# Design an Alternative Electricity Supply System to Offset Peak Load

Jueming Bing

U4928976 ENGN2225 Individual Design Portfolio

# Introduction

The project is to design an alternative electricity supply system to offset peak load for the households in Canberra. Several factors are considered in this portfolio following a system engineering approach. The main recommendation is to adopt a solar electricity generation system with a rechargeable battery installed in the house, with advantages of utilising natural resources for free and providing a better electricity demand management.

The project starts from problem scoping, followed by requirement analysis, idea generation, functional flow analysis, system architecture and evaluation. A final design communication section including the primary prototype and a future plan will conclude the portfolio.

# Problem and Motivation

**Portfolio Topic: Selecting an alternative energy supply to offset electricity peak load for an individual household in Canberra**

This portfolio is to explore the most suitable electricity peak load offset pathway for an individual household in Canberra (4 people) following a system engineering approach. This portfolio has the following motivations: (1) Reduce emissions from conventional fuel-electricity generation process; (2) Make use of other energy resources in Canberra and Australia; (3) Save money on electricity expense during peak hours

# Recommendation Pre-visit

The main recommendation for the alternative electricity supply system to offset peak load is solar electricity generator with rechargeable battery supported by evaluation of different ideas against customer and design requirements. The system is expected to integrate with grid.

Problem scope has been developed using system boundary, narrowing down the factors to be considered in this portfolio. Requirement analysis further determined the importance of different requirements and shapes the main focus as well as some basic ideas of essential functions. 8 electricity generation ideas and 8 electricity storage ideas were classified into two idea generation trees. A primary feasibility assessment and a support scenario planning yielded 6 possible ideas for further analysis and they would be compared against design requirements at a later stage.

From functional analysis and system architecture section, analysis further supported the selection of solar generator and rechargeable battery due to components flexibility for less complex structure and easy modulation within the overall system, serving as the **first reason** to adopt solar generator and battery. From testing and evaluation, the weighted-average results of both ideas exceeded other possible ideas within their own streams for a more balanced satisfaction for various requirements. Serving as the **second reason** to adopt solar generator and battery.

## Background

Peak electricity demand is a problem for both the electricity supplier and consumer. The electricity network must be able to support the electricity spike during the peak time and to do so more investments are needed for the infrastructure. The result is a higher electricity cost. High energy demanding appliances such as air-conditioning, heater and dryer are the major components for this high demand. Many devices such as refrigerator and television have become more energy-efficient but the peak demand is still relatively high. Thus, if there is an alternative electricity supplying system installed at household level, peak load can be reduced and consequently residents can save electricity costs.

In order to design a system to offset peak load, understanding of load demand in the target region is important. From the report from Centre for Energy and Environmental Markets, average load demand for an individual household in Newington region with respect to four seasons can be found (Watt, et al., 2006). It is assumed to be the same electricity usage level for an individual household in Canberra. The following graph will summarize the daily power of load profile in four seasons and an average daily total consumption will be calculated for four seasons.

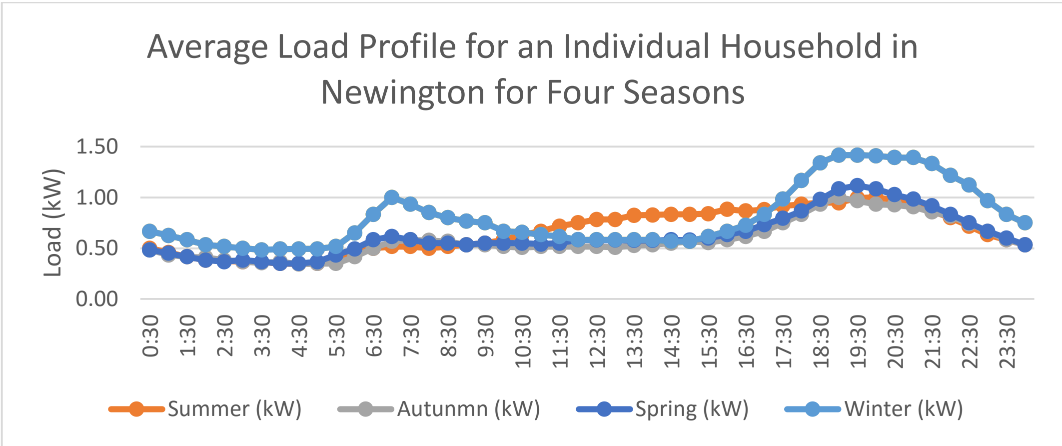



**Figure 1 Average Daily Load Profile for a Single Household in Newington During Four Seasons**

The area under load curve is the total electricity consumption in kWh. According to calculation, average daily load consumption varies from 13.84kWh to 18.99kWh during a year while peak load happens during the evening. When designing the system, the electricity generation system is assumed to work all day time. A peak load in the evening might require the installation of electricity storage, which will be discussed in requirement analysis section.

On the other hand, electricity prices during the evening are usually to be higher. Therefore, there is an opportunity to save costs if the house does not consume electricity from grid. On the other hand, if the new electricity generation system need electricity supply for operation, it is better to generate during day time for low electricity cost. Furthermore, most of the current electricity from grid (63%) is from fossil fuel, while renewable energy only contributes to 1.8% (Office of the Chief Economist, 2015). Those factors lead to the motivation of this project.

# Problem Scoping

## System Boundary

The system boundary has been identified with help of identification of stakeholders. There are five top level stakeholders: household clients, system designers, electricity suppliers, system manufacturers, alternative electricity supply system. Household clients have a system problem and the problem requires system designers to come out with a solution; electricity companies provide electricity to household and charge them expense; household client can obtain benefits of offsetting peak load from alternative electricity supply system; system designers and manufacturers communicate with each other to make the system come true. Understanding the relationship between different stakeholder facilitates identifying variables for this projects. For example, system manufacturer's interaction with the electricity supply system can lead to ease of maintenance and ease of use. Those variables can be divided into the following three categories, which can further provide guideline on determining subsystem interface in system architecture section:

**Table 1 System Boundary Variables**

| Internal | External | Excluded |
|---|---|---|
| Safety issues, Costs, Size of the system, Weight of the system, Electricity generation, Electricity storage, Ease of use, Ease of maintenance | Household users, Electricity supplier, Power source, Daily electricity load | Weather Condition, Electricity price, Number of users, End-of-life issues |

Although external variables cannot be controlled, the design should also account for their impacts. Due to resources limitation, the variables in excluded category will not be considered at the current stage but also provide warnings for the users (Sterman, 2000). Hence, those internal and external variables need to be considered in the designing the solution for the problem. Some basic ideas are presented as follows:

- this improved electricity supply system should offset peak load;
- the system should consider size, costs and safety issues in design phase;
- the system should make use of available energy resources;
- the system should generate and also store electricity;
- the system should be easy to use and maintain.

# Requirement Analysis

## Requirements and Rankings

Requirement analysis is closely related to previous problem scoping. If problem scoping gives the first insight of how the system will be, requirement analysis will further shape the most important parameters and help to determine the main focus in the design. A friend in Canberra has been interviewed on the topic of desired electricity supply system and some customer requirements have been developed and summarised in the following table based on his key words in interview transcript in Appendix (Cheng, 2016). Pairwise analysis is an effective decision making technique with calculating and aggregating meaningful preference or choice (Dym, et al., 2002). With pairwise analysis (table included in appendix), the ranks have also been listed:

**Table 2 Customer Requirements**

| Key Points | Requirements | Requirement ID | Rank | Priority |
|---|---|---|---|---|
| **Reduce electricity load** | On-site generation | CR-01 | 1 | High |
| | On-site storage | CR-02 | 5 | Medium |
| **Green energy** | Environment friendly | CR-03 | 3 | High |
| **Not expensive** | Affordable | CR-04 | 4 | High |
| **Family friendly** | Easy to install and use | CR-05 | 6 | Low |
| | Easy to maintain | CR-06 | 7 | Low |
| **Legal** | Follow standards and regulations | CR-07 | 2 | High |

Those requirements are interpreted with my own interpretation so customer feedbacks are necessary after expanding those key points. Approval has been received from the interviewee. Those customer requirements can be translated into design requirements in the form of measureable TPM, which are summarized in the following table:

**Table 3 Design Requirements Measurable**

| CR-ID | DR-ID | Description | Unit | Direction |
|---|---|---|---|---|
| **CR-01** | DR-01 | Electricity production capacity per day | kWh/day | Increasing |
| | DR-02 | Energy consumption per unit electricity | Amount/kwh | Decreasing |
| **CR-02** | DR-03 | Storage capacity | kWh | Optimal |
| | DR-04 | Energy conversion rate | % | Increasing |
| **CR-03** | DR-05 | Life-span | Year | Increasing |
| | DR-06 | Embodied energy | MJ | Decreasing |
| **CR-04** | DR-07 | Upfront system costs | Dollar | Decreasing |
| | DR-08 | Subsequent maintenance costs per year | Dollar/year | Decreasing |
| | DR-09 | Levelized costs of electricity | Dollar/kwh | Decreasing |
| **CR-05** | DR-10 | Number of components | Number | Optimal |
| | DR-11 | Size of system | M^3 | Optimal |
| | DR-12 | Assemble time | Hours | Minimum |
| **CR-06** | DR-13 | Cleaning time | Hours | Minimum |
| | DR-14 | Frequency of changing components | Times/year | Decreasing |
| **CR-07** | DR-15 | Legality | YES/NO | Optimal |
| | DR-16 | Connection to grid | YES/NO | Optimal |

TPMs provide a clear indication on how to measure design requirement, which can be used for system verification at a later stage. The directions represent the expectation of design characteristics of the system when it is not possible to determine the exact value of certain design requirement. For example, I want the system to generate as much electricity as possible so the direction of improvement is increasing. After interpreting customer requirement, there will be a rough idea of sub-systems functions for the solutions, which flows to the next topic. For example, subsystems for this problem could be electricity generation unit, electricity storage units and electricity distribution unit emerging from customer requirements CR-01 and 02.

## House of Quality

House of quality is able to provide 'the means for inter-functional planning and communications' which can be used to determine design priorities based on the evidence put in the ‘house’ (Hauser & Clausing, 1988). A relation matrix is adopted to investigate the relationship between customer requirement and design requirements. Meanwhile, trade-off between various design requirements have also been examined in Appendix.

From the relation matrix, some design requirements are most related to their source customer requirements, so there should be a major focus on the most related design characteristics; while some design requirements are related to other customer requirements, so there should be a comprehensive assessment of various design requirements for a single customer requirement.

Correlation analysis between different TPMs has been included for trade-offs. For example, the most important customer relationship is ability to generate electricity (CR-01). The corresponding TPMs include electricity generation capacity. If it is desired to be a maximized value, there will be a trade-off between generation capability in kwh and system costs in dollar value as they are negatively related because more money would be spent, which is not desired. Within the same category, for example, the requirement of being environmental-friendly (CR-04) has two TPMs: lifespan and embodied energy. However, those two TPMs are negatively related as increasing in lifespan (desirable) could increase in embodied energy (undesirable). Hence, when selecting components against requirement, there will be a careful consideration to balance those two TPMs and make a wise trade-off decision. Although not all requirements are important, it is still necessary to consider all requirements starting from the most important ones.

# Idea Generation

## Concept Generation

Ideas can be generated with support of problem scopes and will be filtered based on requirements developed from previous section. Based on requirements, there will be electricity generation and electricity storage so both streams should be considered. Ideas of electricity generation and electricity storage are summarized below coming out from the research issue ‘How might we design a system to reduce electricity load for a household’. Generated ideas have been grouped into different themes, creating two classification tables

**Table 3 Idea Generation Classification Table**

| | Theme | Idea | | Theme | Idea |
|---|---|---|---|---|---|
| **Electricity Generation** | Water | Hydropower | Electricity Storage | Electrochemistry | Rechargeable Battery |
| | | Raindrops | | | Fuel Cell |
| | Electrochemistry | Portable Fuel Cells | | Mechanical Storage | Compressed Air |
| | Renewable Energy | Photovoltaics | | | Flywheel |
| | | Wind Turbine | | Thermal Storage | Water Thermal |
| | | Combined PV and Wind | | | Latent Heat Materials |
| | Fuel Sources | Stand-alone fossil fuel | | Other | Pumped hydro |
| | Other | Geothermal | | | Superconducting Magnetic |

## Primary Selection

Renewable energy and fuel sources are worth of consideration as there are many successful applications. However, water energy really depends on the surrounding environment of a house. If there is no significant height difference or enough water resource, the power generated by hydro-system is quite limited. Raindrops also depend on weather. With respect to fuel cell, it is not quite practical as users have to buy fuel cells to release electricity for the house. A scenario planning table can be used to further eliminating some electricity generation ideas. Two variables are set to be electricity conversion efficiency and Levelized costs of electricity. Information regarded the above two variables has been summarized in the following table:

**Table 4 Generation Ideas Scenario Planning Table**

| Generation Ideas | Conversion Efficiency (Eurelectric and VGB Powertech, 2003) | Levelized costs of electricity with 3% discount rate (International Energy Agency, 2015) |
|---|---|---|
| **Wind Turbine** | 35% | $139/MWh |
| **Photovoltaics System** | 15% | $150/MWh |
| **Gas Turbine** | 39% | $100/MWh |
| **Fossil Fuel System** | 40% Coal | $80/MWh |

Although PV system has lower efficiency and higher costs, solar resources is free to use. Wind turbine has a higher efficiency and the cost is lower than PV's electricity cost, which can be a better choice here. For fossil fuel system, even if the cost is the lowest, it has the most negative influence over environment. Therefore, three ideas both have pro and cons. Among all of the above ideas, three potential systems could be photovoltaics system, micro-wind turbine, as well as stand-alone fuel generation system.

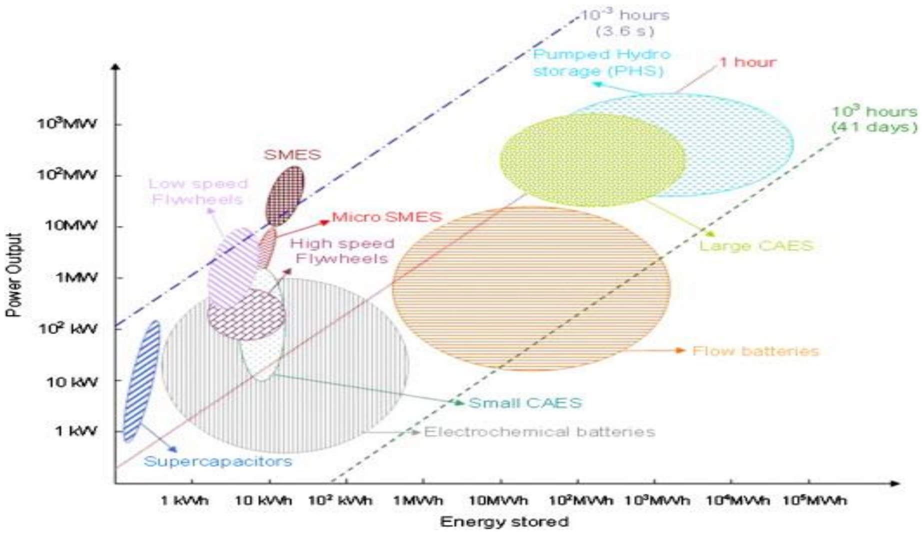



**Figure 2 Storage Ideas Scenario Planning Diagram**

For mechanical storage, although they could have larger energy store capacity, the sizes are too large for a household application except that compressed air system can be built underground. Pumped hydro also depends on the water resources so it is less competitive compared to other storage techniques. Scenario planning can be used for electricity storage idea elimination as well by setting two variables as storage capacity and power instant output rate. Information regarded the above two variables has been summarized in Figure 2 (Ibrahim, et al., 2008).

Flow batteries have higher capacity and power output than small sized compressed air storage, which is also better than electrochemical batteries. Larger CAES could be a suitable choice if there is enough underground space for the household. However, the selection should also take discharge time, life time and energy store efficiency into consideration. For now, potential storage unit could be rechargeable batteries, fuel cell, compressed air storage and thermal storage.

Therefore, primary selection has been made by eliminate impractical and other uncompetitive ideas by examination and scenario planning. Systems with high efficiency and low costs are preferred for generation unit while systems with high storage capacity and high energy conversion rate are better candidates for storage units. Although that technique can give a preliminary result in selecting ideas, other systems have potential as well for other advantages. For a final concept selection, there are a number of factors to be considered, including customers' requirement as well. The final concept selection will be covered in evaluation matrices in evaluation section using a weighted average method by taking all requirements into account.

# Functional Analysis

## System Function Assumptions

The main function of the system is to offset peak load with help of independent electricity generation system and a built-in electricity storage technique. That top-level function could be divided into sub-functions of generating electricity and storing electricity based on requirements analysis.

In order to make the system clear and simple to understand, it is assumed that the system can produce electricity at certain rate constantly. Meanwhile, there is an electricity-consumption rate which represent the instantaneous electricity demand in the house. Besides, electricity generation for all ideas generated in previous sections happens only during day time from 9AM to 5PM. As mentioned in the background part, peak load usually happens after 6PM at night when working people come home to use household electrical appliance. Therefore, some electricity is able to be stored in the system during day time and be prepared to be used during evening time. A logical diagram is constructed in Appendix representing the decision points of storing and releasing electricity, with implication of some other required functions.

## Functional Flow

A functional analysis focuses on functional steps, which are the actions required to achieve a given objective. The functional analysis aims to translate system requirements into detailed design with certain level of resources identification for system operation (Blanchard & Fabrycky, 2011). In this section, FFBDs for a traditional household electricity grid supply system and an improved electricity supply system with peak load offset are constructed respectively. The FFBD for the traditional grid selected system will be examined to identify any improvement potentials. For the traditional household without alternative electricity supply system, all electricity could come from the grid from electricity supplier.

Only three functions are included in the top-level FFBD for the traditional system, which are switch on appliances, using electricity and paying electricity fees. The process loop again from FF3.0 to FF1.0. Using electricity and paying fees can be further divided into sub-level FFBDs. By examining the traditional electricity supply system, the following improvement potentials can be identified:

- FF2.1: grid electricity is the only source of supply so reducing supply from grid can decrease electricity fee;
- FF2.2 and FF2.3: focusing on safety issues can be an essential part for those two functions; avoiding overloading is important;
- FF2.5: It is necessary to ensure electricity monitoring system to work smoothly and provide accurate figures so regular maintenance of recording unit should be performed.

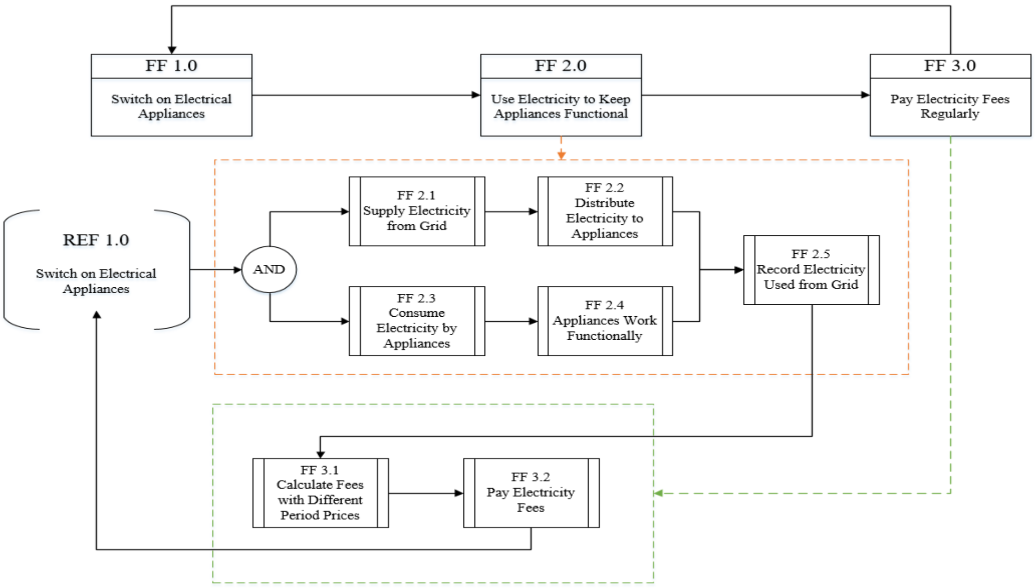



**Figure 3 Current System FFBD**

Based on customer requirements, an electricity storage system to store extra electricity is needed. Hence, the improved system FFBD can be constructed with the similar top-level FFBD. The main difference is that the independent household electricity supply system generates and stores electricity in parallel to grid electricity supply.

The new system will be much more complex than the original. After switching on electrical appliances, grid and generation unit will both provide electricity. Generated electricity will firstly be used to offset grid load at any time so a dash line connected from FF 2.0 to FF 5.0. Additional electricity can be converted into different forms of energy based on storage techniques and will be released as electricity during the evening to offset grid electricity usage so a dash line connected from FF 4.0 to FF 5.0. Sub-level functions have also been structured in the diagram. Solar PV electricity supply with chemical battery system is taken as an example presented in Figure 5.

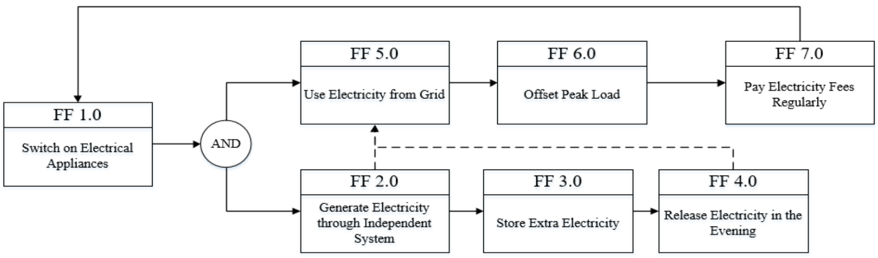



**Figure 4 Improved System Top Level FFBD**

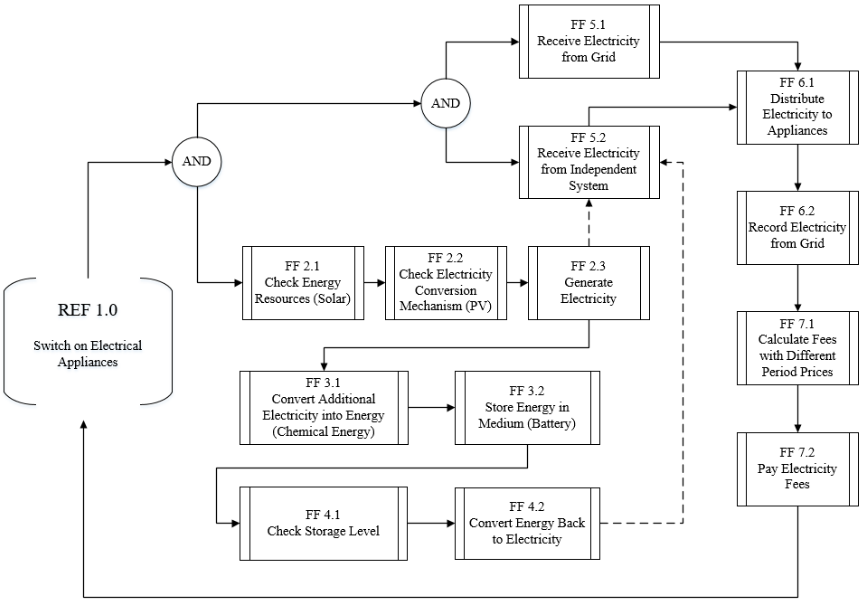



**Figure 5 Improved System Second Level FFBD**

The following benefits have been added over traditional electricity supply system from the above FFBD diagram:

- FF 5.2: Independent electricity generation system can supply electricity to the grid, which can effectively reduce usage of electricity from the grid;
- FF 3.2: storage of extra electricity represents effective electricity management and reduce the pressure of using electricity when generation unit cannot generation electricity;
- Check functions in the above FFBD ensures system safety by checking whether there is any issue before system's switch on.
- Reduction in electricity use does not only happen during peak time with stored electricity, but when generating electricity during day time, electricity will be delivered to appliances first.

FFBDs do not give an idea on the components or any indication of relationship and interaction. In order to have a deeper understand on system design, the next step is system architecture which helps to identify suitable components and complex interactions. A practical way is to group related functions and try to identify the system which can perform those groups of functions, which will be discussed in the next section.

# System Architecture

## System Interface

Based on functional allocation which is presented in appendix, the improved electricity supply system has two key sub-systems, which are electricity generation system and electricity storage system. Some other possible sub-level systems are power distribution system, power control system, grid-integration system (Zandbergen, 2016). Maintenance system should also be one of the sub-level systems based on previous functional allocation. On the other hands, external systems are interacting with those sub-level systems as indicated in problem scoping, including house system consist of users, electricity grid and house structural components, as well as environment system consisted of energy resources. Climate under environment system will not be considered here.

A top-level subsystem interface map is presented in Figure 7. Control and monitor system plays an important role as a central unit. It delivers signals to other important sub-systems to perform functions. Electricity supplier will have direct interaction with control system for electricity usage record. On the other hand, grid integration system integrates the independent electricity supply system with the grid, ensuring legality and safety. Electricity generation system has direct interaction with environment system for energy resources and house system provides structural support to both electricity generation and storage system.

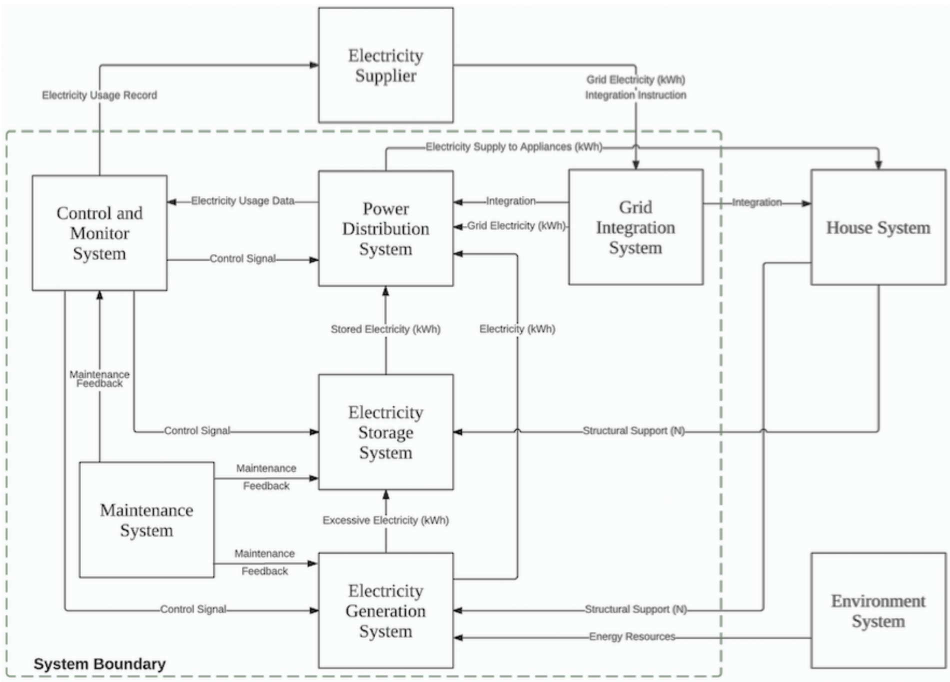



Figure 6 System Architecture of Overall Improved System

Subsystems can be further broken down into components. Taking solar photovoltaics electricity generation system and rechargeable battery as an example to construct sub-level system interface map. This diagram does not show control, maintenance and grid integration subsystems.

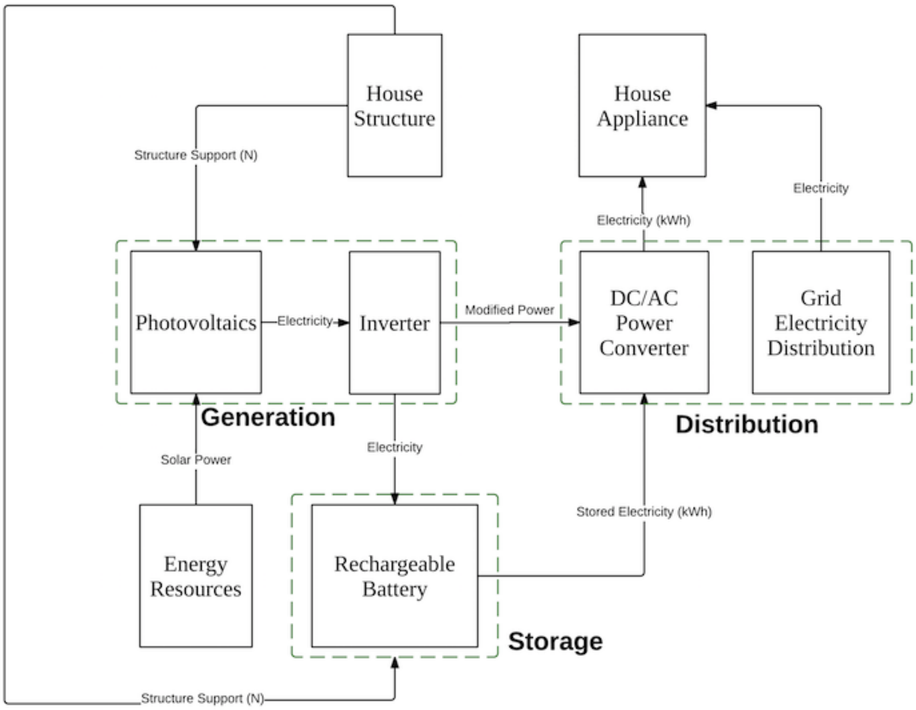



**Figure 7 Sub-Level System Architecture for Selected Subsystems**

For other ideas generated in previous section, sub-level components mapping will be different based on technology. For generation part, micro-wind power system, photovoltaics panels are replaced by wind turbine with an inverter (Huskey, et al., 2010). However, a standard-alone fuel generation system required an engine or pump as well as a storage tank for fuels (Critical Fuel Systems, 2012). For storage part, compressed air storage system is consisted of a compressor, a tank of air, air dryer and so on (Energy Stroage Association, 2016). The whole system might be installed underground so there will be an interaction with environment system instead of house structure. Similarly, for a thermal storage system, chillers, cooling coils and storage tank are needed (Energy Storage Association, 2016). In regards to a sub-system with more components, the flexibility of that system decreases due to complex interaction with surrounding components. One single issue might affect many other sub-systems. Meanwhile, complex system might potentially exert higher pressure on structural support of the house due to greater size. Hence there is another implication to select simple and user-friendly systems in order to minimize interactions just like rechargeable battery compared to compressed air or thermal storage.

## Component Selection

With respect to subsystem concepts selection, control and monitor system, distribution system and grid integration system are currently available in a household and no change is needed. The only two sub-systems requiring selection are electricity generation and electricity storage. Most of the generated ideas are COTS and are ready to be implemented into the system, reducing time and labor efforts for engineers. As discussed above, although solar PV system and battery have fewer components and fewer interaction with other systems, it is still necessary to evaluate all other primarily selected ideas from idea generation section. With all possible system model set and all previous analysis coming together, a final step is to evaluate ideas for the most suitable system.

# Evaluation

## Evaluation Matrix

Evaluation matrices can be constructed for generation and storage system respectively. Three concepts from generation and storage system respectively are evaluated against design attributes and the importance of each design attributes come from previous requirement analysis. CR-07 is not applicable for evaluation as it is a must condition for all systems. The performance against each design requirement will be marked from 1 to 5 with 5 being the best performance compared to other systems. The results of evaluation matrices are listed below with supporting information for similar product on the market or testing methods included in Appendix.

**Table 5 Evaluation Matrix for Generation and Storage Systems**

| DR | Weight | Generation System | | | | | | Storage System | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Photovoltaics | Score | Micro-Wind | Score | Fossil Fuel | Score | Rechargeable Battery | Score | Compressed Air | Score | Thermal Storage | Score |
| **DR-01** | 7 | 4 | 28 | 3 | 21 | 5 | 35 | | | | | | |
| **DR-02** | 7 | 3 | 21 | 4 | 28 | 5 | 35 | | | | | | |
| **DR-03** | 3 | | | | | | | 4 | 12 | 5 | 15 | 5 | 15 |
| **DR-04** | 3 | | | | | | | 5 | 15 | 3 | 9 | 3 | 9 |
| **DR-05** | 5 | 5 | 25 | 5 | 25 | 3 | 15 | 3 | 15 | 5 | 25 | 4 | 20 |
| **DR-06** | 5 | 4 | 20 | 4 | 20 | 2 | 10 | 5 | 25 | 3 | 15 | 3 | 15 |
| **DR-07** | 4 | 3 | 12 | 3 | 12 | 4 | 16 | 5 | 20 | 2 | 8 | 2 | 8 |
| **DR-08** | 4 | 5 | 20 | 4 | 16 | 2 | 8 | 5 | 20 | 3 | 12 | 3 | 12 |
| **DR-09** | 4 | 3 | 12 | 4 | 16 | 4 | 16 | | | | | | |
| **DR-10** | 2 | 4 | 8 | 4 | 8 | 3 | 6 | 5 | 10 | 1 | 2 | 2 | 4 |
| **DR-11** | 2 | 4 | 8 | 2 | 4 | 3 | 6 | 5 | 10 | 1 | 2 | 1 | 2 |
| **DR-12** | 2 | 3 | 6 | 3 | 6 | 3 | 6 | 5 | 10 | 2 | 4 | 2 | 4 |
| **DR-13** | 1 | 5 | 5 | 3 | 3 | 3 | 3 | 5 | 5 | 1 | 1 | 1 | 1 |
| **DR-14** | 1 | 5 | 5 | 5 | 5 | 3 | 3 | 3 | 3 | 5 | 5 | 3 | 3 |
| **DR-15** | 6 | | | | | | | | | | | | |
| **DR-16** | 6 | | | | | | | | | | | | |
| **Sum** | | | 170 | | 164 | | 159 | | 145 | | 98 | | 93 |

From the above matrix, photovoltaics system is preferred for electricity generation and rechargeable battery is preferred for electricity storage. With respect to the electricity generation system, although photovoltaic system does not perform the best for ability to generate electricity, weighted average mark indicated that that system has the most balanced fulfillment for all requirement, similar to rechargeable battery. Besides, those two selected systems have less system components, leading to easier FFBD and system architectures, which can bring great benefits even if clients change ideas.

Therefore, the overall system will have PV panels to generate electricity and a rechargeable battery to store electricity. Those components can be integrated into the current electricity supply system without any need for new power control, distribution system. A grid integration system should be implemented. Before setting up a prototype, there will still be some steps for design communication: estimating solar size and payback period. Design communication will provide such information.

# Recommendation and Conclusion

To sum up this portfolio, the main recommendation for the alternative electricity supply system to offset peak load is solar electricity generator with rechargeable battery according to evaluation of different ideas against customer and design requirements. The system is expected to integrate with grid.

Based on FFBD analysis, valuable benefits have been added to current electricity system in the household: reducing usage of electricity from the grid and storing extra electricity for effective electricity management. It is also remarkable that reduction in electricity use does not only happen during peak time with stored electricity, but when generating electricity during day time, electricity will be delivered to appliances first. However, there are still some potential issues associated with the improved system: safety check functions should be added to rule out hazards; maintenance for system units is also necessary - although some status check functions have already been included, but there are other aspects which need maintenances.

System mapping also implies using systems with less components to increase components flexibility and reduce pressure on structural support, making the concept selection even more appealing to solar electricity generation. Control and monitor system, distribution system and grid integration system are currently available in a household and no change is needed. The only two sub-systems requiring selection are electricity generation and electricity storage and most of the generated ideas are COTS, which are ready to be implemented into the system, reducing time and labor efforts for engineers. Final tests and verifications can be done to ensure a stable electricity supply to the household before installation.

# Design Communication and Future Plan

## System Diagram

The following diagram depicts the configuration of all major components in the roof-top PV system. Two strings of PV panels are contained in the designed system, each string has 6 panels (determined by system sizing), and each string is connected to a charge controller. The green boxes in the diagram represent circuit breaker. These circuit breakers are used to ensure the safety and performance of the system.

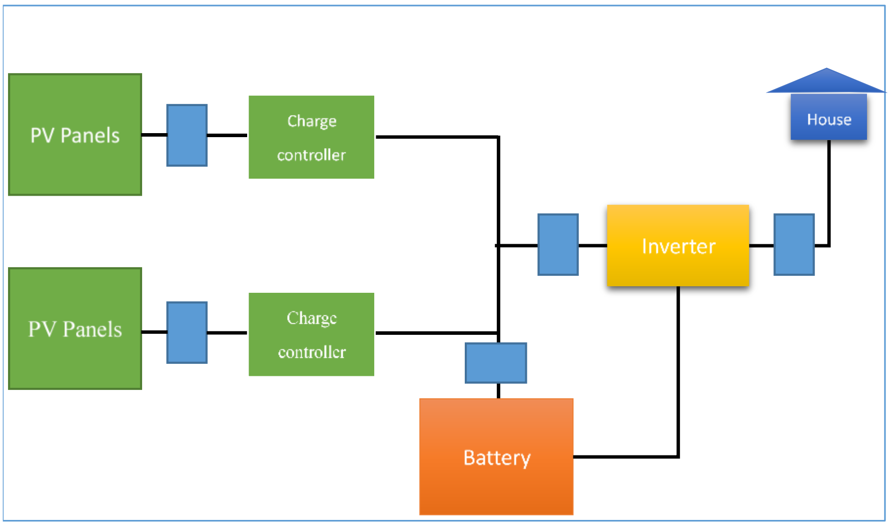



**Figure 8 Circuit Diagram for the Improved System including All Necessary Components**

From the above diagram, apart from PV panels and rechargeable battery, there is another group of components which has a name of Balance of System. Balance of system includes inverter, DC/AC converters/ inverters and any other components except solar panels, which facilitate smooth operation for solar power generation (Wenham, et al., 2013). Some of the components are pre-built in the house but other systems have to be purchased. The number of solar panel is 12 based on size estimation of Tindo PV modules (Appendix) and the PV panels should be mounted at 10 degrees based on calculation. Other components are selected from the most common commercial available products:

**Table 6 Primary Components Selection**

| Components | Manufacturer | Model | Number of units |
|---|---|---|---|
| **PV modules** | Tindo | Kara260W (Tindo Solar, 2016) | 12 |
| **Inverter** | SMA | SB3000 (SMA Australia, 2016) | 1 |
| **Charge Controller** | EP | Solar Tracer-1215RN (EP-Solar, 2016) | 2 |
| **Battery** | Winston | LFP1000AHC LiFePO4 (Winston, 2016) | 1 |

For a 3kW system installed in Sydney, normal payback time is around 10 years (6800/668 annual saving), which is much lower than the lifespan (Solar Choice Staff, 2016). The installation need to follow AS/NZS 5033:2014 regulation (Standards Australia, 2014), which includes all the standards regarding installation and safety for photovoltaic arrays.

## System Lifecycle Consideration

The life cycle of the system starts with drawing of raw materials, manufacturing of the product, packaging and selling the product, transporting the product, utilising the product, maintenance of the product and finally retirement of the product.

Table 7 Lifecycle Issues

| Lifecycle | Description |
|---|---|
| **Raw Materials and Manufacturing** | Solar panels will from the market suppliers with no manufacturing required. Inverters and other BOS components can also be purchased as a bundle. |
| **Transportation** | The product will be transferred from warehouse to clients using transportation (truck). There will be special stabilisation measurement to protect system components from breaking. |
| **Installation** | Technicians will help to install the system over the roof with desired tilt angle. Safety protections are necessary for installation. |
| **Maintenance** | The design will be user friendly such that there is little maintenance needed while some BOS components can be replaced depending on use status. The maintenance will be the responsibility of solar panel companies after purchase but the cost of replacement of components need to be covered by customers |
| **Retirement** | The system will aim to be recycled after use. The expected life-span is around 25 years. Special treatment such as recycling by relevant organisations in order to minimise negative effective to environment. |

## Comparison on Existing System

As discussed in functional flow analysis, four benefits have been added to the existing systems, including additional supply of electricity, storage of extra electricity for load management, safety function check, and reducing electricity consumptions to save electricity cost. However, building a new electricity supply system could take a longer time with a higher cost. Although electricity costs will be reduced, the payback period is 10 years. It really depends on the clients: whether they want to save money now or gain benefits in the future. Besides, the additional system increases the complexity of house grid application, which is really a downside.

There are still some potential risks associated with the improved system:

- Although there are some check functions with electricity storage and generation, safety should also be ensured when the system dissipate power to appliance so possible sub-level functions like voltage check can be added;
- There could be energy loss when converting between electricity and other forms of storage energy;
- System-grid integration can be further broken down into sub-level FFBDs with an emphasis on safety checks;
- Maintenance for system units is also necessary that some check functions have already been included; but there are other aspects which need maintenances such as monitoring system

Other risks include overweight and oversize issues for the household. Besides, shading could also affect the performance of PV panels. There is still probability for future additional improvement such as increasing concept energy conversion rate and make pre-caution measures.

## Future Plan

Some major future steps have been identified. Although solar electricity concept is selected for Canberra's household, it does not mean this concept is the best solution for client. Future potential improved has been covered in previous sections. Besides, the size of the system is just a rough estimation and more detailed examination should be conducted with a more careful selection of concepts. On the other hand, a careful examination of costs and benefits is essential to persuade the client to use the design. Lifecycle issues should also be accounted. At current stage, the most important thing is the feedback from clients so additional improvement could be identified starting from modified problem scoping. With clients' approval, system designers can hand the project over to system manufacturing for more detailed components selection and installation. Also, it is necessary to contract electricity supplier for grid-integration issues.

# Reflection

## Reflection on System Engineering Process

In doing this project, I have followed a system engineering approach starting from problem scoping all the way to evaluation. I personally think my flow is quite logical in this portfolio. However, I exchanged the steps of idea generation and customer requirements. In this portfolio, customer requirement is a further step following from problem scoping. After determine the things I have to consider in this design, customer requirements can further decide the most important factors to be considered in the design process. Idea generations can then start with various generated ideas while the primary selection of the ideas should depend on the most important factors decided in requirement analysis in order to narrow down possible ideas. A final evaluation matrix is used to determine the most feasible concept here. That is why I change the process step of requirement analysis and idea generation. From this portfolio, I started to have a sense on real world design process to solve problems from the clients.

For this project, I learned to use the most applicable system engineering techniques. For each section, I did not use all the techniques taught in the course as I think the techniques I didn't use do not convey much insights for me to make recommendation decisions such as stakeholder analysis compared to the techniques I used in this portfolio. From this portfolio, I learned that the most important thing for analysis is the effectiveness. For example, in FFBD section, some functions have already implied logical flows with different decisions from the check functions, so it is not necessary to construct another logical flow diagram.

With respect to the portfolio topic itself, which is the alternative electricity generation system, I found it is quite interesting and there will be more research directions to be considered in the future. Also, I learned that solar industry has a great potential in Australia due to large solar resources. Besides, I have also identified issues with solar-electrical applications such as after-life treatment and sizing issues. Besides, it is also recommended to increase photovoltaic efficiency for a better application in the market.

## Reflection on Peer Review

All three reviews have provided some useful comments on how to add values into the portfolio. Overall, those comments are very useful to improve the quality of my portfolio.

Firstly, all of the reviewers recommended me to include more reference on the side of system engineering. What I did in the draft was including different sources of technical side references. Although technical side references help the whole portfolio to be more reliable with reliable support evidence, it is also necessary to describe system engineering techniques and their underlying purpose. Hence, I included a number of useful references on system engineering design techniques in the final portfolio.

Secondly, some reviewers recommended me to construct a more obvious conclusion instead of a stand-alone recommendation section. From my point of view, my recommendation is just the conclusion excluding process summary but it is still better to write a process overview in the conclusion to summarized the steps involved in this portfolio. I tried to include the links between techniques and recommendations (two reasons for the desired system from previous analysis) more logically. Also, I tried to incorporate the design process within recommendation to form a better conclusion.

Thirdly, I managed to cut down the length of portfolio by excluding factors which are not so important to this portfolio or contain repeated contents. I also put more description stating that appendix is necessary as supporting material to have better understanding on the whole engineering system design process.

With respect to other comments, I am much appreciated for those advices. I did change the diagram colours to be more consistent. However, with respect to the techniques in problem scoping, I still insist on using system boundary instead of the recommended mud diagram as I personally think there are more useful insights from boundary mapping while mud mapping is not so related to this project. Also, for design communication, it is really difficult to incorporate lifecycle considerations into previous design process. Hence, I just keep that section in the original place.

# Appendix

## Interview Transcript

'I wish to use the new system to reduce electricity load, especially during peak times; It is better to adopt green energy as environment is a big focus nowadays; the cost should be reasonable and not too expensive; the system should not cause any difficulty when using it; last but not the least, I do not expect that relevant origination comes to me saying that the system does not meet regulations'

## Pairwise Table

The pairwise analysis is conducted the following table in order to determine the relative importance of requirements CR-01 to CR-07:

| | CR-01 | CR-02 | CR-03 | CR-04 | CR-05 | CR-06 | CR-07 | Sum | Rank |
|---|---|---|---|---|---|---|---|---|---|
| **CR-01** | | 1 | 1 | 1 | 1 | 1 | 1 | 6 | 1 |
| **CR-02** | 0 | | 0 | 0 | 1 | 1 | 0 | 2 | 5 |
| **CR-03** | 0 | 1 | | 1 | 1 | 1 | 0 | 4 | 3 |
| **CR-04** | 0 | 1 | 0 | | 1 | 1 | 0 | 3 | 4 |
| **CR-05** | 0 | 0 | 0 | 0 | | 1 | 0 | 1 | 6 |
| **CR-06** | 0 | 0 | 0 | 0 | 0 | | 0 | 0 | 7 |
| **CR-07** | 0 | 1 | 1 | 1 | 1 | 1 | | 5 | 2 |

## House of Quality

The following table provides the implication of relationship using relationship matrix, with 9 being highly related, 3 being moderately related, 1 being weakly related, and 0 for no relationship.

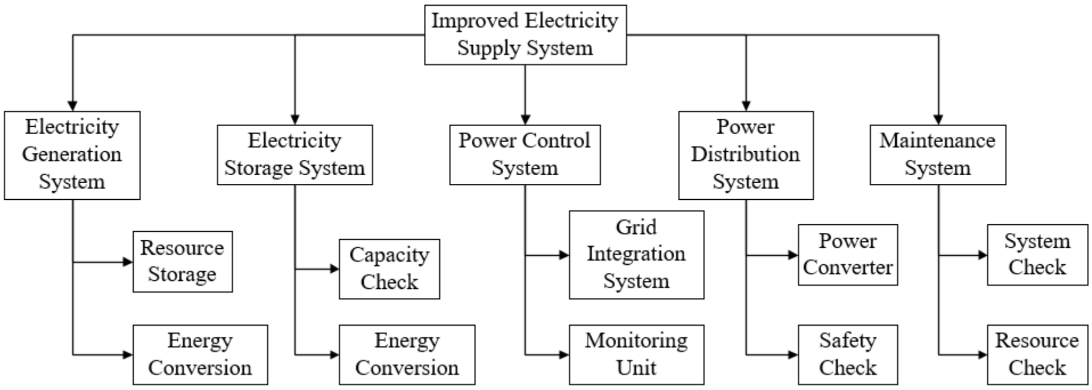
| CR | DR | Electricity production capacity per day | Energy consumption per unit electricity | Storage capacity | Energy conversion rate | Life-span | Embodied energy | Upfront system costs including installation and material | Subsequent maintenance costs per year | Levelized costs of electricity | Number of components | Size of system | Assemble time | Cleaning time |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Unit | kWh/day | Amount/kwh | kWh | % | Year | MJ | Dollar | Dollar/year | Dollar/kwh | Number | M^3 | Hours | Hours |
| **CR-01** | | 9 | 9 | 3 | 9 | 9 | 3 | 3 | 3 | 3 | 9 | 9 | 9 | 3 |
| **CR-02** | | 3 | 3 | 9 | 9 | 9 | 3 | 3 | 3 | 3 | 9 | 9 | 9 | 3 |
| **CR-03** | | 1 | 9 | 1 | 9 | 9 | 9 | 3 | 3 | 3 | 1 | 1 | 0 | 0 |
| **CR-04** | | 1 | 1 | 1 | 1 | 1 | 1 | 9 | 9 | 9 | 1 | 1 | 1 | 1 |
| **CR-05** | | 1 | 1 | 1 | 1 | 3 | 9 | 1 | 1 | 1 | 9 | 9 | 9 | 3 |
| **CR-06** | | 1 | 1 | 1 | 1 | 9 | 3 | 1 | 1 | 1 | 9 | 9 | 3 | 9 |
| **CR-07** | | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |

The following table provides relationship between different design variables. A '++' means two variables are strongly positive related that a better change in variable A can lead to a better change in variable B; A '--' means two variables are strongly negatively related that a better change in variable A can lead to a worse change in variable B. A '+' or a '-' indicate medium level positive or negative relationship.

| | DR-01 | DR-02 | DR-03 | DR-04 | DR-05 | DR-06 | DR-07 | DR-08 | DR-09 | DR-10 | DR-11 | DR-12 | DR-13 | DR-14 | DR-15 | DR-16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **DR-01** | | | | | | - | -- | -- | | | - | - | - | | | |
| **DR-02** | | | | | | | | | ++ | | | | | | | |
| **DR-03** | | | | | | - | -- | -- | | | - | - | - | | | |
| **DR-04** | | | | | | | | | ++ | | | | | | | |
| **DR-05** | | | | | | -- | | | + | | | | | | | |
| **DR-06** | | | | | | | | | | | ++ | | | | | |
| **DR-07** | | | | | | | | | ++ | | + | + | + | | | |
| **DR-08** | | | | | | | | | ++ | | + | + | + | | | |
| **DR-09** | | | | | | | | | | | | | | | | |
| **DR-10** | | | | | | | | | | | ++ | + | + | | | |
| **DR-11** | | | | | | | | | | | | + | + | | | |
| **DR-12** | | | | | | | | | | | | | + | | | |
| **DR-13** | | | | | | | | | | | | | | | | |
| **DR-14** | | | | | | | | | | | | | | | | |
| **DR-15** | | | | | | | | | | | | | | | | |
| **DR-16** | | | | | | | | | | | | | | | | |

## Functional Allocation

With the above analysis of FFBD, a functional breakdown structure for the improved system can be constructed. The functional breakdown provides a clear indication for system architecture. Possible subsystems have been identified. It helps to determine the sub-systems.




## Evaluation Parameters

The most important factor for this design characteristic is energy resources. Fossil fuel can be supplied continuously upon purchase so it assumed to have good performance. Based on Australia Energy Resources Assessment Report (Geoscience Australia, 2010), although Australia has one of the world's best wind energy, average wind speed for Canberra is less 7m/s. However, there is a constraint of grid availability, limiting wind electricity production. On the other hand, solar resources present better potentials with more than 14MJ/m2 in Canberra, better than equivalent energy for wind (7 m/s wind speed). Hence, solar electricity production is better than wind energy production. With respect to energy conversion efficiency, as discussed above in idea generation, fossil fuel station is better than wind power and solar PV.

CR-02: DR-03, 04

With respect to storage capacity, the diagram in idea generation has provided clear indication that rechargeable battery is a small system while the other two can be made big. In regards to energy conversion rate (International Renewable Energy Agency, 2012), compressed air system has a typical conversion efficiency of 45–60% while Li-ion battery has the DC power conversion rate of 90%. Thermal energy storage such as hydrogen has a normal round up efficiency of 50% (Energy Storage Association, 2016). Therefore, Li-ion battery has the best performance, which is much better than the other two.

CR-03: DR-05, 06

For generation systems, life span of solar panel is around 25 years as discussed before with a similar lifespan for household micro-wind system. However, coal turbine depends on fuel supply and a normal life span for a larger turbine is around 30 years so the lifespan for a normal household mini system is less than 30 years. As is known, fossil fuel can release huge amount of greenhouse gases, leading to the worst performance for being environmental-friendly. For storage system, Li-ion battery has the least lifespan for 8 to 15 years while compressed air system has more than 30 years' life. Thermal system sits somewhere in the middle based on thermal storage medium. Li-ion battery has the smallest size so the embodied energy is estimated to be much lower than the other two technologies.

CR-04: DR-07, 08, 09

Both upfront installation system cost and subsequent maintenance costs are related to levelised cost of electricity. From the previous analysis (idea generation), levelised cost of electricity for PV is the highest, followed by wind system and then traditional fossil fuel plant. With respect to storage techniques, overall storage cost for CASE system is around 2100/MWh while Li-ion system is 1800/MWh. Thermal system is also around 2000/MWh (Rastler, 2010). However, CASE and thermal system are set to be oversized for this storage of a household and can be hard to change size while Li-ion can reduce size according to client requirement. Hence, the cost of Li-ion system is can be further reduced.

CR-05 and CR-06: DR-10, 11, 12, 13, 14

For electricity generation, all three systems could perform similarly as they all have many components. But due to the lifespan discussed above, fossil fuel system is less durable, indicating more maintenance required. For electricity storage, Li-ion battery is the best option as it is smaller and easier to maintain. The other two systems have complex component and structure as discussed in system architecture section, making them less user-friendly.

## System Sizing

The position of panels on the roof is an important consideration. Tilt angle is to be set to a fixed value over the year since tracking system will impose higher costs and higher level of maintenance. In Australia, the standard roof angle is around 18° to 22.5° (Solar Quotes, 2016). Here, the target house is assumed to have a 20° roof angle and the house is facing true north.

There will be an optimum tilt angle for panels to receive maximum sun light during the year. The latitude of Canberra is around 35 degrees south so the solar panel is set to be facing north in order to be exposed to the greatest amount of sunlight through the whole day. The sun is usually higher in summer and lower in winter so it is better to set a lower angle for more sunlight during summer. According to the formula provided by Porter (2015):

$$\beta = 0.76 \times |\emptyset| + 3.1^\circ = 29.7^\circ$$

Hence, solar panel tilt for this system is around 10 degrees.

A common brand of solar panel is Tindo Solar Cell. Each cell has an efficiency of 15.6%, rated power at 260W under STC (Tindo Solar, 2016). However, a 35% PV power loss is assumed due to operating temperature and system components. In order to determine the size of the system, following parameters were obtained from data sheet (Tindo Solar, 2016). Module rated power: 260W; Module nominal voltage: 40V; System require voltage: 240V; Lifespan (performance warranty): 25 years; Assumed offset daily load: 8.05kWh (around 50% of load); Average daily available irradiation: 5.5kWh using the value for Watt's analysis (2006); Assumed Safety factor: 1.2

The size of the PV system using BP solar modules can be determined as follows:

$$P_{nom,without\ \ loss} = \frac{F_{GS} \times Load}{G(\beta)/G(STC)} = \frac{1.2 \times 8.05}{5.5/1} = 1.76kW$$

$$P_{nom} = \frac{P_{nom,without\ \ loss}}{0.65} = 2.71kW$$

A 240V system voltage requires 6 modules with 40V connected in series: $N_s = 6$

The number of parallel connection can be calculated: $N_p = \frac{P_{nom}}{N_s \times 260W} = 1.77 \approx 2$

The size of the system would then be:

$$P_{nom,G} = 2 \times 6 \times 260W = 3.12kW$$

According to the datasheet, the effective area to collect sunlight can be calculated:

$$A = 60 \times 156mm \times 156mm \times 12 = 17.52m^2$$

# Bibliography

Blanchard, B. & Fabrycky, W., 2011. Systems Engineering and Analysis. 5th ed. New Jersey: Pearson.

Cheng, L., 2016. Client Interview [Interview] (05 March 2016).

Critical Fuel Systems, 2012. An Engineering Guide to Modern Fuel Systems, Butner: s.n.

Dym, C., Little, P., Orwin, E. & Spjut, R., 2002. Rank ordering engineering designs. Research in Engineering Design, 13(4), pp. 236-242.

Energy Storage Association, 2016. Hydrogen Energy Storage. [Online]
Available at: http://energystorage.org/energy-storage/technologies/hydrogen-energy-storage

Energy Storage Association, 2016. Thermal. [Online]
Available at: http://energystorage.org/energy-storage/storage-technology-comparisons/thermal2

Energy Stroage Association, 2016. Compressed Air Energy Storage. [Online]
Available at: http://energystorage.org/compressed-air-energy-storage-caes

EP-Solar, 2016. Tracer-1215RN. [Online].

Eurelectric and VGB Powertech, 2003. Efficiency in Electricity Generation, s.l.: Union of the Electricity Industry.

Geoscience Australia, 2010. Australian Enery Resource Assessment, Canberra: s.n.

Hauser, J. & Clausing, D., 1988. The House of Quality. Harvard Business Review.

Huskey, A., Bowen, A. & Jager, D., 2010. Wind Turbine Generator System Duration Test Report for the Gaia-Wind 11kW Wind Turbine, Golden: s.n.

Ibrahim, H., Ilinca, A. & Perron, J., 2008. Energy storage systems—Characteristics and comparisons. Renewable and Sustainable Energy Reviews, 12(5), pp. 1221-1250.

International Energy Agency, 2015. Projected Costs of Generating Electricity, Paris: International Energy Agency.

International Renewable Energy Agency, 2012. Electricity Storage, s.l.: IEA-ETSAP.

Office of the Chief Economist, 2015. Australian Energy Update 2015, Canberra: Commonwealth of Australia.

Porter, L., 2015. The Renewable Energy Home Handbook. In: Chapter 3: Installation. s.l.:Veloce Publishing Ltd.

Rastler, D., 2010. Electricity Energy Storage Technology Options: A White Paper Primer on Applications, Costs, and Benefits, California: Electric Power Research Institute.

SMA Australia, 2016. THE Universally Applicable Sunny Boy. [Online].

Solar Choice Staff, 2016. 3kW solar PV systems: Pricing, output, and returns. [Online]
Available at: http://www.solarchoice.net.au/blog/3kw-solar-pv-systems-pricing-output-and-returns/

Solar Quotes, 2016. Is Your Roof Angle Suitable For Solar Panels. [Online]
Available at: https://www.solarquotes.com.au/panels/angle/

Standards Australia, 2014. AS/NZS 5033:2014 Installation and safety requirements for photovoltaic (PV) arrays, Sydney: s.n.

Sterman, J., 2000. Business Dynamics - Systems Thinking and Modelling for a Complex World. s.l.:McGraw Hill.

Tindo Solar, 2016. Grid Connect Solar Electricity. [Online].

Watt, M., PAssey, R., Barker, F. & Rivier, J., 2006. An analysis of photovoltaic output, residential load and PV's ability to reduce peak demand, Sydney: University of New South Wales.

Wenham, S. et al., 2013. Chapter 6 Stand Alone Photovoltaic System Components. In: Applied Photovoltaics. s.l.:Routledge, pp. 89-116.

Winston, 2016. Winston Battery BAT-LFP1000AHC 1000Ah LiFePO4 cells. [Online].

Zandbergen, B., 2016. Functional design and main components. [Online]
Available at: http://www.lr.tudelft.nl/en/organisation/departments/space-engineering/space-systems-engineering/expertise-areas/spacecraft-engineering/design-and-analysis/subsystems/electric-power/eps-subsystems/