Seasonal storage for solar thermal systems in Australia?

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Abstract

Seasonal storage systems have been operating in various European countries since 1985. Combined with solar collectors, these systems are known as 'central solar heating plants with seasonal storage' (CSHPSS). While these systems have been shown to be technically feasible, their cost is still too high to make them competitive with fossil fuels. In Australia, we have quite different conditions to those countries where CSHPSS have been trialled. In general, we experience higher radiation levels, ambient temperatures and cooling loads. Our heating loads and energy prices are also usually lower. As a result, any evaluation of CSPSS operating in a European context may not be valid for Australian conditions. To the authors' knowledge, no evaluation of these systems has been carried out for Australia. This paper therefore attempts an initial assessment of these systems and their viability for Australia. The paper first describes the various types of CSHPSS and then reviews their current status. The performance of one type of CSHPSS operating in several locations of Australia has been predicted using a TRNSYS model. The simulations indicated that the design guidelines for Europe are appropriate for Australia and would result in systems with solar fractions equal to or better than those achieved in Europe. An indication of the financial viability of the system was determined by calculating a simple payback period for a variety of fossil fuels. This type of seasonal storage systems does not currently appear to be financially attractive, although improved payback periods are likely to occur if the fixed storage temperature limit used in the simulations is raised. The best performing systems, in financial terms, are likely to be in areas where the solar system is displacing bottled LPG.

1. INTRODUCTION

Australia has a rich solar resource, which needs to be exploited on a massive scale if a real reduction is to be made in the carbon emissions associated with our energy use. Electricity generation is the prime source of CO_2 from stationary sources and naturally attracts most attention from the renewable energy industry and researchers. Photovoltaic and high temperature solar thermal technologies both offer huge potential to replace fossil fuels used for electricity generation and cut emissions. However, Australia also has a long history in the development and use of low temperature solar thermal systems for use in industrial processes, horticultural and residential heating (e.g. Read, 1979; Fuller et al., 1985). These systems have usually included some kind of thermal storage system, either water or rock. The purpose of the thermal storage has been to cover short periods (hours or days) when solar radiation levels were unable to meet the load instantaneously.

Over the last 20 years, there has been significant interest in long term or seasonal thermal storage systems in several countries, particularly in northern Europe. This work has been driven by the need to overcome the low solar radiation levels experienced in their latitudes during their winter months. As a result of the European research, a significant number of large centralised solar heating plants with seasonal storage (CSHPSS) have been built, monitored and reported. To the authors' knowledge, however, there is little or no research published about the possibility of using seasonal storage systems with low temperature solar thermal systems in Australia. The aim of the paper is therefore to explore the potential for such systems in this country. The paper begins with some definitions and brief review of the experiences of overseas systems. Australian and European conditions are compared for similarities and differences. A TRNSYS model of a CSHPSS has been developed and used to predict its performance to meet both a constant and seasonal load in a selection of Australian climates. Some conclusions about the relevance of CSHPSS in an Australian context are finally drawn.

2. SEASONAL THERMAL STORAGE TYPES

A seasonal storage system can broadly be defined as one which stores energy in one season and delivers that energy in another season. Typically for seasonal storage systems using solar thermal collectors, this means that energy is collected in summer during periods of high radiation and delivered in winter during periods of low radiation. This definition clearly distinguishes seasonal storage systems from short-term storage systems, which normally provide thermal storage to cover periods of inadequate energy lasting 3-5 days. Large-scale solar heating plants with diurnal storage systems (CSHPDS) have been built or investigated in Europe as well as large seasonal storage systems that have not used solar collectors (e.g. Reuss et al., 1997). While the experience gained in these systems is obviously relevant to storage construction, economics and performance, this paper is restricted to those systems that can be genuinely identified as CSHPSS. Various types of storage technologies are possible and this has produced differing classifications. Heller (2000) suggests that there are six categories: pit, steel tank, bore hole clay, bore hole sand, artificial aquifer and prefabricated concrete tank. Lottner et al. (2000) reduce the number of storage options by combining some of the previous types to suggest only four generic types. This paper adopts this latter classification but has renamed them for greater clarity. These four seasonal storage types and their key features are briefly described below.

2.1. Tank Systems

The tanks can be constructed from concrete, steel or possibly fibreglass. The storage medium is water and liners are commonly used with concrete tanks to prevent leakage. The prime advantages of burying the tank are to use the insulating and structural properties of the surrounding ground, and to minimise the above-ground space requirements. Insulation is applied to any above-ground surface of the tank. Examples of tank systems have been constructed in Cheju in Korea (Chung et al., 1998), and in Hamburg and Friedrichschlafen, Germany (Fisch et al., 1998).

2.2. Pit Systems

This system is one of the most popular type of seasonal storage system, due to its low cost and ease of construction. These systems are essentially large artificially-dug holes usually filled with water and gravel. The gravel provides structural support but reduces the effective storage capacity compared to water alone. Impervious liners are used to prevent water leakage. An insulated floating cover completes the storage unit. Examples of pit systems have been constructed in Ottrupgaard, Denmark (Heller, 2000) and in Chemnitz, Germany (Fisch et al., 1998).

2.3. Borehole Systems

In these systems, heat is stored directly in the ground. Heat exchangers are installed in boreholes drilled in ground that is suitable for heat storage. These bores can be between 30-100 metres in depth and 100-150 mm in diameter. The heat exchangers are U-shaped tubes, providing an inlet and outlet for the heat transfer fluid, which is usually water. Insulation is installed at the ground level to minimize heat losses from this top surface. Examples of borehole systems have been constructed in Alberta, Canada (Wong et al., 2007) and in Neckarlsulm, Germany (Schmidt et al., 2004).

2.4. Aquifer Systems

In this system, a naturally-occurring water-saturated media (usually sand) is used as the storage medium. Because the natural occurrence of such bodies in the right location is uncommon, the system is not as commonly used as the previous three types. Examples of natural aquifer systems have been constructed in Rostock and Berlin in Germany (Schmidt et al., 2004).

3. EXPERIENCES WITH SEASONAL STORAGE SYSTEMS

Experience in the design, simulation, construction and operation of CSHPSS has been accumulated in Europe over the last 20 years, firstly through an International Energy Agency's Task VII and then in country-specific programmes such as Solarthermie 2000 in Germany. Most of the systems have been installed in the cool climate countries of central and northern Europe. A few have been constructed in a southern European countries e.g. Greece. In order to provide some insight of the magnitude of the storage volumes and collector areas of CSHPSS, Table 1 shows some key data of operating systems.

Table 1 Key data of operational CSHPSS

Location	**Type**	**Storage Size (m^3)**	**Collector Area (m^2)**	**Reference**
Hamburg, Germany	Tank	4500	3200	Kubler et al. (1997)
Cheju, Korea	Tank	600	184	Chung et al. (1998)
Stuttgart, Germany	Pit	1050	211	Hahne (2000)
Marstal, Denmark	Pit	70000	26000	Fisch et al. (1998)
Neckarsulm, Germany	Borehole	63300	6500	Schmidt et al. (2004)
Alberta, Canada	Borehole	35000	2313	Wong et al. (2007)
Rostock, Germany	Aquifer	20000	1000	Schmidt et al. (2004)

Table 1 indicates that the storage volume-collector area ratios are considerably larger than short-term storage systems. A smaller area of collector can be allowed to progressively heat a large thermal mass over an extended period of good radiation in summer. High temperatures (up to 90°C) are therefore sometimes achieved and normally energy is progressively withdrawn from the store only in the extended periods of poor solar radiation in winter. The literature reporting experiences with actually systems has been reviewed and the main technical and economic findings are summarized below.

3.1. Technical

The overall impression from the literature is that technically systems are working satisfactorily. In the early stages of the technology, some problems were encountered e.g. in Denmark (Heller, 2000). These were expected and identifying them was the purpose of the funding programmes. The CSHPSS solar fraction target is 50% and measured contributions from the first generation of German systems range from 30 to 50 (Schmidt et al., 2004). Generally these German systems were found to meet expectations with no major problems encountered during construction.

3.2. Economic

Economic viability of CSHPSS remains the central goal of researchers. Currently the cost of energy from CSHPSS is more than 2-3 times higher than that from conventional fossil fuel systems (Lottner et al., 2000). Seasonal storage systems costs have naturally declined with experience but costs do vary depending on system type and size. Figure 1 illustrates this observation from the German experience with CSHPSS. Aquifer and borehole (duct) systems clearly appear to be the cheapest in terms of equivalent water volume i.e. the thermal capacity of gravel, borehole and aquifer storage system volumes expressed in terms of a volume of water alone.

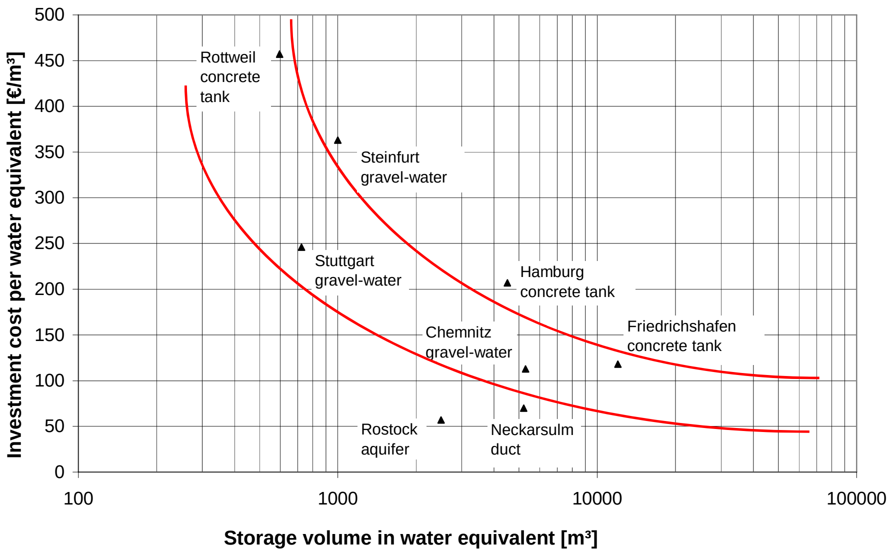

Figure 1 Investment costs in seasonal storage systems

(source: Schmidt et al., 2004)

Solar collector costs are minimized when the panels are purpose-built and integrated into the roof structure. Schmidt et al. (2004) suggest a cost of Euros 150-250 m^{-2} installed cost, when this approach is used. Fisch et al. (1998) calculated the ratio of investment cost to delivered heat for CSHPSS and found this to be between 1.8 and 2.5 ECU kWh^{-1} a^{-1}. (Note an ECU – European Currency Unit – was the predecessor of the Euro). Although this cost-benefit ratio range was twice that of CSHPDS, the CSHPSS ratio was significantly better than that for small systems (4.3-8.1 ECU kWh^{-1} a^{-1}).

4. SIMULATION STUDIES

Various simulation programmes have been developed to assess the performance of seasonal storage systems. SOLCHIPS (Lund and Peltola, 1992) and MINSUN have been designed for the pre-design or feasibility phase of CSHPSS, whereas TRNSYS (SEL, 2005) is used for detailed design and research studies. Pahud (2000) used TRNSYS to produce design guidelines for a borehole seasonal storage system for typical Swiss conditions for various magnitudes of heat load. Average air temperature and daily solar radiation level were 10°C and 11.8 MJ m^{-2} d^{-1} respectively. He found that a borehole store was economically superior to a seasonal tank store when solar fractions of 50-60% were desired. For all heat loads, the collector area should be 2-4 m^2 per MWh (3.6 GJ) of annual heat demand and the borehole storage volume should be between 4 and 13 m^3 per m^2 of collector area for a solar fraction of 70%.

Heller (2000) cites the simulations of Wesenberg et al. (1996) which compared six different thermal storage systems operating under Danish conditions. A fixed solar fraction (65-70%) and an optimised solar collector area were assumed. Pit systems were superior in terms of energy price, namely US$0.083 kWh^{-1}. The CSHPSS simulations by Argiriou (1997) are of interest because of the climatic similarities to Australia. Three types of CSHPSS (tank, pit and borehole) were simulated in four locations in Greece – latitudes 35.5° to 41.1°. Varying annual heat loads of 800, 3200 and 16000 MWh were simulated; equivalent to the demand of 50, 200 and 1000 housing units. Collector area, storage volumes and cost are predicted as a function of solar fraction for the four locations and system types. For example, for a 50-house load scenario (2880 GJ) and a steel tank, Argiriou (1997) found that approximately 1150 m^2 of collector was required for a solar fraction of 0.7 at the lowest latitude.

5. COMPARISON OF AUSTRALIAN AND EUROPEAN CONDITIONS

Any appraisal of the potential for seasonal storage systems in Australia using data from overseas experience must consider the differences between the overseas and Australian conditions. Various conditions are compared and discussed below.

5.1. Energy loads and costs

Lottner et al. (2000) provide data which enables overseas heat loads per unit area to be calculated and compared to those in Australia. German housing heat loads ranged from 300-400 MJ m^{-2} respectively. Housing heat loads in Australia will vary considerably depending on house construction and location. AGO (1999a) reports the predicted range of (unconstrained) heating loads for generic detached houses of various constructions. In Melbourne, space heating loads for detached houses can be as high as 745 MJ m^{-2} for a brick veneer house with a timber floor and ceiling insulation. However, the space heating load for a high efficiency house is predicted to fall to 158 MJ m^{-2} if 5-star energy efficiency measures are adopted. Residential space heating loads are obviously linked to climate and housing design. Improved house design will reduce loads but it is unlikely to obviate the need for space heating completely in southern parts of Australia. For a new 200 m^2 home, therefore, the space heating load (A) might be expected to be approximately 12.6 GJ, using a constraint factor of 0.4 (Eqn. 1)

$$A = \frac{158 \times 200 \times 0.4}{1000} = 12.6 \text{ ....} \; Eqn.1$$

In addition to providing energy for space heating, CSHPSS can also contribute hot water for washing. This requirement provides a more constant load throughout the year. In Victoria, the average annual household (delivered) energy use for a natural gas storage hot water system is approximately 19.1 GJ (Wilkenfeld, 2005). Assuming a combustion efficiency of 0.8, the annual water heating load is approximately 15.3 GJ. As a result, a space and water heating load (B) of 139 MJ m^2 could be expected in southern Australia (Eqn. 2). This figure is 35-46% of the European loads cited above.

$$B = \frac{(12.6 + (19.1 \times 0.8)) \times 1000}{200} = 139 \text{ ....} \; Eqn.2$$

5.2. Housing Density

Most of the CSHPSS have been used to provide residential heating and the minimum number of apartments is 100 (Schmidt et al., 2004). High density housing obviously assists in cost reduction because the heat delivery system is concentrated. High density housing, particularly apartments, however, has limited roof space and collector arrays must be ground mounted, rather than using individual roofs. In Australia, our cultural preference has been for the 'quarter acre block' on which we build a detached house. This preference produces a low housing density and creates unfavourable conditions for CSHPSS. There is also evidence, however, that this preference is changing. Apartment living in some of the main cities of Australia has become fashionable as family sizes decline. Current CSHPSS are definitely feasible for medium density housing (Figure 2) and such housing can certainly be envisaged in Australia.

Figure 2 CSHPSS in Hamburg, Germany (source: Schmidt et al., 2004)

5.3. Climate

CSHPSS have been constructed in numerous countries, including Germany, Denmark, Korea and Greece. In order to appreciate the possible impact that climatic differences may play on the viability of this technology in Australia, the climate in some cities close to the CSHPSS has been compared with cities in Australia (Table 3).

Table 3 Seasonal solar radiation and ambient air temperature at various overseas and Australian locations

	Solar Radiation (MJ m^{-2} d^{-1})		**Ambient Air Temperature (°C)**	
Location	Summer mean	Winter mean	Summer mean	Winter mean
[1]Stuttgart,	14.7	2.1	16.8	0.5
[1]Copenhagen,	16.1	1.3	13.3	-2.0
[1]Athens	24.7	6.1	23.0	5.5
[1]Seoul	22.2	10.4	23.5	-5.7
[2]Adelaide	24.2	9.6	22.5	11.8
[2]Canberra	25.3	10.3	19.4	6.1
[2]Hobart	22.1	6.4	16.0	8.4
[2]Melbourne	23.5	7.6	19.3	10.2
[2]Perth	27.2	11.1	22.9	13.4
[2]Sydney	21.5	10.8	21.7	12.6

(sources: [1]SoDa (2007); [2]Czarnecki (1976))

Table 3 clearly indicates the very favourable nature of Australia with respect to solar radiation levels and ambient temperature, particularly when compared to the northern European countries, which have led the research effort into CSHPSS. In winter, our coldest and least sunny capital city, Hobart, has solar radiation levels 3-5 times the mean winter level in Stuttgart and Copenhagen, and it is also 8-10°C warmer than these cities. Intuitively therefore, these climatic advantages should prove beneficial for CSHPSS systems.

6. SIMULATION OF SEASONAL STORAGE SYSTEM IN AUSTRALIA

In order to determine the feasibility of a CSHPSS in Australia, a simulation study of a hypothetical system has been conducted. The simulation software, TRNSYS, has been used for the study. Type 342 [XST- Seasonal Ground Heat Storage (Multiflow stratified thermal storage) (L. Mazarella)], developed for investigating the potential of CSHPSS, was used in conjunction with other standard TRNSYS subroutines. The following provides a broad outline of the approach taken.

- An underground tank system was chosen from the four possible seasonal storage types to be the system investigated. Although in equivalent water volume terms, aquifer and borehole systems appear to be the cheapest to construct (Figure 1), a tank system was considered easier to construct. In addition, aquifer systems require specific geological conditions and this might limit the applicability of the simulation results.
- The hot water storage and supply water temperature were fixed at 55°C. If the storage temperature reaches 55°C, solar charging is terminated. This decision was made to facilitate the modelling of the system.
- Two scenarios were modelled. In Scenario 1, an operation with a seasonal load was imagined. Monthly energy demand is highly dependent on solar radiation and ambient temperature levels. The highest demand is in July and this demand progressively reduces either side of mid-winter in the months of spring and autumn. There is a very small load in the summer months. The energy demand used (1345 GJ) is based on the annual heating load of a 4000 m^2 greenhouse (Fuller et al., 2003). In Scenario 2, an operation with a constant monthly load was envisaged. In order to provide some comparison, the annual load used in Scenario 1 was divided by 12 to determine the constant monthly load for Scenario 2.
- A fixed storage-to-collector ratio of 1.75 m^3 per m^2 and a collector area of 1.9 m^2 per MWh of annual heat demand were selected, based on the design guidelines suggested in Table 1 of Schmidt et al. (2004).
- A solar collector specific flow rate of 0.007 kg/s per m^2 of collector area was applied for the simulations.
- The slope of the collector was assumed to be the same as latitute angle for each city.
- The performance of the chosen system was predicted in six locations around Australia. Since TMY data is available for the capital cities (Morrison and Litvak, 1999), these were used in the simulations. The locations used were Adelaide, Canberra, Hobart, Melbourne, Perth and Sydney. In each location, the performance of a CSHPSS with both a seasonal and constant load was predicted.
- A simple payback figure for the systems was calculated assuming the financial savings for a variety of conventional fossil fuels, namely coal, natural gas, heating fuel oil, electricity and bottled LPG, in the various locations.

7. SIMULATION RESULTS

Table 4 shows the solar fractions predicted for for six cities in Australia for the two load scenarios based on the European recommendation of 1.9 m^2 per MWh of annual demand. The solar fraction in all capital cities is equal to or better than 0.5, which is the desired target for European systems. Considering the limitation on tank storage temperature, this result is encouraging. Higher solar fractions would have been achieved if higher storage temperatures had been allowed, as in the European systems, where tank temperatures approaching 90°C are achieved.

As a first estimate of the cost effectiveness of seasonal storage systems in Australia a simple payback figure was calculated. Schmidt et al. (2004) reported the costs of the first generation of CSHPSS in Germany. Hamburg and Friedrichshafen were both tank systems with similar solar fractions. The cost of these seasonal solar systems was Euros 733 and 571 per m^2 of collector respectively. An average of these figures was used to calculate the approximate cost of the hypothetical seasonal storage system in Australia, which has a similar storage-to-collector ratio of these German systems. Assuming a currency conversion of one Euro = A$1.6, the cost of the Australian solar system would be approximately A$ 750,000.

Data in Table 5 from a variety of sources indicates the approximate cost of primary energy (PE) in Australia. Table 6 shows how this data has been used to determine the cost of delivering 1345 GJ from a variety of technologies. Table 7 gives the range of payback periods (years) calculated for the two load scenarios, the various fossil fuels, their associated heating systems and the solar fractions predicted. It is clearly evident that the systems are currently not financially viable, whether servicing a seasonal or constant load. The best performing systems, in financial terms, are likely to be those used to replace bottled gas. System costs need to fall and/or energy prices need to rise for the systems to be financial attractive. Higher solar fractions achieved by allowing higher tank temperatures would improve the financial viability.

Table 4 Solar fractions for total constant and seasonal annual load of 1345 GJ

	Area 720 m^2, volume 1260 m^3	
Location	*Constant load*	*Seasonal load*
Adelaide	0.95	0.72
Canberra	0.95	0.77
Hobart	0.85	0.57
Melbourne	0.86	0.50
Perth	0.95	0.62
Sydney	0.93	0.60

Table 5 Typical costs for primary energy (PE) sources in Australia

Source	$/quantity	Conversion	$/GJ PE
Coal	$ 0.06/kg	0.0307 GJ/kg	1.95
Natural gas	$ 0.0091/MJ	0.0010 GJ/MJ	9.10
Heating fuel oil	$ 0.40/L	0.0408 GJ/L	9.80
Electricity	$ 0.07/kWh	0.0036 GJ/kWh	19.44
Bottled LPG	$ 0.70/L	0.0257 GJ/L	27.24

Table 6 Costs of delivered energy for various sources and specified heating systems

Source	$/GJ PE	Heating system	Efficiency	$/GJ delivered	$/1345 GJ
Coal	1.95	Boiler	0.80	2.44	3 282
Natural gas	9.10	Boiler	0.95	9.58	12 885
Heating fuel oil	9.80	Boiler	0.90	10.89	14 647
Electricity	19.44	Heat pump	2.50	7.78	10 464
Bottled LPG	27.24	Boiler	0.95	28.67	38 561

Table 7 Payback period range (years) for large (720 m^2) and small (180 m^2) seasonal storage systems in various locations in Australia

Replaced Fuel	Constant 720 m^2 (years)	Seasonal 720 m^2 (years)
Coal	240-270	299-460
Natural gas	61-69	76-117
Heating fuel oil	54-60	67-103
Electricity	75-85	94-144
Bottled LPG	20-23	25-39

8. SUITABLE APPLICATIONS IN AUSTRALIA

In overseas countries, the energy from CSHPSS has been predominantly used for residential heating. The more benign climate in Australia means that the demand for residential heating will be limited to southern locations. However, other differences, particularly infrastructure development, between this country and other industrialised countries mean that there may be additional opportunities for CSHPSS in Australia. Some possible applications are suggested below.

8.1. Remote Area Food Production

Fresh vegetables are currently moved by refrigerated truck from production centres to more isolated parts of Australia. Energy is used for motive power and refrigeration. This transportation process often compromises final product quality. A more sensible approach would be to build greenhouses suitable for remote food production and processing. Heat is required at night in greenhouses for optimum food production in the winter months, particularly in inland areas. Significant quantities of low temperature heat are used in the food industry in a number of processes such as pasteurisation, washing, cooking and canning (Proctor and Morse, 1977).

8.2. Commercial Buildings

Commercial premises e.g. hotels and hospitals in inland areas of Australia, which have a continental climate could use CSHPSS to meet space and water heating loads. In Australia, there is some previous experience with large solar arrays on hotels. Yulara, a hotel in Central Australia, installed a 3855 m^2 solar water heating system to provide hot water and space heating for guests. The original system has now apparently largely been replaced by individual systems on new buildings. Seasonal storage systems have lower costs than individual systems, according to Fisch et al. (1998). Hospitals also have a large heating load for both space and water heating. They are responsible for 13% of the commercial building sector's greenhouse gas emissions, ranking second to offices and are therefore a priority area for abatement (AGO, 1999b). Those hospitals in regional centres would be a more likely target for CSHPSS technology because of land availability. Some rural hospitals e.g. the nurses' accommodation in Finley, NSW have used large solar heating systems.

8.3. University Campuses

Regional university campuses might represent an ideal environment for CSHPSS. They usually have the physical space for the solar collectors and experience a variety of winter loads (hot water, ventilation air and space heating). Academic expertise is often available on site and the student population can be used for monitoring and evaluation. One of the oldest CSHPSS is located at the University of Stuttgart in Germany, where it supplies heat and cooling to an office building and lecture theatre. Built in 1985, the system uses unglazed solar collectors and a heat pump (Hahne, 2000).

8.4. Rural Industries

Some rural industries use large volumes of hot water and may be suitable for CSHPSS. Abattoirs, for example, use water at approximately 43°C for hand and apron washing and above 82°C for sterilising. The potential to use solar energy for water heating in abattoirs has long been recognised in Australia. A 750 m^2 solar system with short term thermal storage was designed for an abattoir at Forbes, NSW, which used up to 500,000 litres of hot water per day, in the late 1970s but installation was cancelled at the last minute due to financial problems of the company (Gammon, 1980).

9. CONCLUSIONS

There is considerable evidence from overseas that CSHPSS are viable technically and practically but there is no experience in Australia of this technology. TRNSYS simulations of an underground tank system were used to predict the solar fraction for two types of annual thermal load for six cities in Australia. The European guidelines were found to be appropriate for Australia and solar fractions of 50% or greater were predicted if a seasonal load is being met. The solar fraction improves considerably if the load is non-seasonal. Simple payback calculations for a variety of fuels indicated that at present fuel costs, none of the systems are financially viable. The most competive are those systems that replace bottled LPG for either a seasonal or constant load. These findings are generally in line with European experience. This conclusion must be viewed with caution, however, because higher solar fractions, achieved by allowing higher storage temperatures to occur, would improve the system's financial viability. Further work is required to optimise the current model.

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