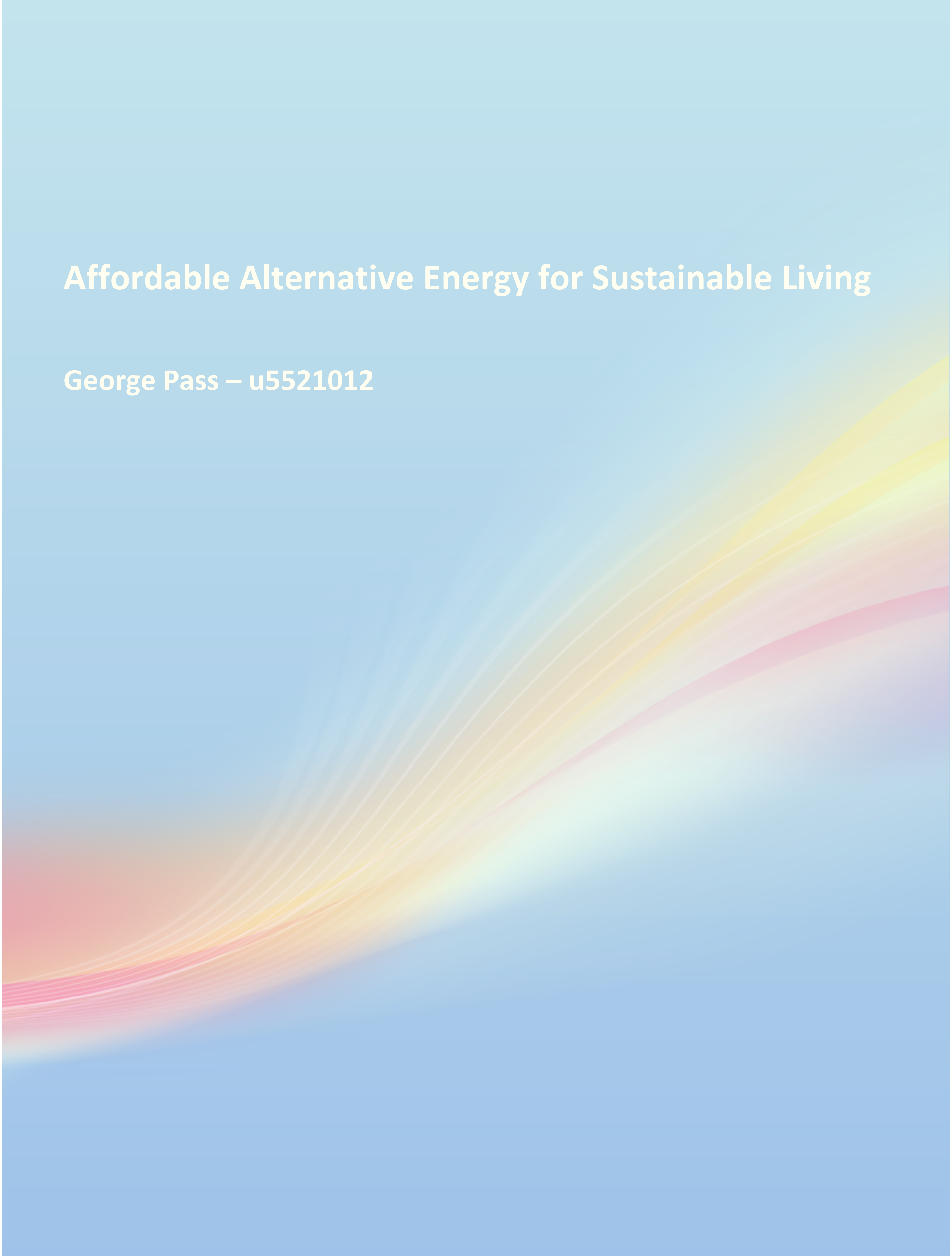

Affordable Alternative Energy for Sustainable Living

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1 Abstract

This report documents the design of an individual residential renewable energy supply system that aims to be both cost effective and reliable, using an ANU student home as an example. It employs a systems engineering approach to dissect and optimize the system design, ensuring that the end result is in harmony with the end user's requirements. A number of technologies are evaluated against the design requirements to select the most appropriate components to meet energy requirements while minimizing cost, before optimizing the system using modeling techniques. Once systems engineering methodologies are applied, it is shown that a grid connected solar PV system incorporating a Lithium-ion battery bank for energy storage is the most appropriate solution to meet the client's needs. In addition, the design includes a 'smart-controller' to optimize the charging behavior of the battery bank, minimizing external energy sourcing costs.

2 Introduction

In todays developed world, energy consumption in the modern family home has reached staggering proportions. Residential consumption contributes to roughly a third of the worlds energy needs (*Bocci, Zuccari, Dell'Era, 2011*).

The majority of Australia's energy is provided by coal; a non-sustainable and finite resource. Not only is the depletion of this source inevitable, with a national average growth in energy consumption between 1970 and 1996 of 4.9%/year (*Schipper et. al, 2001*), but it is an industry that nationally outputs half a billion tons of pollutants (CO_2-e) each year (*Lenzen, 1998*).

Currently only 14.76% of Australia's energy is provided by renewable sources (*Clean Energy Council, 2013*). In an effort to boost this figure, this report documents the design of an affordable renewable energy supply for an Australian home.

3 Design Scope

Table 3.1 shows the aspects of design that can be controlled, and the external factors that will and will not affect the design.

Table 3.1 System boundaries for individual residential renewable energy supply

Included (Endogenous)	**Excluded (Exogenous)**	**Outside**
Energy Source Used	Transport Cost	House Construction Type
Energy Conversion Capacity	Energy Source Availability	House Size
Energy Conversion Efficiency	Weather	Neighbours
Energy Storage Capacity	Available Installation Space	Appliances Used
Energy Storage Type	Energy Usage	Pest Presence
Initial Set Up Cost	Fabrication Costs	User Gender/Age
Design Look/Finish	Maintenance Cost	Water/Gas Usage

4 Requirements Analysis

The client has specified that the system should be expandable allowing for increased supply with increased consumption, and should have the potential to become completely independent of the main electricity grid. It should be sufficiently cost effective when compared to the current energy supply from ActewAGL, and should be able to supply at least half of the household's energy demands from renewable sources. If possible, the system should also be aesthetically pleasing and unobtrusive to daily life in the home.

A pairwise analysis of the initial requirements was performed to rank them in order of importance, with 1 being the most important and 4 being the least important. Table 4.1 shows the result.

Table 4.1 Pairwise analysis of customer requirements.

	Low Cost	Environmentally Friendly	Reliable	Aesthetically Pleasing	Sum	Rank
Low Cost		1	0	1	3	2
Environmentally Friendly	0		0	1	1	3
Reliable	1	1		1	4	1
Unobtrusive/Aesthetically Pleasing	0	0	0		0	4

It should be noted that while environmental impact is the second least important factor, there is a benchmark for the percentage of energy obtained from renewable sources.

To ensure the design fulfills the customer's needs, quantifiable design requirements are attributed to each customer requirement. Specific engineering characteristics will then be defined to achieve the design goals. Tables 4.2 and 4.3 show the fully expanded design requirements and engineering specifications needed to facilitate a successful solution.

Table 4.2 Design Requirements of the System

Customer Requirement	ID	Design Requirement	Metric	Direction
Cost Efficient	DR01-01	Low Capital Cost	\$/kW	-
	DR01-02	Low Ongoing Costs	\$/kWh	-
Reliable	DR02-01	Long System Lifetime	Years	-
	DR02-02	High Energy Supply Volume	kWh/day	+
Environmentally Friendly	DR02-02	High Energy Supply Volume	kWh/day	+
	DR03-01	Low C02 emissions	t-CO$_2$-e/kWh	-
	DR03-02	Minimal Deforestation	m^2	-
	DR03-03	Low environmental impact	kg waste	-
Aesthetically Pleasing	DR04-01	Aesthetic design options	#	+
	DR04-02	Minimal space required	m^3	-
	DR04-03	Low obtrusiveness factor	scale	-

The aesthetic requirement of the design is difficult to quantify, as it is very subjective and can vary on a client-by-client basis. As such, a customer rating metric is introduced whereby the customer will rate the aesthetics of the design on a scale of 1-10.

A back up power supply is also required, but since this is a simple yes or no requirement, it doesn't need to be analyzed in depth, and wasn't included as a design requirement.

Table 4.3 Specific Engineering Characteristics of the System

Design Requirement		Engineering Characteristic	TPM
Low Capital Cost	-	Manufacturing cost	$/kWh
	-	Transport cost	$/kWh
	-	Installation cost	$/kWh
Low Ongoing Cost	+	Mean Time Before Maintenance	years
	-	Maintenance Cost	$/kWh
Long System Lifetime	+	Mean Time Before Failure	years
	-	Number of moving components	#
	+	Storage Cycle Life	# Cycles
High Energy Supply Volume	+	Peak energy conversion rate	kW
	+	Available energy at conversion site	kW
	+	Energy conversion efficiency	%
	+	RMS Power Delivered to Home after transfer losses	kWh
	-	Storage self-discharge	% per month
	+	Storage Energy Density	Wh/L
	-	Storage Discharge Profile	Volt/DoD
	-	Storage Charge Time	hrs
Low C02 emissions	-	CO_2 emissions	Kg/lifetime
Low Environmental Impact	-	Waste Output	Kg/lifetime
	-	Bio-hazardous Materials Used	Kg/lifetime
Minimal Deforestation	-	Paper and cardboard packaging required	kg
Aesthetic design options	+	Number of component housing options	#
	+	Number of colour options	#
	+	Number of Integrated Components	#
Minimal space required	-	Size of components	m^3
	+	Storage Energy Density	Wh/L
Low obtrusiveness factor	-	Area of largest obstruction	m^2
	-	Visibility Factor	Scale/10
	-	Operating noise	dB

In addition to the more technical engineering aspects, there are a number of environmental factors that should be considered when evaluating a solution, such as deforestation and waste output.

Cost related characteristics will be measured with respect to the system's energy output over its lifetime. This recognizes that while a larger system will cost more initially, it may be more cost effective over the lifetime of the system.

5 Functional Architecture and Logical System Flow

Figure 5.1 shows the top-level functional architecture of a renewable energy system.

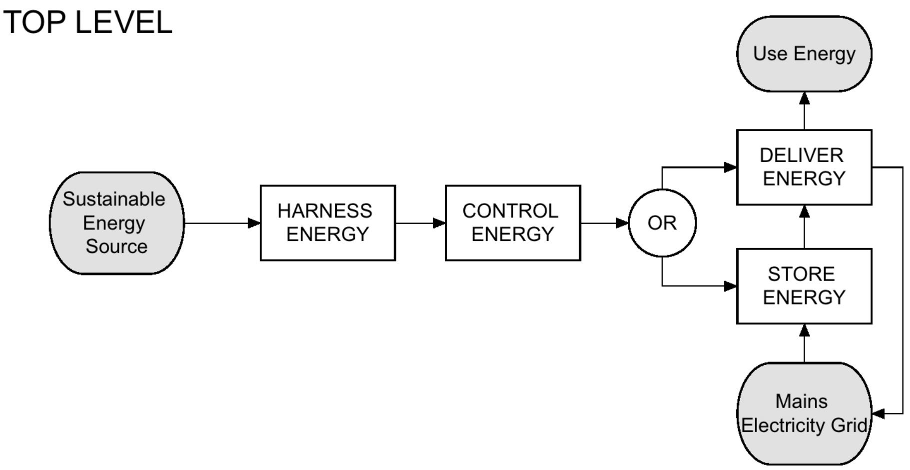

Figure 5.1 Top level functions of renewable power supply system

As with any renewable energy system that aims to be self-sufficient, an energy storage function should be included, as renewable sources often are not available consistently (*Divya, Ostergaard, 2009*).

The direct energy delivery will pass through the storage bank, supplying DC power, which must be converted to 240V AC to be used in the household. This is achieved using an inverter, which includes a step up transformer. If the renewable generation is unable to meet household demand, mains connectivity is required.

Regarding the mains connectivity, it was initially thought that mains electricity would be delivered directly to the house, but after research was conducted it was discovered that costs could be lowered by sourcing electricity from the main grid during off-peak usage periods, storing it for use during on-peak usage periods *(Ibrahim, et. al, 2008).* In addition to sourcing energy from the main grid, the system will be able to supply energy back in to the main grid when storage is full, selling energy back to the electricity provider at a rate of $0.075/kWh (*ActewAGL, n.d).*

Figure 5.2 shows sub-level functional architecture of the proposed system.

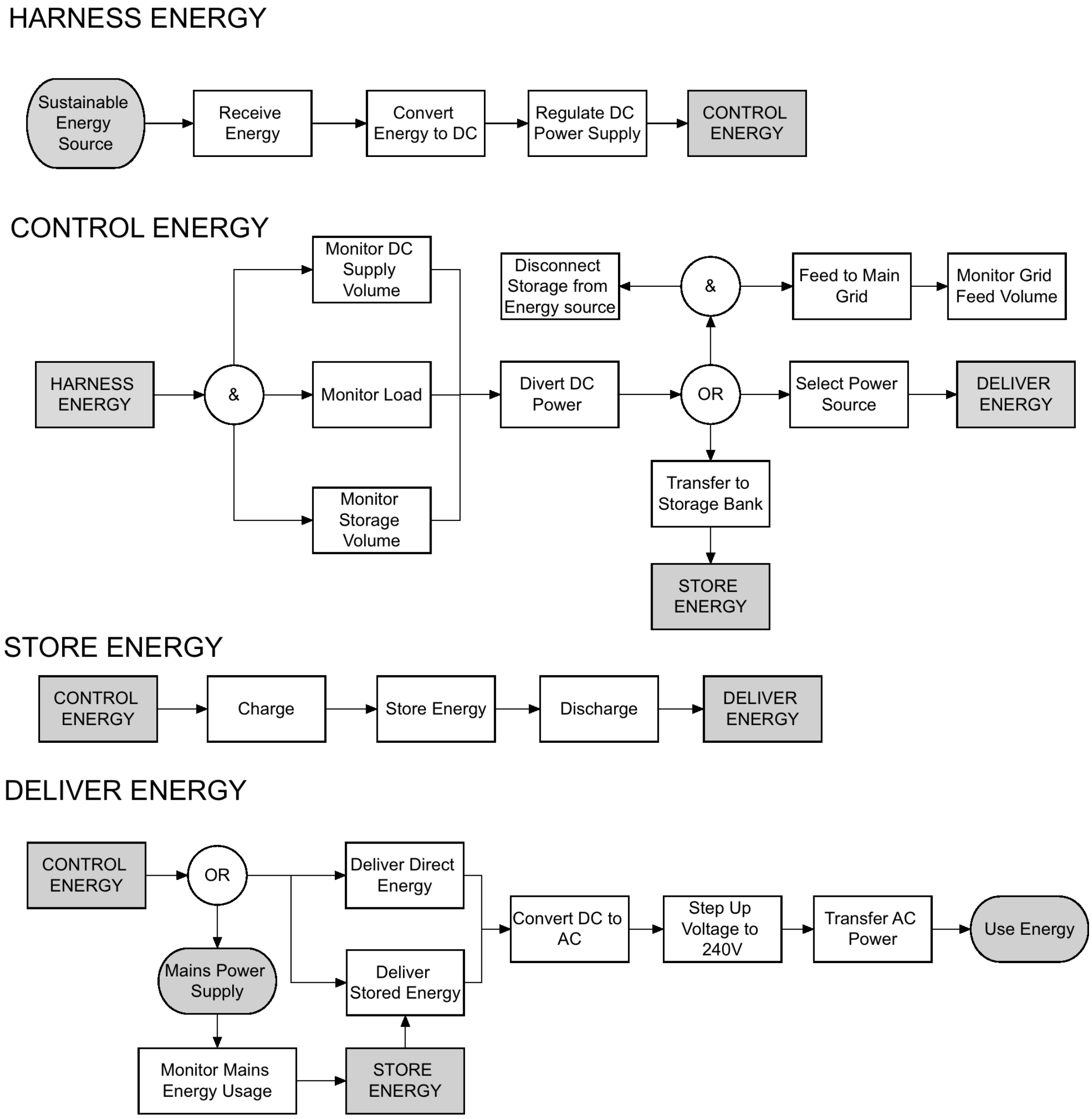

Figure 5.2 Detailed sub-level functional flow block diagram for renewable power supply system

In order to run efficiently and make the most of the renewable energy available, energy control functionality is included to monitor the demand and supply capacity, and select the appropriate power source accordingly. Figure 5.3 shows the logical slow for selecting and switching between power sources to charge the storage bank.

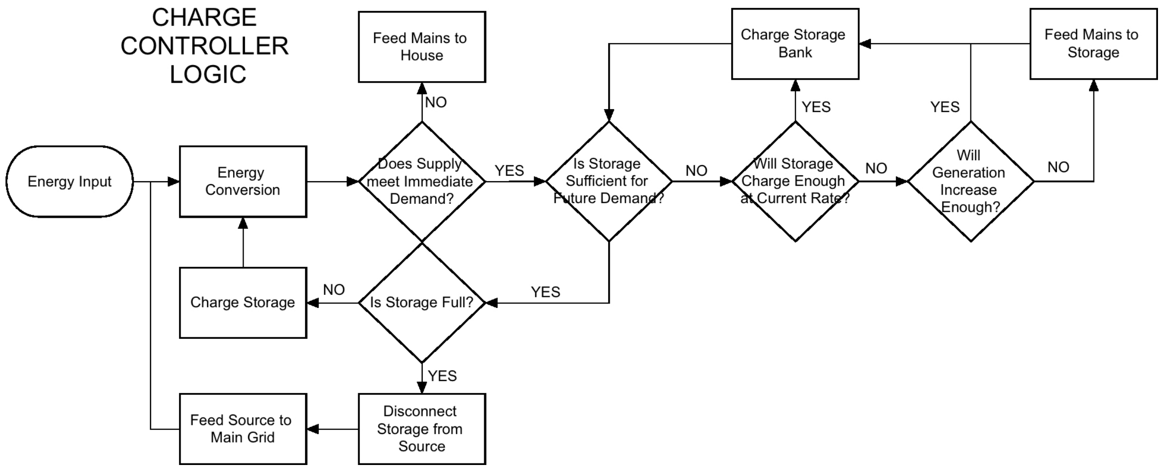

Figure 5.3 Logic flow for charge controller.

This logic flow was reconsidered after the final design was conceptualized to incorporate the functionality of a ‘smart controller’ system, as discussed later in this report.

6 Subsystem Analysis

The discreet subsystems of the design are already segregated in the functional flow block diagram in figure 5.2, though clearly defining how they interact will reveal the modularity of the design. This is important, as the client has specified that the system should be expandable. Figure 6.1 details how each of these subsystems interact.

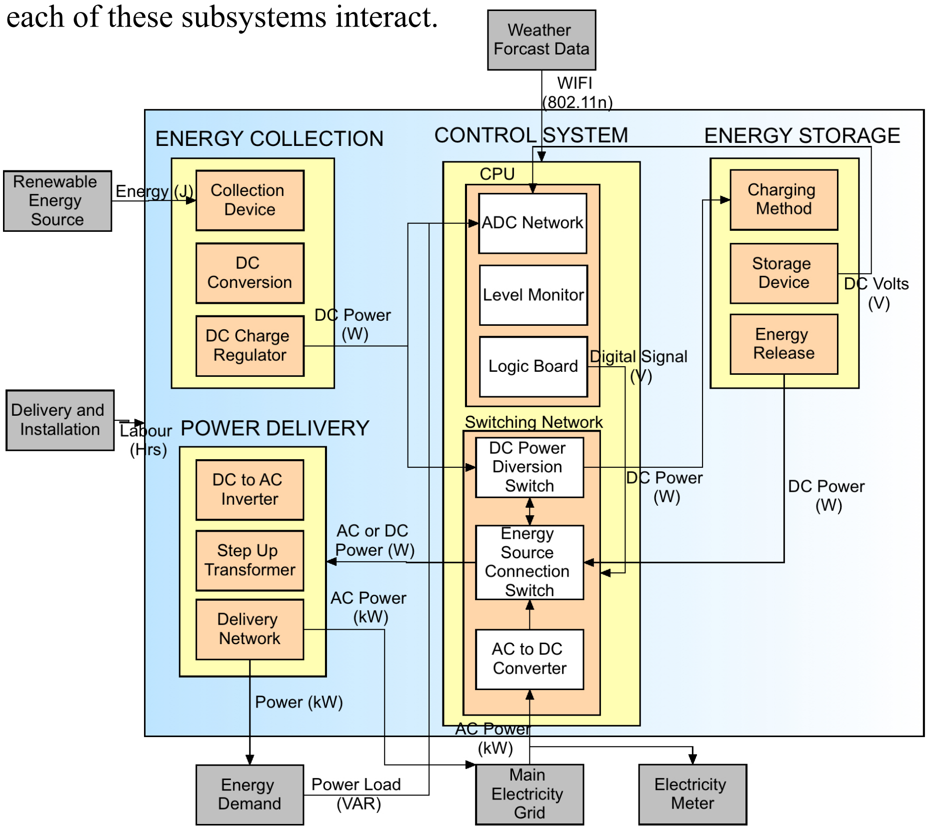

Figure 6.1 Subsystems integration of renewable energy system for a home

Weather forecast data has been included as an input into the system so that the ‘smart controller’ is able to gauge whether or not the storage will fully charge in time for peak energy use.

To ensure the system architecture will meet the client’s needs, an attributes cascade has been drawn up as shown in table 6.1.

Table 6.1 Attributes cascade for renewable energy system

Customer Requirement	Design Requirement	Engineering Characteristic	Related Subsystem
Cost Efficient	Low Capital Cost	Manufacturing cost	ALL
		Transport cost	ALL
		Installation Cost	ALL
	Low Ongoing Cost	Mean Time Before Maintenance	ALL
		Maintenance Cost	ALL
Reliable	Long System Lifetime	Mean Time Before Failure	ALL
		Number of moving components	EC
		Storage Cycle Life	ES
	High Energy Supply Volume	Peak energy conversion rate	EC
		Available energy at conversion site	EC
		Energy conversion efficiency	EC
		Power Delivered to Home after transfer losses	ALL
		Storage Self-discharge	ES
		Storage Energy Density	ES
		Storage Discharge Profile	ES
		Storage Charge Time	ES
Environmentally Friendly	Low C02 emissions	CO_2 emissions	ALL
	Low Environmental Impact	Waste Output	EC, ES
		Bio-hazardous Materials Used	EC, ES
	Minimal Deforestation	Paper and cardboard packaging required	ALL
Unobtrusive /Aesthetically Pleasing	Aesthetic design options	Number of component housing options	ALL
		Number of colour options	ALL
		Number of Integrated Components	ALL
	Minimal space required	Size of components	ALL
		Storage Energy Density	ES
	Low obtrusiveness factor	Area of largest obstruction	ALL
		Visibility Factor	ALL
		Operating noise	EC

This shows which systems are achieving which design requirements. There is little design freedom in the power delivery system and so the focus of this report will exclude this aspect. Table 6.1 shows that the most influential subsystems on the design performance are the energy collection system and the energy storage system. The majority of costs are incurred by these two subsystems, so great care should be taken in selecting the technologies here.

7 Design Concepts for Subsystems

To explore the solution space, a concept tree has been drawn up for each of the subsystems of focus. Table 7.1 shows the concept tree for the energy collection subsystem.

Table 7.1 Concept tree for energy collection technologies

Energy Collection	Photo-Voltaic	~~Solar Paint~~	
		Solar PV Panels (SPV)	~~Flexible Thin-Film~~ Rigid Cell Panels
		~~Solar PV Clothing~~	
	Kinetic	Wind	Parallel Axial Turbine ~~Orthogonal Axial Turbine~~ ~~Kinetic-electric Trees~~
		~~Hydro-electric~~	~~Pico-Hydro~~ ~~Micro-Hydro~~
		~~Dielectric elastomer clothing~~	
		~~Geothermal~~	~~Steam Power Turbine~~ ~~Vapour Power Turbine~~
	Thermal	~~Geothermal~~	~~Heat Pumping~~
		~~Bio-Fuel~~	~~Methane Gas~~ ~~Waste Combustion~~ ~~Corn-based Fuel Ethonol~~
		Solar Thermal	~~Low Temperature~~ ~~Mid-Temperature~~ ~~High Temperature~~
	Electro-magnetic	~~Radio signal harvesting~~	

The marked out concepts were eliminated for various reasons. High temperature solar thermal and geothermal powered turbines are not cost-effective at small scale due to the extensive infrastructure required. Resources for Hydro-electric and biofuel are not available at the install site. Dielectric elastomer clothing, solar PV clothing, radio signal harvesting, low-mid temperature solar thermal, and polymorphic thin-film solar PV systems do not generate sufficient power. The solar paint and orthogonal axis wind turbine technologies are still in their infancy, and will not be considered here due to the lack of available data. The concept selection pool has been narrowed down to just two technologies; SPV and parallel axis wind turbines.

Table 7.2 details various energy storage concepts.

Table 7.2 Concept tree for energy storage technologies

Energy Storage	Electro-Chemical	Lead-Acid (Pb-Acid) Lithium-Ion (Li-ion) Nickel-Cadmium (NiCd) Hydrogen Fuel Cells (HES) ~~Flow Batteries~~
	Kinetic	~~Flywheel~~
	Potential	~~Compressed Air~~ ~~Pumped Hydro~~
		~~Super/Ultra-Capacitors~~ ~~Superconducting magnetic~~

Again, the selection pool has been narrowed down for the following reasons: Compressed air and pumped hydro storage are both technologies that require vast chambers or reservoirs, superconducting magnetic storage requires high energy refrigeration to obtain superconductive states of matter, flywheels require a large wheel and a vacuum chamber to minimize friction losses, and ultra-capacitors are only suitable for short burst applications (Ibrahim et, al, 2008). The suitable technologies for small-scale renewable energy systems for individual residential use are limited to electrochemical storage mechanisms.

8 Research and Design

Figure 8.1 shows the average wind-speed and solar irradiation compared to the household usage throughout 2014, compiling weather data from the Australian Bureau of Meteorology and average usage data for each quarter from the energy provider, ActewAGL.

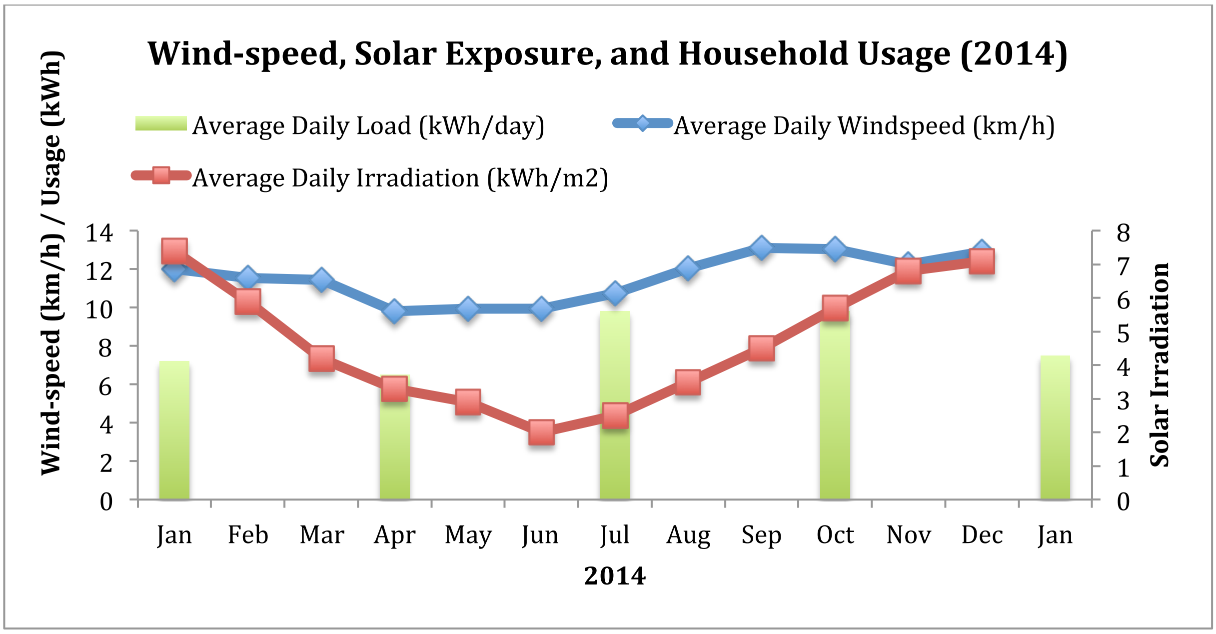

Figure 8.1 Average daily renewable sources available and average daily energy usage

The current price for energy in the client's home is \$0.274/kWh. By inspection of figure 8.1, the winter months have the highest household usage (9.9kWh/day), while providing the lowest solar irradiation. It is observed that the average solar irradiation varies greatly, with a maximum daily average of 7.4kWh/m^2, and a minimum daily average of just 2.2kWh/m^2. Conversely, average daily wind-speed is more consistent, with variation following the usage trend more closely.

The theoretical output of each renewable energy technology will be calculated and measured against the energy requirements of the household to determine system sizing. While different products have different technical specifications regarding power output, this report will examine a use case scenario for a particular product for each technology.

8.1 Wind-Turbine Power

In this use-case scenario, the selected wind turbine is the Ampair 600 wind turbine (*Ampair, 2007*). The method for calculating the theoretical energy output for this turbine was taken from the NSW Farmers Association's Farm Energy Innovations Program *(NSW Farmers Association, 2013)*. Hourly wind-speed data for Canberra over a period of 72 hours was obtained from the Australian Bureau of Meteorology. Figure 8.2 shows the wind-speed distribution for the data.

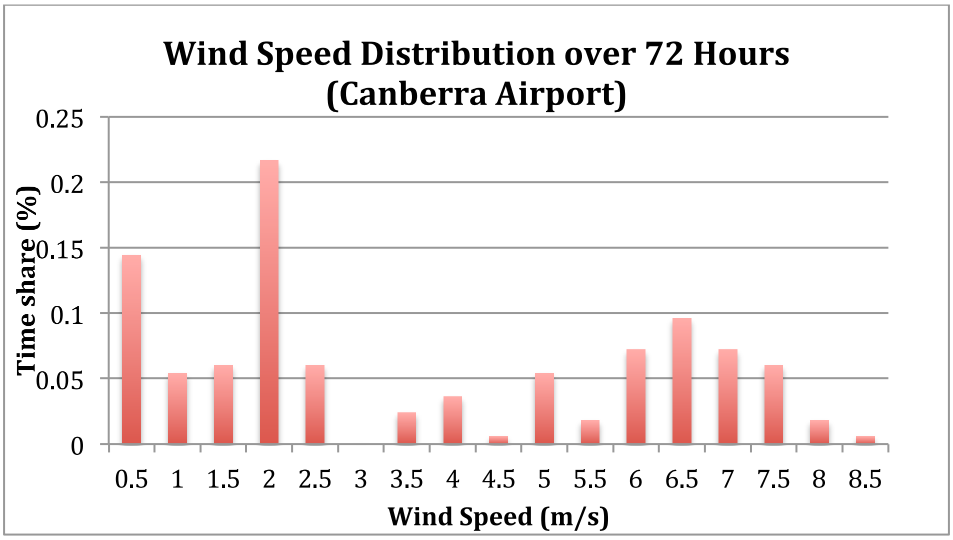

Figure 8.2 Wind-speed distribution for Canberra Airport for May 17th – May 20th

The wind-speed power curve was obtained from the Ampair 600 product manual, noting the cut-in speed at 3m/s. Using this information with the data shown in figure 8.2, and accounting for 20% losses due to self-discharge of the storage and inverter efficiency, the total energy output for a single turbine over a 24 hour period was calculated to be 1.58kWh.

The Ampair 600 can be purchased for $3,925, with a charge regulator for $1,270 *(isustainaustrlaia.com.au, n.d)*. To meet the demand of 9.9kWh, the system would require 6 of these turbines, culminating in a total cost of $24,220. Additional to the capital cost, wind turbine systems have an average ongoing cost of $40/kW/yr for mainatenance, adding a yearly cost of $144 (Elliston, et. al, 2013). Aside from high cost of the system, at 1.7m diameter for each turbine, and with each turbine needing to be mounted at least 5m above surrounding objects, total space required for a purely wind-based system exceeds the available on-site space.

8.2 Solar PV System

The selected product for analysis of solar PV is the Wanaico 260W WST-260P6 polycrystalline solar panel. For an estimate of the required system size, the following equation was used:

$$E_{req.}=ArSP$$ (*Photovoltaic-Software, n.d*)

Where E = the daily energy output (kWh), A = the required solar panel area (m^2), r = the module efficiency (%), S = the average daily global solar exposure (kWh), and P is the performance after losses ratio (PR)(%). Losses are again assumed to be 20%, giving a PR of 80%. The maximum efficiency for the selected product is 15.65%. However, the average degradation rate of a solar PV panel is 0.5%p.a (*Bhandari, 2015*). Given a nominal efficiency of 15.65%, the average lifetime efficiency of the panel will be 14.74%.

Data gathered from the Bureau of Meteorology shows the average daily solar exposure between the years 1990 and 2014 was 4.8kWh/m^2. However the lowest period of exposure occurrs in June with just 2.2kWh/m^2 (*Bureau of Meteorology, n.d*). Since the system needs to operate year round, it must be designed to meet demand even during the lowest daily exposure period. The required panel area was calculated to be:

$$A = \frac{E_{req.}}{rSP} = \frac{9.9}{0.1474\times2.2\times0.8} = 38.2m^2$$

The selected panel is 1.67m^2, so 23 of these solar panels will be required to meet the household demand. The Winaico WST-260P6 can be purchased for $399, with a charge regulator for $429, culminating in a total cost of $9606 (*solaronline.com.au, n.d*).

It should be noted that these calculations are based on a horizontal plane of irradiation, and that the system performance could be improved by varying the angle throughout the year. By optimizing the angle of tilt, the solar exposure received by the solar panels becomes more consistent over the year, and total energy production can be boosted by around 32% (*Tina, Gagliano, 2011*).

While this size of system meets energy demands in winter, the PV system would theoretically be capable of producing up to 43.4kWh/day in summer, greatly exceeding demand.

8.3 Energy Storage

The primary factors in sizing a battery bank are capacity, lifecycle, and discharge capabilities. The longevity of a battery bank is significantly affected by the depth of discharge (DoD) per cycle. Ideally, most batteries should not be drained below 50%, and the maximum DoD to maintain nominal battery lifetime is around 80% *(Linden & Reddy, 2002)*.

Given the average daily household demand, the bank should be able to provide 9.9kWh with 80% of its stored energy. A nominal voltage of 12V is selected, as this provides a reasonable efficiency for charging and discharging. Using basic electrical theory, the estimated battery capacity required is given by the following formula:

$$Capacity \ = \frac{Demand}{Votlage\times DoD}\times(Days\ of\ Autonomy)$$

Since the system will be connected to the main grid, numerous days of autonomy is not critical. The calculated battery capacity is 1031Ah.

A comparison analysis of different battery technologies was carried out in the *Handbook of Batteries*, and table 8.1 shows the comparative scoring of the 5 battery types being considered.

*Table 8.1 Comparison of Secondary Battery Technologies (Linden & Reddy, 2002)**

Type	Energy Density	Power Density	Flat Discharge Profile	Low Temperature Operation	Charge Retention	Charge Acceptance	Efficiency	Life	Cost
Pb-Acid	4	3	3	2	3	3	2	3	1
Li-ion	1	2	3	2	2	1	1	1	2
Ni-Cd	4	1	2	1	4	2	3	3	2
Ni-MH	3	2	2	2	4	2	3	3	3
Ni-Zn	2	3	2	3	4	3	3	4	3

**1 to 5, best to poorest*

From table 8.1, Lithium-Ion battery storage appears to have the best overall performance. A 90Ah 12V deep cycle lithium battery can be purchased for $999 *(ebay.com.au, n.d)*. To achieve the energy storage needed, the system will require 12 of these batteries, resulting in a total cost of \$11,998. The predicted cycle life for Li-ion batteries is typically 3000 at 100% DoD, and over 20,000 at 20%-40% DoD (*Linden & Reddy, 2002)*. At a DoD of 80% the cycle life can be conservatively estimated to be at least 6000. Assuming the bank is discharged to this capacity every day, the estimated lifetime would be 16.4 years, resulting in a lifecycle cost of \$731/year. By comparison, the equivalent lead-acid storage bank would cost approximately \$2,500, and achieve a cycle life of approximately 1,500, or 4.1 years, resulting in a lifecycle cost of \$609/year.

8.4 Charge Control

As mentioned, the system will be grid connected to provide a backup from the main electricity grid. However the periods in which the backup energy is required will mostly occur during peak electricity times. ActewAGL offer a time-of-use plan in which they charge more for electricity between the hours of 7am-9am and 5pm-8pm, and charge up to \$0.05/kWh less than standard rate from 10pm-7am (*ActewAGL, n.d*). A charge controller has the potential to minimize the cost of sourcing electricity from the main grid by charging the storage bank during off-peak periods if the renewable system is unable to deliver the energy required to charge the bank in time to meet demand. A wireless feed from the Bureau of Meteorology to predict generation capacity could be used as a means to optimize the charge periods.

As mentioned previously, connecting to the main grid will also allow the user to export any excess energy produced at a rate of \$0.075/kWh (*ActewAGL, n.d).*

9 Lifecycle Considerations

As a move toward a sustainable future, the design should take into account the carbon emissions in manufacturing, transport, and end of life activities, including recycling or refurbishment. Figure 9.1 shows the estimated CO_2 emissions for the system life of various energy generation technologies.

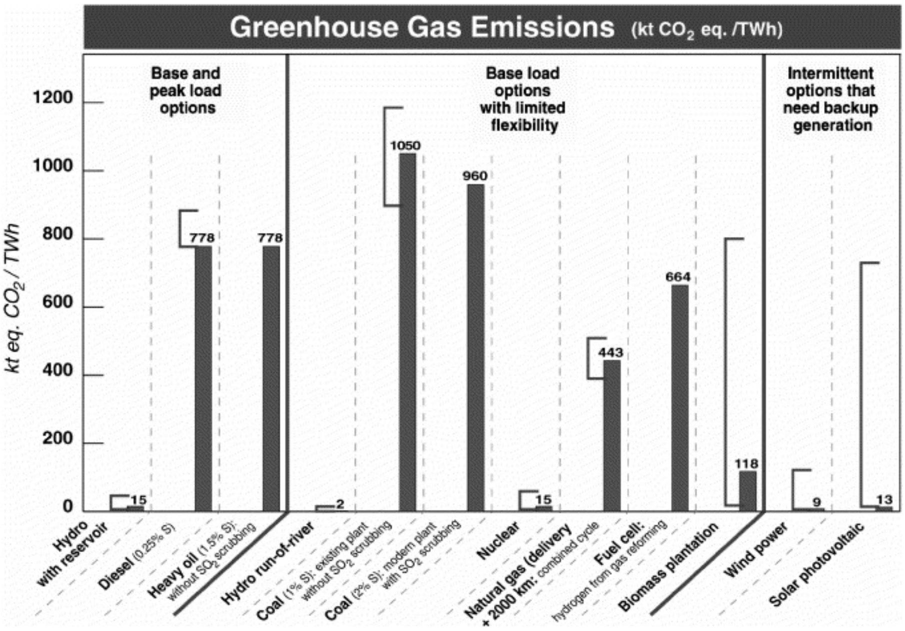

Figure 9.1 Lifetime carbon emissions for various energy generation technologies

From figure 9.1, solar PV has the highest carbon emissions per kWh over its lifetime of any renewable energy technology, at anywhere between 53.4 to 250 g-CO_2/kWh, though this is still just a fraction of that produced by conventional energy sources. The lowest carbon emission renewable energy technology is run-of-river hydro-power, with wind power coming in at second lowest, with between 9.7 and 123.7 g-CO_2/kWh (Varun, et. al, 2009).

End-of-life recyclability should also be considered to ensure an ethically responsible design and a sustainable production line. The majority of components for a solar PV panel are recoverable, including glass, aluminium, and semiconductor materials. There is already a high percentage of PV recycling, with up to 70% of European PV manufacturers engaged in PV recycling *(Gomez, 2009).* Wind-power systems, while do use many recyclable materials, are less recyclable due to the use of composite materials (*EWEA, 2011*).

In addition to considering environmental aspects, design should address opportunities throughout a system's life to improve on the system. For a renewable energy system, it is important to design it to be as modular as possible, as the field of renewable energy and it's technologies are continually expanding. As new higher performance and lower cost technologies become available, the design should be able to incorporate these to improve the overall lifetime performance. For example, the field of energy storage for renewable technologies is one of the highest researched fields in the energy sector (*Leadbetter, Swan, 2012*), and the release of Tesla Motors' Powerwall deep cycle lithium-ion battery could be a game changer when it comes to decentralized renewable energy systems (*Tesla Motors, 2015*). The system should be redesigned periodically to be up to date with current technologies and to minimize cost as technologies become cheaper.

10 Evaluation

An evaluation matrix has been draw up to evaluate the various technologies against the design requirements with a scalar of importance included to incorporate order of preference of needs.

Table 10.2 Evaluation matrix for renewable energy and energy storage technologies

Design Requirement	Scalar	Mains		Wind		Solar		Pb-Acid		Li-ion		NiMH		NiCd		NiZn	
Low Capital Cost	3	5	15	1	3	3	9	5	15	2	6	1	3	2	6	1	3
Low Ongoing Costs	3	3	9	2	6	4	12	3	9	5	15	3	9	3	9	2	6
Long System Lifetime	4	5	20	2	8	4	16	3	12	5	20	3	12	3	12	2	8
High Energy Supply Volume	4	5	20	3	12	3	12	1	4	5	20	3	12	1	4	3	12
Low C02 emissions	2	1	2	5	10	4	8	-	-	-	-	-	-	-	-	-	-
Minimal Deforestation	2	1	2	4	8	5	10	3	6	3	6	3	6	3	6	3	6
Low environmental impact	2	1	2	4	8	5	10	2	4	3	6	4	8	1	2	5	10
Aesthetic design options	1	1	1	3	3	1	1	4	4	3	3	1	1	1	1	1	1
Minimal space required	1	5	5	1	1	4	4	2	2	5	5	3	3	2	2	4	4
Low obtrusiveness factor	1	5	5	1	1	4	4	2	2	5	5	3	3	2	2	4	4
Total		-	**81**	-	**60**	-	**86**	-	**58**	-	**86**	-	**57**	-	**44**	-	**54**

**1 to 5, poorest to best*

From table 10.2, the best technology to meet our client's needs uses a Solar PV system with a Lithium-ion storage bank. The system that has been designed consists of 23 260W solar panels, with 12 90Ah deep-cycle lithium batteries, not exceeding 80% DoD. A specially designed 'smart controller' will be used to optimize the charging period to minimize external energy sourcing costs.

11 Testing and Refinement of Design

The suggested technologies are well documented with regards to performance and efficiency, so proof of concept on the specific technology is not necessary. Prototype testing is not feasible due to the high cost and extensive integration of a power system into the household. However, the energy source will vary greatly on a site-by-site basis, theoretical calculations and analytical modeling should be employed extensively to ensure the system will meet the needs before implementation.

11.1 Modeling and Analysis

The proposed system was modeled using a MATLAB simulation. Given the cost and specifications of the storage and collection systems, the simulation will calculate the total energy produced, battery storage level, total energy purchased and sold, lifetime energy costs, and renewable/mains supply ratio. A cost of $3,000 was added to account for system components, transport, and installation costs. Figure 11.1 shows a plot of energy production and battery level after daily use for each day of the year.

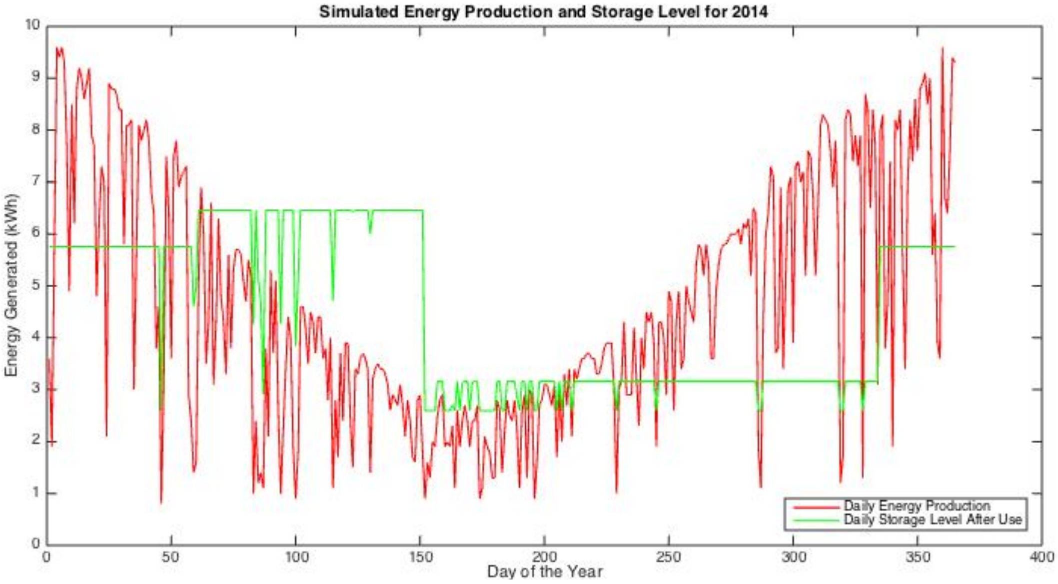

Figure 11.1 Simulated energy production and storage level for 2014

Table 11.1 shows the simulated results.

Table 11.1 Simulated results for initial design.

Data	Figure
System Cost ($)	24,165
Total Energy Production (kWh)	7,626
Renewable Energy Cost ($/kWh)*	0.179
Short Days	33
Energy Purchased (kWh)	81.0
Energy Sold (kWh)	4,669
Total Energy Cost ($/kWh)*	0.417
Supply Ratio (%)	97.3

**costs are distributed over the lifetime of the product*

From the data, the power supply falls short of demand just 35 days of the year. Being that the battery reaches 80% DoD only 10% of the year, and barely falls below 50% roughly half of the days in the year, we can revise our previous estimate of cycle life to 10,000 cycles. Assuming this, the system gives a total end cost of $0.321/kWh. By comparison, if lead-acid batteries were used instead, we would expect a cycle life of 1,500, and the predicted total energy cost would be $0.403/kWh.

It can be seen that the cost of the renewable energy is much lower than the current supply rate, but the overall cost is significantly higher. The reason for the high rate is that while the total energy purchased from the main electricity grid is very low, a flat rate supply charge exists of $251.49 per year, significantly increasing the total power bill.

The simulation also uncovered some interesting trade-offs and correlations. Decreasing the number of panels used had the effect of increasing total energy cost, as the amount of energy sold decreases. However decreasing the storage capacity had the effect of reducing total energy cost as it both decreases the system cost significantly and increases the energy sold. It should be noted that doing so severely impacts the supply ratio. It should also be noted that reducing the storage size results in the batteries reaching 80% DoD every day, which will impede cycle life and therefor overall cost.

11.2 Refinement of Design

By running various configurations, it was determined that the most influencing factor in the simulation is the DoD of the battery bank. Since the lithium batteries are the most expensive component of the system, maximizing their lifetime will significantly decrease lifetime costs of the system. Table 11.2 shows the simulated results for reducing the DoD of the system to 50%, estimating a cycle life of 16,000.

Table 11.2 Simulated results for revised design.

Data	Figure
System Cost ($)	24,165
Total Energy Production (kWh)	7,626
Renewable Energy Cost ($/kWh)	0.119
Short Days	365
Energy Purchased (kWh)	708
Energy Sold (kWh)	5,295
Total Energy Cost ($)	0.277
Supply Ratio (%)	76.7

While this configuration falls short of demand every day, 76.5% of the household usage is still obtained from renewable sources, and the total energy cost is only slightly higher than the client's current supply rate.

It should be noted that this simulation is assuming that all energy purchased is at the off-peak rate of $0.1163/kWh, which is possible due to the 'smart-controller' prediction technology. Though occasionally, during winter periods, energy may need to be purchased at the on-peak rate, so the actual total energy cost will likely be slightly higher than predicted.

Considering the current price of the components, it is difficult to design a renewable energy system with storage bank that will result in cheaper overall costs without having an immense solar array, which far exceeds the available space of the site. This is due to the high capital cost of Lithium-ion batteries. This technology however, is at the forefront of energy storage research due its superior performance and versatility (*Leadbetter, Swan, 2012*). Indeed, Tesla Motors have just announced the release of the Powerwall deep cycle Lithium-ion battery. The Powerwall will offer 7-10kWh of storage for daily cycle needs, and cost just US$3000-3500 (*Tesla Motors, 2015*). Such a technology would significantly reduce capital cost, making it possible to achieve a total energy cost lower than the current supply rate, even with mains connectivity for backup supply. This technology was not included in this report as there is very little available data to be able to analyse it. As such, while the design proposed herein is optimized to meet client needs at the lowest cost possible, it is recommended that the client postpone installing the system until the cost of Lithium-ion storage reduces enough to make the renewable system cheaper than the current utility supply.

12 Design Communication

In order to communicate the design of the client, several points should be made at the outset of discussion, the first being the inherent necessity of converting to a greener energy source for a sustainable future. Once the need for greener energy is conveyed, the comparisons made in this report should be articulated, using charts to clearly explain the various technologies' advantages and disadvantages that were considered in making design decisions.

By appointment, a member of the design team could also meet with a new client wishing to convert to a solar PV system to optimize the system sizing, so that the methodology used in this report can be reused for any household, thereby increasing the client base.

13 Conclusion

This report has explored in detail the possibility of converting to a residential renewable energy system, analyzing the costs, benefits, and limitations that need to be overcome to make this type of system viable. By applying systems engineering techniques, the most suitable system was designed, and it was shown that a solar PV system coupled with a Lithium-ion storage bank, as well as a grid connection with 'smart-controller' technology to predict daily energy usage in order to select the appropriate charging source. It has also been shown that while the system was optimized to achieve the lowest cost possible, the lifetime energy cost of the renewable system is greater than that of the current supply, due to the high capital cost of Lithium-ion batteries. This technology is set to drop in price in the near future, and the client should postpone installing the proposed system until more cost effective Lithium-ion batteries hit the market.

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