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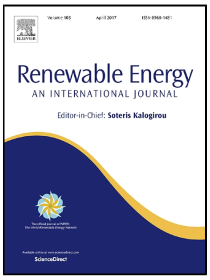

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S. Rezvani, P.A. Bahri, T. Urmee, G.F. Baverstock, A.D. Moore

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Techno-economic ancomparoid reliability assessment of solar water heaters in Australia based on Monte Carlo Analysis

S. Rezvani [a], G.F. Baverstock[a], T. Urmee [a], A.D. Moore[b], P.A. Bahri [a1]

a. School of Engineering and Information Technology, Murdoch University, Murdoch, WA 6150, Australia

b. Life Cycle Logic, PO Box 571 Fremantle WA 6959, Australia

Highlights

- The reliability of solar water heaters with flat plate collectors (FPC) in Australia
- Estimation of component failures using Monte Carlo analysis based on a modified inverse Weibull probability distribution function
- Reliability study of FPC solar water heaters with different storage tank materials
- Assessment of non-scheduled service cost based on maintenance cost distribution
- Economic analysis of solar water heaters with glass-lined storage
- Sensitivity analysis and comparison of specific thermal cost of solar water heaters against conventional systems

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[1] Corresponding author: Professor Parisa Arabzadeh Bahri, email: P.Bahri@murdoch.edu.au, phone: +61 8 93607227

Techno-economic and reliability assessment of solar water heaters in Australia based on Monte Carlo Analysis

S. Rezvani [a], P.A. Bahri [a1], T. Urmee [a], G.F. Baverstock[a], A.D. Moore[b]

a. School of Engineering and Information Technology, Murdoch University, Murdoch, WA 6150, Australia

b. Life Cycle Logic, PO Box 571 Fremantle WA 6959, Australia

Abstract

Monte Carlo analysis is used in this study to estimate the techno-economic benefits and reliabilities of solar water heaters. The study focuses on a product range manufactured by a local company in Australia. The historical data provided by the company forms the basis of this investigation. The inverse Weibull distribution function is a good match for representing the historical data in the model in terms of the number of failures per operating time for each component. The overall system reliability is determined as the sum of individual component failures during the product lifetime. The analysis is carried out for different system configurations using copper, stainless steel and glass-lined storage tanks. All the systems utilise flat plate collectors. The product with glass-lined storage tanks and electric boosters show a good overall reliability if systems are maintained.

Based on the probability model, the variable maintenance costs of solar water heaters were estimated over the product lifetime. This together with capital expenditures and fuel charges are used to compute the specific price of hot water supply for different system configurations. Moreover, a sensitivity analysis is implemented to show the impact of auxiliary heating on the economic viability of the products. The results show that solar water heaters can offer significantly better long-term economic viability compared to conventional systems at moderate auxiliary energy consumptions.

Keywords: Monte Carlo Analysis, Weibull probability distribution, reliability analysis of solar water heaters, flat plate collectors, economic analysis of solar water heaters

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[1] Corresponding author: Professor Parisa Arabzadeh Bahri, email: P.Bahri@murdoch.edu.au, phone: +61 8 93607227

Nomenclature

a	Location parameter
A_{SP}	Area of the solar thermal collector m^2
ABUR	Annual Booster Usage Rate in %
c_b	Energy cost for operating the booster in \$/kWh
c_{boiler}	Specific cost of thermal energy provided by the conventional water boiler in \$/kWh
c_{fuel}	Cost of fuel or energy used in the boiler or booster in \$/kWh
c_j	Service/maintenance cost for year *j*
c_{therm}	Thermal cost of using solar heater in \$/kWh
$c\kappa$	Cost of repair or replacement of the component κ (\$)
CC	SWHs capital cost (\$)
CC_{boiler}	Capital cost for conventional water boiler installation (\$)
cont.	Percent contingency expressed in decimals
d	Days of operation in a year (days/year)
DCF	Discounted cash flow in decimals
E_{boiler}	Daily energy provided by the conventional boiler in kWh/day. This energy is equivalent to that of a corresponding SWHs with booster
E_{solar}	Average solar radiation in $kWh/m^2/day$
E_{SWHs}	Thermal energy generated by a solar water heater in kWh/day
$f(t_i)$	Failure rate after t_i time of operation
$f(t_{k,j})$	Failure rate for component κ at time t_j
$f(t_{x,j})$	failure rate of component *x* after *tj* time of operation
G	Energy gap between solar thermal and load demand *in kWh/day*, if $E_{SWHs}>L, G=0$
$g(t_i)$	Failure rate expressed in percentage
$g(t_i)$	Failure rate given in percentage for the changed interval of *j* to *m*
k	Shape parameter
L	Load demand kWh/day
m	Total number of components
M(t)	Maintenance cost estimated at time t_j *(\$)*
MLE	Maximum Likelihood Estimation
n	Total number of operation time e.g. years or months
P*(t)*	Probability of the entire system failure at time t_j
R	Rebate on SWHs costs (\$)
SWHs	Solar water heaters
t_i	Operation time intervals in years or months
t_{max}	Maximum product life expectancy
TMC_{NS}	Total maintenance cost for non-scheduled services during the product life time (\$) year t_j to t_n
TMC_S	Total maintenance cost for scheduled services during the product life time
U_{solar} =	Utilisation factor for solar energy (%)
z	Normal curve areas, $z = t-\mu /\sigma$
ε_{boiler}	Efficiency of the water heater in decimals
$\varepsilon_{booster}$	Efficiency of the booster given
η_{solar}	SWHs efficiency in decimals
λ	Scale parameter
μ	Mean value of $f(t_i)$
σ	Standard deviation
Γ	Gamma function
$\Phi(t)$	Cumulative system failure after *t* period of operation

1. Introduction

Hot water supply accounts for around 20% to 26% of residential energy use in Australia (Energy rating 2007, Australian Bureau of Statistics, 2012, Department of the Environment, Water, Heritage and the Arts, 2008). This corresponds to an annual energy consumption of around 91 PJ or about 10 kWh per household per day. The resulting emissions amount to values between 5 Million and 18.4 million tonnes of CO_2 per annum considering natural gas and electricity as the source of energy respectively. The emission factor for electricity in Australia is given at around 0.73 kg CO_2/kWh (Australian Government, 2014). The size of the market in 2007 was given at around 8.12 million households in 2007 including group, single and family households (Australian Bureau of Statistics, 2010). In average, the annual increase of household numbers is around 1.5% between 2001 and 2021 (Australian Bureau of Statistics, 2010, Australian Bureau of Statistics, 2015). This increase is due to the reduction of household sizes and the population growth.

The annual IEA Solar Heating and Cooling Programme (Mauthner et al., 2016) and earlier reports from IEA (2000-2014) show annual market penetration trends for SWHs in Australia over the last 16 years. Unglazed flat plate systems usually used for water heating in swimming pools dominate the market. SWHs with glazed flat plate collectors (FPC) are the common systems used for commercial and residential hot water generation in Australia. The total installed capacity culminated to a value of 2.26 GW_{th} in 2014. The market for the more efficient Evacuated Tube Collectors (ETC) is limited in Australia. Comparing the number of installed systems against the total thermal capacities, we see a drop in the total thermal capacity since 2010 although the numbers of installations have increased. The installation numbers were taken from 2012 report of Clean Energy Australia (Clean Energy Council, 2012) and juxtaposed against the thermal capacities published by IEA Solar Heating and Cooling Programme (Reports from 2000-2015). Based on the above information, the penetration of SWHs in the Australian market is estimated at around 9% for year 2012.

To improve the uptake of SWHs in Australia, it is important to highlight the long-term system performance characteristics and juxtapose them against the conventional water heaters. Eicker (2003) identified the major issues and challenges with SWHs. Major issues are leakage in pipes, air in the system, faulty control systems and valves, corrosions, dirty collectors and broken glasses. The Australian standards for testing the performance of thermo-siphon solar hot water system AS 2813 (Australian Standard, 1985) and AS 2984 (Australian Standard, 1987) are now superseded by newer standards such as ISO 9459-4 (International Standard, 2013) and ISO 9806 (International Standard, 2013(E)). The former is conducive to performance characterisation of systems with auxiliary heaters and ensures product quality and reliability through component tests. ISO 9806 (International Standards, 2013) describes the test methods for assessing durability, reliability and safety for solar thermal collectors. It also includes performance characterisation of glazed and unglazed systems for fluid and air heating in open and closed loop configurations. This standard will replace other existing standards for collector efficiency and performance specification (Meyer, 2013). ISO 9860 is based on the European standard EN 12975 (CEN, 2006 part 1 and part 2). This standard acts as uniform international collector standard for global certification (Berner, 2012). The objectives of the above standards are to meet the minimum product requirements such as the use of anti-corrosive materials, resistance against extreme temperatures and pressures, resistance against water contaminations; protection against lightning and electrical faults and the reduction of heat losses.

This study is an initial attempt to use the service and maintenance data of a particular brand of solar water heater gathered over 15 years of operation to generate a reliability model. Consequently, the results are translated into a maintenance cost distribution model, which enables assessing the economic impacts of system failures over time. The total value of the maintenance costs over the product lifetime along with the costs of auxiliary energy is used to estimate the specific cost of hot water supply in $/kWh. This cost includes inflations, which is captured over an assumed discounted cash flow rate.

A number of techno-economic studies are available in the literature with similar aims to demonstrate the techno-economic benefits of solar water heaters. The methodologies vary from case to case. Kalogirou (2004) uses lifesaving analysis. Likewise, this method uses time value of money to evaluate the economic performance of solar processes. The operating costs are based on assumed values. Loomans and Visse (2002) used Genetic Algorithm to estimate and optimise the cost of large solar hot water systems based on technical and financial data of the system components. The maintenance cost is based on expected values. Hang et al. (2012) carried out life cycle analysis and estimated life cycle cost of different SWHs configurations in the USA. The initial costs of system components were used to estimate the payback period. The service and maintenance costs were not considered in the study. Higgins et al. (2014) studied the uptake of solar water heaters under different government incentives. Multi-Criteria Analysis and diffusion models were employed to do carry out the assessment. The model takes into account economic drivers such as upfront cost, running cost and demographic suitability. The running costs (maintenance and service) are estimated as a function of expected physical life expectancy of components. For this analysis, they used Weibull distribution to estimated system reliabilities. Koroneos and Nanaki (2012) examined the environmental and economic benefits of utilizing solar water heaters. They calculate the life cycle saving and payback time of SWHs with flat plate collectors in Greece. Net present value was used to assess the economics using a set of assumptions. The maintenance costs were set to 5% of initial costs. Fraisse et al. (2009) compared a number of optimisation criteria to evaluate the techno-economic benefits of domestic solar water heaters in France. They use life cycle cost saving to compare different system configurations. The costs included the initial investment, the annual maintenance and operation expenses, which was assumed at a fixed rate. The study concludes that best results can be achieved by oversizing collector surface areas rather than increasing tank volumes.

Along with the compliance to current standards, the manufacturers work on ways to improve the long-term SWHs operations. Historical data deliver important information on the long-term performance of SWHs operations. This information can be utilised by the manufacturers to model the reliability and long-term economic performance of their systems. This study uses Monte Carlo analysis to estimate the reliability and the economics of SWHs with flat plate collectors based on the historic operating data. The selected Monte Carlo analysis utilises a modified inverse Weibull probability distribution function to estimate the possibility of component failures with regard to operating time. Consequently, the values are translated into a running cost distribution.

The selected system configurations include flat plate collectors, hot water storage tanks made of glass-lined steel, stainless steel and copper and natural gas fired or electric auxiliary heaters. The individual component reliability is modelled based on Weibull distribution. Subsequently, the results are used to estimate the overall system reliabilities and economics. SWHs with glass-lined storage tanks provide good reliabilities as a mainstream technology with proven records.

2. Methodology

This chapter elucidates the the application of Monte Carlo analysis to assess the reliability and the long-term economic characteristics of a locally manufactured solar water heater in Australia. The analysis is based on repair and maintenance data gathered from 1996 to 2011. The selected thermo-siphonic SWHs include a 300 litre rooftop storage tank and two 2 m^2 glazed flat plate solar thermal collectors with selective coating. In practice, this collector type has proven itself as a simple and economic solution to hot water supply in Australia. The collectors are based on riser type configuration using brazed copper tubes on aluminium plates. With regard to storage tanks, three material options are available: Glass lined steel, stainless steel and copper tanks. The systems can be equipped with either electric or instantaneous gas boosters.

Perth (William Street, Perth, WA 6000 Australia) is selected for the location of this study. The latitude corresponds to -32^o. The solar thermal collectors are installed to face north at a tilt angle of 18^o. This orientation will provide daily solar radiations of around 5.87 kwh/m^2. The reliability and the long-term economic assessment in this study are limited to the described product and operating conditions. The results can vary significantly depending on products, brands and operating conditions. The selected distribution function in this study provides a good match for the selected product range and is limited to this study. The distribution of component failures can be significantly different for other product types and operating conditions. With regard to the latter, the boundary conditions are described in section 2.4.

2.1. Reliability modelling

Mun (2006) describes Monte Carlo simulation as a random number generator, which is useful for forecasting, estimation and risk analysis. Monte Carlo analysis makes predictions about stochastic processes through probability models. The collections or generations of relevant and reliable data in specific scenarios deliver probability distribution functions, which is accessed by Monte Carlo to simulate possible results in an uncertain environment. Monte Carlo analysis is widely used in many disciplines such as science, industry and economy to solve complex problems.

We can classify Monte Carlo analysis as a sampling method, which accesses a probability distribution to simulate stochastic processes. The probability distribution for input data needs to match the data, which represents the knowledge base. In short, probability distribution is considered as the main techniques used to implement Monte Carlo analysis. In this study, probability distribution functions were generated based on historic data from a manufacturer of SWHs representing operation and maintenance of their products. The Monte Carlo analysis accesses the probability distribution function to predict possible failures after a certain operation times (failure model), overall system reliabilities (cumulative wear model) and the maintenance costs distributed over the product lifecycle. The reliability engineering can be extended to other areas such as warranty analysis, maintenance and renewal scheduling, material modelling including fatigue tests and corrosion modelling.

The Monte Carlo analysis in this study was performed based on a database provided by a local SWHs manufacturer in Australia. The information in the database contains information about the operation and maintenance of installed SWHs in Australia covering a service period between 1996 and 2011. The database is publically not available; however, we were given the permission to base our study on those trends. To find out the probability of system failures, the data was first classified into individual components, which were replaced or fixed over the operational period. The number of component failures during the product lifetime was used to approximate the probability distributions for reliability and lifetime of individual components.

If we consider the number of failures for component (x) in each time interval during a fixed product life time as a sequence of random numbers ($t_{x,1}, t_{x,2}, \ldots t_{x,n}$), the failure rate for each component will follow the distribution function $f_{x,n}(t)$. Based on $t_{x,n}$ observations, $f_{x,n}(t)$ approximation follows a Weibull distribution.

The Weibull distribution is an important method for reliability assessment, maintenance scheduling and prediction of service intervals. Models based on Weibull distributions are conducive to addressing many important service and maintenance issues and help to resolve trade-offs between competing objectives such as system repair versus replacement, scheduled versus non-scheduled maintenance and corrective action versus inaction (Abernethy, 2010). The classical Weibull probability distribution is given by the following equation.

$$f(t_i) = \frac{k}{\lambda}\left(\frac{t_i}{\lambda}\right)^{k-1}.\,exp\left(-\left(\frac{t_i}{\lambda}\right)^{k}\right) \tag{1}$$

The use of reverse or so-called inverse Weibull distribution was first introduced by Keller and Kanath (1982). The model was proposed to predict the degradation phenomena of mechanical components in a diesel engine. This form of Weibull distribution corresponds to Type-II maximum distribution (Rinne, 2008). Equation 2 shows the probability distribution according to inverse Weibull.

$$f(t_i) = \frac{k}{\lambda}\left(\frac{t_i - a}{\lambda}\right)^{-k-1}.\,exp\left(-\left(\frac{t_i - a}{\lambda}\right)^{-k}\right); t_i > a \tag{2}$$

The above equation supposes a location parameter of zero. For SWHs, however, we need to modify the above equation so that ti is smaller than *a parameter* ($a = t_{max}$). The probability distribution for a failure will occur between t_1 – the start of operation – and t_{max} – maximum SWHs lifetime. The modified Weibull probability distribution is given in equation 3. The integral of the equation will be equivalent to 1 (100% failure rate between t_1 to t_{max}).

$$f(t_i) = \frac{k}{\lambda}\left(\frac{t_{max} - t_i}{\lambda}\right)^{k+1}.\,exp\left(-\left(\frac{t_{max} - t_i}{\lambda}\right)^{k}\right); t_{max} > t_i \tag{3}$$

In comparison to mechanical components, thermo-syphon SWHs do not require many moving parts. This characteristic improves the reliabilities in the initial years. It is assumed that all the SWHs will be replaced after t_{max}. The modified inverse Weibull probability characteristics can be modelled according to equation 4. This distribution follows similar trend to the data recorded in the database showing a distribution skewed more to the right. This indicates higher reliability during the initial operation period. The Maximum Likelihood Estimation (MLE) is an effective method of approximating the distribution parameters. Calabria and Pulcini (1990 and 1994), Murthy et al. (2004) and Sultan et al. (2014) describe the MLE method for inverse Weibull parameters.

$$f(t_i) = \frac{k}{\lambda}\left(\frac{t_{max} - t_i}{\lambda}\right)^{k-1}.\,exp\left(-\left(\frac{t_{max} - t_i}{\lambda}\right)^{k}\right); t_{max} > t_i \tag{4}$$

The scale and shape parameter variations are illustrated in figure 1. The calculation was carried out for 150 time intervals. Larger time intervals result in larger percentage of failures. The area under the curve, however, stays constant at 100% for all the cases.

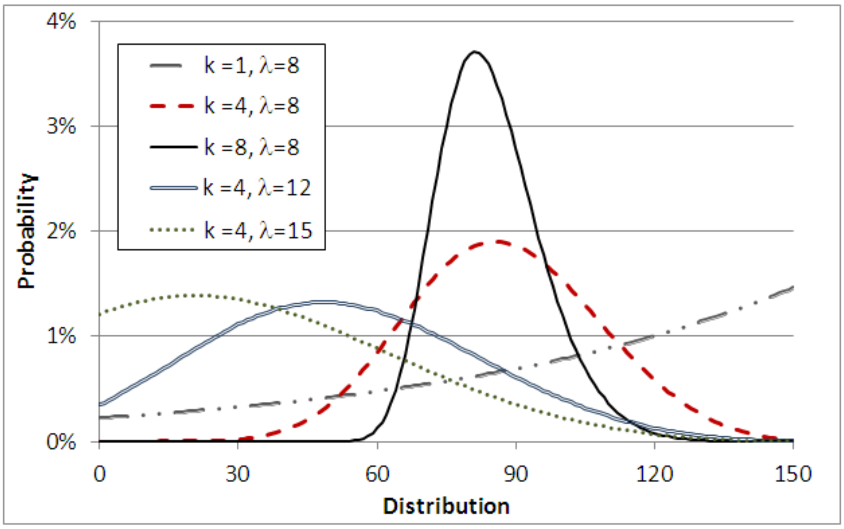


Figure 1: the influence of shape and scale parameter on the probability distribution

The difference between equation 3 and 4 is given in figure 2. The graph shows the failure rates of solar collectors after t_i years of operation. The calculation is done with shape (k) parameter of 2.5 and scale parameters (λ) of 6.5.

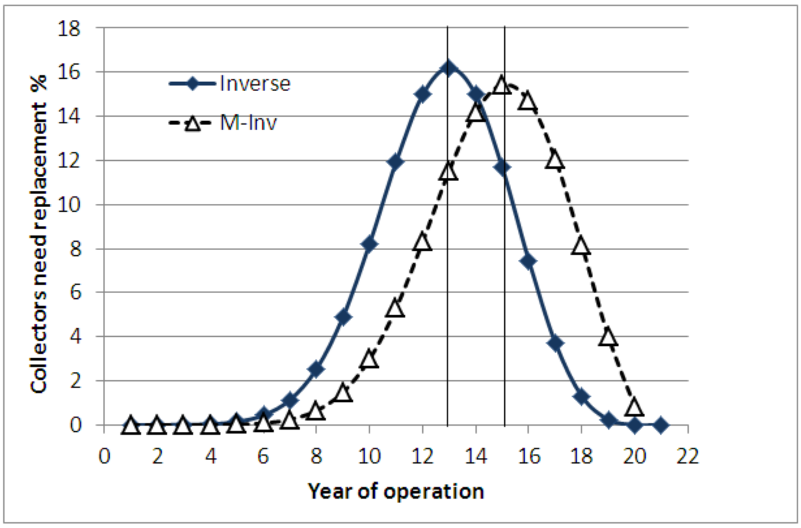


Figure 2: Inverse and modified inverse Weibull distribution for flat plate solar collector components

To change the scale of *f(t)* into percentage, equation 5 is used.

$$g(t_i) = f(t_i) \times 100 \times \left(\sum_{i=1}^{n} f(t_i) \right)^{-1} \qquad (5)$$

For a better service scheduling and failure prediction, it is sometimes more effective to choose shorter time intervals e.g. weeks or months during the product lifetime. The shorter intervals can be converted to longer intervals e.g. years by using equation 6.

$$g(t_j) = \sum_{j}^{m=j+l} g(t_i) \tag{6}$$

The mean value of the Weibull probability density is calculated over the following function (Jiang, et al., 2001):

$$\mu = \lambda.\Gamma.\left(1+\frac{1}{k}\right). \tag{7}$$

The gamma function is given by

$$\Gamma(\mathrm{z}) = \int_0^\infty t^{z-1}e^{-t}dt. \tag{8}$$

The standard deviation can be calculated in various ways. A more convenient approach is to use the factors listed in a table by Abramowitz and Stegun (1964) –see equation 9. The list is given in table 1.

$$\sigma = \sqrt{\lambda^2\left[B_2 - B_1^2\right]} \tag{9}$$

The connection between the above equation and gamma function is given in equation 10 by McCool (2012).

$$B_2 - B_1^2 = \Gamma\left(\frac{2}{k+1}\right) - \Gamma^2\left(\frac{1}{k+1}\right) \tag{10}$$

Table 1: parameters for the calculation of equation 9 and 10

k	*B₁*	$B_2 - B_1^2$
1.0	1.000	1
1.1	0.965	0.771
1.2	0.941	0.62
1.3	0.934	0.513
1.4	0.911	0.435
1.5	0.903	0.376
1.6	0.897	0.329
1.7	0.892	0.292
1.8	0.889	0.261
1.9	0.887	0.236
2.0	0.886	0.215
2.5	0.887	0.144
3.0	0.893	0.105
3.5	0.900	0.081
4.0	0.906	0.065
5.0	0.918	0.044

The estimation of the standard errors for individual estimations is given in equation.

$$s_{\bar{t}} = \frac{\left(\sqrt{\left(\frac{1}{n-1}\right)\sum_{i=1}^{n}(t_i - \bar{t})^2}\right)}{\sqrt{n}} \tag{11}$$

The cumulative probability distribution for failures is given according to equation 12.

$$\Phi(t) = \int_{t_i}^{t_n} g(t).dt \tag{12}$$

The above equations describe the failure of individual SWHs components. To estimate the reliability of the entire SWHs, we take the sum of the failure rates *P(t)* of individual components (*x*) at the time interval t_j according to equation 13.

$$P(t) = \sum_{x=1}^{z} f(t_{x,j}) \tag{13}$$

Based on the above methodology, the probability of main SWHs component failures is modelled. The models show the probability of system failures after a certain period. Equations 1 to 4 is made of two terms, which include reliability function *R(t)* or so-called survivor function (Khan and king, 2012) and the hazard function *h(t)* (Lai, 2014). The latter is an indicator for instantaneous failure rates. A rise in *h(t)* indicates increased vulnerabilities. If *h(t)* decreases with t_i, this means that vulnerability diminishes because weaker system components fail earlier (McCool, 2012). *R(t)* indicates the probability that failure will not occur up to time t_i (Abernethy, 2010).

2.2. Economic assessment

In connection with the economics, two type of operating costs are considered: scheduled and non-scheduled maintenance. With regard to the latter, a fixed cost is spent after certain operating intervals. It is assumed that SWHs will operate reliability within each service intervals. The cost of non-scheduled maintenance follows the probability of component failures. . This scenario may not be representative of individual households, which operate SWHs. However, the probability based costing enables SWHs manufacturers or system installers to plan and estimate the probability of the overall maintenance costs incurring after a period for the non-maintained SWHs. Equation 14 summarises the method of non-scheduled maintenance cost estimation based on the probability of component failures.

$$M(\mathrm{t}_j) = (1 + cont).(1 + DCF)^{t_j}.\sum_{\kappa=1}^{m} f(t_{\kappa,j}).c_{\kappa} \tag{14}$$

The total maintenance cost for non-scheduled services over the product lifetime is given according to equation 15.

$$TMC_{NS} = \sum_{j=1}^{n} M(t_j) \tag{15}$$

Equation 16 on the other hand provides the estimation for scheduled maintenance. The maintenance costs depend on the scheduled service requirements suggested by the SWHs manufacturer. The service cost c_j is equivalent to zero in years, where there are no services scheduled.

$$TMC_S = (1 + cont).\sum_{j=1}^{n}\left((1 + DCF)^{t_j}.c_j\right) \tag{16}$$

The thermal cost for using SWHs in \$/kWh is given in equation 17. The calculation can be done separately for TMC_{NS} and TMC_S. The results can be compared to see, which service programme to select. The utilisation factor reflects the exploitation level of the SWHs. The value is usually one ($U_{solar}=100\%$) if $c_b >0$. In case of partially occupied premises, the utilisation factor can be lower even if solar energy can satisfy the load demand ($c_b=0$).

$$c_{Therm} = \frac{TMC + CC - R}{E_{solar}.A_{SP}.\eta_{solar}.U_{solar}.d.n} + c_b \tag{17}$$

The energy costs for running boosters are calculated according to the equation 18. If U_{solar} is below 100%, the booster will supply the additional thermal energy to the hot water system. An Annual Booster Usage Rate (ABUR) of 0 means that booster is not in use and SWHs are able to cover entire thermal requirements. This equation can also be used to calculate the energy cost for the conventional water heaters if ABUR is set to 100%. ABUR is the capacity factor of the booster given as a percentage of the energy supplied by the booster (100% -ABUR = energy supplied by SWHs).

$$c_b = \left(n.\varepsilon_{booster}\right)^{-1}.c_{fuel}.ABUR\sum_{j=1}^{n}(1 + DCF)^{t_j} \tag{18}$$

The capacity factor is the ratio of the difference between thermal load requirement and the useful energy, which can be exploited by the SWHs (L-ES_{WH}) to thermal load requirement (L). This parameter provides indications on the amount of energy, which needs to be provided by additional heating e.g. through electric or natural gas boosters.

$$ABUR = \frac{L - \left(E_{solar}.A_{SP}.\eta_{solar}.U_{solar}\right)}{L} = \frac{L - E_{SWHs}}{L} = \frac{G}{L} \tag{19}$$

The specific cost for conventional water heater (boiler) in \$/kWh is calculated according to equation 20. Equation 18 can be used for the estimation of c_{fuel}. However, *ABUR in equation 18* has to be set to 1 (100%).

$$c_{boiler} = \frac{(1 + cont).\sum_{j=1}^{n}\left((1 + DCF)^{t_j}.c_j\right) + CC_{boiler}}{E_{boiler}.d.n.\varepsilon_{boiler}^{-1}} + c_{fuel} \tag{20}$$

2.3. SWHs selection criteria

Flat plate solar thermal collectors are the main type of solar collectors used for domestic water heaters in Australia. The information provided by the local SWHs manufacturer is also limited to this type of collector, which is used for this case study. The performance of flat-plate collectors is achieved through a selective coating and antireflective glazing to maximise the conversion of solar radiations into heat. The selective coating allows the effective transmission of short wave solar radiation into heat through dark paints, while reducing the emission of the long-wave heat radiation from the absorber itself through low emissive selective coating. The glazing consists of a low iron glass type to maximize solar radiation transmitted to the absorber. The flat plate collectors have usually efficiencies between 50 and 60% (Faninger, 2012). Flat-plate collectors are in general robust and have long lifetimes, if the operating conditions are within the designed limits. The main issues with collectors relate to the improper installation and system operations. Partial shading, inadequate orientation and tilt, undersized collector size, inept pluming and dirty glazing are among the possible causes (Ramirez-Vargas, 1998).

The performance and reliability tests for collectors are covered by ISO 9806. Laughton (2010) provides the details for testing collectors. The aging process is one of the important factors affecting the performance of collectors. Wu (2013) examined the thermal aging characteristics of CrNxOy solar selective absorber coating used flat plates collectors. His examination shows an interfacial diffusion of copper into CrNxOy coatings causing the chemical formation of copper oxides. This interaction increases the emissivity of the coating (Barshilia, 2008). High temperature further accelerates aging and can induce microstructure degradations.

Alshamileh (2010) suggests a coating based on nickel–aluminium (NiAl) alloy mixed into black paint. Apart from a better system performance, the metallic particle coating has shown better resistance against corrosion. Grupp (2012) highlights that high performance materials and components do not necessarily contribute to system reliabilities. Many designs, which are aimed to achieve high performance characteristics, suffer from temperature stagnations and prohibitive pressure accumulations in the system. This condition exacerbates during the hot summer holiday seasons when the hot water is not used. It is imperative to avoid such conditions by venting off steam instead of superheated water and, if necessary, by allowing collectors to run dry. The provision of a buffer tank with sufficient size can further help preventing temperature and pressure peaks, while also improving the performance (Peuser, 2011).

The hot water storage tanks examined here work on the principle of thermo-syphon circulation, which is based on natural convection. Three types of materials are considered in this study: 1. glass lined, 2. stainless steel and 3. copper storage tanks. The quality and performance of storage tanks in Australia is regulated by AS 1056 standards (part 1 to 3). The thermal performance tests of storage tanks are implemented according to AS/NZS 4692.1. (EEE, 2014). Water quality is an important factor, when it comes to the reliability and durability of hot water storage tanks and the complete solar hot water systems. The level of corrosion and scaling of tanks and other parts depends on factors such as the total dissolved solids (TDS), pH value and water hardness.

Stainless steel and copper storage tanks tend to have a longer life where the water quality is good. In particular, copper storage tanks can fail prior to designed lifetime if the water temperature, pressure and quality levels are not within the designed operating conditions.

Vitreous enamel (glass) lined storage tanks are selected in regions with poor water qualities. These types of storage tanks are made of mild steel with a thin glass-line coating inside. Corrosion can still be a potential problem due to damages caused by overheating and pressure build-ups. Sacrificial anodes are commonly used with glass-lined tanks to increase the lifetime. They are based on magnesium with smaller percentages of manganese, aluminium or zinc. The total dissolved solids are attracted to the sacrificial anodes instead of attacking the tank itself (DCCEF, 2010). Sacrificial anodes require periodic replacement (Cooper, 2013). In general, glass-lined tanks are less expensive than stainless steel tanks but have shorter life times and require higher operating costs.

The chemical and physical properties of stainless steel depend strongly on the composition and molecular structure of materials. With regard to the latter, stainless steel can be categorised in ferritic, precipitation hardening, martensitic, austentic and duplex. The composition contains various percentages of alloying agents such as carbon, chromium, nickel and molybdenum. For hot water applications, austenitic (304L and 316L) and Duplex stainless steels (2205 and 2304) are the most common alloy types (O'Brien, 2014). The passive film created on the surface of metal makes the material resistant against corrosion. However, chromium can gradually leach out from the alloy to react with carbon in form of carbide. This condition makes the steel vulnerable to corrosion. On this ground, low carbon steel is preferred for this application. The presence of chlorides in hot water storage tanks is another important factor, which limits storage tank durability. Chlorides attack stainless steel materials and can gradually cause stress corrosion. Insulation materials represent the main source of leachable chlorides (O'Brien, 2014).

Copper, on the other hand, is more inert against chlorides attacks. In the Building Code of Australia, stainless steel and copper are specified as better materials for storage tanks. They withstand high water pressures and temperatures (Wilkenfeld, 2009). However, compared to stainless steel, the yield stress of copper is lower. To compensate for the lower yield stress, the storage tanks require thicker material walls. This affects the economics of copper storage tanks significantly.

ISO 9459 test standards examine the complete performance characteristics of SWHs. The tests cover daily solar radiation range between 8 and 25 MJ/m^2. The water supply temperature is given in relation to the ambient temperatures. The standard specifies a water storage temperature of above 60 ^{o}C. The overnight heat loss should not affect the value. The required durations for different tests are given in five parts of ISO standards (Morrison 2013). These parts of the ISO standards cover both whole and component tests at different conditions in outdoor or indoor environment (Simulations). ISO 9459-4 describes the procedures for the characterisation of components such as hot water storage tanks and heat exchangers. ISO 9459-5, on the other hand, specifies the whole system tests without any consideration of system components. ISO 9459-1 describes indoor tests of SWHs operating on different circulation regimes without auxiliary boosters at identical ambient conditions. ISO 9459-2 relates to both solar only and preheated system tests at a given range of operating conditions and loads. The annual performance of systems with supplementary components is tested according to ISO 9459-3 for a given load pattern. Apart from performance tests, the reliability of the SWHs is also tested.

Fraisse (2009) performed a comparative study of various optimization criteria for SWHs. The exergy optimization based on the heat entering the solar thermal collectors suggests high flow rates and large collector areas connected to a large tank. This approach also reduces potential overheating of the system and minimises the use auxiliary heaters. On the other hand, the exergy optimised system suffers from high thermal losses and requires a higher initial investment, which affects the pay-back time. Accordingly, the highest exergy efficiency is not always the most advantageous solutions. Economic factors need also to be considered in the design.

A large collector area connected to a relatively small hot water storage tanks is the main cause of system overheating. Marken (2011) suggests 82 litres of storage for each square meter of collector in the warm and dry South-Western United States. Large storage capacities, however, need more time to warm up; they are more expensive and require more space. To reduce overheating, a number of measures are considered in the design such as drain-back systems, collector surface cover, check-valve bypass, vacation mode controller, tilt considerations, finned tube radiator and heat dump to other sources.

Frost can be a potential problem in parts of Australia. Similar to overheating protection, drain-back design can be adopted to empty the collector during the frost. In temperate zones with infrequent frost possibilities, frost dump valves can be installed to mix warmer water from the storage tank with the cold water in the collector. The disadvantage of this configuration is the heat loss from the storage tank (Ramlow, et al. 2010). The indirect heating approach through a primary circulation with glycol-based anti-freeze is applied in cold regions of temperate zones with frequent frost conditions in winter. This condition is not relevant in Australia.

2.4. Boundary conditions

Based on the methodology highlighted in previous sections, a number of scenarios are examined. The systems selected use 4 m^2 flat solar thermal collectors connected to 240 litre roof top storage tank. All systems work on the principle of thermo-syphon. The Monte Carlo analysis is carried out for all three storage tank materials. However, the economic analysis is limited to the most reliable storage tank. We also consider electric and natural gas fired boosters.

The daily solar radiation selected in this case study corresponds to the Perth region in Western Australia (Carson, et al., 2014; Otilt, 2015). Table 2 shows the maximum resource availability for the selected case study. We assume that the system is optimised and well integrated to satisfy all the hot water requirements.

Table 2: Main assumptions for SWHs

Location	Perth/ Australia	
Annual Radiation	2142	kWh/m^2
Daily Radiation	5.87	kWh/m^2/day
Flat plate solar collector area	4.00	m^2
Daily energy available	23.47	kWh/day
SWHs efficiency	60	%
Thermal energy utilised	14.08	kWh/day
Total annual thermal energy	5140	kWh/year

Table 3 shows the shape and scale parameters used for different SWHs components. The values were derived according to MLE method. The table also provides the estimations for mean (see equation 7) and mode values (the year with highest failure rates). Since the data is skewed to the right, the mode values are larger. The standard deviation in this example is only a rough measure on variability around central values (see equation 9). However, since the data is skewed, it is not an adequate measure for probability assessment.

Table 3: Scale and shape parameters used for the Weibull probability distribution including the estimation of mode, mean and standard deviation

	λ	k	Mode (years)	Mean (years)	St. dev. (years)
Collector	6.5	2.5	15	10	2.5
Glass-lined ST	7.5	3	12	9	2.4
SS ST	7	3.5	10	8	2
Copper ST	10	5	7.5	6	2.1
E. Booster	6.5	2.5	15	10	2.5
Gas Booster	8.2	5	7.6	8	1.7
Valves	6	2.8	10	7.5	2.2
Misc. Parts	5.7	3	10.7	7.5	1.8

The assumptions for the economic analysis are given in table 4. The table provides the size of installed system and the main economic parameters.

Table 4: The economic data of the selected SWHs

Discounted Cash Flow rate (DCF)	6.00	%
Contingency on maintenance	15.00	%
Storage tank	300.00	litre
Number of solar thermal collectors	2.00	2 sq. m each
Life time	20	Years
Cost of SWHs with GL-tank	4,400.00	Australian $ (A$)
Cost of SWHs with SS-tank	5,100.00	A$
Cost of SWHs with C-tank	4,700.00	A$
Additional cost for a gas booster	500.00	A$
Rebate	-1000.00	A$

The cost for scheduled maintenance amounts to A$500 (Australian dollars) for every 3rd year. A major service is scheduled for year 10. The cost of the major service is A$750. The scheduled maintenance provides a guarantee for smooth and reliable operation. In contrast, the non-scheduled maintenance corresponds to the probability of system component failures. The service cost depends on components, which need to be fixed or replaced. Table 5 shows the cost for replacing parts as part of the non-scheduled maintenance scheme.

Table 5: Cost of changing the SWHs parts

Solar thermal collector cost	950.00	$ each
Cost for changing the collector	175.00	A$
Cost of glass-lined tank	2800.00	A$
Stainless steel tank	3600.00	A$
Copper tank	3100.00	A$
Cost of changing a tank	330.00	A$
Valves changed	250.00	A$ labour included
Electric booster changed	250.00	A$
Gas booster changed	700.00	A$
Misc. maintenance costs	350.00	A$

If the SWHs are not able to cover the entire thermal load demand, the additional thermal energy needs to be provided by a booster. The main data on the electric and gas booster operations in connection with the selected SWHs are given in table 6.

Table 6: Economic data for the electric and gas boosters

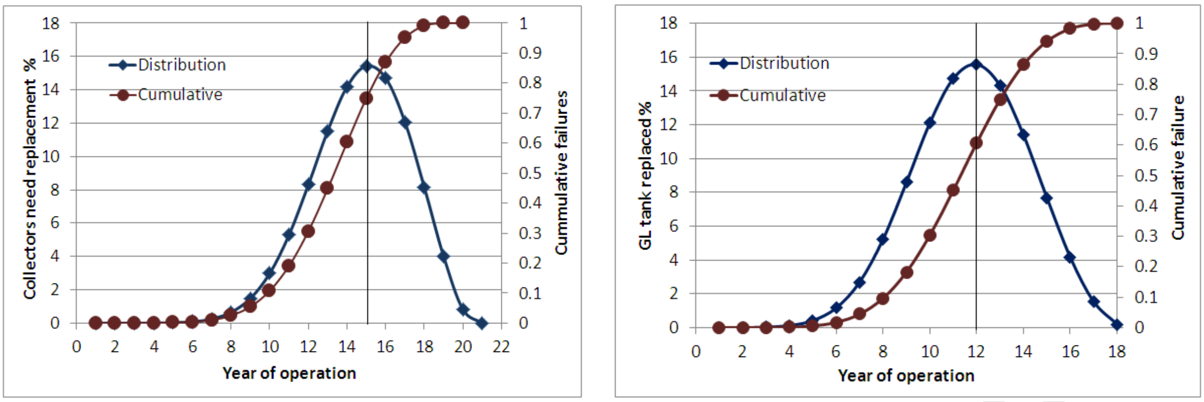
Gas heater efficiency	0.83	%
Supply charge for gas (not considered)	74.14	A$/year
First 12 units	14.01	Cent/kWh
Over 12 units	12.64	Cent/kWh
Gas tariff	1.94	A$/day
Total natural gas charges over a year	855.06	A$/a
Electric heater efficiency	90	%
Supply charge for electricity (not considered)	172.22	A$/year
Electricity charge per unit	25.70	Cent/kWh
Total electricity charges	3.62	A$/day
Total cost of electricity over a year	1467.9	A$/a

3. Results and discussion of MC analysis

According to the Weibull distribution, collectors are the most reliable part of the SWHs. The analysis, however, only covers operations according to the boundary conditions and excludes issues related to installation and possible physical damages e.g. through handling or hail impacts. Most issues with collectors are related to improper installations and maintenance works such as partial shading, inadequate orientation and tilt, wrong collector sizing, unprofessional pluming and dirt depositions. National and international standards such as ISO 9459, EN 12975 and AS/NZS 2712 ensure high collector performance characteristics and system reliabilities through tests such as internal pressure assessments, leakage tests, material degradations and mechanical load tests; high temperature tests and exposures to harsh conditions. Figure 3a illustrates the percentage of flat-plate collector failures due to the age. The mode value is around 15 years. The number of failure decreases after this point because of the reduction in the number of remaining collectors, which are still intact.

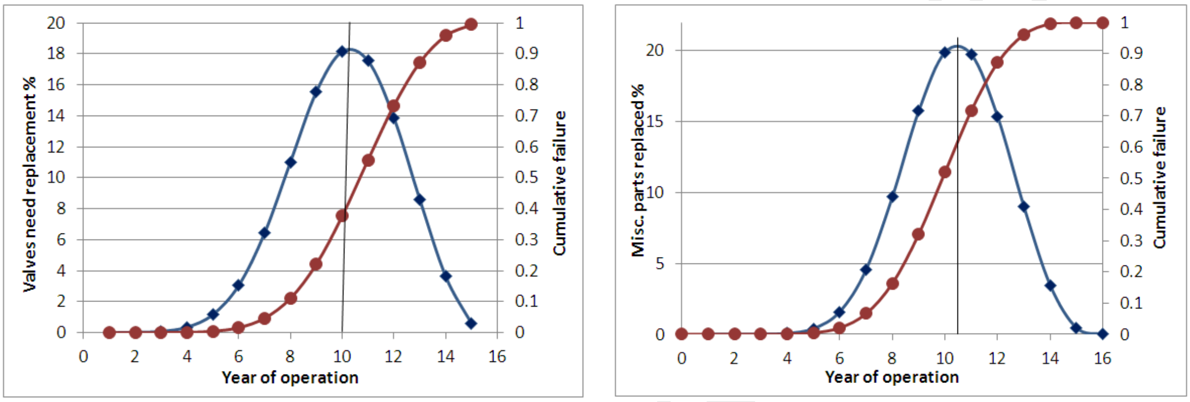
Figure 3b shows the failure rates for glass-lined storage tanks. Vitreous enamel (glass) lined storage tanks are usually robust in areas with poor water qualities. However, they need periodic maintenance. What is important here is the regular replacement of sacrificial anodes. Without this care plan, the product lifetime can be considerably affected. The Weibull graph for the glass-lined storage tanks is shown in figure 3b. The cumulative probability function in figure 3 shows the total amount of component failures with time.

The valve set consists of pressure limiting valve for incoming water (AVG PLV 15500F), Pressure reducing valve for water supply (Caleffi 533555), Safety Pressure Relief Valve (Caleffi 2.5 Bar) and fitting elements such as socket reducer, inline reducer and brass connections. The lifetime of the valve sets is estimated between 6 to 14 years. According to the probability density (see figure 3c), most valve sets requires replacement after 10 years. Other parts and accessories such as pipes, mounting elements, connection points and electrical wiring usually require some sort of maintenance after 7 to 14 years (see figure 3d). Although the probability of valves and accessories are higher than that of collectors and storage tanks, the cost impacts are considerably lower.



a. Flat plate collector

b. Glass-lined tank



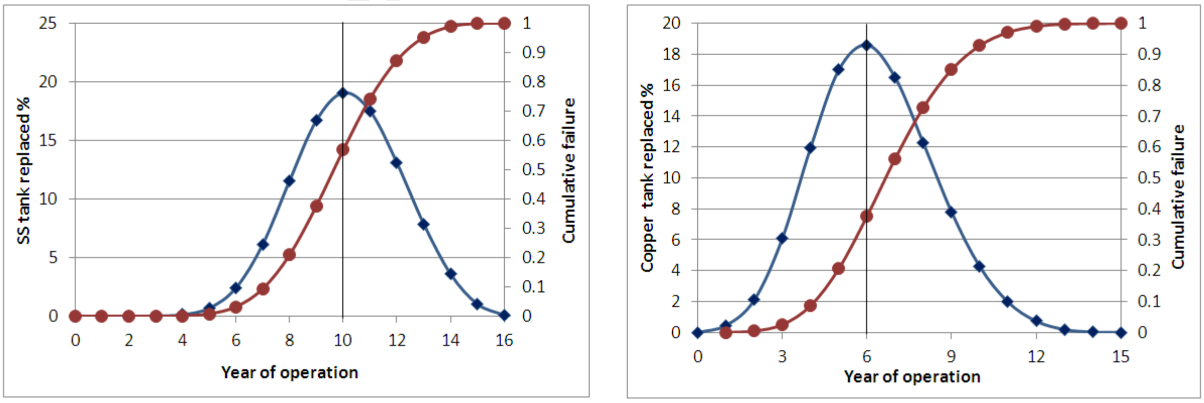
c. Valves

d. Miscellaneous parts

Figure 3: The reliability of the investigated SWHs parts

The reliability of stainless steel and copper storage tanks are illustrates in figure 4a and 4b. Stainless steel tanks are very durable where the water quality is good. Chlorides, for example, can attack stainless steel materials and cause stress corrosion. Moreover, the composition and molecular structure of stainless steel can affect the physical and chemical properties of the material.

Copper storage tanks can also be very dependable as open vented systems. However, due to pressure issues, this product configuration is not very popular. Operations at medium to high pressures, on the other hand, can significantly reduce the reliability rate.



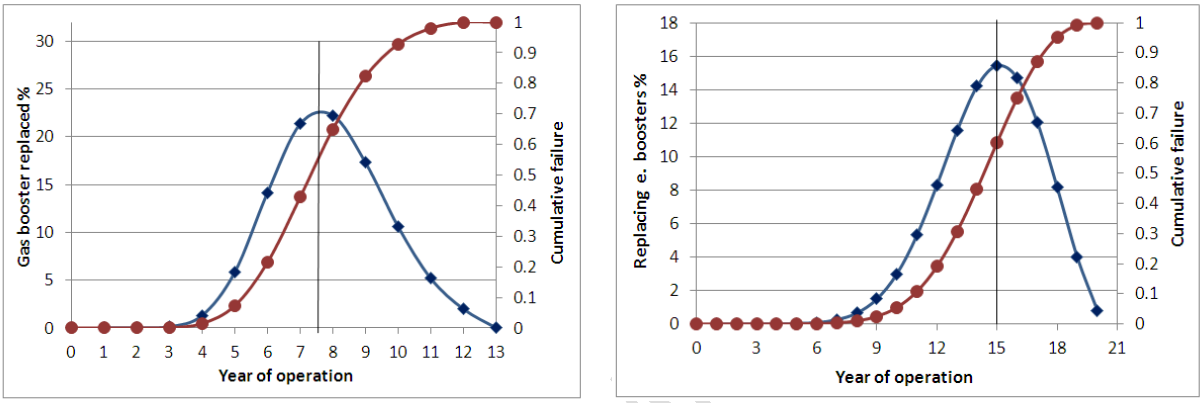
a. Stainless steel tanks

b. Copper tanks

Figure 4: The reliability of stainless steel and copper storage tanks

The reliability of gas and electric boosters are shown in figure 5a and 5b. The experience has shown that in-tank electric backups are more reliable and cheaper to install. They are, however, more expensive to run and have larger carbon footprint. Main issues with electric boosters are related to electricity interruption to heating elements followed by control system malfunctioning such as faulty thermostats and high temperature cut off points. The heating elements can also fail after a certain operating time. The replacement costs of electric heating elements are relatively low.

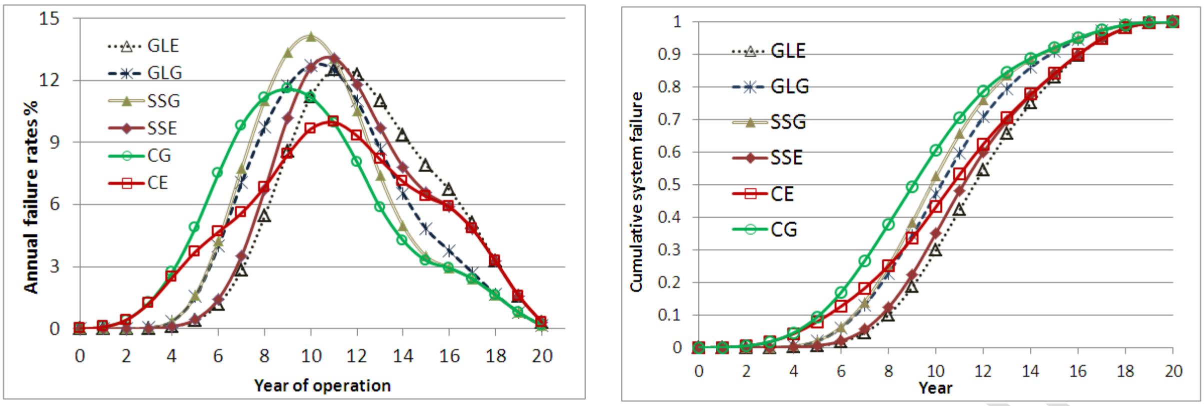
SWHs with inline instantaneous gas boosters are more expensive and more susceptible to failures due to larger numbers of mechanical parts and thermal elements. On the other hand, gas boosters are cheaper to run and emit less greenhouse gases. Main problems with instantaneous gas boosters are connected with electronic ignitions, clogged burners and hot spots in heat exchangers. Water quality can also affect the operation of gas boosters. A further issue with gas burners are the inadequate installations. Many connection points in homes are fitted with gas pipes, which are smaller in diameter than those required by gas boosters.



a. Gas booster b. Electric booster

Figure 5: The reliability of auxiliary heaters (boosters)

Based on the failure rate of individual system components, the overall system reliabilities are calculated according to equation 13. Figure 6 shows the frequency of failures during 20 years of operating time. The graph, however, does not show the impacts of maintenance costs. This will be discussed in the next section. The products are SWHs with following configurations: a. glass-lined storage tanks and electric booster (GLE), b. glass-lined storage tanks and instantaneous gas booster (GLG), c. stainless steel storage tanks and gas booster (SSG), d. stainless steel storage tanks and electric booster (SSE), copper storage tanks and gas booster (CG) and copper storage tanks and electric booster (CE). According to figure 6a, the probability of failure for copper tanks is higher in the first years than other systems. The mode values for all the systems are around 9 to 11 years. Figure 6b illustrates the cumulative system failures. According to the graph, 30% of all the SWHs products with glass-lined storage tanks and electric boosters will face some sort of component failures within 10 years of operation. In comparison, the failure rates for systems with copper storage tanks and gas boosters culminate to 60% after 10 years of operation. All the other values are between these two failure rates.



a. Annual failure rates b. Cumulative possibility of failures

Figure 6: Possibility of failures for selected SWHs configurations (GLE: SWHs with glass lined storage tank and electric booster, GLG: SWHs with glass lined storage tank and instantaneous gas booster, SSE: SWHs with stainless steel storage tanks and electric booster, SSG: SWHs with stainless steel storage tanks and gas booster, CG: SWHs with copper storage tanks and gas booster and CE: system with copper storage tanks and electric booster)

4. Economic assessment

The maintenance and capital costs constitute the main expenses for operating SWHs. With regard to the former, the cost estimation can be carried out using scheduled or non-scheduled maintenance. The latter consists of A$500 service fees, which incurs every three years, and A$750 major service after 10 years. All the costs are subjected to a discounted cash flow rate of 6% and a contingency level of 15%.

Non-scheduled maintenance cost is a function of cost to replace or repair a part and the probability of the failure for the corresponding part. Equations 14 and 15 are used to spread the maintenance costs over the 20 years of SWHs operating time. Similar to scheduled maintenance, we use a DCF of 6% and a contingency level of 15%. Figure 7 shows the maintenance cost distribution for different system configurations. In comparison, figure 6 shows the frequency of failures without any reference to cost impacts. This explains the discrepancy between the two figures.

SWHs with copper tanks are more expensive to run, because of relatively high replacement or repair probabilities of around two storage tanks during 20 years lifetime. Due to a lower material yield stress, copper tanks fail earlier when there are pressure fluctuations in the system. Since glass-lined storage tanks are among proven technologies and are well established products in the market, they are usually considered more reliable and demonstrate better cost distribution during the product lifetime. Therefore, the economic assessment in this paper will be from this point only limited to SWHs configurations with glass-lined storage tanks.

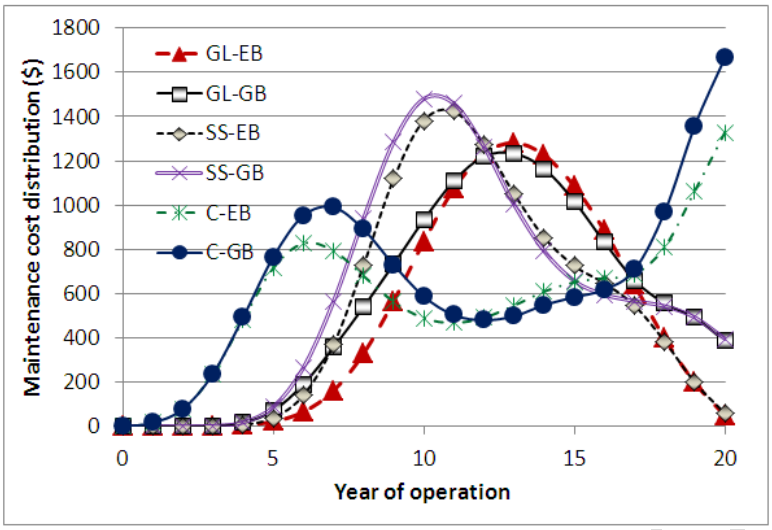


Figure 7: Distribution of maintenance costs according to possible annual failure rates.

Based on equation 17, the thermal cost of providing hot water per kWh is determined. The calculation is implemented using a ABUR variation between 0% (no booster used) and 80% (the energy provided by the booster = 80%) for both scheduled maintenance and non-scheduled maintenance. The main assumptions for this calculation are provided in table 4 and 5. Figure 8 shows specific cost of thermal energy in cent/kWh. Removing the government rebate of $1000 per installation increases the thermal cost by 0.97 cent/kWh for all data points. The horizontal line at 35.7 cent/kWh shows the specific cost of hot water supply based on conventional natural gas water heater systems. The intersection between this line and that of specific SWHs costs at different ABURs signifies the the viability of SWHs operations. According to figure 8, SWHs are economically more advantageous if only 37 to 44% of thermal load is provided by boosters in connection with non-scheduled and schedule maintenance scheme respectively. In comparison to conventional water heaters, around 68% to 56% cost reduction can be achieved at an ABUR of 0% depending on maintenance schemes. However, SWHs can be more expensive to run if they are not properly installed. Incorrect orientation, improper tilts and partial shadings are among the main issues.

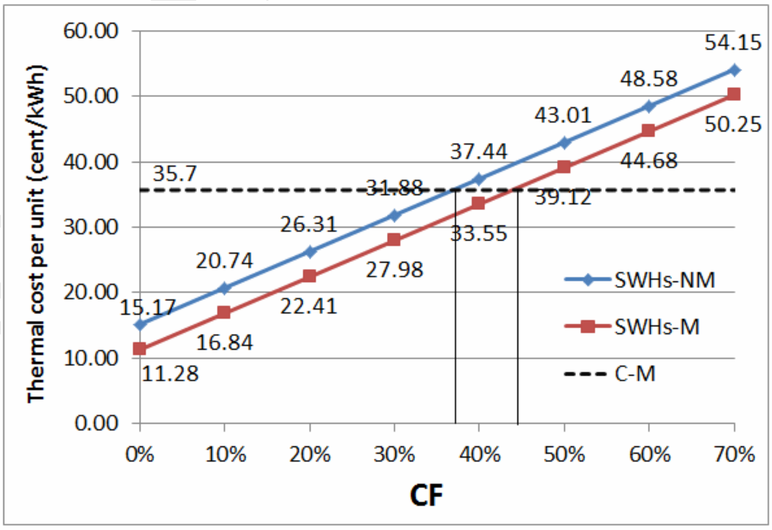


Figure 8: Economic analysis of SWHs with glass-lined storage tanks and electric boosters at different ABURs

In contrast to the above case, SWHs with natural gas boosters have slightly lower economic benefits if the boosters are not used. However, they are more advantageous if ABUR is higher. This is because of the lower natural gas prices compared to electricity tariffs. Figure 9 shows the specific cost of hot water supply (cent/kWh) in connection with different ABURs. SWHs with natural gas boosters have the potential to provide better techno-economic performance characteristics than conventional natural gas water heaters if the booster operations are below 55% and 73% for non-maintained and maintained systems respectively. Without the government rebate of $1000 per installation, the thermal cost increases by 0.97 cent/kWh for all data points, similar to the SWHs economics with electric boosters. This cost reflects the additional expenditure spread over 20 years of operation.

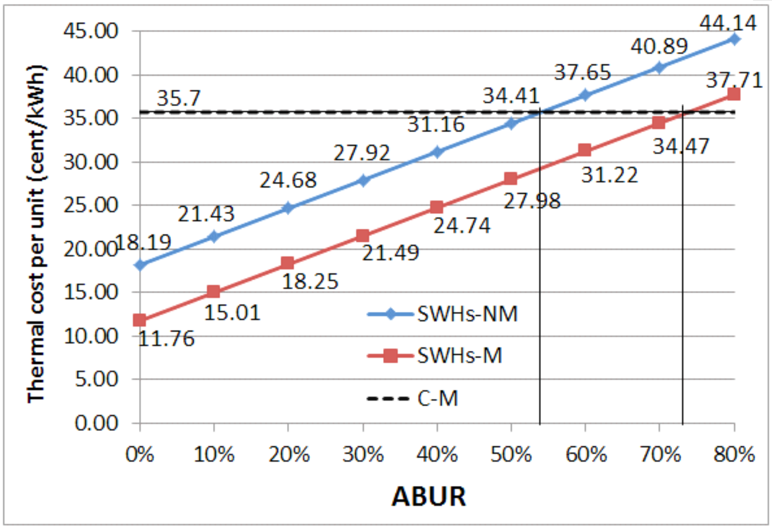


Figure 9: Economic analysis of SWHs with glass-lined storage tanks and gas boosters at different ABURs

Our calculations have shown that if innovations were able to reduce the capital cost of supply and installation by 30% the specific thermal cost would be reduced to less than 10 cent/kWh for the regularly maintained system with electric boosters. The value for a system with a gas booster will be around 10.33 cent/kWh. The above figures correspond to reductions of 11% to 12 % of specific thermal costs. An overall savings of 24% can be achieved if the part and maintenance cost can be reduced by around 30%. The thermal cost can be cut by 32% for not-maintained system and 35% for regularly maintained SWHs if both capital cost and maintenance cost could be reduced by 30%.

In looking at the four main seasons, we estimated that a standard family using a standard 300 litre/4 m^2 solar thermal collector system with a hot water consumption of 200 litres per day would require 35% (5.5 kWh/day) boosting in June, 31% (4.8 kWh/day) in July, 23% in May (3.5 kWh/day) and 10% (1.5 kWh/day) in August. The heat loss coefficients for the tank and piping (20 m) used in the calculation are 1 W/m^2K and 1.5 W/m^2K respectively. Extending the calculation over the whole year, the amount of boosting will be around 5 % (ABUR = 5 %).

In the above example, the unused solar energy is around 41%. The difference between the solar energy availability (E_{solar}) and the thermal energy load (L) can be significant during late spring, early autumn and summer months ($E_{solar} >> L$). The annual values are usually high if SWHs are designed to minimize ABUR. Accordingly, the optimization issue with SWHs is to offset the overall solar energy capture against the dissipation of unused thermal energy.

A significant decline of performance in high cloud cover winter months presents a further problem in this case. In contrast to flat plate collectors, PV cells as a source of solar energy collection will still provide substantial percentage of rated capacity from the total winter day radiation. A higher overall efficiency could be achieved through a more flexible use of PV panels either indirect or direct via induction heaters or heat pump systems.

Apart from delivering higher cost efficiency of collectors and tanks, the industry could apply innovations in the future that will drive costs down even further, and possibly eventually reducing the need for government rebates.

However, it is obvious at this stage of technology development that the standard flat plate collector SWHs are still a better economic and environmental solution to standard gas or electric storage systems over a 20-year lifetime.

5. Conclusions

Based on the historical data provided by a manufacturer of SWHs in Australia, the probability of component failures were modelled in this paper using Monte Carlo analysis. The modified inverse Weibull probability distribution was found to be a good method of representing the data. The overall system reliability was determined on the basis of the individual system component failures. Six different system configurations were identified using copper, stainless steel and glass-lined storage tanks along with electric and natural gas boosters. The generated probability model was conducive to estimating the non-schedule maintenance costs of SWHs. The maintenance costs along with capital expenditures and fuel charges for operating the boosters were used to calculate the specific price of hot water supply for different system configurations. The result shows that SWHs can be techno-economically superior to conventional systems at certain ratios of booster operations.

On the long term, Solar Water Heaters are from an economic point of view more attractive than conventional fossil fuel operated water heaters, if the boundary conditions are right. In this case study, the specific cost per thermal unit is more than 40% lower than natural gas operated system in connection with a regularly maintained Solar Water Heater with an electric booster. The annual booster usage rate (ABUR) does usually not exceed the 20% mark in Perth area if the system is properly installed. Solar Water Heaters with instantaneous natural gas operated boosters show more than 50% lower specific costs. The values are based on the boundary conditions specified in this manuscript. The location factor in Australia can affect the economics considerably. Lower radiation in Tasmania, for example, will result in smaller economic benefits. Due to a higher boosting rates and lower radiations the economics are only marginally improved for systems with electric boosters. Solar Water Heaters with gas boosters can still offer 20% to 30% cost savings.

With regard to technical aspects, the industry needs to focus on improving reliabilities. Innovative technologies and new system configurations can help to reduce maintenance intervals, circumvent valve failures, and solve corrosion issues and metal fatigues. Apart from emission reductions and fuel savings, the environmental performance of Solar Water Heaters can be improved through end of life recyclability and sustainability of production and system operation from the cradle to grave.

The future of SWHs market depends on the development of more versatile, reliable and efficient designs at reduced costs. The innovation in material development and selection is a crucial step. Low weight and flexible materials with durable properties are conducive to an economic and faster production process. Engineering and high performance polymers such as polycarbonate, poly methyl methacrylate and polyamide-imide are interesting materials, which can be operated at high temperatures [Kohl, et al., 2012]. However, more tests are required to prove long-term reliabilities under different conditions. With more specific data from industry, the methodology and computational technique described in this work could be applied to give the industry better predictions of the economic worth of their particular technologies. Apart from material development and selection, alternative designs need to be tested for Australian conditions. Future technologies can combine various elements to improve reliabilities, cost and efficiencies.

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