System Architecture Design of a Robust Heating System

by

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Submitted to the System Design and Management Program
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ABSTRACT

Power outages are exponentially increasing because extreme weather conditions are occurring more frequently. In addition, the duration of the power outages are increasing. Unfortunately, the will to expand or convert the current electric grid is not there. The objective of this thesis is to design a new system – at a high level – that would protect homeowners from the effects of power outages. To do this, interviews were conducted with people who have actually experienced power outages during winter. Their preference for continued space heating during power outages prompted a design that uses natural gas fuel cell to power a furnace (or boiler) independent of the electric grid. The same system could also provide electricity to the homeowners, if the furnace is turned off. In addition to the system architecture design, surveys were conducted to determine pricing and financial analyses were performed to determine the commercial viability of the design. Consequently, the design proved to be too expensive. What's more, prices would have to drop significantly and / or other stakeholders, such as utility companies, insurance companies and governments, would have to cover most of the cost of the product for there to be a mass adoption.

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1. INTRODUCTION

The electric power grid in the United States (US) is made up of parts: the generating plants, the transmission lines and the distribution. The generating plant, which is also called the power plant, is the part of the system that produces the electricity. [1] Currently, most of the electricity generated within the country is from coal and natural gas powered plants. [2] There are other sources of electricity, such as nuclear powered plants, hydroelectric powered plants, solar powered plants and wind powered plants. The transmission lines are the part of the system that carries electricity over long distances. To achieve this, its voltages are stepped up to at least 115 kV before transmission and stepped down to 240V at the point of distribution. [3] The distribution is the part of the system that most people are aware of. From a substation, the electricity is distributed to homes and small businesses. (See Figure 1.1)

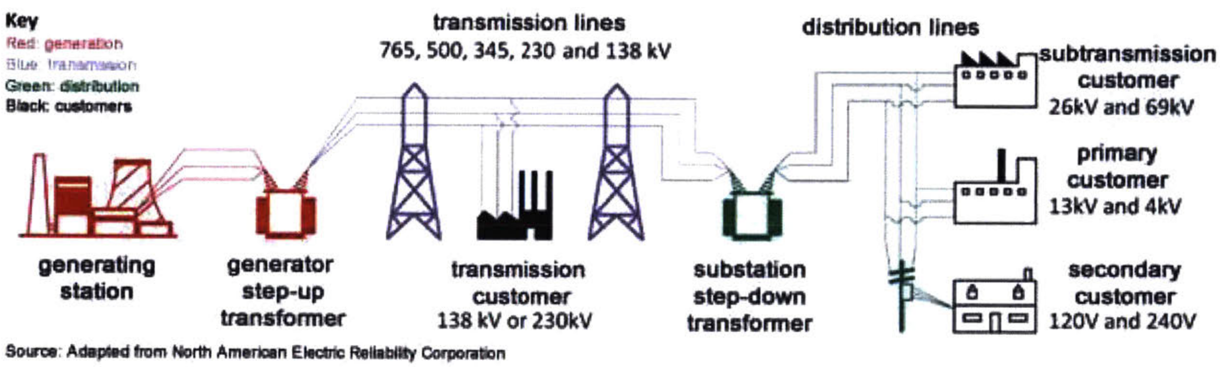


Figure 1.1 The US Electric Grid

1.1 Situation

In the daily lives of most people in the United States, electricity is used for brewing coffee in the morning, microwaving left-overs, preserving food, powering televisions, recharging smart phones and for some, driving around. In fact, the use of electricity is so pervasive, with all the new technologies available today, and taken for granted that a lot of people are unprepared for power loss. But power outages do occur every year and it affects millions of people [4]. Some power failures are triggered by bad weather events like tornadoes, hurricanes and winter storms while others are caused by humans intentionally (e.g. physical attack and cyber-attack) or unintentionally (e.g. human error and vehicle accident). [5] Some power failures also result from equipment breakdown, which increases with the age of the electric power infrastructure. For people living in the northeastern states of the US, power failure during extreme winter conditions can be very uncomfortable or be life threatening – since many people now have home-based medical devices for managing their medical conditions. Furthermore, power failures lead to financial losses: spoiled foods, repair bills, hotel bills, insurance deductibles, increased police presence, gasoline bill, lost man-hours of work and lost revenue.

1.2 Complication

Interestingly, it seems many factors are coming together to push the electrical power grid closer to its limits. These factors include peak-to-average demand ratio, rate of new constructions (capital expenditures) and frequency of extreme weather conditions. Since 1993, the peak-to-average demand ratio, a ratio of annual peak-hour demand to average hourly demand, has been increasing steadily, as shown in Figure 1.2. Because of this increase, the average utilization level of power plants, especially the ones in New England, has been decreasing. In other words, the system is becoming more inefficient. [6] In addition, the rate of new constructions to expand or upgrade the electrical grid has been slower that the depreciation rate. Over time, that system has become relatively old and its capacity stressed. A trend that would most likely continue as more cars, buses and trucks become electric vehicles, and drones become widely used for monitoring crops, delivering products and taking aerial shots.

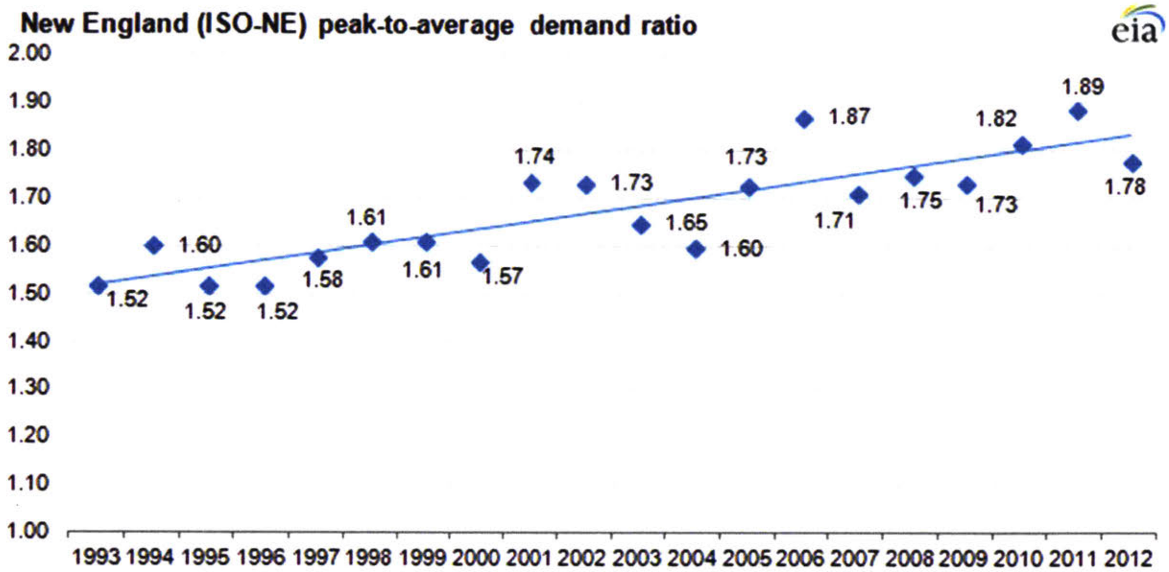


Figure 1.2 Peak-to-Average Demand Ratio

Source: www.eia.gov

Like the other two factors, the frequency of power outages has revealed the weakness of the electric power grid. With climate change, there has been an increasing number of extreme weather events, which, unfortunately, has led to an exponential increase in the number of large-scale power outages, as shown in Figure 1.3. [7] According to climatecentral.org, "weather caused 80 percent of all outages between 2003-2012." [4]

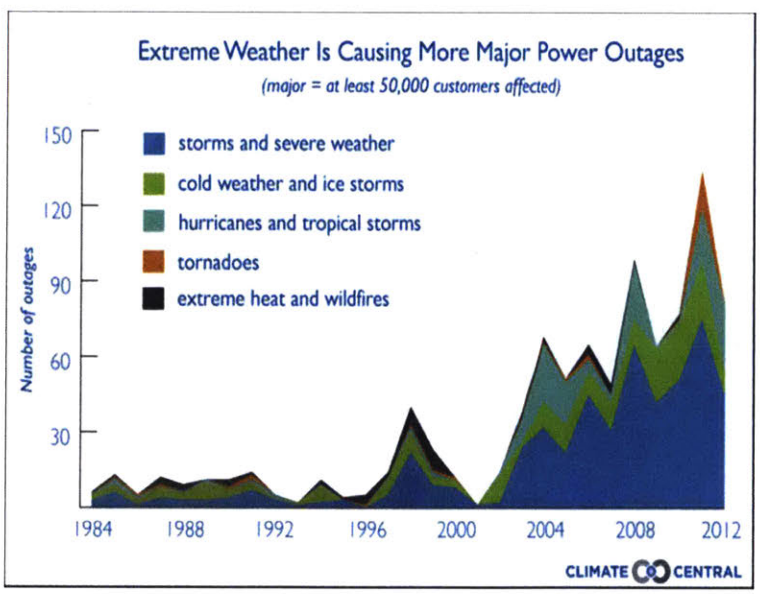


Figure 1.3 Number of Power Outages Caused by Extreme Weather

Meanwhile, the duration of weather related power outages has also increased. [8] Typically, power outages last several hours to several days, but as shown in Figure 1.4, they sometimes last more than a week. On rare occasions, they have lasted months as in the case of the power outage in Michigan and Iowa states, which started on June 21, 2013 and lasted 131 days. [5]

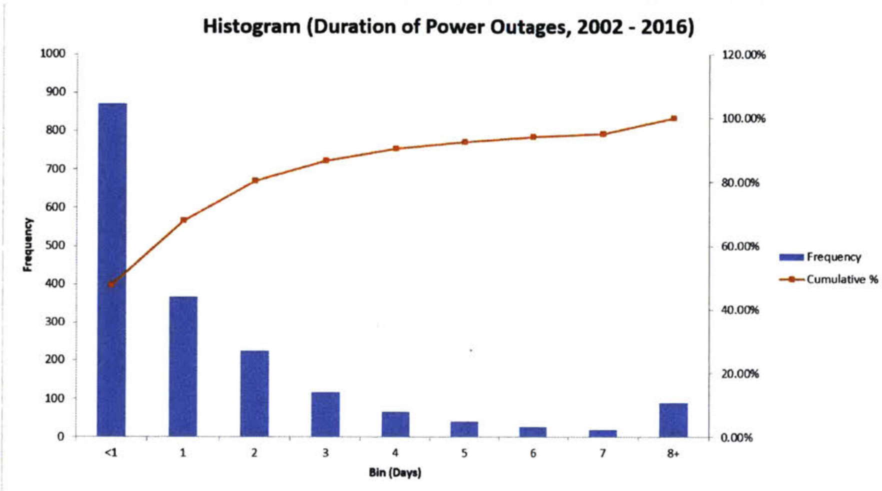


Figure 1.4 Histogram of the Duration of Power Outages

1.3 Question

Considering the increasing odds of experiencing a power outage, many homeowners now have backup systems such as generators and battery systems while others have off-grid systems such as solar power and wind power. However, the number of households with backup systems, which are mostly generators, is about 15% of the number of single family, owner occupied homes in the US, a number that represents a low market penetration. [9], [10].

So:

- Why is the market penetration of existing systems so low?
- Can a new product protect homeowners and be commercially successful?

1.4 Approach

To answer these questions, existing solutions were reviewed, stakeholders were identified, many concepts were generated, one architecture was designed, multiple business models were analyzed and one business model was proposed.

The structure of this thesis, as described below, follows the logical progression of activities that led to a system architecture design of a robust heating system and the financial analysis that supported the business decision.

Chapter 2: Describes the primary research performed to understand the benefits and limitations of existing solutions.

Chapter 3: Describes the actual process of identifying stakeholders and their needs, generating concepts and developing a concept into a system architecture.

Chapter 4: Describes the results of a pricing survey and various financial analysis performed.

Chapter5: Discusses the answers to the questions in chapter 1.

Chapter 6: Discusses any future work that could further this topic.

2. RESEARCH

Before attempting to propose a solution, the problem of power outage was investigated from different points of view. Naturally, there are a number of solutions homeowners are currently using. There are also solutions that experts have proposed. Some solutions are at the community / neighborhood level while others are at the household level. Furthermore, some solutions protect homeowners from the effect of power loss while others allow homeowners to recover quickly. In the following sections, all these solutions will be discussed in detail.

2.1 Existing Solutions

What are people doing to prepare for power outage in the winter? In this section, the focus of the discussion is on solutions that have nothing to do with installing alternative sources of electrical power. Of those solutions, some homeowners depend on emergency community shelters in towns and cities in which they live. Other homeowners have friends and family they can stay with. Some homeowners plan to stay in hotels or partially live at work – since some companies have bathrooms and kitchens. Many also have insurances and savings to help defray the cost of repairs, if needed. In general, most people only prepare for a few hours of power outage by having flashlights, batteries, candles, blankets, canned foods, charged cell phones, car with full tank of gas and fire stove / place.

Regrettably, depending on the community shelter has some disadvantages: first, privacy is lost. Homeowners have to share the same space with everyone else. Second, homeowners may not have access to toilets and bathrooms when they need it. Last, water damage from pipes bursting would not be prevented – since no one will be in the house.

Planning to stay with friends and relatives assumes that the roads will be accessible during a power outage. It is very possible that the roads are slippery and that power lines or trees are on the road.

Similarly, planning to stay in a hotel or planning to stay late a work and maybe use its shower and kitchen also assumes that the roads are in good conditions or hotel rooms would be available. As with all the other plans that involve leaving the house, any damage, including vandalism from thieves, would not be detected on time.

Since most homes have mortgages, lenders typically require homeowners insurance. Presumably, most homeowners have home insurance. While home insurance helps to cover cost of replacing damaged property – at least the replaceable ones, it does not prevent damage in the first place nor the inconvenience of living through power outage in the winter.

While it is good to prepare for power outage using flashlights, blankets and fire stoves, there is potential for CO poisoning or fire damage. Depending on how cold the outside temperature is, it may be difficult to survive several days without power.

2.2 Proposed Solutions

There have been several solutions proposed for reducing the number of power outages, the duration of each outage and the number of people affected by each outage. There are people who believe that the US should build more transmission lines, a desperately needed infrastructure, and there are some who believe that the US should modernized the electric grid to be a "smart grid." [11], [12] There is another camp who believes that the US should have micro grids or distributed grids, a de-centralized form of power grid that can help limit the impact of power failure. [13]

Increasing the number of transmission lines has several advantages. It would allow utility companies to have alternate routes for providing power to the end customers while isolating a faulty component. It would also help them to better meet current peak demands and future demands, as more systems, like electric cars, get connected to the grid. In general, upgrading the current system by expanding capacity, placing utility lines underground, elevating substations and relocating facilities are some recommendations that have been proposed for improving the grid. [12]

Alternatively, a smart grid would detect small events, like a tree branch falling onto a power line, before they become major events, such as blackouts. [14] A smart grid might include smart meters that would allow utility companies to know which customers have power and on which side of the meter the failure is. [15] A smart grid might have storage systems that allow load balancing and additional sources of power, including renewable energy sources. [12] A smart grid will be able to respond quickly to potential problems and quickly restore the grid to normalcy, if problems do occur.

Unlike the current system, micro grids, a form of distributed grids, generate power close to the customers they serve. Because of this, they are more reliable. Micro grids can automatically isolate itself from the main grid when there is a fault and reconnect itself when the fault is removed. [16] Interestingly, many recommendations tend to combine micro grids and smart grids as the future electric grid.

2.3 Alternate Power Source for Home Use

As mentioned before, most people get their electricity from the electric power grid via utility companies, while others get part of or all of their electricity from other sources of power. In the following sections, many of the alternate sources of power installed in people's homes will be discussed.

2.3.1 Solar

Solar power is the power harvested from the Sun. Unlike some other sources of power, solar power does not get depleted, so there is no worry about it ever running out. The typical solar power system is comprised of solar panels, which are made up of photovoltaic cells that converts sunlight to direct current (DC) electricity, a charger for charging a bank of batteries, and an inverter for converting DC electricity to alternating current (AC) electricity, which is what the house uses. Some solar power systems include meters that enable power to be put on the grid and sold to utility companies.

Compared with other sources of power, solar power is still very expensive. Even with federal government tax credits of 30%, insurance discounts and clever business models – 0 down, 20-year monthly payments, market penetration is still low. [17] [18] [19] At night when there is no sunlight, pure solar power systems are useless. It needs a battery or any charge storage device to store electricity during the day and provide electricity a night. Same conditions apply during a winter storm. Sunlight is typically available for shorter times and a snow covered solar panel does not work well. Solar power systems tend to occupy a large area, such as roofs of houses. These roofs need to be in the right orientation and be free from shadows caused by neighboring structures or trees. So, not all house can use solar power.

For all the disadvantages of solar power systems, there are many advantages. First, the system emits no pollution; therefore, it is very good for the environment. Second, it is quiet. Third, it requires little maintenance. Forth, it is reliable. That is, the system can last up to 25 years, excluding batteries. Last, it requires minimum intervention during use.

Another form of solar power worth mentioning is from the Sun's radiated heat. It can technically be used to generate electricity. A device is needed to collect and concentrate the sun's rays, the heat produced is then used to generate steam, which is then used to drive a turbine to generate electricity. [20]

2.3.2 Wind

Like solar power, wind power is a renewable source of electric power. A wind power system is made up of a wind turbine, which converts kinetic energy of the wind into electricity, a tower to hold the wind turbine, a controller for controlling the blades, a charger for charging batteries, which store electricity for later use, and an inverter for converting DC electricity to AC electricity. Many homeowners consider wind power systems unsightly (18 feet wide, 80 feet high) and expensive, which may explain why they haven't really caught on. They need an average speed of at least 12 mph to produce reasonable levels of electricity and they generate noise. [21] They have also been known to kill birds.

On the flip side, wind power has so many benefits. It produces zero emissions, and it is reliable – though less reliable than solar power system. It also requires minimal intervention during use and can produce electricity day or night. In short, it is the kind of electrical power source that a homeowner in a remote area or in a rural area will want to use.

2.3.3 Battery System

A battery is a device that converts chemical reactions into DC electricity. Normally, a battery has an electrolyte and two terminals: anode (negative terminal) and cathode (positive terminal). These terminals are used for delivering electrical power to a device.

Also worth mentioning is that some batteries are rechargeable (li-ion), which means they can be charged and discharged multiple times. For this reason, rechargeable batteries are sometimes used with solar power or other systems that require energy storage for later use. When a battery is charging, it is storing electricity.

Batteries can be combined together to power a house as in the case of Tesla's Powerwall. A full battery system consists of batteries, a transfer switch for isolating the grid or connecting to the grid, a charger for managing battery charging, and an inverter for converting DC electricity to AC electricity. It can be expensive, if it is meant to protect against days without power. Also, if it is used in an application that requires charging and discharging every day, it may require changing the battery every three years.

Conversely, a battery system is quiet, easy to use and does not produce emissions. It can work day or night and it is invisible to neighbors.

2.3.4 Generator

An electric generator (or generator) is a device that converts mechanical energy to electrical energy. In the residential market, generators are typically made up of an internal combustion engine (ICE), which burns fuel (e.g. gasoline) mixed with air to produce mechanical energy. This energy is then used to drive an alternator, which converts mechanical energy to AC electricity. So, as long as there is fuel in the generator, electricity will be produced. However, generators that use gasoline or diesel require shut down of generator plus time for generator to cool down plus time to fill up the tank with appropriate fuel every 6 to 10 hours. Furthermore, some small generators have a cord that requires significant human effort to start it. Overall, there are two types of generators: portable generators and standby generators. Portable generators are typically less than 7 kW, require a fuel tank and are cheaper than the standby generators. [22] They do not require installation by an electrician nor do they require local government permit for use. They are loud, and they produce carbon monoxide (CO), a deadly fume, and other air pollutants. For this reason, they have to be operated several feet away from the house. Lastly, they require electrical appliances to be plugged in it directly or indirectly via an extension plug. Standby generators, however, are typically between 7 kW to 60 kW. [23] Unlike portable generators, they require electricians, plumbers - to connect the natural gas line, and local government permits. They are less noisy and are more reliable than the portable generator. They also produce lower emissions because they use natural gas or propane. Since natural gas is piped into homes in the US and others have propane tank, standby generators can in theory run for a very long time. However, most are designed to provide continuous electricity for a few days only. Compared with portable generator, standby generators come on automatically when there is a power outage.

2.3.5 Fuel Cell

A fuel cell is a device that converts hydrogen mixed with air into DC electricity. Unlike a generator, the fuel cell uses a chemical reaction to produce electricity. Fuel cells have an anode, a cathode, an electrolyte membrane and wires for connecting to a load. [24] Fuel cell systems sometimes use a reformer to convert natural gas, a more readily available product, into hydrogen. Sometimes, a compressor is used to deliver more oxygen to the fuel cell to increase the electricity produced. Additionally, an inverter is used to convert DC electricity to AC electricity for powering home appliances. Fuel cells are very expensive because the commercially available ones used platinum as a catalyst. Fuel cells require batteries or any other charge storage device for starting. Fuel cells don't respond fast enough to spike in demand.[25]–[27]

Hydrogen powered fuel cells require changing hydrogen cylinders every few hours. Since hydrogen cylinders are not widely available, several hydrogen cylinders need to be stored somewhere on a homeowner's property - a potentially hazardous situation.

Compared with batteries, fuel cells can provide electricity for a very long time (day or night) as long as there is a continuous supply of hydrogen and air. Fuel cell systems are quiet, reliable and produce zero or near zero emissions. Once installed, natural gas or propane powered fuel cell systems require minimal human intervention.

2.3.6 Thermoelectric generator

A thermoelectric generator (TEG) is a device that converts temperature difference into DC electricity. A TEG is made up of p-type and n-type semiconductors sandwiched between two non-electrically conductive materials. These materials, however, are thermally conductive. [28] In practical applications, a heat source, such as wasted heat, is applied to one side of the TEG and the other side is cooled by a passive or active system, such as heat sink or liquid coolant. [28] An inverter is also needed to convert the DC electricity to AC electricity. When there is power outage and it is dark, heat for one side of the TEG would have to come from either the ground (more than 6 feet under) or fire (burning wood / pellets). Commercially available TEG is expensive and has low efficiency. Consequently, it is not widely available and it is mostly used for harvesting waste heat.

On the other hand, a TEG is quiet, reliable and it produces zero emissions.

2.3.7 Water turbine

A water turbine is a device that converts mechanical energy to electricity. Like the wind turbine, water spins a turbine, which in turn spins a generator to produce AC electricity. However, water turbines require a constant source of water, such as stream, rain or city water. Since most people don't live near streams, it is not scalable. Rain is seasonal and it is not a good source for producing electricity. [29] However, city water can be used. A full system would require a way to circulate water; otherwise, there would be so much waste. It can be expensive to operate. It is less reliable than a battery system or a solar system and it produces zero emissions. It can be used day or night. Since the same amount of electricity is generated regardless of load, a battery and a battery charger may be needed to store electricity for later use.

2.3.8 Micro Combined Heat and Power (CHP)

Instead of just providing electrical power for home use, a system can be employed to provide both electrical power and heat for space heating or water heating. Another word for this concept is cogeneration. For example, a fuel cell could be used to generate electricity and all the waste heat could be used for space heating. Combined, the efficiency goes up to 90% [30]. Similarly when a solar system is used to produce both electric power and useful heat, then the overall efficiency goes up. In micro CHP, the primary out need not be electricity.

2.3.9 Hybrid

In hybrid systems, the idea is to combine two or more power sources to leverage their positives. For example, solar power and wind power could be combined to increase the number of hours of power generation. Typically, wind speeds are low in the summer while the reverse is true in the winter. [31] Another example that comes to mind is fuel cell and solar. Solar power can be used to provide the electricity needed for extracting hydrogen from water. So during the day, excess solar energy can be stored indirectly as hydrogen and at night, the fuel cell converts the hydrogen into electricity. The advantage of this hybrid is that the reliability of the system is greatly improved.

Homeowners trying to go off-grid may sometimes find out that they have no choice but use hybrid systems.

For reference, Table 2.1 provides a summary of the different power sources, including the disadvantages of each one.

Technology	Principle of operation	Installation price @ 5kW	Disadvantages
Solar	Solar panels convert sunlight into electricity	$19,485 [32]	Requires sunlight, which may not be available during or shortly after a snow storm
Wind	Wind turbines convert winds' kinetic energy into mechanical power, which is then converted into electricity via a generator	$38,225 [32]	Requires wind and a tall pole, which may be considered unsightly.
Battery	Stores electricity from the grid and then provides the electricity during power outage	$5,000 – $10,000 [33]	Limited run-time - several hours.
Generator	Combustion engines convert fossil fuel into mechanical power, which is then converted into electricity via a generator	$599 – $3,699 [Source: Home Depot]	Produces carbon monoxide and noise. Must be operated outside a house or an apartment
Fuel cell	Fuel cells converts hydrogen into electricity	$27,000 – $41,000 [34]	Relatively new technology and hydrogen is not readily available
TEG	Based on Seebeck effect, temperature differences is converted to electricity	Not available.	Low efficiency
Water turbine	Water turbines convert moving water's kinetic energy into mechanical power, which is then converted into electricity via a generator	$15,990 [35]	Require moving water, which is not available everywhere all the time.
Biomass Combustion Micro CHP	Combines any technology above with a means to convert wasted heat into useful heat	$28,960 [32]	May be useful only in places when there is a need for high thermal energy and the cost of electricity is high.

Table 2.1 Summary of Power Sources

2.4 Interviews

In addition to understanding all the solutions out there, including some proposed solutions, interviews were conducted with individuals who had experienced power outages during winter in the Northeast.

Thirteen people (7 males and 6 females) were interviewed and their experience with power outage varied from a few hours to 7 days. Here in Figure 2.1 are the results of the interviews.

Note: Each interviewee contributed only one power outage experience – their longest experience.

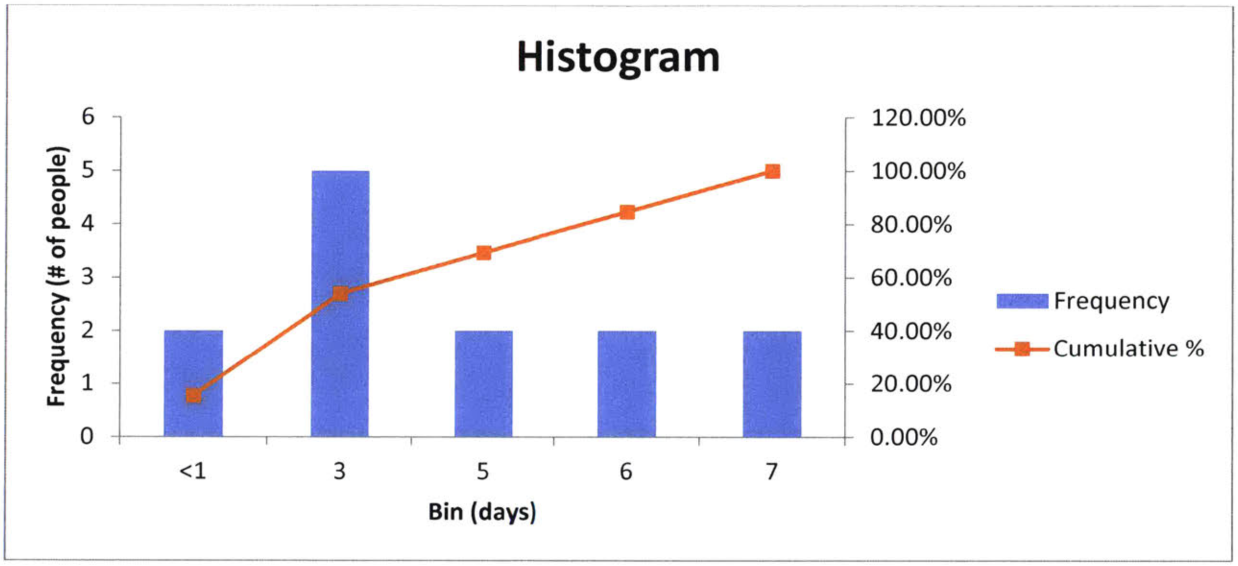


Figure 2.1 Histogram – Number of Days of Power Outage

Of the 13 people that were interviewed, only two had experienced power outage less than 24 hours. One person had experienced power outage for 1.5 days and four other people had experienced power outage for three days. Both groups of people were included in the bin labeled "3" days. All other bins (5, 6, and 7) show the number of days of power outage that one or more interviewee experienced. Clearly, from the result, most people had experienced power outage for three or more days.

Table 2.2 shows overwhelmingly that people want their heating systems to work during a power outage. They also don't want to pay more than $1000 for a solution that they may or may not need. Interestingly, in another survey conducted by YouGov Definitive Insights, people expected to be paid more than $1000 for power outages lasted more than 2 days. [36]

Categories	Results
% of people who prepared for the next power outage	30%
% of people whose first choice is space heating	85%
% of people who would consider going off-grid to protect themselves from power outage, if money wasn't an issue	62%
How much people are willing to pay for a solution	$500 - $1000*

Table 2.2 Results of Interviews with Power Outage Survivors

*One person was willing to pay $5000.

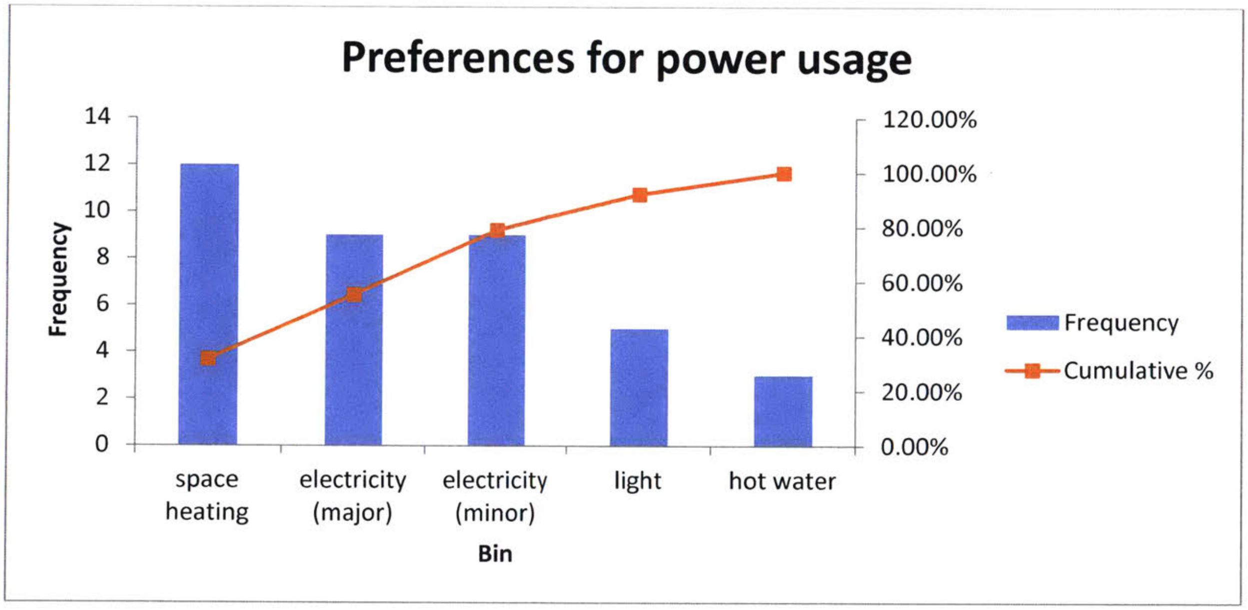


Figure 2.2 Histogram - Customer Preferences of Electrical Services

Each interviewee was asked to list and rank their top three choices out of the choices listed in the histogram above. Their first choice had to be one thing they would rather have working during a power outage. Once the first choice was made, the second choice was what else they would rather have working during a power outage. The same question was repeated to get their third choice. Examples of a major appliance is sump pump, microwave, refrigeration and freezer. Whereas examples of a minor appliance is router, cell phone and tablet. If an interviewee mentioned an electrical service, then the corresponding bin increases its frequency by 1.

After the interview, it was clear that space heating was a priority. Most of the interviewees also showed interest in a product that provided some electricity in addition to providing heat as illustrated in Figure 2.2. This is somewhat in line with a more comprehensive survey by Harris Poll. [37] Other insights from the interviews were: solution must be environmentally friendly, its fuel must be readily available, should require minimal intervention during use and be well known – people seem to want to buy or use what they know.

Considering the results of all the surveys, interviews and research, it became evident that the lead adopters of the eventual products would have be vulnerable homeowners (e.g. family with at least one kid or seniors that maybe live alone or persons that depend on electricity for managing their medical conditions) who live in a single family house in the suburbs – off major streets. Houses on small streets tend to be of lower priority to power utility companies. Consequently, they are more likely to be without power for longer periods of time. [38]

2.5 Types of Heating Systems

There are many types of heating systems people have in their homes. For example, people have furnaces, boilers, heat pump, solar heating, wood heating, portable heaters and electric resistance heating. However, furnaces, boilers and heat pump are the most popular. In fact, the relative mix of new homes with these systems has shifted over time. According to www.census.gov, in 1973, the mix of newly constructed homes were 74% homes with furnaces, 6% homes with boilers and 0% homes with heat pump, but in 2015, the mix of new homes were 56% homes with furnaces, 41% homes with heat pump and 1% homes with boilers. [39] Overall, in the US there are 70% homes with furnaces and 11% homes with boilers. [40] Interestingly, different regions in the US favor one heating system over all others. The same is true for heating fuel. [41]

2.5.1 Furnace

Furnaces, also called forced-air systems, heat up rooms by delivering warm air to all the rooms in the house. A heating system that includes furnaces have the furnace itself, air duct to distribute warm air and thermostat to regulate the temperature of the house or room. The furnace consists of a combustion chamber, where fuel mixed with air is burned, a heat exchanger, which transfers heat to its surrounding air, a blower, which forces air to all the rooms, a flue pipe, which vents the combustion gases and a control system, which manages the blower, electronic ignition (if used), relays, valves and a pump, if the fuel used is oil. The heat created in the furnace can come either from burning oil, gas or from passing electrical current through a device with electrical resistance. [42] Newer furnaces have to meet an efficiency standard (Annual Fuel Utilization Efficiency, AFUE) of 78%, but are typically higher than 82%. Also worth pointing out are: 1) All furnaces require electricity to work. 2) People with several allergies tend to prefer houses with boilers, since water rather than air is circulated.

2.5.2 Boiler

Unlike furnaces, boilers heat up rooms by circulating hot water through pipes to all the radiators in the house. Each radiator then takes the heat in the water and radiates it, thereby heating up a room. This type of heating system is called a hydronic system and it includes a thermostat as well. Note: some hydronic systems circulate hot water through tube embedded in the floor.

The boiler consists of a combustion chamber, where fuel mixed with air is burned, a heat exchanger, which transfers heat to the water, an expansion tank, which helps maintain pressure, a pump, which distributes hot water to all the radiators, a flue pipe, which vents all the combustion gases, and a control system, which manages a water pump, a relay, a valve and a smaller pump, if the fuel is oil. Boilers work with gas, oil or electricity, as an energy source. [42] They also have to meet an AFUE requirement of 80%. [40]

2.5.3 Heat pump

Heat pumps are different from the other two because they use only electricity. So, without electricity, they are pretty useless. Heat pumps take in heat from outside, even when the temperature feel cold, and use it to warm up the house. They can also be used to cool down a house. Similar to the force-air system, heat pumps use blowers to circulate warm air and thermostats to regulate room temperature. A heat pump consists of a refrigerant, which absorbs heat by turning gaseous from liquid, an outdoor heat exchanger, which facilitates the exchange of heat, a compressor, which pressurizes and increases the temperature of the gaseous refrigerant, an indoor heat exchanger, which heats up the indoor air, a blower, which circulates the warm air, and a control system, which manages all the electrical components in the system.[43] There are other types of heat pumps. One type draws its heat from a nearby lake while the other type draws its heat from underground. This second one is called a geothermal heat pump.

3. SYSTEM ARCHITECTURE DESIGN

In this chapter, the process of designing the system architecture of a robust heating system will be described in great detail. Once again, a heating system was chosen because most people prioritized space heating above all other needs normally met with electricity. And, they wanted the cost of the heating system to be less than $1000. The use of the word "robust" means that the system will work, even if there was a power failure.

3.1 System Boundary and Interfaces

The first thing to do was to determine the system boundary. To do that, the operational environment of the system was chosen, and from there all the interfaces were identified. Figure 3.1 shows a Functional Block Diagram (FBD) of the system, which is meant to be installed inside an apartment or a house. The figure also shows three different types of interfaces: Energy flow – Electricity, Heat and Noise; Material flow – Natural gas / propane and Air, and Information flow – User input and Display.

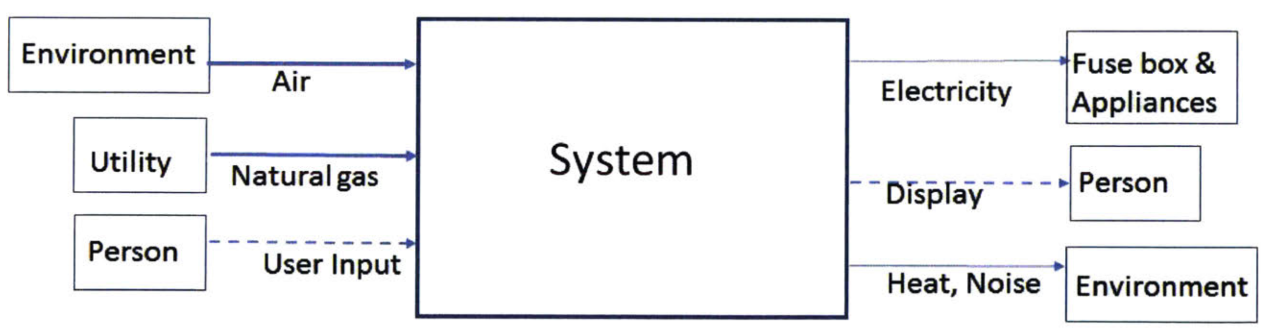


Figure 3.1 System Boundary and its Interfaces

3.2 Stakeholder identification

After determining the system boundary, the next thing to do was to determine and classify all the stakeholders.

3.2.1 Beneficial stakeholders

These are people who provide inputs for a success of the project and receive benefits provided by the project. [44] They are:

- Homeowners – These are the customers that would buy the product for an existing home.
- Home Builders – These are customers that would buy the product for new homes.
- Enterprise – Is the entity that manages one or more projects. For the purpose of these thesis, the enterprise is a startup with only one project.
- Suppliers – These is an aggregate of all suppliers of key components.
- Regulators – These is an aggregate of all regulators.
- Local community – These include local government as well as citizens of the town or city.
- Utilities – These include electricity and gas companies.
- Insurance – These stand to gain a lot, if the system prevents property damage.

3.2.2 Problem stakeholders

These are people who provide inputs for the success of a project, but they don't derive any benefits from the project. [44] They are:

- Media – TV, social media, radio and trade journals. They provide free publicity when they like a product.
- Retail stores – An aggregate of physical stores. Some products will be sold online while others would require physical space in stores.
- Installers/Maintenance – These may be electrician and plumbers. They know what makes a product easy to install and maintain.

- Competitors – These include direct competitors (use same technology) or indirect competitors (use different technology).
- Investors – An aggregate of investors who expect a certain return on their investments.

3.2.3 Charitable stakeholders

These are people who receive benefits provided by a project, but they do not provide a valued input to the project. In this project, there are no charitable stakeholders. [44]

3.3 Stakeholder Analysis

After classifying all the stakeholders, the next step was to identify the exchanges between the project and a stakeholder, and between stakeholders. The result of these analysis is shown in Figure 3.2. Interestingly, this figure reveals not only the needs of all the stakeholders but also a few feedback loops, which are also known as value loops. The first value loop is: Project – Local community – Media – Project. One could set up a re-enforcing loop (System Dynamics, [45]) that drives word of mouth high and good publicity high, which should help drive sales. In other words, the project could use the local community as a lever in balancing the relationship between the media and itself. Another loop is Project – Local community – Retail stores – Project. Similar to the first value loop, a re-enforcing loop can be set up to drive more retail spaces across local retailers. The last value loop of interest is Project – Homeowner – Competitors – project. This loop is a high priority loop because the future of the project depends on the exchanges between the project and homeowners and the exchanges between the competitors and homeowners.

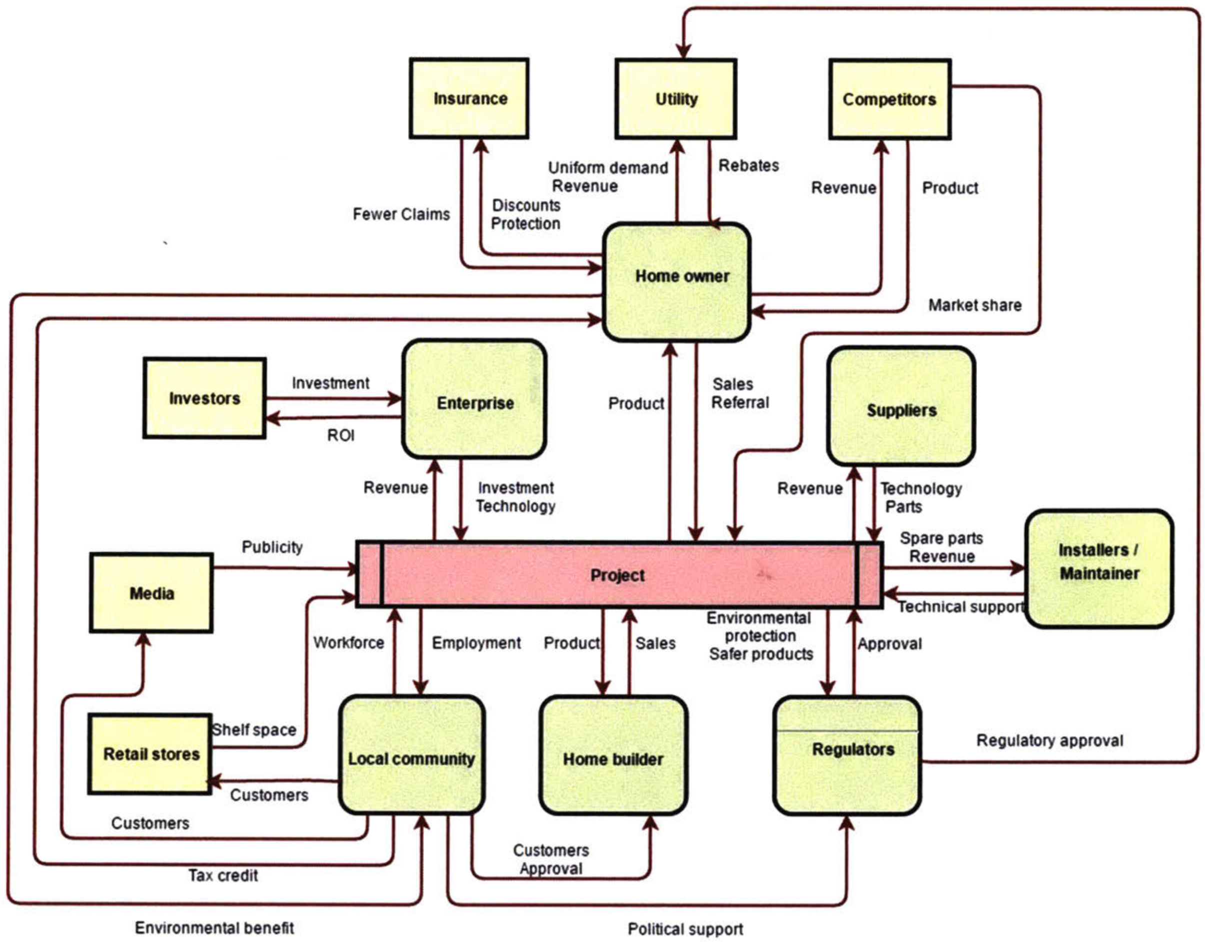


Figure 3.2 Stakeholder Value Network

3.4 Needs and Needs Ranking

Once the stakeholders and their needs were identified, the next step was to rank all the needs. First, the needs of each stakeholder was ranked as Must have, Should have and Might have. Next, those same needs were ranked according to the availability of alternative suppliers. The more alternatives there are, the lower the ranking. Third, both ranking were combined to form a single rating as shown in Table 3.1. [44] Note: the rubric for the weight is shown in Appendix A.

To	Needs	Must Have	Should have	Might have	Supply Importance	Weight
Project	Sales	Y			Med	0.8
	Technology	Y			Med	0.8
	Investment	Y			Hi	0.95
	Regulatory approval	Y			Hi	0.95
	Retail space		Y		Lo	0.5
	Workforce		Y		Med	0.4
	Referrals			Y	Lo	0.1
	Good publicity			Y	Lo	0.1
	Market share	Y			Hi	0.95
Enterprise	Revenue	Y			Hi	0.95
	Investment	Y			Hi	0.95
Home owner	Heater product	Y			Med	0.8
	Tax Credit			Y	Lo	0.1
	Discount			Y	Lo	0.1
	Rebates			Y	Med	0.2
Suppliers	Revenue	Y			Med	0.8
Regulators	Environmental protection	Y			Lo	0.4
	Public safety	Y			Lo	0.4
	Political support		Y		Hi	0.5
Local community	Environmental benefit	Y			Med	0.8
	Employment	Y			Lo	0.4
Home builders	Customers	Y			Lo	0.4
	Community support	Y			Hi	0.95
Media	Audience	Y			Med	0.8
Retail stores	Customers	Y			Lo	0.4
Utilities	Regulatory approval	Y			Hi	0.95
	Lower peak demand		Y		Med	0.4
Insurance	Fewer claims		Y		Lo	0.2
	Revenue	Y			Lo	0.4
Investors	ROI	Y			Lo	0.4
Competitors	Revenue		Y		Med	0.4

Table 3.1 Ranking of all Stakeholder Needs

3.5 Target specification

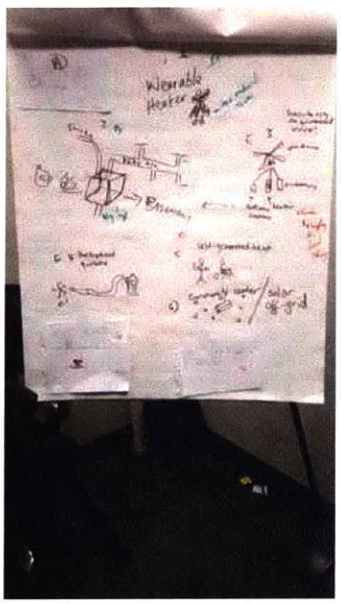
The next step in the process of designing the system architecture of a heating system was to translate the stakeholder needs into specifications. Only a subset of the needs that could be met by a development team, including manufacturing team, were translated into specifications, which are shown in Table 3.2. [46]

Need #	Need	Metric	Units	Marginal Value	Ideal Value
1	Quiet while operating	Sound level	dB	<60	<40
2	Operate for a long time	Time delivering rated power	days	>5	>7
3	Requires minimal intervention	Number of times to refuel the heater in a three days	unitless	1	0
		Number of steps to start the heater	unitless	2	1
4	Safe to operate	Meet local and state laws	binary	pass	pass
5	Reliable	Duration of operation before failure	hours	>2000	>3000
6	Doesn't produce toxic fumes	Meet EPA standards	binary	pass	pass
7	Heat a house	Minimum size of the house to be heated	Sq ft	>2400	>3600
8	Allows different temperature setting in each room	Temperature range	Degrees F	60 – 90	60 – 90
9	It is cheap	Unit manufacturing cost	US $	<750	<300
10	Easy to maintain	Time to assemble / disassemble for maintenance	hr	2	1
11	Power the heating system	Electrical power	kW	>1	>2.5

Table 3.2 Heating System Specifications

3.6 Concept Generation and Selection

Several concepts were generated and evaluated using Pugh chart. During this stage, a few concepts that were outside of the original system boundary were also considered. Discussing them allowed us to see the strengths in other concepts and add one more requirement: system needs to provide a secondary value. Figure 3.3 shows a subset of the concepts that were discussed.



- RefA = standby generator powering the whole house
- B = thermal wear
- C = fire hydrant + turbine
- D = gas stove in the basement
- E = Drones supplying batteries and heaters
- F= Human powered generator
- G = Small standby generator that powered only the heater
- H = Fuel cell that powered only the heater
- I = Thermoelectric generator that used natural gas and snow
- J = tap water + turbine

Figure 3.3 A list of Concepts Generated

Concept A, which served as the reference in the Pugh chart (see Table 3.3), is standard natural gas power generator with automatic turn on. Compared with solar, wind, portable gasoline generator and battery system, it didn't have any major drawback.

Concept B is a special thermal wear that allows individual to be very comfortable but can be annoying to remove.

Concept C is one of the concepts that tried to solve the problem from a different perspective. It has to do with using water from a fire hydrant plus a turbine to produce electricity for a few surrounding houses during power outage. Ignoring bureaucratic nightmare, we found out that water pressure will reduce in other fire hydrants. So, using many fire hydrants would be impractical.

Concept D is a gas stove in the middle of a basement powered with natural gas.

Concept E, another "outside-of-the-box" thinking, has to do with delivering batteries and heaters using drones. Assuming the weather still allowed for flying, it seemed impractical - at least for a startup company.

Concept F is a human powered generator. In other words, every able person takes turn in producing power for heating the house.

Concept G is a small natural gas (or propane) powered generator that powers only the heating system. That is, the heating system becomes isolated from the grid. Unfortunately, there are too many competitors who would do a better job implementing this idea.

Concept H is similar to concept G except a natural gas powered fuel cell is used. It also has a feature that allows it to switch power from the heater, when in shut down mode, to any other appliance in the house.

Concept I is a thermoelectric device that has one of its plate buried in the snow and the other plate has heat from fire applied to it. The fire is powered from natural gas.

Concept J came from concept C. However, it has two drawbacks. First, a lot of water will be wasted. Second, it is not clear whether the pressure would go down if every homeowner is using one of this during a power outage.

After generating several concepts, a Pugh chart was used to combine concepts and eliminate other concepts until one concept remained. In the case of the heating system, two concepts emerged as the potential solutions to go with. Concept H, fuel cell, was better favored than concept G, small standby generator, because it is a new technology and it is easier to compete in the fuel cell market. Also worth mentioning is that concept B was not chosen because it wouldn't protect the house from property damage.

Requirements	Standby gen for whole house (Ref)	Thermal wear	Fire hydrant + water turbine	Gas stove in Basement	Drones supply batteries	Human powered gen	Standby gen for heater	Fuel Cell for heater	Thermoelectric gen	Tap water + water turbine
Heat human & protect house	0	-	-	0	0	-	0	0	0	-
Quiet < 65 dB	0	+	-	+	+	0	0	+	+	0
Cost < $750	0	+	-	-	-	+	+	-	0	-
Meet EPA standard	0	+	-	0	+	+	0	0	0	-
Reliable > 2000 hours	0	+	-	+	+	-	0	+	+	+
Continuous operation for 7 days	0	+	-	0	+	-	0	+	0	+
Minimum intervention	0	-	0	0	-	-	0	+	0	0
Secondary value	0	+	+	0	+	+	+	+	-	-
Total score	**0**	**4+**	**5-**	**1+**	**3+**	**1-**	**2+**	**4+**	**1+**	**2-**
Continue ?	**No**	**No**	**No**	**No**	**No**		**Yes**	**Yes**	**No**	**No**

Table 3.3 Pugh Chart - Selecting a Concept

3.7 Decomposition

Once the fuel cell powered heating system was chosen, the next step was to derive the next level subsystems. Two subsystems were identified: one subsystem that needed to be designed and another that already exists in peoples' homes. The subsystem that needed to be designed would include a fuel cell system and was the focus of subsequent design effort. Figure 3.4 shows the interfaces between the two subsystems and other external entities.

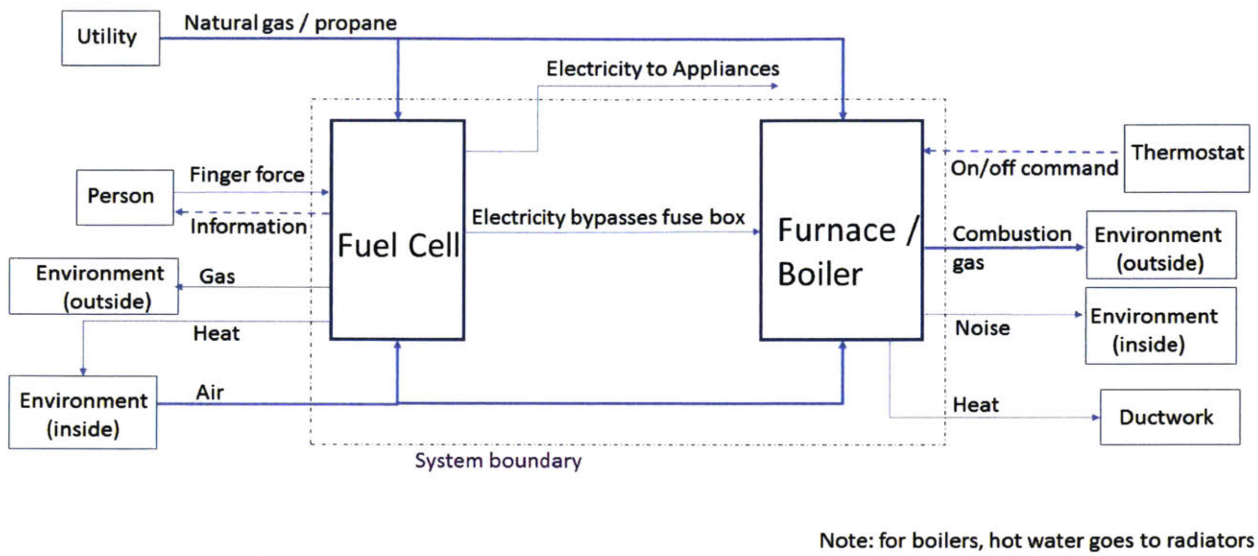


Figure 3.4 Functional Block Diagram of a Robust Heating System

3.7.1 Functional decomposition

Since one of the goals of the thesis is to develop a system architecture of a heating system, the system was broken down functionally and then each function was assigned a component. Afterwards, groups of components were lumped together to form modules. The end result was a mapping of functions to components while also showing the interactions between components.

In this section, the functional decomposition is discussed. First, the high level function of converting natural gas plus air into electricity and heat was broken into several smaller functions as shown in Figure 3.5. Some of the functions are interface functions (1, 2, 3, 4, 8 and 9) and others are transformative functions (5, 6 and 7). To get the second level of decomposition, each function was then broken to interface functions and transformative functions. [47] The result is shown in Figure 3.6. The second level functions are shown in orange.

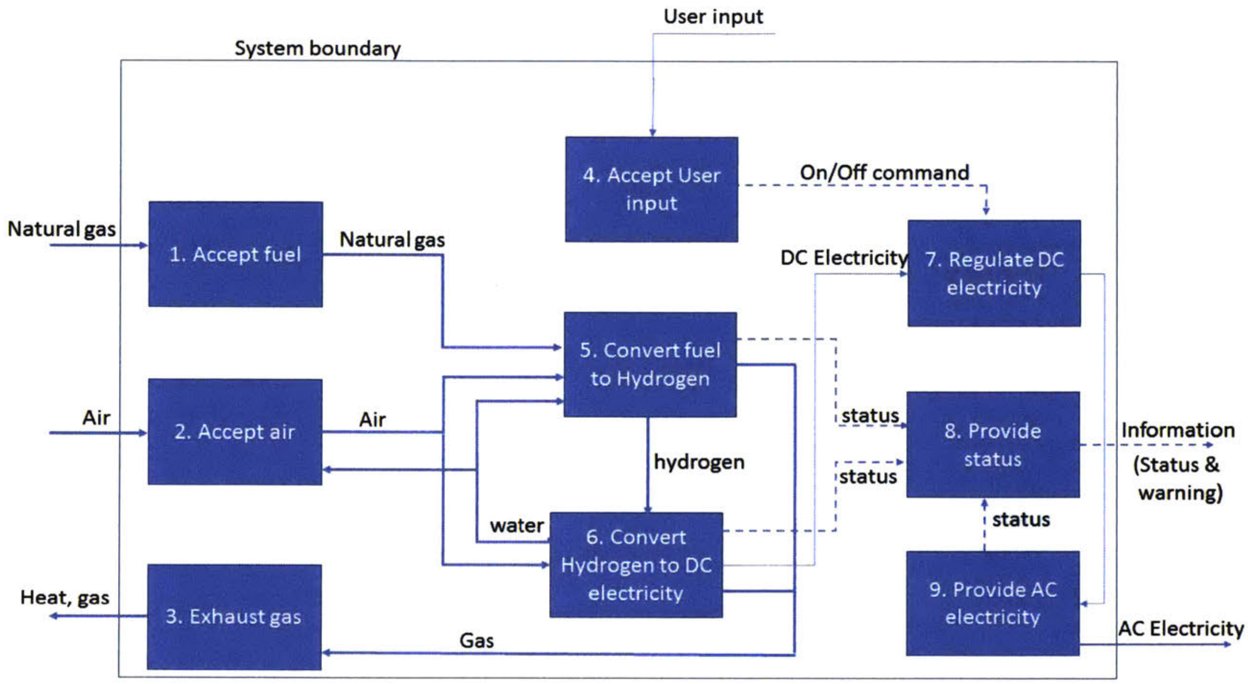


Figure 3.5 Functional Block Diagram of the Fuel Cell System

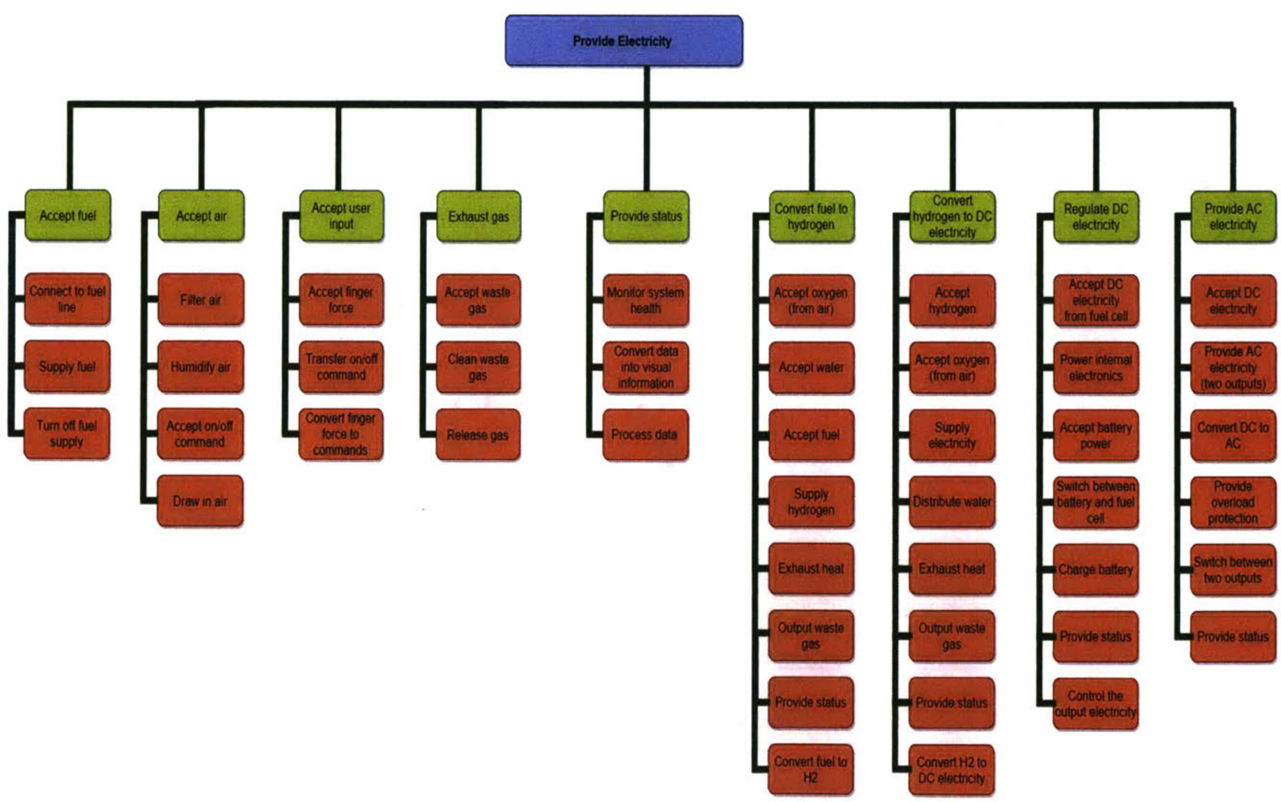


Figure 3.6 Two Levels of Functional Decomposition

3.7.1 Formal decomposition

After creating two levels of functional decompositions, the next step was to come up with components for all the functions. Starting with the top functional level diagram (see Figure 3.5), each function was assigned a physical part, which in reality could be made of hardware and software components. The result is shown in Figure 3.7. Afterwards, each part was broken further and compared with the second level functions to make sure there were no gaps in the list of second level parts. See Figure 3.8 for the two levels of physical decomposition. As shown, there are several custom Printed Circuit Boards (PCB) that need to be created. And, a few of them might have software running on them.

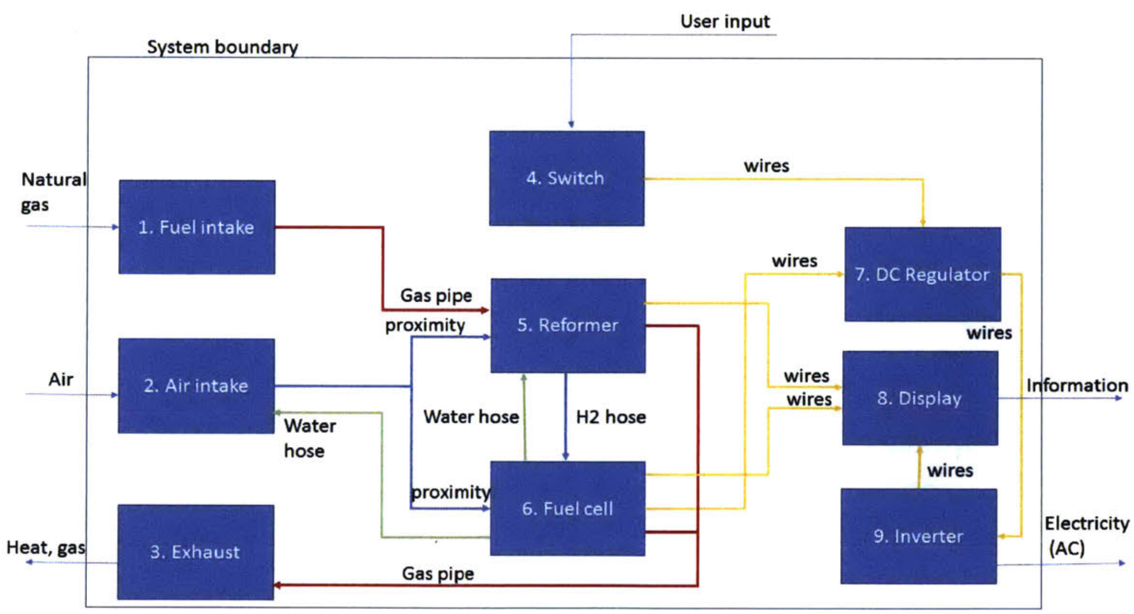


Figure 3.7 Block Diagram of the system

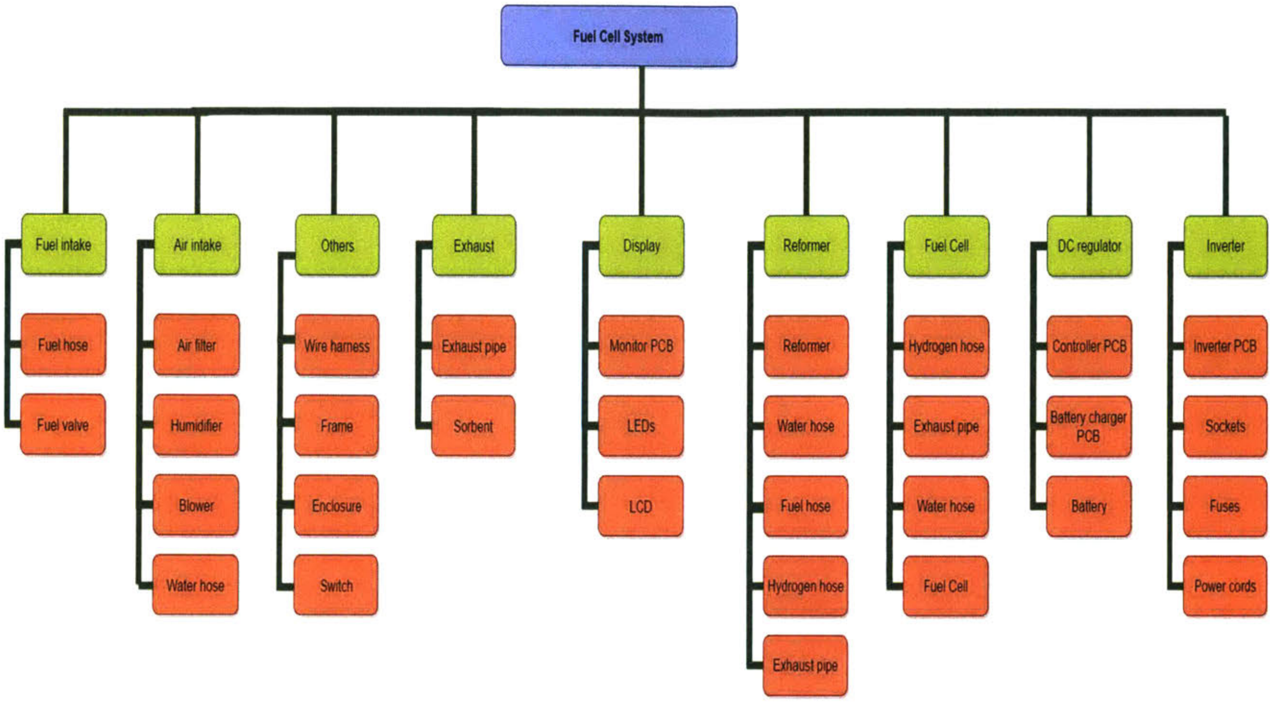


Figure 3.8 Two Levels of Formal Decomposition

3.8 Modularization

Because of the many advantages of modularizing a product, such as ease of reuse and faster response to market demand, the fuel cell system was modularized using a composite of two methods: Design Structure Matrix (DSM) and Modular Function Deployment (MFD). [48], [49]

3.8.1 Design Structure Matrix (DSM)

First, a DSM matrix was created with all the second level components listed in rows and columns in the same order. Second, the number of interactions (physical, informational flow, energy flow, material flow) between any two components were indicated as shown in **Error! Reference source not found.**. Third, a modified version of a macro provided by Professor Steven Eppinger was used to sort the matrix in such a way that clusters of numbers appear on the diagonal of the matrix. Fourth, the clusters were highlighted as shown in Figure 3.10. Interestingly, Fuel Cell and Reformer were merged, and Fuel intake, Inverter, Exhaust and Display were unchanged.

key	Name Sort	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
		#	1	2	3	4	5	6	7	8	9	13	11	12	10	22	21	16	17	18	19	20	14	15	23	24	25	
1	fuel valve	1	1	1					1																1		1	1
2	fuel pipe	2	2	2										2														2
3	air filter	3			3	1																				1		3
4	blower	4				4	1		1																1		1	4
5	humidifier	5					5								1		1								1			5
6	switch	6	1			1		6																		1	1	6
7	monitor - PCB	7							7	3	3														1		1	7
8	LCD	8							1	8																1		8
9	warning LEDs	9							1		9															1		9
10	exhaust pipe	13										13	2	1			1								1			13
11	sorbent	11										1	11															11
12	reformer	12		1					1			2		12	2	2									1		1	12
13	water hose	10					2							1	10		1											10
14	hydrogen hose	22												1		22	2											22
15	fuel cell	21							1			2			2	1	21						1		1		1	21
16	socket	16																16	1	2	1					1		16
17	fuse	17																1	17		1					1		17
18	power cord	18																1		18								18
19	inverter - PCB	19				1			1									2	2	1	19		1		1		1	19
20	battery	20																				20		2	1			20
21	DC regulator - PCB	14						1	2														14		1		1	14
22	battery charger - PCB	15							1													1	1	15	1		1	15
23	frame	23	1		1	1	1		1			1		1			1				1	1	1	1	23	1		23
24	enclosure	24						1		1	1							1	1						1	24		24
25	wire harness	25	1		1			1	1								1				1		1	1			25	25
			1	2	3	4	5	6	7	8	9	13	11	12	10	22	21	16	17	18	19	20	14	15	23	24	25	

Note: assumed material, energy and information move from comp to comp

Figure 3.9 Initial Mapping of Components Interactions

Note: This DSM shows the original level clusters (subsystems).

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
key	Name Sort	#	1	2	6	4	3	5	7	8	9	21	22	12	10	14	15	16	17	18	19	20	13	11	23	24	25	
1	fuel valve	1	1	1					1																1		1	1
2	fuel pipe	2	2	2										2														2
3	switch	6	1		6	1																				1	1	6
4	blower	4				4		1	1																1		1	4
5	air filter	3				1	3																			1		3
6	humidifier	5						5				1			1										1			5
7	monitor - PCB	7							7	3	3														1		1	7
8	LCD	8							1	8																1		8
9	warning LEDs	9							1		9															1		9
10	fuel cell	21							1			21	1		2	1							2		1		1	21
11	hydrogen hose	22										2	22	1														22
12	reformer	12		1					1				2	12	2								2		1		1	12
13	water hose	10						2				1		1	10													10
14	Controller - PCB	14			1				2							14									1		1	14
15	battery charger - PCB	15							1							1	15					1			1		1	15
16	socket	16																16	1	2	1					1		16
17	fuse	17																1	17		1					1		17
18	power cord	18																1		18								18
19	inverter - PCB	19				1			1							1		2	2	1	19				1		1	19
20	battery	20															2					20			1			20
21	exhaust pipe	13										1		1									13	2	1			13
22	sorbent	11																					1	11				11
23	frame	23	1			1	1	1	1			1		1		1	1				1	1	1		23	1		23
24	enclosure	24			1					1	1							1	1						1	24		24
25	wire harness	25	1		1		1		1			1				1	1				1						25	25
			1	2	6	4	3	5	7	8	9	21	22	12	10	14	15	16	17	18	19	20	13	11	23	24	25	

Note: assumed material, energy and info move from comp to comp

Figure 3.10 Final Mapping of Components Interactions

3.8.2 Modular function Deployment (MFD)

DSM tends to cluster components that have high degree of interactions, but does not account for management reasons for modularizing a product. So, MFD was used to determine how the components would cluster in response to module drivers such as common unit, which reduces manufacturing cost from volume discounting and upgrade, which increases sales because customers can add-on later. First, all the important module drivers were listed in a column and all the components were listed in a row. Second, for each module driver, each component was assessed to determine whether there is a strong (9), medium (3) or low (1) reason to be in a module. Third, the seven highest scoring components were marked as module candidates. Fourth, components that shared the highest number of 9s with a module candidate were lumped together. Fifth, components that shared 9 (or 9 and 3) with already established modules were added to the module. Sixth, all other components were added to modules as appropriate. The results are shown in Figure 3.11. Note: each color is a module.

	Fuel valve	fuel pipe	switch	blower	air filter	humidifier	monitor - PCB	LCD	warning LEDs	fuel cell	hydrogen hose	reformer	water hose	Controller - PCB	battery charger - PCB	socket	fuse	power cord	inverter - PCB	battery	exhaust pipe	sorbent	frame	enclosure	wire harness	Total
Carryover	3			9	3																9					24
Technology push								3		9		9														21
Product planning														9	3				9							21
Diff spec		3														9	9	9	9						3	42
styling		1	3					9	9															9		31
common unit	9	9		9	9	9					9		9							3	9					75
process/org																										0
separate testing							9			9		9		9					9							45
black box	3							9	9							9				9		9				48
service	3			9	3	3	9							9	9		9		9							63
upgrade							9			9		9		9	9				9							54
recycling					3					9										9		3				24
Sum	18	13	3	27	18	12	27	21	18	36	9	27	9	36	21	18	18	9	45	21	18	12	0	9	3	

Figure 3.11 MFD for Clustering Components

Both methods revealed different modules that were not really in conflict with each other. For example, DSM shows fuel valve and fuel pipe as a module, but MFD shows these two along with other components in the same module. So, the design would have to make these two components a submodule of the module. The DSM also shows fuel cell, reformer, hydrogen hose and water hose to be in the same module, but MFD shows monitor-PCB (in a different DSM module), fuel cell and reformer in the same module. Again, the design would make monitor-PCB its own module, water hose its own module and hydrogen hose its own module. Table 3.4 shows a list of differences between the modules derived by the two methods. Since the battery is not in a DSM derived module, it would be its own module. In all, there will be six modules with multiple components and seven modules with single components.

Common unit	fuel valve	fuel pipe	humidifier	air filter	blower	exhaust pipe	h2 hose	water hose
Styling	switch	LCD	LEDs	enclosure				
Upgrade	monitor-pcb	fuel cell	reformer					
Multiple	battery charger	Controller - pcb	inverter-PCB	wire harness				
Diff spec	socket	fuse	power cord					
Black box	battery	sorbent						

Table 3.4 List of Modules Created using MFD and DSM

3.9 System Architecture

Figure 3.12 shows the system architecture of the fuel cell system. The diagram (Object Process Methodology, OPM) shows the interactions between components ("instruments") in the form of operands. Furthermore, the diagram shows all the processes that gets executed within the system. Some processes are primary processes while others are supporting processes. Also worth mentioning is that the system architecture of the entire heating system is not shown here, since solution calls for a retrofit onto an existing system.

Note: to understand the diagram below, refer to (https://en.wikipedia.org/wiki/Object_Process_Methodology).

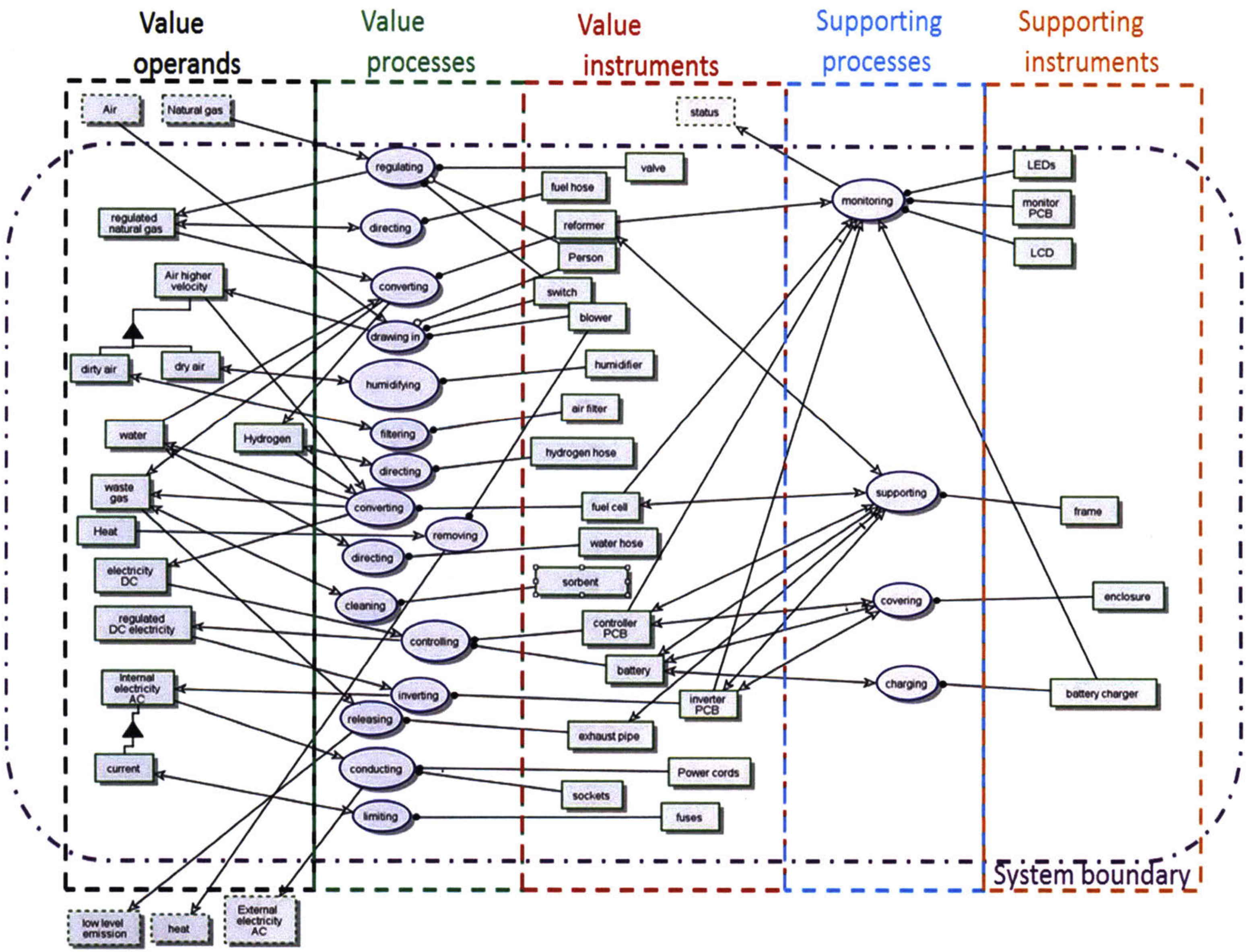


Figure 3.12 System Architecture of a Natural Gas Powered Fuel Cell

In summary, this system provides electricity to the furnace / boiler and also provides space heating, which reduces the fuel needed by the furnace / boiler. Furthermore, if the heating system is turned off, electricity would then be made available to other appliances. Once the heating system is turned on, the electricity switches to the heating system.

4. FINANCIAL ANALYSIS

In the previous section, a fuel cell heating system with a secondary electrical output was presented as a solution to power outages in the winter. However, in this section several analyses will be shown and their results will be presented. One of such analysis is the Net Present Value (NPV) analysis, which shows the profitability of a business model. Another analysis is the Sensitivity Analysis (SA), which shows how the impact of each assumption on the NPV. Equally important were two other analyses: Impact of power loss on homeowners and operational cost of running the system.

4.1 Financial Impact of Power Loss on Homeowners

Many homeowners lose money for variety of reasons after a power outage. The amount lost depends on what got damaged, how prepared the homeowner was, what the cost of living is, whether the homeowner had insurance and what the deductible was. To determine how much a typical homeowner would lose, the following assumptions were made. First, most people have home insurances. If fact, banks only lend money to people that have home insurance. Second, the power outage lasts for seven days. Third, people can leave their houses and find hotels that still have rooms. Fourth, people live in safe neighborhoods. Fifth, people can't go to work and their income is unaffected.

- Deductible (for damaged house) = $500 [50]
- Hotel (7 days @ $120) = $840 [51]
- Eat out (family of three) = $1067 [52], [53]
- Spoiled food = $160 [54]
- Premium hike = 21% of 1053 = $221 per year [55], [55]
- Emergency supplies (batteries, flashlights, food and water) = $76 [54]
- Sentimental / irreplaceable things = priceless!

Total cost = $2864 and $221 for subsequent years.

Based on these calculations, a homeowner wanting to protect himself/herself might be willing to pay up to half of this to cover future losses. Because of this expectation, generator manufacturers tend to show financial losses resulting from power outages as well as product offerings that are cheaper than the loss. For example, one of GE generators is price at $2,199, even though its website shows a financial loss of $3000. [54]

4.2 Exploring Business Models

The first step in developing a business model was to look at various companies to see how they make money and maybe combine business concepts to create a new one. The idea is similar to looking at competitors' products and then coming up with an innovative solution. Table 4.1 shows a list of business concepts and examples.

Strategies	Examples	Comments
Sell products/information to customers	Blender manufacturers, credit report companies	Enough customers have to be able to afford it
Sell services to customers	Doctors, mechanics, Paypal, eBay	Enough customers have to be able to afford it
Sell access to customers and provide free services to customers	Facebook, google	Collect a lot of data
Sell IP to businesses	Sales of patented technology / copyrighted materials	Typically an additional revenue stream
Sell proprietary refills	Ink cartridges of printers, supplies for franchises	Guarantees revenue streams even if you stop selling the product

Sell access to product(s)	Car leasing, rental homes, Zipcar, Sam's club, Solar City	Enables income from customers that can't afford to pay for product
Sell future services that customers may not use	American Automobile Association (AAA), Home insurance companies	Needs a lot of marketing or to be mandated
Sell products to customers that they may or may not use in the future	Standby generators, fire extinguisher, smoke alarm	Needs a lot of marketing or to be mandated
Sell products + free services	Cars with roadside assistance	Services have to be cheap and important
Provide free products + service contracts with monthly fees	Wireless service providers, cable providers	Enables income from customers that can't afford to pay for product but need the service
Sell the same product to different customers at different prices	Retailers, pharmaceutical companies	Predicting demand is very important
Sell the same service to different customers at different prices	Airlines	Predicting demand is very important
Sell the same product to several people who may share its use weekly.	Timeshare vacation homes	Enables income from customers that can't afford to pay for product
Someone else pays (whole or part) for the customer. Customers may pay back small amounts over time or nothing at all.	Bank loans, government (tax credits) , employer benefits, Insurer (Next and Liberty Mutual)	Enables income from customers that can't afford to pay for product

Table 4.1 Exploring Business Concepts

The highlighted strategies were the inputs for the chosen business models. The first model, an obvious choice, is to sell products to homeowners and get someone else to cover part of the bill. It turns out that there is federal tax credit of the smaller of $500 per 0.5kW or 30% of cost (retail price + installation). The fuel cell system must be at least 0.5kW and its efficiency must be greater than 30%. [56], [57] So, in the case of this design, which has a 1kW (=2*0.5kW) output, the maximum tax credit is $1000. Part of the project goal would be to convince insurers that this product minimizes the risk of water damage and that they should offer discounts. The second business model is to work with a utility company provide increased reliability as a service to homeowners. The homeowner would opt for this service and he/she would see at $40 per month increase in electricity bill. In addition to that, a fuel cell system would be install in his/her house.

4.3 Choosing the Right Sale Price

One of the key inputs into calculating an NPV is revenue, which is sales quantity x sale price. To determine sale price, a survey (see Appendix B for details) was conducted and the results are presented as follows:

- There were 110 responses, but only 92 had experienced winter in the US before.
- The number of people that had experienced power outage during winter is 51.
- About 84% of people would buy this product, only if it reduced energy bill by at least 10%.
- About 77% of people would rather own the product or lease it short-term.
- Some people (12%) thought $5000 was okay. [Note – 7/11 said yes to $5000, 5/20 said yes to $7000 and 1/9 said yes to $9000].
- Most people want to pay less than $60 per month for a short-term lease.

Even though the results of my previous analyses suggested a sale price of $1000 - $1500, the market seems to suggest a sale price of $5000, a reasonable price for the early adopters. For other homeowners that want a short-term lease, the sale price was set to $50 per month. In the next section, one of the questions that came out of the survey will be discussed.

4.4 Determining the Amount of Energy Savings

For a heating system that is isolated from the electric grid and powered by a natural gas fuel cell system, there will be an increase in the natural gas usage and a decrease in the electricity usage. In fact, no more electricity will be consumed from the electric grid, since all the electricity that the heater needs would now be generated by the fuel cell system. Knowing this and also realizing that a gas company might charge a different rate from an electricity provider, it was important to determine whether a homeowner's energy bill (gas bill + electricity bill) increased (or decreased) as a result of using this system. To determine this, the cost of electricity per month was deducted from the increase in gas bill for the same period. The calculations are shown below.

Assumptions for a fuel cell powered heating system:

- There are 30 days in a month
- The fuel cell consumes 13 L/min of natural gas [58]
- The fuel cell is 50% efficient and all the waste heat is used to heat up a room [59]
- Price of gas = $1.57 per 100 cubic feet. This is the average price of gas in the Northeastern states (New England and Mid Atlantic) for the month of October, 2016 [60]
- Price of electricity = 0.5 (18.78 cents + 16.16 cents). This is the average price of electricity in New England and Mid Atlantic states for the month of October, 2016. [61]

Important equations:

1) 1 L /min = 0.035 cubic feet / min
2) 1 cubic feet of natural gas = 1030 British Thermal Unit (BTU)
3) 1kWh = 3412 BTU

Cost of fuel cell system (1 kW) = **$16,754 @ 100 units pricing** [34]

Cost of installation = **$11,707** [34]

Maintenance cost = **$100** [62]

Cost of electricity saved (30 days @ 1kW) = 1 * 0.5 (18.78c + 16.16c) * 24 * 30 = **$125.78**

Cost of heating saved (AFUE = 80%) = ((1 * 3412) / (0.8 * 1030)) cubic feet/hr * $1.57 per 100 cubic feet * (30 * 24) = **$46.81**

Fuel cost (30 days @ 1kW) = (13 * 0.035 * 60) cubic feet / hr * $1.57 per 100 cubic feet * (30 * 24) = **$308.60**

Therefore, total energy cost = $308.60 - $125.78 – $46.81 = **$136.01**, which is an increase in energy bills.

Also worth mentioning is that similar calculations were perform on the gas and electricity bills of a friend and there was also an increase in energy bills. Further analysis revealed that a 10% reduction in energy bill, would require the fuel cell heating system to consume 81% less gas or a significant increase in electricity rate and a significant decrease in gas rate.

Since the next best solution is a grid isolated heater powered by a small standby generator, there was a need to see whether the total energy bill increases as well. Using data from a Generac 7kW standby generator, which uses natural gas, the cost of electricity saved was deducted from the increase in the gas bill.

Assumptions for a natural gas standby generator:

- The standby generator consumes 73 cubic feet / hr of natural gas (no load to ½ load)[63].
- There are 30 days in a month.

Important equations:

1) 1 L /min = 0.035 cubic feet / min

2) 1 cubic feet of natural gas = 1030 British Thermal Unit (BTU)

3) 1kWh = 3412 BTU

Cost of standby generator (7kW) = **$1799** [63]

Cost of installation = **$2000** [64]

Maintenance cost per year = **$650** [65]

Cost of fuel (30 days @ 1kW) = 73 cubic feet/hr * $1.57 per 100 cubic feet * (24 * 30) = **$825.19**

Cost of electricity saved (30 days @ 1kW) = 1 * 0.5 (18.78c + 16.16c) * (24 * 30) = **$125.78**

Therefore, total energy cost = $825.19 - $125.78 = **$699.41**. Even with a generator, there is increase in energy bills. For this reason, it is more useful as a backup system.

4.5 Fuel Cell Powered Heating System

The financial analysis for two business models related to the fuel cell heating system are presented in the next two sections.

4.5.1 One-time payment

Since most people require at least a 10% savings in energy bill and a price tag of $5000 or less, the fuel cell option seem to be a non-viable product. However, for homeowners who can spend more than $5000, Figure 4.1 shows the minimum price (=$13,760) a company would have to sell the fuel cell option in order to have a positive cash flow.

Assumptions:

- A discount rate of 60% per year was chosen because it is a number that is typically used for startups. [66]

- The capex came from a paper presented by Battelle Memorial Institute [67]. It includes factory construction cost and equipment cost.
- Installation (= $11,707) is by a third party.
- System cost = $16,754 [34]
- Sales markup = 50%, implies a production cost = $11,169. [34]
- Gross profit margin = 33%, implies a gross profit = $3,686. [34]
- SG&A = $1,899. [34]
- R&D cost is already spent.
- Initial sales = 20 units.
- Sales growth = 5% per month, implies production volume = 100 units.
- Perpetuity growth rate = 3% per year (United States long-term GDP growth rate)[68]

	2016	2017				2018				2019			
	December	Jan - Mar	Apr - Jun	Jul - Sep	Oct - Dec	Jan - Mar	Apr - Jun	Jul - Sep	Oct - Dec	Jan - Mar	Apr - Jun	Jul - Sep	Oct - Dec
Sales		63	73	84	98	113	131	152	176	203	235	272	315
Price		13760	13760	13760	13760	13760	13760	13760	13760	13760	13760	13760	13760
Revenue		867568	1004318	1162624	1345883	1558027	1803612	2087906	2417012	2797994	3239027	3749579	37896560
Production Cost		704205	815206	943703	1092454	1264652	1463993	1694754	1961890	2271133	2629120	3043535	3523273
SG&A		119732	138605	160452	185744	215021	248914	288149	333569	386148	447014	517475	599042
Total expense		823937	953811	1104155	1278197	1479673	1712907	1982904	2295459	2657280	3076134	3561010	35990716
EBITDA		163363	189113	218921	253429	293376	339619	393151	455122	526861	609907	706044	34373287
Depreciation		131049	131049	131049	131049	131049	131049	131049	131049	131049	131049	131049	131049
Capex	-5242000	0	0	0	0	0	0	0	0	0	0	0	0
Taxes		0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
Cash Flow		152376	169371	189045	211820	238185	268705	304037	344937	392285	447095	510545	22730926
Present value	-5242000	138164	132657	127899	123790	120240	117173	114524	112236	110259	108551	107076	3929633
NPV	201.63												
	-5242000	0	0	0	0	0	0	0	0	0	0	0	0

Figure 4.1 NPV Analysis for a Fuel Cell System

4.5.2 $40 monthly service

In this scenario, a fuel cell manufacturer in partnership with a utility company charges $40 a month for extra reliability. The fuel cell manufacturer owns and installs all the fuel cell systems. Assuming the followings:

- Cost covered by the manufacturer of fuel cell system is production cost plus half of third party installation cost ($11,169 + $5,854 = $17,023)
- Financial contract can't be longer than 20 years, which is the same number of years that is offered for solar power systems.[18]

A quick analysis shows that the fuel cell manufacturer would not recover its money is 20 years.

12 months * 20 years * $40 = $9600.

Even if the company could collect $60 dollars, which seems unlikely per the survey results discussed in chapter 2, the total would be 12 months * 20 years * $60 = $14,400 – still less than $17,023.

4.6 Generator Powered Heating System

Because the fuel cell system is not commercially viable, it was important to check the next best concept to see whether it would be different. As discussed previously, the next best idea is a small standby generator powering a heating system, which is isolated from the electric grid. Unfortunately, for reasons mentioned in section 4.4, most people would only buy natural gas powered generators as backup systems. Having said that, what if an existing generator manufacturer decides to offer a low cost 1kW standby generator, would this be a profitable investment?

4.6.1 One-time payment

To answer whether a generator manufacturer should invest in producing a low cost 1kW standby generator, an NPV analysis was performed for a hypothetical manufacturer using Generac's publicly available data. In this scenario, customers pay for the product outright. Figure 4.2 shows the result of such an investment by the manufacturer.

Note: All numbers came from Generac 2015 Annual Report except the ones that have other references.

Assumptions / goals:

- 1kW generator cost about 50% of a 7kW = $1,799 * 0.5 = $900
- Competitors don't put out a similar product until three years pass
- Gross profit margin = 35%
- SG&A = 12% of revenue
- Initial sales per month = 700, implies 10% of yearly capacity (Generac sold 81,328 units in 2013, [69])
- Sales growth = 5% annually (average growth rate expected for standby and portable generators in the Northeast, [69], [70])
- Perpetuity growth rate = 3%
- Discount rate = 15.7%
- Capital Expenditure (capex) = 0 (Generac has enough capacity to meet near future needs)
- Product development = 1M over 1 year

Figure 4.2 shows that the investment generates a positive NPV, which is four times the original investment.

	2016	2017				2018				2019			
	December	Jan - Mar	Apr - Jun	Jul - Sep	Oct - Dec	Jan - Mar	Apr - Jun	Jul - Sep	Oct - Dec	Jan - Mar	Apr - Jun	Jul - Sep	Oct - Dec
Sales		700	700	700	1200	735	735	735	735	772	772	772	772
Price		900	900	900	900	900	900	900	900	900	900	900	900
Revenue		1890000	1890000	1890000	1890000	1984500	1984500	1984500	1984500	2083725	2083725	2083725	69575447
Production Cost		409500	409500	409500	702000	429975	429975	429975	429975	451473.8	451473.8	451473.8	451473.75
SG&A		226800	226800	226800	226800	238140	238140	238140	238140	250047	250047	250047	8349054
Product Development	-1000000												
Total expense		1455300	1455300	1455300	1455300	1528065	1528065	1528065	1528065	1604468	1604468	1604468	61672101
EBITDA		434700	434700	434700	434700	456435	456435	456435	456435	479257	479257	479257	7903346
Depreciation		0	0	0	0	0	0	0	0	0	0	0	0
Capex	0	0	0	0	-20000	0	0	0	-25000	0	0	0	0
Taxes		0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
Cash Flow		286902	286902	286902	286902	301247	301247	301247	301247	316309	316309	316309	5216208
Present value	-1000000	279546	268842	258547	248647	251082	241467	232221	223328	225516	216880	208575	3267518
NPV	4922167.967												

Figure 4.2 NPV Analysis for a Small Standby Generator

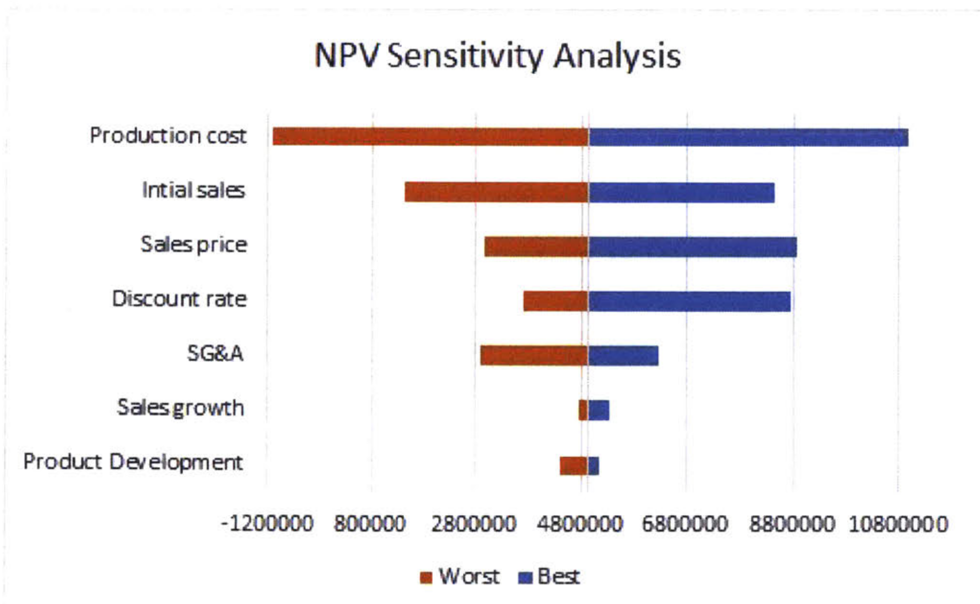


Figure 4.3 NPV Sensitivity Analysis

Figure 4.3 shows that the production cost relative to revenue affects NPV the most. As a result, a generator manufacturer would have to pay attention to its production cost and keep it well below 80%. The Initial sales, Sales price and Discount rate also cause the NPV to vary a lot, but only positive values.

4.6.2 Selling the product for $40 per month for 3 years

In this scenario, a generator manufacturer would have to partner with a bank in order to offer its customers a payment plan - $40 per month for 3 years. The company would make money as described in the previous section and the bank will make money on the interest.

5. CONCLUSION

The process of developing the system architecture and performing financial analyses resulted in three important findings:

1) Even though the solution proposed in this thesis has some competitive advantages, such as 24/7 operation, low noise, low maintenance and near zero emissions, over its competitors, it is very expensive. It will also increase the energy bill of customers, unless the price of gas drastically drops and the price of electricity shoots way up. Because of these facts, **the fuel cell powered heating system is not a financially viable solution**.
2) An investment into 1kW standby generator that uses natural gas (or propane) to power a heating system during power outage will produce a positive NPV. However, its market penetration will be dependent on its installation cost.
3) The reason for low market penetration is that there is no product out there that addresses the needs indicated in Figure 5.1. Homeowners want products that are cheap (smoke alarm cheap), provide immediate value and can operate for days during a power outage.

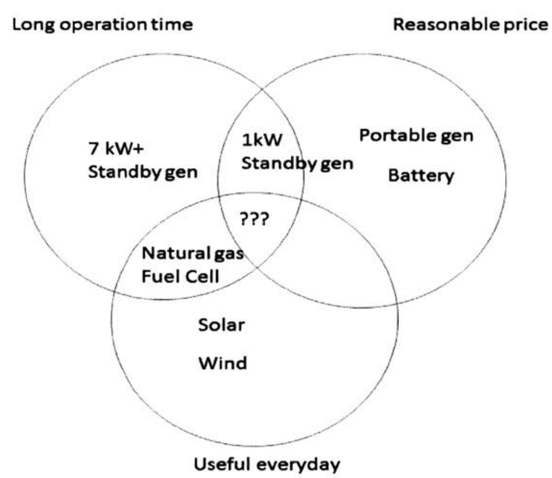


Figure 5.1 Three Key Requirements for Alternative power Source

6. FUTURE WORK

It will be interesting to see whether a similar solution comes up for other areas of the US that have to deal with power outage during very hot summer days. Could such a solution be combined with the fuel cell solution? Also, would an electric utility company make money by installing small natural gas powered generators in people's homes, especially ones they can remotely place online to address peak power demand?

7. APPENDICES

Appendix A

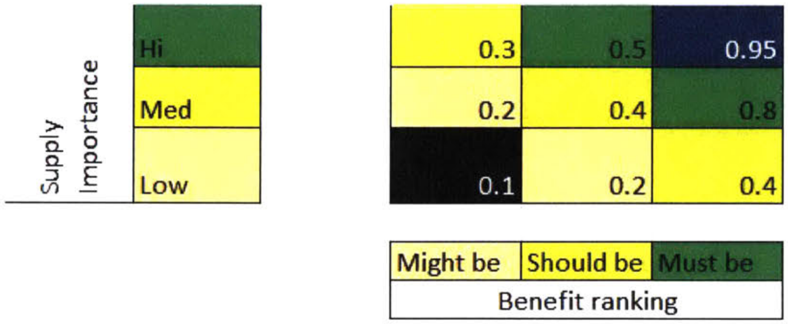


Figure 7.1 Single Measure for Supply Importance and Benefit Ranking

Source: System Architecture: Strategy and Product Development for Complex Systems

Appendix B

<u>Online Survey to Determine Pricing</u>

Have you experienced winter in any of US, Northeastern states before?

- Yes
- No

Who do you live with?

- I live alone
- I live with my spouse
- I have one or more roommates
- I live with my spouse and kids
- I live with my parents

Have you experienced power outage during winter before?

- Yes
- No

Did you know that power outages during winter can lead to expensive (~$18,000) water damage to the house from pipes bursting or roof leaking?

- Yes
- No

Imagine an environmentally friendly product that provides heating to your house, without electricity from the power grid. Now, imagine never having to worry about power outages during winter. How much savings on your energy bill would it take for you to buy this product?

- 5%
- 10%
- 20%

In addition to all the features mentioned earlier, this product enables you to qualify for home insurance discounts, tax credits and rebates, and provides access to 2.5 kW of electricity. So, how would you like to pay for this product?

- Pay full price - own it
- Pay monthly, with a short-term contract - lease it
- Pay monthly, with a long-term contract - lease it

FullPrice

Would you pay $9000 for this product, which is also reliable and easy to operate?

- Yes
- No

What price are you willing to pay?

Would you pay $5000 for this product, which is also reliable and easy to operate?

- Yes
- No

What price are you willing to pay?

Would you pay $7000 for this product, which is also reliable and easy to operate?

◯ Yes

◯ No

What price are you willing to pay?

10 Year Monthly

Would you pay $108 per month, with a 7-year contract, for this product, which is also reliable and easy to operate?

◯ Yes

◯ No

What price are you willing to pay? How many contract years are you willing to accept?

Would you pay $84 per month, with a 7-year contract, for this product, which is also reliable and easy to operate?

◯ Yes

◯ No

What price are you willing to pay? How many contract years are you willing to accept?

Would you pay $60 per month, with a 7-year contract, for this product, which is also reliable and easy to operate?

◯ Yes

◉ No

What price are you willing to pay? How many contract years are you willing to accept?

15 Year Monthly

Would you pay $28 per month, with a 15-year contract, for this product, which is also reliable and easy to operate?

◯ Yes

◯ No

What price are you willing to pay? How many contract years are you willing to accept?

Would you pay $40 per month, with a 15-year contract, for this product, which is also reliable and easy to operate?

- ◯ Yes
- ◯ No

What price are you willing to pay? How many contract years are you willing to accept?

Would you pay $50 per month, with a 15-year contract, for this product, which is also reliable and easy to operate?

- ◉ Yes
- ◯ No

What price are you willing to pay? How many contract years are you willing to accept?

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