Effective Off-Grid Household Energy Generation Solutions

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Abstract

Increased energy demand and fossil fuel depletion are expected to put strain on grid-based energy production. This portfolio investigates one possible solution, which is decentralised household energy generation, for households in Canberra. A systems design process was conducted through which a Hybrid Solar PV/Thermal system was deemed to be the most effective to reducing household dependence on grid technology and meeting part of the household's daily energy needs. Such a system uses a hybrid solar panel with both photovoltaic and thermal conductance properties to generate electric and heat energy concurrently, with storage and dissipation to consuming applications.

This solution was determined through the application of several systems design methodologies. Problem scoping and requirements analysis were used to find a method of comparing options, which were used after concept generation to evaluate these options. After the most suitable option (outlined above) was found, functions & their relations with subsystems were modelled along with testing procedures to provide more insight into the details of system operation. Life-Cycle considerations were also discussed to give insight whole-system energy usage of the design. Lastly, testing requirements were defined for the implementation process.

Contents

1. Introduction

Due to the decline of fossil fuels, long term mass grid-energy generation is becoming increasingly cost intensive (Duncan, 2005). To reduce the costs of maintaining a large energy infrastructure and effectively use available renewable energy resources, it is necessary to consider off-grid energy generation solutions. Household energy generation has the potential to reduce load from the large energy grids, bring more redundancy into the energy system in general, and improve energy security for citizens in declining energy societies.

This portfolio investigates design solutions to off-grid energy generation for a standard household in Canberra. The design objective is to provide potential solutions for households to meet part of their energy needs through small-scale 'backyard' energy generation. System engineering design methodology is used to define, generate, an evaluate solutions, from which the best one is selected. Further nuance is added to the selected design through defining functions, testing standards and discussing life cycle considerations. The final design is then evaluated to judge effectiveness in terms of the original customer requirements.

The stages of system design are as follows:

1. Problem Scoping – the system boundaries are defined first to establish the scope. A use case diagram helps clarify the customer's needs, which are translated into formal design requirements.
2. Requirements Analysis – Pairwise analysis is conducted to help rank the design requirements. These are linked to engineering characteristics to form Technical Performance Measures (TPMs). A House of Quality (HoQ) is formed to find relevant relationships and tradeoffs.
3. Concept Generation & Evaluation – concepts are researched and brainstormed. The most feasible concepts are then assessed by an Evaluation Matrix.
4. Functions and Subsystems – the whole system is partitioned into subsystems, with links between the subsystems and relations to each function mapped out.
5. Life-Cycle Phases – preferences for constructing, disposing/recycling the system to best help meet sustainable design are discussed.
6. Testing & Communication – methods of testing the chosen system to find its operational characteristics are elaborated upon. A final design is provided that sums up the features of the refined system at the end of the systems design process. A conclusion will wrap up the important points of the design with any final reflective remarks.

2. Problem Scoping

The first task required in the design process was to make a general question, i.e. "How can households in Canberra generate energy in their own homes?" into something more specific with particular technical features that could be solved via an engineering process. Narrowing the definition of the primary stakeholder (the household) was absolutely necessary as there is vast diversity in households based on region, demographics, and income. To keep the context relevant, the household targeted was decided to be the absolute average household in Canberra, as found by the Australian Bureau of Statistics.

Average household size in the ACT, as reported by the ABS is 2.6 people which will be rounded to a family size of 3. The most common instance of this type of family in the region is a couple family with children under 15 and/or dependent status (Australian Bureau of Statistics, 2014). This was the basis for demographic based requirements analysis (in future sections). Further details on energy consumption, expenditure etc. were clarified later in requirements analysis (section 2.3).

2.1. System Boundaries

The second main exercise was to determine the scope within the research would be conducted and define the boundaries of the system. Multiple levels of systems exist within each other with interdependence – the households exists within a suburb, which exists in a city, and so on. Defining where the system ends was crucial to constructing a functional but simple model to base the solution on. The systems boundary chart is provided below (Table 1).

Table 1: System Boundary Chart

Endogenous	**Exogenous**	**Outside**
Household members Energy Generation Systems	Climate Land/Soil Power Grid connection (Local) Utilities Household members Government Regulations Local Infrastructure Economic conditions International Market Prices Physical House Building	Climate change National Power Infrastructure Economic growth/contraction (Australian & International) Population growth Inflation Interest rates

The endogenous inputs in the system were the users and any energy generation systems we integrate into it – in short, any factors of smaller systems that we need to control to achieve our desired outcomes. The exogenous systems were those that we rely on for successful functioning of our solution, but have no control over, primarily the housing structure itself, the environment and features of the city/national government administration.

Environmental/economic factors were considered exogenous in their current state, but future changes were excluded from the system. This was particularly important as economic factors such as income & market prices dictate the customer requirements regarding affordability (elaborated in the next section). Climate factors also have a large impact on the type of system that is feasible. However, for the sake of simplicity fluctuations in these complex systems was ignored as that would greatly widen the scope and difficulty of design. The particular restrictions these system boundaries places on the design is that it is only valid if the conditions the households exists in do not change significantly, which can reasonably be assumed for the short term period (over the next 3 years).

2.2. Use Case

After deciding the scope of the stakeholder and the system the group interacts in, it was necessary to understand how the user actually uses the system. This creates the framework for many of the required design stages afterward such as design requirements and functional flow. There are many levels of involvement with energy generation that provide various levels of effectiveness for cost. Daily leisure time, house area and location are also variable factors. To keep the case most general, the preferences of an average Canberra household were taken into account to produce the following use case diagram.

Table 2: Use-Case Diagram for the stakeholder

Primary Actor: Household in Canberra Goal in Context: The system is able to generate energy passively or with minimal time invested, which the household is able to utilize it for a common need (cooking, lighting, heating or to powering applications). Scope: The stand-alone energy generation system and its associated household, existing in the urban environment with a predictable current climate. Stakeholders or Interests: Companies providing the energy system, local government and energy utility companies. Minimal guarantee: The household is able to reduce its dependence on the mass energy grid for energy and is able to fulfil a certain set of essential energy needs from the off-grid energy system. Success Scenario: The household is able to meet their total energy needs from the off-grid energy system, thereby enabling them to operate independently from the mass-energy grid.

2.3. Design Requirements

The most important task in determining the suitability of a technology to meet the households' energy needs. Apart from simply considering the household's energy consumption, it was also important to include other requirements, such as emissions, expenditure on energy, cost of installing the system, maintenance cost etc. The ability and willingness of households to adopt more sustainable local solutions to energy generation rely on the competitiveness of the product as a substitute to more conventional sources of energy generation (Kriström & Kiran, 2014).

Table 3: Customer & Design Requirements

Customer Requirements	Design Requirements	ID
Meet energy consumption needs	Generates adequate amount of energy	DR01-01
Affordable	Low initial cost	DR02-01
	Low maintenance cost	DR02-02
Simple to use	Works passively or with minimal management	DR03-01
	Minor faults are able to be easily fixed	DR03-02
Reliable	Low maintenance cycle	DR04-01
	Is able to provide energy consistently throughout seasons	DR04-02
Environmentally friendly	Low carbon emissions	DR05-01
	Low embodied energy	DR05-02
	Low pollution externalities	DR05-03
Long-life cycle	Lifespan	DR06-01
	Efficient disposal method	DR06-02

The set of customer requirements were decided based on the requirements set out in the introduction section, with educated assessments of what benefits a successful implementation of a system will provide to the customer. These were then converted to design requirements, which provided more specific measurable benchmarks for the system to achieve.

The most important customer & design requirement is that the off-grid household generation system produces enough energy to meaningfully contribute towards the household's energy consumption. The amount of energy it provides will have to be compared to tradeoffs in terms of various costs and externalities (section 3.2). Similarly, affordability can actually be translated into two different design requirements – a low initial cost and a low maintenance cost. These again, have tradeoffs against each other and other design requirements. Simplicity of use is also important, but unlike other customer requirements it is hard to convert into measurable requisites. One particular way to define this is the level of active effort required to keep the system running or to fix small faults in it, where an ideal system operates passively.

Reliable systems can easily be understood as one with a low maintenance cycle, however this particular system can also be interpreted another way. Renewable systems seldom operate under all conditions; they often have a large variance in the energy generated depending on the climate and other conditions. A reliable system can thus also be regarded as one that is most consistent with its energy generation throughout the seasons (DR03-02).

A household energy system is also ideally environmentally friendly. Generally this is the case since the concern and need for this technology is to address resource decline, thereby providing an advantage to renewable resources. However there are options of generating energy that produce some emissions and pollution, so environmental factors are included in the design requirements. This can most easily be split into as low carbon emissions, embodied energy (further elaborated in section 6) and other pollution externalities.

A long lifespan is also important from a consumer point of view and also relates (with tradeoffs) with DR01 and DR02. This can be easily measured as the average lifespan of the technology. Life-cycle considerations should also be included in early stages of analysis for the most sustainable outcome which results in minimal costs of changing the technology in the future (Department of the Environment and Water Resources, 2007). Thus efficient disposal methods are also added to judge the reusability of technology or its components from the early stages of design.

3. Requirements Analysis

The design requirements defined in the previous section had to be analysed to find the relative importance ranking. Furthermore technical metrics had to be defined based on these requirements to effective evaluate designs and provide a common basis for the comparison between different designs. To achieve this, a Pairwise Analysis was done along with definition of Engineering Characteristics.

3.1. Pairwise Analysis

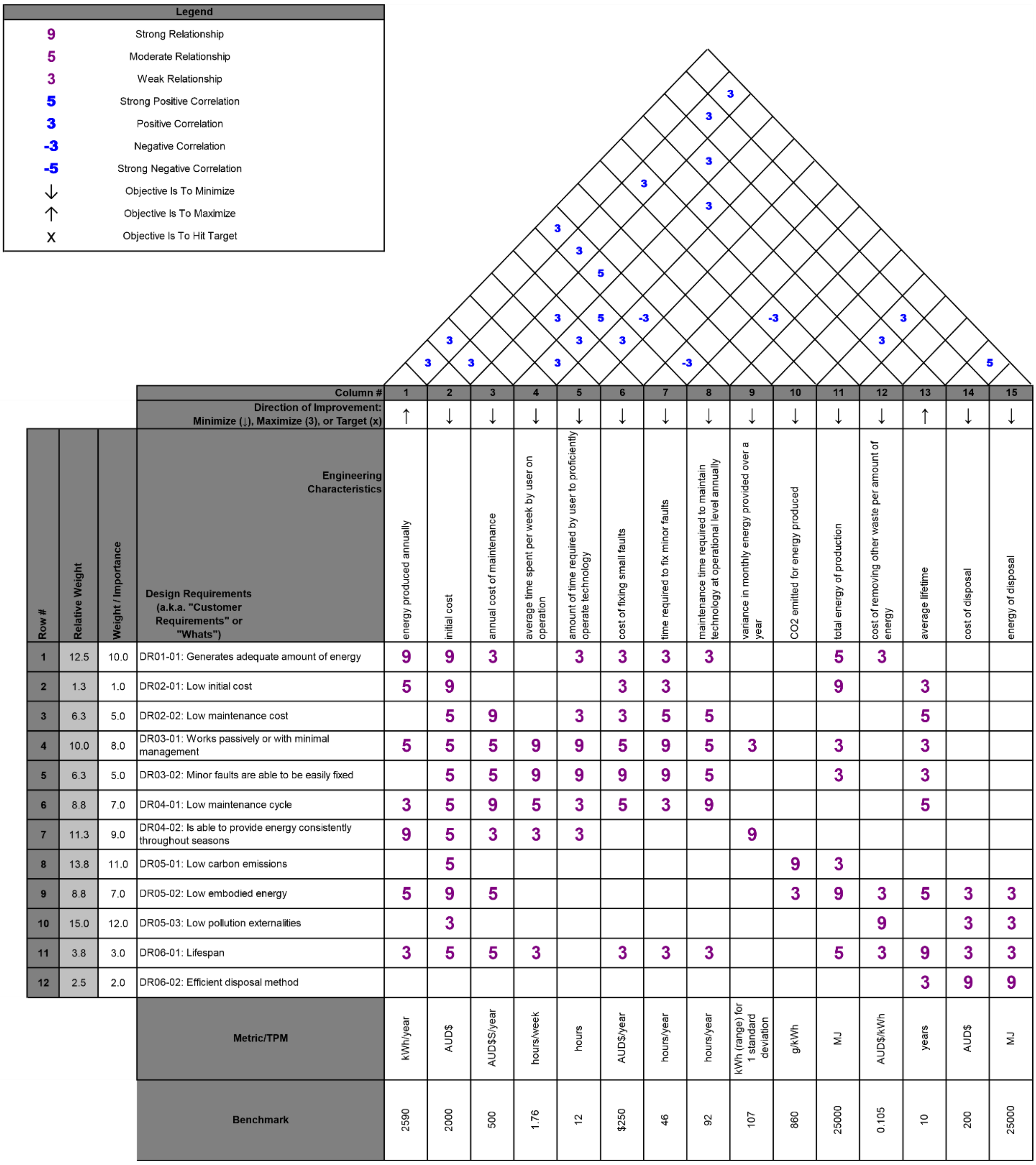
Through pairwise analysis the order of importance of each design requirement was found. This was done by forming a pairwise comparison chart (Table 6, in section 9: Appendix) where combinations of each set of two requirements were weighted against each other for relative importance. The combined score was used to find the ranking of the requirements which was used in future stages of analysis to rank the relative performance of the considered concepts in each metric. The tradeoffs between particular decisions were taken from a whole-systems policy perspective, i.e. at times the requirements that improved whole outcomes for all the stakeholders involved were chosen above those which benefited the primary user (a regular household).

The pairwise comparison chart used to find the weightings of each design requirement is in the Appendix. The resultant rankings are as follows:

1. DR05-03: Low pollution externalities
2. DR05-01: Low carbon emissions
3. DR01-01: Generates adequate amount of energy
4. DR04-02: Is able to provide energy consistently throughout seasons
5. DR03-01: Works passively or with minimal management
6. DR04-01: Low maintenance cycle and DR05-02: Low embodied energy
8. DR03-02: Minor faults are able to be easily fixed and DR02-02: Low maintenance cost
10. DR06-01: Lifespan
11. DR06-02: Efficient disposal method
12. DR02-01: Low initial cost

The most important design requirements are predictably, low pollution & carbon emissions, since that is a major concern in the world today. This is closely followed by the more use-case specific requirements such as production of adequate amounts of energy and year-round operation. Initial cost is ranked the lowest; it is important to note however that this is only contingent on all other requirements (effective operation of the system with minimum externalities) being satisfactorily served. In certain cases there were linear tradeoffs, for which an equal ranking (0.5) was given. For example, in comparing maintenance cost and maintenance cycle, each have equal tradeoffs – either the system has to be maintained sporadically for a greater cost, or frequently for a smaller cost.

3.2. Engineering Characteristics and House of Quality



Legend	
9	Strong Relationship
5	Moderate Relationship
3	Weak Relationship
5	Strong Positive Correlation
3	Positive Correlation
-3	Negative Correlation
-5	Strong Negative Correlation
↓	Objective Is To Minimize
↑	Objective Is To Maximize
X	Objective Is To Hit Target

			Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
			Direction of Improvement: Minimize (↓), Maximize (3), or Target (x)	↑	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↑	↓	↓
Row #	Relative Weight	Weight / Importance	Engineering Characteristics Design Requirements (a.k.a. "Customer Requirements" or "Whats")	energy produced annually	initial cost	annual cost of maintenance	average time spent per week by user on operation	amount of time required by user to proficiently operate technology	cost of fixing small faults	time required to fix minor faults	maintenance time required to maintain technology at operational level annually	variance in monthly energy provided over a year	CO2 emitted for energy produced	total energy of production	cost of removing other waste per amount of energy	average lifetime	cost of disposal	energy of disposal
1	12.5	10.0	DR01-01: Generates adequate amount of energy	9	9	3		3	3	3	3			5	3			
2	1.3	1.0	DR02-01: Low initial cost	5	9				3	3				9		3		
3	6.3	5.0	DR02-02: Low maintenance cost		5	9		3	3	5	5					5		
4	10.0	8.0	DR03-01: Works passively or with minimal management	5	5	5	9	9	5	9	5	3		3		3		
5	6.3	5.0	DR03-02: Minor faults are able to be easily fixed		5	5	9	9	9	9	5			3		3		
6	8.8	7.0	DR04-01: Low maintenance cycle	3	5	9	5	3	5	3	9					5		
7	11.3	9.0	DR04-02: Is able to provide energy consistently throughout seasons	9	5	3	3	3				9						
8	13.8	11.0	DR05-01: Low carbon emissions		5								9	3				
9	8.8	7.0	DR05-02: Low embodied energy	5	9	5							3	9	3	5	3	3
10	15.0	12.0	DR05-03: Low pollution externalities		3										9		3	3
11	3.8	3.0	DR06-01: Lifespan	3	5	5	3		3	3	3			5	3	9	3	3
12	2.5	2.0	DR06-02: Efficient disposal method													3	9	9
			Metric/TPM	kWh/year	AUD$	AUD$S/year	hours/week	hours	AUD$/year	hours/year	hours/year	kWh (range) for 1 standard deviation	g/kWh	MJ	AUD$/kWh	years	AUD$	MJ
			Benchmark	2590	2000	500	1.76	12	$250	46	92	107	860	25000	0.105	10	200	25000

Figure 1: House of Quality for a household energy system

The design requirements formed in the last section were only indicative of the particular criterion that the system was meant to fulfil. However in a wider context these had to be linked to particular engineering characteristics of the system with particular metrics that could be used to assess designs for effectiveness. Together these were used to form Technical Performance Measures (TPMs) that helped quantify the previously qualitative requirements for the system (Table 7 in section 9: Appendix).

Requirements that were specific in nature were directly translated into technical engineering characteristics. Others were subjective, such as amount of time invested by the user in keeping the system operational. In these cases a basket of measures such as cost and time required to keep the system operational and fix minor faults were defined. The most important measures were those that measured the amount of energy that could be produced consistently year round. For these, the mean monthly and annual quantities of energy, as well as the average variance of monthly energy generated between seasons (during a year) was found to be the most useful to evaluate.

In many cases, a design requirement will have relationships with multiple engineering characteristics even when the particular characteristic was created in response to a single requirement. Additionally often there are tradeoffs between characteristics and requirements that need to be quantized to allow for comparison of designs that cater to design requirements differently. A House of Quality was formed to link the design requirements, and engineering characteristics with each other (Figure 1).

According to the House of Quality, cost and energy have the strongest correlation whereas time spent operating the system is relatively independent of the other requirements and characteristics. In order for the system to be suitable for the user, the most important metrics to optimise are the energy produced and the initial cost. Another important piece of analysis found from the HoQ was that there are direct tradeoffs between making a system easy to maintain by the user and lowering the maintenance cost itself which relate to the preferences of the user. A system that is easy to fix, but takes a significant amount of time to do so is less preferable from the user's point of view compared to a system that can be fixed by a professional for a reasonable cost.

From the HoQ, a direct correlation between the complexity of production (embodied energy and disposal energy) and cost was found. This also related to the lifespan and maintenance characteristics of the system. A larger system can produce more energy and meet the users' needs better; however it comes not only with a larger initial cost (as expected) but also with environmental externalities in the form of production and disposal energy.

Benchmarks were also defined for each characteristic. There were determined based on statistical energy consumption habits, expenditure estimates based on income, and for energy and pollution metrics, appropriate comparisons with fossil fuel powered mains electricity. The data and methodology is available in Appendix section 9.1.

4. Concept Generation & Evaluation

A literature review on the subject matter revealed that decentralised household and community energy generation solutions already exist and have been implemented in developing parts of the world such as India, China and Africa. The most well-known of these technologies is solar PV, however other solutions such as wind, biogas, biodiesel and LPG have also been implemented (Sen & Bhattacharyya, 2013). In some cases, hybrid suites of technologies have been implemented to improve the reliability of the systems year round (DR04-02) (Rahmana, et al., 2014). Finding already implemented solutions to decentralised energy generation, and reviewing the available literature to find relevant information that could help judge concepts was then required.

4.1. Concept Classification

Different concepts fall within various categories of energy generation sources. Finding current solutions and organising them with respect to each other was crucial to comparing the most effective concepts. There were several subsystems to an energy generation system that carry out the functions of generation, storage and dissipation. Concept generation mainly focused on the whole energy system, mainly comparing energy generation methods as storage methods largely pertain to the form of generation and are fairly standardized.

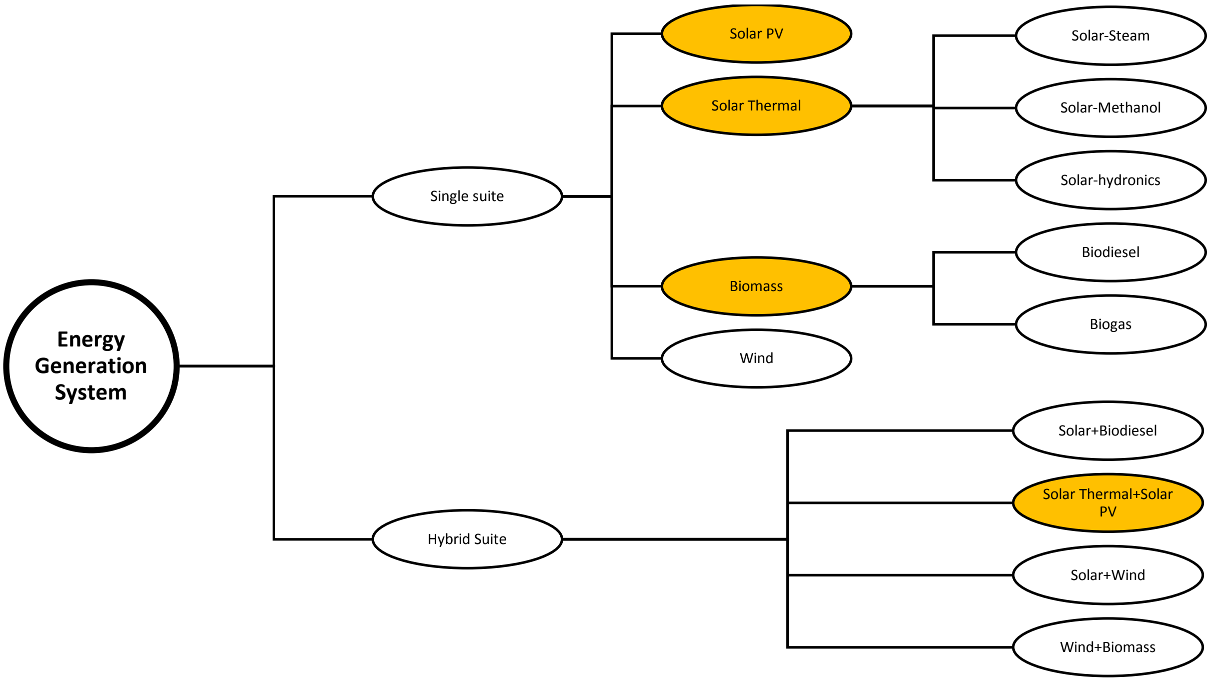


Figure 2: Concept Generation Tree

From the concept generation tree (Figure 2) four concepts were selected for further evaluation. These were mainly solar energy based solutions, which were deemed to be most likely suitable for Canberra due to its ample sunshine hours (Bureau of Meteorology, 2014). For a fair comparison, Biomass was also included (even though it is unlikely that Canberra residents would be able to easily access biomass resources), however wind was excluded as most wind-energy based solutions required larger scale implementation to achieve the necessary economies of scale. The hybrid implementation of solar thermal and solar PV was also chosen as it would form a good feasible substitute to single suite systems.

4.2. Concept Evaluation

Based on the HoQ and Benchmarks determined earlier, an evaluation matrix was formed to compare the generated concepts. Each concept was scored 1-5 on a rank scoring for each engineering characteristic. The scoring was based on the actual TPM and how far it exceeded or undershot the defined benchmark. Engineering characteristic scoring was then scaled and weighted based on its relative relationship to each design requirement (Figure 1). A final score was determined based on the ranking weight of each design requirement. The maximum possible score was 400. A perfectly ‘average’ system, i.e. one with score for 3 in every engineering characteristic, would score 240.

Each system was chosen to best cater to the particular range of benchmarks provided, i.e. approximately 2kW systems that could fulfil 20% of the household’s yearly energy requirement or more. As there was significant diversity in the scale of the implemented systems, the relative comparisons of other engineering characteristics of a small to medium scale household generator would provide the best comparisons of different renewable systems of similar size.

As can be seen in the matrix, the designed that scored the highest was a hybrid solar PV/Thermal system, closely followed by a solar thermal system. This system encompasses the efficiency of both photovoltaic and thermal systems together, and reduces effects of thermal factors on PV generation by an increase in thermal generation. Although this system is expensive, a system of the same size as a standard 2kW Solar PV system can generate far more energy and go further towards fulfilling a household's needs. This also comes at a much smaller increase in cost than anticipated due to linked systems sharing technology (Marsh, 2010).

Table 4: Evaluation Matrix for generated concepts

Engineering Characteristics	**Solar PV Score**	**Solar Thermal score**	**Biomass Score**	**Hybrid Solar PV/Ther. score**
energy produced annually	4	4.5	5	5
initial cost	1	2.5	1	2
annual cost of maintenance	5	4	3	4.5
average time spent per week by user on operation	4	5	2	4.5
amount of time required by user to proficiently operate technology	4	4	3	4
cost of fixing small faults	5	4	3	4.5
time required to fix minor faults	5	5	4	5
maintenance time required to maintain technology at operational level annually	5	5	4	5
variance in monthly energy provided over a year	2	2	5	2
CO2 emitted for energy produced	5	5	4	5
total energy of production	4	4	5	4
cost of removing other waste per amount of energy	5	5	4	5
average lifetime	4	3.5	4	4
cost of disposal	3	3	3	3
energy of disposal	3	3	5	3
Design Requirements				
DR01-01: Generates adequate amount of energy	3.71	4.00	3.46	4.07
DR02-01: Low initial cost	3.85	3.98	3.80	4.18
DR02-02: Low maintenance cost	4.20	4.00	3.14	4.17
DR03-01: Works passively or with minimal management	4.05	4.17	3.33	4.20
DR03-02: Minor faults are able to be easily fixed	4.23	4.25	3.07	4.27
DR04-01: Low maintenance cycle	4.23	4.18	3.17	4.31
DR04-02: Is able to provide energy consistently throughout seasons	3.06	3.44	3.72	3.50
DR05-01: Low carbon emissions	3.65	4.09	3.29	3.94
DR05-02: Low embodied energy	3.51	3.70	3.60	3.77
DR05-03: Low pollution externalities	3.67	3.92	3.50	3.83
DR06-01: Lifespan	3.92	3.91	3.56	4.03
DR06-02: Efficient disposal method	3.14	3.07	4.00	3.14
Total weighted score	299	314.5	273.9	316.5
Ranking	4	2	3	1

5. Functions & Subsystems

After selecting the best option of household energy generation, further design needed to be done on the actual integration of that technology into the wider system of the household and its inhabitants. For this, functional analysis needed to be done to model the interactions in the system, and allocate them to the specific subsystems in the generation system. A Functional Flow Block Diagram (FFBD) and from that, a Subsystem Interface was formed.

5.1. Functional Flow and Allocation

The initiating interaction of the user and the operation of the system thereafter can be displayed visually through the Functional Flow Block Diagram. In a Solar-Thermal Hybrid PV system, the functional flow involves looping that continues as long as the system is operational. There are also parallel processes that occur as energy generation and energy consumption happen concurrently. Thus the systems needs to adequately partition both processes and create appropriate feedback between the both to fulfil the user's requirements.

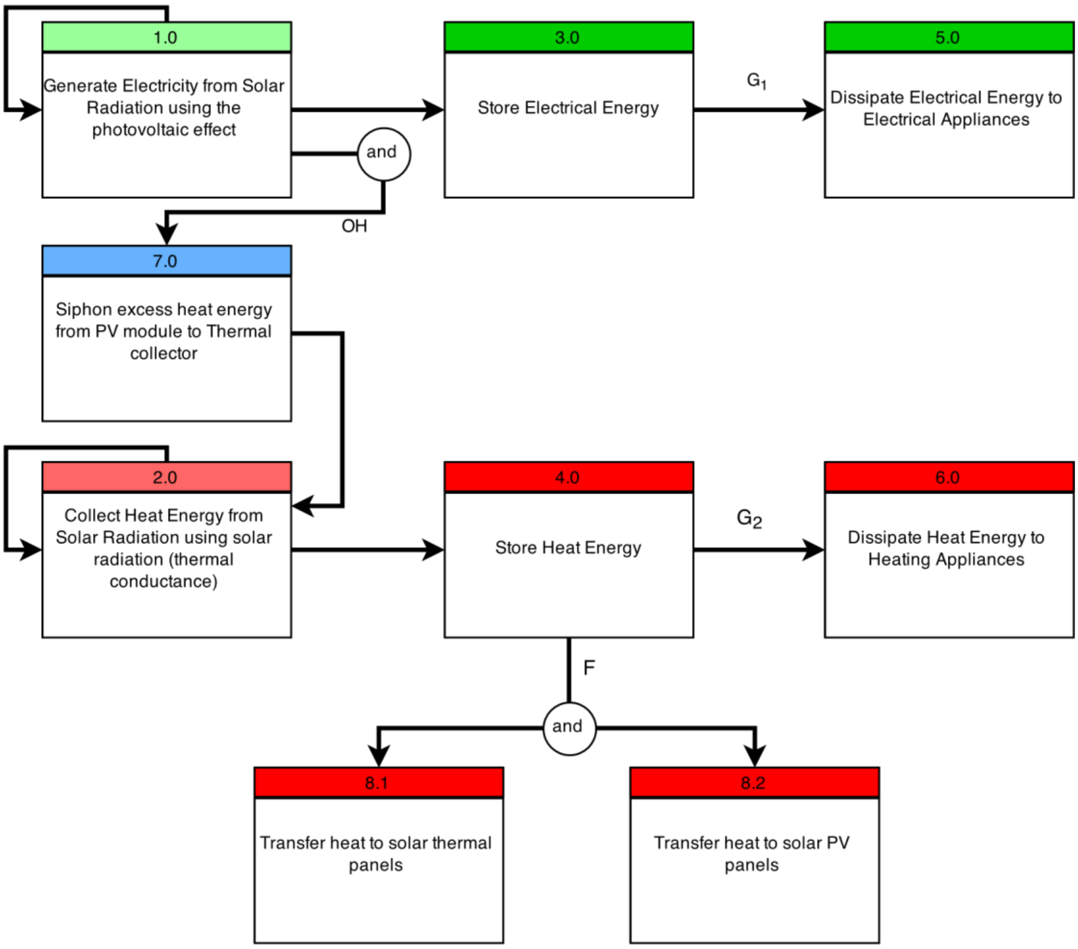


Figure 3: FFBD for a Solar PV/Thermal Hybrid System

Effectively the two functions of generating heat energy and generating electricity were effectively separate. This is to reduce cost; connecting solar thermal systems to battery storage has some energy loss, which is unnecessary since that energy will be used for heating anyway. However, there were some functions that linked the thermal and electric energy generation together. In the 'OH' (overheat condition), excess heat is moved to the thermal generation part of the system through a cooling system. In the event of 'F' (frost), heat is released from the heating storage onto both thermal and PV panel function subsystems. The G_1 and G_2 conditions indicate an electrical and heating appliance being turned on respectively.

With the FFBD (Figure 3) functional allocation has already been done. The red labelled functions relate to thermal energy generation and storage, with light red representing generation and dark red storage. The same shade convention is used for electricity generation and storage (green). Cooling is indicated by blue colouring. The system is partitioned into subsystems using the same colour key for the following section.

5.2. Subsystems Interface

Through the functional allocation in the previous section, four subsystems were already defined: Electric generation, Electric storage, Heat energy collection, Heat Storage, and Cooling. To coordinate all these, two other subsystems are needed: a Sensory Unit and Central Processing Unit. The former provides temperature and other relevant information to activate the cooling system or heat release mechanisms. The latter coordinates all these systems by processing the operational information and regulating energy flows in the system. These interact with the house heating and electrical wiring systems, as well as the environment, climate, and users. Modelling the different feedbacks between the systems was done using a subsystems interface. Secondary and Tertiary level subsystems also exist within the shown subsystems, but were not modelled in detail as that would not allow for variation of the particular generation/storage capacity according to the particular household’s needs and preferences.

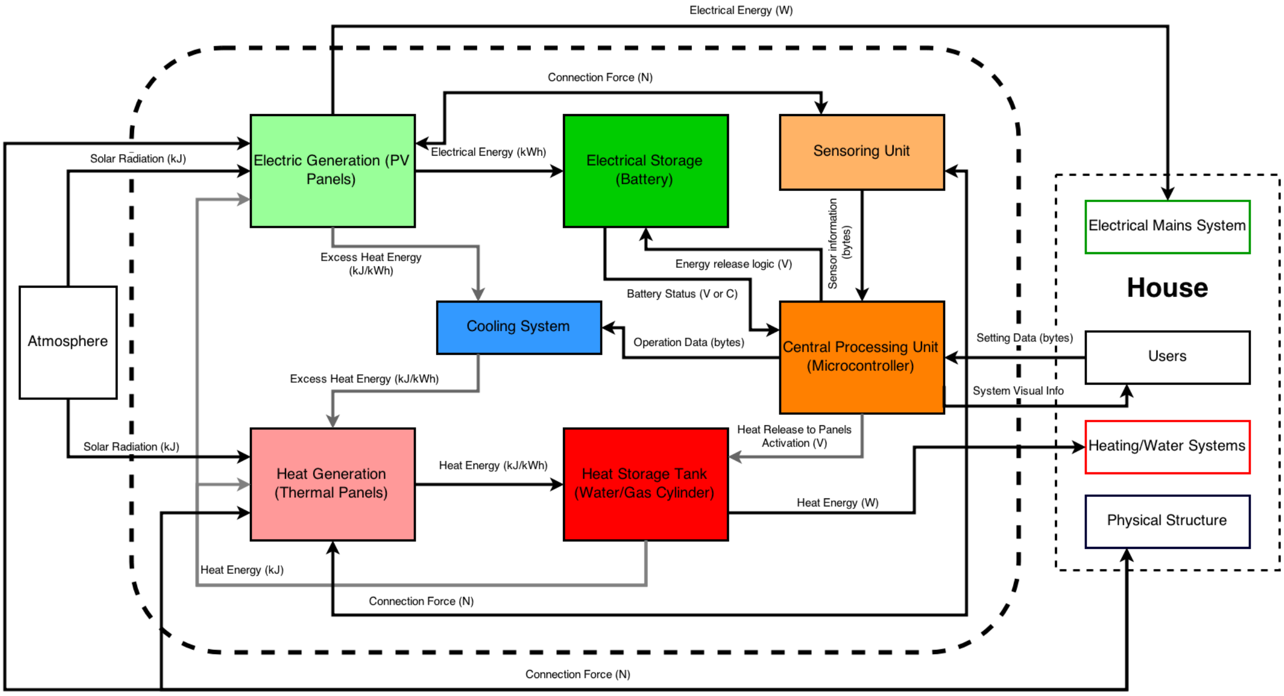


Figure 4: Subsystems Interface for Hybrid Solar PV/Thermall System

The system has a large number of feedback interactions within itself and with exogenous systems (Figure 4). The main system contains the subsystems mentioned earlier, and has interactions with the atmosphere and the house (with particular forms of energy transfer to house subsystems). The thermal heat generation and electricity generation systems are separate, apart from flows that happen indirectly through the cooling system or from heat storage to regulate temperature. As Canberra has a wide range of temperatures, with hot days and frosts, regulation of heat between both systems is important. One of the strengths of this design is that processes are decentralised and abstracted, hence any subsystem inside or outside the energy generation system can be replaced with minimal disruption.

6. Life Cycle Phases

In general, renewable energy systems are perceived to be environmentally friendly and carbon neutral. However, when we think of the entire Life Cycle of a Solar PV/Thermal system, there are significant carbon inputs into the production, disposal and some parts of operation of the technology (Weißbach, et al., 2013). For this reason, embodied energy was included as a design requirement (section 2.3). A proper sustainable design considers all inputs and output externalities throughout the life cycle of the system.

6.1. Production & Operation Efficiency

Through research, the optimum construction processes that minimise whole-system embodied energy and carbon output can be found. The qualitative nature of the production processes involved can help justify the most sustainable system that is preferable for Canberra households from a life-cycle perspective.

China is the major producer of photovoltaics due to vast economies of scale and relatively low production costs, thus most of Australia's PV demand comes from Chinese produced imports (Masson, et al., 2014). However, according to life cycle assessments, overseas produced solar PV cells are far more energy intensive and in comparison to domestically produced ones, with 30% less energy efficiency and double the carbon footprint (Yue, et al., 2014). This occurs due to the embodied energy entailed in all transfer of raw materials and processed goods.

Particular types of PV cells also require different energy inputs due to different energy processes. Monocrystalline Silicon PV cells produced in China are the most energy intensive, requiring nearly 50000MJ of energy to produce. In comparison, Ribbon-Si cells produced in Europe are the least intensive. This analysis excludes the energy cost of shipping, which is expected to increase the embodied energy. Nevertheless the difference is large, with PV cells manufactured in Europe taking 30% to 48% more embodied energy of those in China. Due to these factors Ribbon PV cells produced domestically or in Europe provide the best option for the PV part of the subsystem as they have the largest energy return on energy investment (EROEI), smallest payback time and least carbon emissions from production (ibid.).

Solar thermal collectors also have particular life-cycle issues. By connecting the collectors in parallel, the environmental efficiency of the system can be increased by a large amount (Lamnatou, et al., 2014). The materials that the solar thermal collectors are made out of are common in industrial processes, but are being depleted fast. Sustainable use of these materials and production from recycled parts will reduce the chances of the system's required materials being scarce in the distant future (Pihl, et al., 2012), as well as reducing other externalities such as acidification or eutrophication (leakage of dangerous chemicals into the environment) (Lamnatou, et al., 2014).

6.2. End of life Considerations

There is significant increase in the embodied energy of production and disposal if the materials obtained are from scratch. By producing the solar thermal collection cells out of recycled parts, the energy payback time for a solar thermal collector is 0.3 years compared to 2.1 years for a non-recycled system (Pihl, et al., 2012). Similarly by recycling materials for PV cells, some materials can be salvaged to reduce the energy wasted in extracting new resources. Other rare metals that lose quality after being re-extracted can be used to produce other less-refined goods such as glasses used in other manufacturing applications (Palitzsch, et al., 2014).

The concept of 'cradle-to-cradle' can be applied to the most sustainable life cycle solution for households pursuing solar energy generation system. This type of life cycle philosophy emphasises waste reduction and maximum reusability of parts. Other parts of the system can be chosen to best incorporate cradle-to-cradle processes. Recent batteries that accompany solar PV cells can also meet new sustainable design standards, such as the AHI Battery produced by Aquion energy (Energy Weekly News, 2015).

7. Testing and Communication

To correctly implement the system according to the customer requirements and in accordance with the particular engineering characteristics defined earlier (section 3.2), testing has to be done on various levels to ensure that the various connected subsystems have the correct predicted feedbacks with each other and exogenous systems. The stages of testing, and their desired deliverables or contingencies are outlined below:

Table 5: Testing specifications for the household Solar PV/Thermal Hybrid System

Type of Test	Testing boundaries	Deliverables/Objectives
Analytical	All subsystems defined in subsystems interface, with particular values for exogenous inputs (temperature, sunlight, house shape, consumption etc.).	• Diagram of subsystem parts and connections. • Identification of any incompatibilities between components with proposed solutions. • Predicted energy flows and outputs for yearly operation. • Ensuring that the system operates according to government regulations and standards.
Proof of Concept	Subsystem features, namely positioning of panels, energy dissipation and user interfaces.	• Detailed instructions and specifications for the operation of the system. • Effective design explanation for the end-user.
Operational	All subsystems with open feedback with exogenous systems. Systems tested in appropriate parts, i.e. generation and storage parts for PV and Thermal separately, as well as CPU and sensor.	• Check that all subsystems are operating correctly in the actual working conditions. • Identify and preliminary faults with components and replace/fix them as required. • Ensure that all system interactions and feedbacks are working as intended.
Support	Affected subsystems	• According to manufacturer's specifications, to provide data on faults identified with the system components

The first stage of testing determines whether there are any design issues with the particular components chosen, i.e. whether the particular set of PV panels, thermal collectors, batteries, tanks and CPU connect properly and work as intended. In many cases, systems of interconnected components might interfere with each other in unpredictable ways as feedbacks are non-linear. Based on this some specifications can be drawn up on the estimated amount of energy generated by the system on a day to day and monthly basis with ranges. Any incompatibilities have to be resolved at this stage by choosing suitable components.

Prototype testing is not required as the parts needed to make up the chosen system have already been developed by companies. If any new integrating technologies are developed then these will have to be prototype tested to engineering standards. Therefore the next stage of testing is operational testing, which is done after the system is installed. Manufacturers generally provide operational tests, so the installer needs to conduct the appropriate ones to check that the subsystems are working as intended separately, and then test them all in unison as a whole complete energy generation system.

7.1. Final Design Communication

The previous six sections have created a whole framework from which the ideal household energy system for an average Canberra household have been determined. Based on the system design methodologies applied, the best system for a Canberra household is a Hybrid Solar Photovoltaic and Thermal (PVT) Energy Generation system. The main use of this system will be to generate electricity for appliances and heat water (and possibly spaces).

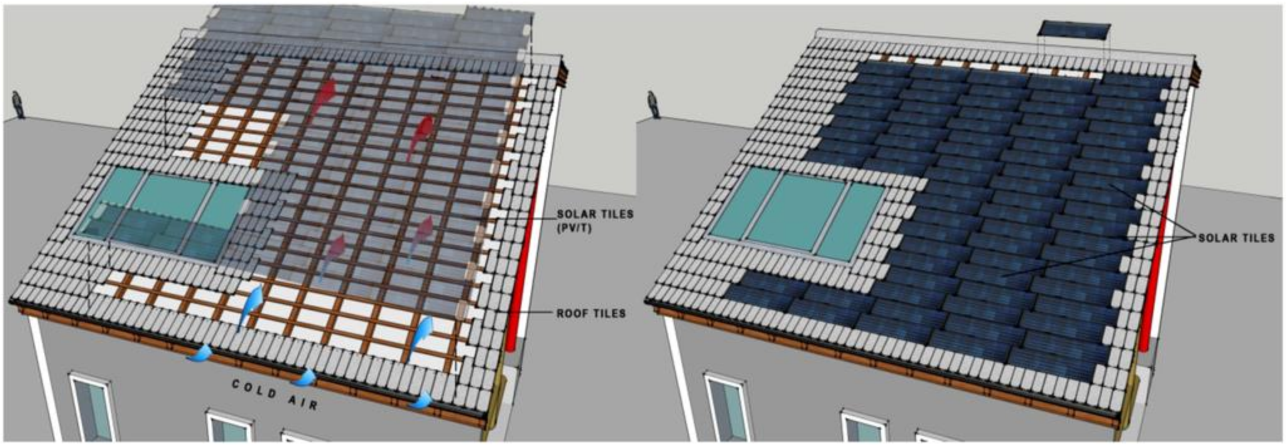


Figure 5: Example mounting for a Hybrid PVT system. Source: Noguchi, 2013.

The solar panels will be roof mounted. Based on the input location of Canberra on the EnergyMatters online calculator, a 2kW system is more than enough to fit the benchmark for energy generated annually – 3332 kWh, resulting in 25.71% reduction in grid energy consumption and 4331 kg less CO2 emitted. Based on an already existing system, the Solimpeks PowerTherm, the thermal components can heat 65L an hour during day hours (Solimpeks, 2011), which provides an average of 494L per day of heated water based on Canberra's average daily sunshine hours (Bureau of Meteorology, 2014). If required, the thermal collectors can also be connected to gas heating systems. It is expected to last over 20 years, and warranties for the first 10-20 years of output are provided (Solimpeks, 2011). The Central Processing Unit and onboard sensors will also automatically cool the PV arrays when above operational temperature, and have frost protection through release of heat from the storage tank when the temperature falls to frost levels. The efficiency of achieving both heating and electricity generation of a significant portion of the average Canberra household's consumption is expected to have a far shorter payback period, both in cost and energy invested, than the total lifetime of the system.

8. Conclusion

Out of a large range of technologies the best method of household energy generation for Canberra households was found through application of the systems design process. A Hybrid Solar PV/Thermal system was deemed to be the best option for the average Canberra household, based on the energy demands and particular characteristics of other factors such as the climate. Due to Canberra's ample sunshine, it is expected that such a system will provide enough energy for water heating, and up to a quarter of the family's average daily energy consumption. The cost of such a system is estimated to be in the range of $7000-$10000 (Clean Energy Council, 2014), with a payback period of less than 10 years. Life-cycle considerations means that it is ideal if the system is produced in Australia or Europe, with materials and manufacturing processes that consume less energy in production.

The systems design methodologies used also defined a connections of functions and subsystems that will allow for maximum redundancy of system operation. The PV Electric and Thermal aspects of the system were separated from each other and into generation and storage subsystems. A cooling system as modelled as well as heat releases from the heat storage to reduce overheating and frosting of the panels. A Central Processing Unit directs all these other subsystems and directs flow of electricity and heat to the house power and heating systems. Testing specifications were also determined to ensure that the system is operating satisfactorily for households at all times.

There is also scope to extend the design process presented in this portfolio, both in scope and for other contexts. The design requirements and engineering characteristics outlined can be reused (with different benchmarks) for different regions in Australia. However, subsequently the technology determined to be best for that particular environment and user might be different, and hence the remaining part of the analysis would need to be re-done. Thus the solution presented is only applicable within the scope and system boundaries set, namely an average 3 person household in Canberra.

At the same time the solution presented was very broad in application. Another design process could be done to compare particular types of hybrid PVT energy generation, in terms of materials and components, as well as particular sets of designs. Analysis can also be done to investigate other energy storage methods, such as gas or hydrogen fuel. Such analysis is expected to narrow down the scope of the design to providing better alternatives to particular parts of the decentralised energy generation process.

9. Appendix

Table 6: Pairwise Comparison Chart

Design Requirement	**ID**	*01-01*	*02-01*	*02-02*	*03-01*	*03-02*	*04-01*	*04-02*	*05-01*	*05-02*	*05-03*	*06-01*	*06-02*	**Score**	**Rank**
Generates adequate amount of energy	*01-01*		1	1	1	1	1	1	1	0	0	1	1	9	3
Low initial cost	*02-01*	0		0	0.5	0	0	0.5	0	0	0	1	0	2	12
Low maintenance cost	*02-02*	0	1		0	1	0.5	0	0	0	0	0.5	1	4	8
Works passively or with minimal management	*03-01*	0	0.5	1		1	0	0.5	0	1	0	1	1	6	5
Minor faults are able to be easily fixed	*03-02*	0	1	0	0		1	0	0	0	0	1	1	4	8
Low maintenance cycle	*04-01*	0	1	0.5	1	0		0	0	1	0	0.5	1	5	6
Is able to provide energy consistently throughout seasons	*04-02*	0	0.5	1	0.5	1	1		0	1	0	1	1	7	4
Low carbon emissions	*05-01*	0	1	1	1	1	1	1		0.5	1	1	1	9.5	2
Low embodied energy	*05-02*	1	1	1	0	1	0	0	0.5		0	0	0.5	5	6
Low pollution externalities	*05-03*	1	1	1	1	1	1	1	0	1		1	1	10	1
Lifespan	*06-01*	0	0	0.5	0	0	0.5	0	0	1	0		1	3	10
Efficient disposal method	*06-02*	0	1	1	0	0	0	0	0	0.5	0	0		2.5	11

Table 7: Engineering Characteristics and TPMs

ID	**Design Requirements**	**Engineering Characteristics**	**Metric (TPM)**
DR01-01	Generates adequate amount of energy	+ energy produced annually	kWh (energy over time)
DR02-01	Low initial cost	- initial cost	AUD$ (cost)
DR02-02	Low maintenance cost	- annual cost of maintenance	AUD$/year (cost)
DR03-01	Works passively or with minimal management	- average time spent per week on operation	hours/week (time)
		- amount of time required to proficiently operate technology	hours (time)
DR03-02	Minor faults are able to be easily fixed	- cost of fixing small faults	$/year (cost)
		- time required to fix minor faults	hours (time)
DR04-01	Low maintenance cycle	- time required to maintain technology at operational level annually	hours/year (time)
DR04-02	Is able to provide energy consistently throughout seasons	- variance in monthly energy provided over a year	kWh/month (range)
DR05-01	Low carbon emissions	- CO_2 emitted for energy produced	g/kWh (mass per energy over time)
DR05-02	Low embodied energy	- total energy of production	MJ (energy)
DR05-03	Low pollution externalities	- cost of removing other waste per amount of energy	$/kWh (value over energy)
DR06-01	Lifespan	+ average lifetime	years (time)
DR06-02	Efficient disposal method	- cost of disposal	$ (value)
		- energy of disposal	MJ (energy)

9.1. Benchmark Data

- Based on the Australian Government's climate classification, Canberra is in Zone 7 – Cool temperate climate.
- Mean weekly consumption is 248.8 kWh per week = 12937.6 kWh a year. We shall set the benchmark as 20% of this, which is 2587.52 kWh, rounded to 2590kWh.
- Average Weekly expenditure on energy is $48 a week, or $2496 a year. This is used to set the annual cost of maintenance, which is 20% of the total yearly energy expenditure, $499.2 a week, rounded to $500.
- Initial cost was based on analysis of the mean yearly household income, which was $98332. It was estimated that households with interest in investing in renewable energy would be willing to pay at least to 2% of this for an initial renewable system, which is $1966, rounded to $2000 (Department of Infrastructure and Transport, 2013).
- Time dedicated to fixing the system was deemed to be 5% of average weekly Leisure time (21% of total time according to the ABS). This amounted to 1.764 hours or 106 minutes per week.
- The value of time spent to proficiently operate technology was set to 12 hours, or 10% of the recommended driving learning time.
- Cost of fixing small faults was set to 50% of annual maintenance cost (defined earlier), or $100. This is contingent on this amount being included on the annual maintenance cost.
- Annual time spent on fixing minor faults was decided to be a half of weekly operation time and thus was set to 46 hours.
- Similarly maintenance time was tied to cost of fixing mistakes by the user, so total maintenance time was set to 92 hours.
- Variance was set to 50% of the mean monthly energy production, or 107kWh / month.
- CO2 emissions were set to that from grid-purchased electricity in the ACT, currently at 860g per kWh (Department of the Environment, 2009)
- Embodied Energy and disposal energy was set to 2% of that of a house (currently average of 2500GJ), i.e. 25000MJ (Haynes, 2013).
- Cost of removing other waste, assuming 1kg waste per 1kWh, is calculated to be $0.105 per kWh based on the higher rate of $105 landfill disposal per tonne. This is meant to already represent an unsustainable amount (BDA Group, 2009).
- Lifetime was set to 10 years to allow for adequate payback period. Since inflation is outside the system boundary it was hard to provide a strong justification for this decision.
- Cost of disposal was set to 10% of initial cost.

10. Bibliography

Australian Bureau of Statistics, 2012. *4670.0 - Household Energy Consumption Survey, Australia: Summary of Results.* [Online]
Available at: http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/4670.0main+features100072012
[Accessed 20 May 2015].

Australian Bureau of Statistics, 2014. *Australian Capital Territory: Region Data Summary.* [Online]
Available at:
http://stat.abs.gov.au/itt/r.jsp?RegionSummary&region=8&dataset=ABS_NRP9_ASGS&geoconcept=REGION&measure=MEASURE&datasetASGS=ABS_NRP9_ASGS&datasetLGA=ABS_NRP9_LGA&regionLGA=REGION&regionASGS=REGION
[Accessed 13 May 2015].

BDA Group, 2009. *The full cost of landfill disposal in Australia,* Canberra: Department of the Environment, Water, Heritage and the Arts.

Bureau of Meteorology, 2014. *CBoM - Canberra Climate.* [Online]
Available at: http://www.bom.gov.au/nsw/canberra/climate.shtml
[Accessed 20 May 2015].

Clean Energy Council, 2014. *Guide to Installing Solar PV for Households.* [Online]
Available at: http://www.solaraccreditation.com.au/consumers/purchasing-your-solar-pv-system/solar-pv-guide-for-households.html
[Accessed 22 May 2015].

Department of Industry, 2014. *Product Profile: Solar Water Heaters,* Canberra: Australian Government.

Department of Infrastructure and Transport, 2013. *State of Australian Cities: Canberra/Queanbeyan,* Canberra: Australian Government.

Department of the Environment and Water Resources, 2007. Unit 2: The Fundamentals of Systems. In: *Whole System Design Suite.* Canberra: Australian Government.

Department of the Environment, 2009. *National Greenhouse Accounts,* Canberra: Australian Government.

Dey, C. & Lenzen, M., 2000. *Greenhouse Gas Analysis of Electricity Generation Systems.* Brisbane, University of Sydney.

Duncan, R. C., 2005. The Olduvai Theory: Energy, Population and Industrial Civilization. *The Social Contract*.

Energy Weekly News, 2015. *Aquion energy, inc.; aquion energy AHI battery first in the world to be cradle to cradle CertifiedTM.* [Online]
Available at: http://search.proquest.com/docview/1676431423?accountid=8330
[Accessed 23 May 2015].

EnergyMatters, 2015. *Grid Connected Solar Power System Calculations & Output.* [Online]
Available at: http://www.energymatters.com.au/climate-data/grid-calculate-solar.php
[Accessed 24 May 2015].

Haynes, R., 2013. *Embodied Energy Calculations within Life Cycle Analysis of Residential Buildings,* Perth: eTool Consulting.

International Renewable Energy Agency, 2012. Solar Photovoltaics. *Renewable Energy Technologies: Cost Analysis Series,* June.1(4).

Kriström, B. & Kiran, C., 2014. *"Greening Household Behaviour and Energy", OECD Environment Working Papers, No. 78,* OECD Publishing.: http://dx.doi.org/10.1787/5jxrclm3qhr0-en.

Lamnatou, C., Notton, G., Chemisana, D. & Cristofari, C., 2014. The environmental performance of a building-integrated solar thermal collector, based on multiple approaches and life-cycle impact assessment methodologies. *Building and Environment,* 87(May), p. 45–58.

Marsh, G., 2010. Solar PV and thermal - a marriage made in heaven?. *Renewable Energy Focus,* March/April, pp. 52-55.

Masson, G., Orlandi, S. & Rekinger, M., 2014. *Global Market Outlook for Photovoltaics 2014-2018,* Brussels: European Photovoltaic Industry Association.

Mito Energy, 2011. *Solar Hot Water & Heat Pump Study,* Melbourne: Clean Energy Council.

National Renewable Energy Laboratory (USA), 2013. *Distributed Generation Renewable Energy Estimate of Costs.* [Online]
Available at: http://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html
[Accessed 22 May 2015].

Noguchi, M., 2013. Choice of Domestic Air-Sourced Solar Photovoltaic Thermal Systems through the Operational Energy Cost Implications in Scotland. *Sustainability,* 5(3), pp. 1256-1265.

Palitzsch, W., Schonherr, P. & Loser, U., 2014. *Integrated Approach for Economic PV Waste Recycling,* Langenweißbach: IEEE.

Pihl, E., Kushnir, D., Sandén, B. & Johnsson, F., 2012. Material constraints for concentrating solar thermal power. *Energy,* Volume 44, pp. 944-954.

Rahmana, M. M., Hasana, M. M., Paateroa, J. V. & Lahdelmaa, R., 2014. Hybrid application of biogas and solar resources to fulfill household energy needs: A potentially viable option in rural areas of developing countries. *Renewable Energy,* Volume 68, pp. 35-45.

Sen, R. & Bhattacharyya, S. C., 2013. Off-grid electricity generation with renewable energy technologies. *Renewable Energy,* Issue 62, pp. 388-398.

Solimpeks, 2011. *Installation, Operation, and Maintenance: Solar Panels.* [Online]
Available at: http://www.solimpeks.com/wp-content/uploads/2012/06/IMOL-SOL-EN-2011.pdf
[Accessed 24 May 2015].

Stucley, C. et al., 2012. *Bioenergy in Australia: Status and Opportunities,* Sydney: Bioenergy Australia.

Weißbach, D. et al., 2013. Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants. *Energy,* Issue 52, pp. 210-221.

Yue, D., You, F. & Darling, S. B., 2014. Domestic and overseas manufacturing scenarios of silicon-based photovoltaics: Life cycle energy and environmental comparative analysis. *Solar Energy,* 105(July), p. 669–678.