A SURVEY OF DOMESTIC WATER HEATING TECHNOLOGIES

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Abstract: In South Africa, heating water for domestic use is one of the most energy consuming processes in residential buildings. This process represents up to 60% of the total energy in the residential sector. Using more efficient and improved technologies to heat domestic water can make a positive contribution to the fight against the country's current energy crisis which has a direct implication on the yearly increase in electricity prices. The purpose of this paper is to conduct a survey, summarize and critically analyze the different technologies used to heat water for domestic purposes. The results of this survey aim to identify gaps in the existing research, especially in the case of South Africa. Several research papers and other academic studies are reviewed and classified based on their focus, contribution and the type of technology to achieve a comfortable thermal level of water for domestic use. The key findings indicate importance of implementing hybrid systems for increased reliability and hot water availability while minimizing operating costs.

Key words: Electric storage tank water heater; solar collector water heater; heat pump water heater; geothermal water heater; gas-fired tankless water heater; photovoltaic/thermal water heater

1. INTRODUCTION

Water heating for hygienic purposes such as showering and bathing is one of the most energy consuming processes in residential areas. In South Africa, for instance, about 40 to 60% of the total energy of a normal residential building can be allocated to the heating of water [1]. Water needs to be heated from a lower temperature to the user's specific comfortable thermal temperature level. Traditionally, a standard electric storage tank-water heater (EST-WH), also called a geyser in South Africa, has been the main device for residential water heating within the country. However, the increase in the South African population, economy and living standard has led to an energy shortage, which has resulted in a steadily increasing electricity price of 9.4% annually according to NERSA (National Energy Regulator of South Africa) [2]. As an attempt to solve this, Eskom (the main electricity supplier), has recently introduced energy management activities, such as energy efficiency (EE), and use of renewable energy (RE) systems [3]. On the one hand, the EE activities consist of reducing the total (overall) energy consumption during all the time periods, while load management activities aims to reduce the energy consumption during given time periods, such as peak times, when the Eskom grid cannot meet the demand. During peak times, the electricity consumption is charged at higher rates to encourage customers to shift their loads to off-peak and standard periods when the electricity is cheaper. This type of tariff is referred to as time-of-use (TOU) electricity tariff. With TOU, customers can therefore reduce their electricity bills by shifting load demands away from the peak time periods [4]. Some EE activities on EST-WH have been suggested to reduce the corresponding overall energy consumption. The first method is the use of insulation material on the tank for standby loss reduction. However, the cost-effectiveness of this solution has been questionable [5]. The second method, which is the most cost-effective, is to reduce the temperature to which the water needs to be heated. This is accomplished by simply changing the setting of the thermostat to a lower value. The temperature can be reduced to suit the consumers' needs and thermal comfort level [6]. However, by reducing the temperature, a risk of bacterial infection arises and this is an important factor that needs to be considered when assessing thermal comfort level of the hot water users. This can result in the production of the Legionella pneumophila which is hot water bacteria growing at water temperatures ranging from 20ºC to 45ºC. In its most virulent form, it can cause Legionnaire's disease. However, studies have shown that only 1-5% of people exposed to the bacteria were infected [7]. With South Africa's populations ever decreasing health condition and immune viruses, the probability of contracting such a disease can be a higher possibility. The WHO (World Health Organization) has therefore determined that a temperature of 60 ºC can eliminate these bacteria in hot water. Further, it has been determined that the hot water supply should reach a temperature of 60 ºC once daily to prevent infection [8].

2. DESCRIPTION AND OPERATION OF DIFFERENT RESIDENTIAL WATER HEATING TECHNOLOGIES

A. Electric storage tank water heater

An electric storage tank water heater has a cold water inlet, hot water outlet and an element to increase the temperature of the water by using electrical energy. The water heating process takes place inside the storage tank where the element is situated [9]. A temperature sensor detects the temperature level of the water and switches the electrical element on through a thermostat when the water temperature is below a certain pre-set threshold. The hot water is drained when it is needed and cold water flows into the tank where it then mixes with the remaining hot water. The temperature falls due to the mixing and the heating process is started again in order to increase the temperature to the predetermined value.

B. *Electric tankless water heater*

The tankless water heater also referred to as a demand water heater system, heats water directly to ensure instantaneous hot water availability. The heater has a cold water inlet valve and a hot water outlet, the system is switched on when the hot water valve is opened. Cold water flows into the heater where it is heated by a resistive electric element and exits through the hot water outlet. An outlet thermistor is located near the hot water outlet valve in order to measure the temperature of the heated water and provide feedback to the control circuit, similarly an inlet thermistor is situated at the cold water inlet. The control circuit monitors the temperatures and adjusts the power input to the heating elements accordingly through solid state switching triacs to provide the required hot water at the temperature set by the user. This water heater requires less space due to the absence of the storage tank. The heater is usually mounted close to the source where the hot water will be used thereby reducing standby energy losses. The electric element uses a substantial amount of electrical energy to provide the required hot water on demand [10].

C. *Solar water heater*

The solar water heater works by collecting thermal solar radiation and transferring the heat to water. The main benefit of this type of water heating method is that it uses the energy of the sun, which is indefinitely renewable and a free source of energy. The solar collector is usually mounted at an angle on rooftops of residential buildings in order to absorb the maximum amount of radiation from the sun. The majority of standalone solar water heater systems have hot water tanks fixed to the top of the collector arrays. This is due to the effect of thermosiphon which allows water with a higher temperature to rise to the top part of the specific water volume. The hot water is stored in hot water tanks before being supplied to the users [11].

D. *Hybrid Solar Collector Coupled with Electric Storage Tank Water Heater*

In the event of needing access to hot water in a 24-hour day, the solar water heater described in Section A. of this paper can be coupled to an existing electric storage tank water heater (defined in Section B.) in order to heat water when the solar radiation is at insufficient levels. An auxiliary heater situated inside the tank converts electrical energy into thermal energy when the temperature of the water falls below a certain value [12].

E. *Heat Pump Water Heater*

A heat pump absorbs ambient energy in the surrounding air and increases it by means of compression. The principle of operation is based on the refrigerant cycle. The compressor uses electrical energy in order to compress the refrigerant inside the constant volume of the condenser and evaporator loop. The heated refrigerant transfers the heat to the water through heat exchanger action. The refrigerant is isolated from the water and never mixes. A common heat pump system draws only one unit of electrical energy to create three units of thermal energy [13].

F. *Gas Fired tankless Water Heater*

The gas fired tankless water heater (GFTWH) offers instantaneous hot water due to the rapid heat transfer to the heat exchanger. Gas is fed to the heater and is ignited in order to create a constant flame. The gas fired water heater can be categorized into two groups; the low efficiency condensing model and the high efficiency condensing model. The difference between a low efficiency condensing model and a higher efficiency condensing model is their overall heat loss. The high efficiency condensing model has a heat recovery system where most of the heat is reused and exits the exhaust as vapour; the vapour is collected and drained [14]. Therefore, a low efficiency condensing model has a much higher heat loss due to the absence of this heat recovery system. A sensor detects the amount of water that needs to be heated and accordingly adjusts the gas control valve. If an increased hot water demand is detected, then an increased amount of gas will be supplied to the burner [15].

G. *Hybrid Heat Pump Coupled with Gas Fired Water Heater*

This arrangement has two heating systems where each can operate independently or simultaneously (either the heat pump, gas fired water heater or both). Water is heated by one of the two systems; the heat pump receives the cold water from the main water supply of the household first due to its high efficiency of increasing the thermal level of the water from a low temperature [16]. The heated water from the heat pump is transported to the gas fired heater so that thermal energy can be transferred by means of a heat exchanger (gas transfer medium), which is fed from the combustion chamber. This process increases the temperature to the preset comfortable water thermal level of the user [17].

H. *Geothermal Hot Spring Water Extraction*

Geothermal sources of energy are extracted from the earth. Geothermal heating can occur naturally, for example where water is present and forms a hot spring, the heated water from the spring can be pumped to residential areas (as long as they are in close proximity to the hot spring to avoid heat loss). The pumped water can be used for general hygienic purposes. It is usually necessary to first pump the water through a filtration system so that the water has increased purity. In South Africa, only seven thermal springs have high enough thermal levels to accommodate hot water users' requirements (exceeding 50˚C) for bathing and other cleaning type duties [18].

I. *Geothermal Heat Pump System*

Geothermal heat pumps extract thermal energy from the ground. The energy originates from radio-active decay from minerals and solar energy absorbed at earth surface level. The system works on the same principle as a common heat pump, however in this configuration; the heat is extracted from the ground rather than the surrounding air [19]. Heat is absorbed by an exchange fluid flowing through pipes underground. The pipes are usually buried 10m below the surface. At a depth of 10 meters, the temperature stops fluctuating and takes on a constant value. At this level beneath the surface, the earth's temperature ranges from 10° C to 12°C and remains in the respective boundaries even during winter [20]. Due to this, the heat pump is much more efficient than a common air extracting heat pump where temperatures fluctuate out of operating limits.

J. Hybrid Photovoltaic-Thermal Solar Collector Water Heater

The photovoltaic-thermal system is a combination of a solar thermal collector and a photovoltaic module as the PV cell absorbs radiation from the sun in order to generate electricity, it becomes hot and its efficiency drops due to the excess heat. The thermal collector is contained within a glass cover which helps to trap the thermal energy. The heat is absorbed by a transfer fluid such as a refrigerant or water flowing through the ducts of the thermal collector part of the system. Another flow duct separated by a backplane is situated beneath the solar cell to increase the heat absorption of the system [21]. The heated water, as a result of the absorption, can be transferred to an electric storage tank water heater to be reserved, or the thermal level can be increased for household use [22]. Photovoltaic–thermal collectors have a high energy yield due to simultaneous energy conversion and are more efficient when comparing standalone PV modules [23].

3. DISCUSSION

A. Key Results and Findings

Table I presents some benefits, limitations, approximate install cost, average lifetime and average source efficiency of the different technologies in general; this information gives an indication on which technologies are well suited for the specific case of South Africa.

B. Impact of WaterHeating Systems on South Africa Energy Efficiency Program

Renewable energies combined with cost saving strategies in South Africa have seen increased popularity throughout recent years. Government rebate programs have provided large growth in renewable technology implementation, especially in solar water heating setups. Unfortunately, Eskom the electricity supplier of South Africa and other countries have recently halted all rebate programs for the installation of renewable energy water heaters such as heat pumps and solar geysers since January 2014 [25]. Research in renewable energies have improved the efficiency and in turn the feasibility of these technologies, so that more consumers can reap greater benefits from these systems. Consumers face ever increasing electricity prices and are forced to turn to alternative and/or higher efficiency devices if lower energy bills are to be expected [26-27]. A large group of South Africans still have insufficient education on recent developments of alternative energy systems and misunderstand the feasibility and potential savings they might offer. Information needs to be conveyed to the country's populous on recent developments in order to increase awareness.

4. CONCLUSION

Water heating systems are responsible for more than half of the energy consumed in South African households, this is a problem feeding the energy crisis in South Africa. The high energy consumption can be accredited to the inefficiency of these devices making it unnecessarily expensive to the consumer. It is evident that substantial research on improving the efficiency of water heating systems for domestic use has been carried out. Furthermore, heat loss reduction and prevention studies have also seen considerable improvement in current technologies.

This paper has conducted a survey of different technologies used to heat water for domestic purposes, especially in the case of South Africa. Two or more of these technologies combined forms hybrid systems to increase the efficiency and hot water availability. It has been found that hybrid systems have the potential to lower energy costs and increase reliability (if each system can operate independently). The cost effectiveness as well as the ability of hybrid systems to produce proper water heating in South Africa have also been analyzed and their viability in South Africa was assessed. It has been noted that for the specific case of South Africa, solar collector systems seem to overshadow other technologies due to its high efficiency and usage of abundant solar resource. As South Africa has the best solar radiation compared to other countries, the solar collector as a primary water heater makes the most sense. It is expected that a hybrid water heating system when managed properly can have extensive savings in energy bills as a result. Recommendations for future research include optimal energy management of hybrid heat pump systems, improvement on South African policies regarding renewable energy systems implementation such as solar water heaters and other efficient devices needs to be reviewed. Due to Eskom's cancellation of the solar geyser and heat pump rebate program, a decline in energy efficient water heaters implementation has been observed. The people of South Africa should be able to implement a device that suits their geographical and financial needs with the appropriate financial assistance from the government in order to reduce the dependency on fossil fuels. The energy awareness in South Africa needs to be increased through media and government channels in order to mitigate unnecessary energy usage. Efficient devices in conjunction with appropriate knowledge of the benefits these systems might offer, can decrease the severity of the energy crisis that South Africa is currently facing and in turn allow South Africans to improve their financial situation. The authors of strongly believe that the work presented in this paper would be will be of benefit for researchers and engineers in the related field.

TABLE I. Discussion

Technologies	*Comments applicable to South Africa*	*Approximate install cost (ZAR)[a]*	*Average lifetime (years)*	*Source Efficiency*
Electric storage tank water heater	Hot water is always on tap, however the input energy required is substantial. This has a negative impact on the energy costs to consumers and is not a viable system due to the current energy crisis in South Africa.	2584-3800	13	0.27
Electric tankless water heater.	Instantaneous water heating method provides virtually unlimited supply of hot water. Due to the high electrical energy consumption and high payback period, this system can be deemed unviable.	2799-4800	10	0.3
Solar water heater	Hot water availability decreased compared to other water heaters since the sun only irradiates the earth at certain intervals (approx. 10 hours per day) in summer and winter months. The upside of this water heater is that the input energy is free and abundant in South Africa.	7000-11598	30	1
Heat-pump water heater	The heat pump water heater has increased electrical efficiency over the standard ESTWH (energy in ambient surrounding air supplements the production of hot water). Hot water is readily available when ambient air temperature is within operating temperature limits. The only drawback this system has, is the electrical input energy requirement. The electrical energy needed is 1 unit input energy in order to generate 3 units of thermal energy, making it a feasible option for South African residents.	12000-18762	13	0.59-0.70
Gas fired tankless water heater	This method of heating water ensures instantaneous hot water availability, however the gas used for combustion is not free and renewable compared to solar radiation energy used by the solar water heater. Due to increasing gas prices, this may not be the best alternative for cheaper running energy costs in South Africa	3984-5597	20	0.75-0.90
Geothermal water heating (springs)	Geothermal springs can supply virtually unlimited amount of hot water at any given time. The source of the water can be questionable and may contain harmful bacteria and substances, thus requiring a filtration process. The only energy requirement in this type of hot water system is for pumping the already heated water to residential buildings for domestic use. There are only a few locations in South Africa where the temperature of the hot springs are over 50˚C (suitable for hot water user requirements). This means that only a small amount of the South African population can benefit from this method of water heating.	N/A	Pump lifetime	Depends on Pump
Hybrid Photovoltaic/Thermal (PVT) water heater	The PVT water heater has the benefit of simultaneously heating water and converting solar energy into electrical energy. The electrical energy created by the PV panel can be stored for heating water when solar radiation is poor or absent. The PV panel is kept cool by the flowing water but solar radiation is lost due to some of the water duct components blocking the panel. Some drawbacks of this system include high initial cost and difficulty in reaching desired temperature levels. The majority of South Africans will find it difficult to meet the initial costs of implementation for this method, therefore it can be deduced that this method is questionable for South African use.	10000+	30	1
Hybrid heat pump gas fired water heater	This configuration can be highly efficient with a low input energy requirement, the two technologies can work independently from each other, which ensures increased reliability. The drawback of this technology is that the energy required is non-renewable. Furthermore, the initial costs to implement this system can be very high. The objective in South Africa is to move away from fossil fuel consumption and keep all costs to a minimum, this method can therefore be seen as unviable.	15984-24359	13	0.67-0.8
Hybrid solar electric water heater	This hybrid arrangement ensures hot water at all times. The primary water heater (solar water heater) uses solar radiation as its input energy. When solar energy is unavailable, it uses electrical energy to heat the water if required. The secondary water heater uses electrical energy which increases operating costs to the consumer. This method can be implemented with low cost to the consumer due to the fact that the solar collector part can be coupled to an existing ESTWH. By heating water in this way, with the solar collector as the primary heater, this method can be used in South Africa and offer more benefits to the consumer.	16170-22000	30	1
Hybrid geothermal heat pump water heater	The hybrid geothermal heat pump water heater has a higher efficiency than the common air source heat pump. This system requires electrical and geothermal energy to heat water. The initial costs of implementing this arrangement can be high due to the underground network of heat exchangers needed. Approximately 54% of the South African population lives below the poverty line[24], making this option overly expensive to implement, thus the running electricity costs increases the overall expense.	19000-18762	13	0.53-2.67

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