii) during winter when daily hot water demand exceeds the daily delivery capacity of the solar panel.

The following installation cost estimates is provided. Please note that the ESKOM subsidies has already been subtracted for both solar and heat pump systems.

	Solar type	Solar cost	Heat pump type	Heat pump cost
2 users	200l, 2.45m²	R13200	2.4kW	R7000
3 users	200l, 2.45m²	R13200	2.4kW	R7000
4 users	300l, 4.52m²	R17700	2.4kW	R7000
5 users	300l, 4.52m²	R17700	2.4kW	R7000

The following graph indicates the payback period calculated using the above installation cost estimates and the calculated energy savings (kWh), using an average energy cost of 0.45c/kWh.



From the graph it is clear that heat pumps provide a significantly better payback period when compared to solar water heating. The main reason for this is the much lower installation cost of heat pumps, whilst still achieving at least 80% of the savings that solar water heating can provide.

Case study 2: Commercial sector

In this specific case study heat pump installations will be compared to conventional electrical resistance heating installations at a hotel. Solar water heating is not included in this comparison, due to a lack of reference information on how these types of projects are approached.

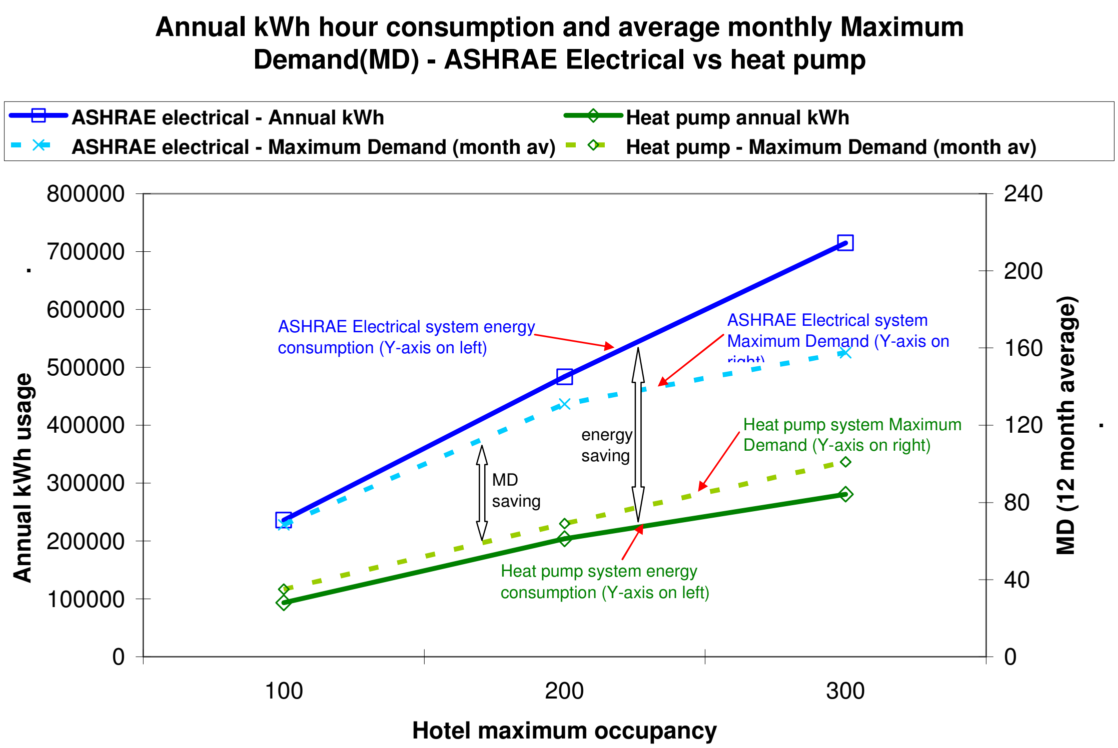
To simplify the study, the results will be shown for hotels having maximum occupancies of 100, 200 and 300 people respectively. Each have occupancies that vary on a day-to-day basis, but with an annual average occupancy of 67%. Typical hot water consumption patterns and figures have been obtained from previous studies funded by ESKOM DSM research [9]. Daily consumption varies between 78 litre at 60°C per person in summer and 110 litre at 60°C per person in winter.

The conventional electrical resistance heaters typically found in centralized installations is usually sized according to ASHRAE principles. There are other existing system designs such as off-peak heating systems. For the purpose of this comparison the focus will only be on the ASHRAE specified systems, since these have the biggest potential for energy savings when replaced by heat pumps.

- Typical ASHRAE design guideline calculates heating capacity as 0.7kW/person, and 60 litres storage capacity per person.
- The heat pump capacity is calculated according to previous studies as a function of average occupancy and available storage capacity [8].

The systems as specified are provided as inputs to the simulation program [8] that performs a first law conservation of energy analysis, taking into account the annual distribution of hot water consumption and daily consumption profile as proposed by Rankin & Rousseau [9]. In addition, an occupancy fluctuation cycle is included to take into account the typical day to day variation in occupancy as experienced in the hotel industry. Most buildings with a centralized water heating system also utilize a ring-main circulation system for a hot water on tap service.

Results for annual energy consumption and electricity costs are shown below. The graph shows the annual electricity consumption for the ASHRAE standard electrical system vs. a heat pump retrofitted system. In addition, the Maximum Demand (MD) contribution of each water heating system type is also shown.

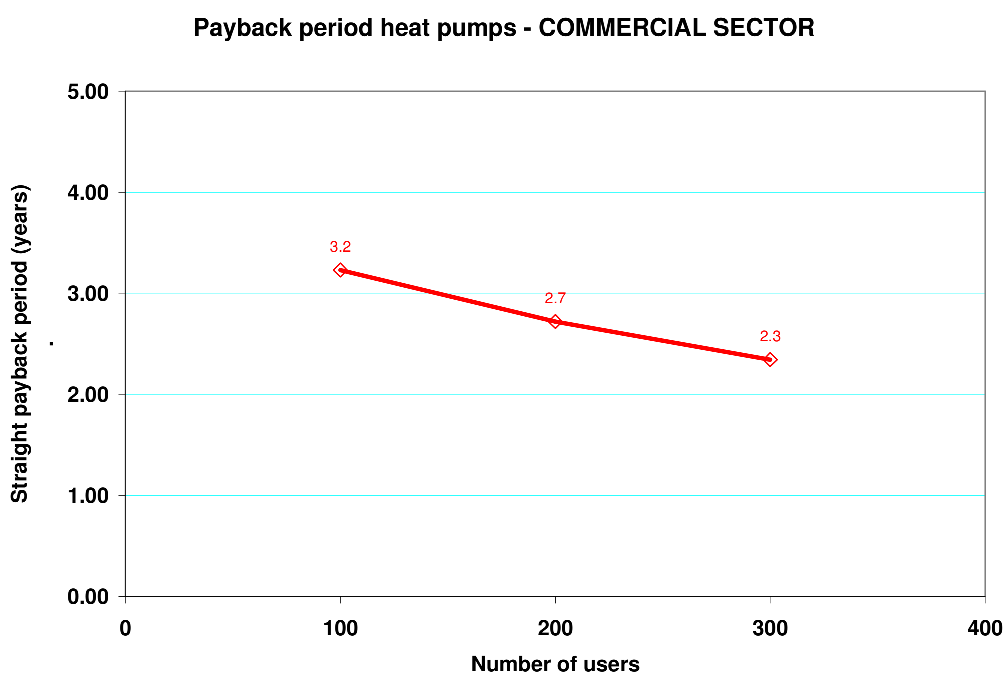


As is evident the heat pumps provide significant energy savings when compared to the conventional ASHRAE specified electrical heating system. Energy consumption is reduced by 60% on average. In addition, the installation of heat pumps allows the MD contribution of the water heating system to be reduced significantly as well. This is achieved mainly by reducing the total electrical capacity of the water heating system. Heat pumps only utilize about 33% of the electrical power needed to drive a similar electrical heater, and utilize only a fraction of the electrical heating system for backup heating.

The following installation cost estimates are provided. Again, please note that the ESKOM heat pump subsidy is already subtracted from the cost estimates.

Maximum occupancy (Average oocupancy 67% in all cases)	Proposed system	Cost estimate
100	1 x 50kW heat pump (Av COP = 2.9)	R195,000-00
200	2 x 50kW heat pumps (Av COP = 2.9)	R303,000-00
300	2 x 70kW heat pumps (Av COP = 3.1)	R350,000-00

The following graph indicates the payback period calculated using the above installation cost estimates and the calculated energy savings (kWh) and MD savings. Estimated costs used were 24c/kWh and R60/kVA (per month)



From the graph it is clear that retrofitting a centralized water heating system at a hotel with heat pumps provide a competitive payback period which improves with an increase in occupancy capacity of a hotel.

The figures as shown above only give an average indication of economic returns on such an installation. Several factors can influence the eventual payback period, such as:

- Average occupancy. If the average occupancy is lower than 67%, the cost savings can be reduced, leading to longer payback periods. If average occupancy is however higher as found at many hotels, the savings are optimized and payback periods can be shorter.

- Ease of installation. Due to potential noise and visual intrusion it is sometimes required to install heat pumps on the roof of a hotel. This has been included in the cost estimates. If roof placement is not required, the cost of installation and rigging can therefore be reduced, leading to improved payback periods.
- The available storage capacity. Due to very high morning (07:00-10:00) peak hot water consumption at hotels, insufficient storage capacity can impact negatively on savings and payback periods [9].

Conclusion

This article reports on a scientific investigation conducted under the auspices of the North West University, to compare the different technologies for water heating that are available to the residential and commercial building sectors.

Lately significant focus has been given to solar water heating in the drive to conserve electrical energy mainly in the residential market. ESKOM DSM has created a comprehensive website where residential customers can provide inputs to a calculator to calculate the required solar system and provide a savings estimate and payback period on investment.

This article showed that heat pumps can provide a very feasible alternative to solar water heating in the residential market. Heat pumps achieve more than 80% of the savings that are possible with a comparable solar water heating system, but at a much lower installation cost, thus leading to a significantly improved payback period. Typical payback periods for heat pumps vary be between 2.3 – 3.7 years for homes with 3 to 5 residents. These payback period estimates are typically 40-55% lower than for solar water heating.

The study finally proceeded to evaluate heat pumps applied in the commercial building sector utilizing centralized water heating systems. This case study was not done for solar water heating, due to a lack of reference information on how this type of projects is approached. It is shown that there is good potential for heat pump installations in the commercial building sector. Typical payback periods for these installations vary between 2.3 and 3.2 years, depending on factors such as occupancy and climatic region. These results also provide a good estimate of savings and payback periods that can be achieved for any centralized water heating system, including those at hospitals, university residences, mine shaft change houses etc.

In conclusion, this scientific investigation shows that alternatives to solar heating exists for energy efficiency applications for sanitary water heating systems. This is a market that has huge savings potential that will benefit both ESKOM and the residential/commercial customer.

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