Hot water: systems design analysis for an off-grid household

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May 24, 2015

Abstract

Systems design techniques were used to develop a procedure to facilitate the selection of a suitable HW system for a given household. In particular, off-grid households were considered, since their requirements are more complex. For the given case study (a 4-person off-grid home in the Canberra region with an existing passive solar thermal heater), it was found that the design requirements would be met most closely by installing an add-on gas storage booster with a predictive temperature control system.

1 Motivation

Heating water accounts for 21% of household energy usage, making it the second most significant single form of residential energy usage after space heating (Riedy, Milne & Ryan 2013). Offsetting this using renewable energy is an easy way to lower one's carbon footprint and energy costs. Systems analysis of hot water (HW) systems for ENGN2226 in 2014 found that significant non-renewable energy must be used annually for solar thermal systems to operate to Australian standards (Schneider 2014). Off-grid households often have a niche setup, with electrical power and pressure limitations that do not exist for grid-connected households, which can make meeting these standards a particular challenge. This portfolio outlines a general systems design methodology (including detailed testing procedures) that will facilitate the selection of a hot water system suitable for off-grid use. This will be done a particular case study for context and practical clarity.

2 Problem Statement

A family lives in an off-grid household near Canberra which currently uses a solar thermal HW system to heat water for 4 people. It performs poorly in the winter months when sunlight is limited and ambient temperatures are low because it does not use an electric or gas booster. During this time, the water is an unsatisfactory temperature for general use and does not comply with the Australian Standard (Standards Australia 2009) for the prevention of legionnaires disease (Schneider 2014). The system has now exceeded its payback period (Schneider 2014), and the owner of the household is looking to alter the system at relatively low upfront cost/inconvenience. However, he is finding it difficult to find a suitable solution due to the constraints on the system primarily imposed by limitations in electricity usage.

3 Problem Scoping

Broadly, the aim of this project is to recommend the best course of action in improving the existing hot water system, and to describe and evaluate its functionality against the design requirements. A use case diagram (Cockburn 2001) presented in appendix A formalises the context and deliverables of this portfolio as described in section 1.

3.1 System boundary chart

The system boundary is defined in table 1. It shows that a relatively broad view of the HW system is taken; clearly elements such as the tank, heater, and control systems are endogenous, but there are many exogenous variables which affect how the HW system interacts with the broader off-grid system. Many forms of energy may be leveraged to heat water; the renewable resource (which fluctuates seasonally) can be a direct input to the HW system. The household's electrical system is based on photovoltaics (PV), which uses the solar resource and may input electrical energy to the HW system, either for heating or control. A header tank supplies the water to the HW tank, from which the members of the household draw hot water. Standards Australia (2009) outlines a number of requirements for HW systems; those that relate directly to water temperature and energy usage are included exogenously, and the others are assumed to be met, since this portfolio focuses on choosing the best HW system to implement within the broader off-grid system, rather than on designing a new HW system from scratch. It is assumed that the supply of water is infinite (the household has never come close to running out), and variables with little effect on the system such as humidity and seasonal and low-volume usage are also neglected.

Table 1: HW System boundary chart

Endogenous	Exogenous	Excluded
HW tank	Seasonal renewable resource	Water supply
Heating system	PV generator	Low-volume usage
Water pressure	PV battery storage capacity	External humidity
Internal water temperature	External water temperature	Seasonal usage fluctuations
Active control system	Australian Standards (legionella)	Final water pressure
Passive control system	Header tank	Final water flow rate
	Non-renewable energy resources	Plumbing design
	Daily HW demand	Safe failure mechanisms
	Australian Standards (scalding)	Water contamination
		Plumbing integrity

4 Requirements Analysis

Design requirements and their rankings are based on Australian standards for hot water systems (Standards Australia 2009), and on the means and outlook of the particular client. The relationship between energy usage, ongoing cost, reliability, and safety are the main points of interest in this case. The system should be safe (in terms of control of legionella bacteria, which can cause legionnaires disease), and provide water temperatures suitable for use all year round. To do this, additional energy may need to be provided by the standalone PV system; in this case, steps must be taken to ensure this system does not fail for the same reasons as the HW system, namely lack of sunlight during winter.
The home-owner is busy, often away, and professional maintenance costs are high due to the remote location. The system therefore needs to be durable, and not require excessive time to repair, if it fails at all. The system warrantee gives some indication of the lifetime of the product (which should be long to reduce ongoing cost), but also the propensity of a system to fail. There is a high correlation between the system being durable and it being low maintenance; low maintenance primarily deals with the time and cost of reparations.
Hot water is used daily, so the user must not have to spend excessive time waiting or starting the system; ideally it is automatic and additional steps are few and/or infrequent. To a lesser extent, the system should be easy to install. This is partially due to unwanted inconvenience to the members of the household (for example a large-scale renovation of the kitchen would be a deterrent to a system that requires this), but also will increase installation costs (which as stated previously are already high due to remoteness).
Cost is ranked low in table 2 because many of the other requirements indirectly influence cost, so to place a high importance on it would be double-counting. Furthermore, the home-owner has explicitly stated that the one-off cost of additional infrastructure and its installation is not a major deterrent, as long as he is confident that the system will perform well for a long time (Schneider 2015).

Each engineering characteristic is assigned a reasonable mathematical measure of relative importance by pairwise multiplying their relationship strengths with the relative weight of that design requirement. These weights are derived from the 1-10 scale by the following expression:

$$W_{j,rel} = 100 \times \frac{W_{j,10-pt}}{\sum_{i=1}^{N} W_{i,10-pt}} \quad (1)$$

Table 2: House of Quality: relationships, TPMs, weightings, benchmarks

Requirement	Low cost	Easy to use	Reliable	Durable	Low Maintenance	Easy to install	Safe	TPMs	Units	Weighting	Rank	Benchmark
Importance (1-10 scale)	3	7	9	8	5	6	10					
Weight	6.25	14.58	18.75	16.67	10.42	12.5	20.83					
Installation cost	3							Cost	AUD	18.8	18	<1000
Infrastructure cost	9							Cost	AUD	56.3	15	<1000
Fuel cost	3							Annual cost	AUD/yr	18.8	18	<500
Setup time		9						Time	mins	131.2	10	<10
Setup frequency		9						Frequency	/month	131.2	10	<10
No. of steps to use		3						Number	Number	43.7	16	<3
Hot water waiting time		3						Time	s	43.7	16	<30s
Failure to meet Australian legionella prevention Standards			9				9	Frequency	/month	356.2	1	0
Failure to meet user standards			9					Frequency	/month	168.8	7	<10
PV storage system failure frequency			9					Frequency	/month	168.8	7	<3
Replacement cost	3			9				Cost/module	AUD	168.8	6	<1000
Warrantee	3		3	9	3			Time	yr	256.3	2	>2
Maintenance frequency	1		1	3	9			Frequency	/yr	168.8	5	<5
Time to repair	1				9			Time	hr	100.0	14	<2
Cost to repair	3				9			Cost/module	AUD	112.5	12	<500
Installation time	3					9		Time	hr	131.3	9	<7
Essential processes disrupted by installation						9		Number	Number	112.5	13	<5
Risk of scaling							9	Outlet temp.	°C	187.5	3	<55 °C
Low risk of harmful fumes							9	Risk level	5 pt. scale	187.7	3	>3

5 Describing the system

5.1 Subsystem interface

It is prudent to understand the interactions between subsystems within the specific off-grid framework, such that informed design decisions can be made. Reference to figs. 1 and 2 will facilitate understanding of the following sections, where descriptions of various system setups will be given. Figure 1 shows both how the system currently operates, and how various categories of change will alter the subsystem interface. These categories are summarised in fig. 2.

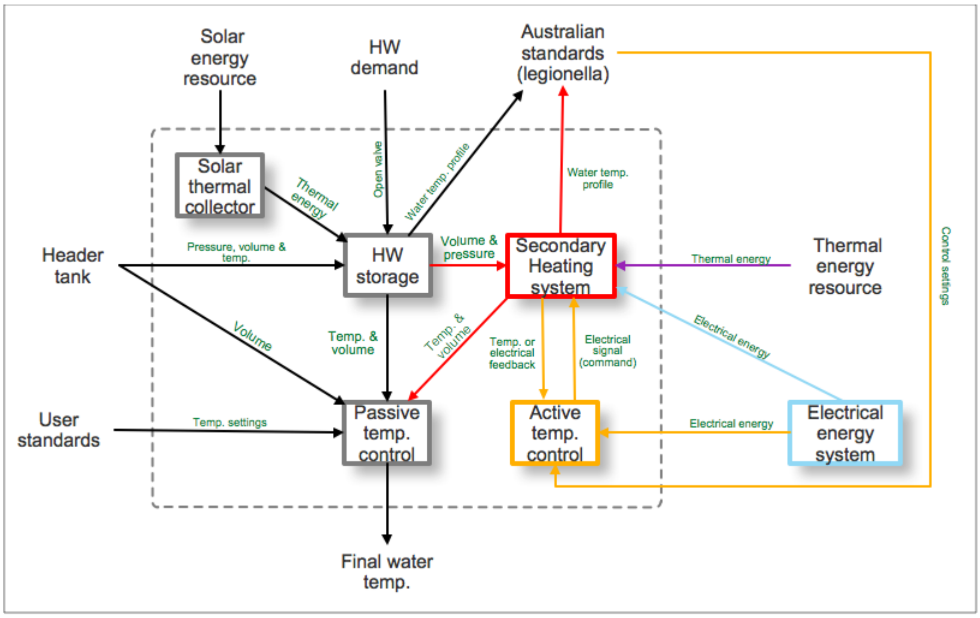

Figure 1: Functional block diagram of hot water system. Black boxes and arrows denote the existing subsystems and their interactions, and other colours represent independent modifications to the system interface

5.2 Subsystem concept tree

HW system concepts cannot be organised into any singular hierarchy describing all possible permutations. The system is instead divided into the six subsystems shown in fig. 1. Each of these subsystems have multiple properties and sub-properties that can be met by several concepts. For example, the active temperature control subsystem can be described by the type of thermocouple it uses to measure temperature, and the type of control functions it uses to manipulate temperature based on these measurements. Since there are many types of thermocouples and control system configurations, each of these are listed in a hierarchy beneath the relevant property. Note that some combinations may not be suitable, or even physically valid; this is not represented in the figure, so user discretion is advised. For example, a predictive algorithm cannot operate if the input is a purely mechanical thermocouple; there is no common way to link the two functions.

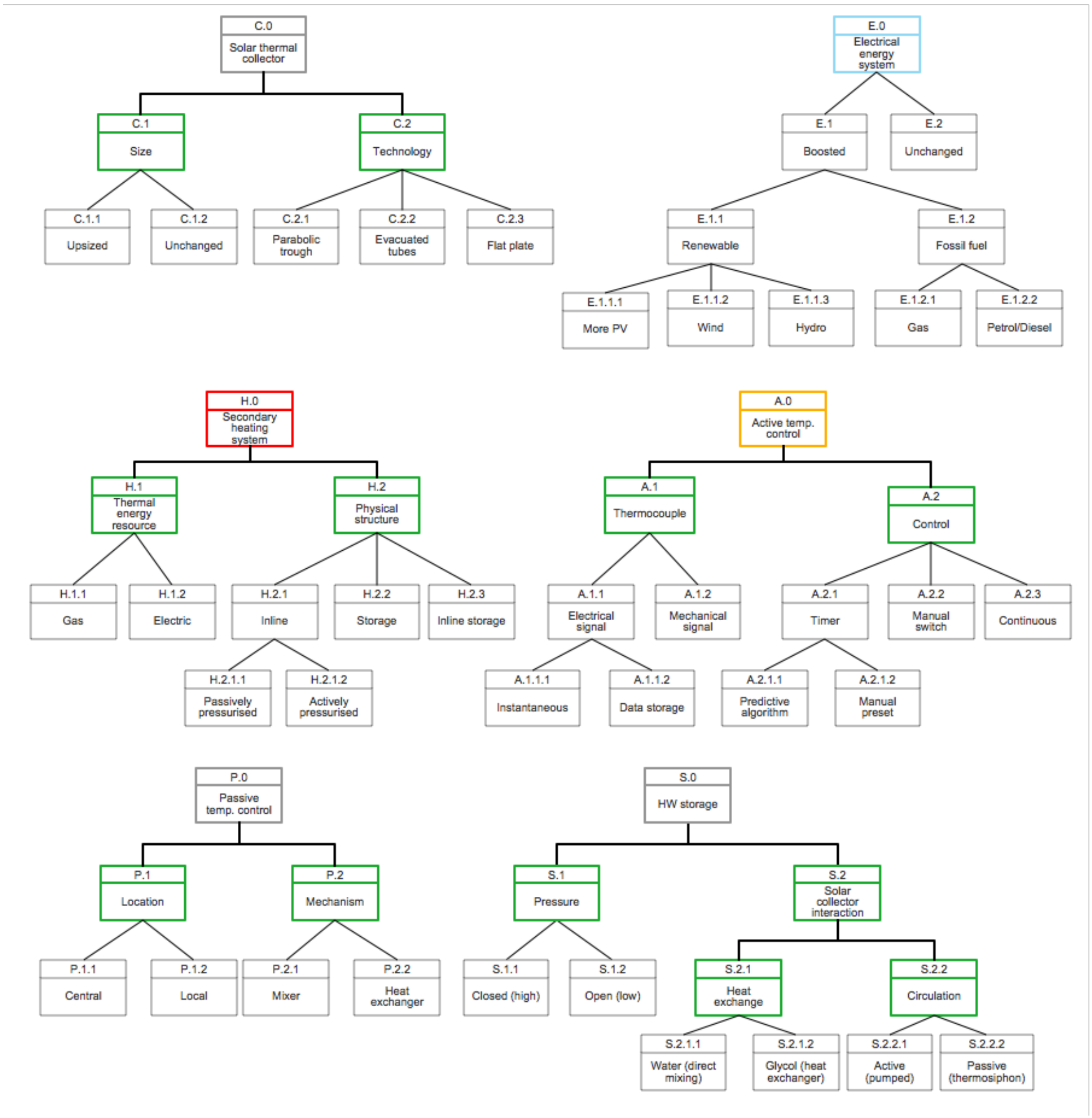

Figure 2: Concept allocation diagram. Note that each tree diagram relates to a different subsystem, colour-coded to match fig. 1. Orthogonal lines to green boxes represent sub-subsystems; a concept must be chosen by following direct lines to the bottom of the tree for each sub-subsystem

5.3 Existing system

5.3.1 System function

Currently, the system is comprised of a HW storage tank, which passively circulates a heat exchanger fluid between itself and the solar thermal collector. This gradually heats the water in the storage tank, which may be drawn off at any point in the day. A passive mixer located next to the tank ensures that the temperature of the water being supplied to the household is below 50°C to eliminate any risk of scalding. Cold water from a header tank located 10m up a slope replaces HW at a gauge pressure of <98kPa (Potter & Wiggert 2002). The system is sealed against atmospheric pressure, so this gauge pressure is maintained throughout. This setup may alternately be described more concisely using fig. 2. This diagram can be used to describe various concepts by systematically referencing concept boxes using their reference number, and combining them using boolean logic (× for AND, + for OR). e.g. the existing system can be described by:

$$\text{Existing} = [C.1.2](Unchanged) \times [C.2.2](Evac.\ tubes) \times [E.2](Unchanged) \times [P.1.1](Central) \times [P.2.1](Mixer) \times [S.1.1](Closed) \times [S.2.1.2](Glycol) \times [S.2.2.2](Passive) \quad (2)$$

5.3.2 System performance

The system does not currently meet Australian standards for legionella control, or user standards during the winter months in general; it is decoupled from any supplementary energy source, and so has zero ongoing costs. Evacuated tubes have a modular design, whereby if a single tube breaks, it can be very easily removed and replaced without any interruption to system function. They are also very efficient, and are well suited to diffuse light and cold climates (Apricus 2013).

Since Canberra is subject to sub-zero temperatures, a glycol solution must circulate through the evacuated tubes to prevent freezing, requiring a heat exchanger to be located in the tank. The glycol is circulated passively by pressure differences caused by temperature gradients (thermosiphon). This setup requires the tank to be horizontally mounted above the tubes, and has lower thermal performance than a pumped system. It is physically more reliable due to its simplicity, and it uses no electrical power (Shukla, Sumathy, Erickson & Gong 2013), so will never cause PV system failure. Thus, the system will automatically operate without any action by its users. This makes it easy to use, but it also means that the user has no control over system performance, which is entirely a function of the abundance of the solar resource. This makes the system unreliable when the resource is scarce, and there is currently no facility to mitigate this problem.

Possible changes to the existing system will be discussed with reference to fig. 1 and 2 in terms of the pros and cons of certain subsystem interactions and internal subfunctions respectively, and how these relate to meeting the benchmarks outlined in table 2.

5.4 Subsystem function and interactions

The secondary heating subsystem fig. 1 can be utilised to introduce a more reliable source of energy to the system; this creates a trade-off between reliability (which is considered to be essential), and all other design requirements, which must be optimised within the constraints of the system concept framework in fig. 2.

The secondary heating system could have two different sources of thermal energy - either electric or gas. If the electrical energy system is the existing standalone PV system, the interaction between that system and the active control and secondary heating system should be minimised to avoid PV storage system failure. Note that the energy used to control the system is separate from the thermal energy used to physically heat the water.

Active temperature control allows Australian standards for legionella (the most important engineering characteristic (table 2)) to directly interact with the system. The strength of this interaction will directly influence system performance, but the complexity of the active control system may increase cost and/or maintenance frequency. Currently there is no interaction between the standards and the system, which is the main reason for its inadequacy. The passive temperature control subsystem eliminates the risk of scalding by limiting the temperature of water flowing past it to 50°C, a condition set by Standards

Australia (2009).

The pressure delivered to the system by the header tank is maintained throughout the HW tank and piping system, as there are no openings to equalise pressure (i.e. a closed system; [S.1.1]). Thus, the pressure delivered to the secondary heating system by the HW storage system is equal to that delivered by the header tank (minus any internal loss). An open system would partially decouple the pressure in the HW storage system from the header tank, causing a significant pressure drop, but also preventing cold water from automatically replacing drawn-off hot water. Such a system will not be considered here because it would increase system complexity significantly without making the system sufficiently reliable.

6 Testing

The performance of a number of concepts, fully described with reference to fig. 2, are evaluated against the engineering characteristics and benchmarks presented in table 2. Analytical modelling is primarily be used for testing, as it will allow identification of system shortcomings before implementation (Blanchard & Fabrycky 2011). Since such a system may represent a significant investment of time and/or money, and is not likely to undergo any iterative development process, prototype testing is not viable.

Four key engineering characteristics are identified against which all concepts can be meaningfully tested at the analytical level: PV system failure frequency, setup frequency, Failure to meet Australian legionella prevention standards, and fuel cost. These characteristics represent trade-offs between the increased reliability/safety the system, and how expensive and difficult it is to run in practice. Two major forms of testing are applied: electrical and thermal.

Thermal testing is conducted to assess the thermal performance of a system lacking a secondary heater. The results can be used to assess the system against the legionella benchmark directly, or to determine energy requirements of a given secondary heater. Electrical analysis can take the energy requirement from the thermal analysis and use it to test the other three characteristics. Note that the following procedures may be generally applied to any HW system setup; the case study is used as a worked example of the methodology.

6.1 Scope

Table 3: Main assumptions and deliverables expected from each analytical test

Test	Thermal	Electrical
Assumptions	3 minute showers are taken 4 times per day, the energy used by a secondary storage heating system is equal to that of an inline electrical booster with its thermostat set to 60°C, plus heat loss due to conduction. Solar collector input based on analysis for an evacuated tube pumped system of variable size.	PV generator output evaluated in the month of lowest insolation (June). Assumed to remain at some constant averaged value each day for the month. Petrol generator assumed to deliver energy to the PV battery storage system at its rated output. Household energy usage a constant average value.
Deliverables	Secondary heating system energy usage estimates, steady state plot of average internal HW storage tank temperature over any given week of the year, similar to that in fig. 6.	Average energy deficit between energy generated and energy consumed

6.2 Apparatus

Raw data for analysis is obtained from the client (Schneider 2015), or reliable external sources if cited. Data is processed using the following tools:

- Thermal analysis: Discretised lumped capacity analysis program developed in ENGN2226 and written in MATLAB. Will henceforth be referred to as the "MATLAB" model. For a detailed explanation of the fundamental assumptions and operation, see (Schneider 2014)

- Electrical analysis: HelioScope is a program which uses the solar module ratings at standard test conditions (STC) and models how they fluctuate with varying temperature and insolation, based on local weather data. It also estimates balance of system losses to give an accurate cumulative output (Folsomlabs n.d.).

6.3 Procedure/Assumptions

The testing procedure is outlined in fig. 3. If there is no secondary heating system, the MATLAB program is run to model the HW storage tank temperature, and the legionella test (fig. 4) applied to determine whether the Australian standards outlined in table 9 are met. Real data could be used, but this is not feasible for testing a range of system sizes.

The standards issued by (Standards Australia 2009) are based on conditions that must be met at least once every week, and the benchmark is 0 failures per month table 2, so based on the program with logic as described in fig. 4, failure to meet the standards over the given week results in failure of the benchmark.

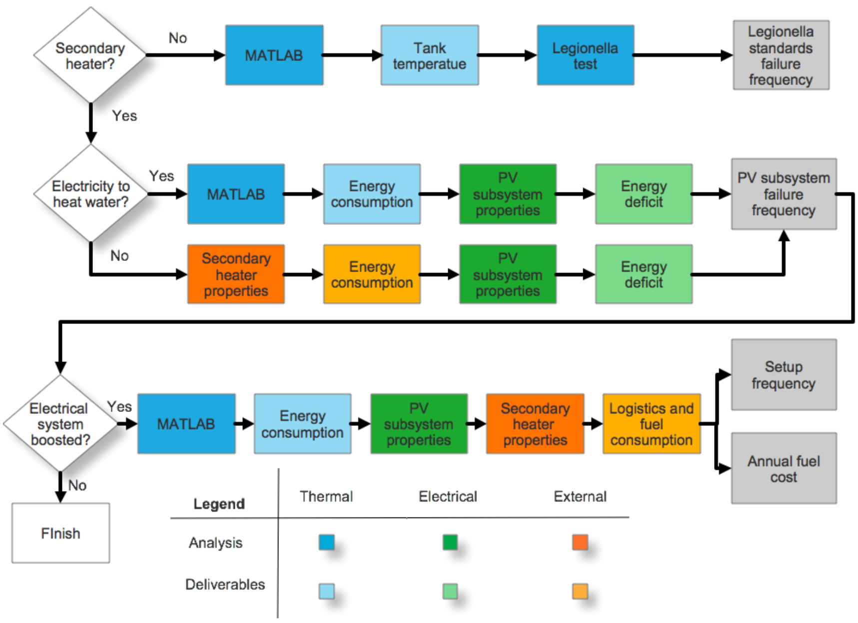

Figure 3: Logical flow diagram for determining when and how to test for the four given engineering characteristics

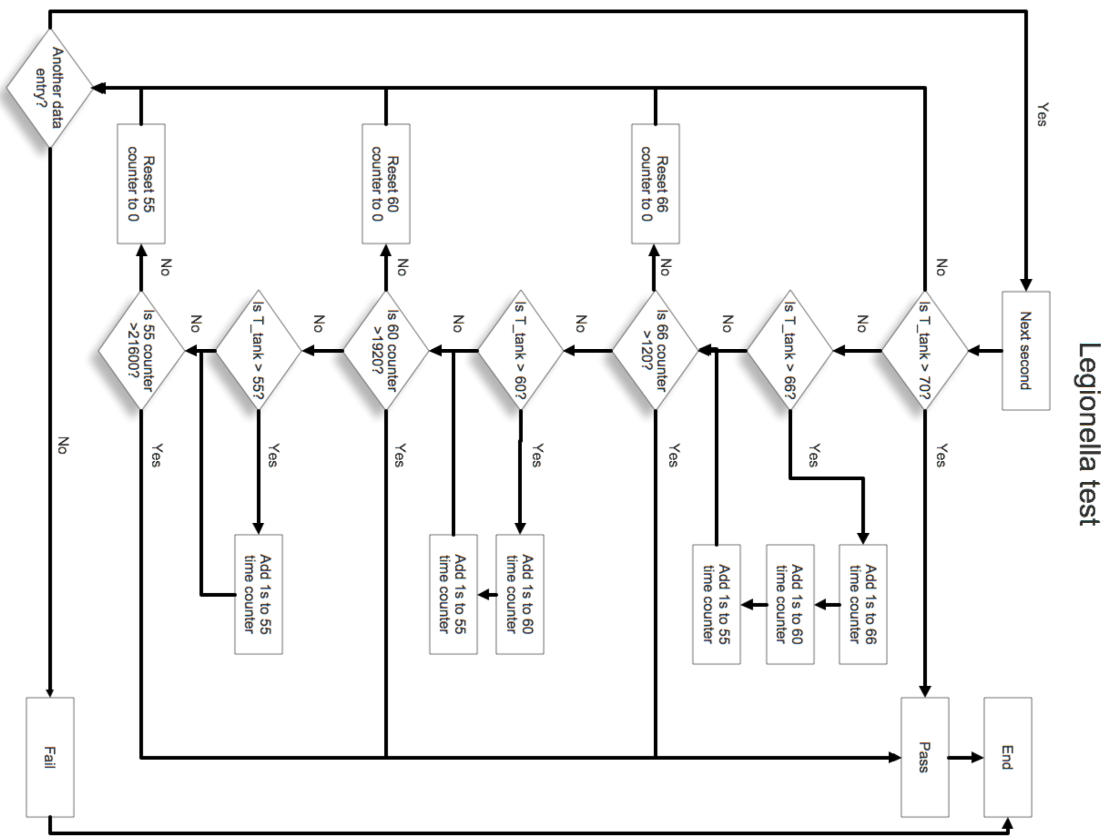

Figure 4: Logical flow diagram of analytical test procedure for Australian legionella prevention standards

If there is a secondary heating system, the legionella benchmark is assumed to be met, and fig. 3 is followed to determine the system's performance against the other engineering characteristics. The secondary heater may have properties such as: idle/non-heating electrical consumption, conditions under which this electricity is used, cost of fuel, logistics of setup. The PV subsystem properties are given in table 4, and its subsystem interface is also provided for clarity (fig. 5).

Table 4: PV subsystem properties

Subsystem	Energy (kWh)	Source
Household usage	5/day	Client
PV generation	7.7/day	HelioScope fig. 8
Battery capacity	15	Client
Petrol generation	21.6/tank	Client

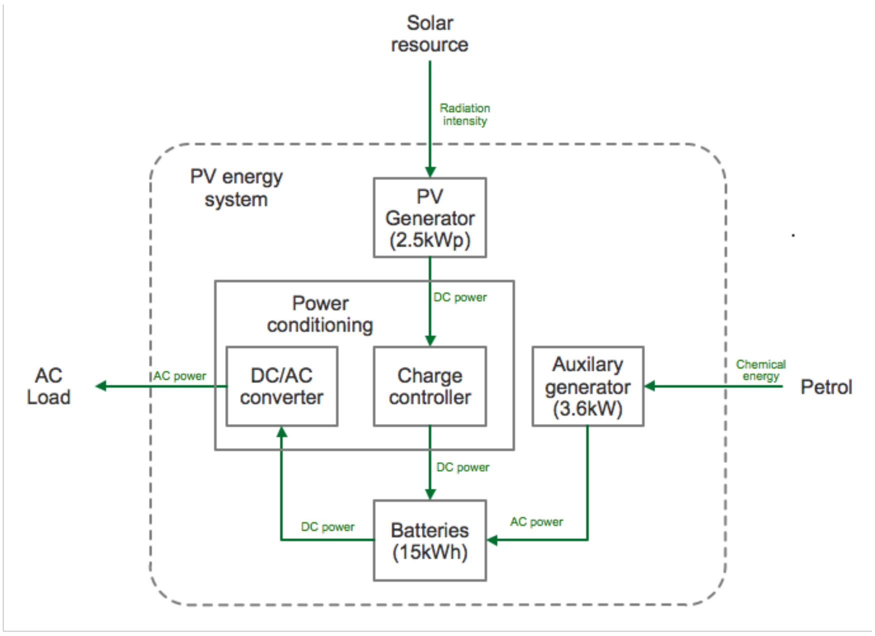

Figure 5: Subsystem interface of PV subsystem

To evaluate the engineering characteristics for each concept, the equations presented in appendix D may be applied, subject to fig. 3. The minimum number of months the secondary heating system must be used in a year can be determined by applying the legionella test for each month and determining how many times the system fails. Figure 4 is thus broadly very useful as a tool under active temperature control: it could use data from the MATLAB model to inform the user directly how to best use a manual switch or preset timer, or be integrated into a predictive algorithm (see fig. 2 for reference).

7 Appraisal of concepts

A number of potentially viable concepts are considered, including boosting the existing system with electrical energy, upsizing the existing solar collector, and boosting with gas using an inline or inline storage system. If a concept cannot meet all of the minimum benchmarks based on the given test, it is rejected unless a creative solution can be found. The trade-offs, limitations and possible extensions of these topics will be discussed to make an informed decision against an evaluation matrix in section 8.

7.1 Electrically boosted

$$\text{Existing} \times ([E.2](Unchanged) + [E.1.2.2](Petrol)) \times [H.1.2](Electric) \times [H.2.2](Storage) \times [A.1.2](Mechanical) \times [A.2.2](Manual) \quad (3)$$

7.1.1 Advantages

This concept is represented by linking the electrical energy system to the secondary heating system as a replacement to the external thermal energy resource (see fig. 1). The existing solar HW tank has the facility to accept electrical boosting; there is a heating element inside the tank that is currently de-activated. This would be extremely cheap and easy to install. A more expensive but very efficient external heat pump module such as that produced by Siddons (2014) could also be easily attached. Electrical boosting would aid the system in meeting the Australian standards for the control of legionella, without compromising other system functions.

7.1.2 Disadvantages

This design places a heavy load on the PV generator and storage system, which may cause failure during the winter months. This can be avoided by using a petrol generator which is already used to boost the PV system during this time of year. The high additional load will increase the frequency of usage (of the generator), and so may be time-consuming and complex a task to complete regularly. A FFBD is constructed to show the process of starting the generator (see fig. 7 in appendix).

7.1.3 PV storage system failure, setup frequency and fuel cost test

Calculations:
The nominated engineering characteristics for this concept are calculated using the procedure outlined in section 6.3; the details may be found in appendix E. The results are summarised in table 5.

Table 5: Summary of test results based on analysis in appendix E. A "G" next to the given concept indicates the petrol generator is in use

Engineering characteristic	PV storage system failure frequency	Setup frequency	Fuel cost
Unit	/month	/month	AUD/year
Electric element	12.6	0	0
Electric element G	0	9	405
Heat pump	6.3	0	0
Heat pump G	0	4.5	202.5
Benchmark	<3	<10	500

Discussion:
Table 5 shows that this concept cannot meet the PV failure frequency benchmark of 3/month without the use of the generator, which in the case of the electric element must be run 9 times per month, barely meeting the setup frequency benchmark. Furthermore, the average setup time is relatively high (fig. 7), and the fuel cost benchmark is met only marginally. Thus, the system will score poorly on ease of use, average on cost (no installation cost), but highly in reliability and ease of installation in particular. If a heat pump is used instead, the fuel cost and setup frequency benchmarks are met reasonably well, although there is now a significant initial cost of approximately $2000. The Bolt-on by Siddons (2014) is easy to install, is reliable, and has a 5-year extended warrantee.

7.2 Upsizing solar collector

$$\text{Existing} \times [C.1.1](Upsized) \tag{4}$$

7.2.1 Advantages

This system has all the advantages of the existing system as described in section 5.3, but will be more reliable due to an increase in the magnitude of the thermal resource.

7.2.2 Disadvantages

Either the cost or reliability requirements are unlikely to be met. Several days of low solar insolation, combined with low external temperatures could still cause even a large system to not meet the user or Australian standard requirements consistently. These collectors are expensive (Elgas 2014), and would only be required during the winter months.

7.2.3 Testing compliance with Australian legionella standards

Calculations:
The feasibility of upsizing the solar collector can be evaluated analytically by testing the engineering characteristic of "failure to meet Australian legionella prevention standards" against its benchmark in table 2.
Tubes are typically sold in sets of 10, 20, 22, or 30 (Apricus 2013) so linear combinations of these sets are tested.

Table 6: Number of monthly failures for different collector subsystem sizes

Number of tubes	Pass/Fail (June)
22	Fail
30	Fail
40	Fail
44	Fail
50	Pass

Discussion: Table 6 shows that a collector subsystem with 50 evacuated tubes would be sufficient to meet the benchmark. Since the existing system has 22 tubes, the smallest collector system that can be readily purchased to comply would thus be an additional 30 tube system, costing approximately $1000-$2000 (Schneider 2014).

7.3 Solar boosted: Inline gas

$$\text{Existing} \times [H.1.1](Gas) \times [H.2.1.1](Passive\ pressure) \\ \times [A.1.1.1](Instantaneous) \times \{[A.2.1.2](Preset\ timer) + [A.2.2](Switch)\}(Manual) \quad (5)$$

7.3.1 Advantages

This heating subsystem is very reliable; hot water will never be scarce as it is heated on-demand, and can be set such that the legionella standards are always met. Strain on the electrical energy system is reduced since thermal energy source comes from natural gas. Furthermore, the household already has a gas system in place for cooking, so the connection will have low additional cost, and can be easily deactivated when not needed (which may be approximately determined using fig. 4 and MATLAB).

7.3.2 Disadvantages

The Australian legionella standards required heating to 70°C during months when the system fails the legionella test, making it very wasteful in winter, since water is mixed back to 50°C to avoid scalding. Electrical heating coils are used to keep water from freezing inside the system; this load may by large enough to warrant use of the petrol generator, reducing ease of use slightly. This can be avoided by installing the system indoors, though this introduces additional health complications due to risk of harmful fumes. This risk can be mitigated by installing the system in the kitchen with a flue , directly below the existing system. Installation would then be intrusive, as it would require some kitchen renovation. Also, these systems operate optimally at a certain pressure; e.g. the Bosch Ci10 (suitable for indoor installation) has a minimum pressure requirement of 50kPa, but to obtain the maximum rated flow rate, 100kPa is required. The header tank delivers <98kPa, so the system may operate at a reduced flow rate, and may be liable to operate inefficiently as a result. An active pump could be used, but this would significantly increase system cost, complexity, and electrical load.

7.4 Solar boosted: Storage gas

$$\text{Existing} \times [H.1.1](Gas) \times [H.2.3](Inline\ storage) \times \{[A.1.1.1](Instantaneous) \times [A.2.1.2](Manual\ preset) + [A.1.1.2](Data\ storage) \times [A.2.1.1](Algorithm)\} \quad (6)$$

Here, the secondary heating system would be a storage tank add-on with a built-in gas burner. It is connected in series with the solar tank, and draws warm water off to heat it up to standard. Hot water is then drawn from this tank. During warmer months when it is not needed, the burner can be deactivated, and water still drawn into the secondary tank.

7.4.1 Advantages

The primary advantages of a storage over an inline gas booster are threefold:

- No electricity usage: No freezing because of large heat capacity and pilot light
- Lower energy consumption: (1) No heating to 70°C in winter; temperature may be maintained at 55-60°C according to table 9 because exposure times are longer. (2) There is also facility to employ more sophisticated algorithms to save energy
- Easier to install: installed outside without risk of freezing, eliminate disruption to daily activity during installation

The existing tank could be replaced with a new tank with gas-boosting capability (rather than a separate inline system). This would tightly couple the two subsystems “HW storage” and “Secondary heating system”, whereby the systems maintain “responsiveness”, but lose their “distinctiveness”, i.e. they interact functionally, but as a single integrated entity (Brusoni & Prencipe 2005). Both of these subsystems have a distinct function, each with complex processes and many components driving them (i.e. relatively high technological complexity). Distinctiveness (modularity) is thus preferable (Brusoni & Prencipe 2005), and so a separate inline storage tank with gas-boosting capability is recommended.

7.4.2 Disadvantages

This system may have lower reliability than the instantaneous inline system in terms of meeting user standards; only a small tank would be used, so limited hot water would be available at any one time.

7.5 Tests for gas heaters

Table 7: Summary of test results based on analysis in appendix F and G

Engineering characteristic	PV storage system failure frequency	Setup frequency	Fuel cost
Unit	/month	/month	AUD/year
Inline gas	1	0.6	83
Storage gas	0	0.375	52
Benchmark	<3	<10	500

8 Concept selection

Concepts were ranked for each engineering characteristic on a 5-point scale in table 10 in appendix H. These rankings were pairwise multiplied by the relationship rows for each design requirement in the HoQ (table 2) and summed. This was done separately for each design concept, and the results are presented in table 8. Each cell thus represents a rigorously weighted ranking, based on the performance against each engineering characteristic, and the strength of that characteristic's relationship strength with each design requirement. These cells are then pairwise multiplied against their respective design requirement weightings and summed again to obtain a score for each concept; a higher score indicates a more suitable design, and the concepts are ranked accordingly. Example calculations may be found in appendix I.

Table 8: Evaluation matrix

Design requirements	Weighting	Electric element, G	Electric heat pump, G	52 Evacuated tubes	Inline gas	Storage gas
Low cost	6.25	107	92	106	83	92
Easy to use	14.58	57	75	120	99	106.5
Reliable	18.75	144	146	101	129	138
Durable	16.67	63	69	87	72	72
Low Maintenance	10.42	69	90	123	81	81
Easy to install	12.5	90	81	81	36	63
Safe	20.83	135	135	108	117	135
	Score	9906.05	10318.58	10299.94	9312.29	10359.08
	Rank	4	2	3	5	1

Table 8 shows that the storage gas boosting system is the most appropriate solution to the design problem. The other rankings are reasonable based on previous analysis of their strengths and drawbacks.

9 Life-cycle phases

This portfolio is a more considered and high-level examination of the practical decisions a consumer makes when purchasing a product that interacts with a wider system, rather than the decisions made by the product designer. Thus, the scope of the project is limited to the use phase; now that the most suitable system design has been selected, what can the consumer do to maintain the product and reduce its impact? The analysis in section 7 suggests that the client pursue the installation of an inline gas storage booster, with specific properties described by eq. (6). This section will examine potential future developments and improvements that can be made by the client to this design framework during the use phase.

9.1 Maintenance

A problem can be envisioned whereby the water in the pipes connecting the solar HW storage thermosiphon tank to the gas boosting tank freezes overnight. This can be mitigated by ensuring the connecting pipe is short, highly conductive internally (e.g. copper), but heavily insulated externally. Freezing water will cause stresses in the pipe which may lead to failure; the users would generally not notice when freezing occurs, since water is drawn from the hot gas water tank, which would not freeze.

The required R-value of the piping insulation may be calculated such that the water will never freeze overnight. However, the value may be impractically large if a very long pipe is required. Piping insulation is very reliable, with a life expectancy in excess of 7 years (Thermotec 2007). It is thus recommended that a small temperature probe be attached to the midpoint of the pipe, contacting the bare copper, with some visible external display. This should be inspected occasionally on cold mornings to check if the pipe is below freezing (the temperature of the copper will be essentially equal to that of the water within, due to its high thermal conductivity (Incropera & DeWitt 2002)). If no freezing occurs, the pipe can be left unchecked for up to 7 years, at which point the effect of its degradation on the internal pipe temperature should be monitored in the winter.

9.2 Energy savings

As a high-power device in constant operation, a non-renewable water heating system will use most of its energy during the use phase of its lifecycle. Thus, a high degree of responsibility is placed on the user to minimise this usage in the interest of sustainability. In this case study, the client is very engaged in this idea, but this should apply generally to households both on and off the grid.

Most existing active control systems for solar-boosting storage systems maintain the tank temperaure at a constant 55-60°C (Solahart 2006). Some more sophisticated active control systems such as "Hotlogic" exist, but they seem to primarily be concerned with eliminating the risk of overheating or freezing of water through the solar collector circuit (Bunnings Trade 2012). This is irrelevant in this case, since the glycol solution and evacuated tubes are extremely resistant to these effects.

Energy saving can be achieved if the control system employs a predictive algorithm, optimised to decrease non-renewable energy consumption. If a suitable storage system with this in-built capability cannot be sourced, a separate module could be installed to serve this purpose. This requires loose coupling between the existing thermostat control system and the thermocouple. The new module would then use input from the existing thermocouple to control the thermostat. A study out of the ANU by Dennis (2002) outlines the design of such a control system which employs predictive energy balance analysis. Using a thermal model written in TRNSYS, based on a Canberran household of 4, such a system is found to reduce auxiliary energy costs by up to 31%. This is a simple way to drastically reduce the carbon footprint of the system over its use phase.

10 Conclusion

An add-on storage gas booster for the existing system (eq. (2)) was deemed the most appropriate to meet the needs of the client. This was found through the development and execution of a systematic method to objectively assess the merit of HW system concepts. The author recommends that the client take steps to mitigate the risk of pipe failure due to freezing, and employ an active control system which uses predictive energy balance analysis to reduce non-renewable energy wastage.

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A Use case

Primary actor
HW users in small family household.
Goal in context
Off-grid household with limited electricity storage is provided with hot water.
Scope
System used to heat water for household use.
Stakeholders and interests
Users: want hot water year-round.
"Bread-winner": wants to spend as little money as possible.
PV generator/battery storage: needs to use very little energy.
Australian government: Requires standards to be met.
Minimal guarantees
Hot water is provided in compliance with Australian standards, without compromising electricity supply.
Success guarantees
Hot water is provided year-round at affordable upfront and low ongoing cost, under compliance with Australian standards.
General household electricity usage is not frequently interrupted.
Hot water company is paid an appropriate amount for their services and products.

B Data to assess legionella standard requirements

Table 9: Australian Standards for the prevention of Legionella. Stagnant water above 20°C must satisfy these requirements at least once in a 7-day period to meet the standard(Standards Australia 2009)

Temperature	Minimum exposure period
70°C or greater	1 s
66 °C	2 min
60°C	32 min
55°C	6 h

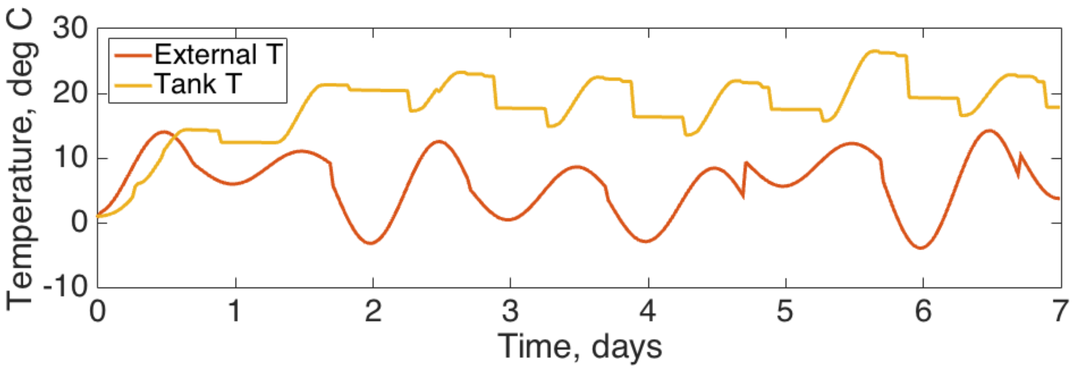


Figure 6: Internal tank temperature over a typical week in June, based on lumped capacity model developed in ENGN2226 (Schneider 2014)

C Electrical generator usage FFBD

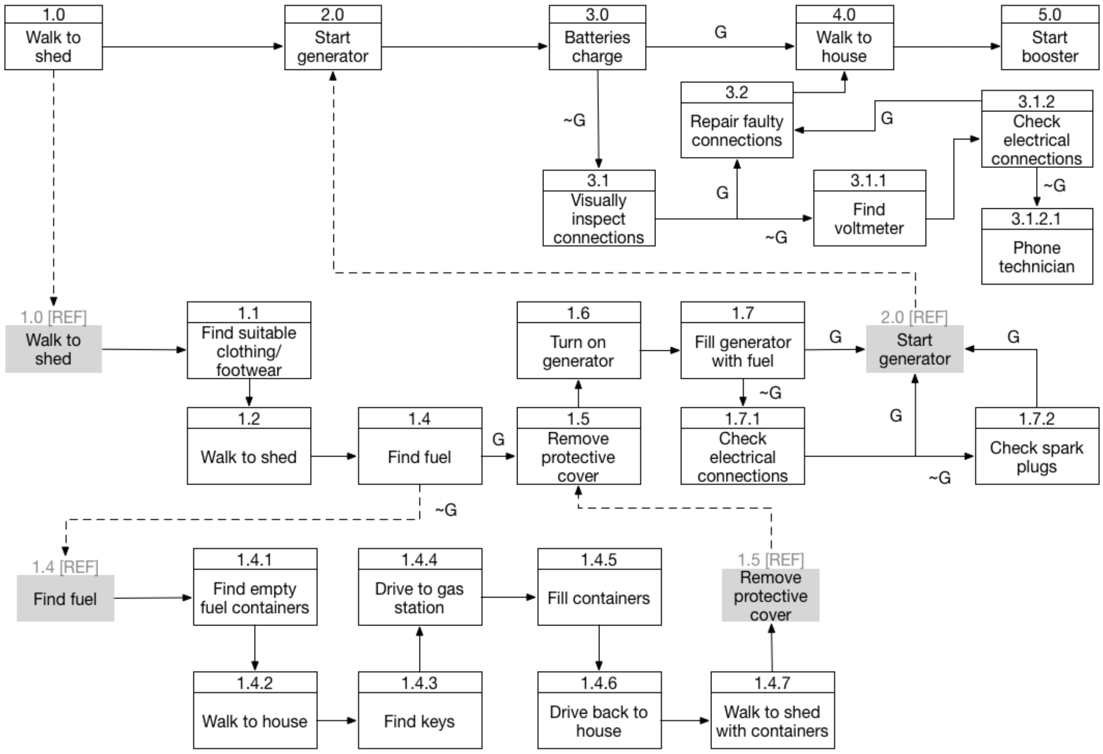


Figure 7: Functional flow block diagram (FFBD) of the process of boosting the electrical energy system with a petrol generator

D Equations to calculate key engineering characteristics for any general case

$$\text{Deficit [kWh/day]} = \text{PV generation [kWh/day]} - \text{Household usage [kWh/day]} - \left(\begin{matrix}\text{Secondary heater} \\ \text{electrical usage}\end{matrix} \text{ [kWh/day]}\right) \tag{7}$$

$$\left(\begin{matrix}\textbf{PV storage} \\ \textbf{failure frequency}\end{matrix}\right) \text{[failures/month]} = \text{Days in a month [days/month]} \times \frac{\text{Deficit [kWh/day]}}{\text{Battery capacity [kWh]}} \tag{8}$$

$$\textbf{Setup frequency [/month]} = \text{Days in a month [/month]} \times \frac{\text{Deficit [kWh/day]}}{\text{Electric boosted generation [kWh/day]}} \tag{9}$$

$$\textbf{OR: Setup frequency [/month]} = \frac{\text{Energy usage [kWh/yr]}}{\text{Energy capacity [kWh]} \times \text{Usage frequency [months/yr]}} \tag{10}$$

$$\textbf{Annual fuel cost [AUD/yr]} = \text{Cost of fuel [AUD/(L or kg)]} \times \text{Fuel capacity [(L or kg)]} \times \textbf{Setup frequency [/month]} \times \text{Usage frequency [months/yr]} \quad (11)$$

E Calculations for electrical booster tests

MATLAB analysis found secondary heater electrical usage to be 9kWh/day. The petrol generator has a fuel capacity of 10L, which can deliver 21.6kWh/day to the batteries. Petrol is assumed to cost around $1.35/L, so using data from table 4 and applying eqs. (7) to (9) and (11), the values in table 5 are calculated. Based on data from Siddons (2014), it is estimated that an electric heat pump with automatic timing presets would be at least twice as efficient as a simple electric heating element in winter. This corresponds to a halving of the PV system storage failure frequency, or the setup frequency and fuel costs (depending on if the generator is used).

F Setup frequency, PV system failure frequency, and cost test for inline gas booster

Following the procedure outline in section 6.3, the energy usage of an inline gas booster over the winter months was calculated. The legionella test described in fig. 4 was applied, and if the HW storage subsystem failed the test, the inline heater was set to heat water to 70°C to maintain compliance with the Australian standard (Standards Australia 2009).

The MATLAB code estimates the energy requirement for natural gas, (Energy usage) to be approximately 1111kWh/yr, with a usage period of 3-months per year (the winter period). A single typical LP gas cylinder for household use costs $140, and weighs 45kg (Fuel capacity) (Gas 2014), and with an energy density of 1389kWh/kg (Natural Gas 2007), this corresponds to an energy capacity of 62500kWh. Equation (10) and 11 are applied, with results presented in table 7.

Inline boosters also use an anti-frost device which will switch on under freezing ambient temperatures, and rely on electrical power. According to Rheem (2013), typical power consumption is about 145W. If the ambient temperature is assumed to be below freezing roughly 1/3 of the time in June, the daily energy consumption may be calculated:

$$E_{defroster} = \frac{145 \times 24 \times}{3} = 1.16 \text{ kWh}$$

Which, using the data presented in table 4 and applying eq. (7), does not produce an electricity deficit on average. However, on a particularly cold and dark day, the generator may need to be run, so assume random failure once a month.

G Setup frequency, PV system failure frequency, and cost test for storage gas booster

The energy used to heat the gas storage system is assumed to be approximately equal to the energy used by an inline booster under the same conditions, but set to heat only to 55°C, plus continuous conduction loss; MATLAB calculated energy usage = 694 kWh/yr.

Following precisely the same argument and taking all other variables given appendix F, the engineering characteristics were determined, and are presented in table 7

H Evaluation matrix - extended

Here, each of the concepts explored in this report were ranked against the individual engineering characteristics rather than the design requirements, which have some overlap, as shown in table 2.

Table 10: Evaluation on a 5-point scale of six concepts as described in section 7. Ratings are based on how well the concepts were shown or perceived to meet the benchmarks given in the house of quality (table 2). A rating of 5 indicates the benchmark is very well-met, 1 that the benchmark is only just met, and 0 that the benchmark is not met

Engineering characteristics	Electric element, G	Electric heat pump, G	52 Evacuated tubes	Inline gas	Storage gas	Existing
Installation cost	5	3	4	2	3	5
Infrastructure cost	5	3	3	3	3	5
Fuel cost	1	2	5	3	4	5
Setup time	2	2	5	4	4	5
Setup frequency	1	3	5	4	4.5	5
No. of steps to use	5	5	5	5	5	5
HW waiting time	5	5	5	4	5	5
Failure to meet Australian legionella prevention Standards	5	5	2	5	5	0
Failure to meet user standards	5	5	2	4	4	1
PV storage system failure frequency	5	5	5	4	5	5
Replacement cost	4	4	3	4	4	5
Warrantee	2	3	5	3	3	5
Maintenance frequency	3	2	5	3	3	5
Time to repair	2	3	5	2	2	5
Cost to repair	2	4	2	3	3	5
Installation time	5	4	4	2	3	5
Essential processes disrupted by installation	5	5	5	2	4	5
Risk of scalding	5	5	5	4	5	5
Low risk of harmful fumes	5	5	5	4	5	5

I Example calculations for results in table 8

A worked example for the first element in table 8 (Low cost weighting, $W_{\text{low cost}}$, of the electrical element with generator concept): From table 2, we find that if we read the engineering characteristic relationships to low cost ($R_{\text{low cost}}$) from left to right, we get the following list:

$$R_{\text{low cost}} = [3, 9, 3, 0, 0, 0, 0, 0, 0, 0, 3, 3, 1, 1, 3, 3, 0, 0, 0]$$

We then find the performance of the first concept ($P_{\text{low cost}}$) against each of these design characteristics from table 10:

$$P_{\text{low cost}} = [5, 5, 1, 2, 1, 5, 5, 5, 5, 5, 4, 2, 3, 2, 2, 5, 5, 5, 5, 5]$$
$$\therefore W_{\text{low cost}} = \sum_{i=1}^{19} R^i_{\text{low cost}} P^i_{\text{low cost}}$$

Similarly, if the relative weightings of each design requirement are given by X_j where j denotes the jth design requirement, the score, S, of any given concept is given by:

$$S = \sum_{j=1}^{7} W_j X_j$$

e.g. for the first concept, we have:

$$W_j = [107, 57, 144, 63, 69, 90, 135]$$
$$X_j = [6.25, 14.58, 18.75, 16.67, 10.42, 12.5, 20.83]$$
$$\therefore S = 9906.05$$

HelioScope Annual Production Report produced by Taeho Jung

Design 1 Karool, 250 Baroona Rd, Michelago

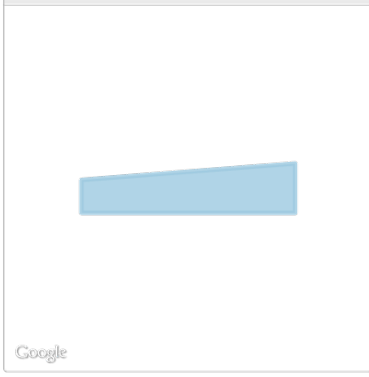
Report

Project Name	Karool
Project Address	250 Baroona Rd, Michelago
Prepared By	Taeho Jung u4997019@anu.edu.au

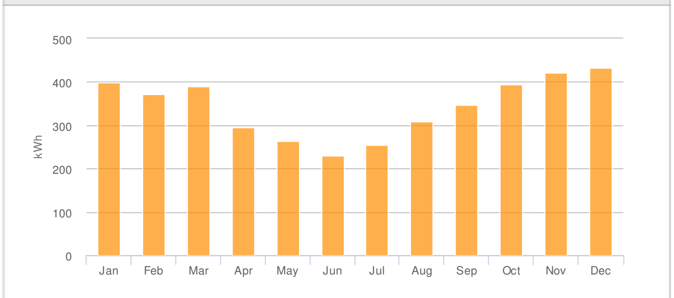
System Metrics

Design	Design 1
Module DC Nameplate	2.50 kW
Inverter AC Nameplate	2.05 kW Load Ratio: 1.22
Annual Production	4.107 MWh
Performance Ratio	82.3%
kWh/kWp	1,642.8
Weather Dataset	TMY, Canberra Airport, RMY (epw)
Simulator Version	99 (d5c0120192-ffbb1ec245-e49ebda4ab-38241b190d)

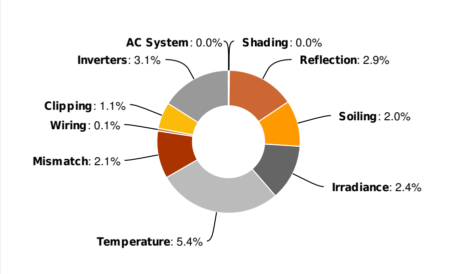
Field Segments



Monthly Production



Sources of System Loss



Annual Production

	Description	Output	% Delta
Irradiance (kWh/m²)	Annual Global Horizontal Irradiance	1,768.0	
	POA Irradiance	1,996.5	12.9%
	Shaded Irradiance	1,995.7	0.0%
	Irradiance after Reflection	1,936.9	-2.9%
	Irradiance after Soiling	1,898.2	-2.0%
	Total Collector Irradiance	**1,898.2**	**0.0%**
Energy (kWh)	Nameplate	4,744.0	
	Output at Irradiance Levels	4,629.2	-2.4%
	Output at Cell Temperature Derate	4,381.0	-5.4%
	Output After Mismatch	4,290.8	-2.1%
	Optimal DC Output	4,285.7	-0.1%
	Constrained DC Output	4,236.8	-1.1%
	Inverter Output	4,107.0	-3.1%
	Energy to Grid	**4,107.0**	**0.0%**
Temperature Metrics			
	Avg. Operating Ambient Temp		15.3 °C
	Avg. Operating Cell Temp		25.9 °C
Simulation Metrics			
	Operating Hours		4644
	Solved Hours		4644

Condition Set

Description	Condition Set 1
Weather Dataset	TMY, Canberra Airport, RMY (epw)
Solar Angle Location	Meteo Lat/Lng
Transposition Model	Perez Model
Temperature Model	Sandia Model
Irradiation Variance	5%
Cell Temperature Spread	4° C
Module Binning Range	-2.5% to 2.5%
AC System Derate	0.00%

Temperature Model Parameters

Rack Type	a	b	Temperature Delta
Fixed Tilt	-3.56	-0.075	3°C
Flush Mount	-2.81	-0.0455	0°C

Soiling (%)

J	F	M	A	M	J	J	A	S	O	N	D
2	2	2	2	2	2	2	2	2	2	2	2

Module Characterizations

Module	Characterization
BP 3125 S (BP Solar)	Default Characterization, PAN

Component Characterizations

Device	Characterization
SunnyBoy 2KW (SMA)	Default Characterization

 1/2 April 27, 2015

Figure 8: HelioScope design report