Active Control of Split System Domestic Solar Water Heaters

Michael Kenneth Dennis

August 2004

A thesis submitted for the degree of Doctor of Philosophy at the Australian National University
Declaration

This PhD thesis contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of the author's knowledge and belief, no material previously published or written by another person has been included in this thesis, except where due reference is made in the text.

Mike Dennis

August 2004
Acknowledgements

This work is spread over a number of engineering disciplines. Without the guidance of a large number of willing minds, a project such as this would not benefit from the integration that has been possible.

I have had generous support from industrial and government organisations. Rheem Australia Pty. Ltd. supplied two hot water systems for testing. The Australian Co-operative Research Centre for Renewable Energy (ACRE) provided funding for the development of practical controllers. The Bureau of Meterology provided significant quantities of weather data at cost and were most helpful in establishing a new insolation forecasting service. The Centre for Sustainable Energy Systems (CSES) at the Australian National University has been an understanding host, providing comprehensive support services and a stimulating research environment.

All research is collaborative. I gratefully acknowledge the many interruptions and casual banter between fellow PhD researchers Joe Coventry, Holger Kreetz, Evan Franklin and Dave Barton from which my experience was the richer.

I wish to thank my technical support staff, in particular Tony Ashmore, Neil Kaines and Jeff Brown, for successfully keeping me from harm when I insisted on doing everything myself.

Finally, thanks to my band of advisors and supervisors. Andrew Blakers and Keith Lovegrove deserve special mention for their dedication to reviewing my work and their sound judgement that I fully respect.

Thank you all.
Preface

My intention is to conduct research in a manner that provides a manufacturer with a readily transferable technology. This has usually resulted in simplified approach to hardware in the project and an attempt to concentrate the value of the technology into the software, which is programmable. I carried out as many of the design, construction, assembly and maintenance tasks as time would reasonably allow. At times I was a plumber, an electrician, an electronics technician, a photographer, a software engineer, a salesman, a fitter and turner, always a student. This has provided me with a far deeper insight into practical issues than would otherwise have been possible.

The experiments were conducted in a time of prolonged drought made all the more difficult by severe bushfires that damaged the water supply for Canberra. I felt it would be irresponsible to conduct experiments that consume 400L of treated water per day for long periods. There are many further aspects of the thesis that implore investigation.

I sincerely hope that further improvements are made to the active controller along the lines suggested in chapter 12.

Research Papers

The following papers were produced during the course of the thesis:


Zealand Solar Energy Society, Melbourne.


**Awards**

The following awards were earned during the course of this thesis:

2003  Diploma in Water Heating from the Technical University of Denmark

2002  Winner of Australian Institute of Engineers Postgraduate Energy Awards

2001  Best Presenter, Australian CRC for Renewable Energy Postgraduate Conference

2000  Best Presenter, Australian CRC for Renewable Energy Postgraduate Conference
Solar water heaters have the potential to make large savings in greenhouse gas emissions in Australia. Long financial payback periods are the main reason that uptake of solar water heating is not more significant. This thesis investigates the potential improvement in performance of split-system solar water heaters by the addition of an active control system.

This work builds upon “low flow” collector circulation theory and addresses the poor control available from the storage tank thermostat. Modelling suggests that the thermal efficiency of the water heater can be improved by about 25%, primarily through reduction of tank standing losses, if the thermostat is replaced by a smart controller. Auxiliary energy consumption is reduced proportionally. If realisable, these savings recover the capital cost of the additional controller in several years. The consumer will benefit from further savings in auxiliary energy consumption over the life of the system and so the payback will be more attractive.

The active control strategy is based upon predicting and controlling the energy content of the storage tank. The control strategy is energy tariff sensitive and may be set by the householder to behave in an energy efficient or a cost effective manner. A number of technologies and design improvements regarding forecasting of the energy supply and demand were also developed in this work.

The auxiliary heater was moved outside of the tank and placed in series with the solar collector via a switching valve arrangement. The collector circulation pump was also used to circulate water through the auxiliary heater effectively providing a variable volume, variable temperature thermostat. A new variable power pump controller was developed for the existing circulation pump to allow fine temperature control of water returning from both the auxiliary and solar heat sources so that disruption to thermal stratification in the tank was minimised. The predictive performance of the collector could then be decoupled from the state of the tank. This thesis explores a practical implementation of
the active control strategy and provides an insight into the actual performance and areas of sensitivity of the technology.

The proposed design changes require more thorough validation including field trials to evaluate the load learning algorithms. Performance of the active controller would be improved if the heating circuit intake position could be actuated vertically within the tank or if hot and cold water could be fully separated in the tank.
## Nomenclature

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<th>Abbreviation</th>
<th>Definition</th>
<th>SI Units</th>
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<tbody>
<tr>
<td>Alt</td>
<td>Altitude of solar collector above sea level</td>
<td>m</td>
</tr>
<tr>
<td>BOM</td>
<td>Bureau of Meteorology</td>
<td>n/a</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
<td>Mt</td>
</tr>
<tr>
<td>JIT</td>
<td>Just in time (auxiliary heating)</td>
<td>n/a</td>
</tr>
<tr>
<td>MEPS</td>
<td>Minimum energy performance standard</td>
<td>n/a</td>
</tr>
<tr>
<td>ORER</td>
<td>Office of the Renewable Energy Regulator</td>
<td>n/a</td>
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<tr>
<td>TTE</td>
<td>Total tank energy</td>
<td>MJ</td>
</tr>
<tr>
<td>UTE</td>
<td>Useful tank energy</td>
<td>MJ</td>
</tr>
<tr>
<td>a</td>
<td>Collector orientation, east of north</td>
<td>radians</td>
</tr>
<tr>
<td>β</td>
<td>Collector slope from horizontal</td>
<td>radians</td>
</tr>
<tr>
<td>βn</td>
<td>Thermistor calibration constant</td>
<td>K</td>
</tr>
<tr>
<td>δ</td>
<td>Earth’s declination</td>
<td>radians</td>
</tr>
<tr>
<td>φ</td>
<td>Solar azimuth</td>
<td>radians</td>
</tr>
<tr>
<td>γ</td>
<td>Incidence angle</td>
<td>radians</td>
</tr>
<tr>
<td>η</td>
<td>Collector instantaneous efficiency</td>
<td>n/a</td>
</tr>
<tr>
<td>θ</td>
<td>Solar altitude (from vertical)</td>
<td>radians</td>
</tr>
<tr>
<td>ϕ(θ)</td>
<td>Altitude of artificial horizon at azimuth θ</td>
<td>radians</td>
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<td>ρ</td>
<td>Density of water at 25°C, 1atm</td>
<td>kg/m³</td>
</tr>
<tr>
<td>σ</td>
<td>Standard deviation</td>
<td>n/a</td>
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<td>Ω</td>
<td>Hour angle</td>
<td>radians</td>
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<tr>
<td>ψ</td>
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<td>ASHRAE collector efficiency co-efficient</td>
<td>W/m²K⁻¹</td>
</tr>
<tr>
<td>αs</td>
<td>ASHRAE collector efficiency co-efficient</td>
<td>W/m²K⁻²</td>
</tr>
<tr>
<td>Ac</td>
<td>Collector aperture</td>
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</tr>
<tr>
<td>Acr</td>
<td>Surface area of crown of tank</td>
<td>m²</td>
</tr>
<tr>
<td>A1</td>
<td>Cross sectional area inside of tank wall</td>
<td>m²</td>
</tr>
<tr>
<td>A2</td>
<td>Cross sectional area of tank wall</td>
<td>m²</td>
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<tr>
<td>Aν</td>
<td>Area of sky dome visible to the collector</td>
<td>m²</td>
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<tr>
<td>b</td>
<td>Co-efficient of the incidence angle relation</td>
<td>n/a</td>
</tr>
<tr>
<td>c</td>
<td>Specific heat capacity of water</td>
<td>kJ kg⁻¹K⁻¹</td>
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<tr>
<td>C1, C2, C3</td>
<td>Co-efficients of diffuse correlation equation</td>
<td>n/a</td>
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<td>C1, C2</td>
<td>Peak and offpeak auxiliary energy costs</td>
<td>$/kWh</td>
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<td>Caux</td>
<td>Thermal capacitance of the auxiliary heater</td>
<td>kJ/K</td>
</tr>
<tr>
<td>d</td>
<td>Ordinal day of year</td>
<td>n/a</td>
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<tr>
<td>D</td>
<td>Air mass</td>
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<tr>
<td>E1</td>
<td>UTE between top of the tank and location x</td>
<td>kJ</td>
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<tr>
<td>Esed</td>
<td>Energy content of hot water load relative to cold supply</td>
<td>kJ</td>
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<tr>
<td>F'U1</td>
<td>Modified collector loss co-efficient</td>
<td>W/m²K⁻¹</td>
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<tr>
<td>gdec</td>
<td>GHG co-efficients for electric energy</td>
<td>kgCO₂-e/kWh</td>
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<tr>
<td>gas</td>
<td>GHG co-efficients for gas energy</td>
<td>kgCO₂-e/kWh</td>
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<td>Height of tank</td>
<td>m</td>
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<td>H1</td>
<td>Beam radiation on a horizontal plane</td>
<td>W/m²</td>
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<tr>
<td>H2</td>
<td>Diffuse radiation on a horizontal plane</td>
<td>W/m²</td>
</tr>
<tr>
<td>H0g</td>
<td>Ground reflected diffuse radiation</td>
<td>W/m²</td>
</tr>
<tr>
<td>H0s</td>
<td>Sky diffuse radiation</td>
<td>W/m²</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
<td>SI Units</td>
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<td>--------</td>
<td>------------</td>
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<td>$H_{DG}$</td>
<td>Sky diffuse radiation with shading effects</td>
<td>W/m²</td>
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<td>Extraterrestrial radiation on a horizontal plane</td>
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<td>Total radiation on a horizontal plane</td>
<td>W/m²</td>
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<td>IAM_B</td>
<td>Incidence angle modifier for beam radiation on collector</td>
<td>radians</td>
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<tr>
<td>IAM_DO</td>
<td>Incidence angle modifier for ground reflected diffuse</td>
<td>radians</td>
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<tr>
<td>IAM_DS</td>
<td>Incidence angle modifier for sky reflected diffuse</td>
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</tr>
<tr>
<td>$I_B$</td>
<td>Beam radiation incident on collector</td>
<td>W/m²</td>
</tr>
<tr>
<td>$I_c$</td>
<td>Total radiation incident on collector</td>
<td>W/m²</td>
</tr>
<tr>
<td>$I_{DG}$</td>
<td>Diffuse ground radiation incident on collector</td>
<td>W/m²</td>
</tr>
<tr>
<td>$I_{DS}$</td>
<td>Diffuse sky radiation incident on collector</td>
<td>W/m²</td>
</tr>
<tr>
<td>$k$</td>
<td>Thermal conductivity of water</td>
<td>W/m K⁻¹</td>
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<td>$K$</td>
<td>Solar constant</td>
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<td>$K_o$</td>
<td>Proportional gain</td>
<td>%/°C</td>
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<td>$L$</td>
<td>Luminance</td>
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<td>$L_1$</td>
<td>Hot water load energy</td>
<td>kJ</td>
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<td>$m$</td>
<td>Variance multiplier for load forecasting</td>
<td>n/a</td>
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<td>$m_c$</td>
<td>Collector mass flow</td>
<td>kg/hr</td>
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<td>$m_{heat}$</td>
<td>Flow rate at which the collector calibrated</td>
<td>kg/hr</td>
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<td>$P_D$</td>
<td>Auxiliary heater power</td>
<td>W</td>
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<tr>
<td>$P_{aux}$</td>
<td>Auxiliary heater power</td>
<td>W</td>
</tr>
<tr>
<td>$P_T$</td>
<td>Rate of UTE loss from storage tank</td>
<td>W</td>
</tr>
<tr>
<td>$P_{TE}$</td>
<td>Rate of UTE loss from tank to environment</td>
<td>W</td>
</tr>
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<td>$P_{TW}$</td>
<td>Rate of UTE loss from tank to cooler water</td>
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<tr>
<td>$Q_{aux}$</td>
<td>Auxiliary energy</td>
<td>kJ</td>
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<tr>
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<td>Auxiliary energy of a small electric heater</td>
<td>kJ</td>
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<tr>
<td>$Q_{aux,SG}$</td>
<td>Auxiliary energy of a small gas heater</td>
<td>kJ</td>
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<tr>
<td>$Q_{aux,LE}$</td>
<td>Auxiliary energy of a large electric heater</td>
<td>kJ</td>
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<td>$Q_{aux,LG}$</td>
<td>Auxiliary energy of a large gas heater</td>
<td>kJ</td>
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<td>$r$</td>
<td>Logistic curve calibration co-efficient</td>
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<td>$r'$</td>
<td>Correlation co-efficient</td>
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<td>$R_0$</td>
<td>Ground reflectance</td>
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<td>$R_0$</td>
<td>Thermistor resistance at 25°C</td>
<td>Ω</td>
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<td>$t_0$</td>
<td>Auxiliary heater start time</td>
<td>hr</td>
</tr>
<tr>
<td>$t_0$</td>
<td>Modified auxiliary heater start time</td>
<td>hr</td>
</tr>
<tr>
<td>$t_1$</td>
<td>Modified auxiliary heater start time</td>
<td>hr</td>
</tr>
<tr>
<td>$T_a$</td>
<td>Time of hot water load draw</td>
<td>hr</td>
</tr>
<tr>
<td>$T_a$</td>
<td>Modified auxiliary heater stop time</td>
<td>hr</td>
</tr>
<tr>
<td>$T_a$</td>
<td>Ambient temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{aux}$</td>
<td>Temperature at exit of auxiliary heater</td>
<td>°C</td>
</tr>
<tr>
<td>$T_c$</td>
<td>Critical temperature that defines UTE</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{cn}$</td>
<td>Temperature at collector inlet</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{cool}$</td>
<td>Temperature at collector outlet</td>
<td>°C</td>
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<tr>
<td>$T_h$</td>
<td>Average temperature of deliverable water in tank</td>
<td>°C</td>
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<tr>
<td>$T_i$</td>
<td>Hot water load temperature</td>
<td>°C</td>
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<td>$T_s$</td>
<td>Cold water supply temperature</td>
<td>°C</td>
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<tr>
<td>$T_{sp}$</td>
<td>Hot water set point temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$T_x$</td>
<td>Water temperature at distance x from top of tank</td>
<td>°C</td>
</tr>
<tr>
<td>$U$</td>
<td>Tank heat loss co-efficient</td>
<td>W/m² K⁻¹</td>
</tr>
<tr>
<td>$V_x$</td>
<td>Volume of the crown of the tank</td>
<td>m³</td>
</tr>
<tr>
<td>$V_T$</td>
<td>Total tank volume</td>
<td>m³</td>
</tr>
<tr>
<td>$V_x$</td>
<td>Tank volume above position x</td>
<td>m³</td>
</tr>
<tr>
<td>$W$</td>
<td>Weighting factor in Brandemuehl integral</td>
<td>n/a</td>
</tr>
<tr>
<td>$x$</td>
<td>Distance from top of tank</td>
<td>m</td>
</tr>
<tr>
<td>$x_c$</td>
<td>Lower boundary of UTE (from top of tank)</td>
<td>m</td>
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1. Introduction

"The reasonable man adapts himself to the world; the unreasonable man persists in trying to adapt the world to himself. Therefore all reasonable progress depends upon the unreasonable man"

George Bernard Shaw

1.1 The Outlook for a Solar Future

Human civilisation is becoming increasingly energy intensive. The current fuel mix supplying this hunger is barely sustainable for another generation, a very short period in terms of our evolution and hopefully our future.

A reduced dependency on finite reserves of fossil fuels implies that sustainable energy technologies must achieve commercialisation and subsequently must achieve market penetration. Developers of emerging technologies have been challenged by the substantial issues of capital cost, operating cost, suitability for mass production, practicality, reliability and acceptability. In this regard, incremental technologies and technologies that exercise leverage on an existing installed base may offer lower commercial risk. Domestic solar water heating is such a technology.

The amount of solar energy available on the average Australian house roof, averaged across day and night, is in the order of 200 W/m². Thus a typical house roof receives solar power at an average rate of about 20 kW. Annual statistics (Australian Bureau of Statistics 1998) indicate an average household energy expenditure of 360 PJ/yr in 1995 (excluding transport), projected to peak at 412 PJ/yr by 2010. This represents an average power consumption of less than 2 kW. Water heating represents about a third of domestic energy consumption in Australia so solar water heaters clearly have an opportunity to provide substantial renewable energy contributions. Solar energy does not require a distribution network or a billing system and substantially reduces life...
cycle greenhouse gas emissions (Jolly & O’Sullivan 1989). It is not unreasonable to expect that solar power should be a significant contributor to the domestic energy solution.

Although current consumer behaviour places heavy emphasis on the financial cost of energy supply, as indicated by poor uptake of solar technologies, a more sustainable model is urgently required. Growing concern over climate change and population health (National Centre for Epidemiology and Population Health et al 2003) has led to reviews of current energy market practices at a global level. This thinking has not enjoyed a stable relationship with the political agenda. The adoption of the Kyoto Protocol is under threat from short term economic concerns in some countries.

1.2 Domestic Water Heating in Australia

1.2.1 Types of Water Heaters
Water heaters used in Australian homes have traditionally been manufactured in Australia. They may be classified as either tankless (instantaneous) water heaters or water heaters with storage (figure 1-1). Recently, imported tankless gas heaters have become popular, particularly in applications where a compact water heater is desirable.

The level of awareness and understanding of hot water systems amongst consumers is poor (BIS Shrapnel 1999). Selection of water heaters is usually influenced by advice to the consumer from the plumber or energy retailer. Both may have vested interests and this could lead to distortion of market share. The choice of water heater is also highly dependent on the local energy infrastructure and the incumbent system (BIS Shrapnel 1999).

A comparison of average end-use energy consumption and primary greenhouse gas emissions per unit water heater for various types of heater is informative. The values presented in figure 1-2 are averaged across states in Australia and averaged for a variety of heater sizes (adapted from Morrison & Tran 1992)
Gas heaters have notably less greenhouse gas emissions than electric heaters despite a slightly lower appliance efficiency. They are also cheaper to operate than electric heaters. Solar boosted heat pumps are very effective in lowering energy consumption and offer similar performance to an electric auxiliary solar water heater but are significantly cheaper to purchase. They work best in warmer climates, and particularly well in humid climates where heat of condensation can be utilised. Gas tankless heaters would appear to be a good all-round choice and indeed a gas tankless heater with solar pre-heater offers a technically excellent water heating solution, but the capital cost is high. Electricity sourced entirely from a greenpower scheme is the ideal auxiliary heat source.

Solar water heaters with gas backup are the least polluting of the common water heating systems. Unless retail energy costs rise significantly, the ideal technical approaches are only marginally cost-effective over their lifetime without rebate assistance.
1. Introduction

Nearly 75% of Australian water heaters are storage based units (Australian Bureau of Statistics, 2002c) and most of these are electrically heated (figure 1-3). The leverage of primary energy consumption for electric water heaters creates a large greenhouse gas footprint for Australia’s domestic greenhouse emissions. A shift towards gas water heaters is evident in some states where gas is readily available and the household is connected. High connection fees sometimes discourage householders to switch auxiliary source. Nonetheless, large energy infrastructure projects are financed on long term supply contracts with utilities. The utilities then have an interest in encouraging consumption.

The ABS survey also suggested a trend towards larger dwellings with multiple hot water systems and fewer people per dwelling. The average household in 1998 consisted of 2.6 occupants and this is projected to fall to 2.2 by 2021. Accordingly, household energy consumption is projected to increase to 20 GJ per person per year at that time (including transport). The implications of

Figure 1-2  
Comparison of appliance energy consumption, greenhouse gas emissions and operating cost for common water heaters

Assumptions:
1. 200L hot water draw per day
2. Off-peak tariff used for electric storage heater
3. Gas heaters have four or five star rating
4. Heat pump has a COP of 3.0
5. Solar water heaters have 70% solar fraction
6. Costs do not include energy connection fee
7. Carbon equivalent emissions based on primary energy consumption
multiple hot water services are that smaller units will be installed. For a given total delivery, a number of smaller heaters have greater standing losses\(^1\) than a smaller number of larger heaters due to their higher surface area to volume ratio. They will also have proportionally greater conduction losses to cold water in the tank due to their short stature and relatively large cross sectional area.

![Diagram]

*Figure 1-3 Most Australian water heaters are storage based units. About two thirds of all heaters use electric auxiliary although this proportion is decreasing (ABS 4602.0 2002)*

Approximately 45% of electric storage heaters access peak electricity (figure 1-4). This corresponds closely to the proportion of heaters of capacity of 160 L or less. To make matters worse, small heaters are connected to continuous auxiliary supply so that heat recovery is rapid and thus the tank is always hot.

Concerns over the energy losses from storage water heaters has resulted in tightening of the Minimum Energy Performance Standards (MEPS) regulations for mains pressure electric storage water heaters, enforceable from October 2004 (National Appliance and Equipment Energy Efficiency Committee 2001).

---

\(^1\) Standing losses for small heaters are estimated to be about 32% of total energy demand drawn by the heater compared to 20% for larger stores
1. Introduction

Figure 1-4  Market share of electric storage tanks by size indicates nearly half of these are small, less efficient tanks (Harrington & Ryan 2001)

Australia’s MEPS were compared to equivalent standards in other countries by Harrington & Ryan (2001). Australia’s large water heaters (>250 L rated delivery) were found to have the lowest standing losses using the Australian Standard AS1056 equivalent test (Appendix G).

Tankless (instantaneous) water heaters have become popular in new dwellings, particularly for small apartments and townhouses, due to their small architectural footprint. Tankless heaters rely on a very powerful heater adding energy to water at full service flow rate. A dwelling may have one or more such heaters located close to the point of use. Since there is no energy storage, the device avoids tank standing losses. Quoted efficiencies for electric units exceed 95% while for gas units quoted efficiencies are around 80% (Rinnai 1999) although their installed performance may be somewhat less due to poor transient control. Most domestic water heaters of this type are gas fired. At full service flow, these units contribute heavily to energy network loading. At typical shower flow of 10 L/min, about 22 kW would be required to heat the water over a 30°C rise. This compares to the common electric storage heater power rating of 3.6 kW. Advertisements for tankless heaters often promote “endless hot water” and this is counter-productive to the important national objectives of reducing greenhouse emissions and reducing water consumption.
An analysis of tankless water heaters should not exclude heat-on-demand water heating appliances such as dishwashers. More than 30% of Australian houses have dishwashers and these devices typically heat their own water using electricity, effectively adding 3,132 TJ (Australian Bureau of Statistics, 2002a) tankless heating capacity per annum. Despite their high efficiencies, tankless heaters have no provision for solar contribution.

The cost of various heating systems differs markedly amongst manufacturers. Table 1-1 shows typical installed costs in Australia for water heaters designed for a family of four, installed in Canberra.

<table>
<thead>
<tr>
<th>Water Heater Type</th>
<th>Installed Cost (AU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric storage (Dux Proflo 315L)</td>
<td>$1500</td>
</tr>
<tr>
<td>Gas storage (Rheem Stellar 330L)</td>
<td>$1600</td>
</tr>
<tr>
<td>Gas tankless (Rinnai Infinity 26)</td>
<td>$2350</td>
</tr>
<tr>
<td>Solar electric thermosyphon (Solahart 302K)</td>
<td>$4000</td>
</tr>
<tr>
<td>Solar gas thermosyphon (Solahart 302KN)</td>
<td>$5300</td>
</tr>
<tr>
<td>Solar electric split system (Rheem Loline 340L)</td>
<td>$4100</td>
</tr>
<tr>
<td>Solar / electric heat pump (Quantum 340T2S)</td>
<td>$4200</td>
</tr>
</tbody>
</table>

*Table 1-1* Retail prices for various water heaters (2003) sourced by the author from local distributors. Prices include installation, a 5 year warranty and local taxes but do not include rebates.

Apart from the additional material and labour costs associated with the solar energy collection, high cost of sales and high installation costs are the main contributors to the price gap to a solar unit (Wagstaff 2003).

1.2.2 The Status of Solar Hot Water in Australia

The installed capacity of about 370,000 solar hot water systems in Australia is estimated to offset 1.20 MtCO$_2$-e of greenhouse gas emissions per year (Meads 1998; Dennis 2003a). About 5% of installed water heaters in Australia are solar
water heaters.

Australian cities have an excellent solar resource (figure 1-5). The experimental work in this research was carried out in Canberra which has an expected annual global horizontal radiation of 6,422 MJ/m² (AUSOLRAD 2003). Of this, 3,866 MJ/m² (60%) is direct beam radiation. It is interesting to note that a solar water heater collector of aperture 3.74m², inclined at a common roof pitch of 20° and facing north in Canberra, will be subject to 23,700 MJ annual insolation on the inclined plane (AUSOLRAD 2003). Under an annual hot water load of 12,096 MJ, typical for a family of four, such a heater will still require an additional 8,280 MJ of auxiliary heating. About 70% of this auxiliary heat is required during winter, but there is a consistent parasitic loss throughout the year due in particular to tank thermal losses. Australian manufacturers have been slow to take up some important ideas proven in international research regarding efficient operation of a pumped circulation solar water heater.

![Figure 1-5 Annual global solar irradiation on a horizontal plane in Australia (courtesy of the Australia and New Zealand Solar Energy Society)](image)

Australia is divided geo-politically into eight states. Each state is partly responsible for its own energy policy and governance. This has led to a variety of energy prices (figure 1-6) and bias towards gas or electricity infrastructure across Australia. Consequently, there is an inconsistency in water heater market
share across the states (BIS Shrapnel 1999).

Noteworthy is the high market penetration of gas water heaters in Victoria, related to the very cheap gas available there and the comprehensive gas distribution network. Tasmania currently does not have reticulated gas, although a pipeline is being built from the Bass Strait gas fields.

This inconsistency of governance has lead to variable penetration of solar water heaters across Australia. Historically the higher capital cost has been offset by various local subsidies leading to boom/bust sales cycles. The stability of the local solar water heater manufacturing industry is partly isolated from these effects because a large proportion of its production is exported (Meads 1998).

The solar hot water industry is a well established renewable energy industry in Australia with extensive existing sales and support infrastructure. The industry is in sound position to implement incremental changes in the energy efficiency of their products. This has the benefit of the leverage of a wide installed base with customers replacing their water heater every twelve years (BIS Shrapnel 1999), and a low perceived technological risk compared to other emerging renewable technologies.

In a comprehensive study, Jolly & O'Sullivan (1989) pointed out that the embodied energy of production and operation is low for solar water heaters when compared to direct gas or electrically heated units.
1.3 The Good and Bad of Hot Water Storage

Energy storage is a requirement for a solar water heater due to the variable nature of solar input and the time offset between solar gain and load demand. No energy store is perfectly efficient and the challenge is thus to provide a suitable compromise between functionality, efficiency and the additional cost of the store. The store efficiency may be further detailed as the efficiency of energy transfer into the storage, thermal loss during storage, and efficiency of extraction of energy from the store. The thermal losses from the studied solar water heater amount to about 25% of its energy consumption. A tankless water heater does not exhibit storage losses, but sacrifices much larger solar potential.

Energy stores may take advantage of the time value of energy. Primitive attempts to address this issue in the form of “off-peak” tariffs for water heating are available in some areas although this has encouraged excessive consumption through inferior control. The use of a large volume of distributed energy storage does provide the energy retailer with potential flexibility regarding the timing of energy supply.

This combined scenario of solar contribution, distributed energy storage and variable tariffs places solar water heaters in a competitive position with traditional hot water energy sources in a de-regulated energy market.

1.4 Energy Market Regulation

This thesis is being considered in an environment of a de-regulated energy market in Australia. The Australian national electricity market model consists of energy suppliers (Generators), energy transporters (Network Operators), energy distributors (Retailers) and customers. The value of energy increases as it moves from generation to distribution to consumption and this places distributed energy sources such as solar water collectors at the high value end of the energy infrastructure. Renewable energy sources are generally intermittent without localised storage and this volatility (as well as other factors) has hindered wide scale acceptance of renewables in the wholesale
market. These factors make renewable energy infrastructure far more attractive at a retail level. Renewable energy contribution to the wholesale electricity pool is around 9% and dominated by hydro-electricity (Australian Bureau of Statistics 1998).

The time-varying wholesale electricity price is the result of a supply and demand balance and is seen to change significantly over the course of one day as well as across a number of days. An example of this variation in the spot price for wholesale electricity is presented in figure 1-7.

Energy retailers supply at fixed tariff structures and thus carry significant exposure to the wholesale energy price fluctuation. The actual risk is often reduced by raising the connection and distribution charge to consumers while maintaining a fixed energy rate.

![Electricity demand and wholesale spot price for NSW (Jan 2003), source National Electricity Market Management Company archives](image)

Figure 1-7 Electricity demand and wholesale spot price for NSW (Jan 2003), source National Electricity Market Management Company archives

The increasing use of electric air conditioners in Australia is one technology that has caused strain on electricity supply capacity and led to very high spot electricity prices on the wholesale market. Technologies that reduce the exposure of an energy retailer to peak wholesale energy costs should be encouraged by the retailer. Such technologies fall into three categories:
1. Introduction

- Peak shedding – energy efficiency, demand side management
- Peak shifting – strategic energy storage
- Enhanced predictive energy balances.

The latter is more subtle in that technologies that are able to provide a predictable (not necessarily steady) supply or demand will help reduce financial risk to both suppliers and consumers in the energy markets since their energy balance will be able to be forecasted with greater confidence. Solar water heating with intelligent control is able to contribute to all three categories.

1.5 Greenhouse Gas Emissions and Primary Energy Use

Australia’s stationary energy production is heavily reliant upon fossil fuel consumption (Wilkenfield 1998) and this has serious greenhouse gas emission consequences. The consideration of greenhouse gas emissions must necessarily refer to primary energy consumption, comprising the energy consumed at the appliance, the energy losses over transmission infrastructure and the generation losses. The amount of raw energy consumed at the point of generation is referred to as the primary energy consumption. It is enlightening to review emissions for Australian storage water heaters from the perspective of primary energy consumption (table 1-2).

<table>
<thead>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>1.0</td>
<td>1.33</td>
<td>1.54</td>
<td>4.26</td>
<td>0.43</td>
</tr>
<tr>
<td>Gas</td>
<td>1.0</td>
<td>1.67</td>
<td>1.70</td>
<td>1.74</td>
<td>0.10</td>
</tr>
</tbody>
</table>

*Table 1-2 Greenhouse gas emissions for storage water heaters in Australia relative to one unit of heated water in Canberra*²

The high greenhouse gas intensity of electricity as an auxiliary heating source combined with the low efficiency electricity generation relative to gas results in large greenhouse gas penalty for using electricity to heat water in Australia. It is clear that demand side management or a switch to gas water heating at the household level can have dramatic leverage on greenhouse gas emissions. Despite a gas water heater’s less efficient conversion of gas to hot water (compared to an electric water heater), the primary gas energy consumed is less than half of the primary energy consumption of the equivalent electric heater. The greenhouse gas intensity co-efficient for electricity in Australia is, on average, four times that for natural gas (Office of the Renewable Energy Regulator (ORER) 2004a). A potential problem with mass migration to gas water heaters is the increase in NO$_x$ and SO$_x$ emissions as gas water heating appliances age and the concentration of large numbers of these water heaters in an urban environment.

Domestic electric water heaters in Australia produce around 11.8 MtCO$_2$-e/yr (The Australian Greenhouse Office, 1999). Gas water heaters produce around 3.1 MtCO$_2$-e/yr but their primary energy consumption is far less (10% of all gas consumption). There is a clear imperative to move away from electric water heaters to gas and ultimately to solar (preferably with gas or greenpower auxiliary).

1.6 Greenhouse Gas Reduction for Water Heaters

Australia is adopting policies that influence both manufacturers and consumers to reduce greenhouse gas emissions from water heaters. Australian consumers have been encouraged to purchase solar water heaters through rebate schemes both local and federal. Australian manufacturers are being encouraged to increase the performance of their hot water storage tanks through the MEPS program (National Appliance Equipment Energy Efficiency Committee 2001b).

The most recent revision to this standard defines mandatory performance criteria for the standing losses of the hot water tank as defined in Australian Standard AS1056.
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<table>
<thead>
<tr>
<th>Rated delivery (L)</th>
<th>Maximum heat loss (MJ/day)</th>
<th>Maximum heat loss (W)</th>
<th>Daily loss of temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>5.04</td>
<td>58</td>
<td>48.0</td>
</tr>
<tr>
<td>50</td>
<td>6.26</td>
<td>71</td>
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<td>80</td>
<td>5.29</td>
<td>61</td>
<td>15.8</td>
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<td>125</td>
<td>6.3</td>
<td>73</td>
<td>12.0</td>
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<tr>
<td>160</td>
<td>7.05</td>
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<td>315</td>
<td>9.58</td>
<td>111</td>
<td>7.2</td>
</tr>
<tr>
<td>400</td>
<td>10.33</td>
<td>120</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Table 1-3  Minimum Energy Performance Standards for Storage Heaters (1999),
Allowable heat losses for tanks of 80 L or less are to be reduced by 30% during 2005/6

These requirements, enforceable since 1999, are based on the size of the storage tank (table 1-3). The MEPS standard does not take into account the effects of pipework conducting heat from the tank or the poor installation practice whereby hot water pipes are often not insulated between the storage tank and the points of service.

Comprehensive surveys of the likely impact of MEPS on Australia's future energy consumption and greenhouse emissions are detailed in (Ellis 2001; National Appliance Equipment Energy Efficiency Committee 2001b). Expected greenhouse gas reductions from MEPS total about 0.57 MtCO₂-e/yr or about 3% of projected electric water heater emissions in 2010. These documents also assess the potential for manufacturers to implement the MEPS improvements. These improvements brings Australia to the forefront of electric hot water energy tank manufacture by world standards for large (>80 L) water tanks (Harrington & Ryan 2001). There has since been a review (Wilkenfield 2003) that recommends stringent new standards for small heaters to bring them in line with world’s best practice. This 30% reduction in maximum standing losses will ensure they too are amongst the world’s best by 2005/6. The National
Appliance and Equipment Energy Efficiency Committee’s charter was initially to devise standards that would help reduce greenhouse intensity from domestic water heating by implementing world’s best practice. This imposes a performance level on imported products but also provides a default potential ability for Australian water heater manufacturers to export to any trading partner.

The Energy Partners report (Energy Partners et al. 2000) concluded that there is further scope for improvements in MEPS as tested by Australian Standard AS1056 (isolated storage tank) but highlighted far greater improvements through better installation of complete systems. These installation improvements are estimated to exceed 50% of the AS1056 rated standing losses of the storage vessel. The report hinted at losses from conduction and convection through water connections and the tank thermal loss parameter used in this thesis has been modified from the AS1056 figure to account for this. One might note that correct sizing of water heating for an application is equally important. This is very difficult to address since a water heater lasts, on average, for twelve years (BIS Shrapnel 1999) and household circumstances may change over that time. Water heaters are sized conservatively for that reason. Incentive schemes such as time-of-use tariffs and solar rebates often favour larger storage units. The conservatism in tank sizing leads to the increased standing losses that MEPS aims to address. Perhaps the best solution is to have a variable effective volume storage tank where the volume varies with demand on a real time basis. This thesis presents technology that allows a storage heater to mimic the behaviour of a tankless heater while allowing solar gain. Tankless heaters are not yet subject to minimum energy performance standards.

While MEPS is useful for incremental efficiency improvements, a fundamental shift in heater type is required to have a real impact on Australia’s greenhouse gas emissions. This shift would be characterised by an emphasis on gas and solar water heating technologies. Further emphasis on greenhouse gas emissions must favour solar water heating as the heating technology of choice. Modelling performed by the author (Dennis 2003a, summarised in Appendix E)
1. Introduction

compares the impact of MEPS legislation (Harrington & Ryan 2001) against improvements in hot water storage efficiency and solar hot water market penetration (table 1-4).

MEPS requirements help by raising the cost of cheaper conventional heaters, thus reducing capital cost differential to solar. Importantly, the effect of MEPS is immediate by mandate and will take effect over the following years as the water heater replacement cycle progresses. The uptake of improved storage and solar technologies is rather more incremental and unlikely to saturate the market in one replacement cycle.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Improvement Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEPS</td>
<td>0.016 MtCO$_2$e/yr (2004) rising to 0.30 MtCO$_2$e/yr (2019)</td>
</tr>
<tr>
<td>Storage technology</td>
<td>0.05 MtCO$_2$e/yr for every 1% storage thermal efficiency</td>
</tr>
<tr>
<td>Switch to gas auxiliary</td>
<td>0.15 MtCO$_2$e/yr for every 1% switch from electric to gas</td>
</tr>
<tr>
<td>Solar hot water sales</td>
<td>0.26 MtCO$_2$e/yr for every 1% market penetration</td>
</tr>
</tbody>
</table>

Table 1-4 Comparison of potential greenhouse gas mitigation from improvements to domestic water heaters

Perhaps the greatest long term incentive for renewable energy uptake would be a tax on greenhouse gas emissions. Governments stand to gain a significant boost to consolidated funds at the political risk of offending some companies and the economic risk of constraining export markets. This form of taxation may be viewed as the removal of a long-standing environmental subsidy for traditional generators. Under this scenario, it is likely that solar hot water will become the water heating method of choice in Australia. Interested readers are referred to Watts & Outhred (2000).
1.6.1 Likely Potential of Solar Water Heating to 2010

A study was performed (Dennis 2003b) on the potential greenhouse gas savings of solar water heaters in Australia over the upcoming decade. If all electric and gas storage water heaters were replaced by solar water heaters, with matching proportions of auxiliary heating sources, the study showed a ceiling of potential mitigation of 42 MtCO$_2$-e/yr or about 8% of Australia's total greenhouse emissions (Wilkenfield 1998). The study went on to examine various scenarios for solar water heater uptake by consumers over the next decade and concluded that the likely reduction in carbon emissions would be about 1.2 MtCO$_2$-e/yr. The difference in uptake was attributed to:

- About 25% of dwellings in Australia are not owner-occupied and there is no incentive for the landlord to invest capital while providing low operating costs to tenants. A growing number of city dwellings do not have a separate or suitable roof for solar water heaters.
- Solar water heaters represent a major capital investment. Householders are being expected to pay for future energy savings up front and the water heater is not easily transportable should the family move house.
- Availability of cheap gas and electricity.
- Lack of public awareness of water heating options and inertia to change.

At least one of these points would need to change if solar market penetration is to exceed 10% in Australia.

1.6.2 Australian Standards for Domestic Water Heaters

There are a number of national standards relating to the design, construction, installation and performance of domestic water heaters in Australia. The performance standards are stringent by world standards. Design changes proposed by this thesis for the split system solar water heater will need to be reviewed in the context of these standards. A list of relevant standards is presented in Appendix G.
1.7 Importance of this Work

Most previous works on solar water heaters focus on one or two isolated factors in a system, perform some modelling and generate recommendations based on the results of this localised optimisation work. Such an approach led many researchers to believe that high collector flow rates were desirable. This is a compromise dictated by the needs of manageability and limited analysis (modelling) capability and there are several obvious shortcomings to this technique. Perhaps the greatest failing is that this approach does not recognise that the factors of the machine studied are part of a wider system which involves not just the hardware but variables associated with the installation (site + environment) and use/users of the system. Thus, models which make assumptions regarding the unknown or difficult to model system components ignore a number of complex interactions. Often these are left out because they are too difficult for conventional models. Most importantly, and seriously for models, is that many of these variables and environments change with time whereas most models have parameters that are time static and set before or soon after installation. There is a need for a learning approach to optimisation and some way to provide practical optimisation on an on-going basis. This thesis discusses some approaches to adaptive technologies that are suitable for use beyond the research laboratory.

A further major impediment to efficient solar water heating is the small range of systems available and the mismatch between the design of the system and its mode of use. This "one size fits all" approach with its inherent conservatism inevitably leads to inefficiency in operation. Manufacturers have understandably treated reliability as top priority so that the industry becomes well regarded. The time is now right to apply leverage to this foundation and address the inefficiency issues. This thesis provides evidence of how poor the performance of a standard solar hot water system can be, even if reasonably well sized for the application.

This chapter has outlined the context in which this thesis was conducted and provided some rationale from which the research direction was established. The
charter of this thesis is to develop technologies that decrease greenhouse gas emissions and energy consumption of domestic water heating in Australia. This introduction has highlighted solar water heating and electric storage heaters as opportunities for improvement. The by-product of such research will be reduced operating cost for the consumer and reduced exposure to wholesale energy prices for the utility. The following chapters detail methods used to achieve these goals, both primarily concerned with intelligent control of solar heat collection and storage.

1.8 Chief Research Objectives

- Increase thermal efficiency of the hot water storage
- Increase solar energy collection in solar hot water systems
- Reduce operating costs by intelligently purchasing supplementary energy
- Enhance useability and viability of domestic solar water heaters
- To explore holistic factors that affect the technology and its integration with systems and users
- Consider the manufacturability of proposed technologies.

The thesis explores the use of active control on a split system solar water heater. The development and realisation of a control algorithm and supporting technologies is the key objective. The purpose of the thesis is not to construct a specific controller although a controller was constructed for testing purposes.

1.9 Thesis Layout

Clearly the potential for improvement extends beyond purely technological solutions. The emphasis of this work is to establish a commercially oriented technology based contribution that is amenable to uptake by an existing manufacturing infrastructure and thus be effectively implemented in the short term.
Chapter 2 discusses some background ideas and their relevance to this research. The basic principles and premises of the thesis are introduced here. This chapter identifies the opportunities to apply active control. The experimental split system infrastructure is also introduced here.

Modelling is introduced in Chapter 3 to obtain a quantitative baseline of the performance of a conventional system. Modelling will be used throughout the thesis and results compared to this reference. Modelling is useful to explore a variety of aspects of the proposal's performance with a minimum of investment in experimental infrastructure. Chapter 4 discusses the core theory of predictive energy balance using heat shadows and extends this approach to optimising the cost performance of the system as well as the energy efficiency. Chapters 5, 6 and 7 introduce some supporting technologies that are required by the control algorithm. Modifications to the water heater that enable the active control to work are presented with experimental confirmation of performance in chapter 8. This is supported by active control of the water circulation pump discussed in Chapter 9. The final technology chapter continues to explore the environment in which the water heater operates and how it might interact with its users and provide "value-added" facilities based on the available infrastructure.
2. The Split System Solar Water Heater

"When people thought the earth was flat, they were wrong. When people thought the earth was spherical, they were wrong. But if you think that thinking the earth is spherical was just as bad as thinking the earth is flat, then your view is wronger than the both of them put together"

Isaac Asimov, “The Relativity of Wrong”, 1996

2.1 Introduction

This chapter provides some background to the specific research content of this thesis. The “Split System” solar water heater used in the study is introduced. The present use of a thermostat to control the auxiliary heater and a fixed power high flow pump to provide collector flow are highlighted as areas for improvement. Finally, the experimental apparatus used to test the active control proposals is described here, since results will be presented in-line with the presentation of the ideas in later chapters.

2.2 Description of the Split System

This thesis studies a specific class of solar water heaters known as “split systems”. Research was carried out on this design since it has several features that allow flexibility to use active control. These features include a pumped circulation collector and a vertical tank. The more common thermosyphon solar water heater will still benefit from some ideas developed in this thesis, but to a lesser extent.

A typical split system component schematic is shown in figure 2-1. With split systems, thermosyphon action to move hot water between the solar collectors and the storage tank is replaced by a small water circulation pump. Thus, the hot water tank does not need to be located in proximity to the solar collectors and is usually located conveniently on the ground closer to the hot water loads as shown in figure 2-2.
2. The Split System Solar Water Heater

1. Solar collectors
2. Storage tank
3. Cold water inlet
4. Hot water outlet
5. Circulator pump
6. Pump controller
7. Auxiliary heater
8. Thermostat
9. Isolating valve
10. Non-return valve
11. Pressure reducing valve
12. Filter
13. Tempering valve
14. Collector bleed valve
15. Safety valve

Figure 2-1  Configuration of a "Split System" solar water heater

- Tank capacity: 340 L
- Collector area: 3.7 m²
- Auxiliary heater: 3600 W
- Circulation pump: 28 W
- Collector flow: 3 L/min
- Thermostat setting: 70°C
- Warranty: 5 years
- Installed cost: $AU 4100
- Energy savings: 3175 kWh/yr

Figure 2-2. Installation of a typical "Split System" solar water heater (courtesy Rheem Australia)
The benefits of a split system are:

- Ease of installation
- Potential for improved aesthetics
- Potential for active control of water circulation
- Potential for improved tank stratification
- Potential for reduced tank thermal losses
- Reduced roof stress and lighter roof fittings
- No need to route gas or electrical cable through roof cavity
- Shorter pipe runs from tank to service.

The addition of a pump and small control unit adds a small capital cost to the system and a potential reliability concern. The split system has proven less popular than thermosyphon systems in Australia, possibly due to a lack of marketing of split systems.

2.3 An Opportunity for Improved Active Control

The split system solar water heater has active control in two areas:

- Auxiliary heating via the thermostat
- Collector water circulation using the differential temperature pump controller.

This thesis aims to significantly improve the efficiency of the storage tank and pump active control by allowing them to interact co-operatively.

Due to variations in solar gain and mode of use, the solar water heater cannot be expected to operate independently of external energy sources with 100% availability. The obvious questions arise:

- How much water is to be heated?
- Where in the system should the auxiliary heater be located?
- How and when should it be operated?
• How should energy be collected from the solar collectors?

There are no simple answers to these questions as they depend upon the conditions prevailing in the system’s environment at the time. Manufacturers have so far adopted very simple control strategies that are biased towards reliability of hot water service rather than energy efficiency.

Typical energy savings figures for solar water heaters are published on the Office of the Renewable Energy Regulator website (ORER 2004b). The energy savings figures are based on modelled performance using the TRNSYS thermal simulation package (TRNSYS 2000). TRNSYS is a modular software program commonly used to model solar thermal systems and is also used in this thesis. The actual TRNSYS model configuration for the experimental system was obtained from the manufacturer (Rheem Australia Pty, model 511340-2SCT) and run in TRNSYS. The ORER TRNSYS model uses the TRNAUS (Morrison 1998) software extensions for TRNSYS and weather data representative of Adelaide. Thus the ORER model provides slightly different results. Nonetheless, the proportions presented in table 2-1 are representative of a standard split system installation in Canberra.

<table>
<thead>
<tr>
<th>Performance Indicator</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy incident on solar collector</td>
<td>24,012 MJ</td>
</tr>
<tr>
<td>Solar energy collected</td>
<td>11,390 MJ</td>
</tr>
<tr>
<td>Auxiliary energy required</td>
<td>5,512 MJ</td>
</tr>
<tr>
<td>Solar fraction(^3)</td>
<td>54%</td>
</tr>
<tr>
<td>Hot water load demand</td>
<td>12,096 MJ</td>
</tr>
<tr>
<td>Thermal losses (tank + pipework)</td>
<td>4,880 MJ</td>
</tr>
</tbody>
</table>

*Table 2-1*  Performance of typical split system in Canberra as modelled in TRNSYS using the ORER methodology

\(^3\) Solar fraction is defined as the compliment of auxiliary consumption divided by load energy demand
2. The Split System Solar Water Heater

Despite the solar collectors gathering 94% of the energy drawn from the system, an extra 46% of the load energy is required from the auxiliary heater! The load is thus oversupplied by 40%. The aim of active control is to reduce the total energy demand of the system and to increase the solar fraction in the matching total supply. This has the consequent effect of lowering the auxiliary heating requirement and operating cost of the system.

2.3.1 Auxiliary Heating Control
Perhaps the biggest impediment to hot water system efficiency is the simple thermostat. The thermostat is usually fixed to the outside of the tank wall so that it controls a fixed volume of water heating and its temperature settings are also fixed. The thermostat switches a very powerful auxiliary heater, usually greater than the maximum heat output of the solar panels.

The thermostat makes a control decision based on the instantaneous temperature at one point in the storage tank. This very limited scope of information leads to the following consequences:

- The thermostat's operation pre-empts and often displaces potential solar gain
- The thermostat does not take advantage of the time value of electricity

Clearly, replacement of the conventional thermostat is a key objective.

2.3.2 Collector Circulation Control
The simple ON/OFF differential temperature control used in most split systems for collector circulation control is also worthy of examination. This strategy provides good instantaneous collector efficiency. However, it does not necessarily optimise the system performance.

Several studies (Van Koppen et al/1979; Veltkamp 1981; Phillips & Dave 1982; Jesch & Braun 1984) suggest that system solar efficiency improves in well thermally stratified tanks if the collector flow rate is reduced from the conventional 0.83 Lmin⁻¹m⁻² to around 0.16 Lmin⁻¹m⁻². The average daily collector temperature is reduced due to a constantly cold supply, and the hotter
2. The Split System Solar Water Heater

return water combined with its low flow rate lead to less mixing and thermal de-stratification in the storage tank. This was found in the studies to more than compensate for the reduced instantaneous collector efficiency, particularly late in the afternoon.

This premise is also dependent upon the hot water load pattern. The low flow / differential temperature controller may still not be an optimal solution since there is potential for some cool water to return to the tank and upset stratification. Active control and variation of the collector flow rate is an important part of the advanced control strategy.

2.3.3 Control Strategies
How much control is appropriate? A classification of control approaches is presented (table 2-2). The choice of level of complexity is a compromise between cost, comprehensibility and functionality.

<table>
<thead>
<tr>
<th>Control Technology</th>
<th>Comment</th>
<th>Typical Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive</td>
<td>Natural processes, limited optimisation potential</td>
<td>Thermosyphon solar water heater</td>
</tr>
<tr>
<td>Regulatory control</td>
<td>Operates independently. Simple loop focus, sensing and feedback</td>
<td>Air conditioner, timer</td>
</tr>
<tr>
<td>Advanced control</td>
<td>Local focus, still regulatory control, limited scope</td>
<td>Furnace, distillation column, boiler, grinding mill</td>
</tr>
<tr>
<td>Model based control</td>
<td>Usually static model, many assumptions, strategic control possible</td>
<td>Gold flotation circuit, paper mill, economic control</td>
</tr>
<tr>
<td>Fuzzy logic, expert Systems</td>
<td>Rule based, niche applications, good for non-linear problems</td>
<td>Decision support systems, safety systems</td>
</tr>
<tr>
<td>Neural networks</td>
<td>Learning, I/O mapping, experienced based, limited by sensory perception</td>
<td>Forecasting electricity prices</td>
</tr>
<tr>
<td>Human</td>
<td>Applies judgement. Deep and complex experience base</td>
<td>Driver of vehicle, Doctor</td>
</tr>
</tbody>
</table>

Table 2-2 Control techniques ranked by level of sophistication
2. The Split System Solar Water Heater

Considering the levels of complexity and acceptance in other domestic appliances such as the motor car, the personal computer, the video recorder or the telephone, there is evidence to suggest that application of advanced technology to enhance the performance of a water heater should be acceptable to householders, provided that the human interface to this technology is mature.

There is a trend towards increasing cost with control complexity and this will be a strong driver in the choice of control technology.

2.4 The Experimental Split System Apparatus

Since this thesis does not use detailed parameterised models, verification of the active control techniques relied upon experimental comparison of two split system solar water heaters. One of the heaters retained its conventional means of operation while advanced control was applied to the other. All other factors (installation, insulation etc) were kept as similar as possible.

2.4.1 Hot Water Systems

Two split systems (model Rheem LoLine 511340-2SCT) were used in the experiments. They were installed at ANU in Canberra, Australia (Lat −35.27°, Long 149.11°), a frost zone in winter. The collectors were mounted on open frames at a slope of 20 degrees above horizontal and facing 35 degrees east of north with significant early morning and late afternoon shading (figure 2-3).

The site offered some protection from the wind in all directions by way of nearby buildings and trees. Since the collectors were raised from the roof, one might expect collector thermal losses to ambient to be higher than the test laboratory ratings.

Both systems were installed by professional plumbers and electricians in the manner of an ordinary domestic installation. The systems were installed with a valving arrangement that allows each collector to provide energy to either tank. This helped to identify any inherent differences in system performance.

Each system had a 3.6 kW electric auxiliary heater that is located about two
thirds of the distance down the tank. The auxiliary heater was mounted on a flange in the side wall of the tank and protruded horizontally into the tank. Auxiliary heating was controlled by a thermostat located on the outside of the tank wall immediately above the auxiliary heater.

Figure 2-3  Installation of the experimental solar water heaters at the Faculty of Engineering, ANU

The site is subject to shading from nearby trees and buildings at certain times of year (figure 2-4). The loss of beam and diffuse insolation due to this shading were analysed by the solar shading calculator (chapter 6) developed in this project. Modified diffuse insolation incidence angles were also produced for this installation. An assessment of ground albedo was made for this site based on a photographic technique detailed in the same chapter.

The hot water storage tanks were ground mounted on concrete slabs, up against a brick wall facing 35 degrees east of north. This wall is exposed to the sun only during mid to late morning and is well sheltered from wind. The water supply temperature sensor had to be shielded from the heat radiating from this
wall. The system control cabinet was conveniently located adjacent to the two tanks and there was a nearby drain for dumping hot water from the systems.

Each system was also supplied with a pump controller working in differential temperature mode between the tank cold supply inlet temperature and the collector outlet temperature. This required a separate mains electricity connection to the auxiliary heater connection. Collector supply water was drawn from a tee piece at the cold water supply entry to the tank. The collector return entered the storage tank very close to the height of the auxiliary heater. All pipework was lightly lagged as it would be in a typical installation.

2.4.2 Load Draw Controller
A microprocessor controller was designed and built specifically to extract energy from both systems according to a given load profile. For most of the experiments, this was the Australian Standard AS4234 seasonal load profile.
This schedule was pre-calculated and loaded into the controller memory. Although the controller had provision for separate treatment of weekdays and weekends, the standard does not differentiate. The controller maintained a real-time calendar and clock. From this, it interpreted the day of year, day of week and time of day from which the correct load was referenced.

A schematic of the important components is shown in figure 2-5. The load controller shared the same cabinet as the datalogger and main water heater controller (figure 2-6). Also visible in this figure are the electricity consumption meters used to check auxiliary energy consumed in the experiments.

The load is defined as:

\[ \text{Load}(t) = \text{Daily Maximum load} \times \text{Season multiplier} \times \text{Fraction of daily energy draw} \]

For a large water heater located in Canberra’s climate zone, these multipliers are given in table 2-3.

<table>
<thead>
<tr>
<th>Month</th>
<th>Seasonal Multiplier</th>
<th>Daily Energy Draw (MJ)</th>
<th>Time of day</th>
<th>Fraction of daily energy draw</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.70</td>
<td>26.6</td>
<td>07:00</td>
<td>0.15</td>
</tr>
<tr>
<td>February</td>
<td>0.80</td>
<td>30.4</td>
<td>08:00</td>
<td>0.15</td>
</tr>
<tr>
<td>March</td>
<td>0.85</td>
<td>32.3</td>
<td>11:00</td>
<td>0.10</td>
</tr>
<tr>
<td>April</td>
<td>0.90</td>
<td>34.2</td>
<td>13:00</td>
<td>0.10</td>
</tr>
<tr>
<td>May</td>
<td>0.95</td>
<td>36.1</td>
<td>15:00</td>
<td>0.125</td>
</tr>
<tr>
<td>June</td>
<td>1.00</td>
<td>38.0</td>
<td>16:00</td>
<td>0.125</td>
</tr>
<tr>
<td>July</td>
<td>1.00</td>
<td>38.0</td>
<td>17:00</td>
<td>0.125</td>
</tr>
<tr>
<td>August</td>
<td>1.00</td>
<td>38.0</td>
<td>18:00</td>
<td>0.125</td>
</tr>
<tr>
<td>September</td>
<td>1.00</td>
<td>38.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>October</td>
<td>0.95</td>
<td>36.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>November</td>
<td>0.90</td>
<td>34.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>December</td>
<td>0.80</td>
<td>30.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2-3  Australain Standard AS4234 hot water load draw as applied to the test equipment in Canberra
The controller dumped hot water through a tempering valve, a turbine flowmeter and across a temperature sensing element. Tempering valves were installed on the hot water outlet lines and delivered hot water to a drain at a temperature \( (T_L) \) of 50°C. The flowmeter was located downstream of the tempering valve to prolong its service life and simplify calibration. The rate of load flow \( (F_L) \) was about 8 L/min although this is not specified in the standard.
The load flowmeters were monitored continuously by the controller and the energy flows updated every $\Delta t = 15$ ms, giving an approximate energy extraction resolution of 0.5 kJ. The amount of energy extracted ($E$) was found from equation 2-1.

$$E = F_L \Delta t \ c \ (T_L - T_s) \quad (Eqn \ 2-1)$$

The timing of the load events was synchronised to the data logger’s 30 second intervals to help with later data reconciliation. Software protection was provided so that the system did not dump water continuously should the outlet temperature fall below 45°C.

The load draw controller also allowed randomly generated load profiles to be tested. This allowed assessment of the hot water controller’s ability to learn a new and varying load pattern. Further details of the load controller are available in a technical report (Dennis 2002c).

2.4.3 Main Controller
A microprocessor based controller offers a degree of flexibility and low cost such that generic controller hardware may be used with the functionality being modified in software.

Such a controller was developed by the author for the purpose of solar tracking of concentrating photovoltaic/thermal troughs at the Australian National University (figure 2-7). This controller needed only to be modified in software to be used as the solar water heater controller.

The controller was based on the Tiger microprocessor, model TCN 4/4, manufactured by Wilke Technologies GmbH. This device is suitable for developers with limited development time or experience with microprocessors. The unit is programmed in Wilke’s version of the BASIC programming language (Wilke 1999) and comes with a number of pre-written device drivers to assist with rapid development. Further details and specifications of this device are given in Appendix D.
2. The Split System Solar Water Heater

The controller operating system used a scheduling system called a real time kernel (RTK). The RTK also prioritised controller tasks and enabled it to carry out the sensing and control activities. There were two task streams:

**Daily Tasks**
- Reception of insolation and ambient temperature forecast
- Processing of weather data to forecast solar contribution
- Updating the load forecast
- Calculation of energy and auxiliary profiles
- Optimising the timing of auxiliary heating
- Calculating performance statistics.

**Periodic Tasks**
- State variable and environment sensing (30s)
- Recording of hot water load profile (12mins)
- Active regulatory control of pump (200ms)
- Active regulatory control of auxiliary heater (30s).

The daily tasks ran soon after midnight each day so that the controller would have time to heat the tank for a morning load.
The controller circuit boards were designed and constructed by the author. They are shown, as installed, in figure 2-8. These circuits are generic in design and were constructed with spare capacity in memory and communication capability. This controller is not intended to be a manufacturing solution. It provides a flexible supporting infrastructure upon which the control algorithms can be evaluated.

![Figure 2-8 Main controller in instrument cabinet with datalogger obscured below](image)

The datalogger circuit board is obscured by the main controller mounted above it. Both are housed in a metal box to help screen the circuits from electromagnetic interference from the mains wiring.

### 2.4.4 Datalogging

Datalogging was performed by the same controller that performed the active control of the water heater. This logical device will be referred to as "the controller" or "the datalogger" depending upon the context. Use of the controller in this way was convenient since the controller required extensive data acquisition anyway and it was over-specified for the control task alone. Data was sampled every 30 seconds before being stored in FLASH non-volatile memory in the Tiger CPU.
The following variables were logged

- Ambient temperature
- Cold water supply temperature
- Hot water load temperature
- Tank profile temperatures (10 thermistors)
- Collector inlet temperature (near pump outlet)
- Collector return temperature (0.7 m upstream from return tank fitting)
- Collector flow (totalised every 30s)
- Load flow (totalised every 30s)
- Auxiliary energy consumption.

Global horizontal radiation was recorded on a remote DataTaker Model 50 device in the vicinity of the solar panels.

The datalogger had about two weeks' capacity when operating on the two water heaters. The controller's network connection was used to upload data over the university computer network to an office personal computer. A custom Microsoft Excel Visual Basic program was written for this purpose (figure 2-9) (code is available upon request). It was not included in the appendices because of its large size.

Key performance indicators were summarised from the raw data on a daily basis. The parameters and their definitions are:

- Solar Fraction (%) – the compliment of the ratio of auxiliary energy to hot water load drawn
- Solar Efficiency (%) – the proportion of global horizontal insolation captured by the solar collectors and delivered to the tank
- Tank Losses (MJ) – total energy lost from the storage tank derived from the difference between total supply and total demand, corrected for change in stored energy in the tank
- Under Temperature Delivery (MJ) – for loads that cannot be delivered at a
temperature above 45°C, this is the shortfall in delivery. Load delivery is terminated by the load controller when the tempered water temperature drops below 45°C

- Load Turnovers (ratio) – the ratio of the total volume of water passing through the solar collector to the load volume for a given day.

Figure 2.9 Upload of data from the datalogger to spreadsheet for processing. Data can be transferred over a network or serial link.

Temperature Sensing

All temperature sensing was achieved using Siemens B57703MG103G negative temperature co-efficient (NTC) bead thermistors mounted on metal tags (as supplied). These devices have good sensitivity over a temperature range of 0-70°C (thermistor $\beta_0=3920$ K, $R_0=10$ kΩ @25°C) and a maximum operating temperature exceeding 120°C.
The thermistor resistance ($R$) as a function of temperature ($T$, in Kelvin) is given by equation 2-2.

$$R = R_0 \exp \left( \frac{1}{T} - \frac{1}{298} \right)$$  \hspace{1cm} \text{(Eqtn 2-2)}

A table of resistance vs temperature (steps of 5°C) was obtained from the manufacturer. The manufacturing tolerance is 2% in $R_0$, so the thermistors used in the experiments were carefully matched from a large batch of 50 thermistors. Thirty devices (based on $R_0$) were selected for use in the experiments. The variance in $R_0$ after matching was reduced to 10 Ω corresponding to a temperature error of 0.11°C at tank working temperatures of 60°C and an error of 0.01°C at cold supply temperatures.

The thermistor beta has a manufacturing tolerance of 1%. This corresponds to variance in temperature reading of 0.2°C at tank working temperatures and 0.1°C at cold supply temperatures. Further matching of thermistors based on the thermistor beta was not conducted due to funding constraints.

Furthermore, the use of the thermistor approximation equation leads to a linearity error. Trials with various values of $\beta_0$ suggest reduced approximation error between the manufacturer's tabulated resistance and the resistance given by the thermistor approximation equation when the beta values are modified for limited ranges of operation (figure 2-10). A $\beta_0$ value of 3865 K for temperature measurement in the vicinity of 60°C and a value of 3810 K for measurements in the vicinity of 15°C reduces the approximation error to 0.1°C over the operating range of the sensors in the experiments.

The maximum power dissipated by the thermistor due to sensing current was 0.62 mW and the thermistor had sensible heat capacity of 73 mJ/K. Since the thermistors were in good thermal contact with a metal body (copper pipe or tank wall) of large thermal capacitance relative to themselves, the measurement error introduced through self heating of thermistors was ignored.
Separate power and sensing wires were not used for the thermistors. The thermistor voltage at 60°C was 1016 mV and the voltage drop along the cables was calculated to be 0.2 mV. The quantisation step of the datalogger was 4.8 mV.

The quantisation error of the 10bit converter was much less than the error in the sensor itself. Electrical interference was minimised by the use of screened cables and filtering in the sampling electronics. This low-pass filter was designed to attenuate 50 Hz mains interference.

The total thermistor error at 20°C was 0.14°C rising to 0.24°C at 60°C.

If budgets allow, the author recommends the use of the MAXIM 6682 semiconductor device for temperature sensing. This integrated circuit has its own voltage reference and conversion circuitry. Most importantly, it sends out a digital temperature signal so that electrical interference will not change the temperature reading. Many such devices can use the same two wire communication path and the controller overhead in software (memory space and CPU time) and hardware is reduced. Another self contained digital thermometer is the Dallas Semiconductor DS1820. These devices are currently too expensive (A$10ea) for mass manufacturing.

Figure 2-10  The error in the thermistor approximation equation can be reduced over a small range of operation by appropriate selection of thermistor beta value.
Measurement of pipework temperatures (hot water load, cold supply, collector inlet and return) involved mounting thermistors on the outside of copper pipework, under the insulation, using Loctite 315 thermally conductive epoxy. Pipework insulation consisted of 5/8” inside diameter by 3/8” wall polyethylene foam tube.

The existing collector outlet temperature thermistor was retained. The auxiliary heater temperature sensor was screwed to the top of the auxiliary heater case near the heater outlet. The tank temperature profile sensor described in chapter 5 used identical thermistors mounted directly to the tank wall using thermally conductive epoxy.

**Insolation Sensing**

Global horizontal insolation was recorded in the vicinity of the collectors. A Kipp & Zonen model CM11 heliometer was used to sense global horizontal radiation. Data was sampled every thirty seconds and recorded as hourly averages using a DataTaker model 50. This process operated independently of the main controller datalogger. The CM11 is defined as a “secondary standard” device with an expected accuracy for daily sums of ±3% (Campbell Scientific 2001). It is interesting to note that this device has spectral sensitivity exceeding 50% up to wavelengths of 2800 nm. This provides a good match to the absorption of the selective surface of the solar collector and the transmission characteristics of the collector glass cover.

The heliometer was positioned away from bright reflecting walls and away from hot exhaust stacks near the university engineering laboratories.

**Flow Sensing**

Sensing of low water flows is difficult. Small turbine flowmeters, RadioSpares models 257149 and 257133, were used for the collector and load flow metering respectively. These devices were specifically designed for use with water heaters. The turbine impellers form an optical barrier for an infra-red photointerrupter pickup and the resulting digital pulses were accumulated every 30 seconds by the controller.
The load flow was calibrated at the service temperature (50°C) by running hot water from the tank via the tempering valve and flow meter into a large bucket. The load draw controller was used to open the load solenoid valve for a predetermined period and the resulting load was weighed on electronic scales (accurate to 50 g). Variation of the flowmeter calibration with temperature (due to changing water viscosity and density) was ignored in this case due the flowmeter's downstream proximity to the tempering valve.

The collector flow meter was identical to the load flowmeter but fitted with a smaller orifice in the case of the collector circulation measurements. The use of this modified flowmeter introduced a significant pressure drop, thereby reducing the maximum collector flow rate from 2.7 L/min to 1.9 L/min. The flowmeters were separately calibrated at cold supply temperature using a similar approach to the load flowmeter. A solenoid valve was temporarily installed on the collector bleed pipe and water was run into a bucket before being weighed. Each system was fitted with a gate valve in the collector feed pipe so that the collector flows could be matched for comparative performance testing. This valve was used to throttle the collector flow rate for in-situ calibration. The test was repeated using hot water from the storage tank, since it provided a nearly constant temperature water over short periods at the end of a summer day when the calibration was conducted. Linear temperature correction for each flowmeter calibration was performed.

The flowmeters were installed with straight runs in excess of 100 pipe diameters upstream and 70 pipe diameters downstream to reduce sensitivity to uneven flow in the pipework. The flowmeter datasheet shows a linear frequency response over the range of the flowmeter (normal flowmeter 1.5-30 L/min, low flowmeter 0.25-6.5 L/min). This was found to be correct within the 1.5% linearity tolerance given by the manufacturer.

Calibration curves were derived for each flowmeter and stored in the datalogger ($r^2=0.9994$, 0.9983 respectively).
Auxiliary Consumption Sensing

Auxiliary consumption was monitored by both the datalogger and independent electricity metering.

The power draw of each auxiliary heater was measured after installation and found to be in exact agreement with the rated power. The auxiliary heater power relay switched a parallel sense relay that signaled the datalogger when the auxiliary heater was in use. A time aliasing problem arose because that datalogger sampled every 30 seconds and the thermostat's switching of the auxiliary heater use was asynchronous. This introduced a maximum error of 108 kJ per auxiliary heater switching event. To overcome this problem, the datalogger sent a synchronisation signal to all controllers (main controller, pump controller and load controller) just before a datalogging event. However, the system without advanced control retained this source of error. In practice, this was typically found to average 1.2% for that system only and no corrective action was taken. This error works out to be approximately 50 kJ per load event. Appendix D-3 shows a synchronising mechanism that might help with future data acquisition of this nature.

A potential problem for the experimental system arose when the independent auxiliary heater over-temperature protection circuit activated. The datalogger recorded that the auxiliary was still operating, leading to an over-estimate of the auxiliary consumption. Observation of the auxiliary heating with and without collector pre-heating showed that this does not normally occur although the transient temperature during auxiliary heater power-up can come to within 5°C of the cut-out temperature. A separate sense relay connected in parallel to the actual heater terminations would be required to overcome this problem.

2.4.5 Cabling and Signal Noise

All sensor cables were separate twin-core with screen earthed at a common point at the controller termination to reduce electrical noise. Analog operational amplifiers in the datalogger provided buffering between the sensor and sampling circuits. They also provided low-pass filtering to remove mains voltage interference and amplification where necessary.
2.4.6 Remote Monitoring
To assist with running of the experiments, a remote monitoring system was developed using the controller's network interface. The mechanism consisted of a serial link from the datalogger to a Siteplayer network interface module. The Siteplayer module was provided by Netmedia Inc. The module has 584 bytes of memory for the storage of temporary variables (the solar water heater performance data) and provision for a small web server interface. Two simple web pages (figure 2-11) were stored in the Siteplayer module.

![Figure 2-11](image.jpg)

The web pages used internet addresses that were only accessible within the university and were remotely accessed over the university network.

The first page summarised the status of each water heater. It includes information on water temperatures, flows, energy totalisers and auxiliary status. A quick assessment could be made of each system based on this page. The second web page provided a temperature profile of the tank in the experimental system. This was useful to observe the variation in thermal stratification under various conditions. Such a profile is not so interesting in a conventional system as the thermostat maintains 60% of the tank at 65°C. This monitoring provided valuable insights into the operation of the experimental system without requiring constant attendance.
3. Modelling

"...man will occasionally stumble over the truth, but usually manages to pick himself up, walk over or around it, and carry on"

Winston Churchill

3.1 Introduction

Modelling was used to establish a quantitative baseline by which the merits of new technologies might be compared before going to the effort of construction and experimentation. As the active control technologies were developed, they were tested in the modelling environment. Most of the modelling results are presented in subsequent chapters, in context.

The purpose of this modelling work was not to obtain a detailed and parameterised model that would accurately predict the performance of a system with active control. This would require extensive parameterisation of the model and that parameterisation exercise would be valid for only one system at one point in time. In this thesis, modelling was used to provide a before and after comparison of split system performance for a generic configuration and was a feasibility study. The results of the modelling were also used to gain an understanding of the sensitivity of active control algorithms to disturbances in the load and solar forecasts.

The TRNSYS 15 simulation program (TRNSYS 2000) was used in this work. TRNSYS was designed by the University of Wisconsin-Madison during the early 1970’s and has grown with a number of upgrades and additions. TRNSYS is a modular program whereby a model is constructed from a number of components, called TRNSYS types, that are linked together. Each component has a type number and is a distinct FORTRAN subroutine. All types have a common format and interact with a master controlling routine known as the TRNSYS kernal. Although TRNSYS comes with a large number of native components, third parties have also developed components and offer them for
sale. A new TRNSYS component has been developed in this thesis for the predictive controller.

To run a simulation, one would carry out the following steps:

1. Assemble the necessary components from the TRNSYS type library
2. Configure the parameters of each component
3. Interconnect the components
4. Compile the FORTRAN simulation into a TRNSYS "deck" file
5. Run the deck file.

TRNSYS comes bundled with a number of utility programs. The graphical user interface IIsibat 3.0 speeds up the configuration of models and is helpful in debugging. Experienced TRNSYS users may find direct creation and examination of the deck file more productive. The TRNSHELL utility allows TRNSYS to run repeatedly with parameter variation. This is useful for sensitivity analysis. There are several other utilities not used in this thesis. The choice of TRNSYS as the modelling package was made early in the research.

A reference model was configured in the IIsibat graphical environment (figure 3-1) based on the Rheem Solar Loline Water Heater Storage Tank (Model 511340) and Rheem Domestic Solar Controller Kit (PN 299121). Subsequent testing of active control strategies were compared to this reference model. The model was parameterised from data from the manufacturer and for the Canberra location of the research experiments. Details of the model parameters may be found in Appendix B.3.

The processing of a large number of iterative simulations was performed in the TRNSHELL package. A custom program was written to process the TRNSYS output and produce the performance indicators.
3.2 Model Description

3.2.1 Timestep
The model simulated a 12 month period to test the system with seasonal variation. A number of simulations were run with the reference and active control models to determine a suitable timestep and integration tolerance for the model iterations. When further shortening of the timestep and tightening of the integration tolerance produced consistent results, a suitable timestep (0.02 hr) and integration tolerance (0.02) were selected. These values were also found suitable for active control simulations. Although the use of a TRNSYS type 38 tank model generally allows longer timesteps to be used than with tank models of fixed segment volume, the predictive control strategy introduced in this thesis requires a very short timestep to provide accurate operation.
3.2.2 Insolation
Weather effects are simulated with a typical meteorological year (TMY) weather data file, a file reader (type 9) and a radiation processor (type 16).

The TMY file for the Canberra location (Latitude −35°17', Longitude 149°7') contains sequences of concurrent weather information representative of a location, including:

- Global solar radiation on a horizontal surface
- Direct beam solar radiation on a sun tracking surface
- Dry bulb ambient temperature
- Wet bulb ambient temperature
- Wind speed and direction
- Cloud cover.

The data is sourced from historical meteorological records and the Australian Solar Radiation Data Handbook (AUSOLRAD 2003). The Canberra TMY file was assembled from meteorological records for 1983-1986 by Morrison & Litvak (1988). Most of the TMY file records consist of data from 1984. The “typical” year is chosen so that modelling of a thermal system using actual weather data over a long period gives similar results to using the TMY file over the same period. The methodology is set out in greater detail by Morrison.

The TMY file has one hour resolution and was interpolated within TRNSYS to match the model’s discrete timestep. Since both the global horizontal and direct beam radiation were known, the approximation for diffuse radiation introduced by a correlation with global radiation could be avoided. The solar collector was configured at 20 degrees tilt from horizontal as in the experimental configuration. Tilted surface correction for diffuse radiation was derived from the Hay and Davies model (Hay & Davies 1980), which accounts for the anisotropy of sky diffuse caused by bright circumsolar diffuse radiation and is an improvement on the pure isotropic sky model. Shading effects were ignored for the model since substantial modifications would have been required to the radiation processor type and the effects were common to both the conventional
and experimental models. Ground reflectance of 0.1 was used as a result of albedo measurements taken at the test site, rather than the default value of 0.2

3.2.3 Solar Collectors
The solar collector in the Rheem LoLine 511340 SCT system consisted of two solar panels connected in parallel, each of aperture 1.87 m². In TRNSYS, the collector (type 1) was considered as one unit of aperture 3.74 m² and used the same efficiency co-efficients as for the single panel. The model assumes even flow in all the riser tubes.

One might expect the model to slightly over-estimate the collector performance from this assumption, but the effect would be very small. The collector model uses a quadratic efficiency relation, the efficiency co-efficients were obtained from the manufacturer. The efficiency co-efficients are based on the collector inlet temperature. No account of thermal inertia in the collector was included in the model. The heat capacity of the collector was calculated to be 33 kJ/K, mainly in the water and glass. The heat capacity effect is expected to be minor (Duffie & Beckman 1974) and in retrospect, the variable speed pumping of the active control scheme resulted in significantly less pump start cycles and presumably less thermal cycles in the collector. The incidence angle modifiers were derived from ASHRAE testing of the collector and obtained from the manufacturer. The model does not account for long wavelength radiation from the collector cover to the sky. Because of this, and exposure to wind, heat loss from real collectors is likely to be greater than the model results suggest.

3.2.4 Water Circulation Pump and Pipework
The water circulation pump (type 3) and an ON/OFF differential temperature controller (type 2) were configured with settings from the manufacturer. This control scheme switches the pump on when the collector outlet temperature becomes higher than the cold supply temperature by more than 8°C and switches the pump off when that temperature difference drops below 4°C. The length of insulated interconnecting pipework was measured and its insulating properties estimated from AS4234 to be 2.7 Wm⁻²K⁻¹. This loss is expected to
be slightly less than the published figure of 3 Wm\(^{-2}\)K\(^{-1}\) since the pipework runs up the side of a north facing brick wall. The model simulated ten metres of standard half inch copper pipe of each of the collector supply and return lines. The control scheme switched the pump OFF if the pump inlet temperature exceeded 70°C.

### 3.2.5 Storage Tank

A number of storage tank models were examined. No tank model in the TRNSYS 15 standard component library is sufficiently complex to cope with the subtleties of flow induced mixing in the storage tank. The preservation of thermal stratification by low collector flows and control of the location of auxiliary heating are important requirements of the active control model. Some TRNSYS tank models (type 4, type 60, type 140) divide the tank into a fixed number of segments, each of fixed volume. When a low collector flow is utilised, the return water is expected to trickle up or down the side of the tank with a lesser degree of mixing than for higher collector flows and provides less disruption to the stratification (Knudsen 2004). Modelling of low-flow systems using one of these types requires a large number of segments so that small collector return volumes (at elevated temperatures relative to the tank) are not lost to mixing within a segment. A large number of small segments implies that a short timestep must be used so that large convective flow during load draws does not exceed one segment volume in a timestep.

The plug flow model (type 38) is best suited to well thermally stratified tanks of the type used in this thesis since the node sizes adapt to the volumetric flows present. This allows the short time constant convection effects to be separated by the longer time constant conduction losses from each segment.

Storage tank parameters were obtained from the manufacturer (see Appendix B.4). There were some modifications relating to the observed heat loss from the tank (increased to 3.5 WK\(^{-1}\)), the conductivity down the tank (calculated to be 2.3 Wm\(^{-1}\)K\(^{-1}\)) and the thermostat temperature (set to 60°C).
The tank model was modified by the addition of code to calculate the tank energy content based on the existing segment temperature and volume arrays in the type 38 subroutine (see Appendix B.3). Two new outputs were added to the model and these are connected to the new active controller, type 256.

The tank model does not account for energy lost from overheating when a temperature relief valve would release hot water in a real system.

3.2.6 Active Controller
A new TRNSYS component, designated type 256\textsuperscript{4}, was constructed to provide the proportional pump control and active auxiliary heater control. The operation of type 256 is explained in chapter 8 after some definitions are established in subsequent chapters. Code for type 256 is listed in Appendix B.1.

3.2.7 Hot Water Load
The AS4234 load profile commonly used for TRNSYS modelling of domestic water heaters appears at first glance to be unrealistic in the frequency and volume of each load draw event.

The control algorithm introduced in this thesis learns and predicts the hot water load. Modelling of the learning capability of the algorithm using a consistent load such as AS4234 would not be a good learning challenge. The load profiles should vary from day to day but have some kind of underlying pattern as might be the case in a domestic dwelling.

Other load profiles were tested following similar lines to International Energy Agency (IEA) Task 26 (Jordan & Vajen 2000). A number of random load profiles were generated statistically based upon the following IEA Task 26 methodology:

- Identify a number of sources of hot water load
- Characterise each source with a load volume distribution (figure 3-2)
- Characterise each source with a probability of occurrence at each timestep of a day (figure 3-3). For each timestep in a day, calculate

\textsuperscript{4} ANU was allocated TRNSYS type numbers 251-262 for generation of new components
how many load events for each source are expected in a year and randomly distribute these events across days in the year

- Find the energy draw for each event based on a random number index on a cumulative distribution of the volume of the load source.
- Sum up the daily total energy draw and scale each load event to match the AS4234 daily load total
- Distribute each load event across a number of timesteps given that the load power is limited by delivery flow rate (assume 10 L/min @50°C temperature rise).

![Figure 3-2 Probabilities of load occurring at given time of day](image)

**Figure 3-2** Probabilities of load occurring at given time of day

![Figure 3-3 Discrete probabilities of load volumes (left) and cumulative probabilities of load volume (right) from which a random index may extract a random load from the distribution](image)

**Figure 3-3** Discrete probabilities of load volumes (left) and cumulative probabilities of load volume (right) from which a random index may extract a random load from the distribution
The probability distributions were estimates and were not representative of any sampled dataset. Load profiles generated by these means tended to have a larger number of load events of a smaller volume than the AS4234 profile. This led to a distribution of daily load volumes of larger variance than for the AS4234 load and were considered by the author to provide a more realistic assessment of a system's short term modelled performance.

A visual comparison is drawn between the AS4234 load profile (figure 3-4) and a sample random load profile. The spectral content of the load profiles is clearly different (figure 3-5).

![Figure 3-4 Comparison of AS4234 winter load profile and a typical stochastically generated profile](image)

![Figure 3-5 Histogram comparing the daily load draw volume for AS4234 and random load profiles](image)

For the purposes of comparing load profile effects in TRNSYS, a random load profile was generated for each day of the year and these were saved. The annual total load of the random profiles matched AS4234 for a large system.
Results from the TRNSYS model of the conventional split system with the random load profile were compared to the same model with the AS4234 load profile (table 3-1). While there were day to day variations in performance, the random load yielded only a small annual increase in system performance in the order of 2 percent. Perhaps the more frequent water draws lowered the average collector inlet temperature in an otherwise well mixed tank.

<table>
<thead>
<tr>
<th>Performance Indicator</th>
<th>AS4234 Load</th>
<th>Random Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar energy collected</td>
<td>9187 MJ</td>
<td>9367 MJ</td>
</tr>
<tr>
<td>Auxiliary energy</td>
<td>8338 MJ</td>
<td>8075 MJ</td>
</tr>
<tr>
<td>Solar fraction of supply</td>
<td>30.7%</td>
<td>33.1%</td>
</tr>
<tr>
<td>Storage tank losses</td>
<td>5285 MJ</td>
<td>5188 MJ</td>
</tr>
</tbody>
</table>

Table 3-1 Annual comparison of performance of conventional system with AS4234 load profile and random load profile

Since the difference in modelled performance resulting from the use of a random load is small, the hot water load profile from AS4234 was used in all subsequent models. This provides both morning and evening load with a slight evening bias.

3.2.8 Energy Tariff
A simple tariff was used, representing a typical off-peak supply as follows:

- 8pm – 6am: 5c/kWh (1.38c/MJ)
- Other times: 10c/kWh (2.7c/MJ)

No additional costs for supply and network charges were included as these are independent of auxiliary energy consumption. These values are chosen arbitrarily to demonstrate the operation of the active control algorithm.
3. Modelling

3.2.9 Model Outputs
A number of key performance indicators were calculated and summarised by month using the TRNSYS simulation summary component (type 28). This type also allows an energy balance to be calculated for the storage tank to check that the model is operating correctly. The performance indicators are:

Energy Supply Indicators

- Global horizontal solar insolation (from type 16)
- Solar gain from the collectors (from type 1)
- Solar energy fraction, the complement of the ratio of auxiliary consumption to load drawn
- Auxiliary energy input from pump and auxiliary heater
- Cost of auxiliary energy
- Pump energy consumption
- Number of pump starts
- Total energy supply.

Energy Demand Indicators

- Total hot water load energy
- Storage tank thermal losses
- Pipework thermal losses
- System thermal efficiency, defined as the load drawn divided by the total energy supplied to the system
- Load turnovers defined as the ratio of the volume of water pumped through the collector to volume of water drawn as load
- Amount of water supplied that fails to meet the required delivery temperature.

These indicators were calculated with a time resolution of 1.2 minutes and summarised monthly. The simulation summary (type 28) produced a monthly
energy balance for the storage tank and the energy quantities usually balanced within 2%.

### 3.3 A Basis for Comparison

The conventional split system was modelled with parameters of the conventional split system (see Appendix B.4). The modelling results (table 3-2) show poor solar performance and poor system thermal efficiency compared to what the modified system will later be shown to be capable of.

<table>
<thead>
<tr>
<th>Performance Indicator</th>
<th>Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar energy collected</td>
<td>9,187 MJ</td>
</tr>
<tr>
<td>Auxiliary energy</td>
<td>8,338 MJ</td>
</tr>
<tr>
<td>Pump energy</td>
<td>558 MJ</td>
</tr>
<tr>
<td>Total supply</td>
<td>18,083 MJ</td>
</tr>
<tr>
<td>Solar energy fraction</td>
<td>30.7 %</td>
</tr>
<tr>
<td>Auxiliary energy cost</td>
<td>$208</td>
</tr>
<tr>
<td>Hot water load</td>
<td>12,096 MJ</td>
</tr>
<tr>
<td>Storage tank losses</td>
<td>5,285 MJ</td>
</tr>
<tr>
<td>Pipework heat loss</td>
<td>414 MJ</td>
</tr>
<tr>
<td>Total demand</td>
<td>17,795 MJ</td>
</tr>
<tr>
<td>System thermal efficiency</td>
<td>66.9%</td>
</tr>
<tr>
<td>Load turnovers</td>
<td>4.74</td>
</tr>
</tbody>
</table>

*Table 3-2* Baseline modelled annual performance of the split system (collector slope 20°, latitude 35°S) is somewhat poorer than the ORER rated values as a result of changes to a few parameters in the model and the use of different weather data.

The poor solar performance is primarily due to high collector flow rates. Low system thermal efficiency is due to the use of a thermostat that excessively heats the tank leading to high standing losses and due to a relatively flat
collector slope requiring a large winter auxiliary contribution.

The summer bias of the collector had a strong influence on the results. The solar collectors often completely filled the storage tank with hot water and this manifested as increased demand from tank losses. The energy supply and demand were not exactly balanced since the pump energy consumption was totally included in energy supply. The pump only adds a proportion of its energy to heating the water through work done on the fluid and this was not accounted for in the collector gain. There was also a small gain in internal energy in the tank over the year due to a cold initial tank state.

These performance figures indicate significantly poorer solar performance than those published for the Rheem 511340-2SCT system (ORER 2004b). The parameters of the model used for the renewable energy certification process were not representative of this experimental installation regarding collector flow, auxiliary heater power and system losses. The ORER model used a TMY data file representative of Adelaide$^5$ whereas the results in table 3-2 represent Canberra. The ORER model also uses the TRNAUS type subroutines in place of the standard TRNSYS types.

However, the purpose of the table is not to check the ORER results, but to provide a comparative performance baseline for later simulations using a parameter set that is representative of a typical installation in Canberra. The model was also used to gain an understanding of the time constants involved with thermal de-stratification. The TRNSYS tank models were not designed to deal with complex mixing phenomena and may be inaccurate for this reason. A deeper understanding may be gained from work with computational fluid dynamics models (Knudsen 2004) although discussions with Knudsen suggested that this approach is far from deterministic.

The active control algorithm developed in this thesis used approximate insolation and collector models. It is possible to construct a practical controller that contains code algorithms of similar complexity to those used in the TRNSYS simulations using technology currently available.

$^5$ Adelaide and Canberra are allocated the same climate data in the ORER model
With sufficient development, it may be possible to make such a controller cost-effective. The great difficulty in full model based control is in parameterising and tuning the model to a suitable level of detail so that its forecasts are accurate given the specific installation. This level of parameterisation may incur large cost overheads. The investigation of how this process might be achieved would be an avenue for further interesting work.
4. Predictive Energy Balances

“It is my task to convince you not to turn away because you don’t understand it. You see, my physics students don’t understand it...that is because I don’t understand it. Nobody does”

Richard Feynman, Physicist

4.1 Introduction

In this chapter, control strategies that preserve thermal stratification in the storage tank are presented, including the idea of heating a variable volume of water. This leads to the idea of predicting future energy balances to determine how much auxiliary heat should be added to the storage tank and when best to add the heat.

The energy balance methodology aims to delay auxiliary heating as long as possible to allow greater solar contribution to the tank’s deliverable hot water. While this approach works best for powerful auxiliary heaters, all auxiliary heating sources will require a finite period to heat the tank in readiness for an upcoming load. The rate of energy addition to the tank from the auxiliary heater is related to the heater power. This chapter explores how the predictive energy balance identifies the “when” and “how much” of the auxiliary heating. In this chapter, it is assumed that the load and solar profiles for the day ahead are known.

The complete algorithm code listing is detailed in a technical report (Dennis 2004) at the Australian National University.

4.2 Thermal Stratification

The term “thermal stratification” refers to the formation of a vertical temperature gradient in a hot water storage tank. Thermal expansion of heated water causes its density to decrease. The effect of gravity on water of varying density is the generation of a buoyant force on the warmer water. When hot
water is generated below cooler water, temperature equalisation occurs due to conduction and mixing from convection currents.

Consider the three tanks illustrated in figure 4-1. Each tank contains 150 L of hot water and 150 L of cold water, about 30 MJ of heat energy relative to the cold water supply.

![Figure 4-1](image)

<table>
<thead>
<tr>
<th>Delivery</th>
<th>Useful energy</th>
<th>Stratification</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 L</td>
<td>0 MJ</td>
<td>0 %</td>
</tr>
<tr>
<td>125 L</td>
<td>25 MJ</td>
<td>80 %</td>
</tr>
<tr>
<td>150 L</td>
<td>30 MJ</td>
<td>100 %</td>
</tr>
</tbody>
</table>

*Figure 4-1 Thermal stratification and useful hot water capacity*

The rated delivery or useful hot water in these vessels is very different. The useful energy in the tank (UTE) is proportional to the degree of thermal stratification for a given energy content.

A high degree of thermal stratification is important so that for a given energy content in the tank:

- Tank delivery at an acceptable minimum temperature is maximised
- Collector efficiency is improved due to lower inlet temperatures.

Perhaps the greatest threat to thermal stratification is due to water flows through the tank. A hot water load typically draws 10 L/min and results in violent disturbance to the thermal stratification as cold water enters the bottom of the tank in jets. Several manufacturers add diffusing devices in an attempt to minimise vertical mixing of water due to water draw.
A comprehensive study on the implications of tank inlet design carried out by Jordan & Furbo (2003) indicates that 7% savings in auxiliary energy are possible with well designed inlets compared to standard tube inlets. This difference is due to preservation of thermal stratification around the thermostat. There is an additional gain from increased collector performance due to increased stratification in the tank.

Solar collector flows have a similar mixing effect but for different reasons. The flow velocity is typically only 25% of the load flow but warm water returns to the tank part way up the thermal gradient and thus rises or falls until it reaches water of its own temperature, thus creating a convection mixing process. Studies of optimum location of the solar return were carried out by Knudsen (2004) for tanks with a mantle type heat exchanger. Knudsen concluded that there was an optimum collector return pipe location for a particular set of circumstances and implied that this position would vary with operating parameters such as the load. The use of a mantle tank somewhat reduces the system’s sensitivity to collector circuit return jets.

A variable location solar collector return location was trialed by van Koppen et al (1979). This device was simply a length of flexible tube attached to the solar return with its open end left free to dangle inside the tank. The free end would release water at the appropriate location due to its neutral buoyancy. This device realised 20% gains in system thermal efficiency until it became blocked by lime deposits.

Perhaps of greater importance, particularly for systems without a collector loop heat exchanger, is the control of the collector return jet. The effect of this pumped jet is minimised if the collector loop returns water at the same temperature as the location at which the jet impinges on the tank and if the flow rate is reduced. This may be assisted by using a variable collector flow rate, discussed in Chapter 9.

Stratification degeneration also comes from conduction. Conduction primarily occurs down the wall of the storage tank. For the Rheem split system tank, the thermal resistance (per unit length) of the tank wall, sacrificial anode and water
are 4.7 \, \text{KW}^{-1}\text{m}^{-1}, \, 8.3 \, \text{KW}^{-1}\text{m}^{-1} \text{ and } 8.6 \, \text{KW}^{-1}\text{m}^{-1} \text{ respectively. The effective thermal resistance is thus } 2.2 \, \text{KW}^{-1}\text{m}^{-1}, \text{ so the effective thermal conductivity is } 2.3 \, \text{Wm}^{-1}\text{K}^{-1}. \text{ Experimental results from the conventional test system show that the auxiliary heater will switch on about every 6 hours (for an } 8^\circ\text{C deadband) overnight, due to stratification losses. Thermal stratification is more difficult to obtain and more easily upset in horizontal tanks due to the increased cross-sectional area and reduced vertical column available. This is important for advanced control where maintenance of thermal stratification is essential for making the best use of the minimised amount of stored energy. The advanced control algorithm works best for tanks with small cross-sectional area to height ratios.}

4.3 State Variables

Active control is not possible without the sensing and feedback of the state variables. State variables are a set of quantities that are considered representative of the system being controlled. In this thesis, a state variable is introduced to describe the quality of the energy in the tank or the amount of Useful Tank Energy (UTE) stored in the hot water tank, relative to the cold supply.

For practical purposes, the tank is discretised into a number of volume quanta \((V_n)\), each with an associated measured temperature \((T_n)\). For now, \(T_n\) is assumed to be representative of the entire quantum. Any volume quantum with a temperature exceeding the critical temperature \((T_c)\) is considered to have useful heat and its energy contributes to the state variable.

The state variable UTE is defined as

\[
\text{UTE} = \rho c \sum_{n=1}^{N} V_n (T_n - T_s) , \, T_n > T_c
\]

\text{(Eqtn 4-1)}

Here \(\rho\) is the density of water at temperature \(T_n\), \(c\) is the specific heat capacity
of water at $T_n$ and $N$ is the total number of quanta. The control algorithm uses 100 volume quanta and this is considerably more than suggested by Kleinback et al. (1993) for conventional modelling purposes. A practical upper bound on $N$ is limited by the number and quality of the tank profile sensor temperature readings.

It is also useful for a smart algorithm to understand the total amount of energy in the tank, relative to the cold supply. Changes in the tank energy content give an indication of heat flows in the tank and provide an indication of how much heating is required to meet a given tank state at a later time (for some heating strategies). The tank energy content is referred to as Total Tank Energy (TTE) and is defined by equation 4-2.

"The amount of energy embodied in the stored heated water relative to the cold water supply temperature, $T_s$"

$$TTE = \rho \ c \ \sum_{n=1}^{N} V_n (T_n - T_s)$$  \hspace{1cm} (Eqtn 4-2)

The third state variable used by the algorithm refers to the first vertical location in the storage tank, measured from the top of the tank, where the temperature falls below the critical temperature. This is the lower UTE boundary, denoted $x_c$, and is different to the proportion UTE/TTE. The state variable $x_c$ defines the location of the boundary between useful hot water and the rest of the tank.

Knowledge of the tank state in this detail is very useful. The controller with this knowledge has the flexibility to provide an arbitrary level of storage tank UTE. In effect, it can mimic a variable temperature, variable location thermostat.

The choice of definition for $T_c$ and hence the state variables derived is somewhat arbitrary since users may consider water at 40°C to be useful for all domestic purposes. However an important concern for water storage systems is the health implication of reduced storage temperature. Most health guidelines for hot water storage systems recommend a minimum tank storage
temperature of 60°C (see Appendix C).

The fitting of a tempering valve\(^6\) is now mandatory in many areas. The operating parameters of this valve set the temperature threshold for the definition of the state variable. Typically, a tempering valve will require the hot water set-point temperature to exceed the delivery temperature by a minimum of 10°C to ensure the valve shuts off in the event of cold water supply failure. The Australian Standard AS3500.4.2 (1997) requires that all domestic sanitary fittings have a maximum hot water delivery temperature of 50°C\(^7\). A "critical" tank delivery temperature of 60°C defines a threshold whereby hot water will be delivered at a predictable temperature and thus may be considered useful in the context of the state variable.

Importantly, the tempering valve becomes an energy delivery limiting device rather than a volume delivery limiting device when operating in its mixing mode. This has important implications for smart control of hot water systems since the state variable may take account of energy in high temperature regions near the top of a stratified tank. One may argue that users form their own tempering valves at the point of delivery (e.g. a shower) although other volume users such as washing machines would be less discerning in the amount of energy that they draw. Sensing of the tank temperature profile allows the controller to vary the effective thermostat temperature and placement while retaining knowledge of UTE. With a conventional thermostat, the state of the thermostat was the only indication of UTE, and the indication was then only a binary value.

4.3.1 Estimation of the State Variables
The state variables are derived from a temperature profile of the tank. Interpolation may need to be performed between discrete sensor measurements. The temperature profile of a stratified tank is observed to be of the form of a logistic curve represented by the general equation \(y = (1 + e^{-x})^{-1}\) (NIST/SEMATECH n.d.). If the form of this logistic equation is modified to suit

\(^{6}\) A tempering valve limits the hot water delivery temperature to a safe level, typically 45-50 °C by mixing cold supply water with hot water from the tank.
the temperature profile of a water heater, and fitted to the measured
temperatures, the temperature $T_x$ at any location $x$ from the top of the tank can
be found from the equation 4-3.

$$T_x = T_s + \frac{(T_{sp} - T_s)}{1 + s e^{-r(x-x_c)}}$$  \hspace{1cm} (Eqtn 4-3)

Here $T_{sp}$ is the temperature that defines the lower boundary of the deliverable
volume of hot water, $T_s$ is the cold water supply temperature and $r$, $s$, $x_c$ are
fitted to the sensed profile. The variable $x$ is measured from the top of the tank.
The parameter $r$ represents the degree of stratification in the tank and $s$ is
related to the total energy content of the tank.

This would be useful if the integral of the logistic curve simplified later
derivation of the state variables. The integral of the difference between the
temperature profile and the water supply temperature gives a measure of the
energy content of the storage tank. Equation 4-4 shows the analytic
methodology for determining $\text{UTE}$ from the integral of the logistic curve shown
in equation 4-3.

$$\text{UTE} = \rho c \int_{0}^{x_c} A(x) (T_x - T_s) \, dx$$

$$\text{UTE} = \rho c \int_{0}^{x_c} \frac{A(x) (T_{sp} - T_s)}{1 + s e^{-r(x-x_c)}} \, dx$$  \hspace{1cm} (Eqtn 4-4)

This model for deriving tank $\text{UTE}$ leads to difficulties with many
microcontrollers. Firstly, three parameters must be fitted to characterise the
tank temperature profile and this will require considerable controller resources.
The integral itself must be evaluated numerically and the resulting value for
$\text{UTE}$ will be very sensitive to the goodness of fit of these parameters.

Linear interpolation between temperature measurements provides a
simplification whereby neither $s$, $r$ or $x_c$ needs to be explicitly evaluated. If the

\footnote{This temperature is reduced further to 45°C for childcare, schools and nursing homes}
tank is vertically divided into 100 equal volumes, the temperature of each volume is easily found by linear interpolation between the two nearest sensors. By making a single pass through this temperature array, the control algorithm is able to calculate UTE and TTE and this simplifies the computation required.

4.4 Predictive Auxiliary Heating

The most energy efficient water heater would be a tankless design. That is, one that heats water when and where the water is required. Already noted is the requirement of having storage to allow solar contribution and to take advantage of the variable price of auxiliary energy and so the aim must be to mimic the action of a tankless heater as much as possible while maintaining the function of an energy store. This is achieved by delaying the action of the auxiliary heater as much as possible, a practice denoted in this thesis as "just-in-time" (JIT) auxiliary heating.

By actively delaying auxiliary heating to the last possible moment, solar efficiency is maximised and standing losses from the tank are reduced. JIT heating works best with advanced knowledge of the timing and magnitude of upcoming loads.

The predictive energy balance strategy aims to maintain a reduced volume of heated water in the storage tank. With this strategy, it is essential that the mixing of heated and ambient water within the tank is minimised so that the quality (temperature) of the deliverable water is not degraded. The split system with its vertical tank is able to perform much better in this regard than a thermosyphon system with a horizontal tank.

4.4.1 The Predictive Energy Balance

Consider the energy balance for a solar hot water system. The energy demand consists of the load drawn and the parasitic energy losses incurred by collecting and storing the energy. The energy supply consists of solar collection and auxiliary energy, supplemented by any existing energy in the storage tank (figure 4-2).
The balance between energy supply and energy demand must be predicted by the control algorithm for some future period of time since the auxiliary heating cannot heat water instantaneously.

The energy balance is evaluated by the control algorithm by totalising energy quantities over 12 minute intervals. This time interval was chosen as a compromise between fine time resolution leading to tight control of the auxiliary heater, and memory capacity constraints in the controller. The energy balance has greatest significance close to the time leading up to a hot water load. The controller maintains a “safety margin” of hot water at all times, proportional to the uncertainty in the future energy balance. Aspects of forecasting the solar contribution, hot water load, and auxiliary heating, are discussed in Chapters 6, 7 and 8 respectively.

Consideration of the time variation of the energy flows through the tank (figure 4-3) may lead one to deduce the required timing of the auxiliary heater operation. If there is sufficient energy in the tank to meet an upcoming load, then no additional auxiliary energy is required. The future state of the tank needs to be forecasted since auxiliary heating takes time and time-of-use auxiliary heating is not always the cheapest auxiliary heating. This implies that temporal profiles for the insolation, solar hot water, load and system losses will need to be predicted.

The predictive energy balance is an immediate improvement on the traditional thermostat operation since the auxiliary heating is only used when there is a
load demand for extra heat, rather than when the tank temperature drops below the thermostat temperature.

Others have attempted to optimise the analytical energy balance using highly parameterised models and supervisory optimisation programs. These programs ran through large number of combinations of free parameters (e.g. timing of the auxiliary heating) until the optimal solution was found (Prud’homme & Gillet 2000). These methods are based upon minimising a defined evaluation function and are not practical solutions due to the need to parameterise a model for every installation and the fixed nature of both the parameters and the evaluation function.

![Figure 4-3](image)

*Figure 4-3  Time variation of the energy balance without active control of the auxiliary heater. Energy quantities are totalised over 12 minute timesteps as used by the controller*
The optimisation needs to be continuous so that the control algorithm adapts to changes in the system environment over time. Furthermore, approaches to date do not consider the time value of auxiliary energy.

4.4.2 Auxiliary Heating Strategies
Since a temperature profile sensor is being used rather than a thermostat, there are two options for heating a body of water to a given energy content:

- Energy storage as additional volume at the set point temperature
- Energy storage as additional temperature at the current volume.

Adding heat to a volume of water already at or exceeding the set point temperature will provide additional, immediately useful UTE while there will be some time delay to heat cooler water as additional volume.

Comparing the tank losses from each strategy may help to decide which is more appropriate. If the tank temperature gradient is assumed to be linear for this simple analysis, then the rate of energy loss (P_T) from the deliverable volume of UTE (from an isolated tank) is given by equation 4-5. The losses consist of conduction loss to ambient and loss through de-stratification to cooler water.

\[ P_T = U (A_w + A_{cr}) (T_{sp} - T_a) + k A_t (T_{sp} - T_s) / \Delta x \]  

(Eqtn 4-5)

- \( U \) = average heat loss co-efficient of tank
- \( A_w \) = area of tank wall exposed to the UTE volume
- \( A_{cr} \) = area of crown of tank
- \( A_t \) = cross sectional area of tank
- \( T_{sp} \) = average temperature of UTE volume
- \( T_a \) = ambient air temperature near the tank
- \( k \) = effective average conductivity of tank wall, anode and water

\( (T_{sp} - T_s) / \Delta x \) = vertical temperature gradient in the tank
1. Additional Volume Strategy - If an additional $\Delta E$ of energy is to be stored as additional volume ($\Delta V$) then this volume is

$$\Delta V = \frac{\Delta E}{\rho \ c \ (T_{sp} - T_s)} \tag{Eqtn 4-6}$$

If the storage tank is cylindrical and the UTE volume occupies more volume than the volume of the crown of the tank, this adds an additional surface area of $\Delta A$ to the tank wall only.

$$\Delta A = \frac{2 \ \Delta V}{R_t} \tag{Eqtn 4-7}$$

This additional volume will incur a further de-stratification loss since the tank temperature gradient increases with UTE.

The incremental wall losses and de-stratification losses are given by $\Delta P_T$ (equation 4-8).

$$\Delta P_T = U \ \Delta A (T_{sp} - T_a) + k \ A_t \ (T_{sp} - T_s) \left( \frac{1}{\Delta X - \Delta V/A_t} \right) - \frac{1}{\Delta X}$$

$$\Delta P_T = \frac{2 \ U \ (T_{sp} - T_a) \ \Delta E}{\rho \ c \ R_t \ (T_{sp} - T_s)} + \frac{k \ A_t \ (T_{sp} - T_s) \ \Delta E}{(\Delta X \ \rho \ c \ (T_{sp} - T_s) \ A_t - \Delta E)} \tag{Eqtn 4-8}$$

2. Additional Temperature Strategy - If an additional $\Delta E$ of energy is to be stored, in the existing UTE volume $V$, as additional temperature then the additional temperature ($\Delta T$) is

$$\Delta T = \frac{\Delta E}{\rho \ c \ V} \tag{Eqtn 4-9}$$

The losses through both the tank side and top walls to ambient will be increased by $\Delta P_T$ where:

$$\Delta P_T = U \ (A_w + A_{cr}) \ \Delta T = \frac{2 \ U \ \Delta E}{\rho \ c \ V} \left( \frac{2}{R_t} \ V + \pi \ R_t^2 \right) \tag{Eqtn 4-10}$$
The increased losses to de-stratification are:

\[ \Delta P_T = k A_t \Delta T/\Delta x = k A_t \frac{\Delta E}{\rho c V \Delta x} \]  \hspace{1cm} (Eqtn 4-11)

In this case, the total incremental losses are:

\[ \Delta P_T = \frac{2U}{\rho c V} \left( \frac{2}{R_t} \left( \sqrt{V + \pi R_t^2} \right) \right) + k A_t \frac{\Delta E}{\rho c V \Delta x} \]  \hspace{1cm} (Eqtn 4-12)

If a storage tank has parameters \( U=1.5 \text{ Wm}^{-2}\text{K}^{-1} \), \( k=2.3 \text{ Wm}^{-1}\text{K}^{-1} \) and diameter 0.5 m, as used in the TRNSYS models, then the heat losses for the increased temperature scenario are at least three times higher than for the increased volume scenario under all controller operating conditions. The losses in each case are dominated by conduction energy loss through the tank wall.

The conclusion is that the control algorithm should use the additional temperature strategy in combination with a tempering valve to provide very fast recovery of heat up to the tank temperature safety valve limit (usually about 95°C). Such a situation may occur if a load has been underestimated and rapid recovery of tank UTE is desirable. There is a small energy loss penalty due to increased thermal de-stratification and a long term reliability issue with increased thermal stress on the tank. However, the increased volume scenario is the more energy efficient means to add auxiliary heat. A validated simulation model would be useful to verify this result.

Again, the use of a variable location and temperature thermostat provides useful flexibility to the system. Practical means of achieving the variable volume and variable temperature auxiliary heating are discussed in Chapter 8.

4.4.3 Uncertainty in the Energy Balance

It would be foolhardy to aggressively operate the auxiliary heater assuming that all hot water loads can be perfectly predicted and all solar contribution perfectly forecasted. The use of an energy saving controller increases the risk of the service running out of hot water. In practice, it would be prudent to maintain some minimum energy content in the tank. The amount of “safety margin” is
related to the accuracy of the forecasting of the energy balance.

If the load could be perfectly predicted, uncertainty in the solar forecast would be of no consequence to the controller since it could control the tank’s UTE to the minimum UTE profile derived from the hot water loads with feedback from the tank temperature profile sensor. Uncertainty in the solar forecast is important if the load forecast is uncertain or the time value of auxiliary energy is to be considered. This will be explored more fully in Chapter 7.

The load predictor algorithm has a statistical tool used to forecast the error associated with its prediction and thus a means to operate conservatively. The human user may wish to widen or tighten this confidence interval depending upon their bias towards energy efficiency or reliability of service. This modification is performed through the controller’s human interface and effectively multiplies the forecast variance. The human interface allows for stringent energy efficiency optimisation to be overridden.

4.5 Auxiliary Heating Shadows

The following derivation assumes that the tank is perfectly insulated, there is no solar input, the contents of the tank are at the water supply temperature and that a precise volume of cool water is able to be converted to UTE by heating without the threat of de-stratification. Although unrealistic, this provides a good starting point for later refinement of the auxiliary heating requirements.

Assume for now that an upcoming hot water load is to occur at \( t_L \) and is to have energy requirement \( E_{\text{load}} \). If solar contribution is ignored for the moment and the tank is assumed to be cold, the latest time \( (t_0) \) that the auxiliary heater may be activated is given by equation 4-13.

\[
 t_0 = t_L - \frac{E_{\text{load}}}{P_{\text{aux}}} 
\]  

(Eqtn 4-13)

Here \( P_{\text{aux}} \) is the auxiliary heater power rating. The load effectively casts a “heating shadow” back in time (figure 4-4).
A high powered heater casts a shorter time shadow and will favour lessor standing losses and greater solar gain for this reason. A tankless heater would not cast a heating shadow at all.

Now consider the case where there are several loads of equal magnitude following closely in time (figure 4-5). There is some likelihood that the heating shadow from one load will overlap that of the previous load. In this case, heating for the first load must be effectively ahead to an earlier time since the auxiliary heating rate cannot be accelerated.

It is apparent that the controller should be controlling the amount of UTE in the tank since the purpose of the system is to deliver useful energy. The derivation of an auxiliary heating profile is secondary to the generation of a UTE profile for the tank, although it is used later for consideration of variable tariff structures.

The question now arises “What time horizon must be considered for the energy balance?” For the case of JIT auxiliary heating, and ignoring tank thermal
losses, one might consider that an entire storage tank of volume $V_t$ may be heated to the set point temperature, from cold, in a time given by equation 4-14.

$$t = \frac{\rho V_t c (T_{sp} - T_s)}{P_{aux}}$$

(Eqtn 4-14)

For large tanks, this period is usually in the order of four to six hours. There is little need to forecast heating requirements for loads further into the future than this period since any load may be met by auxiliary heating in this interval and the computational requirements may be reduced accordingly. Later, it will be shown that this assumption will need to be revisited if operating cost is considered.

Existing tank energy (from solar input or left over from over-estimation of previous loads) will shorten the auxiliary heating shadow (figure 4-6). If the controller is able to forecast UTE at the time the load is drawn, then the auxiliary heating may be delayed until time $t_1$ given by equation 4-15.

$$t_1 = t_0 + \frac{E_{base}}{P_{aux}}$$

(Eqtn 4-15)

*Figure 4-6  The auxiliary heating time is shortened if there is stored heat and/or solar input*

The ideas of delayed auxiliary heating and heating shadow form the basis of the algorithm developed to evaluate the UTE profile forecast.
4.5.1. Tank Heat Losses
There will be some loss of UTE from the tank between load draws and during auxiliary heating. The control algorithm will need to account for that when calculating a future energy balance as the time interval might be significant (e.g. offpeak auxiliary heating). Only heat losses from the deliverable part of the tank ($T_x > T_{SP}$) will be considered for the energy balance. These losses come from heat loss through the tank walls to the outside world and de-stratification heat losses down the tank to cooler water. The total loss will increase with the tank UTE and thus increase with auxiliary heating (if required) as the impending load draws nearer.

The heat loss from a volume of UTE to environment ($P_{TE}$) is given by:

$$P_{TE} = U (A_w + A_e) (T_{sp} - T_a) \quad \text{(Eqtn 4-16)}$$

The heat loss from a volume of UTE to de-stratification ($P_{TW}$) is given by:

$$P_{TW} = k A_e (T_{sp} - T_s) / (H - x_e) \quad \text{(Eqtn 4-17)}$$

Here $A_e$ is the effective surface of the tank that surrounds the volume containing the UTE, $H$ is the height of the tank and $x_e$ the lower boundary of the volume containing the UTE (assumed to be at temperature $T_{sp}$). For the purposes of an approximate calculation, it is reasonable to consider that in a well stratified tank, there will be a linear temperature gradient from $T_{sp}$ at the boundary of the useful volume to the bottom of the tank at temperature $T_s$.

Some geometry is required to determine the tank wall surface area exposed to a known UTE volume given that the tank has a spherical cap (figure 4-7).

If the edge of the spherical cap is subtended by an angle $\gamma$ from the centre of the cap's imaginary sphere, then the volume $V_{cr}$ of water contained in the spherical cap of radius $R_{cr}$ is found from simple integration (equation 4-18).

$$V_{cr} = \frac{\pi R_{cr}^3}{4} \left( \frac{8}{3} - 3 \cos \gamma + \frac{1}{3} \cos 3\gamma \right) \quad \text{(Eqtn 4-18)}$$
For a given volume $V$ of heated water, corresponding to a measured or forecasted quantity of UTE, the angle $\gamma$ is determined by numerically solving the above equation. The surface area $A_{cr}$ of the same spherical cap is then:

$$A_{cr} = 2\pi R_c^2 (1 - \cos \gamma) \quad (Eqtn 4-19)$$

The depth of hot water in the spherical cap, $x_{cr}$, corresponding to the UTE volume is given by:

$$x_{cr} = R_c (1 - \cos \gamma) \quad (Eqtn 4-20)$$

If the volume of UTE exceeds the capacity of the cap, the extra volume will be exposed to the cylindrical tank sides. Using dimensions supplied by the manufacturer, the volume of the spherical cap is about 30 L. The location, $x_c$, of the lower boundary of the deliverable volume of UTE is now:

$$x_c = x_{cr} + \frac{(V-V_{cr})}{\pi R_t^2} \quad (Eqtn 4-21)$$

The total surface area for the water is also derived from the volume by:

$$A_w = A_{cr} + 2\pi R_t (x_c-x_{cr}) = A_{cr} + \frac{2(V-V_{cr})}{R_t} \quad (Eqtn 4-22)$$

Tank losses to ambient and de-stratification can now be estimated.

The effective tank heat loss co-efficient $U$ may be estimated by simply observing the storage tank overnight between water draw and heating periods.
For the experimental tank, this was estimated to be 1.5 Wm\(^{-2}\)K\(^{-1}\) from datalogging of overnight cooling. This exceeds the manufacturer's TRNSYS model value by 50%. The use of this single value for U is questionable since the effective surface area to volume ratio of the heated volume will change with the highly variable tank UTE. The heat loss for the top of the tank may need to be considered separately from the sides of the tank and factors such as warming of the shell by solar insolation and differential insulation are ignored. Since the error introduced by these assumptions is far less than the error in the load forecast, the controller assumes a constant U, as derived, and calculates the effective surface area the heated water is exposed to at each timestep from the tank diameter.

The effective thermal conductivity down the tank is influenced by the metal sacrificial anode, the tank wall and the enamel lining in the tank and calculated to be 2.3 Wm\(^{-1}\)K\(^{-1}\), somewhat higher than the conductivity of water alone (0.61 Wm\(^{-1}\)K\(^{-1}\)). The heat loss \(P_{TW}\) derived from the equation becomes very large as the tank UTE approaches the tank UTE capacity at temperature \(T_{SP}\). In practice, a large heat gradient tends not to form at the bottom of the tank in such circumstances and the control algorithm places a cap on \(P_{TW}\) of 120 W, corresponding to a maximum temperature gradient of 2.5\(^{\circ}\)C/cm.

The total heat loss \(P_T = P_{TE} + P_{TW}\) is dependent upon ambient temperature and tank UTE. Both of these are known in advance. The control algorithm also requires knowledge of the tank geometry to forecast tank losses. It is difficult to completely avoid model based control. The total heat loss is dominated by losses to ambient and figure 4-8 shows the tank loss is sensitive to ambient temperature even when the controller operates to minimise tank UTE.
Energy loss from a volume of UTE is dominated by losses through the tank walls to ambient for all but small values of UTE. The algorithm's capping of destratification losses tends to curb total losses when the tank is almost entirely full of hot water with a temperature exceeding $T_{sp}$. For very small values of UTE, losses to ambient are proportionally large due to the large surface area to volume ratio for small incremental volumes in the crown of the tank.

These assumptions allow the control algorithm to reasonbly predict future tank losses based on a future UTE profile and make allowances for tank losses in the future energy balances. Before this can be done, the heating shadows must be modified for the non-linear effects of UTE tank losses (figure 4-9). This will allow the new auxiliary heating start ($t'_0$) and end ($t'_1$) times to be determined and allows for times at which the control algorithm takes advantage of lower tariffs by advancing auxiliary heating. Here, standing losses of UTE become important.

The tank UTE losses are related to the surface area of the volume containing the tank UTE and the location of the lower boundary of the UTE volume (i.e. the tank temperature gradient). Equations 4-17 to 4-21 show the relationship between these two variables and the volume of UTE.
However, the rate of loss of UTE is not a linear function of time. The control algorithm uses a numerical technique to approximate the integral of tank UTE standing losses. The time boundaries of the period of standing losses, \( t'_L \) and \( t_L \), are both known from the tariff schedule and load forecast respectively. Although the initial tank UTE condition (before auxiliary heating) may not be predicted with great accuracy, the quantity of UTE \( (E'_{load}) \) immediately before the load is delivered is known from the load forecast. The tank UTE loss at this time is thus able to be predicted from equation 4-18.

If tank UTE is considered constant over a short period, then the required UTE one time period earlier than the load is the sum of the load energy and the tank losses over that period. The total tank losses between \( t_L \) and \( t_L \) are summed in this manner, back until the end of the low tariff period. At this time, the control algorithm has calculated the tank UTE \( (E'_L) \), required at time \( t'_L \), to deliver the correct load at time \( t_L \), accounting for UTE standing losses.

The auxiliary heating start time, \( t'_0 \), may then be calculated using \( t'_L \) and \( E'_{load} \) as initial conditions. With each summation timestep, the UTE total is increased by the tank UTE losses and decreased by the auxiliary energy supplied during the timestep. The summation continues until some summation condition is reached, usually zero tank UTE.
This modification to the heat shadow is particularly important when there are variable tariff structures that provide incentive for energy to be supplied some time in advance of the load.

4.5.2 Heating Shadows with Solar Contribution
Calculation of solar contribution in the energy balance is more complex. The solar collector efficiency depends upon the collector inlet temperature, which in turn depends upon the state of charge of the tank. Solar heated water will cause convection mixing within the tank and so an iterative procedure is required to solve for the tank state. Is the control algorithm destined to employ a generalised model based control approach? A parameterised model for each installation could hardly be considered a practical solution. One might argue that a smart control algorithm that has learning capability would be able to characterise the entire hot water system and comprehensively learn about its installation and use. Certainly, the first order problem is limited in its dimensionality and might be feasible. Second order effects would incorporate human behaviour and would be far more challenging, although not impossible. The real problem is one of the sparseness of the learning set. The controller would not encounter enough experiences to learn from in a reasonable time-frame and thus would not be able to perform sufficiently adequate interpolation to provide accurate modelling. It would likely rely on extrapolation to events not encountered, a difficult procedure.

Fortunately, the control algorithm is able to de-couple the performance of the collector from the state of the storage tank. Since the storage tank is operating in a mode whereby a minimum amount of hot water is stored, where thermal stratification is expected to be well maintained and where water makes only one heating pass through the solar collector, the temperature at the bottom of the storage tank should approximate the cold water supply temperature. This is found to be true in practice. If this assumption is incorrect, the collectors will provide more “solar” contribution than the control algorithm predicted.

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8 That would not be the case for a conventional auxiliary heater unless the water temperature near the heater exceeds $T_{sp}$, but is the case for the auxiliary heating method discussed in chapter 8.
The solar collector efficiency may then be predicted from knowledge of the incident solar radiation and ambient temperature alone. In this mode of operation, either the collector flow rate or the outlet temperature is controlled while the other becomes the dependent variable. The solar contribution can thus be reasonably forecasted.

4.5.3 Algorithm for the Refined UTE Forecast
The control algorithm uses the auxiliary heating shadow approach to make a first guess at the tank UTE profile forecast. This forecast is based only on the upcoming hot water loads, ignoring any residual tank energy, tank losses and solar input. This UTE profile will be met by a combination of solar and auxiliary heating and represents a minimum state of heat content of the tank required to meet a load. Solar input is then superimposed on this profile so that the maximum of the load shadow profile (minimum auxiliary heating) and the solar profile represents the forecasted state of the tank. Heat losses are then evaluated from a correlation with the tank UTE for each timestep and added to the energy supply profile. Heat losses from the tank are only relevant with respect to this minimum UTE, so the tank losses may be calculated on the basis of the minimum UTE profile. If there is excess solar contribution, then the excess heat loss is not of concern to the minimum UTE state.

At timesteps when this profile exceeds the solar input, auxiliary heating will be required and so an auxiliary heating profile is produced. This profile is refined by closing any gaps between successive auxiliary heating timesteps (for a given load) and moving them as late as possible before the load is to be delivered. This results in the just-in-time (JIT) auxiliary heating profile.

The load forecasts include a margin for uncertainty so the controller may provide auxiliary heating in an energy efficient and reliable manner.

The energy balance forecasting algorithm thus generates a sequence of auxiliary heating states and state variable setpoints, one for each timestep. The controller will later control the tank state by measuring the current tank UTE and comparing the measurement with the forecast UTE profile.
The controller will activate auxiliary heating if there is a deficit in UTE. The control algorithm is then certain to meet load requirements regardless of the amount of initial energy in the storage tank or the uncertain solar contributions. Auxiliary heating is delayed as late as possible to minimise tank thermal losses. Although the auxiliary heating profile is not used for control purposes, it is useful when the time value of auxiliary heating is considered.

The controller’s predictive action is shown in figure 4-10. With no solar contribution and fixed auxiliary tariff, the controller activates the auxiliary heater in just-in-time mode.

![Profiles of the state variable UTE and estimated auxiliary heating requirement for AS42334 load profile with and without solar input](image)

The loads are met by auxiliary heating only the amount of hot water required and as late as possible to minimise tank thermal losses. When solar energy forecast information is available, the control algorithm’s delaying of auxiliary switching allows the solar contribution to meet the load and displaces auxiliary heating for the remainder of the day. Overnight tank thermal losses are minimised in each case.

This forecast is generated daily either in a smart controller or in a remote computer and communicated to the controller.
4.6 Tariff Sensitive Auxiliary Heating

The just-in-time heating profile provides the system with the most energy efficient strategy for supplying auxiliary energy to the tank. It mimics the action of a tankless heater while minimising tank thermal losses and displacement of solar gain. This approach correlates to reducing greenhouse gas emissions. There may be other priorities influencing the auxiliary heating options, the most common being minimum operating cost. This will be particularly apparent where the price of auxiliary energy varies in time. The simplest case would be the availability of an off-peak or time-of-use energy tariff. By choosing the degree of advance auxiliary energy supply, the controller has the ability to act as an off-peak thermostat, an energy optimised solar heater and a continuum of modes between.

Many utilities market time of use energy tariffs. This trend is likely to continue as utilities reflect the true cost of their wholesale energy purchases in a deregulated market by price signals to consumers. Only systems with energy storage are able to take advantage of variable tariffs. The control algorithm might choose to bring some auxiliary heating forward in time to benefit from lower auxiliary cost at the expense of energy storage efficiency.

The difficulty of the problem is understanding how to treat the relative values of energy efficiency and cost efficiency from the various perspectives. How much is the user prepared to sacrifice cost performance for energy performance? How important is it to the utility to alleviate peak loading? Will utilities introduce time-of-use greenpower tariffs that might help minimise greenhouse gas emissions?

It is reasonable to assume that the utility will set price levels to its best financial advantage within its operating constraints. From the householder’s perspective, the cost saving of purchasing energy ahead of time and storing it may offset the dollar value of the standing losses incurred. The difference in costs reflects the user’s spot cost of energy efficiency.
Let $L_1 =$ the upcoming load (kWh)
$P_T =$ storage tank loss rate (kW)
$C_1 =$ peak tariff ($/kWh)
$C_2 =$ lower tariff ($/kWh)

The cost of JIT auxiliary heating is the load energy plus the tank thermal losses incurred during the auxiliary heating period. The tank losses will increase during the auxiliary heating period in a non-linear fashion (see figure 4-8), and so must be integrated over the period of the auxiliary heating (equation 4-23).

$$\text{JIT Cost} = C_1 L_1 + C_1 \int_{t_0}^{t_l} P_T \, dt \quad (\text{Eqtn 4-23})$$

When heating during a lower tariff period, the control algorithm forecasts the amount of extra heat it will need to store to account for standing losses of UTE and sources this extra energy during the low tariff period. The period of auxiliary heating is shifted ahead in time from JIT heating, now starting at $t_0'$ and ending at $t_L'$ where the period $t_0'$ to $t_L'$ is slightly longer than $t_0$ to $t_L$ due to the extra heating required. Equation 4-24 shows the cost of auxiliary heating with the lower tariff.

$$\text{Lower Tariff Cost} = C_2 L_1 + C_2 \int_{t_0}^{t_l} P_T \, dt + C_2 \int_{t_0'}^{t_L'} P_T \, dt \quad (\text{Eqtn 4-24})$$

Before the two costs can be compared, the tank UTE loss integrals for the auxiliary heating and standing loss periods must be evaluated using the numerical approach described in earlier.

The normalised premium for energy efficiency (equation 4-25) suggests that if the auxiliary heating for a given load $L_1$ is moved from a lower tariff period to JIT heating (a time shift of $\Delta t$) then the user will pay a quantifiable premium for this.
\[
\frac{\text{JIT Cost} - \text{Lower Cost}}{L_1} = (C_1 - C_2) + \frac{C_2}{L_1} \int_{t_0}^{t_1} P_T dt + \frac{C_2}{L_1} \int_{t_0}^{t_L} P_T dt - \frac{C_1}{T_1} \int_{t_0}^{t_0} P_T dt
\]

(Eqtn 4-25)

Alternatively, if the controller does not take advantage of off-peak tariffs, then there is an opportunity cost associated with this "energy efficient" behaviour. The additional cost is due to the higher tariff if peak energy is required to heat the water just before a load is delivered. There is a small offsetting reduction in cost associated with decreased tank thermal losses and increased solar efficiency.

The auxiliary energy cost premium is plotted in relation to the load size and delay from the offpeak tariff availability to the time of load in figure 4-11. Parameters used for the graphs are \(C_1 = 10\text{ c/kWh}, \ C_2 = 5\text{ c/kWh}, \ P_{aux} = 3.6\text{ kW}, \ k = 2.3\text{ Wm}^{-1}\text{K}^{-1}, \ U = 1.5\text{ Wm}^{-2}\text{K}^{-1}, \ T_a = 15^\circ\text{C}.\)

For a given load (corresponding to a period of auxiliary heating), and a maximum tolerable energy premium, the left hand graph shows the maximum time period between the time of auxiliary heating and time of low tariff that makes the lower tariff worthwhile. The effect is highly non-linear for loads less than 50 L. For these small loads, there is little benefit in taking a low tariff since tank standing losses from the auxiliary heating may exceed the size of the load.

![Figure 4-11](image)

*Figure 4-11 Two representations of the energy efficiency premium relation as explained in the text. Users select an acceptable level of energy premium*
The control algorithm interprets the energy premium relation differently. The algorithm is aware of the upcoming loads (compensated for accumulated solar gain) and the user’s willingness to pay a premium to ensure that the controller operates the storage tank in an energy efficient manner. Energy efficient behaviour is characterised by purchasing auxiliary energy during peak tariff and providing JIT auxiliary heating, even though there is a lower tariff available. The algorithm calculates the minimum time shift between the load delivery and period of lower tariff that may be used if the premium is not to be exceeded.

If the householder can decide upon an acceptable premium for the cost of energy efficiency, then the algorithm will be able to decide when best to purchase auxiliary energy. The spot value of energy efficiency is largely independent of the load size and the forecasted solar input, provided that the auxiliary heating requirements are derived from a predictive energy balance and provided that the tank is well thermally stratified.

Even if the householder wishes to operate the system in a manner that minimises auxiliary energy cost by use of low tariff auxiliary energy (figure 4-12a), the solar water heater with active control will still operate with greater solar gain potential than a water heater with a thermostat. This is because the algorithm has a-priori knowledge of upcoming solar gain and load so that the off-peak auxiliary requirement is reduced. The controller’s action is “patient” while the thermostat action might be described as “anxious”. Increasing willingness by the user to pay for energy efficiency results in the control algorithm tending towards JIT auxiliary heating (figure 4-12 b,c,d).

Another method of modelling the cost of energy efficiency is with a cap on the daily total premium. This may be more acceptable to householders because it is independent of (rather than proportional to) the load. Starting with the just in time auxiliary heating profile, the control algorithm’s methodology would be to move those auxiliary heating periods that come before expected solar gain to the time of lower tariff until the cost cap is breached. This method results in the greatest solar opportunity.
Figure 4-12  Profiles of the state variable UTE and estimated auxiliary heating requirement for AS4234 load profile with various energy efficiency premiums (no solar contribution). The energy tariff is high between 6am and 6pm and there is no solar contribution in this example.

A completely different approach to the auxiliary optimisation problem is to divide the timespace into timesteps and analyse a combinational problem. With this approach, a timestep either does or does not require auxiliary heating as determined by the JIT heating profile. The total amount of auxiliary heating before a given load must not be reduced, but there is an opportunity to move auxiliary heating timesteps to an earlier time to take advantage of lower tariffs. This is a combinational problem with an order of the number of timesteps in the horizon considered. Computationally, this is very demanding and excludes the potential to find a globally optimal solution with limited computational power.

Simplifications in the form of dynamic programming were tried and gave reasonable results but it was difficult to include an interpretable bias relation between cost savings and energy efficiency using this method. The method also
produces a locally optimal solution that becomes particularly apparent when the user is only prepared to tolerate a low (but non-zero) premium for energy efficiency.

The ability of the controller to operate the water heater at a defined level of cost and energy performance provides both the householder and the utility with a degree of flexibility. The householder has the ability to influence the performance of the hot water system in efficiency and cost. The utility has the ability to move energy demand to avoid high market spot prices for energy (as reflected in the tariff). The mechanism allows the utility to send a daily tariff forecast to the controller and these directives may be related to the utility’s exposure to a forecasted wholesale energy tariff.

4.7 System Performance Including Energy Premiums

The effect of shifting auxiliary heating periods to an earlier time to take advantage of lower tariffs compromises the solar contribution to tank UTE. TRNSYS modelling was used to investigate the extent of this compromise.

The predictive energy balance programs were run with the TRNSYS typical meteorological year weather data. The levels of energy premium were changed from completely energy efficient behaviour (an additional 5 c/kWh on the lowest available tariff) to completely cost efficient (no premium). The simulations were performed with and without the solar forecast to check the effects of a breakdown in communication in the internet link to the Bureau of Meterology (figure 4-13).

When the control algorithm was functioning with a solar forecast, cost efficient behaviour resulted in a large increase in auxiliary consumption, at the expense of solar fraction and tank losses. The cost savings in this example were only $12 per year but may be more significant for other tariff regimes or systems without solar collectors.
When there was no solar forecast available and the minimum auxiliary cost was sought, the control algorithm had to act in the most conservative manner. This implies that it must mimic a conventional thermostat controlled off-peak water heater and heat the tank sufficiently to cover all of the anticipated loads and the tank losses associated with meeting these loads. The cost of not having a weather forecast when acting in cost-efficient mode was $69/yr. The benefit form having a weather forecast when acting in cost-efficient mode was only $12/yr!

One might conclude that the complexity and expense of having a weather forecast is unwarranted and the system should run in its most energy efficient mode at all times. The weather forecast is needed when there is uncertainty in the load forecast so that the control algorithm can limit the degree to which it must (excessively) auxiliary heat to cover uncertain load timing and magnitude.
4. Predictive Energy Balances
5. State Variable Sensing

"The theory of our modern technic shows that nothing is as practical as theory"

Robert Oppenheimer

5.1 Introduction

If a hot water system could be perfectly modelled, temperature sensing in the storage tank would not be necessary. Models of this complexity do not currently exist and the thermostat is the first approximation to estimating the energy content of the tank by deterministic means. However, the thermostat does not provide sufficient information to carry out advanced control of a water heater.

Any energy optimising algorithm will need to understand the current state of charge of the thermal store in far greater detail. The thermostat must be replaced by an energy content detector. For conventional hot water storage tanks, a measure of sensible heat content is given by the temperature profile in the tank.

For the purposes of control, the tank temperature profile quantifies the state variables UTE and TTE. The state variable has important secondary roles in sensing the hot water load drawn from the system and in propagating the predictive balance algorithm error as performance feedback to the energy optimising algorithm.

Only with the state variables UTE and TTE as initial conditions can a control algorithm make a sound judgement on predicting future energy balances. The thermostat does provide an initial condition, but one that precludes optimisation. When coupled to a suitable intelligent controlling agent, this sensor provides the functionality of a variable position, variable temperature thermostat.
5.2 Sensing Options

The control algorithm requires a measurement of tank UTE to compare to the required UTE predicted by the energy balance. Control action is based on this comparison. A number of tank energy measurement technologies were investigated including direct temperature measurement and measurement of a temperature related property of water. They were as follows:

1. Series electrical resistance devices – A number of temperature sensing devices (thermistors, p-n junction devices, bimetallic switches, thermocouples) placed in series simplifies wiring arrangements, particularly for in-tank sensors. Each series sensing element adds resistance or voltage to the sensor string according to its local temperature. Total series resistance is measured requiring one pair of wires. Designs of this nature integrate the energy content of the tank but cannot distinguish energy content above the “useful” temperature threshold.

2. Ultrasonic devices – an ultrasonic transmitter sends a series of packets of pressure waves to reflecting targets at regular intervals down the tank. The waves are reflected from the targets and picked up by an adjacent receiver. The speed of sound is related to the density and compressibility of the medium in which it travels, and hence proportional to the temperature of the water for each wave packet. The effect is non-linear and the speed of sound in water is greatest at 74°C (approximately 1550 m/s). The sensor would need to have complex signal processing capability to detect phase delays and deal with signal reflections and may be expensive.

3. Tank weight measurement – This is based on the principle that water is less dense when hot. There are a number of obvious problems with this approach and it was not investigated further.

4. Viscosity measurement – measuring the torque required to turn a long paddle wheel in the tank provides a measure of the water dynamic viscosity. Stirring of the water by the device is undesirable for the preservation of thermal stratification.
5. Discrete temperature measurement – A number of individually wired temperature sensors could be connected to a local sampling device that derives values for UTE and TTE. It is possible to use discrete sensing elements connected to a common two-wire bus (eg. Dallas semiconductor DS1802) to simplify wiring.

6. Optical fibre measurement – The University of Sydney has developed a distributed temperature sensing technique using a single optical fibre. Diffraction gratings are formed in the fibre at regular intervals where the temperature is to be measured. The optical properties of the grating change with temperature. Each grating is made sensitive to a different wavelength of light and so frequency division multiplexing may be used to sense a number of temperatures using one fibre. The temperature range of these devices is limited by the fibre sheath material. Conventional fibres would tolerate temperatures typical of water heaters. Temperature measurement accuracy is reported to be within 1°C. This is an emerging technology, but still expensive due to the extensive signal processing required at the end of the fibre.

5.3 Sensor Solutions

Bearing in mind that a simple, robust and cheap manufacturing solution is desirable, options 1-4 were not pursued and a sensor using discrete sensing elements was designed. Discrete temperature sensing could be applied internally or externally to the tank. External mounting offers a number of advantages during assembly of the device:

- The device does not need to be mains pressure rated
- There is no concern over water leakage
- There is no corrosion or contamination problem
- Ease of maintenance (if required at all).

Tests were performed on an old enamel lined steel tank to check whether the proposed external mounting of temperature sensors would introduce any error.
Three temperature sensors were bonded to the outside of the tank steel wall (using Loctite 315 thermal epoxy $k= 0.185$ Wm$^{-1}$K$^{-1}$, 0.15 mm film). They were located as closely as possible to each other. A further three sensors of the same type were suspended within the tank at the same vertical position as the external sensors, but in three separate positions across the tank. Averages of each set of three temperatures were used for the comparisons.

Since the thermal resistance of the enamel lining, tank wall, thermal epoxy and sensor (and any silt deposits) is small compared to the enveloping insulation, there is a small temperature drop from the water inside the tank to the measured temperature on the external tank wall (figure 5-1). The effect of external mounting of the sensors may be interpreted as a temperature difference or a time lag since the temperature profile of an operating hot water system is never in "steady state". The temperature difference is related to the rate of change of temperature of the water and was essentially zero when the system was initially filled with cold supply water (within 2°C of ambient) and left to stand. This is the "equilibrium" point on figure 5-1.

![Figure 5-1](image)

*Figure 5-1  The error from placing temperature sensors outside of the tank is proportional to the rate of change of temperature of the water. Although the absolute error is small, it has important timing implications for the controller*

During auxiliary heating at 3.6 kW (as used in the split systems), the average error was 0.84°C. From a plot of the inner and outer temperatures against time, this error was found to be equivalent to a time lag of around 75 seconds. The
consequence of the external mounting of the temperature sensors is that the system will use up to 3 control periods (30 s each), or 324 kJ, of excessive auxiliary heat for each heating event. The controller will also be late in detecting that auxiliary heating is required when UTE is decreasing. Despite the lower sensor error (0.56°C), the low rate of natural cooling leads to a long delay time in the detection of an under-supply of tank UTE. This subtle time delay is in the order of 15 minutes which represents a serious error for a just-in-time auxiliary heating controller. This led to the investigation of an internal tank temperature profile measurement.

5.3.1 Internal Temperature Probe
It was decided to test an internal temperature sensor assembly, rather than applying correction to the external temperature sensors. The sensor assembly consisted of a thin wall stainless steel tube that had indentations containing thermistors at discrete intervals (figure 5-2). There are 10 sensing elements placed at 15 cm intervals down this tube and bonded with high temperature epoxy resin. The tube ends were sealed in resin also and the device was located in the sacrificial anode access hole. It was sealed with compression fittings. The anode was temporarily removed during the tests.

Figure 5-2  Internal temperature profile sensor and its installation in the anode boss in the crown of the tank
This device was difficult to manufacture since all the eleven cables had to be tediously threaded down the tube, connected to the thermistors, electrically insulated and bonded in place. Two of these probes were constructed. Although they worked well while left alone, the sensors' robustness was questionable. The epoxy seals would sometimes fail, possibly due to thermal fatigue, and the device became prone to leakage. Perhaps a mass manufactured device based on a number of surface mount digital thermistors with a common two-wire bus would be a workable solution. The sacrificial anodes were eventually replaced and external temperature sensors fitted.

5.3.2 External Temperature Measurement Assembly
The degree to which compensation must be applied for the external temperature sensing depends upon the rate of heat change in the tank and is most critical during slow temperature movement about the critical temperature. An analytical solution to anticipating the sensor delay would be prone to individual sensor noise and lead to incorrect switching of the auxiliary heater. A good solution is to develop an experimental rule of thumb for the delay time that provides reliable operation. The predictive algorithm switches the auxiliary heater one predictive timestep (12 minutes) early to account for sensor delay. This action increases auxiliary energy consumption but provides some additional UTE should the load forecast be inaccurate.

A strip of the metal shell was removed from the experimental system's tank. The insulation in this strip was removed, exposing a strip of tank wall to which ten thermistors were fixed with Loctite 315 thermal epoxy (figure 5-3) as with the trial tank in section. The gaps in the insulation were filled with rockwool and the shell resealed.

The sensors were placed as accurately as possible on the side of the tank but had to be calibrated (in position) to give a correct reading of tank energy. This calibration was achieved by draining the tank slowly (i.e minimal inlet mixing) from a known temperature profile. Measurement of the time delay between the outlet temperature and the temperature profile led to direct location of each sensor in the string since the load flow was measured.
Conduction mixing of the hot water did not cause problems over the short period of the test. The tempering valve was bypassed for this operation.

5.3.3 Sensor Noise Problems
It was found in practice that the sensors produced significant noise in the value of UTE. This is undesirable for control purposes and the sources of this noise were examined. Variation in one sensing element resistance of 1% at 65°C leads to a temperature error of 0.1°C and a potential error of 75 kJ in UTE. If this variation occurs in the supply temperature sensor, it affects all energy calculations. Since a practical assembly will always exhibit temperature variation from manufacturing tolerances, filtering of the results was attempted. More specifically, a low-pass or averaging filter was required.

Any low pass filter introduces a time lag between the actual temperature measurement and the filtered measurement. A time lag exceeding one controller decision period (30s) is undesirable since this amounts to 108 kJ of wasted auxiliary heating for each heating event. Although UTE was used every 30 seconds for control purposes, it was sampled every 6 seconds. Before being used for control, the highest and lowest of the 5 samples were disregarded and the remaining three averaged. This was found to provide results consistent over time to within 10 kJ when no flows were impinging on the tank.
Most disturbance to the temperature profile occurred from transient hot water inflow and water draw events. Sometimes, there was inconsistency in the amount of energy flowing into and out of the tank with the UTE measurement. This is suspected to be the result of plug flow\(^9\) occurring between sensors in the tank. If this was occurring then the assumption of linear temperature profiles between sensors is not valid. Sudden changes observed in some measured temperatures suggest that this was happening. Such a temperature plug will not be stable over time and will decay to a more linear profile between sensors, but an accurate profile is needed in the short term for accurate auxiliary heating control. Anticipation of the temperature plug location from the collector flow (from the pump power setting which was known to the controller) did not provide an accurate solution. The best practical solution may be the mass production of a printed surface mount sensing device which contains a larger number of thermistor elements (perhaps 100) and an integral processor chip. This sensor would be bonded in place during tank assembly (before insulation) and use a serial connection to the controller (three wires in total).

### 5.4 Hot Water Load Sensor

The change in temperature profile in the tank provides the controller with an indication of the load drawn from the tank. Detection and subsequent learning of load events is an integral part of the control algorithm's predictive energy balance strategy (chapter 7). The use of the tank profile sensor eliminates the requirement for an extra discrete flowmeter and temperature sensor for detecting loads.

### 5.5 The Tank “Fuel Gauge”

A further use for the temperature profile sensor is to provide the human user with a view to how much energy is available in the storage tank. This is analogous to the fuel gauge in a car. This would provide a basis for a householder to make a decision regarding whether the controller action may

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\(^9\) Plug flow may be visualised as an unmixed body of water in the tank at a different temperature to the surrounding water, that moves as one body with the tank flows.
need to be overridden. It would provide information to service personnel or the conscientious owner on the performance of the system. Several such devices were designed and constructed (figure 5-4). The original water heater "fuel gauge" gave a simple indication of the amount of available hot water \((T > T_{sp})\) in the tank by way of an illuminated bargraph. This unit connected directly to the tank profile thermistors and calculated the state variables \(U_{TE}\) and \(T_{TE}\) directly. This information was then passed to the main system controller by way of a serial peripheral interface (SPI) bus.

![Figure 5-4](image_url) Original water heater "Fuel Gauge" with its bargraph indicator is now incorporated into the digital user interface

This functionality was later built into a digital user interface that allows users to observe the state of the system, the forecasted tank state, the system’s performance and make adjustments as necessary. The device allows users to influence the control the water heater operation in some detail. It is similar in operation to a domestic air conditioning controller.

The digital interface allows users to select an acceptable energy premium and thus dictates how much auxiliary energy is sourced from off-peak supply (where available). When the digital interface is used, sensing of the tank state variables is carried out by the main controller and the SPI bus is used to communicate bi-directionally between the main controller and the user interface. This removes one point of failure in the system as the controller can operate on default settings without an operating human interface.
Since the controller collects information on the system load, calculates tank losses and controls auxiliary heating, it is able to provide the digital interface with energy consumption and solar contribution information. This has not yet been programmed into the software. Any modifications such as this are simply a software revision.

The digital user interface was based on the same Tiger CPU used by the main controller. A demonstration unit was constructed to show manufacturers but was not connected to the main controller during the experiments. The demonstration unit had four graphics that users could toggle between by repeatedly pushing a button on the front panel of the unit. The four displays were:

1. A temperature set point with adjustment
2. A manual over-ride to set auxiliary heating on, set auxiliary heating off, or to leave the controller to run the system
3. A display of the anticipated tank UTE profile for the day that might enable a user to intelligently set the manual over-ride
4. A summary of the energy consumption of the unit, including solar contribution, auxiliary consumption and operating cost.

The design of the hardware and software for the digital user interface was a diversion to the main direction of the thesis and its detailed design is not presented.
6. Forecasting Solar Contribution

"It is unworthy of excellent men to lose hours like slaves in the labour of calculation which could be relegated to anyone else if machines were used"

Gottfried Liebnitz, Mathematician

6.1 Introduction

The hot water output of a solar collector is primarily dependent upon the radiation incident upon it. The predictive control algorithm needs to know how much hot water the storage tank will receive from the collectors and when it will be received. Solar insolation consists of beam radiation, diffuse radiation from the sky, and diffuse radiation from the ground and nearby objects. Even on a clear day, some of the insolation will be diffuse. The component of each of these sources incident on the collector is now evaluated.

The required steps are:

- Obtain a forecast for solar insolation and ambient temperature (24 hour duration)
- Calculate the insolation expected to be incident on the collector
- Calculate the expected collector efficiency
- Calculate the amount and timing of expected hot water delivery to the tank.

6.2 Weather Forecast Service

Considerable time and effort went into establishing a new solar insolation forecasting service in co-operation with the Bureau of Meteorology (BOM) in Melbourne, Australia as part of this research. After searching various media services and BOM public services, no detailed quantitative information on insolation forecasting for even the following 24 hours could be found. The BOM forecasting supercomputer was already calculating insolation and ambient temperature at the time of the enquiry (October, 2001), but the information
was not being used. BOM agreed to carry out some formatting and administration tasks to make the data available on their secure ftp server. BOM also agreed to carry out initial checking on data validity based on daily recorded observations. It was desirable that the controller received the data electronically and automatically. The ftp service was established in April 2002 at no cost to this project on the proviso that ANU carry out a validation study based on local observations after a period of a few months. There were a number of problems initially with the quality of the forecasts (since the calculation process had not been validated) and the reliability of the service. The service now runs with an availability of about 85%.

The service provides a 72 hour electronic forecast of hourly global horizontal insolation and ambient temperature. This data is uploaded from BOM each night to the controller for processing and recording. A sample data file is shown in Appendix A.

The BOM forecasting computers utilise 12 km$^3$ (i.e. cubic elements) spatial resolution and hourly temporal resolution. The forecasts are updated every 3 hours by the BOM forecasting model but downloaded to the controller once daily at around 3am. The global horizontal insolation and ambient temperature are instantaneous forecasts at the beginning of each hour. The processing program on the controller interpolates the hourly values into 12 minute values using linear interpolation. There has been discussion in the literature regarding the difficulty of modelling the temporal movement of clouds and various means of predicting sub-hourly climate data from hourly values (Tovar et al 2001; Gansler et al 1995; Liu & Jordan 1963). The interpolation options include:

1. Assume a constant value over the hour
2. Use linear interpolation between successive hourly values
3. Obtain historical local data and fit a cumulative probability distribution using Fourier analysis.

Instantaneous values of solar radiation have a bi-modal distribution indicating
cloudy or clear sky whereas daily average insolation tends to have a uni-modal distribution caused by the averaging of the clearness index and the inability to use air mass as a variable (Suehrke & McCormick 1988). The extent to which this occurs for hourly averages is unclear although the use of solar altitude in a correlation for hourly diffuse (from hourly global horizontal forecasts) will help address this. The fitting of the co-efficients of this correlation to Canberra weather data is also helpful although insufficient data resolution was available to develop a cumulative probability distribution of sub-hourly insolation. A further problem is the auto-regressive nature of high-resolution insolation and ambient temperature data (the current value is closely related to the previous value) that is not addressed by a purely probabilistic model and not always apparent in lower resolution data. Linear interpolation of hourly global insolation from the forecast is used in this thesis.

The use of linear interpolation for the ambient temperature near ground level seems reasonable given the proximity of a large thermal mass (the ground). Heat loss from the collector and tank due to wind are likely to be highly localised and difficult to model. This was not included in the forecast.

6.2.1 Forecast Validation
Once known and obvious problems with the BOM service had been corrected, a dataset representing five months of forecasts and observations (November 2002 to March 2003) of insolation and ambient temperature was gathered. Global horizontal insolation data was collected from a pyranometer (Kipp and Zonen CM11) at ANU while the ambient temperature data came from the BOM Canberra observation station located at Canberra Airport. There is difficulty in conducting a valid comparison using spot values since the temporal formation and movement of clouds is difficult to model (Rikus, L., 2002, BOM Research Centre, personal communication, Mar 21st). A comparison based on hourly integrated totals would be better.

Nonetheless, a comparison was performed on the data available. The comparison was performed only for daylight hours and some data was not available. The dataset had 82% completeness (n=1273) over the sample
Firstly, forecast solar insolation was compared to the observed global horizontal insolation. The error in the forecast was defined as:

\[
\text{Forecast value} - \text{Observed value}
\]

The percentage error in the forecast was defined as:

\[
\frac{\text{Forecast value} - \text{Observed value}}{\text{Forecast value}} \times 100\%
\]

The insolation forecast error was less than 20% for only a third of the forecast period. A number of correlations were performed to try to characterise this variation. A histogram of the percentage insolation error (figure 6-1a) suggests a strong tendency towards over-estimating insolation in the forecast. A plot of the insolation percentage error against the forecast itself (figure 6-1b) suggests large errors were occurring at low insolation levels. This is not surprising since the pyranometer is noticeably less accurate at low light levels and local shading effects would result in the forecast over-estimating the observed insolation.

Figure 6-1 Investigation of insolation forecast errors
These checks were repeated only for insolation levels exceeding 150 W/m² to eliminate this as a source of error. Solar collectors will not collect much energy in such low light levels so ignoring low light forecasts is not a problematic assumption. The revised data showed substantially reduced incidence of the large errors but still a dominant trend towards over-forecasting the insolation.

The next step was to investigate potential systematic forecasting model errors. A plot of the insolation error against time of day (figure 6-1d) shows a slight trend to an error increasing with time from the model initial conditions. A range of correlation fits were attempted including straight line, polynomial and logarithmic. Even the best correlated fit revealed no obvious relationship ($r^2=0.11$). A second check on the model was to look for variation of the error with the magnitude of the insolation itself. Again, no correlation was apparent ($r^2=0.03$). As a result of the validation, the conclusion is that there is a systematic error in the insolation forecast of +20% with a high standard deviation of 50%. The Bureau of Meterology are aware of the problem but have not modified the algorithm to date. A possible cause is the poor characterisation of the surface albedo of the earth, particularly the localised aberrations. This affects the energy and moisture balance for each 12 km³ grid space and hence the possible formation of a cloud in that grid. A second possible cause is that the temporal movement of clouds, particularly strato-cumulus clouds, is poorly understood.

Investigation and correction of the insolation model is not a trivial exercise and this work should to be carried out by BOM. For now, the controller subtracts 20% of insolation forecasts it receives from BOM.

The ambient temperature forecast was considerably better than the insolation forecast. The mean error of -2.9°C indicates that the forecast was underestimating the actual ambient temperature. The ambient temperature error histogram (figure 6-2a) shows no marked skewness in the error distribution. Importantly, the standard deviation in the error is only 5°C. Once again, sources of systematic errors were sought. A correlation of the error
against ambient temperature (figure 6-2b) shows no significant relationship \( (r^2=0.14) \). A correlation of the error against time of day (figure 6-2c) shows no relationship at all \( (r^2=0.00) \).

The surface albedo estimation is again suspected of causing this error. The controller will add 2.9°C to all ambient temperature forecasts received from BOM.

![Ambient Temp Error Histogram](image1)

![Ambient Temp Error vs Ambient T](image2)

![Ambient Temperature Error vs time](image3)

*Figure 6-2  Investigation of ambient temperature forecast error*

The forecasts with their associated error will be used by the control algorithm to evaluate the predictive energy balance. The control strategy copes well with errors in the weather forecast provided that:

- The user wishes the controller to operate in the most energy efficient manner rather than the most cost-effective manner (if a variable auxiliary tariff is available)
- The error in the load forecast is reasonably small.

The errors introduced into the predictive control algorithm from the errors in the weather forecast will be analysed later.
6. Forecasting Solar Contribution

6.2.2 Sensitivity of Energy Balance to Insolation Forecast Error

There will always be some error in the forecast insolation and the subsequent processing. It would be useful to understand how seriously this error affects the predictive energy balance algorithm.

Intuitively, the insolation forecast is not very important if the controller is operating in "just-in-time" heating mode with well known loads. In this mode, the controller reacts to deficits in current tank UTE from forecast UTE. When the controller is acting strategically, either to take advantage of lower tariffs or to provide security against uncertain upcoming loads, solar gain between the advanced auxiliary heating and the anticipated time of the load is important as it may reduce the extent of the auxiliary heating.

The TRNSYS model was used to check the algorithm performance against errors in the forecast hot water gain, ranging from a 50% under-estimate to a 50% over-estimate applied to each timestep in the simulation (figure 6-3). This approach is used, as opposed to a random error, since the BOM forecast tends to be biased consistently in this manner over a day. The simulations were repeated for a range of energy premium settings to provide a time offset between auxiliary heating and the anticipated load. The model was based on the external auxiliary heater design and the constant outlet collector strategy to be presented in later chapters.

As expected, there was no detectable performance sensitivity to forecast hot water gain when the system operated in its most energy efficient manner (figure 6-3c). This is when the user is prepared to pay a high premium for the controller to act in an energy efficient manner (5c/kWh in this case). This is equivalent to "just-in-time" auxiliary heating and maximum solar gain is achieved simply by delaying the auxiliary heating as late as possible.

When low tariff period (off-peak) auxiliary heating was used, the behaviour was more sensitive to errors in the solar forecast (figure 6-3a,b). If the solar input was over-estimated, the controller would not use as much pre-emptive auxiliary heating. This resulted in it behaving more like a just-in-time heater (with guaranteed hot water delivery to load forecast set point). This means that the
cost savings of running in low tariff period mode will be partly negated but hot water will still be deliverable when required since the auxiliary heating will be delivered “just in time” by the controller.

Figure 6-3 Errors in the forecasted solar hot water gain are significant when the cheapest auxiliary heating solution is sought.

Under-estimation of solar gain degraded controller performance more noticeably. The controller increased its low tariff period auxiliary heating in preparation for a lack of solar input, acting in the manner of an off-peak
thermostat. Solar gain was presumably reduced due to an increase in average collector inlet temperature from conduction down the tank. Interestingly, the increased auxiliary heating requirements generally had a lower impact on auxiliary cost when solar input was under-estimated than when it was over-estimated since most of the auxiliary heating in the later case was from the low tariff period.

There are times when the weather forecast will not be available at all through failure of the network connection or processing infrastructure. The TRNSYS model was again used to estimate the resulting performance penalty. The model was run with a perfect weather forecast and again with no weather forecast (no solar hot water input assumed) over a range of energy premium values (figure 6-4).

![Diagram](image)

**Figure 6-4** Controller performance without a weather forecast is degraded severely if off-peak tariffs are sought
Since the performance of the just-in-time controller is not affected by errors in the weather forecast, it is also not affected by the absence of a weather forecast. When low tariff auxiliary heating is used without a weather forecast, the controller acts similarly to an offpeak thermostat heater, although with the ability to reduce the heating volume to match a known upcoming load. In this case the controller would be best to revert to a failure mode of swapping to a higher energy premium mode, say 4c/kWh in order to minimise auxiliary cost.

6.3 Estimating Beam and Diffuse Insolation

Although the forecast provides only global horizontal radiation, the controller needs to understand the relative contributions of beam and diffuse components since they are absorbed in differing amounts. There are a number of correlations that predict diffuse component \( H_D \) of the total horizontal radiation \( H_T \) and hence the beam radiation \( H_B \) from the difference. The incidence angles of each component are also important since the collector cover transmittance is a function of light incidence angle.

This thesis uses the Reindl correlation method (equation 6-1) (Reindl et al. 1990) modified for local conditions. The correlation relies upon a ratio \( M \) of the forecast global horizontal \( H_T \) to the extraterrestrial radiation \( H_E \) on a horizontal projection and has three co-efficients \( c_1, c_2, c_3 \) for each of three ranges of \( M \).

\[
H_D = H_T (c_1 - c_2 M - c_3 \cos \theta) \quad (Eqtn \ 6-1)
\]

\[
H_E = 1373 (1 + 0.033 \cos(2\pi \left( \frac{\text{day} + 10}{365.24} \right)) \cos \theta) \quad (Eqtn \ 6-2)
\]

A study performed by Spencer (1982) indicated that the co-efficients of this correlation were dependent upon latitude (air mass) and correlations were performed from measured data for some Australian cities. The correlations were performed from three years of observations and carried out using the method of Orgill & Hollands (1977). The original correlations performed by Spencer had no separate correction for solar altitude or season. Work presented in this
thesis extends Spencer’s correlation to include a term for solar altitude and to examine seasonal variation of the correlation. Both of these factors are important to the controller if an accurate solar contribution is to be forecasted. Data from the correlations for Wagga Wagga are relevant since the latitude and locale are similar to Canberra.

A sample of five years of half-hourly global, beam and diffuse radiation was obtained from the Bureau of Meterology for the Wagga Wagga weather station for the period 1997-2002. Data was grouped into four seasonal sets, then further grouped into bins in the quantity $M = \frac{H_T}{H_E}$ of span 0.05. Some filtering was performed to eliminate a small number of erroneous data triplets wherever:

- $H_T < 20\text{W/m}^2$, $H_T < H_D$
- $M > 1.1$, $\cos \theta < 0.25$

The correlation technique was repeated for each seasonal dataset but included an additional term for solar altitude ($\theta$) and resulted in correlations for the diffuse content of global horizontal radiation. An average and standard deviation were plotted for each bin of the quantity $M$ (figure 6-6) so that the curve might be visualised before being divided into a series of regional linear approximations. For each season, consistent breakpoints in this trend were found at $M=0.35$ and $M=0.8$, consistent with the literature mentioned previously. The resulting two dimensional correlation yields equations of the form of equation 6-1.

The correlation results for each season are presented in table 6-1. The comparison shows that seasonal considerations are important. A 20% increase in diffuse component is evident in winter relative to summer and this closely matches the seasonal change in humidity at this location, although this link may not be causal (figure 6-5). For the range $0.35 < M < 0.8$, solar altitude had a much greater effect on diffuse fraction during the Australian spring and autumn.
6. Forecasting Solar Contribution

<table>
<thead>
<tr>
<th></th>
<th>$M &lt; 0.30$</th>
<th>$0.30 \leq M \leq 0.8$</th>
<th>$M &gt; 0.8$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C_1$</td>
<td>$C_2$</td>
<td>$C_3$</td>
</tr>
<tr>
<td>Spring</td>
<td>1.023</td>
<td>-0.709</td>
<td>-0.042</td>
</tr>
<tr>
<td>Summer</td>
<td>0.978</td>
<td>-0.837</td>
<td>-0.007</td>
</tr>
<tr>
<td>Autumn</td>
<td>0.991</td>
<td>-0.664</td>
<td>0.068</td>
</tr>
<tr>
<td>Winter</td>
<td>1.000</td>
<td>-0.337</td>
<td>0.060</td>
</tr>
<tr>
<td>Annual</td>
<td>1.030</td>
<td>-0.669</td>
<td>-0.041</td>
</tr>
</tbody>
</table>

Table 6-1 Correlation co-efficients for diffuse component of total radiation

It is interesting to note that the diffuse content is only very weakly related to solar altitude, vindicating Spencer's earlier findings for the same site. There is considerable variation in the diffuse fraction data (standard deviation typically 0.15 to 0.25) and this will partly undermine the usefulness of the diffuse fraction forecast for practical purposes, since the beam component is found indirectly from the global horizontal forecast and diffuse estimation.

A comparison is drawn between the annual average correlations developed by Spencer, those used in the TRNSYS modelling package (where diffuse data is not available) and the results of this study (figure 6-6).
The local conditions of the Reindl correlation, selected from TRNSYS radiation processor (type 16), are unknown. The sky in the vicinity of the Wagga weather station was found to have a significantly lower diffuse content in most conditions than the Reindl correlation used in TRNSYS. This is possibly due to low atmospheric turbidity and atmospheric water column near Wagga Wagga. Spencer decided to ignore any variation in diffuse content for M>0.75, arguing that the sky would be consistently clear at these times. Similarly for M<0.3, Spencer argued that the skies would be consistently diffuse. The authors study broadly agrees with Spencer’s first argument but suggests there is more information available for the diffuse sky insolation.

At first glance, diffuse contribution to solar water heater UTE may seem trivial. Consider Rayleigh scattering of monochromatic light passing through the earth’s atmosphere encountering water vapour, aerosols and air molecules. Simplified relations for the transmittance ($T_\lambda$) of monochromatic diffuse light (of wavelength $\lambda$) given in Duffie and Beckman (1974) are:

- Scattering due to small air molecules
  
  \[ T_{\omega \lambda} = 10^{-0.0039} \lambda^{-4} \]

- Scattering due to larger aerosols
  
  \[ T_{d \lambda} = 10^{-0.0353} \lambda^{-0.75} \]

- Scattering due to water vapour
  
  \[ T_{w \lambda} = 10^{-0.0075} \lambda^{-2} \]
A more comprehensive treatment may be found in Keogh (2001). The Rayleigh scattering relations show that diffuse light generated by atmospheric scattering is predominantly in the visible and shorter wavelengths. These wavelengths are readily absorbed by a solar collector and so diffuse light may embody significant useful energy and should not be ignored.

6.4 Quantifying Insolation Losses due to Collector Shading

As the controller attempts to make an accurate forecast of the solar contribution, solar shading is an important consideration for the predictive energy balance.

Solar engineers will be familiar with the sunpath diagram as a useful design aid to predict the occurrence of solar gain on a system. Obstructions to the beam insolation may be tediously measured using surveying equipment or a device such as the Solar PathFinder (Quirk’s Victoria Solar Light Co. Pty. Ltd.) and superimposed upon the sunpath diagram for the locale of the system allowing the times of shading to be deduced. This method does not capture the time weighted energy of the shading and one must have a sunpath diagram for the locale at hand. An automated means of horizon capture and digital output of shading loss determination is thus desirable.

A new photographic technique has been developed in this thesis to provide a partially automated means of capturing the artificial horizon information. The artificial horizon is defined as the lower boundary of the visible sky as viewed from the solar collector. A program was written to process photographic images of the artificial horizon and provide meaningful data regarding insolation energy losses due to shading of the system. The basic steps are:

1. Mount a digital camera on a rotating tripod head and align it with the horizon and the sun as references

2. Take a sequence of 6 photographs, each covering 60 degrees of azimuth, representing a complete 360 degree panorama of the horizon in the vicinity of the solar collector
3. Load these images into a computer program which then graphically superimposes them on a sunpath diagram and deduces when and where shading will occur. It also displays shading energy losses by month and by azimuthal sector.

4. Apply a filter to the forecast insolation such that if shading is deemed to occur, then the beam component of the insolation is reduced to zero. The diffuse component is effectively reduced by the percentage of the sky dome that is blocked by shading using spherical trigonometry.

This method has been simplified so that it may be used by unskilled workers with minimal training. The shading evaluation process takes no more than 5 minutes to set up and capture the images followed by less than two minutes of processing on a personal computer. A salesperson might use this tool to offer clients on-site evaluation of solar potential.

The effective incidence angle of the diffuse radiation will also be affected and is calculated using the Brandemuehl integral (Brandemuehl & Beckman, 1980).

6.4.1 Capturing the Artificial Horizon

A horizon capture device needs to take images of the sky dome in a form that may be processed electronically. Image capture in the form of scanning video and a sequence of still digital photographs were considered.

A video capture board was constructed and trialed as this allows fully automated horizon capture. A connected computer controlled the rotation of the video camera, the frame capture and its subsequent processing. The problem with this approach is the need to have mobile computing facility in the vicinity of the solar collector (usually a roof) and this may be inconvenient. The cost and size of video capture cards is also a deterrent.

The solution was to use a low-resolution digital camera to capture a sequence of images of the horizon on the basis of cost and practicality. The digital camera was mounted on a level tripod (figure 6-7) and is actuated by an azimuthal drive. The original drive consisted of a stepper motor controlled electronically to move exactly 60 degrees in an azimuthal direction upon the
push of a button. This mechanism has been simplified to a simple manual ball- indent indexing system to make it more convenient and portable. After each movement, a digital photograph is taken and stored in the camera's memory. Use of the indexed head allows six images to be captured and thus cover the entire horizon. This procedure takes about 5 minutes.

![Image of horizon imaging setup]

**Figure 6-7** Capturing horizon images for shading analysis using a digital camera mounted on indexed tripod

The camera used has a field of view of approximately 64 degrees in azimuth and 48 degrees in altitude. The tripod is aligned so that the bottom of the image represents an elevation of 0 degrees relative to the horizontal. For distant horizons, this elevation represents the elevation of the horizon. The images are later cropped automatically to be exactly 60 degrees wide so that they align with neighbouring images. It is recognised that shading objects that subtend an angle exceeding the camera's vertical field of view will not be captured. A second set of images at greater elevation would need to be captured for such occurrences. Such a site is probably a poor choice for solar collectors.

Most camera lenses suffer a degree of non-linearity near the edges of the image, often referred to as the pin cushion effect. To account for this, an image
of an angular grid (drawn on a cardboard screen) was taken and superimposed upon an actual angular grid. Assuming that the lens is a point focus device, one may readily observe any image distortion. The image distortion was found to be noticeable near the boundaries of the image. Although some of these areas are cropped during processing, no further corrective action was taken. The linearisation of a digital image is not a trivial matter considering that the artificial horizon is to be detected on a pixel by pixel basis. It is therefore important to understand quantitatively the errors that might be introduced by this approximation. Analysis of the grid image produces the error quantities listed in table 6-2 for this particular camera. These small errors were subsequently ignored for the shading analysis.

<table>
<thead>
<tr>
<th>Elevation (deg)</th>
<th>Azimuth error (deg)</th>
<th>Altitude error (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
<td>0.5</td>
</tr>
<tr>
<td>10</td>
<td>0.0</td>
<td>0.4</td>
</tr>
<tr>
<td>20</td>
<td>0.0</td>
<td>0.2</td>
</tr>
<tr>
<td>25</td>
<td>0.0</td>
<td>0.2</td>
</tr>
<tr>
<td>30</td>
<td>0.0</td>
<td>0.2</td>
</tr>
<tr>
<td>40</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>50</td>
<td>0.2</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 6-2 Errors introduced by camera lens distortion

The algorithm uses an angular resolution of one degree in azimuth and altitude for its calculations. Thus the camera must have a frame at least 60 pixels wide. Most digital cameras use a minimum resolution of 640*480 pixels and this extra resolution is utilised by the horizon discrimination algorithm. It is not uncommon for pixels in CCD devices to fail and so an average of a number of neighbouring pixels is used in the discriminator. The camera used in this case was an Olympus C-990 Zoom.
6.4.2 Processing the Images.

Each image is downloaded from the camera to the PC using the Olympus CamMedia software provided with the camera. Each picture is de-compressed from JPEG form into a pixel form known as device independent bitmap (DIB) using this software. This format allows inspection of individual pixel elements.

A custom program was written in Visual Basic for processing the DIB images (figure 6-8). A technical report (Dennis 2002a) provides the details on the design and operation of the software. The process requires detecting the difference between sky and the artificial horizon, commonly defined by trees and buildings. Colour alone is a poor discriminator in most circumstances and it has been found better to use luminance for this purpose.

\[ \text{Horizon Scanner} \]

\[ \text{Images from Horizon Photographs} \]

\[ \text{Figure 6-8} \quad \text{The top row of colour images show good colour contrast between sky and ground. The lower set shows the luminance signal with the horizon detected and plotted as a dashed red line.} \]

For the purpose of selecting the horizon, the sky must be bright and objects representing the horizon must be dark. Software modification of the colour balance of the luminance signal is used to achieve greater contrast. Reasonable contrast is given with a luminance composition (L) that brightens the blue sky
and darkens ground features (equation 6-3) where red, green and blue are the respective colour bias components of each pixel.

\[ L = 0.3 \text{Red} + 0.2 \text{Green} + 0.5 \text{Blue} \quad (\text{Eqtn 6-3}) \]

The algorithm now scans each image from top to bottom, one column of pixels at a time, searching for this change from light to dark luminance that represents the artificial horizon. Through trial and error it was found that a weighted average of groups of three neighbouring vertical pixels gave best differentiation and best tolerance to false indication of the artificial horizon.

This method was good enough to allow deciduous trees to be detected in winter. The elevation and azimuth of every object forming the artificial horizon may thus be recorded after suitable scaling of the pixel density. Problems associated with clouds can be overcome by covering the clouds with a black rectangle if necessary and by adjustment of the colour balance and contrast factors in software. A number of sites have been surveyed and reliable horizon detection has always been achieved.

6.4.3 Calculating the Timing of Beam Shading Events

The solar coordinates may be obtained from a number of algorithms given the local latitude, longitude and time (Blanco-Muriel et al 2001; Rabi, 1985). Solar co-ordinates in this paper are represented by the quantities azimuth and altitude. The locus of the sun in this coordinate system may be plotted for a range of days of year and times of day, giving rise to a sunpath diagram that may be represented in cartesian form (figure 6-9).

The artificial horizon is also plotted on the sunpath diagram. The region of overlap between filled area and the solar coordinates represents a period of shading at the represented location. The sunpath diagram may be used to retrospectively identify the objects causing the greatest losses by locating the objects in the original images using the azimuth as an index.
6. Forecasting Solar Contribution

The computer program was written to quantify each shading event and analyse the results in terms of beam insolation losses due to shading (Dennis 2002a).

6.4.4 Predicting Clear Sky Insolation
The above results use the solar coordinates as the basis of predicting the timing of shading on the solar system. The timing of shading may then be used to predict solar energy loss due to the artificial horizon, provided that temporal breakdown of insolation is known.

Insolation incident upon the Earth's upper atmosphere varies with the distance between the Earth and Sun (i.e. seasonal). This is approximated by the solar constant, K (equation 6-4) where d is the ordinal day of the year.

\[ K = 1373 \left( 1 + 0.033 \cos \left( 2\pi \frac{d + 10}{365.25} \right) \right) \text{ W/m}^2 \quad (Eqtn \ 6-4) \]

The relative path length of direct radiation from the sun through the Earth's atmosphere to the locale of interest is referred to as the dimensionless air mass (D) and depends upon the solar altitude angle (θ) from local zenith (equation 6-5).

\[ D = \frac{1}{\cos \theta} \quad (Eqtn \ 6-5) \]
This approximation ignores a small change in insolation due to atmospheric refraction at low solar elevation. This is usually ignored since the sun’s intensity is low at these times. However, this is when shading is most likely to occur. Thus the empirical refraction correction (equation 6-6, Hu & White 1983) is included.

\[
D = \left( \frac{1}{\cos \theta} + 0.15 (3.885 + \theta)^{-1.253} \right) e^{-0.0001184 \text{ Alt}} \quad (\text{Eqn 6-6})
\]

Alt is the local altitude above sea level in metres. This equation accounts for atmospheric absorption and the altitude of the site but ignores changes in air pressure and temperature.

The direct beam insolation incident on a two axis tracking collector with known location and time can be found from the Hu and White expression (equation 6-7), also discussed in Wenham et al (1994).

\[
H_B = K \times 0.7^D 0.678 \quad \text{W/m}^2 \quad (\text{Eqn 6-7})
\]

This insolation may be readily modified into insolation incident upon a flat plate of known orientation or other mode of tracking (Rabl 1985). The processing program is capable of forecasting insolation on a tracking surface or a flat plate of any orientation. Shading losses are quantified for these surfaces. The software also allows the user to examine clear sky insolation for any particular day of the year.

The shading algorithm assumes that the collector is a point, or that the collector size is small compared to the distance to the object causing the shading. Since this is often not the case (e.g. large trees near the collector), a further enhancement to the software would be required to allow defined collector boundaries in relation to the image capture location.

6.4.5 Incorporating Weather Effects
Local weather conditions will have a major influence on the amount of solar energy lost as a result of shading effects. The shading analysis program was not intended to provide a detailed energy availability analysis of a site. The
program provides an elevation profile of the artificial horizon and this may be used in other more detailed models. To incorporate weather effects, the artificial horizon information can be imported into the TRNSYS modelling program that utilises local weather data.

A new TRNSYS type, number 257, was constructed (see Appendix B.2). Type 257 opens a data file containing the elevation of the artificial horizon at one degree intervals in azimuth (360 values). By comparing the solar altitude from the radiation processor (type 16) with the elevation of the artificial horizon, it essentially acts as a digital filter on the beam insolation output. The diffuse radiation reduced by a constant percentage of the sky dome that is covered by shading objects. This type connects between the radiation processor type and the solar collector type in the simulation. The algorithm is simply:

\[
\text{IF } \left( \frac{\pi}{2} - \theta > \theta_s(\varphi) \right) \text{ THEN } H_B = H_B \quad \text{ELSE } H_B = 0
\]

Shading would be better treated in its entirety by incorporating the blocking of beam insolation and fractional reduction of diffuse within the TRNSYS type 16 radiation processor. This would allow the collector slope to be included in the insolation calculations. If shading analysis was not required, a default flat horizon of zero elevation could be used in the radiation processor. Modification to the type 16 radiation processor was not carried out as part of this thesis.

The TRNSYS model of the conventional split system was used to give quantitative results for average annual weather conditions at the surveyed site in Canberra. The model only used type 257 to remove beam insolation during shading events. These results may be tabulated by arbitrary time interval. Monthly summary results are presented in table 6-3. These results show the reduction of beam insolation on a 2 axis tracking surface due to shading. The shading effects are most noticeable winter, particularly in the mornings and evenings.

The simulation results for the test site in Canberra indicate an annual loss of beam normal radiation availability of around 9% due to shading from nearby buildings and trees. The actual reduction in collected solar energy is somewhat less due to the collector slope.
### 6. Forecasting Solar Contribution

#### Table 6-3

<table>
<thead>
<tr>
<th>Month</th>
<th>Global horizontal (clear sky) insolation (MJ/m²)</th>
<th>Beam insolation without shading (MJ/m²)</th>
<th>Beam insolation with shading (MJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>1,238</td>
<td>932</td>
<td>896</td>
</tr>
<tr>
<td>February</td>
<td>1,033</td>
<td>702</td>
<td>655</td>
</tr>
<tr>
<td>March</td>
<td>1,008</td>
<td>752</td>
<td>684</td>
</tr>
<tr>
<td>April</td>
<td>824</td>
<td>500</td>
<td>461</td>
</tr>
<tr>
<td>May</td>
<td>713</td>
<td>399</td>
<td>338</td>
</tr>
<tr>
<td>June</td>
<td>619</td>
<td>392</td>
<td>346</td>
</tr>
<tr>
<td>July</td>
<td>677</td>
<td>342</td>
<td>292</td>
</tr>
<tr>
<td>August</td>
<td>799</td>
<td>526</td>
<td>468</td>
</tr>
<tr>
<td>September</td>
<td>922</td>
<td>565</td>
<td>536</td>
</tr>
<tr>
<td>October</td>
<td>1,102</td>
<td>706</td>
<td>626</td>
</tr>
<tr>
<td>November</td>
<td>1,177</td>
<td>788</td>
<td>734</td>
</tr>
<tr>
<td>December</td>
<td>1,267</td>
<td>763</td>
<td>691</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>11,387</strong></td>
<td><strong>7,380</strong></td>
<td><strong>6,696</strong></td>
</tr>
</tbody>
</table>

**Table 6-3**  
_Demonstration of loss of beam normal insolation due to the effects of shading at the ANU Faculty of Engineering test site_

Loss of diffuse insolation due to shading is modelled separately in section 6.4.7

#### 6.4.6 Calculation of Beam Insolation Incidence Angle

The amount of beam radiation absorbed by the collector depends upon the angular transmittance function of the collector cover glass. Determination of this requires the knowledge of beam transmittance or incidence angle modifier (IAM) of the solar collector glass cover at all incidence angles ($\gamma$) (figure 6-10) and is often approximated by a tangent relation (equation 6-8).

$$T_b(\gamma) = 1 - \tan^{b(\frac{\gamma}{2})}$$  

(Eqtn 6-8)

Manufacturer's data for the experimental system is best approximated by the tangent relation when $b=3.2$. 

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For beam radiation, the solar coordinates are given by a sequence of calculations based on the earth's declination ($\delta$) determined from a location's latitude ($\lambda$), longitude and the local time and date represented by the hour angle ($\omega$) (Blanco-Muriel et al, 2001). The angle of incidence ($\gamma_B$) of beam radiation on the collector of slope $\beta$ from horizontal and orientation $\alpha$ from true north is then given by equation 6-9 (Duffie and Beckman, 1974).

$$\cos(\gamma_B) = \cos(\delta) \cos(\lambda) \cos(\beta) \cos(\omega)$$
$$- \sin(\delta) \sin(\lambda) \cos(\beta)$$
$$- \cos(\delta) \sin(\alpha) \sin(\beta) \sin(\omega)$$
$$- \cos(\delta) \cos(\alpha) \sin(\lambda) \sin(\beta) \cos(\omega)$$
$$- \sin(\delta) \cos(\alpha) \cos(\lambda) \sin(\beta)$$

(Eqtn 6-9)

The variation of the beam insolation angle of incidence on the test collector is shown for a summer day, a winter day and at equinox (figure 6-11).

The average collector transmittance to beam radiation ($T$) is found from the Brandemuehl integral (Brandemuehl & Beckman 1980) shown in equation 6-10.

$$T = \frac{\int T_B(\gamma) \cos(\gamma) H_B(t) \, dt}{\int H_B(t) \, dt}$$

(Eqtn 6-10)
Brandemuehl and Beckman performed a weighted average transmittance for light entering the collector. The weighting factors related to the transmittance of the glass cover at the incidence angle of the component of light and the loss of intensity due to the incidence angle itself. For beam insolation, the limits of the integral relate to the position of the sun throughout the day. For diffuse insolation, the limits of the integral relate to the visible sky dome. The Brandemuehl integral is re-evaluated in this thesis using the artificial horizon to change the integral limits.

For the test site (latitude -35.27°, collector slope 20°), the average (energy weighted) beam transmittance calculated from this integral is 0.98.

The inverted tangent relation (equation 6-11) indicates a corresponding average incidence angle of 32.4°.

\[ \gamma_b = 2 \tan^{-1} (1 - T_{avg})^{1/b} \]

(Eqtn 6-11)

6.4.7 Loss of Diffuse Insolation due to the Raised Artificial Horizon

For all domestic solar water heater installations, part of the sky dome is obscured by land features above the horizon. The diffuse radiation received by the collector will be reduced by some amount. A spherical coordinate system is used to analyse modifications to sky diffuse insolation due to local shading. Consider the sky dome in figure 6-12 where the angle \( \theta \) represents solar
altitude and $\varphi$ represents an azimuthal angle.

If the diffuse sky radiation is assumed isotropic, then the visible area ($A_v$) of the unobscured sky dome is given by the integral of $dA_v$ over the hemisphere, where $dA_v = \sin\theta \, d\theta \, d\varphi$ (equation 6-12)

$$A_v = \int_0^{\pi/2} \int_0^{\pi/2} \sin\theta \, d\theta \, d\varphi$$  \hspace{1cm} (Eqtn 6-12)

For an unobstructed hemisphere, this integral evaluates to $2\pi$. For a raised artificial horizon, the upper limit of the inner integral will be $(\pi/2 - \theta_s(\varphi))$ and the horizon altitude varies with the azimuth as found from the photographs. The fractional loss of diffuse radiation is then found from the ratio of the new integral to $2\pi$. For the test site the loss of diffuse insolation was about 26%.

The reduction in diffuse as seen by the collector is also influenced by the amount of the sky dome visible to the collector (due to its slope from horizontal) and the degrading influence of angular transmittance of the glass cover. Without this new technique, diffuse radiation from the non-sky surroundings would be assigned an “average” incidence angle ($\gamma_{ds}$) from the Brandemuehl correlations, where $\beta$ is the collector slope from horizontal (equation 6-13). For the test site, with a collector slope of $20^\circ$, the default incidence angle is $\gamma_{ds} = 57.5^\circ$. 

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\[ \gamma_{DS} = 59.68 - 0.1388 \beta + 0.001497 \beta^2 \]  
(Eqtn 6-13)

This correlation does not account for shading effects and represents the angular transmittance properties of an unknown glass cover.

The coordinate system shown in figure 6-13 will be used to describe the analysis of the effective incidence angle of the resulting sky diffuse and its transmittance by the collector.

![Coordinate system for calculation of diffuse incidence angles.](image)

Figure 6-13  Coordinate system for calculation of diffuse incidence angles. Radiation coming from point P with direction (altitude, azimuth) = (\( \theta, \varphi \)) meets the collector at the origin O. The collector lies parallel to the x axis, raised up at a slope \( \beta \) from the horizontal xy plane.

The angle of incidence of a component of diffuse light on the collector is given by the dot product of the normal vector to the collector and a unit vector in the direction of P.

The normal vector has coordinates \( (x, y, z) = (0, \sin \beta, \cos \beta) \) and the unit direction vector has coordinates \( (x, y, z) = (\sin \theta \sin \varphi, \sin \theta \cos \varphi, \cos \theta) \). The incidence angle \( (\gamma) \) is then given by equation 6-14.

\[ \cos \gamma = \sin \theta \cos \varphi \sin \beta + \cos \theta \cos \beta \]  
(Eqtn 6-14)

The sky dome integral (equation 6-13) is now repeated but the integrand \((\sin \theta \, d\varphi \, d\theta)\) is replaced by \((W \sin \theta \, d\varphi \, d\theta)\) where W is the window function defined as:
The integral is thus limited to the partial sky dome visible to the collector. The results (figure 6-14) show a loss of about 15% for most collector slopes with increased fractional losses for flat collectors due to exposure to the more heavily shaded southerly landscape. The average direction of diffuse is elevated about 10 degrees by the effect of the artificial horizon.

Figure 6-14 Illustration of the decrease in average altitude (i.e. increase in elevation) of diffuse insolation due to shading effects. Loss of diffuse insolation due to shading and collector slope relative to horizontal unshaded diffuse is also shown.

So far the analysis has considered diffuse insolation available to the collector. Now the effect of the angular transmittance properties of the glass cover will be included.

The average transmittance of diffuse light in the sky dome above the horizon and visible to the collector is given by equation 6-15 where the integration limits are unchanged.

\[
\frac{\int W T(\gamma) \cos \gamma \, dA}{\int W \, dA} = \frac{\int \int W T(\gamma) \cos \gamma \sin \gamma \, d\gamma \, d\varphi}{\int \int W \sin \gamma \, d\gamma \, d\varphi}
\]

(Eqtn 6-15)

This integral is evaluated for all pixel elements in the horizon photographs and results in an average transmittance of diffuse radiation to the collector absorber (figure 6-15). The inverted tangent relation can again be used to obtain the effective incident angle of diffuse light on the collector.
6. Forecasting Solar Contribution

Figure 6-15  Average transmittance of diffuse with and without shading effects. Also shown is the elevation of effective incidence angle for diffuse light weighted by transmittance, for a range of collector slopes.

The overall effect of shading on diffuse light is a combination of loss of available diffuse by the reduction of the visible sky dome and loss (or gain) of acceptance of diffuse by the collector due to the angular transmittance dependency. The combined effect is plotted in figure 6-16. Note that these results are characteristic of this test site and this collector.

Figure 6-16  Overall effect of shading on the proportion of clear sky diffuse insolation reaching the collector absorber

For the test site, about 40% of total hemispherical diffuse insolation is incident upon the absorber. Only 7% of the losses is attributed to shading. It is reasonable to conclude that the controller may ignore the shading of diffuse insolation, due to the high average incidence angle of diffuse insolation.
6.5 Calculation of Ground Albedo

The artificial horizon capture technique has a further use: that of calculating the ground reflectance (albedo) of light and the apparent incidence angle of ground diffuse light on the collectors.

Without this new technique, diffuse radiation from ground features are assigned an “average” incidence angle (γDG) from the Brandemuehl correlations (equation 6-16) where β is the collector slope from horizontal. For the test site, with a collector slope of 20°, the default incidence angle is γDG = 79.5°.

\[ \gamma_{DG} = 90.0 - 0.5788 \beta + 0.002693 \beta^2 \]  
(Eqn 6-16)

These equations assume a clear, flat horizon and isotropic ground reflectance. The actual incidence angle for ground diffuse at the experiment site was evaluated using a new photographic method that took into account the elevated local horizon and anisotropy in ground reflection.

Engineers usually estimate ground reflectance based on a table presented by Hunn & Calafell (1977). In doing so, one value of ground reflectance is used to represent the non-sky hemisphere visible to the collectors and that this assumed to be a weighted average of the landscape feature reflectances. Studies were performed by NASA during the 1950s to determine reflectance of various materials and landscapes. This was used by Hunn & Calafell to estimate albedo by photographing the landscape as seen by the collector using a 180° field of view fish-eye lens. The image was then divided into 40 regions of equal solid angle and the reflectance of each region estimated from the NASA tables. A weighted average albedo was then generated. Hunn & Calafell’s laborious method relies upon human judgement and the availability of appropriate reflectance data for the landscape features photographed.

A common alternative method of albedo measurement is to invert a global horizontal insolation measuring pyranometer. This method provides only an approximate albedo measurement since it ignores the profile of the artificial horizon and will most probably underestimate albedo.
6.5.1 The Photographic Technique

A useful evolution of albedo measurement follows the principles of the automated shading calculator previously discussed. It is difficult to re-use the shading images since the horizon finding images need a clear day to index the azimuth (based on the solar position and time of day), while the albedo images require a diffuse day to reduce the effects of beam reflection. This implies that the true ground albedo will vary with time of day, something that is difficult to assess and not attempted by this technique.

The camera is again mounted on the (horizontally) rotating head of a tripod. The lower vertical field of view of the camera must exceed that of the collector so that all ground reflectance visible to the collector will be captured by the camera images. This is most easily visualised by the photographer by looking at the landscape down the surface of the collector. A suitably (forward) titled camera mount may need to be used for steeply sloped collectors.

The entire horizon is again captured in six images, each of 60° azimuth (figure 6-17) and the images are downloaded, converted to bitmaps and stored as for the horizon scanner.

*Figure 6-17* One of the six albedo images from the test site showing the gray card of known reflectivity against which the ground reflectances of all other pixels below the horizon and within the field of view of the collector are measured.
The first image is aligned in the same direction as the images from the shading photographs so that the artificial horizon may be conveniently super-imposed later. This allows the processing to consider all non-sky reflections in the ground albedo calculation.

Another PC based processing program (Dennis 2002b) was written to analyse the images for ground reflectance. All pixels located below the artificial horizon and within the field of view of the collector are assessed for brightness compared to a known reference brightness within the image. This reference is the gray card shown in figure 6-17. The luminance and incidence angle of every qualifying pixel then contributes to the Brandemuehl integral to determine ground albedo. The program outputs are the amount of diffuse light reflected by ground features and the average transmittance of the collector to this radiation.

6.5.2 Modified Brandemuehl Integral

The isotropic sky and ground assumptions used by Brandemuehl and Beckman allowed the use of a simple integrand where \( dA = \sin\theta \, d\varphi \, d\theta \). The integral limits assumed a flat horizon infinitely far away that determined the break between sky and ground. Average values for sky and ground diffuse transmittance (and implicitly the incidence angles) could then be calculated for any collector orientation. The isotropic assumptions imply that the diffuse transmittance results are independent of collector azimuth.

The photographic approach requires modification of the Brandemuehl integral in two ways:

1. The flat horizon is replaced by the contour of the artificial horizon as detected by the horizon scanner

2. Since ground reflectance is highly anisotropic, the integral is considered on a pixel by pixel basis from the photographs. The luminance and incidence angle are calculated for each pixel in each image that would be visible to the collector and below the artificial horizon.
The general approach of Brandemuehl and Beckman for the incidence of diffuse light on the collector cover is again used. Equation 6-17 shows the form of the Brandemuehl integral to find the average ground reflectance ($R_g$).

$$R_g = \frac{\int W L(\gamma) \, dA}{\int W \, dA} = \frac{\int \int W L(\gamma) \sin \gamma \, d\gamma \, d\phi}{\int \int W \sin \gamma \, d\gamma \, d\phi} \quad (Eqtn \ 6-17)$$

$L(\gamma)$ is the luminance of a pixel with incidence angle $\gamma$ on the collector, and $A$ is the region visible to the collector below the artificial horizon. The region $A$ extends below horizon level and depends upon the collector slope. The incidence angle window function $W$ and the incidence angle $\gamma$ are evaluated using the same co-ordinate system used for the sky diffuse analysis. The approach is again extended to find the average transmittance of ground diffuse radiation (equation 6-18).

$$T_{dg} = \frac{\int \int W T_b(\gamma) L(\gamma) \sin \gamma \, d\gamma \, d\phi}{\int \int W L(\gamma) \sin \gamma \, d\gamma \, d\phi} \quad (Eqtn \ 6-18)$$

This leads to the effective incidence angle of ground reflected light by inversion of the tangent relation for angular transmittance of incident light.

### 6.5.3 Spectral Sensitivity

The most difficult challenge of the technique is matching the spectral response of the camera charge coupled device (CCD) image sensor to that of the solar spectrum and to the absorption bandwidth of the solar collector.

The selective surface of a typical solar collector will absorb short wavelength light strongly to about 3µm and is not limited by the transmittance of the glass cover. Wavelengths exceeding 3µm are less important for albedo considerations if the collector is considered to be well insulated.

A typical CCD has limited spectral response (figure 6-18). The CCD relies upon incoming photons having sufficient energy to displace an electron to provide detection. The ratio of electrons to photons is denoted the quantum efficiency of the CCD.
It is clear that a CCD detector, even with spectral correction, will not be capable of accurately determining albedo across the range of wavelengths available to the collector in its sensitive region of operation.

Given that around 80% of the energy in the AM1.5 solar spectrum energy occurs at wavelengths below 1.1 µm (Wenham et al 1994), a reasonable approximation may be salvaged. Longer wavelength thermal radiation from nearby buildings and hot objects is unlikely to be absorbed by the collector since the glass cover is largely opaque to these wavelengths.

A crude compensation was carried out by photographing a Kodak calibrated gray card. This is a coloured piece of cardboard that has an even colour bias in red, green and blue. The gray card was photographed in diffuse light at various angles and the images were examined for colour content. The following compensation factors were generated as average correction factors for the CCD detector in the camera across a number of images:

- Red 1.18
- Green 1.04
- Blue 0.95
When processing the albedo images, each pixel colour element is modified by multiplication by the above corresponding factor.

6.5.4 Image Brightness Calibration

The CCD response to image brightness is largely linear until the potential wells in the detector become saturated. It is important to use an iris control to prevent detector saturation. Most digital cameras have an auto-iris to prevent saturation. This implies that the calibration of brightness must be performed externally since the camera iris setting is usually unknown. Furthermore, the iris and shutter speed must be consistent from image to image unless each image brightness can be individually calibrated.

A means of calibrating the brightness of the ground reflection from the image itself would be convenient. This may be achieved by placing an object of known reflectivity in the photographs. If the photographs are taken during an overcast day, there will be no interference from beam insolation. Using this method, there is no need to know the exact amount of radiation present, or the iris setting of the camera. The only condition is that the CCD detector is not saturating. Photographers commonly use the same gray card to assess image brightness, since the card has a known 18% reflectance. Most photographic films and camera light meters are designed for an average image luminance of 18%. If a gray card can be placed somewhere within the image, all other pixel luminances may be scaled from this known reflectivity.

A further correction is usually made for the characteristics of the observer. The human eye has very limited spectral response over the range 380 nm to 700 nm, whereas a solar application requires the use of consistent contributions from the red, green and blue signals. Since the image has been corrected for non-linear detection, the luminance \((L\text{ in percent})\) for the solar albedo measurements is detected from equation 6-19.

\[
L = 0.33 \text{ Red} + 0.33 \text{ Green} + 0.33 \text{ Blue} \quad (\text{Eqtn 6-19})
\]
This expression is evaluated for each pixel in the image (180 x 135 pixels) and multiplied by 100/256 since the RGB components use an 8 bit scale.

6.5.5 Evaluation of the Modified Brandemuehl Integral

All of the data are now available for the evaluation of the ground albedo. The computer program evaluated the integral for ground reflectance pixel by pixel from the photographs and gave an average ground reflectance of 0.11 and average collector cover transmittance of 0.15 at the weighted average incidence angle. The effective incidence angle is 87.0° for the test site with collector slope of 20°. The properties of the glass cover have a strong influence on this result. Albedo values for this site estimated from Hunn & Calafell fall in the range 0.2-0.25.

It is interesting to compare the proportions of each light component on a horizontal surface compared to the proportions of each component that are incident upon the collector absorber (under the glass cover) (table 6-4). These results take into account the effects of local shading, the elevated collector and the angular dependence of the transmittance of the glass cover.

<table>
<thead>
<tr>
<th>Proportion of annual global horizontal</th>
<th>Proportion of component of light reaching the collector</th>
<th>Incidence angle modifier</th>
<th>Proportion of component of light reaching the absorber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td>70%</td>
<td>0.91</td>
<td>0.98</td>
</tr>
<tr>
<td>Sky Diffuse</td>
<td>28%</td>
<td>0.72</td>
<td>0.48</td>
</tr>
<tr>
<td>Ground Diffuse</td>
<td>2%</td>
<td>0.08</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 6-4 Allocation of light absorbed by the collector shows the low effectiveness of diffuse light.

Although Canberra’s insolation is influenced by frequent clear skies, the collector incidence angles severely reduce the diffuse contribution and essentially eliminate any ground reflectance contribution. This is despite the
good anti-reflective properties of the textured glass cover! Even with a ground reflectance of 0.5 and a collector slope of 60°, the contribution from ground reflectance is less than 5%.

The contribution of ground reflectance may be of greater importance to the forecasting controller in European climates where there is frequently snow on the ground (and possibly on the collectors). Ground albedo is included in the method for the sake of completeness since it is a small extension to the photographic technique and essentially a repeat of the integration process used for diffuse modification.

6.6 The Daily Insolation Profile

Now that the forecast insolation has been apportioned into its beam, sky diffuse and ground diffuse components with their associated incidence angles, the amount of radiation incident on the collector's absorber for each of these sources can be calculated. A typical daily insolation profile calculated using this method is shown in figure 6-19.

![Figure 6-19: Forecast global solar radiation for a summer day with interpreted diffuse and beam components (without shading effects)](image)

The solar transmission characteristics of a solar collector depend upon the angle at which radiation impinges upon the top surface. The tangent relation for angular transmittance of light is again used to determine the fraction of
each component of light reaching the absorber plate in the collector. These fractions are referred to as incidence angle modifiers (IAM). The incidence angle modifiers for each insolation component are found from equations 6-20 to 6-22.

\[
IAM_B = 1 - \tan^2 \left( \frac{\theta_B}{2} \right) \quad (Eqtn \ 6-20)
\]

\[
IAM_{DS} = 1 - \tan^2 \left( \frac{\theta_{DS}}{2} \right) \quad (Eqtn \ 6-21)
\]

\[
IAM_{DG} = 1 - \tan^2 \left( \frac{\theta_{DG}}{2} \right) \quad (Eqtn \ 6-22)
\]

Finally, equations 6-23 to 6-26 show the actual insolation getting into the collector, found from the total of each component modified for its angle of incidence on the solar collector.

\[
I_B = H_B IAM_B \quad (Eqtn \ 6-23)
\]

\[
I_{DS} = H'_{DS} IAM_{DS} \quad (Eqtn \ 6-24)
\]

\[
I_{DG} = (H_B + H'_{DS}) \times R_g \times IAM_{DG} \quad (Eqtn \ 6-25)
\]

\[
I_c = I_B + I_{DS} + I_{DG} \quad (Eqtn \ 6-26)
\]

The total radiation incident on the absorber is now able to be predicted from a simple hourly forecast of global horizontal radiation.

### 6.7 Estimating Solar Hot Water Collection

The efficiency of a solar collector depends upon the variables solar insolation, collector inlet temperature, water circulation rate and collector parameters. In this thesis, the collector efficiency \( \eta_c \) is evaluated from a second order polynomial that is derived from ASHRAE testing of the collector in the form of equation 6-27.

\[
\eta_c = a_0 - a_1 \frac{(T_{cin} - T_a)}{I_c} - a_2 \frac{(T_{cin} - T_a)^2}{I_c} \quad (Eqtn \ 6-27)
\]

\( T_{cin} \) is the collector inlet water temperature \( (^\circ C) \), \( T_a \) is the ambient air temperature \( (^\circ C) \) and \( I_c \) is the total solar insolation effectively incident upon the...
collector cover (W/m²). The co-efficients a₀, a₁ and a₂ are experimentally
determined by a standards house such as the USA Solar Rating and Certification
Corporation (SRCC). The co-efficients of the ASHRAE performance correlation
are valid only for the tested collector flow rate and must be corrected for other
flow rates that the pump may use. A correction multiplier is applied to reduce
the collector efficiency for collector flows lower than the test flow rate (\(\dot{m}_t\)), as
will usually be the case for the variable collector flow. This correction is shown
in equation 6-28 and plotted in figure 6-20.

\[
\text{Correction Ratio} = \frac{\dot{m}_c \frac{A_c F'U_L}{(1-e^{\frac{T_c}{\dot{m}_c}}) \frac{A_c F'U_L}{F'U_L}}}{\dot{m}_t c \frac{(1-e^{\frac{T_c}{\dot{m}_t}}) \frac{A_c F'U_L}{F'U_L}}{F'U_L}} 
\]

\((Eqtn\ 6-28)\)

\(F'U_L\) is calculated from the tested collector efficiency curve (and is considered
independent of collector flow rate). All other factors are known. This correction
factor is largely independent of collector inlet temperature. Collector flow rates
below about 0.3 L/min result in severe loss in collector instantaneous efficiency
for the test system.

![Figure 6-20](image)

*Figure 6-20  Collector efficiency modification at low collector flow rates*

The efficiency of the collectors on the experimental system at various flow rates
is plotted in figure 6-21 using collector parameters supplied by the
manufacturer. Severe degradation of performance is only apparent at very low flow rates. During experiments, collector flows in the range of 0.16-1.0 L/min were commonly used for the experimental system. As an example, the experimental data indicates an average collector flow (during periods of solar gain) of 0.24 L/min during autumn. This low flow reduces the average collector efficiency by 20% from the efficiency calculated, for a given collector inlet temperature.

![Collector efficiency curves at various collector flow rates](image)

If one considers that in a well stratified storage tank (particularly where the volume of heated water is actively minimised) the bottom of the tank will always be at or close to the cold water supply temperature. The only times this will not be true is either:

a). The tank is full of hot water (e.g. in summer when excess solar heat is available) in which case there is no need for advanced control and a safety circuit will most likely override the control action.

b). No hot water has been taken from the tank for some time and thermal de-stratification has been significant. The error in assuming a cold collector inlet will lead the controller to start auxiliary heating a little earlier but not so early as to significantly reduce solar contribution i.e. the error causes more conservative behaviour.
Since plumbing services in metropolitan areas are generally underground, the variation of cold water supply temperature can be reasonably predicted from meteorological records. The auxiliary heating control algorithm uses a sinusoidal approximation to the Australian standard AS4234 cold water supply temperature (figure 6-22). The daily variation in supply temperature is usually negligible. There is no reason why it could not be sensed by the controller if it is suspected to vary due to the nature of the location.

![Figure 6-22](image)

Figure 6-22  Cold water supply temperature from AS4234 and sinusoidal approximation for Canberra. The fitted curve is easier for the controller to manage.

The de-coupling of the collector inlet temperature from the tank state has allowed the collector efficiency to be determined for every 12 minutes of the day.

Collector return water is to arrive at the tank at a minimum temperature $T_{sp}$ if it is to make a direct contribution to tank UTE. This imposes a minimum requirement for incoming insolation before collector flow should be established.

The constant collector outlet temperature strategy proposed by Jesch & Braun (1984) is used to forecast the collector flow rate (and hence solar gain) for given insolation ($I_c$), collector inlet temperature ($T_{cin}$), ambient temperature ($T_a$) and desired collector outlet temperature ($T_{cout}$). Jesch & Braun recommended a collector mass flow ($m_c$) shown in equation 6-29.
6. Forecasting Solar Contribution

\[
\dot{m}_c = \frac{- A_c F' U_L}{c \ln \left(1 - \frac{F_R(T_{cout} - T_{cin})}{F_R(T_{cin} - T_a)}\right)} \quad (Eqtn \ 6-29)
\]

This relation effectively provides a minimum insolaton \( I_{min} \) below which there is no solar hot water gain at all (equation 6-30).

\[
I_{min} = \frac{(T_{cout} - T_a) F_R U_{L, test}}{F_R (\tau_{ao})_{test}} \quad (Eqtn \ 6-30)
\]

At a set point temperature of 65°C and an ambient temperature of 10°C, over 400 W/m² is required before the setpoint temperature can be achieved in the test system. Jesch & Braun’s equation highlights the difficulty of using the constant outlet temperature approach in winter with poor solar collectors. On a clear winter day in Canberra, solar collection may only be possible for a few hours per day using the constant collector outlet temperature strategy. The controller could decide to switch to another collector circulation strategy during winter.

The estimation of the quantity and timing of hot water returning to the tank from the heating circuit is repeated for each 12 minute timeslot throughout the day and produces a forecasted solar contribution profile (figure 6-23).

This is the estimated hot water collected but not necessarily the amount of UTE effectively gained by the tank. Conduction and mixing of the solar collector return flow with water in the tank reduces the effective solar contribution by an experimentally estimated factor ranging from 10% to 25% depending upon the mode of operation of the heating circuit (see table 8-1).

A small increase in effectiveness comes from the simultaneous use of the auxiliary heater with the solar collector. In this solar pre-heat mode, a higher flow rate is required and this increases collector efficiency. Since this mode should only be invoked for a small proportion of the day, its effect is ignored by the forecast.
6. Forecasting Solar Contribution

Figure 6-23  Solar collector contribution profile derived from the BOM insolation forecast, including shading effects, for summer and winter operation. The incident insolation refers to radiation on the collector glass cover.

This procedure provides the controller with an estimate of the upcoming solar contribution to the predictive energy balance.

6.8  Checking the Forecast Solar Contribution

The accuracy of the solar contribution was compared with the experimentally measured results. The forecast amount of solar energy collected was calculated from the BOM weather forecasts by the procedure set out in this chapter. It included a 20% reduction in insolation for the over-estimate in the BOM forecast and corrections due to shading effects. To bypass the errors in the forecast itself, the forecasting process was repeated on observed data for global horizontal insolation and ambient temperature collected during the
experiments. This should identify errors in the methodology that calculates the solar hot water gain. The results are plotted in figure 6-24.

The experiments need to run for a longer period to be statistically sure of what is happening. The average hot water gain based on the observed insolation agrees on average with the expected hot water gain (average error = 0.80 MJ) but the spread of values is large (standard deviation = 7.2 MJ) and this is a concern for the accuracy of the predictive energy balance. The average hot water gain based on the BOM forecast insolation shows a larger average error (2.0 MJ) and the same spread.

![Figure 6-24](image)

**Figure 6-24**  A comparison of the solar hot water collected against the solar gain derived from the BOM forecast and the solar gain if the forecasts were replaced by the actual observed solar conditions

The most obvious cause of error is the assumption that the collector inlet temperature will be the same as the cold water supply temperature. At times, experimental results showed an increase in the collector inlet temperature from 0°C to 15°C above the supply temperature, presumably due to thermal conduction. It would be difficult to forecast this effect without a fully parameterised tank model in the controller.

Other causes might be:

- The placement of the collector outlet temperature sensor that causes
delays in the circulation pump startup (reduces actual solar gain)

- Poor pump control (reduces actual solar gain)
- Errors in the sensing of actual solar gain
- Errors in interpolating the hourly weather forecast
- Incorrect forecasting of the collector flow and efficiency correction factor due to low flow. This correction is very sensitive at low collector flows.

The errors are significant and will limit the ability of the controller to perform cost optimisation. The priority of the thesis is to identify a practical methodology that an active controller might use and to solve as many problems as time permits.

A comprehensive experimental effort would be required to isolate each source of error and provide practical recommendations on how a practical controller might improve its solar forecast. The most pressing concern is the variability in the insolation forecast.
7. Energy Profile Forecast

"It is a capital mistake to theorise before one has data. Insensibly one begins to twist facts to suit theories instead of theories to suit facts"

Sherlock Holmes

7.1 Introduction

The predictive energy balance requires an automated means of forecasting the magnitude and timing of hot water loads to be drawn from the system. There are risk/reward compromises for solutions of a range of complexity, indeed estimating the upcoming loads and their associated uncertainties is the main source of compromise to hinder an otherwise aggressive energy saving controller.

There is little data available regarding domestic hot water consumption patterns. Several specific studies were found (Pollard et al 2002; Lloyd et al 2000; Guthrie 1987), but the only useful generalisation that can be drawn is that the results are specific to the case study. One might expect significant variation between households due to:

- The number of residents
- The type and number of appliances using hot water
- The demography of residents
- Local climate and seasonality.

For a service that keeps regular hours (e.g. a milking shed), a hot water load schedule might be easily defined and have little error. In this case the controller could be a simple time switch connected to the auxiliary heater with it's operating time set as late as possible to just meet the known load. There would be a small loss in potential solar input with this method, justified by the low cost and simplicity of the approach.

Taking this argument a step further, a domestic household with regular habits
could also be modelled reasonably well by pre-defined schedules. There may be separate schedules for weekdays and weekends and the schedules are likely to have higher associated uncertainties. This could work well provided the users have the ability and inclination to override the controller’s operating plan as necessary (e.g. if away on vacation or having visitors to stay).

In both of the above cases, some work would have to go into pre-defining and programming a suitable schedule upon installation of the controller. This would be inconvenient for a production line device and would require re-programming should the circumstances of the household change. An appropriate solution would have a controller quickly, and passively, learn the hot water consumption habits of the household. By its nature, the learning capacity would have the ability to adapt to seasonal variation and changes of operating environment through suitable choice of the learning time constant.

In general, learning methods require the controller to accumulate a range of experience from which a prediction may be generated. This requires on-line sensing of the hot water draw and data storage capability. Modern micro-controller technology is quite capable of performing this task at low cost but is rather limited in computational capacity.

There have been many studies performed on load forecasting techniques for power transmission companies (Khotanzad et al 1995; Fan & McDonald 1994; Park et al 1991; Papalopoulois & Hesterberg 1990; Ho et al 1990; El-Hawary & Mbagamal 1990; Jabbour et al 1988; Campo & Ruiz 1987; Hagan & Beir 1987; Dehdashti et al 1982; Krogh et al 1982; Irisarri et al 1982; Vemuri et al 1981) with useful review papers by Liu et al (1996) and Lotufo & Minussi (1999). The problem for electricity network load forecasting is essentially a time series of past and future network loads with variables of ambient temperature, insolation and time (implicitly). The hot water load learning problem is analogous to the electricity network load learning problem. Few studies were found relating to forecasting domestic hot water loads. The most relevant references were Yoshida & Inooka (1997) and Haissig (2000).
In the absence of known relationships regarding load patterns, time of day and previous experience comprise the domain considered for the domestic hot water time series.

7.2 Sensing the Hot Water Load

Ideally, the sensing of the load would be achieved using a flowmeter and two temperature sensors so that net heat delivery relative to the cold supply could be measured. In a domestic system, this would be an expensive solution and potentially unreliable should the flowmeter fail or become clogged. An alternative solution, based on the calorimeter principle, was trialed but found to give poor performance. The device used two glass bead thermistors (Thermometrics model GM472W) immersed in the load stream. One acted as a temperature reference while the other was actively heated 10°C above the reference temperature. The duty cycle of the thermistor heating circuit was proportional to the rate at which the fluid stream removed heat from the second thermistor. When high loads were drawn (10 L/min) and water had been stagnant in the pipework for some time, a rapid temperature transient was expected in the water. A thermistor of very low thermal mass (C=5 mJ/K) was used to provide the fast response required. The devices used had glass encapsulation that cracked after a short period of use, possibly due to the fast temperature change or pressure shocks from the nearby solenoid valve.

It was found that the calorimeter method could not reliably detect the difference between moving and static water and this led the calorimeter to over-estimate the hot water load. Perhaps with a great deal of persistence and patience in calibration this device could be made to work satisfactorily. Avoiding the addition of dedicated sensors in the collector flow circuit is an important commercial consideration. With commercial simplicity in mind, a more reliable load sensor was sought.

The solution adopted is to use the existing tank temperature profile sensor and look for a change in measured UTE or TTE. The change in either of these
quantities, corrected for auxiliary heating (set by the controller) and solar contribution (known from the pump speed and collector set point temperature), provides a direct measurement of the load drawn from the system. A minimum rate of loss of UTE or TTE is required to signify a load. The threshold chosen was 400 kJ/min (approx 2 L/min) so that normal tank losses to environment and most sensor noise were excluded. This implies that any true load of flow less than 1 litre in each 30 second sample will be ignored. In practice, the total tank energy was found to be a better indicator of hot water load than UTE. This supports the theory that mixing of hot and cold water occurs at the top of the tank. The controller maintained a buffer of the current and previous two TTE values so that back summation could be carried out once a load was detected. It is important that the controller correctly discretised measured load information so that a single load did not become fragmented by time slicing when it was really one load event. Although the state variables were evaluated every 30 seconds, loads were accumulated in 12 minute blocks for the load learning algorithm (figure 7-1) so that there were 120 load blocks in each day. This implies that a load must be discontinuous for at least this period before it was treated as a separate load by the learning algorithm.

Figure 7-1  Contiguous measured loads spanning several timesteps are interpreted as one aggregated load which is deemed to occur at the beginning of the timestep where the first load was detected.
This event based learning, rather than learning by timeslot, overcomes several problems of small loads and end of loads influencing the forecasting statistics.

Good agreement was observed between the AS4234 hot water load generated by the load dump controller and the load detected by the controller during the experiments (table 7-1). At this point, the analysis was not concerned with load learning ability, just load detection. The mean and median of the detected loads were very close for all sizes of load. The standard deviation of the load error was less than 10%. From a control perspective, the minimum and maximum errors are of interest. The worst case was an overestimate of 20% and the larger errors seemed to coincide with times of solar gain in the logged data. This implies that the correction for solar contribution requires attention. This has not been addressed in this thesis due to time constraints.

<table>
<thead>
<tr>
<th>Actual Load</th>
<th>Detected Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morning (x2)</td>
<td>5,400</td>
</tr>
<tr>
<td>Daytime (x2)</td>
<td>3,600</td>
</tr>
<tr>
<td>Evening (x3)</td>
<td>4,500</td>
</tr>
</tbody>
</table>

Table 7-1  Comparison of hot water loads detected by the controller against the actual load drawn

Nonetheless, the agreement is reasonable and does not seriously inhibit the commercial application of the predictive heating strategy. A better temperature profile sensor might understand plug flow or simply have more sensing elements to reduce these errors, as suggested in chapter 5.

Increased accuracy of the method would require knowledge of the relationship between pump power setting and the collector flow. This will vary with the number of collectors on the system and to a lesser degree the length of
installed pipe in the collector circuit. The software loaded into controllers is capable of storing and using this information at the expense of additional complexity.

7.3 Load Learning Algorithm

The aim of the load forecasting is to provide a conservative daily profile of the maximum load likely to be drawn from the tank at each discrete timestep. The simple forecast of a rolling average and variance is not sufficient for this purpose since it does not perceive the underlying process or take into account the user's perception of risk in the tank running out of hot water.

Since no hot water load information will be available to the controller upon installation, it must initially assume that the tank will need to be heated as a conventional thermostat based system at all times. Only when the forecast (including error margin) reduces below this level of UTE can the controller make energy savings.

The only general observations that may be included in the model are that weekdays and weekends may be different, that there may be a seasonal variation in demand and that the loads depend upon time of day. The hot water load series was divided so that there was a separate time series for each weekday time step and for each weekend timestep. Thus there were 120 time series representing weekdays and 120 time series representing weekends. Each of these series was characterised by the previous 30 days of load patterns and updated daily using the previous day's load information. This allowed the next value in each series to be extrapolated as the load forecast for the current day.

A UTE profile for the tank consisting of 120 values was thus produced based on the forecasted load using the method outlined in Chapter 4.

The learning methods available for this kind of time series analysis may be generally classified as either statistical methods or intelligent methods (figure 7-2). The intelligent systems shown are excellent at building up interpolation nets from a history of experience (i.e. a number of input variables) by defining associations of varying strengths or by defining a set of rules or guidelines for
various combinations of inputs. This approach is often used in electricity demand forecasting where there are correlations with ambient temperature, the time of day and day of week. The univariate nature of the hot water load learning problem makes these approaches unnecessarily complicated.

The literature on time series is dominated by economic applications with several niche areas such as electricity market load. The methodology adopted for predicting domestic hot water loads is to choose a simple approach and test its validity before incorporating greater complexity.

The statistical methods rely on correlations of varying degrees of complexity. The more complex methods such as the Kalman filter and state estimators imply that there is a substantial information content in the data being modelled. Since the hot water load datasets are univariate time-series, the simple auto-regressive, moving average (ARMA) statistical method was chosen for this thesis.

Figure 7-2   Approaches to the load learning problem
7.4 Statistical Time Series Forecasting

The statistical treatment of time series is the traditional approach to common forecasting problems in the time domain such as stockmarket movements, airline bookings, weather phenomena and process control.

Statistical methods are used to identify and characterise the time series from which a prediction may be generated. The general approach is to remove known trends or bias from the data so that the residual process is statistically stationary. The residuals are then modelled using a time series structure.

This hot water load model is identified from the characteristics of the auto-correlation and partial auto-correlation functions derived from the data values and fitted using co-efficients derived from the correlation co-efficients themselves. The goodness of fit may be checked by a least squares method and the forecasting series is usually truncated during this process. The resulting model is subsequently used in forecasting future values of the series, in this case just the next value – the expected hot water load at this timestep for the current day.

7.4.1 Removal of the Deterministic Components

A time series may be considered the aggregate of a deterministic component and an unrelated purely stochastic component using the Wold Decomposition Theorem (Cox & Miller 1965). In the treatment of time series, the deterministic component is firstly identified and removed from the series so that the stochastic residuals may be modelled as a statistically stationary series. This condition is satisfied if the mean of the residuals is constant, the variance is constant and the residual auto-correlation function is independent of time. A constant mean is a reasonable assumption in this case since a linear trend is first extracted from the data (figure 7-3) and the length of the series is much less than the expected seasonality in the series. A constant variance is likely to be a poor assumption in which case the series is said to be weakly stationary provided that the third condition still holds true. To ensure reliable performance, the controller cannot assume that auto-correlation function will be
consistent (in time) and that the process will even be weakly stationary. This implies that the auto regressive model will be valid for one set of data only and should be updated each day with regard to its length and co-efficients.

The deterministic component could be a trend (linear, logarithmic, polynomial) or a periodic function as in seasonal data. Trends may be removed by simple linear regression or a transformation followed by linear regression.

This trend is then added back into the later forecast and its variance also contributes to the forecast variance. Seasonal components may be removed using the technique of differencing. Since the hot water loads need to be learnt quickly (an owner would not be satisfied with a controller that took several years of seasons before "learning" the load seasonality), seasonality is included by treating the seasonal variation (if any) as a piecewise linear sequence of time series where each time series spans around 6 weeks. The model may be further refined by taking each 6 week series as a sliding 6 week window so that seasonality is accounted for by a linear trend over a quasi-continuous period. Thus each weekday series will have length 30 values and each weekend series will have length 12 values. The weekend forecasts will have greater variance and be less statistically valid than the weekday forecasts. This implies that the controller will need to be less aggressive in energy saving over the weekend.

The choice of window length is a somewhat arbitrary compromise between a
7. Energy Profile Forecast

7.4.2 Selection of the Time Series Model

The simplest choice of model would be to take the mean of the residuals and add some multiple of the variance of the residuals to reflect a confidence interval. A more comprehensive approach would be to look for trends in the residuals. Chatfield (1984) is a useful reference for ARMA statistics.

The common choices for time series are moving average models, auto-regressive models or combinations thereof. The forecast value $X_t$ is derived from a multi-dimensional moving average time series of order $q$ in the form of equation 7-1.

$$X_t = \psi_0 Z_t + \psi_1 Z_{t-1} + \ldots + \psi_q Z_{t-q}$$  \hspace{1cm} (Eqtn 7-1)

Here $\psi_i$ are constants and $Z_i$ is a random variable with zero mean and finite variance. The forecast is essentially a combination of past errors, $Z_{t-j}$ (from the mean).

Alternatively, $X_t$ may be calculated from a multi-dimensional auto-regressive time series of order $p$, in the form of equation 7-2.

$$X_t = \phi_1 X_{t-1} + \phi_2 X_{t-2} + \ldots + \phi_p X_{t-p} + Y_t$$  \hspace{1cm} (Eqtn 7-2)

Here $\phi_i$ are constants and $Y_i$ is a random variable with zero mean and finite variance. The forecast is a combination of past values, $X_{t-j}$.

The solution for the co-efficients of an auto-regressive time series is a set of $p$ linear simultaneous equations and is thus tractable. The solution for the co-efficients of a moving average time series is an optimisation problem in $q$-dimensional space. The order of the weekly time series is 30 and thus the solution is not easily reached. Although one sometimes finds that the correlation plots indicates a reduced moving average series might be acceptable, no such assumption would be reliable for the hot water load problem. A simplification comes from the equivalence of an infinite order
moving average series and a finite order auto regressive series (Chatfield 1984). Thus the controller will always take the auto regressive time series approach, initially of order 30 for weekdays and 12 for weekends.

7.4.3 Auto-Regressive Time Series Identification
The time series is characterised by calculating the auto-correlation ($\rho_k$) of the time series at all time lags (k). The auto-correlation at lag k is calculated from its covariances (equation 7-3, 7-4).

$$\rho_k = \frac{\text{Cov}(k)}{\text{Cov}(0)} = \frac{\text{Cov}(X_t, X_{t+k})}{\text{Cov}(X_t, X_t)} \quad (Eqtn 7-3)$$

$$\text{Cov}(k) = \text{Cov}(X_t, X_{t+k}) = \frac{1}{(N-k)} \sum_{t=1}^{N-k} (X_t - \mu)(X_{t+k} - \mu) \quad (Eqtn 7-4)$$

The mean of the residuals is expected to be close to zero if the removal of the trend component was effective. The calculated correlation co-efficients are compared to those generated by an auto regressive series of order q. (Eqtn 7-5)

$$X_t = \phi_1 X_{t-1} + \phi_2 X_{t-2} \ldots + \phi_q X_{t-q} + Z_t \quad (Eqtn 7-5)$$

To find these co-efficients, multiply both sides by $X_{t-1}$ and take expectations:

$$E(X_t X_{t-1}) = \phi_1 E(X_{t-1} X_{t-1}) + \phi_2 E(X_{t-2} X_{t-1}) + \phi_q E(X_{t-q} X_{t-1}) + E(X_{t-1} Z_t) \quad (Eqtn 7-6)$$

$$\text{Cov}(1) = \phi_1 \text{Cov}(0) + \phi_2 \text{Cov}(1) \ldots + \phi_q \text{Cov}(q-1) \quad (Eqtn 7-7)$$

Now multiply both sides firstly by $X_{t-2}$ and take expectations:

$$E(X_t X_{t-2}) = \phi_1 E(X_{t-1} X_{t-2}) + \phi_2 E(X_{t-2} X_{t-2}) \ldots + \phi_q E(X_{t-q} X_{t-2}) + E(X_{t-2} Z_t) \quad (Eqtn 7-8)$$

$$\text{Cov}(2) = \phi_1 \text{Cov}(1) + \phi_2 \text{Cov}(0) \ldots + \phi_q \text{Cov}(q-2) \quad (Eqtn 7-9)$$

This process continues q times and generates a series of q simultaneous equations from which the co-efficients $\phi_i$ may be found, given that the covariances are known from the measured time series.

7.4.4 Truncation of the Auto-Regressive Series
The weekday series forecast will require the evaluation of 30 series co-efficients derived from 30 correlation calculations and an equivalent number of simultaneous equations. There is the possibility that some of this information
may be redundant in which case the series might be truncated. A least squares goodness of fit test may be performed between the reduced model series of order q and the measured load series. If the error is within the acceptable tolerance, the series is truncated by one term to order q-1 and the model series is again compared to the measured series using a least squares comparison. This process repeats until some criteria of acceptable error is exceeded. Granger & Newbold (1986) suggested the contrary approach known as stepwise auto-regression whereby a first order auto regression fit is carried out. The least squares test is carried out and the model series increased in order until the model series test passes some accuracy criteria. This is the lower computation approach used by the load forecasting algorithm. The model fit was deemed acceptable if the sum of squares error between the residuals and modelled data was less than 10% over the period of the sliding window.

7.4.5 Production of the Load Forecast
Variance in the forecast comes from errors in estimation of the measured loads and the error between the model and the residuals. A conservative estimate of the total forecast variance would be to sum these variances and then include the total variance \( \sigma \) in the hot water load forecast.

This is an average (expected) deviation from the mean (expected) forecast. The auto-regressive series does not provide a confidence interval or any probability that this forecast will be exceeded since the underlying distribution is unknown. A rule of thumb may be required so that the user’s expectation of reliability of service may be honoured.

The proposed solution (equation 7-10) is to set the load forecast as then sum of the truncated auto-regressive series, the extrapolated trend component \( T_{t+1} \) and a multiple of the expected total variance in the forecast (but not in the auto-regressive model since this is unknown).

\[
X_{t+1} = T_{t+1} + AR_q(X) + m\sigma
\]

*Eqtn 7-10*

The value of \( m \) would be set initially to a high value (say \( m=3 \)) and the controller would aim to reduce this when the variance of the residuals in the
auto-regressive series tends constant i.e. m is partly a measure of the degree of stationarity of AR₉(X).

A maximum value for Xₜ₊₁ is constrained by the product of the tank volume and the tank's maximum operating temperature.

7.5 Calculating the Energy Profile Forecast

The calculation of the UTE setpoint profile is a manifestation of the energy balance with corrections for tank standing losses. The coming day is divided into 120 intervals of 12 minutes duration and energy quantities are deemed to occur at the start of the timestep. The algorithm keeps a minimum energy in the tank at all times as a "safety" margin.

The general algorithm is:

- Determine auxiliary requirements from a balance of existing tank UTE, solar contribution and forecasted load at each timestep
- The auxiliary power is limited, implying that the energy balance casts an auxiliary heating shadow back in time. Add these auxiliary shadows to the UTE profile
- Tank standing losses are proportional to the tank UTE. Back-calculate total UTE standing losses from each load and account for these in the energy profile
- Check that the load profiles are still being met after accounting for tank losses. Add more auxiliary heating if required. Where appropriate, close in gaps where auxiliary heating is required for part of a timestep.

The auxiliary heating profile is obtained as a by-product of producing the UTE profile for the controller. The auxiliary heating profile is denoted the "just in time" auxiliary profile and is the most energy efficient use of the auxiliary heater for the prevalent solar and load conditions.
7.6 Calculating the Tariff Sensitive Energy Profile Forecast

The controller has the ability to move the auxiliary heating periods in time to take advantage of variable auxiliary energy tariffs. This will depend upon the user's willingness to pay a premium for the controller to operate in an energy efficient manner. This premium is expressed in c/kWh.

The algorithm for determining the tariff sensitive UTE profile takes the JIT auxiliary heating profile as its starting point and produces a modified auxiliary heating profile which then allows the retro-calculation of the UTE setpoint profile. Auxiliary heating across multiple timesteps is treated as a number of separate auxiliary heating events. The general algorithm is:

- If there is a lower tariff available and if the auxiliary heater is not already being used during all of this period then check that shifting the auxiliary heating to this time will not exceed the user's premium
- Any auxiliary heating period that fails either of these tests is not moved in time
- Close up any fractional time periods of auxiliary heating for periods that have been moved
- Reform the UTE profile and estimate standing losses
- Check that each load is still satisfied, and add auxiliary heating during the low tariff period as required.

The UTE profile produced by this procedure was the one that was implemented in the controller on a daily basis.

7.7 Modelling the Effects of Load Forecast Errors

The TRNSYS model of the predictive control algorithm (using type 256) was used to investigate the effects of errors in the quantity and timing of the load forecast.

The TRNSYS typical meteorological year weather data for Canberra was used with the predictive energy balance to forecast the auxiliary heating
requirements for every 12 minute interval of the year. The predictive algorithm was modified to produce two TRNSYS input files:

1. A setpoint profile for tank UTE for every 12 minutes of the simulation year. This timestep was chosen for the predictive energy balance program since it was written to pass setpoint profiles to the real controller. The controller has memory limitations that restrict it to a minimum of 12 minute intervals. The TRNSYS model ran with a timestep of 1.2 minutes and interpolated between stored UTE values.

2. A file indicating when additional low tariff auxiliary heating was required. This occurred whenever a just-in-time auxiliary heating strategy was not being used and over-rides the normal set-point control of the auxiliary heater. TRNSYS input files were generated for energy premium levels from 0c/kWh to 5c/kWh in 1c/kWh steps.

Firstly, errors in magnitude of the forecast load were modelled in steps of 10% between -50% (a 50% under-estimate of the actual load) to 50% (a 50% over-estimate of the actual load). Combined with the 6 steps in energy premium, there were in total 66 simulations to examine the effects of load magnitude error. The simulation results are shown in figure 7-4.

One might expect that over-estimation of the upcoming load would provide a small penalty in auxiliary heating that becomes more significant when auxiliary heating is brought forward (energy premium=0c/kWh) and compounded by additional tank losses. There would be no reliability of service problems. This is indeed shown. Solar contribution decreases in proportion to the additional auxiliary heating due to additional conduction down the tank and the resulting elevation of the collector inlet temperature.

Under-estimation of the load has more troublesome implications, particularly for an energy efficient controller. A real controller would need to over-estimate its forecast UTE profile to avoid this circumstance. There is an energy penalty for this. Fundamentally, it is imperative that the controller has a good idea of the upcoming load if it is to perform well.
Figure 7-4 The effect of load forecast magnitude errors on the annual active control performance. Load errors are expressed as a percentage of the actual load; negative errors being an underestimate by the forecasting program. Cold delivery (in L) refers to water delivered from the tank below 55°C. All other quantities are annual energy in MJ/yr.
Figure 7-5  The effect of load forecast timing errors on the active control performance. A negative timing error means the load arrives later than forecast.
Secondly, errors in timing of the load of ±1 hour in 12 minutes timesteps were modelled (figure 7-5). When low tariff heating was used, performance was largely unaffected since the auxiliary heating (if required) was carried out well in advance of the anticipated load. Only when energy efficient auxiliary was used was the controller caught out.

If the load arrived late, tank UTE would have been eroded through conduction and thermal losses. This was tempered to a degree by the opportunity for additional solar gain.

When the load arrived earlier than expected, the controller may be partly prepared since auxiliary heating often began well before the load was due, and again there will be some solar hot water available in the tank. Cold delivery was reduced somewhat in the model by the margin between the controller UTE criteria of 60°C and the tempering valve setpoint of 45°C. Maintaining a UTE buffer in the tank is an important consideration for load timing errors as well as load magnitude errors.

The definition of acceptable performance is somewhat arbitrary as it depends upon the hot water service in question. The minimum acceptable hot water delivery temperature used in the model, measured at the tempering valve outlet, was set to 45°C (AS2813 Class B operation).

7.8 Reviewing Controller Performance

The controller maintained a small database of the previous day’s activity and had available to it communication media to both the user (the user interface) and to the utility (the network connection). Daily aggregates of solar contribution, auxiliary energy, auxiliary cost and load drawn were routinely calculated. These values were not stored for longer than one day although the utility may wish to do so. The controller performed a diagnostic procedure based on the measured solar contribution and the aggregated data to check that the solar collection system was operating effectively. Only conscientious owners would otherwise be aware of diminishing performance of the solar collection system in units currently available.
The controller carried out self-diagnostics a daily basis using the logged energy quantities. The diagnostics were programmable and thus arbitrarily complex, limited by the sensing capability of the controller. Diagnostic information was available on the human interface shown in chapter 5. Daylight hour alarming capability could be easily added. Real performance data on solar (and other) water heaters is potentially visible with this mechanism and this would surely be a valuable resource for the utility. An infrastructure to realise this potential is proposed in section 11.4

7.9 Application to Non-Solar Water Heaters

Forecasting the load applies equally well to conventional water heaters as solar devices. By setting the solar contribution to zero, the predictive algorithm would proceed as previously described.

The predictive controller provides a simplified potential migration path from a conventional heater to an actively controlled split system solar water heater. A conventional tank could be installed and an external auxiliary heater fitted. This heater may be a gas or electric unit. The tank would have an external circulation pump fitted at this time to operate the auxiliary heater. The active controller, including the variable power pump controller, would be factory fitted.

At a later time, solar collectors may be fitted to the heating circuit by attaching a pair of solenoid valves to two tee piece stubs that were fitted at the factory. The collectors would be plumbed to these valves as part of the heating circuit. Once the collector temperature sensors are connected to the controller, the control algorithm would automatically switch to solar operation by auto-detection of the collector outlet thermistor.

Using this methodology, replacement hot water services can be up and running in a very short time without compromising the choice of fitting solar collectors at a later date.

Perhaps every electric and gas storage tank above 220 L in capacity should be mandated to have extra tank fittings suitable for later addition of solar panels.
8. The Auxiliary Heater

"The difficulty lies, not in the new ideas, but in escaping the old ones, which ramify, for those brought up as most of us have been, into every corner of our minds"

John Keynes, from K. Eric Drexler “Engines of Creation: the Coming Era of Nanotechnology"

8.1 Introduction

An efficient storage tank should not heat a volume of water from auxiliary sources exceeding that of the upcoming loads and associated losses. This implies that the volume of water that must be heated varies with demand if a water heater is to operate with high thermal efficiency. How can a variable volume of water be heated in a pressurised tank?

It is worth considering the thermal properties of water before designing any heating equipment. Water has a poor thermal conductivity (0.61 Wm⁻¹K⁻¹) and its density decreases with increasing temperature. This leads to the possibility of hot water movement by natural convection when temperature differences exist in the tank. The hottest water rises to the top of the tank. It would be desirable to keep auxiliary heated water away from the tank walls and away from colder water. The control algorithm would then be able to operate more efficiently.

This chapter introduces a number of options for non-conventional auxiliary heating. Some were tried by other authors and some are unique to this thesis. Some of these methods attempt to generate heat remotely and rely on transport mechanisms to deposit heat where it is required. Others attempt to generate heat at the desired location directly.
8.2 Fixed Location Auxiliary Heaters

8.2.1 Natural Convection Auxiliary Heaters
Two fixed location heating devices are illustrated in figure 8-1. They are the side-arm heater proposed by Furbo and Shah (1997) and the heat funnel which operates on the same principle. Either the diameter of the heater outlet tube or a thermal valve controls the thermosyphon rate through the friction head loss and thus influences the tank top temperature.

![Figure 8-1 Heat funnel and side-arm auxiliary heating both rely on thermosyphon action to heat the tank from the top down](image)

Both strategies attempt to heat a tank from the top down. The control algorithm requires water at the heater outlet to directly contribute to the tank UTE. Its temperature must exceed the set point temperature (65°C) for this to occur. An insulated heat funnel illustrated in figure 8-1 was constructed and tested by the author. It was found that the diameter of the chimney pipe had to be restricted to about 8mm diameter to achieve a noticeable temperature rise across the device. The pipe outlet temperature never exceeded 45°C in this arrangement before lower temperature water spilled from under the funnel base and heated the tank in the usual manner. The stopping of the thermosyphon flow in the side-arm heater was also noticed by Furbo in the side-arm heater which works on the same principle.

A further problem with this arrangement for highly stratified tanks is that the
8. The Auxiliary Heater

heater always heats the coldest water in the tank. If the cooler water was pumped to the collectors and warmer water sourced for the auxiliary heater, then the thermal efficiency of the collector would improve and the auxiliary heater would provide more UTE for its input energy. With these arrangements, the energy embodied in any warm water (from the collectors or gained through de-stratification in the tank) is not useful. How can this design be improved?

8.3 Variable Location Auxiliary Heaters

A better arrangement is to always heat water from the part of the tank where its temperature is just below $T_{sp}$. The ideal scenario would be to have a heater with continuously variable penetration depth in the tank. Listed are methods considered to achieve this:

- A passive neutral buoyancy valve
- A rotary sleeve valve with actuator
- A segmented heater with electronic control
- Moving the auxiliary heater in the tank
- External auxiliary heater with variable return position.

8.3.1 Neutral Buoyancy Valve

The buoyancy valve method relies on a water inlet mechanism 'floating' at the level of the tank where its buoyancy matches the buoyancy of water at temperature $T_{sp}$. The water inlet mechanism is coupled to a heater in a vertical tube near the top of the tank in the style of the Furbo smart tank (Furbo & Shah 1997; Furbo & Knudsen 2000) and is essentially the heat funnel thermosiphon device with a variable inlet. The restriction of limited temperature rise may be less of an issue since the water being heated is predominantly warmer than supply water. This assumption is only valid for small heated volumes. This is a difficult approach due to lateral instability of the float, the lack of useable force due to buoyancy, longevity of the float properties and disturbances to the float position due to water flows in the tank. No experimental equipment was built to test the buoyancy valve.
8.3.2 Rotary Sleeve Valve
A better means of controlling the effective location of heating was sought. Variable heater inlet position may be provided by a rotary sleeve valve as shown in (figure 8-2).

![Diagram of Sleeve Valve Assembly](image)

**Figure 8-2** Sleeve valve assembly consisting of a fixed inner sleeve with a spiral slot and a rotating outer sleeve with a vertical slot. The auxiliary heater is located inside the inner sleeve and operates with feedback from the temperature profile sensor.

An outer tube is sealed at its bottom and cut with a vertical slot. Inside this tube is another concentric tube with a spiral slot. The auxiliary heater is located in the top of the inner tube and the hot water outlet is at the top of the tube. Again there is a restriction in the inner tube outlet diameter to control the outlet temperature. As the inner tube turns, the effective entry point for water to be heated moves vertically within the tank and the heater can be made to heat water in the region of $T_{sp}$. Any heat spillage through the water entry point of the valve heats up the zone of water required for the load, so no energy is wasted as was the case with the heat funnel concept.

This arrangement faces actuation difficulties across the boundaries of a pressure vessel. The main functional disadvantage is that the water may have to pass over the heater several times (by thermosiphon action) to reach useful
8. The Auxiliary Heater

temperature and so there is a slow response time (although faster than a conventional heater). This is a problem for a just in time strategy when there is an unanticipated load. A PVC sleeve valve assembly was constructed with the intention of testing the device in an open top tank using manual actuation. Concerns over actuation through a pressure vessel wall and the difficulty in using gas auxiliary heating with this method led to investigation of other options.

8.3.3 Zoned Auxiliary Heater

Prud'homme and Gillet (2000) attempted to use a crude segmented auxiliary heating arrangement consisting of three separate electric heating elements operating at different penetration depths. A large orifice in the tank wall was required to accommodate the elements. It appears from the diagrams in the paper, but was not explicitly stated, that less than half of the tank could be heated by the element with greatest operating depth in the tank. The models used small hot water loads so the system was able to meet the loads reliably and provide decreased auxiliary consumption since a smaller proportion of the tank was heated compared to the conventional auxiliary heater placement.

An extension of this approach, without the low load limitation, is to add more heater segments or heating zones and to be able to switch them individually (figure 8-3). This zone heating approach provides very flexible control of energy input location and timing.

Prud'homme & Gillet found that zone heating also helps to preserve thermal stratification. Each zone of the heater does not need to be particularly powerful since only a small local volume is being heated, and typically the water just below \( T_{sp} \) is being heated so that the amount of energy required is often small. This leads to fast recovery times for this auxiliary heating strategy.

It is difficult to produce a single heating element with a number of heating zones exceeding two or three. There are problems with electrical insulation, power density and thermal conduction along the element. Nonetheless this kind of apparatus is something to aspire to.
Various zones of this heater could be efficiently and cheaply switched under semiconductor electronic control. Thick film heaters offer a possible solution and were discussed with a manufacturer (Stokes Synertec Australasia Ltd) although there are issues of ruggedness with regard to water hammer.

A crude multi-segment electric heater was constructed to progress testing of other aspects of the solution. It consisted of eight 1000 W heaters located inside a thin wall stainless steel tube (18 mm x 0.5 mm wall) inside the storage tank. The steel tube fitted in place of the sacrificial anode and was sealed with a steel cap at its lower end. Each heating element was 100 mm in length and separated form other elements by a 10 mm ceramic spacer. The elements were electrically isolated from the (electrically earthed) tube using magnesium oxide powder. Each element was tediously centred in the steel tube before being surrounded with the powder. Figure 8-4 shows the design and construction of the device.

The heating elements were constructed from 14 mm diameter air heater ceramic bobbins wound with nichrome heating wire of resistivity 13.77 Ω/m. Each element was designed to consume 1000 W. The maximum surface power density of the heater was calculated to be 19.4 W/cm², a high value for electric resistance heaters (typically 10-15 W/cm²). Electrical joints between the power
supply cables and the element heating wire were accommodated in flats ground at the end of each bobbin. The wires were joined using compact crimp connectors. The nine cables from the elements were insulated in high temperature sleeving and routed up through the hollow core of each bobbin and out the top of the tank through the upper open end of the steel tube. The steel tube was sealed to the tank using a compression fitting and adaptor.

![Diagram showing the segmentation of auxiliary heaters](image)

**Figure 8-4** Cross section of the segmented auxiliary heater showing two heating elements separated by an insulating spacer. The thin oxide layer inside the stainless steel case is also visible.

A simple electronic circuit was designed to drive the segmented heater. It consisted of a microcontroller and one semiconductor driver for each element. This controller communicated with the main system controller over a two wire, bi-directional serial peripheral interface bus (SPI Bus). The temperature profile thermistors were connected directly to the heater controller which then calculated tank UTE, TTE and the location of the lower boundary of tank UTE. This information was passed over the SPI bus to the system controller which then compared the measured tank UTE to the set point and sent a reply to the
heater controller. This reply indicated whether auxiliary heating was required. The controller was designed to activate the heating element just below the lower boundary of the tank UTE. Each heating element was individually fused. The semiconductor drives were SGS model BTA10-400T. This operation of this circuit was not proven as there were problems with the heater itself. Problems were experienced with very high temperatures in the core of the heater segments leading to breakdown of the (high temperature) insulation on the wires. The poor thermal conductivity of the stainless steel sheath and packing powder (25 Wm\(^{-1}\)K\(^{-1}\)) is partly to blame for this.

These tests co-incided with the implementation of the internal temperature profile sensor. The difficulties associated with both devices led to thought about options for external auxiliary heating and external temperature sensing. A pressing concern was the ability to use gas auxiliary heating to reduce a water heater’s greenhouse gas footprint.

Should other researchers continue this work, a larger diameter bobbin would be desirable to help separate the electrical cables and lower the surface power density of the heater. A ceramic coating directly applied to the heating element could offer better heat transfer from the element to the water.

8.3.4 Moving Auxiliary Heater

Variable auxiliary heating location could be achieved using a conventional electric heating element and physically moving it inside the tank using an electrical servo mechanism (figure 8-5). In this design, which was constructed, a conventional heating element was winched by a cable attached to a revolving anodised aluminium drum located at the top of the tank. The winch device screwed into the existing anode fitting in the tank.

The anode was removed for the purposes of the experiments. The stepper motor actuator was located outside of the winch housing and its shaft sealed using o-rings. The heater cables were restrained so that they could not come into contact with the element. Shielded high temperature power cabling for the heating element was directed through the tank wall where the heating element was previously located.
A fine strand cable was used since mechanical fatigue of the fly wires to the element was a concern. The auxiliary heater element was suspended from the winch cable by three stainless steel wires that formed a pyramid. The winch assembly was operated in closed loop control with the temperature profile sensor to locate the element at the boundary between hot and cold water in the well stratified tank. This design was never operated due to concerns about its electrical safety, reliability and manufacturability. These concerns primarily regarded the need for flexible and moving power cabling. Another use for the winch device was to actuate the auxiliary heater inlet location (section 8.3.6) in a way that would allow an electric or gas auxiliary heater to be used.

8.3.5 External Auxiliary Heater
External mounting of the auxiliary heater offers a degree of flexibility regarding the auxiliary energy source without requiring major tank modification. Tank construction would also be simplified. These are distinct manufacturing advantages.

In order to overcome the convection problems noted with the side arm heater, forced circulation through the auxiliary heater is required. For solar water heaters, it is possible to use the collector circulation pump (for split systems) with the addition of a three-way valve to divert water either through the collector, auxiliary heater or both. This allows the option of gas auxiliary
heating.

This arrangement has a number of important operational advantages:

- Controlled temperature and volume heating is possible
- Pumping water through the heater overcomes problems associated with natural convection auxiliary heating without the addition of another pump
- The solar collector may be used as a pre-heater when the auxiliary heater is in use.

Two solenoid valves S1 and S2 divert water through either the collector or auxiliary heater (figure 8-6). They act as a non-return valve when neither auxiliary heating nor solar heating is in use. Further, it may be possible to remove valve S1 if the natural flow resistance of the collectors and associated pipework is greater than the resistance of the path through S2. This refinement was not confirmed by experiment. All of the experiments were conducted with both valves in place so that observation of the loss of UTE due to return mixing could be directly characterised.

![Figure 8-6](image)

**Figure 8-6** Operation of the heating circuit solenoid valves and selection of the control temperature sensor
8. The Auxiliary Heater

**Figure 8-7** Auxiliary heater installation

1. Hot water outlet
2. PTR valve and collector return
3. Heater assembly
4. Over-temperature switch and relay box
5. Solenoid valves
6. Pump controller
7. Tempering valve
8. Load solenoid valve

**Figure 8-8** External electrical auxiliary heater design and construction shown with insulation removed

1. Heater inlet
2. Insulation
3. Electrical element
4. Over-temperature cut-out switch
5. Outlet temperature sensor
6. Heater relay box
7. Heater outlet

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An external electric auxiliary heater (figure 8-7) was installed on the experimental split system. The heater consisted of a compact 3.6 kW, 240 Va.c. screw mount electric element of conventional design. It was housed in a stainless steel tube of dimension D x L x wall = 50 x 270 x 3 mm with 6 mm end caps welded in place (figure 8-8). Bosses with standard pipe threads were welded to the tube to form the heater inlet and outlet. The heater housing was wrapped in rockwool and fitted with a weather-proof aluminium cover. A temperature sensor was installed on the heater housing adjacent to the hot water outlet and was monitored whenever the auxiliary heater was in use. The pump controller used this sensor to control the pump flow so that the auxiliary heater returned water to the tank that immediately contributes to tank UTE (providing fast recovery) and did not disturb thermal stratification. It would be possible to use this sensor for the solar only mode but control would be poor due to the long transport time between the collector and sensor, made worse by the low-flow collector regime. The return pipe from the auxiliary heater to the tank entered next to the temperature and pressure relief valve at the top of the tank to minimise de-stratification.

Thermal protection was provided by an auxiliary heater over-temperature thermal cut-out switch located in the auxiliary heater assembly. The device was a capillary thermostat, Radiospares model 250-6077. This actuated a relay in series with the main auxiliary heating control relay. It was set to cut power to the electric auxiliary heater at 90°C with hysteresis of 10°C.

It is important to ensure that the pump has sufficient capacity to control the return temperature when the collector is in full sunshine and the auxiliary heater is in use. The standard collector pump was adequate for the task although only just when the low flow flowmeter was used (figure 8-9), since this reduces maximum flow by around 30%. The strategy still works provided that thermal stratification in the tank keeps the hot water inlet temperature below about 35°C.

Further protection was provided by the tank’s pressure and temperature relief valve, located in-line with the heater return pipe. The location of the heating
circuit return needs to be near the top of the tank since the return water should always be hot and UTE losses due to mixing are to be avoided. For the same reason, the auxiliary heater outlet should be located close to the top of the tank or installed within the top of the tank housing.

![Operating range](image)

*Figure 8-9*  
*Pumping capacity with varying solar conditions. Auxiliary heater is switched on*

With the use of this design, the storage tank and auxiliary heater may be installed without solar collectors at first. Predictive energy balance mechanisms would still operate and produce energy and cost savings. These savings could offset the later cost of retro-fitting solar collectors.

### 8.3.6 Actuated Auxiliary Heater Inlet

The external auxiliary heater design (section 8.3.5) that was tested experimentally used a fixed location water inlet. That location was the bottom of the tank, so the auxiliary heater always heated the coolest water in the tank. This shortcoming was described for the thermosyphon action water heaters.

A possible enhancement is to move the heater's effective inlet and outlet locations using the winch system previously described (figure 8-10). The water inlet would be moved to the lower boundary of the body of UTE. In the experiments, a consistent temperature gradient was observed in the experimental tank. The auxiliary heating time and energy input could be reduced by marginal heating in this manner.
The temperature profile sensor is required to locate the lower boundary of the UTE volume. The stepper motor provides a deterministic locating actuator for the auxiliary inlet water. A predictive control algorithm is required to get the best performance out of this approach.

The inlet actuator was not installed due to time constraints but would be a next logical step after the installation of the external auxiliary heater. This device could fit into an existing tank with minor modification to the tank cold water inlet fitting.

### 8.3.7 Passively Actuated Auxiliary Heater Inlet

A passive replacement for the external auxiliary heater inlet actuator would be preferred to an active design on the grounds of simplicity and perhaps reduced cost. A design based on a vertical tube with bi-metallic valves is proposed but has not been constructed (figure 8-11). This device would not fit into a tank of conventional design and would require a flange fitting on the tank crown. The actively actuated design should be evaluated first to check that the actuated inlet idea has experimental support. The design uses conventional bi-metallic strips as passive actuation elements.
A long vertical water collection tube is placed in the hot water tank. The bottom of the tube is open to the tank while the top is piped to the heating circuit pump inlet. The collection tube has a number of holes aligned vertically along its length. Covering each hole is a flap valve assembly (figure 8-12, 8-13). The flap valve consists of a short tube with two bi-metallic strips fixed at the inlet and outlet of the assembly respectively. The strip on the inside of the valve (nearest the collection tube) is open at temperatures below 40°C and progressively closes when heated. The strip on the outside of the assembly (directly exposed to the tank water) is closed at temperatures lower than 40°C and progressively opens when heated. The two valves are designed to be open together only in the water temperature range 40 to 55 °C. If there is no water in the tank in this temperature range, water is drawn from the bottom of the collection tube. Since the outlet to the pump is taken from the top of the collection tube, the pump will pick up lower density water from any open valves near the top of the tube in preference to cooler, water at the bottom of the tube.
8. The Auxiliary Heater

Figure 8-12 Detail of the flap valve mechanism


Figure 8-13 Operation of the flap valve pair at various tank temperatures. The valve is only fully open over a defined range of temperatures.
The collection tube mechanism supplies the auxiliary heater with warm water rather than cold water allowing faster recovery of UTE. The mechanism allows the solar gain that has lost temperature due to conduction to be quickly heated before delivery. This may eliminate the need for strict collector temperature control during winter months and thus enhance winter solar gain. Modelling and construction of a device of this nature would be a logical follow-up for improving active control of the split system.

8.4 Active Control of External Auxiliary Heater

The predictive energy balance strategy attempts to minimise stored energy and achieves this by heating a varying volume of water. The fixed location auxiliary heater tends to evenly heat all the water above it due to convection currents it creates within the tank. This methodology cannot be applied when variable volume heating is required.

The solution chosen from the options outlined consisted of an external electric auxiliary heater with a fixed inlet position at the tank cold supply inlet. The schematic is shown in figure 8-14 with a three way valve replacing the two solenoid valves used in practice. An actuated inlet would be desirable and either the bi-metallic flap valve or winch would have been tested if time permitted.

The auxiliary heating active control problem reduces to a simple regulatory digital control loop, working to the UTE setpoint profile determined at the start of the day. The tank UTE was sensed from the temperature profile sensor and compared to the setpoint. The auxiliary was switched ON if the measured UTE was insufficient. This comparison was carried out every 30s so that there was little likelihood of low service temperature due to poor regulatory control.

In practice, it was found that there was a degree of mixing of heated return water with existing tank water. Studies of jet impingement (van Berkel 1996; Kleinback et al 1993; Hollands & Lightstone 1989) indicate complex phenomena that would be difficult to include in a control variable.
The conservative approach is to experimentally determine a correction factor for auxiliary heating so that the auxiliary heater power is reduced for the purposes of the energy balance algorithm. By observing a number of auxiliary heating only episodes (with a stable return flow), it was found that 85% of the auxiliary energy became useful tank energy even though the pump did not initiate flow until the heater outlet was up to 65°C.

This test was repeated for solar only and solar+auxiliary heat sources i.e. a range of flow rates. Approximate extreme case correction factors could be generated for each regime (table 8-1). Correlation factors could be generated for every pump power level, but their practical use is allowing the predictive energy balance to start the auxiliary heating soon enough to meet the load. Thus, the above approximations, based only on the heating mode would be sufficiently conservative.
### Table 8-1
Correction factors for the reduction in efficiency of each water heating mode due to losses in deliverable volume in the storage tank

<table>
<thead>
<tr>
<th>Heating Mode</th>
<th>Efficiency Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aux only</td>
<td>0.85</td>
</tr>
<tr>
<td>Collector only</td>
<td>0.9</td>
</tr>
<tr>
<td>Solar collector and auxiliary heating</td>
<td>0.75</td>
</tr>
</tbody>
</table>

These correction factors may vary from system to system. Ideally, a tank that separated hot and cold water and is very well insulated may not require this correction. It would be interesting to compare the effectiveness of a standard electric auxiliary heater.

#### 8.5 A Return to Modelling

The performance of the proposed auxiliary heating model was examined in the TRNSYS modelling environment. The infrastructure proposed in this chapter was modelled in TRNSYS complete with the active controller (type 256), external heater (type 6), switching solenoids (type 11) and the AS4234 load profile (figure 8-15).

The controller switched a diverter valve with a binary signal to pump water through the auxiliary heater whenever auxiliary heating was required and there was no solar gain available. At all other times, the diverter passed water to the collector. Proportional control with adjustable tuning was provided by the controller for the pump circulation. The controller used separate tuning constants for each mode of operation (i.e. solar only, solar + auxiliary, auxiliary only) since the thermal inputs and time lags were different in each mode. Small seasonal variation of the tuning constants may be expected, particularly for poor collectors. No provision was made for this in the model.

An auxiliary heating setpoint profile for each model day was generated externally to TRNSYS by the same Visual Basic program that provides setpoints.
to the real controller. This information enters the model through a data reader (type 9) which is connected to the controller input. Type 256 compared the tank UTE to the setpoint profile and switched the auxiliary on whenever the observed UTE falls below the setpoint. A narrow hysteresis action (500 kJ) was used to mimic the deadband required in the real heater to overcome switching instability arising from temperature sensor noise. A thermostat has a much greater deadband, in the order of 8°C. This equates to around 7 MJ of UTE. The controller model had the ability to override the UTE setpoint profile and this was used to simulate off-peak auxiliary heating by providing direct access to the heater output from an external file of control signals. This second external file was also generated by the predictive energy balance program whenever the energy premium was used, and read into the model by a second data reader.

The auxiliary heater in TRNSYS tank type 38 was disabled and an external auxiliary heater (type 6) was added to the model between the collector and tank return.

The auxiliary heater was configured with a loss co-efficient of 1.0 W K\(^{-1}\). This estimate takes into account that it was well insulated but connected to copper pipework. The model had no provision for thermal mass of the heater and this may lead to a small over-estimation of the heater’s performance. The actual thermal mass of the heater and water was about 2.9 kJ/K. When the auxiliary heater was in use, water was diverted through the heater alone, unless solar gain was available, in which case solar pre-heat could be utilised. At all other times, water was pumped through the collector. A tee piece aggregated the flows and averaged temperatures from both branches.

Pipework models were used for the long pipe runs to and from the collector but not for remaining pipes where in each case their length was less than 0.5 m.

The pump flow, diverter valve and auxiliary heater were all controlled by the new TRNSYS controller model, type 256 (see Appendix B.1). An external Visual Basic program calculated the required tank UTE profile for every day of the simulated year based on the typical meteorological year data file used in the TRNSYS simulation.
This program produced a profile of tank UTE setpoints in text file format for the entire year (365x24x5= 43,800 values). The controller compared the tank UTE from type 38 to the setpoint and controlled the active heater accordingly. This program also provided the real controller with its daily operational setpoint profiles. A secondary output from the program was a text file with any additional auxiliary heating that may be required as the result of the controller seeking a lower auxiliary tariff. This text file contained 43,800 binary values indicating when the auxiliary heater should be switched on regardless of the tank state. The UTE setpoint profile was still valid and must be met since it is primarily based upon the forecast load profile.

Tank model type 38 was modified to add extra outputs for tank UTE and TTE based on simple summation of node energies relative to the cold supply. The hot side return position was moved from 0.625 m from the bottom of the tank in the conventional tank to 1.35 m for the external heater (tank height is 1.485 m). The tank inlet position mode was set to mode 2 to reflect the lesser degree of mixing with the low collector flow regime.
The pump control strategy bonds the variable volume auxiliary heating strategy and the collector control with the tank thermal stratification strategy. The following chapter details the circulation pump control. For the purpose of this simulation, the reader may assume that the low flow collector circulation strategy had been chosen with flow $0.167 \text{ Lmin}^{-1}\text{m}^{-2}$.

<table>
<thead>
<tr>
<th>Performance Indicator</th>
<th>Conventional</th>
<th>Active Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar energy collected</td>
<td>9187 MJ</td>
<td>10422 MJ</td>
</tr>
<tr>
<td>Auxiliary energy</td>
<td>8338 MJ</td>
<td>6145 MJ</td>
</tr>
<tr>
<td>Solar efficiency</td>
<td>40.0 %</td>
<td>45.5 %</td>
</tr>
<tr>
<td>Solar fraction</td>
<td>30.7 %</td>
<td>49.1 %</td>
</tr>
<tr>
<td>Storage tank losses</td>
<td>5285 MJ</td>
<td>4010 MJ</td>
</tr>
<tr>
<td>Auxiliary cost</td>
<td>$208</td>
<td>$171</td>
</tr>
<tr>
<td>Load turnovers</td>
<td>4.74</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Table 8-2 Annual comparison of modelling results for conventional system and, the proposed active control scheme (collector slope 20°, latitude 35°)

The model assumed perfect knowledge of the upcoming weather and loads. One might conclude that the results (table 8-2) would be optimistic. Nevertheless, they provide a boundary to assess the potential of the approach. The operation of the model did not result in any hot water load water being drawn below 45°C.

More detail of the performance comparison, including monthly trends, is presented in the next chapter after the various collector circulation control strategies are presented.

Simulations of the performance against minimum UTE (figure 8-16) show that the controller’s performance is rapidly degraded with the amount of additional energy that is maintained in the tank to cover for under-estimation in the upcoming load. The conventional tank in the study maintains about 37 MJ of
UTES in the tank at all times (with a deadband of 7 MJ) due to the thermostat action. The controller could only maintain 7.5 MJ of "spare" UTE, about 40 L, before its performance becomes worse than a conventional system.

![Figure 8-16](image)

**Figure 8-16** There is an energy efficiency penalty for maintaining a minimum tank delivery using an external auxiliary heater

This is equivalent to only 35 minutes of auxiliary heating. The reason for the apparent inefficiency is that the external auxiliary heater cannot benefit from energy embodied in the existing low temperature water in the tank whereas the internal auxiliary heater can reduce its heating accordingly.

An improved safeguard mechanism is to use the existing auxiliary heater as an inline outlet heater in times of crisis. The controller could detect load delivery from changes in tank UTE and can understand when water is being delivered under temperature. Load water could be recycled through the auxiliary heater before delivery. This is not common practice since it ignores the time value of auxiliary energy. This method overcomes the losses associated with storing extra UTE previously mentioned, but requires extra plumbing and actuation. The temperature rise at full flow rates, using the 3.6kW auxiliary heater, would be only about 5°C.
8.6 Experimental Performance

The conventional split system was left substantially as installed but with improved insulation on the pipework near the tank. All experiments were performed on the second system and their outcomes compared to the parallel performance records of the conventional system.

There were a number of modifications made to the experimental system. The auxiliary heater was left in place but the thermostat was disconnected and removed. The thermostat cover was insulated. A slot was cut through the tank outer cover and insulation to allow the attachment of thermistors for measuring the tank state variables. The gap was insulated with rockwool and re-covered. An electric solenoid valve was installed immediately in series with the pump and a second between the pump and collector return pipe. This arrangement provided the necessary diversion of water in the heating circuit. The new auxiliary heater was installed on a brass tee adjacent to the pressure and temperature relief valve on the top of the tank. It was well insulated and fitted with an over-temperature cutout switch set to 90°C.

The differential temperature pump controller was replaced by a variable power pump controller as described previously. The solar collector was operated in a constant outlet temperature mode. The collector flowmeter was changed for a similar model that operated over a lower flow range. This flowmeter introduced a pressure drop into the collector circuit such that the maximum collector flow rate for the experimental system was reduced from 2.6 L/min to 1.9 L/min. The maximum steady state flow required by the low flow controller observed in this experiment was 0.6 L/min (autumn), so the flow limitation was of little consequence. The flowmeter was installed on the cold feed pipework and did not measure flows when only the auxiliary heater was in use.

The additional complication of the load learning algorithm was bypassed for this experiment. It is difficult to assess the capability of the load learning algorithm without a real field trial since the system is incapable of learning a purely random load pattern (e.g. a computer generated load) but very quickly learns
the Australian standard load profile used in this experiment. Initial tests were performed with the system operating in its most energy efficient mode (energy premium=5c/kWh).

It was difficult to seal and bleed air from the new system. Control of the diversion solenoids through solid state relays has presented no problems. The pump controller has worked reliably with the exception of an episode of water penetration which destroyed the circuit board through corrosion in a remarkably short time. The microprocessor controller and associated electronics have also proved totally reliable once installation issues were overcome.

A two week period of operation is presented to demonstrate the behaviour of the experimental system (table 8-3). The data sample was taken during April-May 2004 and includes a range of weather conditions. Generally, this period was warmer and sunnier than would be expected from the model typical meteorological year data. Further data from other seasons would be a desirable addendum to this work.

<table>
<thead>
<tr>
<th>Performance Indicator</th>
<th>Conventional</th>
<th>Active Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar energy collected</td>
<td>269 MJ</td>
<td>286 MJ</td>
</tr>
<tr>
<td>Auxiliary energy</td>
<td>353 MJ</td>
<td>343 MJ</td>
</tr>
<tr>
<td>Solar efficiency</td>
<td>36.5 %</td>
<td>39.0 %</td>
</tr>
<tr>
<td>Solar energy fraction</td>
<td>28.3 %</td>
<td>30.5 %</td>
</tr>
<tr>
<td>Deduced losses</td>
<td>134 MJ</td>
<td>138 MJ</td>
</tr>
</tbody>
</table>

Table 8-3 Experimental comparison of the conventional system with the experimental active control in Autumn (two week totals)

This was an inconvenient time at which to conduct such an experiment due to the changing season. Modelling suggests that the performance of the constant collector temperature strategy works marginally better than a conventional system in April and slightly worse in May. The tests were conducted in the final
two weeks of April due to delays in assembling the equipment.

The test system did show a small gain in solar collection and a small reduction in auxiliary consumption in the order of three percent. There was no visible reduction in system losses. The algorithm is particularly prone to tank top losses since all the UTE is stored in the top of the tank. The experimental system had three copper pipe connections within the top 10 cm of the tank and this may have contributed to higher than expected tank losses. An improved design would ensure that all tank connections exit from the bottom of the tank, as is common practice in European systems, so that insulation of the top of the tank is not compromised.

Both the conventional and experimental systems showed poor solar collection performance relative to the model despite greater solar input. Perhaps this is due to extra heat losses from the collectors. They are mounted in an exposed location and the collector model does not account for convection loss. Another contributing factor is that the collectors face 30 degrees east of north and miss out on afternoon sunlight when ambient temperatures are higher. Collectors in the model were configured to face north.

The constant collector outlet temperature method requires either warm weather or efficient collectors to work effectively. In retrospect, the low flow differential temperature strategy might have been more appropriate for this experiment.
9. Collector Circulation Pump Control

“No effect that requires more than 10% accuracy in measurement is worth investigating”
Walther Nernst, Chemist

9.1 Introduction

Forced circulation solar water heater pumps typically remove cool water from the bottom of the tank, or directly from the cold water tank fitting, pump it through a number of collectors and return the water to the tank through a non-return valve. The location of the solar return coincides with the location of the auxiliary heater and has a strong influence on system performance.

At conventional collector circulation flow rates (0.7 L/min per m² of collector area), tank water is stirred by a combination of the momentum of the return jet and its buoyancy, or lack of buoyancy, as described by Hollands & Lightstone (1989). Water plume diffusers are very effective in minimising detrimental effects of return plumes. Some manufacturers already use crude diffusers that extend only a short distance down the tank.

On the test system, the solar collector water circulation pump is a Salmson model NSB04-15-CV-D26 centrifugal device powered by a 240 V.a.c. 27 W shaded pole motor (figure 9-1). This is a small induction motor with the addition of a metal ring on the stator poles that allows the motor to start. The motor shaft directly drives a moulded plastic impeller with raised straight vanes.

On a conventional split system, the pump is switched by a differential temperature controller. This device senses the temperature difference between the bottom of the tank and the collector outlet. The pump switches on when this temperature difference exceeds a preset threshold (typically 8°C) and switches off again when the temperature difference drops below a second threshold (typically 4°C). This hysteresis action is important to reduce the frequency of switching of the pump and hence the life of the pump. Circulation ceases when the tank is full of hot water.
The collector circuit is fitted with a one-way valve which is built into the tank return fitting. This prevents heat being lost from the collector by natural convection when the collector is cold. The differential temperature strategy results in the contents of the tank passing through the collector typically five times per day. This leads to a high degree of mixing in the tank and a dilution of high temperature deliverable water near the top of the tank.

9.2 Alternate Collector Circulation Control Strategies

There has been considerable debate in the literature over the best strategy to operate a split system solar collector circulation pump.

The obvious initial approach, taken by most manufacturers and some researchers (Kovarick & Lesse 1976; Schlesinger 1977; Hill 1978; Winn & Hull 1979) is to examine the solar collector efficiency equations and conclude that a high collector flow rate would result in an increase in the collector heat recovery factor which would lead to higher solar fractions. However, this approach does not necessarily optimise the system performance.

Improved circulation control strategies were investigated in the late 1970s. Most conventional split system solar water heaters still use a differential temperature control strategy.
9.2.1 Constant Collector Outlet Temperature Strategy

Wang et al (1982) presented a "one-pass" solar water heater for application in China where there was only an evening load. Water entered the solar collectors directly under mains pressure but the flow was controlled to maintain a constant collector outlet temperature of about 50°C. Heated water was then stored in a low pressure header tank. The performance of this system was claimed to be similar to a thermosyphon heater. The separation of heated water from cold supply eliminates thermal de-stratification losses due to conduction. This design is denoted the "one pass" system and relies on flow control through the collector based on a constant collector outlet temperature. Auxiliary heating in series with the collector can still be used and it's UTE output would be more accurately predicted using this approach. Indeed, the predictive auxiliary heating strategy presented in Chapter 8 would work very well on this system.

The main problems are the difficulty in obtaining water pressure at service, frost protection and designing a reliable variable volume tank.

The one-pass strategy was refined by Jesch & Braun (1984) to exactly match the daily integrals of the load and collector flows. Again, this is a constant collector outlet temperature approach. Jesch & Braun recommended a collector mass flow given by equation 9-1.

\[
\dot{m}_c = \frac{-A_cF^rU_L}{c \ln (1 - \frac{F_R(t_w)_{test}}{F_RU_{test}} I_c - (T_{cin} - T_a))} \quad (Eqtn \ 9-1)
\]

Here \( T_{cout} \) is the desired collector outlet temperature and \( I_c \) is the incident insolation. This is a useful relation for deriving solar contribution from the insolation forecast but not so useful for control purposes since a measurement of incident radiation would be required.

It is difficult to distinguish between the low-flow and one-pass strategies since they both attempt to minimise disruption of stratification in the tank and maximise system performance over a day. The one-pass approach is not realisable in a tank where hot and cold water are not separated unless the collector outlet temperature far exceeds the load temperature. This would lead
to excessive tank and collector thermal losses. Fortunately, a moderate increase in the collector circulation does not incur a large energy penalty while it does restrict thermal losses.

9.2.2 The “Low Flow” Strategy

In a conventional split system, the auxiliary heating thermostat controls storage tank UTE and is the dominant influence on the performance of the system. Several studies (Van Koppen et al. 1979; Veltkamp 1981; Phillips & Dave 1982; Jesch & Braun 1984) suggest that system solar efficiency improves in well stratified tanks if the collector flow rate is reduced from the conventional 0.7 Lmin$^{-1}$m$^{-2}$ to around 0.167 Lmin$^{-1}$m$^{-2}$. The collector inlet temperature of a well stratified tank will be comparable to the cold water supply temperature except when the tank is full of hot water. This increases the collector efficiency. The collector outlet temperature will be higher due to the low flow rate and this will increase pipework thermal losses in the return pipework. The average collector temperature will also increase leading to a reduction of the instantaneous collector efficiency.

However, the circulation pump energy requirements will be reduced and there will be less mixing and de-stratification in the storage tank. This was found in the studies to more than compensate for the increased collector thermal losses, particularly early in the morning and late in the afternoon. The low flow strategy, controlled by a differential temperature controller, may still not be an optimal solution since there is only a weak control relationship between the collector flow and incident radiation. Cool water can still return to the tank and upset thermal stratification.

This thesis builds upon the premise that low collector flows improve system efficiency. The TRNSYS model of the conventional split system was run at various collector flow rates under control of a differential temperature controller with an upper control differential temperature of 8.0°C and a lower control differential temperature of 4.0°C. The purpose of this test was to understand the sensitivity of the system efficiency to various collector flows, to study seasonal performance of the strategy and to establish a baseline to compare
further improvements from active control (figure 9-2).

The results indicate that the conventional split system is not operating at its highest potential efficiency. A reduction of collector circulation from $0.67 \text{ Lmin}^{-1} \text{m}^{-2}$ to around $0.094 \text{ Lmin}^{-1} \text{m}^{-2}$ is recommended from the modelling.

![Figure 9-2 Annual performance of the conventional split system at various collector flow rates. A flow of 0.35L/min (0.094L min$^{-1}$m$^{-2}$) gives best modelled performance for the conventional split system](image)

The solar energy fraction can be raised from 29% to 42% resulting in an operating cost saving of around $40 per year. This saving can easily be realised by the fitting of a smaller circulation pump. There is also a performance based rebate in Australia amounting to about $100 for the energy savings provided by the best low flow strategy. Improved insulation of the collector return pipe is desirable to minimise the increase in pipe thermal losses from the raised average collector return temperature. It would seem that uptake of this idea should be more prevalent by manufacturers.

The next important step was to check whether the addition of an advanced controller and external auxiliary heating strategy could add to the improvements of the low-flow strategy. Again, the TRNSYS model was used and was run in four variants:

1. Conventional system
2. Low-flow (0.35 L/min) collector circulation on conventional system
3. Low flow (0.35 L/min) collector circulation with the predictive controller
4. Constant collector outlet temperature (65°C) with the predictive controller

The results of the annual simulations are presented in table 9-1.

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Conventional + low-flow</th>
<th>Controller + low-flow</th>
<th>Controller + constant T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar gain (MJ)</td>
<td>9,187</td>
<td>10,375</td>
<td>10,422</td>
<td>9,842</td>
</tr>
<tr>
<td>Aux energy (MJ)</td>
<td>8,338</td>
<td>7,016</td>
<td>6,145</td>
<td>6,433</td>
</tr>
<tr>
<td>Solar fraction</td>
<td>30.9%</td>
<td>41.9%</td>
<td>49.1%</td>
<td>46.7%</td>
</tr>
<tr>
<td>Tank losses (MJ)</td>
<td>5,285</td>
<td>5,202</td>
<td>4,010</td>
<td>3,780</td>
</tr>
<tr>
<td>Pumping duty (MJ)</td>
<td>558</td>
<td>781</td>
<td>176</td>
<td>201</td>
</tr>
<tr>
<td>Pipework loss (MJ)</td>
<td>414</td>
<td>515</td>
<td>533</td>
<td>500</td>
</tr>
<tr>
<td>Thermal efficiency</td>
<td>66.7%</td>
<td>66.4%</td>
<td>72.1%</td>
<td>73.2%</td>
</tr>
<tr>
<td>Load turnovers</td>
<td>4.74</td>
<td>3.84</td>
<td>3.60</td>
<td>3.10</td>
</tr>
<tr>
<td>Auxiliary cost</td>
<td>$208</td>
<td>$175</td>
<td>$171</td>
<td>$178</td>
</tr>
</tbody>
</table>

Table 9-1  Modelled annual performance of various pump control strategies
(load=12,067MJ/yr)

All modified collector circulation strategies significantly improve the solar energy collection. It is clear that the addition of the predictive controller reduces tank losses and thus reduces auxiliary consumption. This results in a large gain in overall thermal efficiency. The apparent low cost of auxiliary heating for the conventional system and conventional + low-flow system results from the thermostat acting during low tariff periods.

The pump energy output from the TRNSYS models is misleading for the modified collector circulation strategies since the pump was not re-sized (in terms of its energy consumption) for low-flow operation. The pump result presented is representative of the amount of time the pump is switched on and thus labelled the pump duty. Conclusions regarding the pump parasitic losses
from the low-variable-flow regime are difficult to deduce. Intuitively, there is far less water passing through the collectors over the year and the water moves at a lower flow rate so one would expect proportionally lower pumping energy requirements.

Pipework thermal losses (including thermal losses from the auxiliary heater) do increase with low-flow strategies. The higher average temperature of the collector return water is only partly offset by the cooler supply water and the daily average pipework temperatures appear to be higher. The conventional system benefits from warmer afternoon ambient when a conventional system operates with warmer pipework.

The low flow strategy combined with the predictive controller appears to offer the best overall performance. It is possible that the controller could switch strategies so that it has a summer constant collector temperature mode and a winter low-flow differential temperature mode. Perhaps this could be taken one step further whereby the strategy could be switched on a daily basis given the solar forecast.

9.2.3 The Photovoltaic Powered Pump
The coupling of a photovoltaic panel to a water circulation pump offers an embedded passive control solution. The idea is to directly couple a photovoltaic (PV) panel to a direct current permanent magnet motor or a series wound field motor. This motor then powers a centrifugal pump. The pump must have a low starting torque so that circulation can be achieved at low insolation and this makes it difficult to use positive displacement pumps.

Several authors have performed optimisation studies on matching the solar panel characteristics to the pump and concluded that the system is workable (Hsiao & Blevins 1984; Salameh et al 1990). Salameh designed a electronic controller that switched multiple PV panels in parallel to enhance startup current then reverted to series operation when the pump gathered speed. Hsiao recommended the use of a maximum power point tracker to optimise the operation of the pump and suggested that batteries could be necessary if the maximum power point tracker was not available. Roger (1979) performed a
comprehensive analysis on the direct coupling of pump and PV characteristics and concluded that this was possible with careful pump sizing and PV panel selection alone. Practical availability of such components led to the suggestions of Hsiao and Salameh.

The drawback of this approach for the experimental active control system is that the circulation pump is also used for auxiliary heating under any solar conditions. The external auxiliary heater flow rate is only partly related to insolation when the system is using the solar collector as a pre-heater. The pump is also required for frost protection, generally overnight unless a glycol/heat exchange system is used.

No studies could be found on the whole system performance of a practical split system running a PV powered pump. The PV panel current (and hence power) is directly proportional to insolation and a centrifugal pump's power is proportional to the cube of the impeller speed. Thus the whole of system performance would be a most interesting modelling and practical study.

9.3 Proposed Collector Circulation Control Strategy

The collector outlet temperature was controlled by continuous variation of the collector mass flow rate using a hybrid one-pass / low-flow strategy. The concept of using the weather forecast as a basis for a circulation strategy was not realisable without model based control. Ideally, the controller would decide whether there was greater solar gain from the low-flow strategy or the one-pass strategy and switch control modes daily. Unfortunately, it was difficult to forecast the switching of a differential temperature controller even with a fully parameterised model. The approximation used was to use the one-pass approach in summer and the low-flow approach for the remainder of the year. The seasonal modelling results (figure 9-3) for the various strategies show that large gains in solar input and thermal efficiency on the conventional design are available but that no one solution is best under all conditions.
9. Collector Circulation Pump Control

![Solar Energy Collected](image1)

**Key:**

- **Conventional** – standard split system as installed with thermostat
- **Low-flow** – Conventional system with collector circulation 10kg/hr/m² on differential temperature control
- **Constant Outlet** – Modified system with pump controller and external auxiliary heater, collector outlet temperature controlled to 67degC
- **Controller** – Modified system with pump controller and external auxiliary heater, collector circulation 10kg/hr/m² on differential temperature control

**Figure 9-3** Modelling results for various collector circulation strategies.
The larger reduction in tank standing losses is the main difference from using the controller and this leads to the reduction in auxiliary consumption. The reduction in standing losses is particularly apparent during winter. The conventional system temperature sensors can be used and one further sensor added at the auxiliary heater outlet. The auxiliary heater sensor, mounted close to the tank, could be used for the collector only heating mode except that control would be poor due to the long transport delay between the heat source and the control sensor.

In one-pass mode, the pump power is proportional to the error between the measured collector outlet temperature and the tank return set point temperature (65°C). The collector outlet set point is chosen to be 2°C higher than the tank set point temperature to account for losses in the pipework (based on $U=3.0 \text{ Wm}^{-2}\text{K}^{-1}$, $L=10 \text{ m}$, $\dot{m}_c=0.167 \text{ L min}^{-1}\text{m}^{-2}$). If the pump is circulating, the return water will contribute directly to tank UTE and will not adversely disturb thermal stratification. This control strategy is blind to insolation and collector inlet temperature.

Active control and variation of the collector flow rate is an important part of the advanced controller's strategy to optimise the system as a whole.

### 9.4 Pump Circuit Modifications

In a single-pass mode, the pump controller must be able to circulate the correct amount of water through the heating circuit to produce return water at the hot water setpoint temperature of 65°C.

Hot water is returned at a temperature that makes a direct contribution to tank UTE and usually at a reduced flow rate so that it does not disturb thermal stratification in a detrimental manner. Nevertheless, the pump must have the capacity to pump enough water through both a fully illuminated collector and an operating auxiliary heater.

The Salmson pump used on the system can provide 2.5 L/min flow through a typical system with the external electric auxiliary heater. Considering an
extreme scenario where the solar collector is exposed to 1200 W/m² insolation, ambient temperature is 25°C above ambient. The collector efficiency is approximately 80% and the solar power input is 3600 W, about the same as the auxiliary heater. The total power input to the heating circuit is 7.2 kW. The temperature rise of water circulating at 2.5 L/min is thus 41°C.

If the tank is well stratified and the return water should be no hotter than 90°C (so there is no risk of tripping the temperature safety valve), then it is reasonable to conclude that the existing pump has sufficient capacity to control the collector circulation without saturation of the control action, provided that the heating circuit inlet temperature does not exceed about 50°C.

The traditional spring loaded one-way valve located in the collector return fitting on the tank was replaced with a solenoid valve (figure 9-4). This allowed the pump to operate over a wider range of flow rates since the flow resistance of the one-way valve was removed.

![Solar collector circulation pump and one of two 240v AC solenoid valves used to direct water to the appropriate heating source](image)

This valve consumes 8 W when open and is switched in parallel with the pump operation so that its quiescent electricity consumption is zero.

In the experiments, these valves were rated for steam since the experimental split system was also used to check the reliability of conventional one-way
valves. The installation of the solenoid valve on the hot side of the collector circuit demanded a unit capable of operation at temperatures in excess of 100°C. The solenoids proposed for the active control system were both installed on the cold side of the heat sources and could be down-rated to much cheaper units.

9.5 Pump Controller Design

9.5.1 Pump Power Modulation
The power output of small shaded pole motors is not usually modulated since the power savings are small. Indeed, most solar water heater manufacturers use their pumps in conjunction with a differential temperature controller that switches the motor fully on or off. There are few commercial power controllers available for this type of motor (RESOL, 2003). They work by removing entire half waveforms from the a.c. voltage (phase lopping) thereby modifying the motor duty cycle. Another approach is to vary the duty cycle of every half sinusoid using phase delay (figure 9-5). This is a common approach used in light dimmers, although does result in increased electromagnetic radiation if the rate of switching is not controlled.

![Variable duty cycle a.c. voltage waveforms](image)

Figure 9-5 Variable duty cycle a.c. voltage waveforms a) Phase lopping b) Phase delay with soft start

There is similar potential for these high frequency current transients to cause heating problems in the motor. Although the pump motor is essentially water cooled, these transients are usually suppressed by a series inductor in the drive.

---

10 Measurements taken of overnight heat leakage through a faulty one-way valve at ANU suggest heat losses of up to 1600 kJ in a single night. The system owner will most likely be unaware of this heat loss.
9.5.2 The Pump Controller

The variable power pump controller was designed as part of this thesis. The designs were implemented as a separate controller to the main controller to eliminate possible interference from the phase control circuit. The pump controller was based on two components:

1. The micro-controller

2. The power electronics

The controller hardware was based on a micro-controller, model AVR 8535. This device is programmed with both the common differential temperature flow control and variable flow rate control based on collector outlet temperature alone. Software for the variable power pump controller is listed in Appendix H.

The pump controller was connected to the existing split system collector inlet and collector outlet temperature sensing thermistors. Additional temperature sensors were located close to the collector inlet for frost detection and on the auxiliary output for heater flow control.

The drive circuit was based on generic textbook designs (Malmstadt et al 1981) and consisted of an a.c. zero crossing detector (figure 9-6) and a power electronic pump driver circuit (figure 9-7).

The zero-crossing detector works by transforming the mains 240 V a.c. voltage to 12 V a.c. and feeding this to a bridge rectifier. There was no filtering capacitor on the rectifier. The rectified a.c. was connected to an opto-coupler. The light emitting diode in the coupler provided electrical isolation to the microprocessor and switches off briefly when the voltage across it drops below about 1.1 V. The phototransistor on the opto-coupler output sends a 0.5 ms pulse to the microprocessor centred close to the zero crossing of the a.c. voltage, every 10 ms.

The microprocessor generates a time delay from this pulse and triggers a TRIAC a.c. semiconductor switch (model SGS BTA10- 400T) to switch the pump on for the remaining phase of the half waveform. The TRIAC stops conducting when the a.c. voltage across its gate terminals drops near zero and so it must
be re-triggered every 10 ms.

The TRIAC used was a snubberless design so that external damping was unnecessary. A small inductor (50 uH) in series with the motor can be used to help reduce motor transient currents upon switching although was omitted for this design. The drive was enclosed in a metallic box but no tests were performed on electromagnetic radiation from the device. A barely audible buzzing sound was apparent during normal operation although neither the pump or driver circuit seems to heat up during constant use.

![Diagram](image)

**Figure 9-6**  A.C. voltage zero crossing detector

![Diagram](image)

**Figure 9-7**  Pump motor phase control a.c. drive circuit
In any case, the pump control strategy and good thermal stratification assures the pump of cold cooling water almost all of the time. The following measures are recommended to reduce the effects of EMI:

1. House the micro controller in a metal case within another metal case containing the power electronics
2. Keep the leads from the pump controller to the pump as short as possible
3. Use damping inductors and possibly resistors in series with the pump to slow the rate of rise of current on each a.c. cycle.

Total component cost for the power electronics and microcontroller was about $A35 in prototype form.

9.5.3 Variable Power Pump Characteristics
Through experiment, a range of phase delays was determined that gave a spread of flow rates designed to have greater sensitivity at low flow. Since these steps are easily programmed, the device may readily be adapted to other pumps and installations. There are 20 discrete steps in delivered power resulting in a tested flow sequence illustrated in figure 9-8. The pump exhibited startup hysteresis of three (of 20) steps in power, possibly due to inertia and friction of water within the pipework or the power required to overcome the reverse thermosyphon head between the tank and the collectors.

![Figure 9-8](image-url)  
*Figure 9-8  Phase delays and corresponding collector flow rates*
The use of semiconductor drives rather than a relay to drive the pump adds to the long term reliability of controller and the significant reduction in pump start cycles should help prolong the pump service life. The cost of drive electronics is comparable to the conventional differential temperature controller.

This unit has been totally reliable throughout the experiments.

9.6 Tuning of the Circulation Pump Control Loop

The pump controller tuning will depend upon the characteristics of the heat source in use e.g. the solar collector thermal mass of 33 kJ/°C whereas the auxiliary heater and housing has thermal mass 0.75 kJ/°C.

Two collector outlet temperature control processes were tried. The first was to rapidly sample the collector outlet temperature and increase or decrease the pump drive power one step at a time to control the collector outlet temperature. There were several problems with this approach (figure 9-9).

Firstly, it was found that the measured collector outlet temperature lagged the actual water temperature in the collector due to its placement on the entry to the return pipe. The trigger temperature was reduced by 5°C to help reduce the over-temperature transient.

![Figure 9-9](image)

*Figure 9-9* Poor performance of “one step” circulation control is indicated by the frequent saturation of the control action.
Secondly, the controller time constants had to be changed so that the correct response could be obtained. The controller has to very quickly reduce flow if a cold plug passes through the collector and rather slowly speed up the flow as the collector temperature rises to try to avoid a cold plug reaching the collector outlet (thus upsetting thermal stratification in the tank). This strategy was never particularly effective, essentially defaulting the solar collectors to batch heating since the controller output was still saturating when the upper limits of the pump power were used (figure 9-10a).

The improved control strategy was to make the controller response proportional to the error between the setpoint collector outlet temperature ($T_{sp}$) and the measured collector outlet temperature ($T_{cout}$). The constant of proportionality is referred to as the proportional gain ($K_p$) of the control loop. The required pump power ($P$, % of full power) is then obtained from equation 9-2.

$$P = P_0 + K_p \times (T_{cout} - T_{sp})$$  \hspace{1cm} (Eqtn 9-2)

$P_0$ is the pump power (%) corresponding to the centre of the control range of temperatures (note that $K_p$ has units %/°C). In practice, $P_0$ varies with insolation and other factors and it is difficult to define a maximum desirable return temperature (and hence set $K_p$).

---

**Figure 9-10**  Improved circulation control with proportional controller

a) Proportional gain=5%/°C  b) Proportional gain =2.5%/°C
In the end, the controller was tuned experimentally by setting $P_0=50\%$ pump power and adjusting $K_p$ to give reasonable steady state control of the flow in the sensitive range of the pump drive (20-70\% full power).

A further complication is the differing time constants of heating and cooling that will require a change in the proportional gain depending upon the change in temperature. This was achieved using a table of lookup values for the proportional gain (table 9-2). Hysteresis of 3°C was provided in the proportional action for rising and falling temperatures before a change in proportional gain was enacted and this was very effective in minimising the frequent switching of the pump for apparent differential temperatures.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Control temperature increasing</th>
<th>Control temperature decreasing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar heating</td>
<td>3.5 %/°C</td>
<td>5.0 %/°C</td>
</tr>
<tr>
<td>Auxiliary heating</td>
<td>3.0 %/°C</td>
<td>4.5 %/°C</td>
</tr>
<tr>
<td>Solar + auxiliary heating</td>
<td>7.5 %/°C</td>
<td>9.0 %/°C</td>
</tr>
</tbody>
</table>

*Table 9-2* Proportional gain values, expressed as percentage in controller output per degree celsius error in the control temperature, for a range of operating modes and conditions.

Most control loop tuning involves taking open or closed loop step responses and gaining an understanding of the process dynamics by observing the thermal time lags in the process, sensors and sampling equipment. From there, control tuning parameters are determined by general rules. Due to the multivariate nature of solar collector operation, the collector flow loop time lags will vary considerably, making these tests less useful.

Performance of the steady state control loop, indicated by a steady actuator signal, is improved by decreasing the proportional gain (figure 9-10b) so that the controller output did not demand a pump power greater than 100\%. The problem with continuing this approach is that the transient performance is adversely affected. Although this is not a problem when operating in solar...
collector only heating mode, it can be a problem when the auxiliary heater is in use since it has a much smaller heat capacitance and is therefore more likely to generate faster temperature transients. The difficulty of the transient temperature is that the over-temperature safety switch may trip and these devices operate with a large temperature hysteresis. Thus the auxiliary heater has to wait for its outlet temperature to drop to the lower hysteresis limit before heating can resume (with the same transient problem). These delays could mean that the auxiliary heater does not have sufficient time to heat water for an upcoming load (using the “just in time” approach). This affect was observed in the experiments. A possible solution is to have a dedicated tank inlet that is remote from the temperature relief valve so that a degree of mixing occurs and the relief valve does not trigger.

Actual performance shown in figure 9-11 shows the typical temperature overshoot when only the auxiliary heater is in use (6.30am, 7.30am, 5.30pm). Good control of the tank return temperature is demonstrated during the day.

![Graph showing temperature over time](image)

*Figure 9-11  Typical day of operation of the collector without transient control on the auxiliary heater*

Transient performance is favoured by high proportional gains at the expense of good steady state control. The usual way to deal with transients is to add
9. Collector Circulation Pump Control

derivative action or feed-forward action to the controller. The controller’s output then changes in part with the rate of change of the error. The difficulty with derivative action is that it is difficult to tune and tends to amplify the effects of sensor noise. A controller with both derivative and proportional action, even if it was a true PID controller would require a degree of setting up upon installation. This could not be reasonably expected of installers, so a compromise is sought based upon proportional action only.

It is possible to add default feed-forward control to the strategy that acts only when the auxiliary is first activated. When the pump controller receives a signal that the auxiliary is required, it waits for a period \( t_d \) given by equation 9-3.

\[
t_d = (T_{sp} - T_{aux}) \times C_{aux} / P_{aux}
\]

(Eqtn 9-3)

\( T_{sp} = 65^\circ C, T_{aux} = \) auxiliary heater outlet temperature at time of start of auxiliary heating (\(^\circ C\)), \( C_{aux} = \) thermal capacitance of the auxiliary heater (kJ/\(^\circ C\)), \( P_{aux} = \) the auxiliary heater power (kW).

The controller then ramps up the pump power to 50%. Upon reaching 50% pump power, normal proportional control is resumed. This strategy allows better steady state control and good transient control at startup of the auxiliary heater.

9.7 Frost Protection

Prevention of damage to solar collectors in frost prone areas is a long standing problem with solar water heaters. The use of gylcol and heat exchangers is expensive and reduces system thermal efficiency at all times, while active pumping to prevent freezing represents a parasitic energy loss only during periods of frost.

The coldest water tends to accumulate at the bottom of the collector, so it would be sensible to locate a frost temperature sensor there. The pump controller in the experimental system switches the pump on at moderate power for 30 seconds when the frost sensor detects a temperature below some threshold, say 2.5\(^\circ C\). During this period, the pump will move approximately 1.4
L of warm water into the collectors (typical volume of the collectors is 6 L). The volume displaced should be minimal and the flow rate kept low so that cold water returning to the storage tank trickles down the inside of the tank with minimal disruption to thermal stratification. The variable speed pump offers flexibility in this regard. Ideally, a thermally sensitive valve would dump this very cold water to drain and allow supply water to enter the bottom of the tank with no effect on thermal stratification at all. This is not permitted by most local authorities in Australia.

9.8 Overheating in Summer

Many solar water heaters will be subject to excess solar heating capacity in Australian summer conditions. This problem can be overcome by appropriate choice of collector slope (where aesthetically acceptable) or by stagnating the collector when the tank is fully heated. The active control system with a weather forecast would be able to circulate hot water at night to provide cooling should collector stagnation be a problem. This was not explored as part of the research.
10. Practical Supervisory Optimisation

"Technology is the knack of so arranging the world that we do not experience it"
Max Frisch

10.1 Introduction

The infrastructure developed in the preceding sections works well when provided with the appropriate information regarding forecasts for the energy balance. It is now worth considering how this information might be obtained by a local controller and what other services may be provided by the infrastructure that provides this information. Would it be better to distribute the intelligence of the controller and thus make a cheaper local controller?

Domestic hot water optimisation approaches to date demonstrate hot water systems working in isolation. Optimisation is carried out on an individual installation basis and is heavily based upon parameterised modelling and supervisory optimisation (Krause et al 2002; Prud’homme & Gillet 2000). There are several draw-backs of this approach:

- Detailed parameterisation must be carried out for each individual system before meaningful modelling can begin. This is a costly and time intensive exercise. The parameters are usually assumed constant over the life of the system
- Some parameters are difficult to quantify and model
- Some inputs are difficult to predict (e.g., timing and quantity of insolation, load demand) without active feedback
- Significant controller and sensing infrastructure is required at each installation with its associated expense
- There is no external visibility for the user
- There is no external visibility for the energy utility.
An important aspect of this research is to depart from strict model based control while maintaining performance improvements, offering an adaptable infrastructure and providing visibility of operational information.

The growth of domestic broadband services encourages householders to have advanced communication infrastructure in place at the home for security systems, entertainment systems, internet/email services, and home automation. The hot water system controller could offload some of its capacity to the household automation infrastructure. A remote information server may or may not be located within the household.

10.2 Distributed Intelligence

A central intelligent information server is proposed that would be able to take care of high level tasks such as the gathering of an insolation forecast, predicting solar gain, obtaining load information from each local controller, performing an advanced load forecast, collecting reports from local controllers and perhaps performing online optimisations. The server's main function is to send an appropriate UTE profile to each controller on a daily basis. The server would most likely be managed by the utility and they would have the ability to influence the UTE profiles to alleviate peak network loading, particularly on marginal networks, by peak shedding or peak shifting.

In a distributed intelligence environment such as this, the distribution of the intelligence "wealth" is somewhat arbitrary. In this case it makes sense to keep each controller as simple and cheap as possible and shift much of the energy balance and supervisory work to the server (figure 10-1). Typically the server would have much greater computing power, routine backup facility and better information access ability. This shift places greater reliance upon the communication infrastructure.

The local controller would require data gathering and recording capability but minimal intelligence. The controller would provide the user with an indication of how much hot water is available and perhaps the forecast for the next 24 hours. The user is then able to make an informed decision on hot water use.
The controller may be over-ridden locally to provide more or less hot water. If the controller detects a change in the tank state variable as measured from the plan (sent from the server), then corrective action may be taken immediately to restore the system to the planned state. The server methodology has a number of natural failsafe mechanisms. If communication between the server and controller is lost, the local controller will persevere using the previous day’s load profile and assume no solar radiation is available. Local over-ride of the controller is possible through the human interface but should not be necessary since the controller would be naturally conservative in its auxiliary heating.

If the server loses its weather forecast, it will operate in a fallback mode as outlined in chapter 6.

Figure 10-1 Distributed intelligence architecture for domestic hot water systems

Similar architectures have been used for other applications (Tan & Taylor 2002; Mayer & Taylor 2002). Communication requirements are low bandwidth and asynchronous. Many existing available technologies may be used and the limiting factor becomes transaction cost rather than practicality. Public telephone networks and GSM technologies have been successfully used by
others (Taylor 2001) at some expense due to the high transaction cost.

The author's preferred technique is domestic networking using broadband domestic communication infrastructure that is now becoming common in Australian cities. The connection cost is covered by other services and the transaction cost is essentially zero. Incremental production costs to network-enable a controller are now minimal.

The networked controller methodology fits well with an intelligent environment for hot water systems. It is conceivable that a hot water system will communicate with other appliances delivering hot water loads and negotiate optimal timing for energy delivery in future intelligent home management systems.

10.3 Development System

A prototype server was developed as part of this thesis based on a personal computer running a Microsoft Access database. The server was responsible for:

- Gathering the daily weather forecasts
- Maintaining up-to-date auxiliary energy tariff data
- Calculating the profile of solar contribution to the tank UTE
- Uploading and learning the hot water loads
- Calculating the predicted UTE profile for the upcoming day
- Communicating the UTE profile to the controller
- Performing periodic reporting functions.

The experimental split system was the only client solar water heater, though the structure is designed to serve many water heaters. Several screen images are presented (figure 10-2, 10-3) to give the reader some idea of the sort of information being stored.

The server functionality was spread over a suite of Visual Basic (v5.0) programs that were custom written by the author for this application.
10. Practical Supervisory Optimisation

![Database Configuration](image1.png)

*Figure 10-2* Server database configuration

![Forecast Table](image2.png)

*Figure 10-3* Database table of forecasted solar performance
These programs were designed to interact with the database and network communication services such as TCP/IP and FTP. Each program sent daily diagnostic information to a log file. If the server mechanism was to be implemented commercially, this logging mechanism would be replaced by an automated email error notification process.

The Microsoft Windows operating system was used to schedule the various automation tasks.

The server has been running for over 12 months with good reliability. The server has a diagnostic view function that quickly allows problems to be identified (figure 10-4). The diagnostics are manually checked each morning to monitor the status of the server. Should problems arise, the server maintained a detailed error logging mechanism since most processing was done overnight. Common sources of problems have been the lack of a weather forecast provided by the Bureau of Meterology and failure of load communication from the controller due to network interface issues.

![Figure 10-4](image.png)

**Figure 10-4** Server diagnostics allow quick assessment of overnight server function

This thesis has identified a need and a mechanism for the distributed approach. There is clearly a need for further development in this area and this development would be supported by work on a customer interface to the hot water system controller.
10.4 Interaction with Human Users

The purpose of the optimisation is to better serve the needs of the users of the system. These needs are complex and include reliability of service, low operating costs, minimum energy consumption, minimum greenhouse gas emissions, flexibility and transparency of operation.

Operation of a traditional hot water system is likened to a car without a fuel gauge. The car has an over-sized fuel tank that gets topped up regularly whether it needs it or not. The traditional hot water system is one of the few modern devices that does not provide an indication of its readiness for service.

Systems that attempt to reduce auxiliary heating (by solar gain or predictive energy balancing) will increase the risk of running out of hot water. Some kind of local manual interface to the controller is required. A local interface is needed to at least indicate state of charge of the tank and to provide the user with the ability to override the system if unexpected circumstances arise. The interface may provide means for product differentiation in a competitive market. Figure 10-5 shows some of the LCD panel displays of the user interface introduced in chapter 5.

Figure 10-5 Four images of display options from the wall mount human/controller interface. The device operates in the manner of a wall mounted air conditioner thermostat.
They include a means to over-ride the auxiliary heating control by setting it on or off, a display of energy and cost performance, a display of the forecasted energy profile for the upcoming day, and an indication of any faults the controller finds from diagnostic routines. A more sophisticated interface may be provided by the server located at the utility. This could provide detailed statistical reporting to both the utility and the user. The utility would then have a great deal of detailed information regarding hot water consumption in both temporal and spatial domains. Temporal demand data would obviously be correlated with energy market price forecasts so that cost optimisation could be carried out. Spatial data could be combined with geographical information system (GIS) database information regarding network topology and loading to allow similar optimisation of line loads. Since both systems are based on relational databases, information integration is straightforward. The utility then has the ability to shift peak loads, shed peak loads or use strategic distributed storage through heating of hot water systems above their normal setpoint temperature.
11. Conclusion

This research set out to explore the application of active control in a split system solar water heater. The work builds upon other research regarding low flow collector circulation and extends the performance gains by improving the thermal efficiency of the storage tank. There is a place for active control in such systems and the challenge is to decide upon a level of application that gives a reasonable compromise between performance, reliability and low cost. The pressing need for reducing Australia’s greenhouse gas emissions, of which water heaters contribute about 3%, provides motivation for this work.

Initial investigations highlighted capital cost as a major inhibitor for the uptake of solar water heaters. An active controller is able to offset this cost in part through performance rebates currently available in Australia and through reduced operating cost over the life of the system.

The thesis proposes that the thermostat be replaced by a smart controller and that the intelligence of this controller is also used to operate the collector circulation in either a low-flow or constant outlet temperature mode depending upon the available radiation. The controller uses a predictive energy balance to delay the auxiliary heating as long as possible, thus minimising the amount of auxiliary heat stored in the tank and the period for which it is stored. This reduces the thermal losses from the tank and in turn the auxiliary heating requirements.

The performance improvements come at a risk of delivering water that is not up to temperature. Since each element of the energy balance must be forecasted, there is a risk of error in the forecast. The algorithm has areas of particular sensitivity depending upon the desired mode of operation. There are ways to address this risk, but they either reduce performance or result in added complexity and capital cost. If active control of the water intake for the collector
(and external heater) can be realised, thermal efficiency improvements in the storage tank in the order of 25% are available. The ideal extrapolation of this theme would be to pass cold water through the heating circuit only once and store only the heated water in the storage tank to eliminate mixing and conduction losses that degrade the thermal efficiency. The passive heating circuit inlet device is showing modelling promise and warrants experimental trials. Variable flow water circulation through the heating circuit is an essential part of this strategy.

The householder would have the ability to operate the controller in an energy efficient or cost effective manner. In its cost effective mode, the system acts like a smart off-peak heater, only using auxiliary heat for that which is not offset by upcoming solar energy. The algorithm failure modes are, at worst case, to mimic a thermostat and usually considerably better.

Several technologies and services were developed as part of this research including:

- An insolation forecasting service in association with the Australian Bureau of Meteorology
- A predictive energy balance algorithm that forecasts the magnitude and timing of future auxiliary energy requirements. It takes into account expected solar gain, expected load draw and expected tank losses by decoupling the tank and collector models
- A means by which the householders might influence the cost effectiveness or energy efficiency of the system
- A human interface that includes the ability to override the controller and a degree of visibility on the system performance
- A supervisory “distributed intelligence” infrastructure that might be used by utilities to communicate with a large number of active controllers to help offset peak energy demand in a wholesale energy market
- A remote diagnostic system that operates over the internet so that the experimental systems were more easily monitored
11. Conclusion

- The physical controller, datalogger and load controller complete with their various software interfaces
- A photographic method for detecting the artificial horizon
- An analytic program for deducing loss of beam and diffuse radiation due to these shading effects. The program also calculates the effective incidence angles for diffuse radiation
- An photographic technique and analytic program for deducing ground albedo and the effective incidence angle for ground reflected radiation
- A variable flow pump controller for a small shaded pole pump
- An external auxiliary heating mechanism and its associated control strategy
- An actively controlled water intake funnel that draws warm water from the tank for heating rather than cold water from the bottom of the tank.

The thesis proposes a modular solar water heater that begins with a simple tank (without auxiliary heater), to which may be added either a gas or electric external auxiliary heater. At any time, solar collectors may be added. The active controller treats both solar and auxiliary heat sources equivalently and will still make energy savings if solar collectors are not used. Models of the proposed system with external auxiliary heater show a 24% reduction in tank thermal losses and a 26% reduction in auxiliary energy consumption. There are corresponding savings in greenhouse gas emissions through reduced auxiliary use. The strategy of increasing the tank thermal efficiency should be coupled with increased tank insulation performance through MEPS and increased market share of solar water heaters to make a major impact on greenhouse gas emissions from Australian water heaters.

The prototype active controller component costs are about the same as the conventional differential temperature controller and only requires two additional temperature sensor units. The controller is programmable and its value is embodied in the software.
In summary, active control on split systems is showing early promise. Field exposure to real load learning experiences is required so that realistic estimates of the load forecast errors may be assessed. The success of the technology depends critically on the ability of the system to forecast its upcoming load. If large load error forecasts persist, it becomes imperative to separate hot and cold water in the storage tank for the active controller to provide benefits over a conventional low-flow thermostat based system.
12. Further Work

Exploratory studies often uncover new areas of research that resources and time do not permit thorough investigation. The split system solar water heater would benefit from further development in a number of areas with the emphasis determined by early field trials.

12.1 Practical Experience with the Load Learning

The most pressing concern is the evaluation of the load learning algorithm in real world situations. This would require field trials where conventional water heaters are monitored by the controller. The loads are detected and recorded by the controller and daily forecasts produced. A flowmeter and datalogger would be required on each trial system to record actual load flow and temperature. If the controller is unable to accurately characterise and forecast the load to within say ±20% in timing and magnitude, the system must be made to store extra energy as a safeguard against cold delivery. This has a performance penalty and the benefits of active control are quickly eroded.

12.2 Reduction of Conduction Losses

A better calibration regarding the amount of UTE lost to mixing during heating cycles is required as this effects the UTE setpoint profiles. Currently, the correction factors are empirically averaged, grouped by heating mode (e.g. 10% UTE loss using solar heating only, 15% using aux only, 25% with both solar and aux together). The calibration needs to be mapped for the domain of pump flowrates in each mode of the heating circuit.

Since the proposed storage tank design is devoid of intrusions (except for the inlet and return diffusers at the extremes of height in the tank), an insulated floatation disk might be tested. This sealed device would have neutral buoyancy at about 60°C. If the disk is not horizontally stable or gets caught within the
12. Further Work

tank, some form of guide may be required (perhaps a bevelled sleeve on the sacrificial anode).

The use of an external auxiliary heater to provide a variable auxiliary volume has the implication that any tank energy that is not UTE cannot be very well utilised as preheat for the auxiliary heater as in a conventional tank, if the heating circuit intake is at the bottom of the tank. To overcome this, methods of using the existing energy in the tank that do not comprise UTE will need to be employed. The most promising alternative is the bimetallic valve proposed in chapter 8. Ultimately, the elimination of conduction losses from hot to cold water in the storage tank is highly desirable. This could be achieved by complete separation of hot and cold water, the difficulty being to maintain consistent working pressure in the variable heated volume.

12.3 The State Variable Sensor

Stability in the state variable is important for prevention of excessive auxiliary heating. Better attention needs to be provided to stabilising this temperature profile. The variation in the UTE measurement is partly due to sensing noise and partly due to inlet jets within the tank. Suppression of jets on the heat source return pipe using an inlet diffuser cone or blind perforated pipe (figure 12-1) would help preserve thermal stratification and perhaps stabilise the sensed temperature profile.

![Figure 12-1](image-url)  Heating circuit return inlet diffuser designs for high collector temperature designs
Development of a high resolution temperature profile sensor that is suitable for mass production is a priority. Such a product might consist of 100 surface mount thermistors connecting to a serial communication bus, all mounted on a common substrate and connected to a custom microprocessor. The microprocessor would communicate tank state variables directly to the main controller.

12.4 The Human Interface

Interaction between human user and the control algorithm is desirable. Substantial work is required to ensure that the system can operate in a transparent manner that householders might expect from a water heater. At the same time, the controller interface must provide the latent ability for users to understand and get the best from the system.

12.5 Phase Change Materials

One of the goals of just-in-time heating is to reduce storage tank losses. Perhaps the ultimate means of increasing energy density without the encumbrance of higher temperatures comes from phase change materials (PCM). There is a commercial hydrated salt produced by TEAP Pty. Ltd. (Perth, Australia) with a melting point of 58°C and a latent heat of fusion 290 kJ/L. This salt has similar sensible heat capacity to water in liquid and solid phases although its thermal conductivity is somewhat lower. Many studies have been performed on tanks containing large bodies of phase change material (Mehling et al. 2003; Barba & Spiga 2003; Syed 1997; Santamouris & Lefas 1988). All of these tanks demonstrated greater energy density but few were found to be trouble free. The PCM materials were found to have a limited thermal cycling life and low thermal conductivity. The PCM material requires a large surface area to volume ratio to operate effectively in a hot water service. Furthermore, there are difficulties in measuring tank UTE and TTE with PCMs since the temperature profile sensor measures sensible heat content while PCM materials are used in a mode where latent heat of fusion is important.
Perhaps the most promising application is in slurries of micro-encapsulated PCM (Egolf et al 2003) where the entire collector and tank might consist of this high heat capacity slurry. A modified circulating pump may be required since the fluid will have higher viscosity. Domestic water would pass through a heat exchanger within the tank. This heat exchanger would be very efficient due to a nearly constant temperature difference along its length.
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Appendix A – Bureau of Meterology Weather Files

A typical Bureau of Meterology (BOM) weather file received daily by the server is listed here. This file provides hourly insolation and ambient temperature for the day of 17th September 2003. Line numbers have been added for clarity.

Only the data file has been listed. The interpretation program, forecast database interface and ftp uploading script are omitted.

Data interpretation begins at line 13. Insolation data are listed as global horizontal radiation in W/m². Each data field is referenced to an hourly timestamp in UTC format. Local standard time in Canberra is UTC+10 h. Thus the first valid data is for 11pm on the 16th September (the BOM model run at 10pm is used for this service) and there are 72 values covering the next three days. Ambient temperature readings (°K) are on line 15.

Line 1: Canberra 20030917 12
Line 2: lat=-35.375000
Line 3: lon=149.000000
Line 4: Base_date=20030917
Line 5: Base_time=1200
Line 6: Valid dates
Line 7: 20030917, 20030917, 20030917, 20030917, 20030917, 20030917, 20030917, 20030917, 20030917, 20030917, 20030917, 20030917, 20030917
Line 8: 20030918, 20030918, 20030918, 20030918, 20030918, 20030918, 20030918, 20030918, 20030918, 20030918, 20030918, 20030918, 20030918
Line 9: 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919
Line 10: 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919
Line 11: 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919, 20030919
Line 12: 20030920, 20030920, 20030920, 20030920, 20030920, 20030920, 20030920, 20030920, 20030920, 20030920
Line 13: Valid times (UTC)
Line 14: 1300, 1400, 1500, 1600, 1700, 1800, 1900, 2000, 2100, 2200, 2300, 0, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400,1500, 1600, 1700, 1800, 1900, 2000, 2100, 2200, 2300, 0, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800, 1900, 2000, 2100, 2200, 2300, 0, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200,
Line 15: forecast_hours
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<th>Screen Temperature (K)</th>
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Appendix B – TRNSYS Model

**Model Outputs**

1. Auxiliary heater control signal (0/1)
2. Collector diverter valve signal (0/1)
3. Variable speed pump control signal (0..1)
4. Auxiliary heater position (0..1)

**Model Derivatives**

**Description**

Type 256 is a predictive auxiliary heater controller and variable speed collector circulation controller for split system solar water heaters.

If there is solar gain to be had, water is diverted through the solar collector then through the external auxiliary heater before returning to the tank. A stratified return should be used in the tank model.

If there is no solar gain available, the collector is bypassed and the pump is connected to the auxiliary heater. The pump speed is varied continuously in solar only mode to keep the tank return water at 65degC. When the aux heater is ON and solar gain is available, the flow rate is set so that the return temperature is 65degC (after aux heating). In aux only mode, the flow rate is set to return water to the tank at 65degC.

---

**Standard TRNSYS Declarations**

```plaintext
double precision xin, out
integer ni, np, nd, no
parameter (ni=9, np=9, nd=4, nd=0)
integer*4 info, icntrl
real t, tdt, par, time
dimension xin(ni), out(no), par(np), info(15)
character*3 ycheck(ni), ocheck(no)
```

**Custom Declarations**

**Parameters**

- `mode` (integer)
- `tset`, `auxpwr`, `pummaxflow` (double precision)
- `acoll`, `ehotdb` (double precision)
- `paux`, `psolar`, `psolaraux` (double precision)

**Inputs**

- `echot`, `ehotsp` (double precision)
- `tcin`, `tcout`, `tsupp`, `taux` (double precision)
- `solar`, `cellflow`, `cauxon` (double precision)

**Outputs**

- `auxhtrctl`, `diverterctl` (integer)
- `pumpctl`, `auxpos` (double precision)

**Derived variables**

- `temperror` (double precision)

**Initialization**

```plaintext
if (its the first call to this unit, do some bookkeeping)
   if (info(7) .ge. 0) go to 100

   first call of simulation, call the typeck subroutine to check that the user has provided the correct number of inputs, parameters, and derivs
   info(6) = no
```

---

9. Collector flow previous timestep kg/hr
Appendix B – TRNSYS Model

B.1 Controller Type 256

TRNSYS type 256 was created in this thesis to implement active control of the auxiliary heater and circulation pump. It has additional inputs to allow over-riding of the auxiliary heating input from a text file of auxiliary heating states (1=on, 0=off). This allows the effect of energy premiums to be modeled. Type 256 also requires a text file input of the required tank state variable UTE.

Both of these text files are provided by the same program that resides in the distributed intelligence server and generates daily UTE and auxiliary over-ride information to the controller. The program was modified to produce text files for the model for a complete year based on the TRNSYS typical meteorological year (TMY) weather data and AS4234 load data.

```fortran
SUBROUTINE TYPE256(TIME,XIN,OUT,T,DTDT,PAR,INFO,ICNTRL,*)
C********************************************************
C Object: Auxiliary Heater Controller
C IISiBat Model: TYPE256
C
C Author: Mike Dennis, Centre for Sustainable Energy Systems, ANU
C Editor: 
C Date: 10/10/00 last modified: 8/04/04 
C
C ***
C *** Model Parameters
C ***
C 1 Mode=external heater 
C 2=variable position internal heater
C 2 Set point temperature of "thermostat" degC
C 3 Auxiliary heater power kJ/hr
C 4 Collector Area m2
C 5 Maximum pump flow rate kg/hr
C 6 Deadband in tank exergy kJ
C 7 Proportional gain, auxiliary heating only
C 8 Proportional gain, solar heating only
C 9 Proportional gain, auxiliary + solar
C
C *** Model Inputs
C ***
C 1 Current tank UTE kJ
C 2 Set point tank UTE kJ
C 3 Radiation incident on collector kJ/hr/m2
C 4 Cold water supply temperature degC
C 5 Collector inlet temperature degC
C 5 Collector outlet temperature degC
C 7 Offpeak auxiliary override
C 8 AuxHeater outlet temperature degC
```

- 243 -
INFO(9)=1
CALL TYPECK(1,INFO,NI,NP,ND)
CALL RCHECK(INFO,YCHECK,OCHECK)
RETURN 1
C END OF THE FIRST ITERATION BOOKKEEPING

C Only do this subroutine once to avoid instability
IF (INFO(7).EQ.-1) THEN
  AuxHtrCtl=0
ENDIF
IF (INFO(7).GT.5) GO TO 120
C GET THE VALUES OF THE PARAMETERS FOR THIS COMPONENT
Mode=PAR(1)
Tset=PAR(2)
AuxPwr=PAR(3)
CollA=PAR(4)
PumpMaxFlow=PAR(5)
EHotDB=PAR(6)
PAux=PAR(7)
PSolar=PAR(8)
PSolarAux=PAR(9)
C GET THE VALUES OF THE INPUTS TO THIS COMPONENT
Ehot=XIN(1)
EHotSP=XIN(2)
SolarG=XIN(3)
Tsppp=XIN(4)
TCin=XIN(5)
TCout=XIN(6)
ECAuxON=XIN(7)
Taux=XIN(8)
CollFlow=XIN(9)
C Maintain a minimum tank UTE if any.
Econserv=0.0
IF(EhotSP.LT.Econserv) THEN
  EhotSP=Econserv
ENDIF
C Check if auxiliary heater required. Assumes no solar
C for this timestep to be conservative.
IF(Ehot.LT.(EHotSP-EHotDB)) THEN
  AuxHtrCtl=1
ELSE
  IF(Ehot.GT.EHotSP) THEN
    AuxHtrCtl=0
  ENDIF
ENDIF
C For energy premium auxiliary override tests
IF (ECAuxON.EQ.1) THEN
  AuxHtrCtl=1
ENDIF
C Now control pump power depending on heat source mode
C IF(Mode.EQ.1) THEN
  IF(AuxHtrCtl.EQ.0) THEN
    C Mode la) All solar, no aux htr
    DiverterCtl=1
    TempError=TCout-Tset
    IF(SolarG.GT.150.0) THEN
      CollFlow=CollFlow+P*TempError
    ELSE
      CollFlow=0.0
    ENDIF
  ENDIF
ENDIF
**Appendix B - TRNSYS Model**

ENDIF

C Delta-T low flow model when used
IF(Tcout.GT.(Tcin+8.0)) THEN
  CollFlow=Maxflow
ENDIF
IF(Tcout.LT.(Tcin+4.0)) THEN
  CollFlow=0.0
ENDIF
ELSE
  IF(SolarG.LT.150.0) THEN
    Mode 1b). Aux only
    DiverterCtl=0
    CollFlow=0.95*AuxPwr/(4.18*(Tset-Tsupp))
  ELSE
    Mode 1c). Solar + aux
    DiverterCtl=1
    TempError=TAux-Tset
    CollFlow=CollFlow+Psolaraux*TempError
  ENDIF
  WANT immediate start of flow if aux
  heater is on
  IF(CollFlow.LE.0.0) THEN
    CollFlow=60.0
  ENDIF
ELSE
  Mode 2 with variable collector flow
  TempError=TCout-Tset
  IF(SolarG.GT.150.0) THEN
    CollFlow=CollFlow+Psolar*TempError
  ELSE
    CollFlow=0.0
  ENDIF
ENDIF

C Limit pump flow to real range of pump
IF(CollFlow.GT.150.0) THEN
  CollFlow=150.0
ENDIF
IF(CollFlow.LT.5.0) THEN
  CollFlow=0.0
ENDIF
PumpCtl=CollFlow/PumpMaxFlow

C Stagnate collector if collector inlet temperature exceeds 65 degC. Auxiliary heater will not be required, but switch off to C
be sure
IF(Tcin.GT.65.0) THEN
  PumpCtl=0.0
  AuxHtrCtl=0
ENDIF

C SET OUTPUTS
OUT(1)=AuxHtrCtl
OUT(2)=DiverterCtl
OUT(3)=PumpCtl
OUT(4)=AuxPos

120 RETURN 1
END
B.2 Controller Type 257

This is the new TRNSYS solar shading type. This type needs to be included in a new version of the radiation processor so that diffuse shading can be properly treated.

SUBROUTINE TYPE257(TIME,XIN,OUT,T,DTDT,PAR,INFO,ICNTRL,*)
C*********************************************************
C
C Object: Shading
C IISiBat Model: Shading
C
C Author: MD
C Editor: 
C Date:      5/7/2002 last modified: 5/7/2002
C
C *** Model Parameters
C ***
C Diffuse Fraction    dimensionless [-Inf;+Inf]
C Shading data LUN
C *** Model Inputs
C ***
C Beam Insolation     kJ/hr [-Inf;+Inf]
C Diffuse Insolation
C Altitude
C Azimuth
C *** Model Outputs
C ***
C Shaded Beam         kJ/hr [-Inf;+Inf]
C Shaded Diffuse      kJ/hr [-Inf;+Inf]
C *** Model Derivatives
C ***
C Description
C Type 257 acts as a filter of insolation between the radiation processor and the solar collector. It reads a horizon profile from an external file containing the elevation of the horizon for every degree in azimuth. Beam radiation is set to zero if the sun is below the artificial horizon. Diffuse radiation is reduced by a set fraction, calculated for the collector slope (needs to be incorporated into the radiation processor).
C (Comments and routine interface generated by IISiBat 3)
C*********************************************************
C
STANDARD TRNSYS DECLARATIONS
DOUBLE PRECISION XIN,OUT
INTEGER NI,NF,ND,NO
PARAMETER (NI=4,NF=2,NO=2,ND=0)
INTEGER*4 INFO,ICNTRL
REAL T,DTDT,PAR,TIME
DIMENSION XIN(NI),OUT(NO),PAR(NF),INFO(15)
CHARACTER*3 YCHECK(NI),OCHECK(NO)

REAL ShadingAlt,SolAzimuth,SolAltitude
REAL Beam_Insolation,Diffuse_Insolation

- 247 -
REAL DiffuseFrac
REAL Shaded_Beam, Shaded_Diffuse
DIMENSION ShadingAlt(360)
INTEGER I, ArrayIndex, LUNI
CHARACTER*31 Filename

C---------------------------------------------------------
IF ITS THE FIRST CALL TO THIS UNIT, DO SOME BOOKKEEPING
IF (INFO(7) .GE. 0) GO TO 100
C FIRST CALL OF SIMULATION, CALL THE TYPECK SUBROUTINE TO
C CHECK THAT THE
C USER HAS PROVIDED THE CORRECT NUMBER OF INPUTS,
C PARAMETERS, AND DERIVS
INFO(6)=NO
INFO(9)=1
CALL TYPECK(1, INFO, NI, NP, ND)
RETURN 1
C END OF THE FIRST ITERATION BOOKKEEPING
C---------------------------------------------------------
C GET THE VALUES OF THE PARAMETERS FOR THIS COMPONENT
100 CONTINUE
DiffuseFrac=PAR(1)
LUNI=PAR(2)
C GET THE VALUES OF THE INPUTS TO THIS COMPONENT
Beam_Insolation=XIN(1)
Diffuse_Insolation=XIN(2)
So1Azimuth=XIN(3)
So1Altitude=XIN(4)
C----------------------------------------------- ---- - - ----
C ADD YOUR COMPONENT EQUATIONS HERE; BASICALLY THE
C EQUATIONS THAT WILL CALCULATE THE OUTPUTS BASED ON THE
C PARAMETERS AND THE INPUTS. REFER TO CHAPTER 3 OF THE
C TRNSYS VOLUME 1 MANUAL FOR DETAILED INFORMATION ON
C WRITING TRNSYS COMPONENTS.
Filename='C:\TRNSYS15\MIKE\SHADINGALT.TXT'
OPEN(UNIT=LUNI, FILE=Filename, STATUS='OLD')
REWIND(LUNI)
DO I=1,360
READ(LUNI,*) ShadingAlt(I)
END DO
CLOSE (UNIT=LUNI)
C---------------------------------------------------------
C SET THE OUTPUTS
Shaded_Insolation
ArrayIndex=INT(So1Azimuth)
IF (ArrayIndex.LT.1) THEN
ArrayIndex=ArrayIndex+360
ENDIF
IF((90.0 - So1Altitude) .GT. ShadingAlt(ArrayIndex)) THEN
OUT(1)=Beam_Insolation
ELSE
OUT(1)=0
ENDIF
OUT(2)=Diffuse_Insolation*DiffuseFrac
RETURN 1
END
B.3 Tank Model Type 38

The following code is added to tank type 38 immediately before evaluation of the outputs. Additional outputs are created in the IIsibat proforma for tank 38 for the tank UTE, location of boundary where tank temperature exceeds 60°C and for 10 temperature readings equally spaced down the tank.

```
C Additional code for evaluation of useful tank energy
C (known as UTE or Ehot)
C MKD (ANU) Aug-2003
C New code added for cooperation with TYPE256 predictive controller
C New Inputs:
C XIN(7) is the location where aux heating should be implemented.
C This is only used to look at variable position auxiliary heating
C New outputs:
C OUT(11)=EHO T is the useful tank energy (kJ), energy above 60degC
C OUT(12)=XCri t is location of the set point temperature in the tank
C OUT(13)...OUT(22) are temperatures sampled every 0.1 tank height
C OUT(23) is the number of nodes in use
C Develop temperature profile by expansion of the node
C temperatures and volumes. X(Norder) is the relative
C volume of norder segment (remember the nodes are not
C in order but scrambled as indicated by the Norder(N) array.

   EHO T=0.0
   ETOT=0.0
   DO 514 I=1,NTOT
   ETOT=ETOT + X(NORDER(I)) * PAR(2) * 1000.0 * CPF *
       (T(NORDER(I))-XIN(3))
   C Heat is useful if above 60 degC
   IF (T(NORDER(I)) .GE. 60.) THEN
       EHO T=EHO T + X(NORDER(I)) * PAR(2) * 1000.0 * CPF *
       (T(NORDER(I))-XIN(3))
   ENDIF
   514 CONTINUE
C Now evaluate a temperature profile for viewing purposes. The
C UTE boundary location is evaluated here also, but could have been
C calculated above
C XCRIT=0.0
C XN2=INT(100.0*X(NORDER(1)))
   DO 504 I=1,XN2
       TINTERP(I)=T(NORDER(I))
   504 CONTINUE
   DO 506 N=2,NTOT
   TN=T(NORDER(N))
   XN1=XN2+1
   XN2=XN1+INT(100.0*X(NORDER(N)))
   IF (XN1.GT.100) THEN
       XN1=100
   ENDIF
   IF (XN2.GT.100) THEN
       XN2=100
   ENDIF
   DO 505 I=XN1,XN2
       TINTERP(I)=TN
   505 CONTINUE
   506 CONTINUE
C Now have higher resolution temperature profile.
```
Appendix B - TRNSYS Model

C Figure out where temperature first drops below 60degC
DO 508 N=1,100
  IF (TINTERP(N).LT.(55.)) THEN
    XCRIT=N/100.0
  END IF
508 CONTINUE
509 CONTINUE

C OUTPUTS
OUT(1)=TRET
OUT(2)=MC
OUT(3)=TDEL
OUT(4)=ML
OUT(5)=QLOSS
OUT(6)=QS
OUT(7)=DELU
OUT(8)=QBTOT
OUT(9)=QIN
OUT(10)=TAVG
OUT(11)=EHOT
OUT(12)=XCRIT
OUT(13)=TINTERP(9)
OUT(14)=TINTERP(19)
OUT(15)=TINTERP(29)
OUT(16)=TINTERP(39)
OUT(17)=TINTERP(49)
OUT(18)=TINTERP(59)
OUT(19)=TINTERP(69)
OUT(20)=TINTERP(79)
OUT(21)=TINTERP(89)
OUT(22)=TINTERP(99)
OUT(23)=NTOT
RETURN 1
END

B.4 Model Parameters

Collector Configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector area</td>
<td>3.74 m²</td>
</tr>
<tr>
<td>Number of collectors in parallel</td>
<td>1</td>
</tr>
<tr>
<td>Collector tilt</td>
<td>20 degrees</td>
</tr>
<tr>
<td>Collector orientation</td>
<td>North</td>
</tr>
<tr>
<td>Test flow rate</td>
<td>35.6 kg hr⁻¹m⁻²</td>
</tr>
<tr>
<td>Intercept efficiency</td>
<td>0.691</td>
</tr>
<tr>
<td>Efficiency slope</td>
<td>5.238 Wm⁻²K⁻¹</td>
</tr>
<tr>
<td>Efficiency curvature</td>
<td>0.001426 Wm⁻²K⁻²</td>
</tr>
<tr>
<td>First order IAM</td>
<td>0.1798</td>
</tr>
<tr>
<td>Second order IAM</td>
<td>-0.0214</td>
</tr>
<tr>
<td>Ground reflectance</td>
<td>0.11</td>
</tr>
</tbody>
</table>
**Storage Tank Configuration**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective tank volume</td>
<td>340 L</td>
</tr>
<tr>
<td>Effective tank height</td>
<td>1.485 m</td>
</tr>
<tr>
<td>Location of pipe to collector</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Location of pipe from collector</td>
<td>0.621 m</td>
</tr>
<tr>
<td>Location of mains inlet</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Location of hot water outlet</td>
<td>1.40 m</td>
</tr>
<tr>
<td>Location of aux heater</td>
<td>0.625 m</td>
</tr>
<tr>
<td>Location of thermostat</td>
<td>0.702 m</td>
</tr>
<tr>
<td>Tank loss co-efficient (incl. fittings)</td>
<td>3.5 WK⁻¹</td>
</tr>
<tr>
<td>Effective thermal conductivity</td>
<td>2.3 Wm⁻¹K⁻¹</td>
</tr>
<tr>
<td>Thermostat set point</td>
<td>65°C</td>
</tr>
<tr>
<td>Auxiliary heater power</td>
<td>3600 W</td>
</tr>
</tbody>
</table>

**Pump Configuration**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum flow rate</td>
<td>152 kg/hr</td>
</tr>
<tr>
<td>Pump power</td>
<td>67 W</td>
</tr>
</tbody>
</table>

**Pipe Configuration**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length</td>
<td>22 m</td>
</tr>
<tr>
<td>Loss co-efficient (insulated copper)</td>
<td>3 Wm⁻²K⁻¹</td>
</tr>
<tr>
<td>Internal diameter</td>
<td>0.01088 m</td>
</tr>
</tbody>
</table>

**Controller**

Control mode: Temperature differential between tank bottom and collector outlet

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump switch ON differential</td>
<td>8.0°C</td>
</tr>
<tr>
<td>Pump switch OFF differential</td>
<td>4.0°C</td>
</tr>
<tr>
<td>Upper temperature cut out</td>
<td>82°C</td>
</tr>
<tr>
<td>Upper temperature reset</td>
<td>75°C</td>
</tr>
</tbody>
</table>
B.5 TRNSYS Deck

The following code is the TRNSYS 15 deck file for the modified split system water heater with the active controller. It used the Canberra TMY file and ORER data for the cold water supply temperature. Shading was not considered in this deck.

VERSION 15
******************************************************************************
*** TRNSYS input file (deck) generated by IISiBat 3
*** on Thursday, March 15, 2004 at 19:02
*** from IISiBat project:
C:\trnsys15\Mike\Models\RheemLoLine\Thesis.TPF
***
*** If you edit this file, use the File/Import TRNSYS Input File
*** function in
*** IISiBat 3 to update the project.
***
*** If you have problems, questions or suggestions please contact your
*** local
*** TRNSYS distributor or mailto:iisibat@cstb.fr
***
******************************************************************************
ASSIGN "C:\trnsys15\Mike\Models\RheemLoLine\Rheem.LST" 6
******************************************************************************
*** Control cards
******************************************************************************
* START, STOP and STEP
CONSTANTS 3
START=0
STOP=8760
STEP=0.02
*SIMULATION Start time   End time   Time step
SIMULATION START   STOP   STEP

* User defined CONSTANTS
*
EQUATIONS 2
DAY=INT(START/24.001)+1
NPLOTS=INT((STOP-START)/168.001)+1

*
TOLERANCES 0.02 0.02
*
Trace limit
LIMITS 25 5 25
*
method
DPQ 1
*
characters
WIDTH 80
Appendix B – TRNSYS Model

* NOLIST statement
* MAP statement
* Solver statement

**********************************************************
*** Units
**********************************************************

* Model "9Weather" (Type 9)
*
UNIT 1 TYPE 9 9Weather
PARMETERS 33
* 1 Mode
   -1
* 2 Header Lines to Skip
   0
* 3 No. of values to read
   9
* 4 Time interval of data
   1.0
* 5 Interpolate or not?-1
   -4
* 6 Multiplication factor-1
   10
* 7 Addition factor-1
   0
* 8 Interpolate or not?-2
   -5
* 9 Multiplication factor-2
   10
* 10 Addition factor-2
   0
* 11 Interpolate or not?-3
   6
* 12 Multiplication factor-3
   0.1
* 13 Addition factor-3
   0
* 14 Interpolate or not?-4
   7
* 15 Multiplication factor-4
   0.1
* 16 Addition factor-4
   0
* 17 Interpolate or not?-5
   8
* 18 Multiplication factor-5
   0.1
* 19 Addition factor-5
   0
* 20 Interpolate or not?-6
   1
* 21 Multiplication factor-6
   1.0
* 22 Addition factor-6
   0
* 23 Interpolate or not?-7
1
* 24 Multiplication factor-7
1.0
* 25 Addition factor-7
0
* 26 Interpolate or not?-8
1
* 27 Multiplication factor-8
1.0
* 28 Addition factor-8
0
* 29 Interpolate or not?-9
1
* 30 Multiplication factor-9
1.0
* 31 Addition factor-9
0
* 32 Logical unit
3
* 33 Format specification
1
(1X,3P2.0,5F3.0,F2.0,F1.0)
*** External files
ASSIGN C:\trnsys15\Mike\Weather\canberra.tmy 3
*>? Which file contains the data to be read by this component? 1000

* Model "9Load" (Type 9)
*
UNIT 2 TYPE 9 9Load
PARAMETERS 9
* 1 Mode
1
* 2 Header Lines to skip
0
* 3 No. of values to read
1
* 4 Time interval of data
0.2
* 5 Interpolate or not?
-1
* 6 Multiplication factor
1.0
* 7 Addition factor
0
* 8 Logical unit
16
* 9 Format specification
1
(F5.1)
*** External files
ASSIGN C:\trnsys15\Mike\Models\RheemHiLine\Load.txt 16
*>? Which file contains the data to be read by this component? 1000

* Model "17Cold Supply" (Type 14)
*
UNIT 3 TYPE 14 17Cold Supply
<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Initial value of time</td>
<td>0</td>
</tr>
<tr>
<td>2 Initial value of function</td>
<td>20.53</td>
</tr>
<tr>
<td>3 Time at point-1</td>
<td>744</td>
</tr>
<tr>
<td>4 Value at point -1</td>
<td>20.53</td>
</tr>
<tr>
<td>5 Time at point-2</td>
<td>744</td>
</tr>
<tr>
<td>6 Value at point -2</td>
<td>20.79</td>
</tr>
<tr>
<td>7 Time at point-3</td>
<td>1416</td>
</tr>
<tr>
<td>8 Value at point -3</td>
<td>20.79</td>
</tr>
<tr>
<td>9 Time at point-4</td>
<td>1416</td>
</tr>
<tr>
<td>10 Value at point -4</td>
<td>21.46</td>
</tr>
<tr>
<td>11 Time at point-5</td>
<td>2160</td>
</tr>
<tr>
<td>12 Value at point -5</td>
<td>21.46</td>
</tr>
<tr>
<td>13 Time at point-6</td>
<td>2160</td>
</tr>
<tr>
<td>14 Value at point -6</td>
<td>18.86</td>
</tr>
<tr>
<td>15 Time at point-7</td>
<td>2880</td>
</tr>
<tr>
<td>16 Value at point -7</td>
<td>18.86</td>
</tr>
<tr>
<td>17 Time at point-8</td>
<td>2880</td>
</tr>
<tr>
<td>18 Value at point -8</td>
<td>16.73</td>
</tr>
<tr>
<td>19 Time at point-9</td>
<td>3624</td>
</tr>
<tr>
<td>20 Value at point -9</td>
<td>16.73</td>
</tr>
<tr>
<td>21 Time at point-10</td>
<td>3624</td>
</tr>
<tr>
<td>22 Value at point -10</td>
<td>14.21</td>
</tr>
<tr>
<td>23 Time at point-11</td>
<td>4344</td>
</tr>
<tr>
<td>24 Value at point -11</td>
<td>14.21</td>
</tr>
<tr>
<td>25 Time at point-12</td>
<td>4344</td>
</tr>
<tr>
<td>26 Value at point -12</td>
<td>10.34</td>
</tr>
<tr>
<td>27 Time at point-13</td>
<td>5088</td>
</tr>
<tr>
<td>28 Value at point -13</td>
<td>10.34</td>
</tr>
<tr>
<td>29 Time at point-14</td>
<td>5088</td>
</tr>
<tr>
<td>30 Value at point -14</td>
<td>9.79</td>
</tr>
</tbody>
</table>
Appendix B – TRNSYS Model

* 31 Time at point-15
5832
* 32 Value at point -15
9.79
* 33 Time at point-16
5832
* 34 Value at point -16
11.82
* 35 Time at point-17
6552
* 36 Value at point -17
11.82
* 37 Time at point-18
6552
* 38 Value at point -18
12.27
* 39 Time at point-19
7296
* 40 Value at point -19
12.27
* 41 Time at point-20
7296
* 42 Value at point -20
15.36
* 43 Time at point-21
8016
* 44 Value at point -21
15.36
* 45 Time at point-22
8016
* 46 Value at point -22
18.14
* 47 Time at point-23
8760
* 48 Value at point -23
18.14

* Model "EC Aux" (Type 9)
*

UNIT 4 TYPE 9   EC Aux
PARAMETERS 9
* 1 Mode
1
* 2 Header Lines to skip
0
* 3 No. of values to read
1
* 4 Time interval of data
0.2
* 5 Interpolate or not?
-1
* 6 Multiplication factor
1.0
* 7 Addition factor
0
* 8 Logical unit
21
* 9 Format specification
1
 Appendix B – TRNSYS Model

(F2.0)
*** External files
ASSIGN C:\trnsys15\Mike\LoadProfiles\LoadTU0ECS.txt 21
* |? Which file contains the data to be read by this component? |1000
*

* Model "Controller SP" (Type 9)
*
UNIT 5 TYPE 9 Controller SP
PARAMETERS 9
* 1 Mode
1
* 2 Header Lines to skip
0
* 3 No. of values to read
1
* 4 Time interval of data
0.2
* 5 Interpolate or not?
1
* 6 Multiplication factor
1.0
* 7 Addition factor
0
* 8 Logical unit
18
* 9 Format specification
1
(F5.0)
*** External files
ASSIGN C:\trnsys15\Mike\LoadProfiles\EHotSPTU0.txt 18
* |? Which file contains the data to be read by this component? |1000
*

* Model "Tariff" (Type 9)
*
UNIT 6 TYPE 9 Tariff
PARAMETERS 9
* 1 Mode
1
* 2 Header Lines to skip
0
* 3 No. of values to read
1
* 4 Time interval of data
0.2
* 5 Interpolate or not?
-1
* 6 Multiplication factor
1.0
* 7 Addition factor
0
* 8 Logical unit
14
* 9 Format specification
1
(F3.1)
*** External files
ASSIGN C:\trnsys15\Mike\Models\RheemHiLine\Tariff.txt 14

- 257 -
Which file contains the data to be read by this component?

* Model "16Radiation Processor" (Type 16)

UNIT 7 TYPE 16    16Radiation Processor
PARAMETERS 9
* 1 Horiz. radiation mode
  4
* 2 Tracking mode
  1
* 3 Tilted surface mode
  2
* 4 Starting day
  1
* 5 Latitude
  -35.27
* 6 Solar constant
  4871.00000000002
* 7 Shift in solar time
  -3.97
* 8 Not used
  1
* 9 Solar time?
  -1

INPUTS 9
* 9Weather:Output 4 - Total radiation on horizontal
  1,4
* 9Weather:Output 5 - Direct normal beam radiation on horizontal
  1,5
* 9Weather:Time of last read - Time of last data read
  1,99
* 9Weather:Time of next read - Time of next data read
  1,100
* [unconnected] Ground reflectance
  0,0
* [unconnected] Slope of surface
  0,0
* [unconnected] Azimuth of surface
  0,0
* [unconnected] Total radiation on horizontal at next timestep
  0,0
* [unconnected] Direct Normal beam radiation at next timestep
  0,0

*** INITIAL INPUT VALUES
  0.0 0 0.0 0 0.2 20
  0 0 0

* Model "TYPE256" (Type 256)

UNIT 8 TYPE 256    TYPE256
PARAMETERS 9
* 1 Mode
  1
* 2 Set temperature
  65
* 3 Aux Power
  12960
* 4 Collector Area
3.74
* 5 Max Pump Flow
152
* 6 Hot Deadband
0
* 7 Prop gain - Aux
1.2
* 8 Prop gain - solar
0.6
* 9 Prop gain - solar+aux
1.0

INPUTS 9
* Tank:Available Hot Water ->Current Tank exergy
16,11
* Controller SP:Output 1 ->Required Exergy
5,1
* Radiation Processor:Total radiation on surface 1 ->Insolation
7,7
* Cold Supply:Instantaneous value of function over the timestep ->Supply Temp
3,2
* Tank:Node10Temp ->Collector Inlet Temp
16,22
* Collector:Outlet temperature ->Collector Out Temp
12,1
* EC Aux:Output 1 ->Ambient Temp
4,1
* Aux Htr:Outlet fluid temperature ->Aux Heater Temp
15,1
* Collector:Outlet flowrate ->Collector Flow
12,2

*** INITIAL INPUT VALUES
20000 20000 500 10 20 60
0 60 20

* Model "12Pump" (Type 3)
*

UNIT 9 TYPE 3 12Pump
PARAMETERS 4
* 1 Maximum flow rate
152
* 2 Fluid specific heat
4.180
* 3 Maximum power
259.2
* 4 Conversion co-efficient
0.5

INPUTS 3
* Tank:Temperature to heat source ->Inlet fluid temperature
16,1
* [unconnected] Inlet mass flow rate
0,0
* TYPE256:Pump Control ->Control signal
8,3

*** INITIAL INPUT VALUES
20.0 0 1.0

- 259 -
* Model "llDiverter" (Type 11)
*
UNIT 10 TYPE 11 llDiverter
PARAMETERS 1
  * 1 Controlled flow diverter mode
2
INPUTS 3
  * 12Pump:Outlet fluid temperature ->Inlet temperature
9,1
  * 12Pump:Outlet flow rate ->Inlet flow rate
9,2
  * TYPE256:Diverter Control ->Control signal
8,2
*** INITIAL INPUT VALUES
20.0 0 1
*---------------------------------------------------------
*
Model "llCollInlet" (Type 31)
*
UNIT 11 TYPE 31 llCollInlet
PARAMETERS 6
  * 1 Inside diameter
0.0095
  * 2 Pipe length
10.0
  * 3 Loss co-efficient
10
  * 4 Fluid density
1000.0
  * 5 Fluid specific heat
4.190
  * 6 Initial fluid temperature
25.0
INPUTS 3
  * llDiverter:Temperature at outlet 2 ->Inlet temperature
10,3
  * llDiverter:Flow rate at outlet 2 ->Inlet flow rate
10,4
  * 9Weather:Output 6 ->Environment temperature
1,6
*** INITIAL INPUT VALUES
25.0 0 25.0
*-----------------------------------------------
*
Model "lCollector" (Type 1)
*
UNIT 12 TYPE 1 lCollector
PARAMETERS 11
  * 1 Number in series
1
  * 2 Collector area
3.74
  * 3 Fluid specific heat
4.180
  * 4 Efficiency mode
1
  * 5 Tested flow rate
35.6
Appendix B - TRNSYS Model

* 6 Intercept efficiency 0.691
* 7 Efficiency slope 18.8568
* 8 Efficiency curvature 0.0051336
* 9 Optical mode 2
2
* 10 1st-order IAM 0.1798
* 11 2nd-order IAM -0.0214

INPUTS 9
* 11CollInlet:Outlet temperature -> Inlet temperature 11,1
* 11CollInlet:Outlet flow rate -> Inlet flow rate 11,2
* 9Weather:Output 6 -> Ambient temperature 1,6
* 16Radiation Processor:Total radiation on surface 1 -> Incident radiation 7,7
* 16Radiation Processor:Total horizontal radiation -> Total horizontal radiation 7,4
* 16Radiation Processor:Horizontal diffuse radiation -> Horizontal diffuse radiation 7,6
* [unconnected] Ground reflectance 0,0
* 16Radiation Processor:Incidence angle for surface 1 -> Incidence angle 7,10
* [unconnected] Collector slope 0,0

*** INITIAL INPUT VALUES
25.0 0 25.0 0 0.0 0.0
0.2 0 20

* Model "21CollOutlet" (Type 31)
*
UNIT 13 TYPE 31 21CollOutlet
PARAMETERS 6
* 1 Inside diameter 0.0095
* 2 Pipe length 10.0
* 3 Loss coefficient 9
* 4 Fluid density 1000.0
* 5 Fluid specific heat 4.190
* 6 Initial fluid temperature 25.0

INPUTS 3
* 1Collector:Outlet temperature -> Inlet temperature 12,1
* 1Collector:Outlet flow rate -> Inlet flow rate
12,2
* 9Weather:Output 6 ->Environment temperature
1,6
*** INITIAL INPUT VALUES
25.0 0 25.0
*---------------------------------------------------------
* Model "llMixer" (Type 11)
*
UNIT 14 TYPE 11 llMixer
PARAMETERS 1
* 1 Tee piece mode
1
INPUTS 4
* 21CollOutlet:Outlet temperature ->Temperature at inlet 1
13,1
* 21CollOutlet:Outlet flow rate ->Flow rate at inlet 1
13,2
* llDiverter:Temperature at outlet 1 ->Temperature at inlet 2
10,1
* llDiverter:Flow rate at outlet 1 ->Flow rate at inlet 2
10,2
*** INITIAL INPUT VALUES
20.0 100.0 20.0 100.0
*---------------------------------------------------------
* Model "6Aux Htr" (Type 6)
*
UNIT 15 TYPE 6 6Aux Htr
PARAMETERS 4
* 1 Maximum heating rate
12960
* 2 Specific heat of fluid
4.19
* 3 Overall loss co-efficient for heater during operation
3.6
* 4 Efficiency of auxiliary heater
1.0
INPUTS 5
* llMixer:Outlet temperature ->Inlet fluid temperature
14,1
* llMixer:Outlet flow rate ->Fluid mass flow rate
14,2
* TYPE256:Heater Enable ->Control Function
8,1
* [unconnected] Set point temperature
0,0
* 9Weather:Output 6 ->Temperature of surroundings
1,6
*** INITIAL INPUT VALUES
20.0 100.0 150 20.0
*---------------------------------------------------------
* Model "Tank" (Type 38)
*
UNIT 16 TYPE 38 Tank
PARAMETERS 17
* 1 Inlet position mode

1
* 2 Tank volume
0.34
* 3 Tank height
1.485
* 4 Height of collector return
1.35
* 5 Fluid specific heat
4.190
* 6 Fluid density
1000.0
* 7 Thermal conductivity
8.28
* 8 Tank configuration
1
* 9 Overall Loss Co-efficient
10.8
* 10 Insulation ratio
1.0
* 11 Initial temperature
20
* 12 Maximum heating rate
0
* 13 Auxiliary height
0.625
* 14 Thermostat height
0.702
* 15 Set point temperature
65
* 16 Temperature deadband
8
* 17 Flue loss co-efficient
0.0

INPUTS
* Aux Htr:Outlet fluid temperature ->Hot-side temperature
15,1
* Aux Htr:Outlet fluid flow rate ->Hot-side flowrate
15,2
* Cold Supply:Instantaneous value of function over the timestep ->Cold-side temperature
3,2
* 25Tempering:Flowrate at outlet 1 ->Cold-side flowrate
17,2
* Weather:Output 6 ->Environment temperature
1,6
* [unconnected] Control signal
0,0
* [unconnected] Heating Zone
0,0

*** INITIAL INPUT VALUES
25 0 20.0 0 25 0
0

Model "25Tempering" (Type 11)
*

UNIT 17 TYPE 11 25Tempering
PARAMETERS 2
* 1 Tempering valve mode
4

- 263 -
* 2 # of oscillations allowed

INPUTS 4
* 17Cold Supply:Instantaneous value of function over the timestep -
  >Inlet temperature
  3, 2
* 9Load:Output 1 ->Inlet flow rate
  2, 1
* Tank:Temperature to load ->Heat source temperature
  16, 3
* [unconnected] Set point temperature
  0, 0
*** INITIAL INPUT VALUES
  20.0 0 60.0 45.0

* EQUATIONS "Equa"

EQUATIONS 10
Colle = [12, 3]/3600.0
AuxE = [15, 3]/3600.0
LoadE = [16, 6]/3600.0
TankLoss = [16, 5]/3600.0
PipeLoss = ([11, 4]+[13, 4]+[15, 4])/3600.0
PumpLoss = [9, 3]/3600.0
CollVol = [16, 1]
LoadVol = [16, 4]
AuxCost = [6, 1]*[15, 3]/3600.0/100.0
UTemp = AND(GT([16, 4], 0.1), LT([16, 3], 45.0))*[16, 4]

* Model "46Energy" (Type 28)

UNIT 19 TYPE 28 46Energy
PARAMETERS 25
* 1 Summary interval
  -1
* 2 Summary start time
  0
* 3 Summary stop time
  8760.0
* 4 Logical unit
  12
* 5 Output mode
  2
* 6 Operation code-1
  -11
* 7 Operation code-2
  -4
* 8 Operation code-3
  -12
* 9 Operation code-4
  -4
* 10 Operation code-5
  -13
* 11 Operation code-6
  -4
* 12 Operation code-7
  -14

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* 13 Operation code-8
-4
* 14 Operation code-9
-15
* 15 Operation code-10
-4
* 16 Operation code-11
-16
* 17 Operation code-12
-4
* 18 Operation code-13
-17
* 19 Operation code-14
-4
* 20 Operation code-15
-18
* 21 Operation code-16
-4
* 22 Operation code-17
-19
* 23 Operation code-18
-4
* 24 Operation code-19
-20
* 25 Operation code-20
-4
INPUTS 10
* Equa:Colle ->Summary input-1
Colle
* Equa:AuxE ->Summary input-2
AuxE
* Equa:LoadE ->Summary input-3
LoadE
* Equa:TankLossE ->Summary input-4
TankLossE
* Equa:PipeLossE ->Summary input-5
PipeLossE
* Equa:PumpLossE ->Summary input-6
PumpLossE
* Equa:CollVol ->Summary input-7
CollVol
* Equa:LoadVol ->Summary input-8
LoadVol
* Equa:UTemp ->Summary input-9
UTemp
* Equa:AuxCost ->Summary input-10
AuxCost
LABELS 10
QCOLL QAUX QLOAD QTANKL QPIPE QPUMP CVOL LVOL UTMP AUX$
CHECK 5.0 1,2,-3,-4,-5,6
*** External files
ASSIGN C:\trnsys15\Mike\Models\RheemHiLine\Rheem.txt 12
*? Which file should contain the summary results? [1000
*---------------------------------------------------------------------
* Model "TYPE65" (Type 65)
*
UNIT 20 TYPE 65 TYPE65
PARAMETERS 10
* 1 # of left-axis variables
2
* 2 # of right-axis variables
  2
* 3 Left axis minimum
  0.0
* 4 Left axis maximum
  60
* 5 Right axis minimum
  0.0
* 6 Right axis maximum
  200
* 7 Number of plots per simulation
  1
* 8 X-axis gridpoints
  7
* 9 Shut off Online w/o removing
  0
* 10 Logical Unit for output file
  -1

INPUTS 4
* Tank: Temperature to heat source -> Left axis variable-1
  16,1
* Tank: Stratification Index -> Left axis variable-2
  16,12
* Tank: Flowrate to load -> Right axis variable-1
  16,4
* Tank: Flowrate to heat source -> Right axis variable-2
  16,2

*** INITIAL INPUT VALUES
TCIN XC FL FC
LABELS 5
C  kg/hr
Temperature
Power
Result

*-----------------------------------------------

END
Appendix C - Bacterial Growth

Since the stored water is not heated unless a load is anticipated, there is potential for bacterial activity in times and places of warm, stagnant water. This will seldom be a problem if the system is used regularly. If the system is idle for over a week and the normal action of the thermostat is over-ridden, health guidelines recommend that a heating sterilisation cycle be operated whereby the entire tank is heated to 65°C (DHS, 1999). Guidelines from AS1056.1 suggest a minimum auxiliary temperature of 60°C.

![Temperature response of legionella bacteria](image)

A conclusive answer to the legionella question could not be obtained from Australian state health authorities for the predictive controller technology. The use of high collector temperatures partly addresses the concern but it is unlikely that such a system would be acceptable in critical applications such as a nursing home, hospital or school.

The use of the auxiliary heater in-line with the delivery could solve this problem but this exposes the householder to potentially higher time of use tariffs.
Appendix D – Controller Details

D.1 Introduction

The active control algorithms require a local controller to sense the state variables and carry out the requisite regulatory control tasks. There are a number of approaches of varying complexity ranging from discrete controllers to networked controllers to supervisory systems. This is a research project with commercial sponsorship and the choice of technology had a commercial bias.

The controller is to be responsible for the following tasks:

- Control of the collector circulation pump
- Control of the auxiliary heater
- Operation of the hot water load system
- Datalogging for the load learning algorithms
- Data communication for state variable setpoints and load profiles

In a commercial environment, this controller would probably be installed on each system at the factory. Issues of size, cost and reliability are important. A review of microcontroller technologies lead to a solution based on the TIGER microprocessor (Wilke, 2004). This is one of many microcontrollers that are capable of the above tasks and it is likely that the cost of these devices will continue to fall.

Design and construction of the controller consumed more of the research time than it should have and was also used in solar tracking projects at ANU.

D.2 Hardware Description

In designing the water heater controller, the input/output (I/O) capabilities, memory capacity and communication capacity are the main considerations. The generic microcontroller is based on the simple structure shown in (figure D-1). CPU speed is usually a secondary consideration. Several variants of this
controller were hand made including the circuit board designs. One variant was used as the hot water load controller in the experiments. It is likely that any commercial derivatives of the controller would be modified to use a cheaper microcontroller and would use surface mount technology to reduce costs and improve long term reliability.

Figure D-1  Generic microcontroller and specifications for the TIGER TCN 4/4 CPU

The generic microcontroller is customised by the addition of ancilliary equipment (figure D-2). Additional analog signal processing is required in the form of filtering, amplification and multiplexing before the thermistor temperature sensors may be read by the controller. The pulse frequency of the collector and load flowmeters is too high for the controller and must be divided by 10 before being sampled. A power supply with battery backup and supervisory watchdog provides reasonable integrity of operation even in the case of power failure.

Each digital output of the Tiger CPU has very limited drive capability (1.6 mA) and a darlington pair transistor package is used to drive the solenoids and relays for the control actuators.
A network interface was assembled from the second serial port. This port is connected to a Siteplayer (NetMedia, 2004) module that contains a serial port, a 10 base-T transceiver, small RAM memory and limited I/O capability. This module is used as a RS232 to 10 Base-T converter so that information may be passed between the controller and a conventional TCP/IP network (running UDP protocol). This capability is especially useful for communications within the distributed intelligence environment (chapter 9). This module has the added benefit of allowing a small web page to be loaded and accessed with real-time controller data. It is possible to send data back to the controller using this mechanism which allows user interaction with the controller using standard web pages (i.e. no custom control panel is required).

**D.3 Synchronising Data Acquisition for Auxiliary Energy**

The water heaters use powerful electric auxiliary heating elements. Since a 30 second data acquisition interval is used, there is potential for a large sampling error in the measurement of auxiliary energy.

If the experiments were to be repeated, it is possible to build a synchronising circuit consisting of a clocked D type flip-flop logic circuit (figure D-3) to overcome this problem. This circuit would use the thermostat as a sense switch but would not pass the thermostat signal on to the heater until a...
synchronisation signal is received from the datalogger.

![Figure D-3](image.png)

*Figure D-3*  Clocked D flip-flop mechanism to synchronise the switching of the auxiliary heater with datalogger sampling interval

This circuit would use the thermostat as a sense switch and require a separate switching relay for the auxiliary heater itself.

**D.4 Software**

**Compiler**

The controller program is written and compiled in TIGER BASIC (Wilke, 2004), a custom adaptation of the BASIC programming language with additions to suit this micro controller. There is a small sacrifice in operating speed by using a high level programming language over assembler or machine code but this is offset by a significantly reduced development time. Extensive use of pre-written device drivers shelters the programmer from low-level coding. The compiler has an in-built debugger although this is of limited use for real-time programs. The device comes highly recommended for developers.

**Device Drivers**

The compiler comes with a number of device drivers already packaged. They include:

- Analog Input
- Keyboard input
- Parallel I/O
- LCD panel output
- Sound output
- Pulse counter
The device drivers save the programmer considerable effort in design and troubleshooting. It is not possible to write custom device drivers in this environment. One further restriction is that the ability to interrupt the CPU has been removed.

**Operating system**

The operating system is a multi-tasking structure known as a real time kernal. This allows a number of tasks to be scheduled in real time and to be run quasi-simultaneously by CPU time sharing on a task priority basis. Each task is defined similarly to a subroutine and may be started, suspended or ended independently. This enhances the system reliability considerably since each task is separate and is allocated CPU time by slices. Thus a supervisory task may look for faults in the running of other tasks and take appropriate action as required. The operating system is supplied with the CPU.

---

**Figure D-4** Solar water heater controller showing Tiger CPU
**Controller Software**

The controller software is not listed here as it comprises 2600 lines of TIGER BASIC code. Similarly, the software extracted from the controller to form the distributed intelligence infrastructure and database consists of many pages of Visual Basic program.

The TIGER BASIC code is modularised into a number of tasks broadly categorised as follows:

1. Operating system and menus
2. Pump control
3. Auxiliary heater control
4. Datalogging
5. Load detection and recording
6. Data communications

The software is available upon request (CSES Technical Report, 2002).
Appendix E – Greenhouse Gas Mitigation Potential

This appendix presents a methodology to examine the likely savings in greenhouse gas emissions by incremental improvements to the state of solar water heating in Australia.

The purpose of this analysis is to gain an insight into the most effective use of resources in making GHG savings from solar water heating.

Annual GHG emissions \( G \) for a solar water heater are given by the product of its auxiliary energy consumption \( Q_{aux} \) and the greenhouse gas intensity \( g \) of the auxiliary energy source.

\[
G = Q_{aux} g \quad (Eqtn \ E-1)
\]

Information has been gathered (by state) for the number of solar water heaters of each type, the proportions of gas and electric auxiliary, the proportions of large and small dwellings, the expected load draw from large and small water heaters, the expected auxiliary consumption and greenhouse co-efficients by auxiliary fuel type. Approximately 97% of solar water heaters use electricity as the auxiliary energy source (AGA, 1998)

The size distribution of solar water heaters is not known. The assumption made is that the number of small solar water heaters (tank delivery < 250 L) is proportional to the fraction of the population living in dwellings of two or less people. The number of large systems is proportional to the fraction of dwellings with three or more people. Auxiliary consumption is related to the size of the system (AS4234, 1994)

The GHG emissions for each state are thus given by

\[
G = %\text{small systems} \times \text{number of heaters} \times Q_{aux/SG} \times %\text{gas auxiliary} \times g_{gas} \\
+ %\text{small systems} \times \text{number of heaters} \times Q_{aux/SE} \times %\text{electric auxiliary} \times g_{elec} \\
+ %\text{large systems} \times \text{number of heaters} \times Q_{aux/LG} \times %\text{gas auxiliary} \times g_{gas}
\]
+ %large systems * number of heaters * $Q_{aux/LE}$ * %elec auxiliary * $g_{elec}$

The data tables E-1 to E-4 show the source data used for the emissions calculations, with their respective references. A spreadsheet is used to perform the calculations. The results indicate that water heaters account for 16 MtCO$_2$-e greenhouse gas (GHG) emissions per year and gas water heaters about 4 MtCO$_2$-e per year. Most of the emissions (~70%) are from large electric storage heaters.

Manipulation of the auxiliary energy consumption figures suggests that GHG emissions from water heaters may be reduced by an incremental 50 ktCO$_2$-e/yr for every 1% reduction in storage losses from the tank. Similar methodology applied to market penetration of solar hot water units suggests a reduction of 260 ktCO$_2$-e/yr for every 1% increase in solar hot water system sales.

### Data Tables

<table>
<thead>
<tr>
<th>State</th>
<th>Climate Zone</th>
<th>Proportion of SHW units</th>
<th>Proportion of small units</th>
<th>Proportion of gas units</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAS</td>
<td>4</td>
<td>0.9%</td>
<td>63%</td>
<td>1.0%</td>
</tr>
<tr>
<td>VIC</td>
<td>4</td>
<td>0.9%</td>
<td>57%</td>
<td>71%</td>
</tr>
<tr>
<td>ACT</td>
<td>3</td>
<td>3.4%</td>
<td>59%</td>
<td>23%</td>
</tr>
<tr>
<td>NSW</td>
<td>3</td>
<td>2.7%</td>
<td>57%</td>
<td>26%</td>
</tr>
<tr>
<td>SA</td>
<td>3</td>
<td>0.6%</td>
<td>64%</td>
<td>33%</td>
</tr>
<tr>
<td>WA</td>
<td>3</td>
<td>18%</td>
<td>60%</td>
<td>64%</td>
</tr>
<tr>
<td>QLD</td>
<td>1</td>
<td>8.0%</td>
<td>60%</td>
<td>11%</td>
</tr>
<tr>
<td>NT</td>
<td>1</td>
<td>44%</td>
<td>55%</td>
<td>3.0%</td>
</tr>
</tbody>
</table>

Table E-1 Water heater statistics by state: Climate zones from AS4234 (1994), dwelling size proportion from ABS 1301.0 (2003), auxiliary source from ABS 4602.0 (2002)
### Appendix E – Greenhouse Gas Mitigation Potential

#### Table E-2 Auxiliary consumption of conventional heaters from AS4234. Climate zones 3 and 4 are treated equivalently.

<table>
<thead>
<tr>
<th>State</th>
<th>Small gas auxiliary consumption (kWh/yr)</th>
<th>Small electric auxiliary consumption (kWh/yr)</th>
<th>Large gas auxiliary consumption (kWh/yr)</th>
<th>Large electric auxiliary consumption (kWh/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAS</td>
<td>3,972</td>
<td>3,250</td>
<td>5,805</td>
<td>4,958</td>
</tr>
<tr>
<td>VIC</td>
<td>3,972</td>
<td>3,250</td>
<td>5,805</td>
<td>4,958</td>
</tr>
<tr>
<td>ACT</td>
<td>3,972</td>
<td>3,250</td>
<td>5,805</td>
<td>4,958</td>
</tr>
<tr>
<td>NSW</td>
<td>3,972</td>
<td>3,250</td>
<td>5,805</td>
<td>4,958</td>
</tr>
<tr>
<td>SA</td>
<td>3,972</td>
<td>3,250</td>
<td>5,805</td>
<td>4,958</td>
</tr>
<tr>
<td>WA</td>
<td>3,972</td>
<td>3,250</td>
<td>5,805</td>
<td>4,958</td>
</tr>
<tr>
<td>QLD</td>
<td>3,389</td>
<td>2,680</td>
<td>4,472</td>
<td>3,833</td>
</tr>
<tr>
<td>NT</td>
<td>3,389</td>
<td>2,680</td>
<td>4,472</td>
<td>3,833</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>State</th>
<th>Large system solar contribution (kWh/yr)</th>
<th>Small system solar contribution (kWh/yr)</th>
<th>( g_{\text{gas}} ) (kg CO2-e/kWh)</th>
<th>( g_{\text{elec}} ) (kg CO2-e/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAS</td>
<td>3,000</td>
<td>2,600</td>
<td>0.245</td>
<td>0.002</td>
</tr>
<tr>
<td>VIC</td>
<td>3,000</td>
<td>2,600</td>
<td>0.231</td>
<td>1.444</td>
</tr>
<tr>
<td>ACT</td>
<td>3,000</td>
<td>2,600</td>
<td>0.259</td>
<td>1.012</td>
</tr>
<tr>
<td>NSW</td>
<td>3,000</td>
<td>2,600</td>
<td>0.259</td>
<td>1.012</td>
</tr>
<tr>
<td>SA</td>
<td>3,000</td>
<td>2,600</td>
<td>0.268</td>
<td>1.186</td>
</tr>
<tr>
<td>WA</td>
<td>3,000</td>
<td>2,600</td>
<td>0.226</td>
<td>1.114</td>
</tr>
<tr>
<td>QLD</td>
<td>2,500</td>
<td>2,100</td>
<td>0.269</td>
<td>1.079</td>
</tr>
<tr>
<td>NT</td>
<td>2,500</td>
<td>2,100</td>
<td>0.192</td>
<td>0.655</td>
</tr>
</tbody>
</table>
## Appendix E – Greenhouse Gas Mitigation Potential

<table>
<thead>
<tr>
<th>State</th>
<th>Small gas water heater GHG (kg CO2-e)</th>
<th>Small elec water heater GHG (kg CO2-e)</th>
<th>Large gas water heater GHG (kg CO2-e)</th>
<th>Large elec water heater GHG (kg CO2-e)</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAS</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>VIC</td>
<td>671</td>
<td>1,391</td>
<td>739</td>
<td>1,598</td>
<td>4,398</td>
</tr>
<tr>
<td>ACT</td>
<td>16</td>
<td>176</td>
<td>17</td>
<td>191</td>
<td>400</td>
</tr>
<tr>
<td>NSW</td>
<td>357</td>
<td>3,260</td>
<td>395</td>
<td>3,766</td>
<td>7,778</td>
</tr>
<tr>
<td>SA</td>
<td>134</td>
<td>981</td>
<td>112</td>
<td>854</td>
<td>2081</td>
</tr>
<tr>
<td>WA</td>
<td>255</td>
<td>567</td>
<td>249</td>
<td>578</td>
<td>1,648</td>
</tr>
<tr>
<td>QLD</td>
<td>75</td>
<td>2,015</td>
<td>66</td>
<td>1,902</td>
<td>4,057</td>
</tr>
<tr>
<td>NT</td>
<td>0</td>
<td>36</td>
<td>0</td>
<td>42</td>
<td>79</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1,510</td>
<td>8,427</td>
<td>1,578</td>
<td>8,931</td>
<td>20,446</td>
</tr>
</tbody>
</table>

*Table E-4 Total water heater GHG emissions by state and water heater type*
Appendix F – The Mandatory Renewable Energy Target (MRET)

F.1 The MRET Mechanism

Australia’s Mandatory Renewable Energy Target came about as a result of the Commonwealth Renewable Energy (Electricity) Act, 2000. The act demands that retailers and other liable parties source a specified percentage of their energy purchases from approved renewable sources of electricity. The target was interpreted to be equivalent to 9500 GWh per annum of fossil based generation by renewable energy generation during 2010 based on forecast demand growth at the time the legislation was drafted. There are annual targets starting 2001, ramping up to the 9500 GWh target and this volume is then maintained until 2020. This legislation is now under review. Many groups suggest the 9500 GWh target is not a fair representation of 2% contribution and some propose an increased contribution to 5% and even 10% over the same period and longer compliance periods. A stable long-term outlook is required for sustained business investment in the young renewable energy industry as projects often have long payback periods. Energy retailers are obliged to supply renewable energy to consumers or pay a $40/MWh penalty. This penalty is not indexed to CPI so its real value decreases in time. Proof of compliance is by means of surrendering Renewable Energy Certificates (RECs) to the value of the liability. Since compliance is not tax deductible, liable parties may be prepared to pay up to $57 per REC depending upon the dividend imputation status of shareholders, assuming a 30% corporate tax rate. This sets an energy supply price benchmark for renewable contribution to MRET.

RECs are created by registered generators or registered persons acting on behalf of a generator. As of August 2003, there are 214 such registered persons comprising individuals, small generators and energy utilities. There are a small number of RECs agents also registered. RECs agents may act on behalf of
individuals.
RECs must be created within 12 months of the energy being generated. Liable parties then purchase RECs at market price (depending upon supply and demand) to meet their MRET obligation where their own renewable energy generation portfolio production falls below their obliged renewable generation target. There is no price associated with the REC until it is redeemed. RECs are traceable to place and time of generation and do not expire until redeemed by a liable party.

As of 2003, there seems to be an over-supply of RECs due to large contribution from efficiency upgrades to old hydro and high early investment in the scheme and this combined with the low early MRET requirement means low RECs price (approx $30, Jul 2003). Liable parties are thus interested in purchasing RECs rather than paying the $40/MWh penalty for the time being.

Generating parties are delaying registration of RECs as long as possible in the hope of higher spot market prices. Liable parties are keen to bank RECs for the same reason. Since RECs only become invalid after redemption, excess RECs accumulate and lower the value of future renewable energy generation.

The MRET is largely designed for moderate scale renewable generators. Some dispensation has been allowed for distributed small generators. Although solar water heaters do not generate electricity, they do displace generation and a special dispensation allowed them, and heat pump water heaters, to be included. Many other displacement technologies, notably energy efficiency measures, were excluded.

Any renewable distributed generation capacity provides leveraged displacement of primary energy in the ratio of about 5:1 for coal based electricity. MRET recognises only energy consumption at point of use and so does not discriminate against inefficient generation practices as a carbon tax would.
F.2 MRET and Solar Water Heaters

The domestic solar hot water industry is in an ideal position to capitalise on the "subsidised" opportunities provided under MRET. The solar hot water manufacturing industry is well established and has mature technology. Supply and sales chains are established and so there are fewer time lags to respond to market demands generated by MRET. In contrast to wind energy and PV solar energy only a small component of solar water heater systems must be imported so that currency risk and cost uncertainty can be largely controlled. There is a predictable market supported by heater replacement cycles. These factors should make SHW business attractive to investors.

To be eligible to generate RECs, a solar water heater must meet the following conditions:

- It must have been installed on or after 1st April 2001
- It must replace an electric water heater that has been in service for at least one year
- If it replaces an existing electric solar water heater, the difference in performance is eligible for RECs
- It is the first heater to be installed in a building
- It is being installed in a new building

Since the cost of individual metering of solar water heaters would be prohibitive, the number of RECs generated by a solar water heater are estimated for a given model of solar water heater operating in a stated location defined by the local postcode. Testing and modelling is carried out for each eligible solar water heater based on the Australian Standards AS1056.1 and AS4234 and the number of generated RECs deemed over a ten year period. Thus all the RECs are granted up front for solar water heaters. There are some 522 (ORER, 2004b) solar water heaters eligible for RECs, almost all of which are Australian manufactured.

After installation, RECs can be created at any time over the following 12
months. The RECs are owned by the purchaser of the solar hot water system and may be registered by the owner, although an individual must register with the Office of the Renewable Energy Regulator (ORER) at a cost of A$20. Alternatively, the owner might choose to assign RECs registration rights to the seller of the hot water system (a RECs agent) in lieu of a rebate from the seller. In this case the seller gathers larger quantities of RECs and registers these either as an individual or as a registered RECs agent. For accumulated quantities exceeding 250 RECs, a registration fee of 8c per REC is charged by ORER.
Appendix G – Relevant Australian Standards

Table G-1 shows a list of Australian standards that the new auxiliary heating and pumped circulation designs will need to comply with. The standards are administered by Standards Australia and are available online to registered users at www.standards.com.au. These standards provide a minimum baseline for the construction methods used in manufacturing the designs. Any feature that complies with all relevant standards and performs well, will be further defined by manufacturing and cost constraints. There may be other relevant standards not listed in the table.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG102</td>
<td>Approval requirements for gas water heaters</td>
</tr>
<tr>
<td>AS1044</td>
<td>Limits and methods of measurement of radio disturbance characteristics of electrical motor operated and thermal appliances for household and similar purposes, electric tools and similar electric apparatus</td>
</tr>
<tr>
<td>AS1056.1</td>
<td>Storage water heaters - General requirements</td>
</tr>
<tr>
<td>AS1308</td>
<td>Thermostats and over temperature energy cutouts for automatic electric water heaters</td>
</tr>
<tr>
<td>AS2002</td>
<td>The installation of household type solar hot water supply systems</td>
</tr>
<tr>
<td>AS2535</td>
<td>Solar collectors with water as the heat transfer fluid – method for testing thermal performance</td>
</tr>
<tr>
<td>AS2712</td>
<td>Solar water heaters - design and construction</td>
</tr>
<tr>
<td>AS2984</td>
<td>Solar Water heaters – methods of test for thermal performance – outdoor test method</td>
</tr>
<tr>
<td>AS3142</td>
<td>Approval and test specification – electric water heaters</td>
</tr>
<tr>
<td>AS3161</td>
<td>Thermostats and energy regulators</td>
</tr>
<tr>
<td>AS3350.2.21</td>
<td>Safety of household and similar electrical appliances</td>
</tr>
<tr>
<td>AS3498</td>
<td>Authorisation requirements for plumbing products - water heaters and hot water storage tanks</td>
</tr>
<tr>
<td>AS3500.4.2</td>
<td>National plumbing and drainage – hot water supply systems – acceptable solutions</td>
</tr>
<tr>
<td>AS4234</td>
<td>Solar water heaters – domestic and heat pump – calculation of energy consumption</td>
</tr>
<tr>
<td>AS4445</td>
<td>Solar heating – domestic water heating systems</td>
</tr>
</tbody>
</table>

Table G-1  Australian standards relevant to solar water heaters
Appendix H – Variable Power Pump Software

This code was written in the BASCOM AVR BASIC compiler for the AVR 8535 microcontroller. It provides variable speed pumping of the collector and auxiliary heating circulation based on a constant tank return temperature strategy. It also allows conventional differential temperature operation so that low-flow strategies can be tested.

The main controller sends signals to the pump controller to indicate when auxiliary heating is required and when collector heat gain is available. The pump controller operates the heating circuit solenoid valves appropriately and switches its control loop sense temperature according to figure 8-6. Control loop tuning is also set differently for each mode.

Frost and over-heating protection are provided.

```
;'---------------------------------------------
;' Solar Hot Water Pump Control
;'---------------------------------------------
;' M. Dennis 18/03/2004
;' Mode 1. DeltaT control
;' Mode 2. Variable speed by phase control to maintain
;' set collector or auxiliary outlet temp
;' Also switches the solenoid valves to collector
;' or aux heater
;' Portc.7=Pump output
;' Portc.6=Collector solenoid
;' Portc.5=Aux heater solenoid
;' Portc.3=Auxiliary heater status
;' Portc.4=Collector heat gain status
;' ADC1=Tcin
;' ADC2=Tcout
;' ADC3=Taux
;
;'---------------------------------------------

$regfile = "8535def.dat"
$crystal = 800000

Const Maxtcin = 80.0
Const Deltath1 = 6.0
Const Deltatlo = 2.5
Const Freezelo = 3.0
Const Consttband = 3.0
Const Rp = 10000.0
Const R01 = 10000.0
Const R02 = 8495.0
```

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Const Beta1 = 3880.0
Const Beta2 = 3400.0

Declare Sub Initvars()
Declare Sub Initconfig()
Declare Sub Measuretemps()
Declare Sub Deltat()
Declare Sub Constt()
Declare Sub Solenoids()
Declare Sub Frost()

'Variables
Dim Controlmode As Byte
Dim Firstpass As Byte
Dim Auxon As Byte
Dim Collon As Byte
Dim Stoppump As Byte
Dim Loopctr As Byte
Dim Valvectr As Byte
Dim Channel As Byte
Dim Frostctr As Byte
Dim Adcw As Word
Dim Speed As Integer
Dim Oldspeed As Integer
Dim Speedincr As Byte
Dim Temp1 As Single
Dim Constset As Single
Dim Temp2 As Single
Dim Tcin As Single
Dim Tc0 As Single
Dim Tc1 As Single
Dim Tcout As Single
Dim Taux As Single
Dim Tcontrol As Single
Dim Pgain As Single
Dim Tdiff As Single
Dim Oldtcout As Single
Dim Dt As Single
Dim Thi As Single
Dim Tlo As Single
Dim Interval(20) As Byte

Controlmode = 1
'Main program
Print "Starting main loop"
'Initialise configuration
Call Initconfig()
'Initialise Variables
Call Initvars()
Do
'Use Tiger signals to switch solenoid valves
Call Solenoids()
'Measure collector and aux outlet temperatures
Call Measuretemps()
'Carry out flow control
If Stoppump = 0 Then
    If Controlmode = 0 Then
        Call Deltat()
    Else
        Call Constt()
    End If
Else

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End If
End If
Call Frost()
'Update hysteresis settings
If Speed > Oldspeed Then
  Speedincr = 1
Else
  Speedincr = 0
End If
Oldspeed = Speed
'Print diagnostic information
Loopctr = Loopctr + 1
If Loopctr = 10 Then
  Tcontrol = Tcontrol
  Loopctr = 0
End If
'Create sampling delay
Waitms 500
' Waitms 2000
Loop
End

Sub Initvars()
  'Initialise program variables
  Loopctr = 0
  Valvectr = 0
  Frostctr = 0
  Firstpass = 1
  Interval(1) = 200
  Interval(2) = 201
  Interval(3) = 202
  Interval(4) = 203
  Interval(5) = 204
  Interval(6) = 205
  Interval(7) = 206
  Interval(8) = 207
  Interval(9) = 208
  Interval(10) = 209
  Interval(11) = 211
  Interval(12) = 211
  Interval(13) = 212
  Interval(14) = 213
  Interval(15) = 214
  Interval(16) = 215
  Interval(17) = 216
  Interval(18) = 217
  Interval(19) = 218
  Interval(20) = 235
  'Switch ON pump and valve to check operation
  Portc.7 = 0
  Portc.6 = 0
  Portc.5 = 0
  Adcw = 0
  Speed = 0
  Oldspeed = 0
  Tcout = 20.0
  Oldtcout = 20.0
  Stoppump = 1
Appendix H – Variable Power Pump Software

Consttset = 57.0
For Channel = 0 To 4
    Adcw = Getadc(channel)
    Print Adcw
    Waitms 100
Next
End Sub

Sub Initconfig()
    'Configuration
    'PIN16=PortD.2=INT0 zero crossing interrupt every 10ms, rising edge
    'PIN22=PortC.0=Pump TRIAC output pulse
    'PIN23=PortC.1=One way valve TRIAC output pulse
    'Timer0 at 7812.5Hz generates phase delay for duty cycle control of
    'TRIAC
    ' overflows and generates an interrupt.
    'Serial port is COM1 by default, 9600,8,N,1 for diagnostic
    'messages.
    Config Int0 = Rising
    Config Pinc.7 = Output
    Config Pinc.6 = Output
    Config Pinc.5 = Output
    Config Pinc.3 = Input
    Config Pinc.4 = Input
    Config Adc = Single, Prescaler = Auto, Reference = Avcc
    Config Timer0 = Timer, Prescale = 1024
    Config Pnb.6 = Output
    On Int0 Int0_int
    On Timer0 Tim0_int
    Enable Interrupts
    Enable Timer0
    Enable Int0
    Baud = 9600
    Start Adc
    Waitms 1000
End Sub

Sub Solenoids()
    'Uses the settings of AuxON and CollON (sent by TIGER) to determine
    'which solenoid needs to be active (0=ON, 1=OFF). Also determines
    'which temperature to control from. The AuxON signal is inverted
    'so AuxON=0v means heater on
    Dim Ttest As Single

    'Only switch solenoids if pump is on
    If Speed > 0 Then
        Auxon = Pinc.3
        'Find out if there is any collector gain potential. Use
        'hysteresis
        Ttest = Tcin + 5.0
        If Tcout > Ttest Then
            Collon = 1
        Else
            Ttest = Tcin + 2.0
            If Tcout < Ttest Then
                Collon = 0
            End If
        End If
        ' Collon = Pinc.4
        Auxon = 1
        ' Collon = 0
    End If

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If Collon = 0 Then
    If Auxon = 0 Then
        Set Portc.6
        Reset Portc.5
        Tcontrol = Taux
        Pgain = 0.6
    Else
        Set Portc.6
        Set Portc.5
        Tcontrol = Tcout
        Pgain = 0.7
    End If
Else
    If Auxon = 0 Then
        'Heat from aux only
        Set Portc.6
        Reset Portc.5
        Tcontrol = Taux
        Pgain = 0.6
    Else
        'No flow
        Set Portc.6
        Set Portc.5
        Tcontrol = Tcout
        Pgain = 0.7
    End If
Else
    'Heat from collector only
    If Auxon = 0 Then
        Set Portc.6
        Reset Portc.5
        Tcontrol = Taux
        Pgain = 1.5
    Else
        Reset Portc.6
        Set Portc.5
        Tcontrol = Tcout
        Pgain = 0.7
    End If
End If
Else
    'Pump
    speed = 0
    Set Portc.6
    Set Portc.5
End If
End Sub

Sub Measuretemps()
    'Measures Tcin and Tcout from ADC. Converts ADC counts to degC.
    'Prevents program making any decisions if thermistor signals are
    'out of range or Tcin exceeds MaxTcin (typ 80degC)
    Adcw = Getadc(0)
    Print "ADC0=": Adcw
    Adcw = Getadc(1)
    Print "ADC1": Adcw
    'Aux output temperature
    Adcw = Getadc(2)
    Print "ADC2": Adcw
    Temp1 = 1024 - Adcw
    Temp1 = Temp1 / Temp1
    Temp1 = Temp1 * Rp
    Temp1 = Temp1 / R01
    Temp2 = Log(temp1)
    Temp2 = Temp1 / Betal
    Temp2 = Temp2 + 0.003355705
    Taux = 1.0 / Temp2
    Taux = Taux - 273.15
    Adcw = Getadc(3)
    Print "ADC3": Adcw
    Temp1 = 1024 - Adcw
    Temp1 = Adcw / Temp1
    Temp1 = Temp1 * Rp
End Sub
\begin{verbatim}
Temp1 = Temp1 / R02
Temp2 = Log(temp1)
Temp2 = Temp2 / Beta2
Temp2 = Temp2 + 0.003355705
Tc1 = 1.0 / Temp2
Tc1 = Tc1 - 273.15

Tc1 = 0.7 * Tc1
Tc2out = 0.3 * Tc2out
Tc2out = Tc2out + Tc1
  If Tc1 > 50.0 Then
    If Tc1 < 100.0 Then
      Tc2out = Tc1
    Else
      Oldtc2out = Tc2out
      Firstpass = 0
      End If
    Else
      Goto Skip
    End If
  Else
    Goto Skip
  End If

Else
  Goto Skip
End If

Stoppump = 0

Adcw = Getadc(4)
  Print "ADC4= " ; Adcw
Temp1 = 1024 - Adcw
Temp1 = Adcw / Temp1
Temp1 = Temp1 * Rp
Temp1 = Temp1 / R01
Temp2 = Log(temp1)
Temp2 = Temp2 / Beta2
Temp2 = Temp2 + 0.003355705
Tc2in = 1.0 / Temp2
Tc2in = Tc2in - 273.15
  Print " Tc2in= " ; Tc2in

End Sub

Sub Deltat()
  'Firstly checks for freezing and switches pump if freezing detected.
  'Otherwise, normal hysteresis control is used. Pump is either full on
  'or fully off.
  If Tc2out < Freezelo Then
    Speed = 5
  Else
    Dt = Tc2out - Tc2in
    If Dt < Deltatlo Then
      Speed = 0
    Else
      If Dt > Deltathi Then
        Speed = 20
        'switch to full power
      End If
    End If
  End If
End Sub
\end{verbatim}
Sub Constt()

' Hysteresis action provided by differential setpoints
If Speedincr = 1 Then
    Consttset = 54.0 'speed up earlier
Else
    Consttset = 57.0 'slow down sooner
End If
Dt = Tcontrol - Consttset
'Now that valves are set, adjust speed to get temperature
Dt = Dt * Pgain
Speed = Int(dt)
If Speed < 0 Then
    Speed = 0
End If
If Speed > 20 Then
    Speed = 20
End If
If Pgain = 0.6 Then
    If Speed > 7 Then
        Speed = 7
    End If
End If
End Sub

Sub Frost()

'If collector outlet falls below 3degC, run pump for 30s
'at low speed
If Tcout < 3.0 Then
    If Frostctr < 60 Then
        Reset Portc.6 'Open collector solenoid
        Set Portc.5
        Speed = 7
        Frostctr = Frostctr + 1
    Else
        Set Portc.6 'Close both solenoids
        Set Portc.5
        Speed = 0
        Frostctr = 0
    End If
End If
End Sub

'------------------------------------ ------- ------- ----- - - -------
'INTERRUPTS
',
Int0_int:
'Zero crossing of AC mains has been detected. Optocoupler actually
switches just
'before zero crossing. Switch OFF TRIAC, forming the end of the
last cycle.
'Load delay into counter and start counting upwards towards 256.
'may need a small delay here
Set Portc.7
'Soft start code not required. If motor doesn't start on low power,
the
'outlet temperature will rise requiring a higher power so the
system
'is self-regulating
If Speed > 0 Then
    Timer0 = Interval(speed)
Start Timer0
Else
  Valvectr = Valvectr + 1
  If Valvectr > 100 Then
    Set Portc.6 'Close both valves
    Set Portc.5
    Valvectr = 0
  End If
End If
Return

Tim0 int:
  'When the timer overflows, it is time to switch ON the TRIAC. Then disable
  'the timer until started by the next zero crossing
  Reset Portc.7
  Stop Timer0
Return