Electricity Markets, Smart Grids and Smart Buildings

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Electricity Markets, Smart Grids and Smart Buildings

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Abstract

A smart grid is an electricity network that accommodates two-way power flows, and utilizes two-way communications and increased measurement, in order to provide more information to customers and aid in the development of a more efficient electricity market. The current electrical network is outdated and has many shortcomings relating to power flows, inefficient electricity markets, generation/supply balance, a lack of information for the consumer and insufficient consumer interaction with electricity markets. Many of these challenges can be addressed with a smart grid, but there remain significant barriers to the implementation of a smart grid.

This paper proposes a novel method for the development of a smart grid utilizing a bottom up approach (starting with smart buildings/campuses) with the goal of providing the framework and infrastructure necessary for a smart grid instead of the more traditional approach (installing many smart meters and hoping a smart grid emerges). This novel approach involves combining deterministic and statistical methods in order to accurately estimate building electricity use down to the device level. It provides model users with a cheaper alternative to energy audits and extensive sensor networks (the current methods of quantifying electrical use at this level) which increases their ability to modify energy consumption and respond to price signals
The results of this method are promising, but they are still preliminary. As a result, there is still room for improvement. On days when there were no missing or inaccurate data, this approach has $R^2$ of about 0.84, sometimes as high as 0.94 when compared to measured results. However, there were many days where missing data brought overall accuracy down significantly. In addition, the development and implementation of the calibration process is still underway and some functional additions must be made in order to maximize accuracy. The calibration process must be completed before a reliable accuracy can be determined.

While this work shows that a combination of a deterministic and statistical methods can accurately forecast building energy usage, the ability to produce accurate results is heavily dependent upon software availability, accurate data and the proper calibration of the model. Creating the software required for a smart building model is time consuming and expensive. Bad or missing data have significant negative impacts on the accuracy of the results and can be caused by a hodgepodge of equipment and communication protocols. Proper calibration of the model is essential to ensure that the device level estimations are sufficiently accurate. Any building model which is to be successful at creating a smart building must be able to overcome these challenges.
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Chapter 1: INTRODUCTION

1.1 Motivation and Rationale

Americans have twice voted on the greatest invention ever made, once in 1947 and once in 2005. On both occasions electricity won by a significant margin [1]. Despite the respect that people have for electricity as a great invention, their reliance on and expectations of electricity have continued to grow, while the capabilities of the electricity network have stalled.

Much of the public both in America and around the world want and need energy, but they want this energy to come from cleaner sources. Americans currently believe energy development is more important than environmental protection, but only by 3% [2]. The large majority (66%) of Americans would like energy development to come from alternative sources, while only 26% think that it should come from increased coal, natural gas and oil production [3]. Chinese, Russian, Brazilian and Indian citizens also prioritize the environment over economic growth [4]. In addition, climate change and pollution have been a significant concern for many Americans [5]. And 34% of the total greenhouse gas emissions are a result of the electricity industry [6].

Therefore, it is evident that much of the public want cleaner sources of electricity that are not derived from coal, oil and natural gas and these sources should minimize environmental impacts. Unfortunately, the current electrical network is not equipped to
be weaned off fossil fuels and nuclear power and replaced with alternative energy sources like wind and solar.

Another issue for the current electricity system is rising prices. Electricity prices in the United States have been increasing faster than inflation for 5 years resulting in a 300 dollar per year increase in electricity costs over the same period [7]. This price increase has occurred even as natural gas prices have fallen [8]. The public appears to want change, but the status quo of the electrical network is not well poised to provide them with it.

At the same time that consumers have been increasingly dissatisfied with the current mode of operation of the electricity system, new dangers have emerged that threaten the security of the electrical network. Throughout the evolution of the electrical network, there were no significant security threats to the network. As a result, many smaller networks eventually merged into three very large networks; the East, West and Texas. These large networks were more efficient, reduced the need for redundant systems, increased reliability and lowered prices. Unfortunately, they also made the electricity network significantly more vulnerable.

For example, in the 2003 northeast blackout, a poorly trimmed tree caused a cascading series of failures resulting in a blackout that affected more than 50 million people [9], likely contributed to almost 100 deaths [10] and cost about $6 billion [11]. If a tree branch can do that, it does not take a great deal of imagination to envision the catastrophe that could be caused by determined individuals.
While it is widely agreed that a smart grid is the solution to these problems, a unified method of achieving a smart grid has yet to emerge. No smart grid strategy has broken down the challenges into manageable, achievable and practical goals. This paper and the strategies presented in it attempt to close this gap and provide a first step toward a smart grid and a supply and demand market.

1.2 Problem Statement

The current electricity network or “grid” has been providing consumers with electricity effectively for over 100 years. Recently, customers have been demanding more from the grid like wind and solar power, lower prices, reduced pollution, competition, increased security, reduced carbon emissions, increased reliability, more information and greater transparency in pricing. Unfortunately, these demands ask far more of the grid than it was designed to do and far more than it is capable of doing. A new method of providing electricity that can meet all of the customers current needs and be flexible enough to meet future needs must be developed. This new grid or “smart grid” must have increased communication and data storage in order to accomplish these goals.

In spite of the large quantities of money that have been devoted to research and development of a smart grid and smart technology, one has not yet emerged. While hopes are high, there is still no clear path that will lead to a smart grid which is sustainable and will continue to improve without significant subsidies and questionable returns.
1.3 Contributions and Proposed Solution

This paper takes a new approach to developing a smart grid by 1) understanding the current electrical grid, 2) determining what a smart grid should do, 3) developing a system to bridge the gap between the current grid and a smart grid and 4) presenting preliminary results from a proposed method. This research should provide the basis for a new path for smart grid research.

- A detailed landscape analysis of the electricity network was developed.
- A vision for the future of the project has been outlined.
- A novel approach to building modeling has been outlined.
- Useful methods of visualizing energy data have been presented.
- Overall results of the model have been presented.
- Recommendations have been made from the building model.
- The future work required to progress the project is provided.

The results of this work show that it is possible to estimate electrical consumption down to the device level using a combination of deterministic and statistical methods. It also illustrates that such methods have the capability to save electricity consumers money while providing the foundations required for a smart grid.
Chapter 2: ELECTRICITY LANDSCAPE ANALYSIS

2.1 History

The modern electricity network or “grid” is like a steam locomotive in a world of high speed trains; it is a truly remarkable invention and a great engineering achievement that has shaped our world, but continued reliance on this outdated technology is holding back progress. A smart grid is the promised solution to the current antiquated grid. Before understanding what a smart grid is, one must first understand what the current grid is and what problems are associated with it.

When Thomas Edison, Nicola Tesla and their contemporaries began to electrify the United States, there was no practical mechanism to charge customers higher rates when power cost more to produce and lower rates when cheap power was available. During this early period, such a supply and demand market was not necessary. Few people had electricity and many sought it, leading to exponential load growth and the “Golden Age” of electricity [12] where prices continually fell and more and more customers were served. During this period of time, there was no need to worry whether a generator would be running at a high enough capacity factor to make a profit, because the desire for electricity often exceeded the generators ability to supply it. Supply and demand simply did not matter because there was always more demand than could be supplied.
Over time, electricity has become as important to daily life as food, water and shelter because it runs the farm equipment and refrigerators that produce and cool food; pumps water from wells and into water towers, or makes it potable in water plants; and powers the tools required to assemble homes, powers the machines that create building materials and is essential to heat homes. Electricity has become a fundamental necessity. As this dependence on electricity developed, there was still no good way to charge customers higher prices during shortages and lower prices when there was excess electricity.

The electrical grid in place today is a very large interconnection of generators, transmission lines and distribution lines designed to turn coal, nuclear fuel rods, natural gas, solar radiation, water, wind and other resources into electricity, which is then used to power the modern world. This network was designed and developed during a period when the only practical sources available for electricity production were coal (1882) [13] and hydroelectricity (1882) [14] and later natural gas (1939) [15] and nuclear (1951) [16]. All of these resources have one very important thing in common, they are controllable; meaning in order to produce more electricity, generators simply use more of their resource.

From the inception of the electrical grid through modern times, the grid operators (system operators) who manage power have had little to no control over consumers’ electrical usage meaning that system operators have no real control over electricity demand. The system operators are required to make sure that the supply (generation) matches the demand (consumption). This is a difficult task because generators require
lead time to produce a desired amount of electricity. Because of this lead time and the inability to influence electrical demand, the system operators developed forecasting methods which are used today to schedule generation in order to ensure that demand (consumption) and supply (generation) exactly match. The electricity market is managed by system operators who purchase electricity from the generators at a market rate and sell it to customers at a flat rate.

Because electricity is a fundamental necessity, it is unacceptable to have blackouts caused by a limited number of generators or transmission lines. As a result, **the electrical grid must be designed to accommodate peak electricity usage that may occur for a few hours per year.** The system operators have to predict how much electricity will be required and ensure that the required electricity is supplied. This applies in the short term when scheduling generators to produce the required amount of power, but also applies in the longer term when system operators forecast the need for new generators and transmission lines to meet future peak demand.

**Put in economic terms, the modern electrical grid does not operate on the principle of supply and demand, but on the principle of predict and supply.** This worked well for many years when electricity was cheap and acceptably reliable. In addition, people rarely thought about running out of fossil and nuclear fuels.

However, the predict and supply market is an inefficient market mechanism requiring expensive infrastructure additions to the grid that would not be necessary if customers would respond to price signals. Because customers pay a flat rate for electricity they have no incentive to respond to market prices. This increases wholesale
price volatility and ultimately the average price of electricity for customers. A supply and demand market would be a more efficient market mechanism that should reduce the average price of power for customers when compared to the current predict and supply market.

2.2 The Grid in the Modern Era

The modern era has seen a fundamental shift in the public view of the “old guard” of power generation. Every resource used to produce electricity has drawbacks: coal produces too much pollution; nuclear power may not be worth the risk of a meltdown; hydroelectricity hurts a river’s ecosystem; and natural gas (while cleaner than coal) still has carbon emissions. Some claim natural gas “fracking” may pollute groundwater and can trigger earthquakes, but the ramifications of this young technology are still being debated. Technologies such as wind and solar have been touted by many as solutions to these problems, but they have their own significant challenges.

Both wind and solar are, for practical purposes, almost entirely unpredictable and uncontrollable resources, unlike the predictable and controllable fossil fuel, hydro and nuclear derived electricity that the grid was developed to utilize. Efforts have been made to predict wind and solar power production, but these predictive models are not as accurate as system operators need them to be. These inaccuracies can be treated as noise in the forecasts and are not a significant problem at low levels of renewable energy penetration when the resources are spread throughout the network. However, at higher penetration levels of wind and solar, the uncertainty can be difficult for system operators to manage because every unit of unpredictable and uncontrollable wind or solar placed on
the grid, replaces one unit of predictable and controllable generation and adds one unit worth of uncertainty. The primary reason that wind and solar (with their unpredictability and uncontrollability) are placed on the grid is because of politics.

System operators manage the unpredictable and uncontrollable nature of wind and solar the only way they can, by continuing to operate fossil fuel (often natural gas) generators that are more easily controllable. This leads to three major problems. First, wind and solar do not replace existing generation on the grid. The fossil fuel generators must be maintained for the periods of time when the renewable resources are unavailable. This problem is complicated because this increases the generation capacity on the grid, without increasing the energy produced, leading to higher costs of electricity. Second, if the grid does not have enough fossil fuel generators to manage the variability of the renewable resources, more fossil fuel generators must be built (which create pollution and carbon during construction) further increasing the cost of electricity. Third, the operation of wind and solar is still very dependent upon fossil fuel resources which are limited in supply and produce a significant amount of pollution.

Therefore, the grid needs a better way of dealing with the unpredictable and uncontrollable renewable resources in order to accept large quantities of renewable power onto the grid. Ideally, this role would be filled with cheap energy storage, but most energy storage technologies are not cost competitive [17] and would increase the cost of renewable energy projects significantly. Because of the difficulties with energy storage, the best solution to the unpredictable and uncontrollable nature of renewables is for consumers to respond to price signals by consuming more electricity when renewable
energy is available and less electricity when renewable energy is not available. *This requires a core shift from the current electrical grid that operates based on the principles of predict and supply, to a smart grid that operates based on the principles of supply and demand.*

### 2.3 Electricity Markets

Electricity must be consumed at exactly the same time as it is generated. There is little to no electrical storage on the grid (other than pumped hydro stations which have a very difficult time finding an adequate location for the site) making the balance between consumption and generation essential to the grid because if they are out of balance, damaged equipment or blackouts can occur. *Unfortunately, the balance of consumption (demand) and generation (supply) in the grid is maintained by an abundance of overburdening regulations, inefficient investments and non-competitive markets, instead of the more natural and elegantly simple solution of an appropriate market clearing price passed through to consumers.* These regulations, investments and markets were created not out of misguidance or ignorance, but instead as the only practical way to operate the electrical grid. In order to understand why the electricity market appears so backwards, it is necessary to understand the physics behind the way power flows through the grid.

**Power Flows**

Power flows in the grid work differently than one would imagine. If someone unfamiliar with electric power were asked how much power could be transferred from point A to point B in the Figure 1, assuming the lines have equal resistances, they would
probably answer the sum of the two lines or 1010 kW. But this is not how power flows. Kirchhoff’s Laws governing such power flows show in this simplified example, that line 1 can carry only 10 kW because if it carried more power, it would overtax line 2 and cause a failure.

![Figure 1: Power Flow Example](image)

This is a simplified example, but in the real world with hundreds or thousands of busses (connection points such as A and B above) and even more transmission lines, these challenges lead to very real complications. The end result of this complexity is a grid where system operators have little to no control over how power flows through the network. As a result, they are left with the option of controlling generators’ output to try to keep the grid operational which is kind of like riding a bicycle with no hands; it can be done, but it is not the easiest or safest control mechanism, especially when there are bumps in the path.

The nature of power flows is the driving force behind much of the difficulties and regulation in the electrical industry. In addition to using generators as the main control mechanism of the electrical grid, it is also impossible for independent power networks to coexist if they are connected using AC power (the main method of transmitting power). For example, if some entity wanted to set up their own lines for any reason, an extensive
planning and permitting process which often takes years would be needed to gain approval because the addition of a new line could cause congestion or even power failures in an entirely separate portion of the grid. Such an elaborate approval system is also needed to prevent unscrupulous individuals from modifying the grid in such a way that they could force customers/system operators to purchase power from them thereby gaming the market.

Consequently, there is usually one entity in control of the local power network (usually a utility company) to manage all of these power flow complications. In addition, the requirement that generators must be used to manage power flows and the near total demand inelasticity means that generator profits are often closely regulated to ensure individuals are not taking advantage of market power (the ability of a generator to charge a rate above competitive levels) and charging customers obscene amounts for electricity.

**Demand**

The term “demand” is often used to mean different things related to electric power and this creates confusion. In order to understand “demand inelasticity”, which is one of the major challenges in electricity markets today, it is important to understand which type of demand is being discussed. Provided below are several ways in which the term demand is used relating to electricity.

**Economic Demand**

Economic demand is the *quantity of goods or services that a consumer will buy at a certain price* and is the term being referred to when speaking of elasticity/inelasticity. It is also the term meant when speaking of supply and demand.
**Electrical Demand**

Electrical demand is similar to the economic demand except that it deals specifically with power in the electricity network. It refers to *the amount of power (kW) being consumed at a given time*. Electrical demand in this paper will refer to a very large scale of electrical demand such as in a country, interconnection, balancing authority, or distribution network. It will not be used to refer to building or campus power requirements for the purposes of this paper.

**Billed Demand**

Billed demand is a measured value that appears on the electricity bill of many large commercial/industrial consumers. It is based on *the largest average power used in a specific interval during a billing period*. In order to calculate billed demand, the utility company first measures the average power consumed during specific intervals (typically 15-60 minutes) for the entire billing period. The largest of these values is the billed demand and it can be a significant portion of a customer’s electrical bill. For instance, billed demand typically represents about 40% of the cost of University of Denver’s electricity. Billed demand is designed to represent the cost of maintaining infrastructure required to provide the electricity consumed. For example, if two customers use the exact same amount of energy, but customer A consumes it evenly over the course of a day and customer B consumes it all in one hour, customer B will require larger distribution lines and a larger transformer for the same amount of energy requiring more infrastructure thereby incurring a higher cost.
**Peak Demand**

Peak demand refers to the *greatest amount of power consumption in a given period of time* (week, day, year, decade). For the purposes of this paper it means the greatest electrical demand that occurs for a few hours per year. It is important to note that the utilities must maintain enough transmission/distribution/generation assets in order to prepare for these rare times. The utility companies also have to prepare for future peak demand because many transmission/distribution/generation projects can take years to plan, permit, design, build and test before delivering a single unit of energy to the grid.

**Demand/Supply Elasticity**

With demand defined, it is possible to understand demand (economic) elasticity. As the purchase price of a certain good or service changes, the quantity of the goods or services that is produced or purchased will change in response. The responsiveness of production and purchasing to prices is called elasticity. Supply (generation) in the electricity industry is elastic enough not to cause market failures on its own. However, demand in the electricity market is almost entirely price inelastic (mostly due to flat electricity rates and consumers’ lack of information). This means that regardless of price changes in the supply market (at least in the short term) most customers will not change the amount of energy they consume or the time they consume it. This contributes significantly to the challenges in the electricity industry and is a primary hindrance to a supply and demand market.
Supply and Demand

Supply and demand is one of the most fundamental concepts in economics and is relevant in all free market systems [18]. The Law of Demand describes the consumer’s desire for certain quantity of goods or services based on the price. Typically as price goes up the economic demand goes down. This results in a curve similar to the one in Figure 2.

![Demand Curve](image)

**Figure 2: Law of Demand**

The Law of Supply describes the amount of a good or service the suppliers produce which is also dependent upon price, except it operates in the opposite way as the Law of Demand. As price goes up, supply goes up. This results in a curve similar to the one in Figure 3.
Market equilibrium occurs where the demand and supply curves achieve a balance and the price of goods and services purchased/sold is equal to the market clearing price – the price at which everyone is satisfied and the quantity supplied is equal to the quantity demanded. This is the most economically efficient solution to consumption and production as there is no excess production and there are no customers who are willing to pay the market price who remain unserved. Market equilibrium occurs at the point where the demand and supply lines meet (at the market clearing price) in Figure 4.
While the supply and demand curves for electricity are not actually linear, the example above illustrates the principle well. The market clearing price in electricity markets is not passed through to customers. It should come as no surprise that the electricity market has so many problems because it lacks one of the most fundamental economic principles. *In order to make supply meet demand at a given time (a requirement for the electricity grid to continue to function) many regulatory strategies have been implemented in order to try to create a faux supply and demand market.*

**Regulation**

A faux supply and demand market is one where regulations and monopolies (in the absence of a true supply and demand market in the electricity sector) have been the only practical mechanism to ensure that the electricity generated is always the same as the electricity consumed at a given time. If the generation exceeds the consumption, the system voltage will get too high and damage equipment; if the generation is lower than the consumption, the voltage will drop and the system will experience a brownout and
potentially a voltage collapse leading to a blackout. The necessity to balance supply and demand in the grid makes a market clearing price passed through to customers even more important than in most other sectors (such as oil where excess and shortages can be managed with storage).

Unfortunately, a market clearing price is not the current market mechanism for making supply match demand and the faux supply and demand market that regulations have created lacks competition which keeps prices high and innovation almost nonexistent. Utility companies often return profits to investors regardless of their performance. This is possible because the electric utilities have no competition so no other force is allowed by regulators to try to drive prices down. This lack of competition is also illustrated in the fact that research investment rates in the electricity sector are lower than all other industrial rates except the paper industry [19]. In addition, individuals who work for these regulated companies also have little financial incentive to perform better and increase efficiency. Members of the public and private sectors are now trying to shoehorn renewable energy into an antiquated grid which is not an effective strategy. The sum of these regulations sacrifice economic efficiency for reliability, when it is possible to achieve both. The grid and the regulations that govern it need an overhaul.

2.4 Energy Use

One of the major consequences of the regulation debacle in the electricity industry is that consumers do not have the wherewithal to consume electricity in an intelligent way. This is a result of a lack of knowledge about how energy is consumed in businesses
and homes. The average electricity consumer has little to no idea how much electricity each of their devices is using resulting in them having no idea how to reduce their energy use in an intelligent way (saving themselves money while making good financial investments). One of the major driving forces behind this ignorance is the current billing structure most homes and businesses use to pay for electricity.

**Current Billing Structure**

Most consumers in the United States pay for their electricity in the form of a monthly bill which simply tells them how much energy they have used during the billing period. This gives the consumers no information about their individual electronics’ energy use. Kepton and Layne compared this to purchasing groceries at a supermarket without any indication of how much any individual item costs, then at the end of the month receiving a bill for 2,362 food items costing $527 [20]. Old billing structures and “dumb” meters have made most people ignorant of the electrical consumption of their devices. One of the first steps toward a smart grid, is a smart consumer and that begins with being well informed about their energy usage and its associated costs.

**Energy Audits**

The main method of informing customers about their electricity usage is an energy audit. An energy audit is an inspection of energy consuming devices within a building or campus which is used to quantify the energy consumption and identify potential areas of energy savings without negatively affecting occupant comfort. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) lists three levels of energy audits [21]: A Level 1 energy audit consists of a walk-through
which is a very simple assessment; a Level 2 energy audit consists of a detailed analysis of costs and savings; and a Level 3 audit includes additional measurements and hourly simulations. There are four major problems with energy audits.

The first problem with energy audits is that they often require a sizable initial investment with no promise of payback. People do not want to make an investment that might pay back, they want to ensure that an investment will pay off and will not end up costing them money. In addition, they are not aware of how much the energy efficiency upgrades will cost them before the audit, so if twenty thousand dollars is required to see a reasonable rate of return they may not have the money to invest and the energy audit will be a waste.

The second major problem with energy audits is that they typically give the investor a one-time analysis (or snapshot) of their electricity usage that is used to calculate the electricity consumption of devices, but does not help them much after the analysis is complete and energy reduction measures are in place. This does little to help them understand their electricity usage because the energy audit only provides a snapshot of their electricity use. This may help the customer know what measures to take, but does little for them after the measures are implemented.

The third major problem with energy audits is it is difficult to quantify the benefits and the return on the investment of the measures after they are implemented. When investors provide capital, they expect to receive returns on their investment and these values are usually quantifiable down to the penny. This is not the case with energy audits. While investors might notice general trends in their electricity bill (like it being
lower after energy recommendations are implemented), they do not understand fully what contributes to their new lower electricity bill. Even the savviest investors would not be able to quantify their financial savings accurately from an energy audit. The problem is not that energy audits and their recommendations are not good investments; it is that investors cannot quantify the financial benefits accurately and must trust that they are good investments. Investors are not known for trusting much, other than a good rate of return.

The fourth major problem with energy audits is that they are too expensive. The large initial costs with no promise of return scare many investors away and the energy recommendations must achieve a higher rate of return in order to make the total investment (the costs of the energy audit and the costs of the energy reduction measures) worth the investor’s capital.

**Energy Modification Measures**

Energy audits typically provide recommendations that inform the customer of the best way to save energy and money. In the past these techniques have been called an Energy Conservation Measure (ECM). Because the techniques proposed in this paper exist to educate the customer, ECMs are not adequate. Informing customers about their energy usage needs to provide them with more than just conservation measures, it must provide them with all potential scenarios including energy reduction, energy neutral, energy increasing and energy generation measures. As a result, this paper will use the term Energy Modification Measure (EMM) which include any modification that affects a
building’s/campus’ energy consumption or generation whether it increases or decreases electricity consumption. Some EMMs are described below.

**Energy Efficiency Measures**

Energy efficiency measures are *actions* that are taken to *reduce average energy consumption* for a building/campus and can affect electricity consumption by replacing incandescent light bulbs or replacing inefficient window air conditioning units for example.

Energy efficiency measures do not necessarily have any effect on billed demand. Billed demand is only affected by energy efficiency measures if the billed demand and the new device’s electricity use are coincident (if a light happens to be on when the billed demand is set for the billing period, the lights and then billed demand are coincident).

The term efficient should not be confused with environmentally friendly as it only refers to the amount of energy saved by the measure during operation, not the entire life cycle (production, use and disposal) of any measure components. A “cradle to grave” analysis is required to determine whether something is environmentally friendly. The term efficient also should not be confused with profitable because it does not consider the initial cost of the product or the cost savings of its benefits.

**Demand Reduction Measures**

For the purposes of this paper, demand reduction measures are *actions* that are taken to *reduce the billed demand* for a site. (This term is sometimes used by others to refer to reductions in demand at the grid scale.) This can be accomplished in conjunction
with energy efficiency measures by replacing inefficient devices that are in use during the periods when billed demand is set. It can also be accomplished using consumption neutral strategies like moving scheduled events to off peak times. It is even possible to reduce billed demand by increasing energy consumption using devices like ice block cooling systems which consume more energy than typical compressors, but do so at off-peak times (at night).

Demand reduction measures are often not as well understood as energy efficiency measures, but in some cases are easier and more cost effective to implement. The challenge is that quantifying their financial and environmental savings is difficult using current methods. The financial savings are difficult to quantify because without an accurate model or extensive and long term measurement it is difficult to determine what is contributing to billed demand. The environmental benefits are difficult to quantify because it is difficult to determine how much not having to build a new generator/transmission line/transformer benefits the environment and it is also difficult to determine how much (if at all) the reduction of a single customer’s billed demand reduced the need for this new infrastructure.

**Renewable Energy**

According to the United States’ Energy Information Administration renewable energy includes solar [solar thermal and photovoltaics (PV)], geothermal, biomass waste, biomass wood, wind and hydropower [22]. Renewable energy will never run out (at least not until the sun explodes or we deplete the heat inside of the earth) and provides a more sustainable energy supply than fossil fuels.
However, renewable energy is not entirely environmentally friendly. Some biofuels have problems similar to fossil fuels with regards to pollution both in burning and in processing; hydro power plants affect the ecosystem of the river particularly fish migrations; wind turbines can kill birds (although this is fairly easily mitigated by keeping the turbines away from birds’ migratory patterns) and PV panels are energy intensive to make and require the use of many harmful chemicals. In spite of these shortcomings, some sort of renewable energy must become the primary means of energy production in the future if mankind wishes to continue to use energy because fossil fuels and nuclear resources will eventually run out.

The most common renewable energy used as a building level EMM would be solar (PV) as it is often the most practical due to its ease of installation on roofs or on ground mounts and low operations and maintenance (O&M) costs and it generally has few negative effects during operation (like pollution or noise) that would annoy surrounding populations or building occupants.

Wind power is also an EMM but it is very site specific. Wind turbines require optimal wind to be practical. Wind turbines are also not typically built near populations (where the power would be consumed) due to noise, visual concerns and the fact that people do not typically like to live where wind conditions are optimal for wind turbines.

Hydro is a resource that is typically very large in scale. Some smaller microhydro plants exist and could be considered EMMs for campuses, but they must be placed on a river and are all around difficult to site making them relatively rare. If sited properly, microhydro electric plants provide near constant stable power with few negative
environmental consequences and do not have significant negative effects on surrounding populations.

Biomass systems burn various forms of biological material (garbage, manure, wood, etc.) in order to produce heat. This heat can then be used directly for building heating, to produce electricity, or a combination of the two. Biomass systems typically produce pollution. If sited properly, biomass can provide very stable and reliable electricity and produce reliable power in a predictable and controllable way much like fossil fuels.

**Changing Schedules**

Changing class/occupancy schedules can also be an EMM. Changing a class time could reduce or increase billed demand, while changing rooms could increase or decrease the electrical consumption/billed demand because different light fixtures and devices are used. Changing class/occupancy schedules is often the best option for reducing electricity bills, if it is not too intrusive, because it costs nothing to implement.

**Changing Temperature Set Points**

The modification of a temperature set point can play a role in building energy consumption making it an EMM. Changing the temperature set point of a building can reduce billed demand and consumption, but this may cause issues with occupants if appropriate temperatures are not maintained during hours of operation. During the summer, changing the temperature set point of a building can result in a change of electricity consumption by reducing the air conditioning load, while changing the set point in winter can reduce the amount of heating fuel used (usually fossil fuels.)
2.5 Factors to Realize Benefits of a Smart Grid

A smart grid holds a great deal of promise for consumers and the electrical industry. Unfortunately, efforts to develop a smart grid to date have involved massive investments in broad based infrastructure with the hope that a smart grid will emerge. But this has not occurred showing that this top down approach has not been effective. Instead, a smart grid will likely emerge from a more practical bottom up approach starting with smart buildings and smart campuses that will advance customer and community knowledge and appreciation of a smarter approach to energy usage.

Residential and commercial buildings consume 41% of all energy in the United States [23]. As a result, buildings present a significant opportunity for energy and cost savings. In larger facilities, it is common to be charged based on energy consumption (units of energy used during the billing period) and billed demand (the maximum amount of power consumed at any 15-minute interval during the billing period). At the University of Denver, the billed demand charges account for roughly 40% of the cost of the electric bill while the consumption accounts for roughly 60%. Reducing the billed demand can have significant financial benefits for a facility, but also has real benefits for the electrical grid and the environment. A smart building/campus has potential to reduce energy consumption but also has the potential to reduce electrical demand through customer education.

A smart building/campus has many benefits for the consumer. These include reduced capital costs on EMMs, reduced financial risks and a more targeted EMM approach than traditional methods (energy audits) resulting in quantified savings for
investors and reducing energy usage. A smart building provides real time information to occupants so they can be aware of their consumption in real time and a method of “looking back” after EMMs are implemented in order to quantify real savings which has been sorely lacking in current methods. It can also predict energy usage based on weather patterns and class schedules. While realizing these benefits, increased knowledge and awareness will be gained by consumers and small infrastructure additions will be made at the building/campus level that will serve as the “backbone” for a future smart grid by creating a local hub for data storage, communication and computation at the building/campus level.

As the number of smart buildings/campuses increase, markets will respond by fueling research into smart electronic devices and the costs of such devices will be driven down making smart technologies more affordable for the general population. Responding to cheaper prices, more consumers will adopt smart technologies -- eventually laying enough of the framework for a smart grid to become operational. A smart grid will provide consumers with the incentive and ability to respond to price signals yielding a supply and demand market that will reduce the burden on the electrical grid and the average price of power. A flexible smart grid would facilitate the integration and acceptance of new technologies, control systems, etc. into the market inciting the rapid evolution of smart technologies and a smart grid as a whole.

**Efficiency**

One of the promises of a smart grid is that it will provide increased efficiency. It is often assumed that this means improving the efficiency (the amount of fuel required
per unit of electrical output) of the generators. However, that is not necessarily the case. Instead, a smart grid will help reduce redundancy in the system by making generators and transmission lines that are required for only a few hours per year, no longer necessary. This leads to a more *economically efficient solution* which will likely require less infrastructure and operate at a higher *capacity factor*, therefore creating less pollution and arguably, require less energy input (by way of less infrastructure) per unit output (electricity generated) system wide over time. The lynch pin for this economic efficiency is demand elasticity which requires demand response techniques as a stepping stone.

**Demand Response**

Demand response is the current method of incentivizing supply and demand which is essential to realizing the benefits of a smart grid. Demand response (for the purposes of this paper) will be used to describe different signals (usually some kind of price signals) which are designed to incentivize customers to modify their energy consumption at a given time. Customers who are able to respond to signals are in the minority [24]. There are many different methods of implementing demand response and the terms and conditions differ significantly from site to site and from utility to utility, but there are some distinguishing features that can be used to form helpful categories. Unfortunately, all of these demand response methods have failed to produce a market where many consumers respond to price signals leading to a supply and demand market.

**Incentive Based**

Incentive based demand response can be divided into two categories: Direct Load Control (DLC) and Interruptible and Curtailable Load (I&C). Mohagheghi, et al., [25]
provides a good review of incentive based demand response. Incentive based demand response typically operates using a flat rate billing structure and provides financial incentives to reduce energy consumption.

**Direct Load Control**

Direct Load Control generally refers to consumer devices that allow the electric company to send a signal to turn a device off or reduce consumption. This technology can work well with typical residential appliances (dishwashers, dryers, hot water heaters) and charging electric vehicles [25]. It is fairly straightforward to implement, but it does not allow the customer to make a choice for themselves during individual demand response events.

Direct Load Control usually allows customers to choose whether or not to participate for the period of the contract, but cannot make a choice of how to respond when the electric company sends a DLC signal. Because most consumers would not take kindly to having their daily electricity use micromanaged by an overzealous electricity provider and because of the fairly fast deployment time, DLC is best suited for emergency situations that are rare and relatively short. This limitation makes DLC impractical for implementing a supply and demand market because it will not incite any demand elasticity.

**Interruptible and Curtailable Load**

Interruptible and Curtailable loads are very similar to direct controllable loads, but are usually larger in scale and are indirectly controlled by utility companies by way of communication with on-site facilities personnel [25]. Interruptible and Curtailable can
include things like commercial lighting, HVAC and manufacturing processes. The time for deployment of this technology varies from a few minutes to a few hours.

Facility managers are even less likely to tolerate micromanagement of their buildings than residential consumers, so I&C load should be used only when it is truly necessary, like during emergency situations. This makes I&C loads impractical for the development of a supply and demand market.

**Bids**

System operators have to manage power for millions of people. To them, a single residential consumer is a drop in the bucket. It would be impractical for them to try to manage the power of all of their consumers. As a result, the system operators only manage the electricity of their largest customers and/or use aggregators who manage multiple smaller customers to act as one large customer. When the electrical demand is too large and the system is overtaxed, the system operator will receive “bids” from these customers which are essentially offers to reduce their electricity by “x” amount, for “y” dollars, for “z” minutes/hours [25].

Because the customer is making their own choice about their electricity consumption and setting their own a value for that electricity, demand reduction bids can be used to manage load more often than incentive based demand response. Bids are best suited for reducing peak demand and managing congestion by shifting consumption to a time when the system can handle it or shedding the load completely. Because this mechanism is only available to very large customers, the demand reductions have limited effect on the grid and this type of demand response cannot be implemented grid wide. In
addition, it is difficult to ensure a facility is reducing its demand by a specific amount because it is difficult to know what the facility would be consuming without the demand response measures – providing opportunities for unscrupulous individuals to game the system. In addition, there are regulatory, technical and practical barriers that must be overcome for bidding to become more widespread. Newell, et al, [26] provide an overview of some of the challenges associated with demand response implementation.

**Rate Based**

Rate based demand response is a mechanism which attempts to reflect the cost of generating and delivering power to consumers using prices that vary throughout the day with the hope that they will change their habits and consume energy when it is cheaper (when grid stress is at a minimum) so that they do not consume as much energy when it is expensive (when the grid is overtaxed). There are two major rate based demand response mechanisms: Time of Use (TOU) rates and Real Time Pricing (RTP).

**Time of Use Rates**

TOU rates set the price for electricity to different levels, usually changing throughout the day. Some common mechanisms for TOU rates are peak pricing where customers pay a higher rate for energy consumed during peak times (e.g. 12:01pm – 7:00pm) and a lower rate for energy consumed during off-peak times (e.g. 7:01pm – 12:00pm). Variations have been made to this to include three or more pricing levels, but the basic principle remains the same [26].

TOU rates help maintain a flatter electricity profile throughout the day, but do not do much to reduce the variations in electricity use from day to day or month to month. In
addition, TOU rates cannot be modified when portions of the transmission system are overtaxed in order to reduce congestion. As a result, this pricing mechanism is better than a flat rate billing structure because it can reduce the peak demand requirements somewhat and can easily be applied to residential customers, but TOU rates fall short because they do not have the ability to reduce the electrical demand on the day of heaviest consumption compared to a day of average consumption. In other words, TAU rates will not incentivize a supply and demand market.

**Real Time Pricing**

RTP charges customers a rate for their energy usage that is proportional to the cost to generate and transmit that energy at the time of consumption. This mechanism is one of the best from a market standpoint because it can vary in real time and ensure that the grid is not overtaxed. It solves the problems of overdesigning the grid and lowers the average cost of energy leading to increase social welfare, but RTP does have some issues with price volatility resulting mostly from consumers not having adequate mechanisms to respond to price fluctuations [27].

RTP is different from all other demand response techniques, because the prices are not artificial values, unlike time of use rates (which are often adjusted seasonally) or bids (which are set for some customers and not others) RTP reflect the actual costs of providing electricity at a given time. RTP is the only technique that truly incentivizes demand elasticity. As a result, it is the best way to get demand response to the masses and solves many of the problems with overdesigning the electrical grid (at least in theory).
**Limitations of Demand Response**

In practice, customers have various market mechanisms that incentivize them to respond to prices and yet, there have been few widely successful demand response or RTP programs.

A total of 19 entities reported retail real-time pricing programs from all but two regions. This is down from the 85 entities reporting at least one real-time pricing program for retail customers in the 2008 FERC Survey [24].

There still is no momentum behind a supply and demand market and the benefits usually do not outweigh the costs for customers.

Consumers have not been fond of real time pricing mainly due to price volatility and their inability to respond to it.

Most RTP programs provide limited assistance to help customers physically manage their exposure to price volatility… Customers that respond to RTP prices generally employ relatively low-tech strategies or onsite generation resources [28].

These two statements indicate that customers have been provided the incentive to use electricity in a more intelligent way, but lack the ability and/or knowledge of how to do it. This can lead to significant financial hardships. For example, in Texas, the average price of power is roughly 11.22 cents/kWh [29], but spot prices are currently allowed to increase to $4.50/kWh with plans to increase this to $9.00 in 2015 [30]. If customers could respond to these prices they would have a significant opportunity for savings, but without the ability to respond, they find themselves exposed to considerable price volatility.
Without the ability to respond to prices, customers could be paying 80 times the average price of energy with little to no way to reduce their consumption. As a result, many customers chose not to use RTP programs because they believe it might increase their electricity bill; they believe they are unlikely to benefit from change; and/or it complicates their energy bill significantly. Even the number of customers enrolled in time of use rates has been declining [24]. While demand response and RTP have failed to produce a smart grid, they are instrumental in providing incentives to spur a supply and demand market in the electricity sector. The missing component appears to be customer knowledge and ability to respond to such incentives. All forms of demand response (and as a result a supply and demand market) are dependent upon quantifying energy consumption at a given time. This requires a new monitoring infrastructure which has the ability to take more measurements and communicate in real time.

**Fault Detection**

Fault detection is also dependent on real time monitoring and is essential to maintain a reliable and stable grid. A fault in the electricity network occurs when lines come in contact with the ground, trees contact the wires, wires are severed, etc. and will often result in a brown out or blackout. Real time monitoring keeps system operators aware of conditions at the distribution level of the electrical grid making it significantly easier to detect faults.

Currently minor faults, like the ones that affect a small number of customers cannot even be detected by system operators and are generally reported by customers. One of the goals of a smart grid is a self-healing and advanced fault detection system in
order to detect faults faster and return power to customers sooner; or even better, stop a power outage before it starts. The challenge for system operators and customers is that this fault detection requires advanced monitoring [31] which is often prohibitively expensive.

**Advanced Metering Infrastructure**

Advanced Metering Infrastructure (AMI) is a term that refers to an advanced digital electricity meter that can not only measure energy usage and store usage data in real time, but can send that information to the electricity provider and receive the current and future prices for energy from the electricity provider. Federal Energy Regulatory Commission and the Energy Information Administration define advanced meters as:

Meters that measure and record usage data at hourly intervals or more frequently and provide usage data to both consumers and energy companies at least once daily. Data are used for billing and other purposes. Advanced meters include basic hourly interval meters, meters with one-way communication and real-time meters with built-in two-way communication capable of recording and transmitting instantaneous data [24].

These meters are a significant part of the nervous system that allows RTP, demand response and advanced fault detection to work properly and is the main point where consumers interact with prices creating demand elasticity.

Many of the individual “components” of a smart grid require an advanced metering infrastructure. Demand response, advanced fault detection and other elements of a smart grid are still novelties and without the technology to support them they will remain novelties and not become widely accepted. Also, it would be difficult for large scale communications to occur without a meter that could connect to the energy provider
and inform customers of current prices in RTP rates. In addition, RTP rates would make it impractical to read meters once a month (common practice today), but must be read with every price change (probably every 15 minutes to one hour).

An advanced fault detection system which detects and responds to faults on the distribution level is likely going to require many sensors to work properly. The most economical solution to this challenge is to piggyback these sensors on the AMI.

Smart meters have many advantages over standard electricity meters such as: meter reading can be performed immediately by computers meaning less overhead and faster billing; electricity providers can better manage their assets meaning less waste; rate structures can be more flexible meaning more novel billing structures that use demand response; energy usage can be benchmarked which can help educate customers; and power outages can be detected faster meaning less time spent without power for customers. Advanced metering infrastructure holds considerable promise and capabilities to help change the way the electricity markets work, but there are many challenges to the implementation of such an infrastructure.

2.6 Challenges for the AMI and a Supply and Demand Market

One major issue for developing a functional supply and demand market in the electricity sector has been that the implementation of smart technologies (e.g., smart meters, integrated sensors, novel control systems) have often been prohibitively expensive and the technologies will not pay for themselves until there is a supply and demand revolution in the electricity industry. But that revolution cannot occur without
the smart technologies -- creating a “Catch 22”. Without a financial justification, the public quickly writes off smart technologies as too expensive for their limited benefits.

In the way they are implemented today, smart meters are often not cost effective. Xcel Energy’s SmartGridCity project had cost overruns that tripled the original price from 15.3 up to 45 million dollars in 2 years [32]. In Advanced Metering Infrastructure – Implications for Residential Customers in New Jersey, the authors found that the net present value (over 15 years) of the savings did not justify the cost of implementing AMI in New Jersey. They further concluded that the utilities would file for a price increase in distribution service rates to pass through the costs to customers and that AMI is not the least cost approach to reducing annual energy use for New Jersey customers [33]. A separate report titled Advanced Metering Infrastructure Overview and Plan found that the total cost for a proposed AMI plan was $377 million, while the 20 year net present value of the savings was $311 million [34].

**Regulators, Utility Companies and Investors**

*Utility companies and regulators have failed to produce a functional smart grid because they have major disincentives to do so.* In a free market, competition among companies drives innovation. However, utility companies do not operate in a competitive market. Many of the elements of a smart grid are not compatible with the current utility business model and the regulatory framework governing said model. The development of a smart grid and the supply and demand market it would create, put utility profits at risk and jeopardize their future as a business.
**Utility Business Model**

Utility companies are typically the entities which operate the grid in regulated markets. They are granted the right to maintain a monopoly in exchange for accepting heavy regulations. These regulated monopolies are designed to reduce the market power (the ability of a firm to charge rates above competitive levels) which keep generation owners from charging unreasonable prices. Electric utility company’s investors are almost always granted a “reasonable rate of return” on their investments to ensure appropriate infrastructure investments are made.

Traditionally, utility companies provide returns for capital investments using financial savings or increasing prices via rate cases. A rate case is where the utility company and/or the regulators make their “case” for new rates to each other and the regulator ultimately decides on a reasonable rate of return \([35]\) in order to achieve a desired rate of return on their investment. The regulators change the price of electricity to customers in order to ensure that the utility company’s investors get their reasonable rate of return. This presents a problem when it comes to funding smart grids because one of the main goals of a smart grid is to inform customers about their electricity consumption ultimately leading to reduced energy consumption, which can adversely affect utilities ability to provide returns (discussed later).

Privately owned utility companies (like companies in any sector) are responsible for providing financial return to investors. Due to the complexities of the electricity industry, this process is very different from how a normal company would profit. Normally, a company would take investors’ money, provide customers with some good
or service making a profit and then return the invested money to the investor plus some extra for the privilege of using the money.

Utilities work very differently because of the heavy regulations. Utility companies take investors’ money and invest in new transmission/distribution/generation resources. They then calculate how much the asset will cost/save them over the life of the product. The regulators and the utility company then make a rate case that will allow the investment, plus a reasonable rate of return, to be given to the investors using the savings provided by the asset, or more commonly by raising rates on customers to pay for the returns. In addition, utility companies are fairly well protected from bankruptcy.

**Infrastructure Investments and Risk**

Upgrades to the electricity network are often 40-year (or longer) investments and few investors are willing to accept risk on investments that take this long to pay back. In order to attract investors, a tacit agreement is made between regulators and investors which reduce risk by guaranteeing a reasonable rate of return.

Public impulses over time are a major reason for this tacit agreement. Few investors are willing to build a 40-year power plant if they fear that regulators (acting on the will of the public and politics) could shut them down before their investment pays off. The reason for this fear can be illustrated through the public’s recent changes in attitudes about electricity generation. The public was opposed to nuclear power for a long time due to the fear of radiation (particularly after Chernobyl and Three Mile Island). Now, they are heavily opposed to coal and to a lesser extent natural gas, because of pollution
and carbon emission concerns; and are in favor of nuclear power plants because of their low carbon footprint.

Investment in the electrical industry must continue in order for the grid to continue to function. Regulators, who dictate payback for investors, have traditionally provided a reliable (low risk) and “reasonable” rate of return (usually equal to what an investor could achieve with a similar investment in the other sectors of the market at the time). If the regulators stop providing a reasonable rate of return on investments, investors will likely flee to other shorter term investments that are not subject to the ever-changing whims of the public. Private investment in the electricity industry would dry up, forcing the government to invest in energy infrastructure which would be contrary to the free market that a smart grid is designed to implement.

**Required Investments**

Utilities are forced by regulators to make upgrades to the electrical grid (e.g., transmission lines, generators, distribution systems, transformers) to meet projected peak demand caused by the *predict and supply* market. When the electricity market changes to *supply and demand*, peak demand will no longer drive economically inefficient investment because customers will respond to high prices with lower consumption (reducing peak demand). The costly upgrades (past and present) associated with the peak demand will no longer be necessary and will become liabilities. These liabilities are known as *stranded costs*. Stranded costs are often the result of investments that had to be made in a non-competitive market which are no longer necessary in a competitive market.
and are a significant disincentive for the utilities and investors to move to a supply and demand market [35].

**Utility Companies Fear Downward Spiral**

Further complicating matters, utilities pay for capital investments by amortizing the costs and charging customers a fee for each unit of energy consumed, increasing the rate for electricity (assuming the investment does not pay for itself in savings). If the amount of energy consumption contracts as smart technologies are installed and users become more aware of their energy usage and potential savings, the utilities must continue to recover these stranded costs. In order to do that, they must increase rates. As the rates increase, the incentives become greater to reduce electricity consumption and it contracts further causing the utilities to raise rates even further. This situation creates a spiral of increasing prices and decreasing consumption. The public would be unlikely to tolerate this for very long and regulators would have to respond. The only real solution regulators have would be to charge all customers a fee for stranded costs, reducing the benefits of a smart grid to the public significantly or they will reduce the rate of return on investments, destroying investor’s profits and threatening the future of private investment in the electricity grid.

A recent Wall Street Journal article [36] illustrates that even without a smart grid, utility companies are already beginning to become tepid about future generation investments, considering cutting dividends or redirecting capital to transmission assets. These changes are caused by a slowdown in growth in the electrical industry. While a slowdown in growth simply means reduced profits, a contraction in electricity
consumption may well mean the death of traditional utility companies and major challenges for the electrical industry.

**Smart Grid Challenges and Solutions**

Given the overwhelming challenges relating to regulation and the responsibilities of the regulators and utility companies, it is impractical to expect any revolutionary smart grid solutions to come from these entities. If a smart grid is to be successful, a new strategy must be developed. Instead of trying to install every piece of smart technology and forcing customers to use smart meters (even when they do not want to) in the hopes that this massive financial investment will payoff in the long run (without a solid idea of how the payoff will occur), it seems much easier, more effective and less confrontational to show customers the savings that smart technology can provide them and let them make choices for themselves. In short, *when smart technologies provide a good rate of return in the current market structure, they will grow in number until they reach a “critical mass.” At that point, a supply and demand market will be the only economically efficient solution and a smart grid will be inevitable.*
Chapter 3: VISION AND GOALS

3.1 Vision

Organize consumers’ energy information in a useful way so that they can make educated energy choices.

3.2 Goals

1. Develop and maintain a smart building operating system.

2. The operating system must readily accept new technologies, rate structures, modeling techniques and sensors.

3. The operating system should provide users the ability, tools and information to consume power in the way that they choose.

3.3 Tactics

1. Never attempt to influence consumers’ decisions, only provide them with reliable information.

2. Provide a secure experience which protects consumers’ information.

3. Make the user interface as simple as it can be, but no simpler.

4. The system should be inclusive not exclusive to technologies, languages individuals, etc.
5. The system must readily accept new technologies, modeling techniques, sensors, etc.

6. The system should be open source.

7. The system should provide clear, accurate results.
Chapter 4: SMART GRID AT THE UNIVERSITY OF DENVER (SGUD)

The smart grid is no longer a technical problem, it is a market problem. Han Slootweg summed it up nicely.

In the recent past, a great variety of sensors, protocols, communication equipment and the like has {sic} been designed to support the move towards Smart Grids. However, many of them have not found wide application, which can be at least partly attributed to the fact that there were no ‘problems’ for which they provided a solution so that it was not possible to draw up a positive business case [37].

In other words, any proposed smart grid approach must clearly address a specific need in the current electricity market not a theoretical need in a future electricity market.

The Smart Grid at University of Denver is an overarching term for different elements brought together by the SGUD Team in order to provide accurate financial, environmental and energy information about proposed EMMs to decision makers. This information will be used to identify which EMMs have desirable environmental and financial benefits and which do not. In this way, the SGUD method provides “a la cart” energy solutions that are specific to the geographic location, building, occupant needs, capital costs, payback periods, required rates of return, etc. In one simple example, the SGUD method would inform users which conventional light bulbs should be replaced with energy efficient bulbs in order to meet their financial/environmental/energy needs, instead of incurring the cost of replacing all of the bulbs.
Taking into consideration the failures of the previous and current smart grid approaches which were driven by utility companies and regulators, SGUD’s approach targets the consumer providing information about EMMs to encourage decisions that will save energy and yield a favorable return on investment while providing the foundation for a smart building/campus. This smart building/campus and many other such projects will provide the technology, knowledge and experience needed for a supply and demand market at the macro level eventually leading to a smart grid.

4.1 Traditional Consumer Information Gap

While appropriate incentives like RTP have been in place to incentivize demand elasticity, a supply and demand market is still not on the horizon because customers lack the wherewithal and knowledge of how to respond to real time prices thereby reducing their electricity bill and the burden on the grid. It is this lack of knowledge of how and why energy is used that is keeping the market from reducing peak demand.

For example, many energy efficient light bulbs are said to save a customer “x” dollars per year. This number assumes that the customer uses the bulb for “y” hours per day at “z” dollars per unit of energy, which is an overly simplified model. This model does not consider many factors including how much the individual consumer actually pays for electricity or the type of bulbs currently used. Replacing an incandescent bulb with a CFL on an exterior light fixture that is on all night may have substantially different financial consequences when compared to an indoor light. The indoor light adds to the heat of the building decreasing heating costs and increasing cooling costs, while outdoor lights have no effect on heating and cooling costs. Exterior lights which are usually only
on at night are not likely to affect peak demand, while lights that are on during the day may affect peak demand. These complications make it difficult to determine the financial and environmental benefits of EMMs which vary depending on the site, usage, location, etc. Complicating matters further, quantifying actual (not estimated) savings after EMMs are implemented is also difficult due to a lack of information, which can make EMMs difficult to justify for consumers and investors.

A new method of quantifying EMM benefits and modeling building electricity usage is necessary. This method must model building energy usage accurately and give investors the data they need to make informed decisions. This will benefit the customer by allowing them to implement EMMs which will have the maximum effect, both financial and environmental, ultimately reducing peak demand which will benefit all customers on the grid by lessening the need for expensive expansion of the network and adding new generators. It will also benefit the environment because more effective EMMs will be implemented thereby reducing energy consumption.

4.2 Previous Building Models

There have been many building models to date. Most of these models are either overly simplified (which leads to insufficient data for a smart building), focused on HVAC or require so many sensors that they become prohibitively expensive and impractical. Many of these models have been designed for a variety of purposes, but none has given consumers enough knowledge to aid in the implementation of a smart grid. Some of these models are described below.
Profile Based Energy Management System for Domestic Electrical Applications [38]

The proposed system uses electricity sensors that monitor consumption of many electricity consuming devices. These sensors connect to an information system that can record and store data and presumably control appliances. This method allows users to profile their devices which can detect “abnormalities” in energy consumption. An example was given that it should only take 2 minutes to boil a kettle of water, but the system detects that it is actually taking 4 minutes for the water to boil. It is unclear how the system would know how much water is in the kettle without a “smart kettle” or how the knowledge of these “abnormalities” would help users.

The challenges for this approach include: the kind of monitoring equipment required for this type of system is most likely very expensive and the paper lacks a clear method of providing a return on investment for the user; most appliances (including presumably tea kettles) require electrical monitoring equipment which would consume energy, increase costs and probably frustrate customers; the ZigBee based communication system means that most customers would have to install a new wireless network into the homes/business in order to take advantage of this method; and it does not appear to have the ability to forecast customer load accurately in the range of minutes to hours.

Part of this paper describes a building level demand forecast which is very closely related to building models. The system “chooses” from past data that are similar in nature (temperature, class schedules, time, etc.) to forecast electricity consumption. The results showed good correlation, but they report results for only a single day, so it is difficult to know overall accuracy. This method also requires electrical sensors, but the methodology is much more dependent upon a single building level sensor and a temperature forecast making it significantly cheaper than many building models. The major challenge with this building level demand forecast is that it is dependent on a significant amount of data being measured (which takes time on the scale of weeks to months) and during this time, the building must be in a steady state with respect to schedules. This method would not work well when changes are made to class/occupancy schedules, changing out electrical devices, changes from air conditioning in the summer to heating systems in the winter, etc. This method also cannot forecast down to the device level which makes its ability to quantify benefits of EMMs questionable.

Supervisory and Energy Management System of Large Public Buildings [40]

This paper proposes gathering information about the building using metering devices. This system also proposes to detect “abnormal” energy use and adjust “running strategies” to ensure occupant comfort and optimal energy use. It further outlines the architecture required to implement a smart grid and it includes a detailed description of architecture for a smart building, but lacks a coherent strategy for what the authors’ smart
building will accomplish other than gathering large amounts of data. There does not appear to be a management scheme for energy. In addition, this data gathering method requires many different interfaces, sensors, control systems, coding languages, wireless protocols, etc. which will likely make it prohibitively expensive and problematic.

**A Scheme for Building Demand Response Based on a Comprehensive Load Profile** [41]

This paper presents a method of optimizing demand response measures based on day-ahead prices. In order to accomplish this, the authors used data from the Reference Energy Disaggregation Data Set or REDD [42]. REDD is a data set provided by the Massachusetts Institute of Technology which provides highly accurate measured power and frequency of energy usage data for six homes over the course of several weeks. These data are invaluable for research purposes, but it is impractical to attempt to perform this type of measurement for all users who need an accurate building model because the amount of data required would make this method costly due to the large number of sensors required.

**EnergyPlus** [43]

According to the Department of Energy’s Website, “EnergyPlus is an energy analysis and thermal load simulation program. Based on a user's description of a building from the perspective of the building's physical make-up and associated mechanical and other systems, EnergyPlus calculates heating and cooling loads necessary to maintain thermal control set points, conditions throughout a secondary HVAC system and coil loads and the energy consumption of primary plant equipment. Simultaneous integration
of these—and many other—details verify that the EnergyPlus simulation performs as would the real building.”

EnergyPlus is a useful tool and has many advantages. It is accurate and its new releases are thoroughly vetted before being made public. It is comprehensive and can model many different aspects of building energy consumption. It can also be upgraded to accept new technology, but only after a time consuming vetting process.

While the model is accurate, it is designed as a thermal model not as a whole building model. While it may be possible to integrate a detailed lighting and plug load simulation into the EnergyPlus model, this would likely be an impractical solution. In addition, EnergyPlus is designed to run based on text files which are feed into the simulator. It would likely prove more practical to integrate the EnergyPlus thermal model into a smart building model than to attempt to turn it into a smart building model. This text file input also would make it difficult to integrate this model with real time data without some sort of a software “wrapper.”

eQUEST

eQUEST is a building model based on the DOE-2.2 engine, which provides significant improvements including a better user interface. eQUEST is probably the most widely used building model available today. eQUEST (like many other models) is very focused on thermal energy consumption (HVAC systems). Figure 5 and Figure 6 below show examples of how in depth the user inputs and by association, the calculations are.
However, this detailed analysis does tend to present some problems. While the creator suggest that eQUEST is easy to use [44], the training manual is roughly 150 pages.
long [45] and its HVAC calculations are comprehensive, but certainly not intuitive. See Figure 7 and Figure 8 for some of the inputs for the HVAC calculations.

Figure 7: eQUEST HVAC Zone Options 1

Figure 8: eQUEST HVAC Zone Options
eQUEST also has some simplistic assumptions for lighting and plug loads like energy intensity values which are based on ASHRAE assumptions. See Figure 9 and Figure 10 for some of the inputs for the schedules and lighting. While this methodology may be adequate for producing an accurate building energy consumption, it falls short of device level consumption.

Figure 9: eQUEST Occupancy Schedule
eQUEST does have a wizard option that is significantly simpler than the methods shown above, but it is still by no means a simple building model. The wizard still requires entering a building shell (which is essentially a CAD drawing of the exterior walls and windows of the building) as well as very detailed HVAC inputs.

### 4.3 What SGUD’s Model Does Differently

Many of the previous building models have had benefits and have proven useful, but they are often purpose-built to solve an individual problem and lack the ability to grow beyond their initial intended use. SGUD’s building model has been designed with flexibility by consolidating different kinds of metered data into a single database, using existing Wi-Fi networks and structuring the logic in ways that make it easy to modify for maximum versatility.
The majority of detailed building models have focused on HVAC because it is such a large electrical load (on average 51% of total energy consumption in buildings) [46] and therefore, one change can have a large effect on building electrical usage. While a lot of effort has been focused on thermal energy savings, there is a significant opportunity for savings being passed over. According to the Commercial Buildings Energy Consumption Survey heating and cooling only accounts for 30% of total electricity use [47]. This means that there is a significant opportunity to reduce electricity consumption which current building models are not addressing.

Furthermore, many of the previous building models lack embedded financial calculations. The financial calculations such as return on investment, payback period, etc. are often some of the most important factors when deciding on implementation of an EMM. Without these calculations, much of the benefits from the data acquired by these building models remain in a language that the people who approve projects do not understand, leaving the facility personnel/engineers/auditors with the responsibility to perform these calculations (requiring time and money) or leaving the projects dead in the water. The SGUD approach contains useful financial calculations which are internal to the system and designed for ease of use.

Another major challenge for many “smart” building models is that they are too dependent upon sensors which can be difficult to install and maintain and are often prohibitively expensive. SGUD’s building model requires electrical sensors for calibration, but most (if not all) sensors can be removed after an initial calibration period, reducing the cost and difficulty of maintaining meters for the customer.
Many previous building models also lack a plan for how they will provide a payback to the users. SGUD’s approach to payback is to provide easy to understand information and strategies for customers to save money and allow them to make their own choices about their energy consumption. This is a non-invasive way of helping customers understand their electricity usage, without making decisions for them, putting them in charge of their own energy consumption, but ultimately directing them toward making smarter choices.

*Previous building models inform a consumer THAT electricity is being used, but do not tell them WHY electricity is being used.* The ability to understand the driving forces of a consumer’s electricity use is necessary for them to make informed decisions. Without this ability, building models cannot accurately forecast the benefits and costs of EMMs. The forecasts and estimations provided by prior building models can sometimes be useful to utility companies if the customer is large enough, but have little practical use for the customers they wish to serve.

The SGUD approach proposes to bridge this information gap by way of an accurate building model which “links” electricity usage to the reason electricity is being used and linking the heating and cooling of the building to internal electrical use, building population, solar radiation and exterior temperature. Linking the electricity consumption to the reason for the consumption allows the SGUD team to inform customers why their electricity bill costs what it does. Combining this model with an accurate billing algorithm that mimics the utility bill and useful financial calculations provides the accurate, reliable and instantaneous financial information required for
decision makers to approve EMMs. These factors allow the SGUD approach to provide customers with knowledge of why they use electricity and the information about the best EMMs to meet their needs cheaply, easily and non-invasively.

4.4 SGUD Building Model

Informing customers why electricity is being consumed requires a new approach to building modeling. SGUD’s building model links energy consumption to the reason the energy is being consumed using information about when a room is occupied, who is occupying it and what electrical devices they are likely using. This method relies heavily on probabilities and the law of large numbers in order to function properly. It begins by determining if a class is in session at time $t$. If a class is in session, it determines what devices are in the room and how much power (watts) each device is consuming when on. Then it determines the probability that these devices are being used, which informs the model of the likely electricity consumption of that room. The probability that a device is being used is determined using meters during the calibration process (see pg. 125).

**Probability in Use**

The probability that a load is being used during a certain activity is known as the Probability in Use (PIU). It is impossible to know exactly what devices and loads are being used at a given time without expensive and cumbersome measurement equipment. Probabilities are vital to the SGUD approach to estimating energy consumption because it does not rely heavily on measurement equipment and can still provide accurate electricity estimates. A PIU indicates the percentage (statistically determined) of the time that the
load is on during a given activity. For example, if a projector is used half of the time during lectures, the PIU would be equal to 0.5 or 50% for the lecture activity.

In principle the SGUD approach relies on a statistical connection (PIU) between devices within a specific room and activities that take place within that room. In order to understand this approach, it is useful to understand the principles using a simple real world scenario. For example, the SGUD building model has been programmed with the knowledge of what lights are in Room #1 and how much power they consume (let’s say 100 Watts). If a class is present in that room, the model knows that there is a statistical probability (determined by past measurements) that the lights will be turned on (let’s say 90%). Therefore, SGUD’s building model determines that the electrical consumption of those lights is likely to be (100 Watts * 90%) 90 Watts. Initially, this seems nonsensical, because the lights cannot be 90% on; they are either on (100 Watts) or off (0 Watts). However, when many of these calculations are taken over a large enough building all of the errors begin to cancel each other out (law of large numbers) [48] and an accurate simulation of building electricity use begins to appear.

This method provides four significant benefits over previous methods.

1. It can accommodate changes in class schedules relatively easily. For example, if a class moves from Room #1 (lights = 100 Watts) to Room #2 (lights = 200 Watts), SGUD’s building model can determine that that class is now (statistically) consuming 180 watts instead of the original 90 watts. This is particularly useful in schools where classes move and schedules change every semester/quarter/trimester.
2. Devices (TV’s, light bulbs, refrigerators, etc.) can be replaced in a room (in the model) without having to perform any structural changes within the model; it just requires changing the link in the model between the device and the room.

3. Once the PIUs can be determined, the electrical meters can be removed and the model will still be accurate regardless of any changes to the schedule, devices, etc. This reduces the costs of meters because they can be moved from building to building where needed.

4. Custom functions for electrical loads that do not follow the neat “linking” structure (like elevators which run based on changes in population of rooms above the first floor or HVAC units which are dependent heavily on exterior temperature) can be added to the model in the form of custom functions which have no set structure. These custom functions can also be integrated with real time or past measurements in the form of feeds.

These four features give SGUD’s building model unparalleled versatility, functionality and usefulness among building models. These capabilities allow the proposed building model to cheaply and easily provide users with the information they require while building the foundations for a smart grid.

4.5 **SGUD Data Warehouse**

The data warehouse is the central storage location for SGUD and is located on a server. The database uses the HSQL protocol which complies with the SQL 1999 standard. Disk caching occurs on the server and in-memory caching is used for specific queries and objects.
A custom object relational mapper was created that has three major advantages over previous mappers: it provides easier querying while allowing more fluid data structures; it re-writes queries to be more efficient; and it adds a layer of caching to all objects. This database is kept in a single flat file which is compressed for storage [49].

For security reasons and to address privacy concerns, this database can only be accessed on campus or a secure VPN, either of which require a University of Denver user name and password. In addition, specific queries cannot be made without a key provided by the SGUD team. Individual keys can be revoked by the SGUD team at any time. All information required from the model must be queried from the database. At the time that this paper is being written there are about 50 gigabytes of data being stored in the database, although it is currently taking up substantially less room due to compression.

**Entity Types**

An entity is any data stored in a database that can be uniquely identified. Various types of entities typically relate to one another and make up the foundation of relational databases. The entity types that are used in the SGUD model for the three-element method (see pg. 73) are listed below.

**Activities**

Activities are typically scheduled events. In the case of a University, this is usually a class. Each activity has a name, building name, room name, activity type, start date, end date, start time, end time, days scheduled and population. For example,
- Activity Name = Physics 101
- Building name = Olin Hall
- Room Name = 105
- Activity type = Lecture
- Start date = September 18, 2011
- End Date = November 21, 2011
- Start Time = 8:00 AM
- End Time = 9:00 AM
- Days Scheduled = Monday, Tuesday, Wednesday, Friday
- Population = 64

**Activity Type**

The SGUD model groups activities by type in order to assess the probability of energy usage for certain kinds of activities. For example, during lectures, teachers are likely to use the projector, but during labs, it is much more likely that the hoods are in use. Activity types include Lab, Lecture, 9-5 work day, etc. The main entry for activity types is *Probability in Use*.

*Probability In Use* identifies the statistical probability that a device is going to be used under a prescribed set of conditions. *Probability in use* for something like lighting during a lab would be 98%, meaning there is a 98% chance that during a lab, the lights will be on. However, devices such as an electric heating element may only be in used 20% of the time during a lab.
**Devices**

Devices are electronics that consume electrical energy. Typical devices are items like refrigerators, light bulbs and televisions. The device entity type has a rated wattage and duty cycle.

**Loads**

The term “load” is used in the SGUD model to describe the linkage of devices to activity types. A load quantifies the number of specific devices present in a certain room. The load entity type contains a building name, room name, Probability in Use, device quantity, multiply by population flag and zone name.

**Zone**

A zone is an area of a building. It can be an entire floor, an area served by a specific HVAC system, a single electrical circuit, or any other designated area.

**Air Handling Units (AHUs)**

Typically, each AHU services a different part of the building. Much of the AHU data come from real time measurements. The AHU entity type sometimes include a zone name, building name, intake air temperature, discharge air temperature, CFM rated capacity, fan status and fan Rated HP. For example,

- Zone Name = AHU1
- Building Name = Olin
- Intake Air Temperature = 80 deg F
- Discharge Air Temperature = 63 deg F
- CFM Rated Capacity = 12,000 CFM
- Fan Rated HP = 15

**Chiller**

A chiller is an HVAC compressor associated with a specific building. The chiller entity type has the following data points: zone name, building name, regression coefficients, outside air temperature, chilled water supply temperature and chilled water return temperature. For example,

- Zone name = Chiller 1
- Building Name = Olin Hall
- Regression Coefficients
  - $\beta_{t0} = 512.7104$
  - $\beta_{t1} = -4.8813$
  - $\beta_{t2} = 11.9937$
  - $\beta_{e0} = 50.5875$
  - $\beta_{e1} = -2.1173$
  - $\beta_{e2} = 1.8375$
- Outside Air Temperature = 90 deg F
- Chilled Water Supply Temperature = 40 deg F
- Chilled Water Return Temperature = 45 deg F

**Building**

The building entity type contains only the building name.
**Room Name/#**

The Room Name/# is used to link loads and activities. The Room name/# entity type contains only a name.

**Feeds**

Feeds are measured values taken from a variety of sources. The HVAC values come from Johnson Controls measurement devices on the building HVAC systems. There are also feeds from the National Weather Service which provides a 7-day weather forecast. In addition, there is a feed from an NREL station in Centennial, Colorado which is used for direct normal solar radiation, global horizontal solar radiation and zenith and azimuth angles of the sun.

**Entity Relationship Diagram**

![Entity Relationship Diagram]

Figure 11: Entity Relation Diagram
Class Schedules

A major challenge for the SGUD team was acquiring building schedules. The information was originally obtained from the Registrar – but this information was slow in coming and was provided in a way that made input difficult. The team needed up to date scheduling information promptly and in a standard, easily interpretable format. Fortunately, the team found a solution in a little known website that the Registrar maintains which contains information on past, present and planned classes for the entire campus. This has been a great help in SGUD’s analysis.

Website - https://myweb.du.edu/mdb/pducrs.p_duSlctCrsOff

Feeds

Feeds are a term to describe data that are taken from various sources either from the University of Denver network or from the internet. Each feed contains the measured value, the time the data were acquired and the name of the incoming feed.

The vast majority of the information stored within the data warehouse is made up of feeds. Feeds are automatically updated to the database and are usually acquired directly from sensors or scraped from web pages. The various types of feeds can be found in the following website http://smartgrid.cs.du.edu/feed/ . Described below are the sources where the original data were obtained for the SGUD feeds.
Iconics

Website - http://iconics/webhmi/ud_campusmap.htm

Iconics is a Graphical User Interface (GUI) and software platform which takes data from the Johnson Controls measurement system and outputs the measured data into a Graphical User Interface. See Figure 12, Figure 13 and Figure 14. This information is sent to a central location in the Iconics system. The SGUD data warehouse queries the Iconics database every day at midnight and updates it with the previous day’s values. These data are then stored in the SGUD data warehouse indefinitely for future use. Iconics is currently archiving thousands of different data points from various buildings and a number of different sensors.

Figure 12: Iconics GUI Campus Map
Figure 13: Iconics GUI Floor 1 Olin Hall

Figure 14: Iconics GUI AHU 1 Olin Hall

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One of the challenges for the SGUD team has been handling the time stamps of the Iconics data. Unfortunately, the Johnson Controls Systems are considerably outdated and cannot store and report large amounts of data at once resulting in data coming into the database at different times. If all measurements are queried at the same time, the system reports them as information becomes available. Depending on the amount of data being requested and the age of the system, time stamps can vary between a few seconds to a few minutes per query. Potential solutions to these challenges are discussed later (see pg. 128).

Many buildings on the University of Denver’s campus are included within the Iconics system as listed below.

**Buildings**

- Boettcher Center
- Cherrington Hall
- Daniels College of Business
- Fisher Early Learning Center
- Margery Reed Building
- Olin Hall
- Physics Building
- Ricks Center for Gifted Children
- Seeley Mudd Science Building
- Shwayder Art Building
- Sturm Hall
• Campus Safety/Paring Services
• Driscoll University Center
• Mary Reed Building
• Ritchie Center Sports/Wellness
• University Hall
• Centennial Towers
• Johnson-McFarlane Hall
• Nelson Hall

Data

Some of the Iconics data that has been used by the SGUD team in Olin Hall is listed below.

• AHU Fan Status (Binary)
• Occupation Status (Binary)
• Chilled Water Supply Temperature (deg F)
• Chilled Water Return Temperature (deg F)
• Interior Zone Temperature (deg F)
• Outside Air Temperature (deg F)
• Return Air Temperature (deg F)
• Mixed Air Temperature (deg F)
• Discharge Air Temperature (deg F)
• Temperature Set point (deg F)
The data available from Iconics are not the same for each building, compressor, AHU, etc. These variations occur for different reasons. First, each building has different components and thus different sensors. Variable frequency drive fans have different sensors than binary fans. In addition, the Iconics system does not measure every data point at every time interval.

A “trend” must be set up by facilities personnel to command Iconics to query the Johnson Controls equipment in order for it to get the data. This can cause some data streams to start and stop unexpectedly and if improperly named, the knowledge of the sensor where the data came from can be lost. This has not been a major challenge up to this point because the SGUD team has only been working in Olin hall and the trends have not been altered.

**NREL Solar Data**

Website - http://www.nrel.gov/midc/srrl_bms/

National Renewable Energy Lab (NREL) maintains the Solar Radiation Research Laboratory which contains measured solar radiation data from different stations. One of these stations is located approximately 20 miles from the University of Denver in Aurora. This site takes real time solar radiation measurements including the azimuth and zenith angles of the sun and the global horizontal solar radiation and direct normal solar radiation. The time intervals on these data are up to the minute or higher, but the data are not made publically available until midnight after all of the data have been gathered for the day.
SGUD currently uses six eMonitors to measure real time electricity data at the circuit level. Each eMonitor is capable of measuring up to 44 circuits. These measurements are scraped from the eMonitor website and stored every 30 seconds. Because of the frequency of measurement, the eMonitor data are currently taking up the largest amount of space in the database. The eMonitor data are currently being used primarily for the calibration process.

**Information Flow during Operation**

Figure 15: Information Flow Diagram
4.6 Building Model Operation

The building model is software written in Java script so that the model can be run from multiple platforms. It is designed to estimate building energy use from a user-specified start date/time to end date/time at a specified time interval and to estimate energy use down to the device level, which is then output into a “detailed table.” Described below are the core calculations used in this model.

Three-Element Method

The three-element method is the core of the SGUD building model. It is, on the surface, a fairly simple approach, but linking the three elements in the correct way is vital to this statistically based method. The key data used for the SGUD approach can be categorized into three elements: devices, loads and activities. Devices are any individual electrical consuming piece of equipment independent of any location. Loads are made up of one or more device which is located in specific rooms. Activities are scheduled events which occur in rooms and likely use the electrical devices, which ultimately consume electricity.

Devices

A comprehensive database is created that contains data on a large number of devices. Devices are nonspecific to the room or building in which they are located and can be added to any building or room (in the model). Devices have 5 main characteristics.

Characteristics

- Name – identifies the device
• Rated Wattage – amount of watts consumed by a device when it is on
• Off Wattage – amount of watts consumed by a device when it is off
• Duty Cycle – percentage that is used for devices like refrigerators which cycle
• Notes/Citation – a place for notes relevant to the device and the citation for the rated wattage, off wattage and duty cycle values

**Example Device Table**

<table>
<thead>
<tr>
<th>Name</th>
<th>Rated Wattage</th>
<th>Off Wattage</th>
<th>Duty Cycle</th>
<th>Notes/Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set Top Box</td>
<td>16.15</td>
<td>15.66</td>
<td>1</td>
<td><a href="http://standby.lbl.gov/summary-table.html">http://standby.lbl.gov/summary-table.html</a></td>
</tr>
<tr>
<td>Clock Radio</td>
<td>2.01</td>
<td>0</td>
<td>1</td>
<td><a href="http://standby.lbl.gov/summary-table.html">http://standby.lbl.gov/summary-table.html</a></td>
</tr>
<tr>
<td>20 Cubic Foot Refrigerator</td>
<td>420</td>
<td>0</td>
<td>0.53</td>
<td><a href="http://www.oksolar.com/technical/consumption.html">http://www.oksolar.com/technical/consumption.html</a></td>
</tr>
</tbody>
</table>

Table 1: Device Table

**Loads**

It is also necessary to gather site specific data from the rooms within the building in order to accurately model the building. This involves performing a SGUD energy audit (see pg. 119) in which every plug-in device along with its location (room) is noted for input into the model. During this process, it is also useful to talk to the facilities personnel to understand if any of the lights are left on at all times; if there is scheduled cleaning of the building; and if there are any abnormalities that may affect the accuracy of the model. It is also necessary to determine the type and number of light fixtures in each room for input into the model. This energy audit is used to form the “loads” element of the model.
Loads can describe a single device or a group of devices that are inherently linked. This could be a television or a group of light fixtures which are on a single switch. Loads have six main characteristics. There is also a flag (multiply by population flag) in each load which describes loads that are not always present within classes, but because people often bring these loads with them. For example, laptops are not typically present during the SGUD energy audit, but are often used in class proportionately to the population of the class.

**Characteristics**

- Name – identifies the load
- Device Name – identifies the device/devices which the load is made up of
- Device Quantity – number of devices that are contained within a load
- Room – room in which the load is located
- Probability in Use (Override) – statistical probability that a device is on during a specific activity type in this room
- Multiply by Population Flag – used for loads which are not always located in the room (laptops, cellphones)

**Example Loads Table**

<table>
<thead>
<tr>
<th>Name</th>
<th>Device Name</th>
<th>Device Quantity</th>
<th>Room</th>
<th>Probability in Use (Override)</th>
<th>Multiply By Population Flag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projector</td>
<td>Projector</td>
<td>1</td>
<td>105</td>
<td>Null</td>
<td>No</td>
</tr>
<tr>
<td>Lighting 1</td>
<td>Light Fixture A1</td>
<td>5</td>
<td>125</td>
<td>Null</td>
<td>No</td>
</tr>
<tr>
<td>Laptops</td>
<td>Laptop (Place Holder)</td>
<td>0</td>
<td>235</td>
<td>Null</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 2: Loads Table
Activities

The third element in the three-element method is the building/occupancy schedule. Each building (often each room) has its own unique schedule that requires individual attention. Activities are how loads interact with the rooms in which they are located. Activity types and Probability in Use (described on pg. 58) are used to determine the statistical probability of loads/devices being used at a specific time.

Activities have 6 main characteristics.

Characteristics

- Name - identifies the load
- Activity Type –identifier which informs the model what sort of activity is occurring in the room, e.g., lab, lecture, work day, cleaning
- Start Date
- End Date
- Start Time
- End Time
- Days of the week
**Example Activity Table**

<table>
<thead>
<tr>
<th>Name</th>
<th>Activity Type</th>
<th>Start Date</th>
<th>End Date</th>
<th>Start Time</th>
<th>End Time</th>
<th>Days of the Week</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Physics I</td>
<td>Lecture</td>
<td>Sept 12, 2012</td>
<td>Nov 18, 2012</td>
<td>12:00:00</td>
<td>12:50:00</td>
<td>M,T,W,F</td>
</tr>
<tr>
<td>Office Work</td>
<td>Work Day</td>
<td>Null</td>
<td>Null</td>
<td>8:30:00</td>
<td>17:00:00</td>
<td>M,T,W,Th,F</td>
</tr>
<tr>
<td>Concepts In Biology</td>
<td>Lab</td>
<td>Mar 21, 2011</td>
<td>May 27, 2011</td>
<td>12:00:00</td>
<td>14:50:00</td>
<td>T</td>
</tr>
</tbody>
</table>

Table 3: Activity Table

These three elements are linked together to form the primary functionality of the SGUD building model. This accounts for the majority of the lighting and plug loads within the building. Certain other loads which do not conform well to this three-element methodology (elevators and HVAC, for example) must be calculated separately in their own custom functions (see pg. 79).
Three-Element Operation Flow Chart

Figure 16: Three Element Method Flowchart
Where

- **Building** = Building Name
- **TNB** = Total Number of Buildings in simulation
- **A** = Activity Name
- **TNA** = Total Number of Activities at time t within the building
- **L** = Load Name
- **TNA** = Total Number of Loads at time t within the building associated with the current activity
- **Multiply Population Flag** is a flag used for identifying which function (custom or standard) to use
- **DC** = Duty Cycle of a particular device
- **%U** = Probability in Use
- **#D** = Number of devices in a load
- **RW** = Rated Watts
- **P** = Population of the activity

**Custom Functions**

For electricity consumption that does not fit the three-element method (such as lights left on, HVAC compressors and elevators) custom functions must be developed to accurately model the system. These functions are not limited by any strict rules and allow considerable flexibility. Three such functions are described below.
**Lights Left On**

In an ideal world, individuals would always remember to turn off lights if they are the last person leaving the room. Unfortunately, people often forget to turn the lights off wasting energy and making estimating building energy use more difficult. Due to the freeform nature of the SGUD custom functions, it is possible to model the electricity consumed by the lights that were left on. This model assumes that there is some probability that lights will be left on after a class ends. If a class is not in session at time $t$, but a class was in session before time $t$, there is an X percent probability that the lights were left on. (Lights are all assumed to be turned off at midnight corresponding with the approximate time that the cleaning staff typically finishes their rounds and shuts off all lights.) The probability that lights are left on is determined during the calibration process which is described in the calibration section (see pg. 125).

**HVAC Functions**

There are many different methods of modeling HVAC systems including expensive (but highly accurate) models which require extensive measurement; or simpler models which use a combination of statistics and measurement; and statistical estimation methods which are cheap and simple. The custom functions accommodate any approach to modeling HVAC because a “one size fits all” would not be consistent with the flexibility required for the SGUD approach. Presented below are a measurement based method that was custom designed for the sensor equipment already in place at the University of Denver and a statistical method which is significantly more flexible,
cheaper and can accommodate a greater variety of systems, but may achieve this at the expense of accuracy.

**Measurement-Based HVAC Method**

The measurement based HVAC method developed by the SGUD team is a custom built function specifically designed to work with measurement systems already in place at the University of Denver. This method was designed around the Iconics data. Put simply, the function calculates the amount of heat energy in the air before and after it passes over the cooling coils for each air handling unit in every building. This value is then added to the energy consumed by the AHU (assuming 100% of this energy is passed directly to the output air). This value is assumed to be the amount of energy that the compressor must remove from the coolant (assuming no losses). Finally, this thermal cooling requirement is passed through the regressed HVAC function (see pg. 126) to determine electrical consumption. This method is very simple to implement assuming the necessary measurements are available, but it can’t consider the cycling of the compressor at low cooling requirements. The specific operation of the function is shown in the flowchart in Figure 17.
Where

- $p =$ Pressure of the air within the AHU
- $ATM =$ Standard Atmosphere $= 101.325$ (kPa)
• Alt = Altitude (m)

• \[ p = \text{ATM} \times 1000 \times (1 - 2.25577 \times 10^{-5} \times \text{Alt})^{5.25588} \]

\[ \rho = \frac{p}{(R_{\text{specificair}} \times \text{IAT(AHU)} + \text{DAT(AHU)})/2} \quad (4.01) \]

Where

• \( \rho \) = Density of the air within the AHU

• \( R_{\text{specificair}} \) = Gas constant for air

• \( \text{IAT(AHU)} \) = Inlet Air Temperature for the given AHU (deg K)

• \( \text{DAT(AHU)} \) = Discharge Air Temperature for the given AHU (deg K)

• \( \theta = \frac{\text{IAT(AHU)} + \text{DAT(AHU)}}{2}/1000 \)

\[ C_{p0} = C_0 + C_1 \theta + C_2 \theta^2 + C_3 \theta^3 \quad (4.02) \]

Where

• \( C_0, C_1, C_2, C_3 \) = Constant pressure specific heats

• \( \theta \) = A constant associated with the specific heat of air

\[ \text{CR(AHU)} = \text{FR(AHU)} \times [\text{IAT(AHU)} - \text{DAT(AHU)}] \times \rho \times C_{p0} + \text{kW} \quad (4.03) \]

Where

• \( \text{CR(AHU)} \) = Cooling Required of a specific AHU

• \( \text{FR(AHU)} \) = Flow Rate of a specific AHU
- kWF = kW Rating of the fan

\[ CR(\text{Building}) = CR(\text{AHU}) + CR(\text{Building}) \quad (4.04) \]

Where

- CR(\text{Building}) = \text{Cooling required by the whole building (Sum of the AHUS cooling required)}

\[ \Delta CWT = CWRT - CWST \quad (4.05) \]

Where

- \Delta CWT = \text{Change in Chilled Water Return vs Supply Temperature across the compressor}
- CWRT = \text{Chilled Water Return Temperature}
- CWST = \text{Chilled Water Supply Temperature}

\[ MC = \beta_{t0} + \beta_{t1} \ast OOT + \beta_{t2} \ast \Delta CWT \quad (4.06) \]

Where

- MC = \text{Max amount of cooling the compressor can provide during current environmental conditions}
- \beta_{t0}, \beta_{t1}, \beta_{t2} = \text{Thermal Regression Coefficients for compressor}
- OOT = \text{Outside Air Temperature}
\[ ME = \beta_{e0} + \beta_{e1} \times OOT + \beta_{e2} \times \Delta CWT \quad (4.07) \]

Where

- **ME** = Electrical consumption that the compressor consumed under max cooling during current environmental conditions
- \( \beta_{e0}, \beta_{e1}, \beta_{e2} \) = Electrical Regression Coefficients for compressor

\[ EC = CR(\text{Building}) / MC \times ME \quad (4.08) \]

Where

- **EC** = Electrical Consumption of the compressor at time \( t \)

**Statistical HVAC Method**

The statistically-based HVAC function uses multiple linear regression (see pg. 89) and a combination of independent and dependent variables in order to determine the electrical consumption of the cooling system. The regressors are:

- North Wall Solar radiation
- South Wall Solar Radiation
- East Wall Solar Radiation
- West Wall Solar Radiation
- North Roof Solar radiation
- South Roof Solar Radiation
• East Roof Solar Radiation
• West Roof Solar Radiation
• Outside Air Temperature

The regressand is the:

\[ \text{total thermal cooling load}[\text{kw}] - \text{lighting and device loads}[\text{kw}] \] \hspace{0.5cm} (4.09)

This statistical regression is superior to the measurement-based method for several reasons. First, it can be used to forecast thermal load assuming solar radiation and outside air temperature can be forecast. Second, there is no need for expensive measurement equipment for the HVAC system or advanced knowledge of the building (e.g., R-value, de-rating, window area, ventilation requirements, etc.) in order to derive accurate values. Such factors are integrated into the regression of the statistically based HVAC function. Third, the statistical regression method can account for the heat and cold held and released by building materials such as brick by adding multiple time steps to the regressors.

While the statistical-method used in the SGUD model is better overall than a measurement-based method, it has some challenges and shortcomings. An inherent challenge in any statistically-based HVAC method is that it can be less accurate initially and may not handle abnormalities (such as maintenance or equipment failures) as well as the measurement based method.

A shortcoming of the SGUD team’s implementation of the statistical HVAC method lies in the measurements of the HVAC system. Ideally, the regressors for the
statistically-based method would be measured using a single electricity meter connected directly to the compressor. Unfortunately, the SGUD team did not have access to one of these meters so measurements based on the measurement based HVAC method’s thermal load were used in its place leading to compounding errors.

Another shortcoming of the current model is that the SGUD Team has not considered the thermal load added to the building by body heat of the population. However, in the future, calculating the thermal load from occupants should be possible because the population data are available in the data warehouse and ASHRAE has data on the average heat output of a person performing different activities.

**Other Calculations**

There are some other calculations that are not linked directly to electricity consumption but are necessary for the HVAC, billing, financial and statistical portions of the SGUD approach. The incident solar radiation at time t is a calculation that is required for the statistical HVAC method. The multiple linear regression function is used extensively in the calibration process and is the main statistical function used in the SGUD approach. The billing algorithm is used to represent the local utility company’s electricity bill as accurately as possible; provide useful summary and analysis of the bill; and provide pollution information. The financial calculator is an embedded algorithm used to quantify the savings of specific EMM’s implemented within SGUD’s building model.
**Incident Solar Radiation**

The incident solar radiation calculation is used to determine how much radiation is incident upon different surfaces facing different directions. This is accomplished using National Renewable Energy Lab (NREL) solar data and the formulas described in equations 4.10 – 4.12 [50].

Direct Solar Radiation on Flat Surface

\[ I_{Dir} = I_{D} \cos(\beta) \cos(\phi_s) \sin(\Sigma) + \sin(\beta) \cos(\Sigma) \quad (4.10) \]

Diffuse Solar Radiation on Flat Surface

\[ I_{Diff} = I_{D} \frac{(1 + \cos(\Sigma))}{2} \quad (4.11) \]

Total Solar Radiation

\[ I_T = I_{Dir} + I_{Diff} \quad (4.12) \]

Where

\[ \beta = \text{Zenith} \]

\[ \phi_s = \text{Azimuth} \]

\[ \Sigma = \text{Angle that the surface is tilted in the z direction from the y axis} \]

\[ I_{Di} = \text{Direct solar radiation incident on a surface normal to the sun on the earth as given by NREL’s data} \]
\[ I_{DH} \] Diffuse Solar radiation incident on a surface parallel to the earth surface and given by NREL’s Data.

**Multiple Linear Regression**

Both the testing of the model and many of the model functions require statistical methods to “fill in the gaps” of knowledge. As a result, a statistical toolbox has been developed for the model. This is currently being used to validate the model by comparing measured energy consumption on a circuit to predicted consumption on that circuit in order to find their standard deviations, \( R^2 \), correlation coefficients, etc. It has also proved helpful in translating some of the data for the compressor from tables into linearized functions for use within the model. The multiple linear regression is also being used as the primary tool for calibrating the model. A list of the outputs that the multiple linear regression can calculate is shown below.

- Mean (of inputs)
- Standard deviation (of inputs)
- Regression Coefficients (Multiple regression)
- Correlation Coefficients
- Explained sum of the Squares
- Residual Sum of the Squares
- Total Sum of the Squares
- Mean Square Regression
- Mean Square Residual
- F Value
• R
• R^2
• Adjusted R^2
• Standard error of the estimate

Calculations

\[ \hat{\beta} = (X'X)^{-1}X'y \quad (4.13) \]

Where

• \( X = \text{Regressor Matrix} \)
• \( y = \text{Regressand Matrix} \)

\[ \sigma = \sqrt{E[(X - \mu)^2]} \quad (4.14) \]

Where

• \( \mu = \text{mean value} \)
• \( E[z] = \text{Expected Value of } z \)

\[ \text{Corr}(X, Y) = \frac{E[(X - \mu_X)(Y - \mu_Y)]}{\sigma_X \sigma_Y} \quad (4.15) \]

Where

• \( N = \text{Number of Cases} \)

\[ \text{RSS} = \sum_{i=1}^{N} (y_i - f(x_i))^2 \quad (4.16) \]
Where

- $y_i = \text{Regressand}$
- $f(x_i) = \text{Predicted Value of } y_i$

$$ESS = \sum_{i=1}^{N} (\hat{y}_i - \bar{y})^2 \quad (4.17)$$

Where

- $\hat{y}_i = \text{Predicted Value of } y_i$
- $\bar{y} = \text{mean value of } y$

$$R^2 = \frac{ESS}{TSS} \quad (4.18)$$

$$TSS = RSS + ESS \quad (4.19)$$

$$AdjustedR^2 = 1 - \frac{(1-R^2)(N-1)}{(N-(p-1)-1)} \quad (4.20)$$

Where

- $p = \text{number of independent variables}$

$$\text{Mean Square Regression} = \frac{ESS}{p} \quad (4.21)$$

$$\text{Mean Square Residual} = \frac{RSS}{(N-p-1)} \quad (4.22)$$

$$F_{value} = \frac{\text{Mean Square Regression}}{\text{Mean Square Residual}} \quad (4.23)$$

Using the multiple regression functions, the compressor’s cooling load and electrical consumption are calculated. The two regressors are the temperature of the air
entering the compressor and the temperature difference between the supply and return chilled water. Using the spec sheet for the compressor along with eq 4.13 – 4.23, these data were formulated into equations 4.24 and 4.25.

\[
kW_{\text{Cooling}} = 50.5875 + 2.11733 \times OOT + 1.8375 \times \Delta CWT \quad (4.24)
\]

\[
kW\text{Elec} = 512.7104 \pm 4.8813 \times OOT + 11.9937 \times \Delta CWT \quad (4.25)
\]

Where

- \( \Delta CWT \) = Chilled water Return Temperature – Chilled Water Supply Temperature
- \( OOT \) = Outside Air Temperature

The \( R^2 \) for equations 4.24 and 4.25 are 0.9973 and 0.9986 respectively.

**Billing Algorithm**

The billing algorithm is used to determine financial costs/savings accurately. Many previous models use a *blended* electricity cost to determine the benefits of EMMs. Unfortunately, those methods are often inadequate because they do not individually consider *billed demand* and *billed consumption* which are the primary drivers of large customers electricity bills. As a result, the best method for quantifying energy savings is to calculate energy bills in the same way that the local utility would calculate them. This is challenging because utility bills are exceedingly complex and certain aspects change monthly, annually, biannually and some others change constantly. Described below is the complex methodology for calculating an Xcel Energy utility bill and a description of associated charges.
**Inputs**

There are two primary inputs into the billing algorithm which are *billed demand* and *billed consumption*.

**Billed Demand**

Billed Demand is equal to the maximum of the average power consumption in a 15-minute period during a billing period. (See Demand section on pg. 12 for an expanded explanation).

\[ Billed \ Demand = X \ kW \]

**Billed Consumption**

Billed consumption is equal to the amount of energy consumed within the billing period.

\[ Billed \ Consumption = X \ kWh \]

**Multipliers**

Multipliers are factors that billed demand and billed consumption are multiplied by in order to determine the cost of an electricity bill. In order to forecast costs accurately, each of these multipliers can be escalated at an electricity escalation rate to accurately approximate costs into the future using the following equation.

\[ New \ Rate = Old \ Rate \times (1 + \text{Electricity Escalation Rate})^{\text{Year}} \quad (4.26) \]

Where the old rate is the rate currently being charged. If no escalation rate is desired, the year is set to zero and the new rate is equal to the old rate.
$GTD\ Multiplier = 8\ (Winter),\ 10.96\ (Summer)$

$DD\ Multiplier = 4.48$

$PCCMultiplier = 4.1000$

$DSMultiplier = .31$

$ElecComAdj\ Multiplier = .02851$

$TransCostAdj\ Multiplier = .07$

$SecondaryGeneral\ Multiplier = .004730$

$Franchise\ Fee\ Multiplier = .03$

$Sales\ Tax\ Multiplier = 0$

$Electricity\ Escalation\ Rate = .0055$

**Demand Charges**

Demand charges are listed on an electricity bill and are a function of the billed demand within the current billing period [51].

**Generation & Transmission Charge**

This charge represents the cost to the utility to maintain and build new generation and transmission infrastructure required to meet the consumer’s billed demand.

$Generation\ &\ Transmission\ Demand\ Charge = Billed\ Demand \ast GTD\ Multiplier (4.27)$
**Distribution Demand Charge**

This charge represents the cost to the utility to maintain and build new distribution infrastructure required to meet the consumer’s billed demand.

\[ \text{Distribution Demand Charge} = \text{Billed Demand} \times DD \text{ Multiplier} \quad (4.28) \]

**Purchase Cap Cost Adjustment**

This charge represents the costs to purchase electricity from other utility companies.

\[ \text{Purchase Cap Cost Adjustment} = \text{Billed Demand} \times PCC \text{ Multiplier} \quad (4.29) \]

**Demand Side Management Cost**

This charge represents a charge which is used by the utility to try to reduce electrical demand.

\[ \text{Demand Side Management Cost} = \text{Billed Demand} \times DS \text{ Multiplier} \quad (4.30) \]

**Transmission Cost Adjustment**

This charge is used to recoup the costs of using other transmission provider’s assets [52].

\[ \text{Transmission Cost Adjustment} = \text{Billed Demand} \times TransCostAdj \text{ Multiplier} \quad (4.31) \]
Consumption Charges

The consumption charges are the costs that are associated with providing a customer with the required amount of energy for the billing period.

Electricity Commodity Adjustment

This charge represents the amount of fuel and electricity that the utility must purchase from other generators/fuel providers.

\[ \text{Electricity Cost Adjustment} = \text{Billed Consumption} \times \text{ElecComAdj Multiplier} \quad (4.32) \]

Secondary General

This charge represents the electric utility’s costs to provide the consumer with their required quantity of energy.

\[ \text{Secondary General Charge} = \text{Billed Consumption} \times \text{Secondary General Multiplier} \quad (4.33) \]

Other Charges

Other charges include items which are not functions (at least not directly) of billed demand or billed consumption.

Service and Facility

This charge represents the cost of meters and meter reading for utility companies.

\[ \text{Service & Facility} = \$40 \]
Renewable Energy Standard Adjustment

This charge represents the costs for utilities to meet their renewable energy targets (usually required by law).

\[ \text{Renewable Energy Std Adj} = \$X \]

Franchise Fee

This charge represents the cost that the utility must pay the city/town for the right to use streets and alleys.

\[ \text{Subtotal1} = \]

\[ (\text{Generation & Transmission Demand Charge} + \text{Distribution Demand Charge} + \]

\[ \text{Purchase Cap Cost Adjustment} + \text{Demand Side Management Cost} + \]

\[ \text{Transmission Cost Adjustment} + \text{Electricity Cost Adjustment} + \]

\[ \text{Secondary General Charge} + \text{Service & Facility} + \text{Renewable Energy Std Adj} ) \] \hspace{1cm} (4.34)

\[ \text{Franchise Fee} = \text{Subtotal1} \times \text{Franchise Fee Multiplier} \] \hspace{1cm} (4.35)

Sales Tax

This charge represents the amount that a local jurisdiction taxes for electricity (Universities pay no sales tax so this is not considered in the current billing algorithm)

\[ \text{Subtotal2} = \text{Franchise Fee} + \text{Subtotal1} \] \hspace{1cm} (4.36)

\[ \text{SalesTax} = \text{Subtotal2} \times \text{Sales Tax Multiplier} \] \hspace{1cm} (4.37)
Total Amount

This is what all charges add up to and what the customer must pay for electricity for the billing period.

\[
\text{Total Amount} = \text{SalesTax} + \text{subtotal}^2 \quad (4.38)
\]

Billing Algorithm Results

An estimated electrical bill is shown in Figure 18 and an actual bill is shown in Figure 19.
Figure 18: Billing Algorithm Results

**Actual Bill**

<table>
<thead>
<tr>
<th>Account Activity</th>
<th>Date of Bill</th>
<th>Previous Balance</th>
<th>Amount Due</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Apr 14, 2011</td>
<td>$4,016.46</td>
<td>$3790.02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electric Service - Account Summary</th>
<th>Invoice Number</th>
<th>Secondary General</th>
<th>44860 kWh x 0.00473</th>
<th>$210.39</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meter No</td>
<td>000000000070</td>
<td>Trans Cost Adj</td>
<td>136 kWh x 0.070000</td>
<td>$9.82</td>
</tr>
<tr>
<td>Rate</td>
<td>5G</td>
<td>Elec Commodity Adj</td>
<td>40800.0 kWh x 0.02851</td>
<td>$1563.21</td>
</tr>
<tr>
<td>Days In Bill Period</td>
<td>31</td>
<td>Demand Side Mgmt Cost</td>
<td>106.0 kW x 0.31</td>
<td>$32.86</td>
</tr>
<tr>
<td>Current Reading</td>
<td>29040</td>
<td>Punch Cap Cost Adj</td>
<td>106.0 kW x 4.1</td>
<td>$434.6</td>
</tr>
<tr>
<td>Previous Reading</td>
<td>29025</td>
<td>Distribution Demand</td>
<td>120.8 kWh x 4.84</td>
<td>$580.8</td>
</tr>
<tr>
<td>Multiplier</td>
<td>160.0</td>
<td>Gen &amp; Transm Demand</td>
<td>186.0 kW x 10.96</td>
<td>$1161.76</td>
</tr>
<tr>
<td>Measured Usage</td>
<td>255.0</td>
<td>Service &amp; Facility</td>
<td></td>
<td>40.0</td>
</tr>
<tr>
<td>Kilowatt-Hours Used</td>
<td>40800.0</td>
<td>Renew. Energy Std Adj</td>
<td></td>
<td>66.0</td>
</tr>
<tr>
<td>Measured Demand</td>
<td>0.663</td>
<td></td>
<td></td>
<td>3679.63</td>
</tr>
<tr>
<td>Billed Demand</td>
<td>120.0</td>
<td>Franchise Fee</td>
<td>3.0%</td>
<td>$110.38</td>
</tr>
<tr>
<td>Sales Tax</td>
<td></td>
<td></td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Total Amount</td>
<td></td>
<td></td>
<td></td>
<td>$3790.02</td>
</tr>
</tbody>
</table>

Figure 19: University Of Denver Electrical Bill Olin Hall
SGUD’s Utility Bill Analysis and Summary

Given the almost absurd complexities of the utility bill provided by utility companies, the SGUD team decided that consumers need the billing information provided in a different format to better understand their electricity usage and identify opportunities for savings. The SGUD’s version of the electricity bill provides useful information which generally cannot be found on a utility bill including the percentage of the total cost incurred by billed demand (\% of bill from demand) and energy use (\% of bill from consumption); and the blended cost per kWh. It also lists the amounts saved by reducing billed demand by 1 kW ($ per kW reduction); by reducing the consumption by 1 kWh ($ per kWh reduction); by reducing the billed consumption by 1 kWh times the number of hours in the billing period ($ per kWh x billed hours); and by reducing the baseline energy consumption by 1 kW ($ per baseline kW reduced). This information is a good first start for those unfamiliar with their energy consumption to understand how much different aspects of the bill are costing them and their potential for savings. An example summary is shown in Figure 20.

![DU Smart Grid Summary](image)

Figure 20: Utility Summary and Analysis
Pollution

Financial metrics are important but they are not the only reason for individuals to implement EMMs. Pollution is also an important factor that consumers may use to make an informed decision on their energy use. To help consumers, the SGUD team also provides a summary and analysis of certain pollution values quantified by using the EPA’s eGRID regions [53] shown below. (Emission rates are in units of lbs./kWh for the state of RMPA Region). An example of a SGUD emission report is shown in Figure 21.

- CO2EmRate = 0.191088;
- SO2EmRate = 0.0025346;
- NOxEmRate = 0.0029224;
- HGEmRate = 0.0000000164;
- CH4EmRate = 0.00002348;
- N2OEmRate = 0.00002926;

![Emissions Report](image)

Figure 21: Emissions Report

Financial Calculator

An embedded financial calculator is essential to achieve the SGUD goal of an informed consumer. This calculator quickly and simply quantifies the payback period.
and return on investment of different EMM’s based on the SGUD building model. This calculator considers inflation, electrical escalation rates, product life and initial cost. Other metrics like annual operations and maintenance and even depreciation can easily be added.

**User Inputs**

*Life of Product = X Years*

*Initial Cost = $X*

**Net Present Value Calculation**

\[
NPV = -Initial\ Cost + \sum_{Year=0}^{Life\ of\ Product} (1 + IRR)^{Year} \quad (4.39)
\]

**Internal Rate of Return Calculation**

Internal Rate of Return (IRR) of return is effectively an “interest rate” that a project will produce (ignoring inflation). IRR is a useful measure to compare EMM projects to determine which project has better returns on initial investment. The flowchart for the NPV calculation is shown in Figure 22.
Simple Payback Period Calculation

The simple payback period is a calculation which indicates how long an investment would take to fully pay back assuming there is no inflation or escalation. This calculation method is similar to the investment calculations shown in the Internal Rate of Return Calculator section. The payback period flowchart is shown in Figure 23.
Figure 23: Payback Period Calculation
Post Processing Tabs

After the core calculations are complete, there is additional post-processing the results of which are displayed in tabs in the building model adding to the functionality of SGUD’s building model. These are primarily used to display data, perform calculations, plot data and calculate investments.

**Detailed Table Tab**

The main output for the model is a detailed table. This table includes most of the useful information from the model and is the central storage location after the building model is run. The sheer amount of information makes this database useful for viewing specific loads, devices, etc. but difficult to interpret as a whole. As a result, much of the data are further broken down into more useful forms in other tables. The detailed table can be seen in Figure 24.

![Figure 24: Detailed Table Tab](image-url)
**Model Log Tab**

The model log tab is used primarily for benchmarking model performance and diagnosing issues. It is useful to the SGUD development team, but does not provide much useful information for general users.

**Electric Bill Tab**

The electric bill tab shows the results from the billing algorithm, the SGUD summary and analysis and the SGUD emission report calculations. This tab is very useful for visualizing electricity bills before and after EMMs are implemented. The bill is designed to resemble electricity bills provided by the local Utility, Xcel Energy. A resulting electric bill can be seen in Figure 25.

![Figure 25: Electrical Bill Tab](image)
**Investment Calculations Tab**

The investment calculations section is used in conjunction with the financial calculator algorithm to calculate the payback and return on investment of new technologies. The investment calculations provide accurate and fast return on investment, payback period and return on investment calculations. This tab is shown in Figure 26.

![Figure 26: Investment Calculations Tab](image)

**kW at Time Tab**

The $kW$ at time tab is a refinement of the detailed table tab which organizes the power usage into specific rooms at specific times. This tab has proved to be one of the most useful for the SGUD team as well as general users because of the ability to quickly and easily compare different rooms’ electricity consumption. See Figure 27 for an example of the $kW$ at Time Tab.
The plot tab is used to display the $kW$ at time function and is the primary display portion of the building model. This plot function is built on a free plot software called Jfreechart. This graphing software apparently has a few issues which causes the colors in the figure not to match the correct the colors in the legend. This issue is currently being resolved by replacing Jfreechart with another graphing program. For graphs that are not being used internally, Excel charts are currently being used to graph these data. Figure 28 shows the plot that results from running the model for one day. Figure 29 shows the previous plot with the actual measured power use overlaid in the form of a red line. Figure 30 shows the Excel chart with the correct colors in both the legend and the plot.
Figure 28: Plot Tab without Meter Data

Figure 29: Plot Tab Overlaid with Meter Data
**Power by Activity Tab**

The *power by activity* tab is a refinement to the detailed table tab. This tab links the amount of power being consumed at any given time to the activity associated with the energy use. This tab is currently being used to separate indoor and outdoor electricity consumption so that the heat load of a building can be calculated. This is illustrated in Figure 31.
Power by Category Tab

The power by category tab separates electricity use into three main categories: lighting, plug loads and HVAC systems. Each category is then further broken down by the activity that is causing the consumption. This allows for useful graphing to understand why electricity is being consumed in different sectors (baseline, from activities, HVAC from outside air temperature, HVAC from Solar Radiation). See Figure 32 and Figure 33.
Figure 32: Power by Category Tab

Figure 33: Power by Category Graph
**Power by Zone**

The *power by zone* table is useful for determining which zone is responsible for what power use. This is particularly useful for calibrating the model because it breaks the estimated electricity use down by the circuit and then compares this to the measured electricity consumption on that circuit using the eMonitor devices.

**Report a Bug**

Reporting a bug has been a very important aspect of the development of SGUD’s building model. The model has a feature which allows users to easily report a bug by linking them to a webpage and allowing them to report the problem along with useful data needed to diagnose the bug. The interface in SGUD’s building model is shown below in Figure 34 while the website is shown in Figure 35.

![Figure 34: Report a Bug Tab](image-url)
4.7 How to Input a Building into SGUD’s building model

SGUD’s Building Model requires the user to input some data themselves, while other data are pulled in automatically (like class schedules) or already available in a pre-existing database (the device database).

New Building

The first step to implementing a new building in SGUD’s building model is to create a new building name. This is done in the GUI show in Figure 36.
New Room

For each room in a new building, one must create a new room in the model with a name/number for each building. This is performed in the GUI shown in Figure 37.

Figure 37: New Room GUI

New Activity

For each activity that is occurring within a building, a new activity must be created in SGUD’s building model. For the University of Denver, these data are automatically uploaded into the system usually rendering this step unnecessary. For
many offices which use Outlook or some similar calendar program, it should be a simple matter to import these data automating the process. The GUI shown in Figure 38 can be used to enter activities into the model manually.

![New Activity GUI](image)

Figure 38: New Activity GUI

**New Standard Device**

Each new device that is implemented in SGUD’s building model requires that the watts consumed while on, the watts consumed while off and the duty cycle be input into a device GUI shown in Figure 39.
New Device Made Of Multiple Devices

Certain devices do not follow the format shown in the New Standard Device section above. The bulk of these devices are light fixtures made up of multiple light bulbs, which can be implemented using the same GUI as shown above, but instead of using a watts (on) it multiplies the watts of the light bulb (the New Standard Device) by the number of bulbs in the fixture. This can be seen in Figure 40.
**New Load**

Loads are the linkages between activities and devices. The user must enter the device type, number of devices, room number and a population flag in the GUI shown in Figure 41.
4.8 Gathering Data (SGUD Energy Audit)

Traditional energy audits are used to assess the amount of energy and money that can be saved by ECMs. The SGUD approach requires an energy audit, but one that is significantly simpler and cheaper to perform than traditional methods which are used to provide similar levels of details.

**SGUD Walk-through**

The SGUD walk-through gives the auditor the ability to enter each room in the building, take note of devices (refrigerators, lab equipment, computers, projectors, etc.) in each room and record this information. In addition, it provides the opportunity to speak with facilities personnel and discover the kind of information not commonly available from other sources (e.g., hallway lights are always left on for safety, number of
employees working 9 to 5 in the building, two of the five air handling units must run at all times for lab ventilation, etc.) and HVAC specifications (compressor and air handling unit power characteristics). As an example, some results from Olin Hall are shown in Table 4.
<table>
<thead>
<tr>
<th>Building</th>
<th>Room</th>
<th>Device Name</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olin Hall</td>
<td>175</td>
<td>Smart Equipment</td>
<td>Needs to be measured</td>
</tr>
<tr>
<td>Olin Hall</td>
<td>175</td>
<td>Pump 1</td>
<td>1+2 only 1 runs at a time</td>
</tr>
<tr>
<td>Olin Hall</td>
<td>175</td>
<td>Pump 2</td>
<td>1+2 only 1 runs at a time</td>
</tr>
<tr>
<td>Olin Hall</td>
<td>175</td>
<td>Pump 3</td>
<td>Boiler</td>
</tr>
<tr>
<td>Olin Hall</td>
<td>175</td>
<td>Pump 4</td>
<td>Boiler</td>
</tr>
<tr>
<td>Olin Hall</td>
<td>175</td>
<td>Pump 5</td>
<td>Boiler</td>
</tr>
<tr>
<td>Olin Hall</td>
<td>175</td>
<td>Pump 6</td>
<td>Chiller</td>
</tr>
<tr>
<td>Olin Hall</td>
<td>170</td>
<td>Lab Compressor</td>
<td>2 motors 1 at a time</td>
</tr>
<tr>
<td>Olin Hall</td>
<td>170</td>
<td>Room Cooling</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>170</td>
<td>Lab Dehumidifier</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>160</td>
<td>Hood 1</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>160</td>
<td>Computer 1</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>160</td>
<td>Monitor 1</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>160</td>
<td>Microwave 1</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>160</td>
<td>Microwave 2</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>160</td>
<td>Coffee Maker 1</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>160 A</td>
<td>Hood 1</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>160 A</td>
<td>Hood 2</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>Unknown</td>
<td>Hood 1</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>Unknown</td>
<td>Television 1</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>Unknown</td>
<td>Computer 1</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>Unknown</td>
<td>Computer 2</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>Unknown</td>
<td>Monitor 1</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>Unknown</td>
<td>Monitor 2</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>Unknown</td>
<td>Fridge 1</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>Unknown</td>
<td>Fridge 2</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>Unknown</td>
<td>Exhaust Fan 1</td>
<td>In utility room</td>
</tr>
<tr>
<td>Olin Hall</td>
<td>Unknown</td>
<td>Incubator 1</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>Unknown</td>
<td>Incubator 2</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>142</td>
<td>Computer 1</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>142</td>
<td>Projector 1</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>142</td>
<td>1 DVD player</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>132</td>
<td>Fridge 1</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>132</td>
<td>Fridge 2</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>132</td>
<td>Fridge 3</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>132</td>
<td>Hood 1</td>
<td></td>
</tr>
<tr>
<td>Olin Hall</td>
<td>132</td>
<td>Incubator 1</td>
<td>DKN600</td>
</tr>
</tbody>
</table>

**Table 4: SGUD Walk-through Table**
**Lighting Diagrams**

The lighting is sometimes difficult to evaluate during walk-through because many of the lighting devices are located out of reach in the ceilings. Counting the number of lighting fixtures would be simple, but determining the power consumed by each light is substantially more difficult. Luckily, lighting diagrams showing which lights are installed in what locations are available for most of the larger buildings (the size of buildings the SGUD approach works best). These diagrams provide important lighting specifications such as bulb types, number of bulbs per fixture, number and type of fixtures in each room, etc. The lighting specifications for Olin Hall are shown in Figure 42.

![Figure 42: Olin Hall Lighting Floor plan](image)

The location of the lights is not enough to determine the power draw of each individual light. On the lighting diagram, the only information is a light fixture identifier (A, A1, B, B1, etc.). Another electrical print provides a table of lighting information that
informs the user how much electricity is consumed, the number and type of bulbs, the voltage and other important information. See an example in Table 5.

<table>
<thead>
<tr>
<th>KEY</th>
<th>DESCRIPTION</th>
<th>LAMP</th>
<th>MOUNTING</th>
<th>MFR. &amp; CAT. NO.</th>
<th>VOLTS</th>
<th>NOTE</th>
<th>MAX WATT</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2 X 4, 3 LAMP, RECESSED TROFFER WITH PARABOLIC LÖYER</td>
<td>3-F03210</td>
<td>RECESSED</td>
<td>LITHONIA #68405-G-332-18-3-277-1/3-GB</td>
<td>277</td>
<td></td>
<td>96</td>
</tr>
<tr>
<td>AI</td>
<td>SAME LUMINAIRE AS TYPE 'A' WITH FLANGED TRIM FOR GYP. BOARD CEILING</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1 X 4, 2 LAMP, RECESSED TROFFER WITH PARABOLIC LÖYER</td>
<td>2-F03210</td>
<td>RECESSED</td>
<td>LITHONIA #68405-G-332-3-277-GB</td>
<td>277</td>
<td></td>
<td>63</td>
</tr>
<tr>
<td>BI</td>
<td>SAME LUMINAIRE AS TYPE 'B' WITH FLANGED TRIM FOR GYP. BOARD CEILING</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>2 X 4, 3 LAMP, RECESSED TROFFER WITH ACRYLIC LENS</td>
<td>3-F03210</td>
<td>RECESSED</td>
<td>LITHONIA #68405-G-332-125-1/3-GB</td>
<td>277</td>
<td></td>
<td>96</td>
</tr>
<tr>
<td>D</td>
<td>RECESSED FLUORESCENT DOWNLIGHT</td>
<td>2-F13010</td>
<td>RECESSED</td>
<td>LITHONIA #4F-2/F13010-64R-277</td>
<td>277</td>
<td></td>
<td>35</td>
</tr>
<tr>
<td>E</td>
<td>2 X 2, 3 LAMP RECESSED TROFFER WITH PARABOLIC LÖYER</td>
<td>3-F03210</td>
<td>RECESSED</td>
<td>LITHONIA #68405-G-332-18-3-277-1/3-GB</td>
<td>277</td>
<td></td>
<td>96</td>
</tr>
<tr>
<td>EI</td>
<td>SAME LUMINAIRE AS TYPE 'E' WITH FLANGED TRIM FOR GYP. BOARD CEILING</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>RECESSED FLUORESCENT WALL WASHER</td>
<td>2-F13010</td>
<td>RECESSED</td>
<td>LITHONIA #4F-2/F13010-64R-277</td>
<td>277</td>
<td></td>
<td>35</td>
</tr>
<tr>
<td>G</td>
<td>NOT USED</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>ONE LAMP FLUORESCENT STRIP</td>
<td>1-F03210</td>
<td>SURFACE (ARCHITECTURAL CONE)</td>
<td>LITHONIA #5-3-32-277-GB</td>
<td>277</td>
<td></td>
<td>32</td>
</tr>
<tr>
<td>I</td>
<td>ONE LAMP FLUORESCENT STRIP</td>
<td>1-F03210</td>
<td>SURFACE (ARCHITECTURAL CONE)</td>
<td>LITHONIA #5-3-32-277-GB</td>
<td>277</td>
<td></td>
<td>32</td>
</tr>
</tbody>
</table>

Table 5: Lighting Diagram Table

**HVAC information**

The relevant HVAC information is determined using mechanical prints which provide information regarding the horsepower of the air handling units (which is then converted to watts for input into the device database) and information on the chiller that is useful to determine the amount of watts it will consume when in use. See mechanical print in Figure 43.
Running the Model

After collecting and inputting all required data and functions, running the model is actually quite simple. Once a user is on the University of Denver network (either by logging onto a computer on the local University of Denver network or connecting to the VPN) one needs to go to the smart grid website and click the link for the web version of SGUD’s building model, which will open it within the browser. The user must then select a start date/time, end date/time, building and time increment (in seconds) and click “Generate.” The model then automatically performs all calculations.

Figure 44: Running the Model GUI
4.10 Calibrating the Model

“Calibrating” is the term used for getting the model’s estimated results to match closely with the measured results. After the SGUD energy audit is performed, the placeholder variables should be replaced with more appropriate values that are specific to the circuit/room/load to ensure that the SGUD’s building model is accurate. In addition, the HVAC function needs to be calibrated because they can operate very differently under various conditions in different buildings. At the time this paper is being written, the SGUD team is currently in this phase of deployment.

HVAC Calibration

The HVAC calibration process is fairly time consuming because HVAC systems are complicated mechanical devices which de-rate over time; their efficiency can vary based on maintenance schedules; and they have many components that can interact in ways that make it very difficult to model accurately.

As a result, the only practical way (at this time) that the SGUD team has to determine the electricity consumption of the compressor is using a three-phase electrical meter which obtains data over a period of time (ideally a month or more). The thermal load of the building is then determined using the multiple regression formulas (see HVAC section). Finally, this thermal load is used as the regressand in the multiple regression formula and the regressors can be seen below in the Regressed HVAC Values section below. These regressors can be determined using measured data from a Wi-Fi thermometer and pyromonmeter (for real time estimates) or online weather data (providing the ability to forecast HVAC loads).
The compressor’s electrical usage also varies based on the exterior temperature and to a lesser extent, the difference between the supply and return coolant temperature. In order to accommodate these variations accurately a multiple regression analysis was performed using the compressor data from the table provided by the manufacturer (shown in Table 6) in order to create a linear function.

**Regressed HVAC Values**

<table>
<thead>
<tr>
<th>Evaporator Leaving Water Temperature</th>
<th>Condenser Entering Air Temperature</th>
<th>Kw Cooling</th>
<th>kW Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>30</td>
<td>424</td>
<td>123.9</td>
</tr>
<tr>
<td>5</td>
<td>35</td>
<td>401.9</td>
<td>133.3</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>378.7</td>
<td>143.9</td>
</tr>
<tr>
<td>5</td>
<td>45</td>
<td>345.4</td>
<td>155.7</td>
</tr>
<tr>
<td>7</td>
<td>30</td>
<td>449.3</td>
<td>127.6</td>
</tr>
<tr>
<td>7</td>
<td>35</td>
<td>426.1</td>
<td>136.9</td>
</tr>
<tr>
<td>7</td>
<td>40</td>
<td>401.9</td>
<td>147.4</td>
</tr>
<tr>
<td>7</td>
<td>45</td>
<td>376.2</td>
<td>159.3</td>
</tr>
<tr>
<td>9</td>
<td>30</td>
<td>475.7</td>
<td>131.3</td>
</tr>
<tr>
<td>9</td>
<td>35</td>
<td>451.1</td>
<td>140.6</td>
</tr>
<tr>
<td>9</td>
<td>40</td>
<td>425.4</td>
<td>151.2</td>
</tr>
<tr>
<td>9</td>
<td>45</td>
<td>398.7</td>
<td>163.1</td>
</tr>
</tbody>
</table>

Table 6: HVAC Regression Data [54]

Full_Load_Electrical = 50.5875 + 2.1173 * OOT + 1.8375 * ΔCWT \ (4.40) 

MaxLoad_Cooling = 512.7104 + -4.8813 * OOT + 11.9937 * ΔCWT \ (4.41)
**Device/Load Calibrating**

Calibrating the device loads in the model involves replacing placeholder *Probability in Use* values with values that are statistically determined using measured circuit level data. This is a currently a cumbersome process done by querying data from the SGUD database and aligning it with measured data. It involves running the model and moving the information from the detailed table into Matlab. Then the information from the circuit level meters is queried using a custom designed Matlab query function and these data are then aligned with the data in the detailed table. A separate function then searches for times when specific activities take place (labs for example) and isolates the total device wattages on each circuit and the measured device wattages on that circuit. Finally, these data are put through the multiple regression algorithm to determine the correlation (PIU) of the lab activity with the load. This is currently a very laborious task, but all of this can (and should) be incorporated into SGUD eventually giving SGUD the ability to “learn” and make the process of calibration much easier.

### 4.11 Challenges for the SGUD Approach

Over the course of designing and implementing the SGUD approach, the SGUD team has discovered various challenges for smart buildings/smart grids and found some resolutions to these challenges. All of these challenges listed below many have been known in the industry previously but have not yet had a definitive solution, while other shortcomings (and potential solutions) that the SGUD team has discovered are described in the future work section of this paper.
**Different Time Stamps**

Data often comes into the database from different sources, in different forms, using different time stamps. This presents a problem because some data (e.g., e-monitor data) are being stored at 30-second intervals while other data (e.g., fan status) are being returned in hour intervals. This can make calculations difficult because the model has to “know” which data should be pulled. The two main methods of pulling data at each time and a hybrid of the two methods, are described below.

**Closest Time**

The closest time method of pulling data was the first attempt by the SGUD team to acquire data. This method would simply search the database for the time which is closest to time requested. The major advantage of this method is that it was fast, but it has two main disadvantages. First, this method was not suitable if running a simulation at a 15-minute interval when the data were stored every 30 seconds because one single value may not be representative of the entire 15-minute period. Second, if data are unavailable for a long period of time the model will still pull the closest point (which could be days before or after the desired time) resulting in inaccurate simulations.

**Averaged Time**

The averaged data method was the second method attempted by the SGUD team. This involves averaging all of the points within the requested dataset between the time interval requested and the next time interval. This method worked well for data measured often but is challenging because if the time interval is lower than the measurement period, there will be no data to be averaged resulting in a zero value. In
addition, this method was significantly slower on the server than the closest time method, which made it impractical.

**Hybrid time**

The third method that has been attempted by the SGUD team was a hybrid of the average time and closest time methods. This method first attempts to average the data points in the time interval and if it discovers that there are no points within that time period, it will then use the closest time method. This model has the best of both worlds with respect to gathering data but there are still two important challenges. First, this method is still slow and the speed on the server must be increased if this method is to be implemented. Second, the closest time method still must have a cutoff to avoid pulling times where data are not available. This time cutoff must be carefully considered to avoid cutting off relevant data that may be stored rarely (like fan status once per hour), but also to throw flags when data are unavailable.

**Chosen Method**

The hybrid approach to pulling data is the most practical way of dealing with stored data that has different time stamps with respect to accuracy. Unfortunately, it is also the slowest. Because the model and the server are still having speed issues (which can often cause SGUD’s building model to crash) this currently makes implementing this approach impractical. The SGUD team is currently using the closest time approach with a limit of three hours to pull data, trading accuracy for speed. One unintended consequence of this is when solar radiation data are missing in the early morning, the
model will sometimes attribute HVAC compressor electrical energy to solar radiation even when there is no solar radiation.

**Missing Data**

The smart technology required to support the SGUD approach currently does not exist in a standard form. Many of the solutions implemented by the SGUD team use measurement devices, web pages and other elements outside of their intended purpose. These “hacks” have resulted in some notable issues. So far, the team has lost connection with the schedule database, the circuit level meters and the model itself due to a security protocol change on a website, several unknown bugs and a java update respectively. These lost connections often leads to inaccurate data being stored in the database. This poses a particular problem when running the multiple regression for the calibration process because the missing data are not currently identifiable by the multiple regression algorithm.

These challenges illustrate two important points. First, missing or inaccurate data must be identified by the SGUD approach if accurate probabilities are to be determined. Second, a hodgepodge of devices and protocols are unruly. A smart building/campus system should be designed to work on a single platform with a single communication infrastructure.

**Communications**

ZigBee was designed and developed as a communication protocol for use in smart networks. It has many advantages including low power consumption and widespread use among sensors, but it has many shortcomings which made it impractical for the SGUD
approach. First, ZigBee requires its own network which means that each time a sensor is moved a significant distance, a ZigBee base station must be moved with it. This requires time and additional cost which is impractical because most large school/office buildings are already outfitted with Wi-Fi throughout. The SGUD team thought it was important to purchase equipment that can be moved from building to building with ease. Unfortunately, many energy devices have been designed to meet the ZigBee protocol making finding Wi-Fi devices difficult.
Chapter 5: DATA VISUALIZATION

The most accurate and easy to use building model is not of much use to anyone if users cannot understand the results. While tabular data are sometimes useful, figures are the best way to communicate the results of the building model, providing users with a visual appreciation of the information.

SGUD’s building model has been built with embedded plot and bill display functionality. Unfortunately, a bug (causing mismatched color coding) currently exists within the system making it necessary to use Microsoft Excel stacked area charts for the time being (until the bug can be fixed) to help users better visualize SGUD’s building model results.

5.1 Stacked Area Chart

One of the best ways to display the type of data generated in a building model is a stacked area chart which is a figure that displays multiple data series on top of one another. In SGUD’s case, multiple rooms or electricity use drivers are stacked on each other. The highest point on the chart represents the sum of all of the electricity use for the building.
5.2 kW at Time Chart

The kW at time chart can reveal a lot of useful information about the electrical usage of a building; however, interpreting the chart requires some guidance. Because the power can be broken down by room, it is possible to visualize the locations of electricity consumption within the building. A person familiar with a building can look at this figure and discern a great deal of information about what is causing electrical usage. The greatest advantage of this chart is also its greatest drawback. The sheer amount of information contained in the figure can make it difficult to interpret. As the number of rooms increase, the figure can get increasingly difficult to read, partially because an individual room’s electrical usage looks relatively small compared to overall electricity consumption and partially because there are only so many colors and they can start to look similar to one another.
Figure 45: kW at Time Chart
**Why Electricity is Consumed (WEC) Chart**

The SGUD approach has promised the ability to inform customers why they are consuming electricity. This process is heavily dependent upon the combination of activities, loads and the statistical HVAC method. The following chart illustrates how the energy consumption can be broken down into its component drivers. This is very useful to customers who can use this figure to determine what is contributing to their billed demand peaks and overall energy consumption. This is quite possibly the most important figure SGUD produces as it is very useful to determining effective EMMs. This figure and the sorting techniques (described in sections 5.3 and 5.4 below) compound the beneficial effects of the WEC charting.
There are many other charts that can be produced by the SGUD model including charts that break down electrical consumption by categories (HVAC, Lighting and plug loads), zones (HVAC areas, floors, or circuits) and many other options. Because the SGUD model was designed to be flexible, it is very simple to add new entities to entity types in the database which makes SGUD capable of graphing nearly anything that users may desire.

Figure 46: WEC Chart

**Future Charts**

There are many other charts that can be produced by the SGUD model including charts that break down electrical consumption by categories (HVAC, Lighting and plug loads), zones (HVAC areas, floors, or circuits) and many other options. Because the SGUD model was designed to be flexible, it is very simple to add new entities to entity types in the database which makes SGUD capable of graphing nearly anything that users may desire.
5.3 Sorting X Axis

Sorting the data based on the X axis is one of the most useful ways to aid in the visualization of data. Data can be sorted by time, estimated peak power or measured peak power. The type of sorting that is used will always be listed on the X label of the chart to help users understand what they are viewing.

**Time**

Sorting the X axis data as a function of time means that the leftmost data point on the chart is the start time and the right most data point is the end time of the model run. This produces a chart that helps viewers visualize energy use throughout the day. This can be useful if users want to know when they consume the most electricity during the day and also for the SGUD team to discover any recurring discrepancies in the model.
Estimated Power

Sorting by estimated power means that the leftmost data point is the largest estimated power during the period and the rightmost data point is the lowest estimated power during the period. This produces a chart that is useful for users to help analyze their largest power draws and potential driving forces of their billed demand. For instance in Figure 48, HVAC from Outside Temperature is the largest contributor to billed demand during this period.

Figure 47: Sorting X Axis by Time Chart
Figure 48: Sorting X Axis by Estimated Peak Power

**Measured Peak Power**

Viewing the measured power means the leftmost data point is the largest measured power in the period and the rightmost data point is the smallest measured power in the period. This is useful to users to help them understand if there are areas where the model is consistently inaccurate so they can resolve these issues. Please note, Figure 49 is substantially different than the other figures in this section because it is the kW at Time figure not the Power by Category chart (differences discussed on later).
Sorting by the data on the Y axis may not appear as important as sorting on the X axis, but proper knowledge and use can provide helpful visualizations. The Y axis can be sorted by lowest standard deviation, average power or estimated peak power. The type of sorting that is being used will always be listed on the Y label of the chart to help users understand what they are viewing.

**Lowest Standard Deviation**

Sorting by the lowest standard deviation often produces easily interpretable stacked area charts because it removes much of the “choppiness” that can appear in the
average and estimated peak methods. This method first calculates the standard deviation of each series. It then moves the lowest standard deviation values (the most stable and least choppy) to the bottom of the chart and the high standard deviation values to the top of the chart. This sorting method is very good for visualizing trends in the data. For instance, in Figure 50, the plug loads have the lowest variability (lowest standard deviation) while the HVAC from Outside Air Temperature has the highest variability (highest standard deviation).

![Figure 50: Sorting Y Axis by Lowest Standard Deviation](image-url)
Average

Sorting by the average means that the largest average energy consumption over the period in the series is shown at the bottom of the chart and the smallest average energy consumption over the period in the series is shown at the top of the chart. This figure is useful to determine what types of loads are the largest overall contributors to energy consumption. For instance, in Figure 51 the largest average energy consumption over the period results from the HVAC from the outside air temperature while the smallest average energy consumption over the period results from the HVAC from scheduled activities.

Figure 51: Sorting Y Axis by Average
**Estimated Peak Power**

Sorting by the estimated peak power means that each series is searched for the maximum overall power over the series. Then the largest of the series maximum is shown on the bottom of the chart while the smallest maximum power draw is shown at the top. This is useful for determining the largest drivers of energy consumption for a building. For instance, in Figure 52 the largest peak power results from the HVAC caused by the outside air temperature while the smallest peak is caused by the HVAC from scheduled activities.

![Energy Estimate](image)

**Figure 52: Sorting Y Axis by Estimated Peak Power**
5.5 Electricity Bill

While plots help users visualize and sort complex data, a figure which displays a mock electrical bill is often the best way to communicate electrical bill information. The electricity bill is currently the consumers’ primary method of understanding their electricity use and the costs associated with their electricity use. The SGUD approach involves showing the customer their current electricity bills (which are often cryptic), the improved SGUD summary and analysis of their electrical consumption and an estimate of the pollution caused by their electricity consumption. These summaries and a detailed description of the analysis can be found in the billing algorithm section (see pg. 92).
Chapter 6: RESULTS

The current SGUD building model has been used to estimate electrical use in Olin Hall (a science building on the University of Denver campus.) This building was chosen because it was small, had adequate measurement, was easily accessible and had limited loads that would be difficult to model. All calculations were made on build 172 and database “svn trunk #23081” from 2012-11-06.

6.1 The SGUD Measured HVAC VS Statistical Method

The SGUD approach is currently using two main methods of calculating the HVAC load, a statistical method and a measurement based method. The statistical method is beneficial because it does not require a great deal of sensors to operate. However, the results are currently poor. The most likely reason for this is missing data which will be discussed in greater detail on pg. 174. The second HVAC modeling method (measurement based) has proved significantly more accurate under a wider range of conditions. This method relies on measurement equipment that was in place prior to the SGUD building model meaning there is no added investment for the University of Denver, but it is unclear how well this method will work at different sites with different measurement equipment and communication protocols. A major goal of the SGUD approach is to produce accurate energy estimates/forecasts without expensive
measurement equipment, so the issues related to a statistical HVAC method must be resolved.

**Measured Without Compressor**

The model’s operation without any compressor can be seen in Figure 53 – Figure 56 (in winter, the compressor should rarely if ever run). The estimated electricity use is a fairly good predictor of the measured electricity use with $R^2$ ranging from 0.80 - 0.87, but the average estimated values tend to be lower than the mean estimated. This is most likely the result of some missing loads. Several pumps relating to the heating system were excluded from this analysis and are likely contributing to this underestimation.
Figure 53: No HVAC January 10th

Mean Estimated = 56.66 kW

Mean Measured = 63.33 kW

$R^2 = 0.870$
Figure 54: No HVAC January 11th

Mean Estimated = 54.17 kW

Mean Measured = 92.67 kW

$R^2 = 0.854$
Mean Estimated = 53.26 kW

Mean Measured = 58.23 kW

$R^2 = 0.805$
Mean Estimated = 48.22 kW

Mean Measured = 51.57 kW

R^2 = 0.818

**HVAC Method on Accurate Days**

The statistical HVAC method and the measured HVAC method both perform fairly well on days where data are available and there are few real world challenges like maintenance or demand response to cause difficulties for the model. In addition, they follow the curves of the measured energy usage fairly well (as seen in Figure 57 – Figure 62.) R^2 for this period are closely clustered around 0.9.
Figure 57: Statistical July 31st

Mean Estimated = 89.41 kW

Mean Measured = 87.05 kW

$R^2 = 0.852$
**Figure 58: Measured July 31**

Mean Estimated = 87.54 kW

Mean Measured = 87.05 kW

\[ R^2 = 0.919 \]
Figure 59: Statistical Aug 6th

Mean Estimated = 99.47 kW

Mean Measured = 95.58 kW

$R^2 = 0.873$
Mean Estimated = 94.96 kW

Mean Measured = 95.58 kW

$R^2 = 0.913$
Figure 61: Statistical August 9th

Mean Estimated = 89.07 kW

Mean Measured = 81.81 kW

$R^2 = 0.889$
Mean Estimated = 86.12 kW

Mean Measured = 81.81 kW

$R^2 = 0.934$

**Statistical HVAC Method Inaccurate Days**

Unfortunately, the statistical HVAC method does not perform as well as the measurement based method on inaccurate days. The probable cause of this is the SGUD database and problems relating to missing data (see pg. 174). As a result, there are many days where the statistical method is very inaccurate. Under these conditions, the measured HVAC method typically provides better results. In addition to lower $R^2$
between the estimate and the measured energy use for the statistical HVAC method, the figures also show that the estimated techniques do not follow the trends of energy use. While the measured HVAC method may not be perfectly accurate at all times, it generally follows the trends of energy consumption better than the statistical method on these days. This can be seen in Figure 63 – Figure 68.

![Energy Estimate](image)

**Figure 63: Statistical July 20th**

Mean Estimated = 91.81 kW

Mean Measured = 98.52 kW

\[ R^2 = 0.440 \]
Figure 64: Measured July 20th

Mean Estimated = 100.69 kW

Mean Measured = 98.52 kW

$R^2 = 0.924$
Figure 65: Statistical July 25\textsuperscript{th}

Mean Estimated = 79.80 kW

Mean Measured = 81.61 kW

R\textsuperscript{2} = 0.634
Figure 66: Measured July 25th

Mean Estimated = 78.14 kW

Mean Measured = 81.27 kW

$R^2 = 0.836$
Figure 67: Statistical Aug 25th

Mean Estimated = 58.00 kW

Mean Measured = 53.75 kW

R² = 0.320
Mean Estimated = 66.93 kW

Mean Measured = 53.75 kW

$R^2 = 0.832$

**Seven-Day Analysis**

In order to get a good representation of the differences between each HVAC modeling method, it is useful to view them over a longer period than a day. While it would be best to run the model over the period of a month or more, it is difficult to find such a long time period with no missing data or anomalies that would otherwise negatively affect results. As a result, SGUD’s building model was run over the course of...
a week. The week of July 10\textsuperscript{th} – 17\textsuperscript{th} was chosen as a good representative week to compare model results. The statistical HVAC method shows an $R^2$ of 0.640 which is low for a building model. The measured method shows an $R^2$ 0.849 which is higher. While both of these numbers are not highly accurate, it should be noted that the calibration process has not been completed so many placeholder values are still present and both of the HVAC calculation methods are still theoretical and have not been tested independently from whole building electrical usage. The measured HVAC method has considerably less noise (shown in Figure 70) which shows that this method is somewhat more accurate. Both HVAC methods appear to forecast the largest 15 minutes of energy consumption during periods when the actual energy consumption is apparently not as high (note the discrepancy between measured and estimated in the left side of Figure 69 and Figure 70). This is likely a function of the lack of a demand simulation that works in conjunction with the energy consumption estimation.
Figure 69: Statistical July 10 – Jul 17

Mean Estimated = 56.51 kW

Mean Measured = 84.06 kW

$R^2 = 0.640$
Figure 70: Measured July 10 – Jul 17

Mean Estimated = 87.90 kW

Mean Measured = 84.06 kW

$R^2 = 0.849$
Mean Estimated = 50.27 kW

Mean Measured = 54.11 kW

$R^2 = 0.809$

**One Month Analysis**

While a one month analysis is subject to significant difficulties relating to speed and missing data, they are useful to illustrate some of the trends in the model and illustrate to what extent bad data affect the results. These results are shown in Figure 72, Figure 73 and Figure 74.
Figure 72: Measured HVAC July 1st - July 31st

Mean Estimated = 85.90 kW

Mean Measured = 85.14 kW

R² = 0.620
Figure 73: Statistical HVAC July 1st - July 31st

Mean Estimated = 72.56 kW

Mean Measured = 78.33 kW

$R^2 = 0.485$
Figure 74: No HVAC January 1\textsuperscript{st} - January 31\textsuperscript{st}

Mean Estimated = 63.9 kW

Mean Measured = 72.84 kW

$R^2 = 0.411$

**Discussion**

The use of the statistical method will likely not be feasible until the majority of the inaccuracies are resolved in the model. The statistical method is dependent upon many different internal calculations regarding the electricity use like the plug, lighting and HVAC loads. Once these loads can be calculated more accurately and the problems
relating to missing or incorrect data can be resolved, the statistical HVAC method will begin to get more accurate. A statistical method will be the most likely long term solution for modeling HVAC systems because it bypasses the need for permanent expensive measurement equipment (one of the SGUD approach’s major goals) while providing an accurate building model.

6.2 Compressor Morning Start-Up

Both the measured and statistical HVAC methods treat the compressor as though it were operational through the night because it was indicated to the SGUD team that the HVAC system never turns off on a schedule. Upon closer inspection of the measured data, this does not appear to be the case. On most hot days, the air conditioning system appears to start up at around 6 AM and cool the building for a short period of time then shuts off which would seem to indicate that the compressor does not run at night and then starts in the morning to remove the heat added to the building from the night. This often causes a discrepancy between the SGUD building model’s energy estimate and the measured energy use. This can be seen in Figure 75 and Figure 76 at roughly 6:30 AM (time interval 26).
Figure 75: Measured July 24th
6.3 Compressor Cycling

The SGUD approach assumes that any inaccuracies due to the cycling of electrical loads can be averaged out because of the law of large numbers. Unfortunately, this law does not apply to the electrical compressor because it is such a large load; it overwhelms all other electrical loads. This cycling typically does not have a very large effect on the accuracy of the results during summer because the compressor only cycles when building cooling is almost unnecessary (typically at night) and is on constantly during the day when the billed demand is usually set. It could potentially cause incorrect billed demand estimates in the fall, winter or spring and may cause inaccuracies if RTP is implemented. The compressor cycling will most likely be solved as part of the demand
modeling described in the future work section (see pg. 189). This HVAC cycling can be seen in the morning and late evening in Figure 76, the morning in Figure 77 and the morning in Figure 78.

![Energy Estimate Diagram]

Figure 77: Measured Aug 5th
6.4 Calibration

It is difficult to illustrate graphically how the calibration process will improve results because many of the changes are not drastic and may not affect a specific portion of a chart. It will however provide increased accuracy and generally make the estimated usage better match the measured usage. The most significant contribution from the calibration process would be making the HVAC calculations run as accurately as possible as this is a major driving force of the discrepancies within the model.

6.5 Bad Feed Data

The largest and most difficult problem with the SGUD building model’s results is cause by missing, incorrect, misplaced or generally unsuitable data. This has been a great
source of frustration because the SGUD approach relies heavily on data (meaning bad data have a large effect on results), the data are being gathered from many different sensors (meaning many different protocols and states of failure) and the statistical HVAC method is dependent upon the accuracy of other calculations (meaning any errors in the other calculations are compounded within the statistical HVAC method.)

The results of the SGUD approach are heavily affected by bad data. The bad data typically occurs in the form of feeds and not in the class schedule/device/load database. This leads to fairly accurate plug/lighting loads, but sometimes can cause entirely inaccurate HVAC loads. Unfortunately, in the summer months (when most of the SGUD model runs were performed) the SGUD building model’s results are heavily affected by bad data because the compressor can be responsible for over 75% of power during peak times. Some of the results are shown in Figure 79 and Figure 80 below. Periods where bad data are clearly present is a fairly common occurrence in the SGUD approach’s current implementation.

The feeds in the database are pulled in from many different sources using many different methods which can make managing bad data challenging. For example: The eMonitor data are scraped from a webpage. When the webpage cannot be reached, no data are stored, but when the sensor is offline, it returns all zeros. The Iconics data are uploaded from a large file which lists hundreds of values. These values are identified by a name which can be changed by anyone with access to the Iconics system causing data to be misplaced. The NREL solar radiation data are pulled from an online text file once per day. Finally, the 15 minute measured data are pulled from a website which exports
the data in a CSV file. It is difficult enough to have to deal with one protocol for data, but with four different protocols and multiple states of failure, it becomes significantly more difficult to discover and manage bad data. This illustrates the need for a single communication protocol for a smart grid.

The third major challenge for bad data comes from the statistical HVAC method. This method relies heavily on data from many sources in order to be correctly calibrated. Unfortunately, when bad data are present within the feeds, it leads to incorrect compressor electrical consumption, incorrect outside air temperature and incorrect incident solar radiation. These affect both the regressors and the regressands which are the foundation of the linear regression. Thus, the linear regression is highly sensitive to bad data, more so than any other function in SGUD’s building model. While other functions like solar radiation or the HVAC function will only produce poor results when bad/missing data are being used in the calculations, the bad/missing data will cause the statistical HVAC method to produce poor results at all times. Therefore, the statistical approach can only be implemented if either: bad data are all but eliminated from the feeds or if bad data can be reliably identified, so that those points can be ignored in the regression.

In July of 2012, about one day in every five has significant periods of missing data and in August of 2012 the number of days with significant missing data was closer to one in three. This poses significant challenges to the SGUD approach in both calculations and the presentation of the results. In order to determine how well the SGUD approach performs, the SGUD team must disregard days with bad data, but
selecting results from days with good data imposes the will of the SGUD team on the results, thereby bringing the objectivity of said results into question.

As a result the management of bad data must be a high priority for the SGUD approach because it will increase the accuracy and the objectivity of the results. Furthermore, while bad data are present, it makes the statistical HVAC method impractical and inaccurate. If the SGUD approach is to achieve its goal of a smart building/campus with minimal measurement, bad data must be both minimized and mitigated by reducing the amount of bad data and identifying and “handling” bad data in an appropriate way.
Figure 79: Measured July 28th

Mean Estimated = 55.96 kW

Mean Measured = 66.69 kW

$R^2 = 0.120$
Mean Estimated = 103.866 kW

Mean Measured = 61.36 kW

R² = 0.069
Chapter 7: PRELIMINARY RECOMMENDATIONS

The facilities department at the University of Denver requested that the SGUD team run several simulations to determine the effects that specific EMMs would have on electricity usage and energy bills. Specifically, there is interest in analyzing the effect of three scenarios: First, in order to represent a full summer class schedule, the 2012 fall classes were replicated in the summer to show the effect that a proposed summer term would have on energy bills. Second, a scenario was devised to represent a consolidated class schedule where Olin hall would not be used for anything other than office work and the classes would be relocated to another building. Third, a scenario was devised to represent what would happen if all scheduled activities were canceled and the building were essentially locked and remained unused all summer. All of these scenarios were compared to the business as usual [BAU (AKA the building’s summer operations today)] scenario.

7.1 Results Summary

Scenario 1 – Summer classes

- Bill ($) – 6.6% Increase
- Demand (kW) – 6.6% Increase
- Consumption (kWh) – 4.9% Increase
• Pollution (lbs.) – 6.1% Increase

This scenario increases electricity bills roughly 7% for the building, while not appearing to have a large effect on the electricity bills of the University.

**Scenario 2 - No classes**

• Bill ($) – 3.9% Decrease

• Demand (kW) – 4.2% Decrease

• Consumption (kWh) – 3.6% Decrease

• Pollution (lbs.) – 3.4% Decrease

This scenario decreases electricity bills roughly 4%, while not appearing to have a large effect on the electricity bills of the University.

**Scenario 3 – Unoccupied**

• Bill ($) – 60.2% Decrease

• Demand (kW) – 78.9% Decrease

• Consumption (kWh) – 49.7% Decrease

• Pollution (lbs.) – 49.6% Decrease

This scenario has a significant effect on the energy bills reducing the cost by 60%. However, it seems impractical to have to move all of the offices and teachers out of the building for the summer.
7.2 Discussion

As a result of the limitations of the first three scenarios, the smart grid team has performed another analysis on a different scenario that has nearly the same financial effects as the unoccupied scenario, but without the difficulty of moving all of the offices. In this scenario, the classes would still be consolidated into a different building and the compressor that cools the building would be turned off for the entire summer allowing the temperature inside of the building to fluctuate, but five 1-kilowatt air conditioners would be used in order to keep the occupied offices cool and allow limited operations. The results of this scenario are shown below.

7.3 Results Summary (Continued)

Scenario 4 – No Classes Window AC Units

- Bill ($) – 55.9% Decrease
- Demand (kW) – 72.94% Decrease
- Consumption (kWh) – 45.83% Decrease
- Pollution (lbs.) – 45.74% Decrease

This scenario has significant energy, financial and environmental benefits savings and will likely be more palatable than scenario 3 above. These results are still preliminary. The model still needs more thorough validation, several improvements and a few fundamental additions before the benefits can be known with a higher level of
certainty. These calculations should serve as a guide and show more than $10,000 savings on energy bills per year is probable if the recommended steps are followed.

**Detailed Results**

Positive values indicate increases from Business as Usual (BAU) case and negatives indicate decreases from BAU.

<table>
<thead>
<tr>
<th></th>
<th>BAU vs. Summer Classes</th>
<th>BAU vs. No Classes</th>
<th>BAU vs. Unoccupied</th>
<th>BAU No Classes AC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand (kW)</td>
<td>6.66%</td>
<td>-4.19%</td>
<td>-78.91%</td>
<td>-72.94%</td>
</tr>
<tr>
<td>Consumption (kWh)</td>
<td>4.87%</td>
<td>-3.63%</td>
<td>-49.70%</td>
<td>-45.83%</td>
</tr>
<tr>
<td>Bill ($)</td>
<td>6.06%</td>
<td>-3.86%</td>
<td>-60.18%</td>
<td>-55.94%</td>
</tr>
<tr>
<td>CO2 (lbs.)</td>
<td>4.98%</td>
<td>-3.43%</td>
<td>-49.61%</td>
<td>-45.74%</td>
</tr>
<tr>
<td>SO2 (lbs.)</td>
<td>4.98%</td>
<td>-3.43%</td>
<td>-49.61%</td>
<td>-45.74%</td>
</tr>
<tr>
<td>NOx (lbs.)</td>
<td>4.98%</td>
<td>-3.43%</td>
<td>-49.61%</td>
<td>-45.74%</td>
</tr>
<tr>
<td>HG (lbs.)</td>
<td>5.06%</td>
<td>-3.38%</td>
<td>-49.37%</td>
<td>-45.57%</td>
</tr>
<tr>
<td>CH4 (lbs.)</td>
<td>4.98%</td>
<td>-3.43%</td>
<td>-49.61%</td>
<td>-45.74%</td>
</tr>
<tr>
<td>N2O (lbs.)</td>
<td>4.98%</td>
<td>-3.43%</td>
<td>-49.61%</td>
<td>-45.74%</td>
</tr>
</tbody>
</table>

Table 7: Detailed Results Facilities Olin Hall Summer Class Study
Figure 81: Billed Demand Results Olin Hall Summer Class Study

Figure 82: Billed Consumption Results Olin Hall Summer Class Study
Figure 83: Simulated Bill Results Olin Hall Summer Class Study

Figure 84: Simulated CO2 Emissions Olin Hall Summer Study
Chapter 8: FUTURE WORK

While the results of SGUD approach show the overarching principle of estimating energy use based on statistics is possible, there is still much to be done before it can reach its full potential. The SGUD approach has thus far formed the foundations of a smart building/campus providing useful insights into energy usage. However, for the SGUD approach to see widespread acceptance, it must be made more accurate, faster, more useful, more informative and must disseminate information to users in real time. Described below are tasks which must be completed for the SGUD approach to be widely accepted. These can be broken into three separate categories: novel functions, improvements and verification and validation.

Figure 85: SCUD Today
8.1 Novel Functions

**Wi-Fi Motion Sensor Integration**

Members of the facilities department have expressed a desire to use motion sensors in rooms to reduce the lighting loads when rooms are unoccupied. The financial payback of motion sensors are difficult to quantify without expensive and time consuming energy audits which often increase the overall costs of implementing EMMs. The smart grid team proposes using Wi-Fi enabled motion sensors in Olin Hall to measure occupancy in order to quantify the financial savings of motion sensors with a high level of accuracy without a traditional energy audit. While the initial cost of the interface to the data warehouse is relatively high, once implemented, the future costs for this type of analysis will primarily be the parts and labor (motion sensors and installation) which will be minimal and cost far less than energy audits.

![Diagram of SCUD with Wi-Fi Motion Sensors](image)

**Figure 86: SCUD with Wi-Fi Motion Sensors**

**Rules Engine**

In order to bridge the gap between sensors and controls, a rules engine will be required. This rules engine will help the buildings at the University to go from a typical high performance building to a smart building. A typical motion sensor will only turn
lights on and off based on motion, but with integration into the SGUD system, it becomes possible to override the control system during scheduled events to avoid occupants “fighting” with light switches. In the future, it will also be possible to optimize lighting levels by knowing how much light the sun is providing; meaning, the required amount of light can be maintained while the electricity usage from light fixtures can be reduced automatically.

![Diagram of SCUD with Motion Sensors and Rules Engine]

**Figure 87: SCUD with Motion Sensors and Rules Engine**

**Device Controls**

Certain devices, like the HVAC compressor, have control systems already in place. In the future, the SGUD may be able to take control of the chiller and change temperature set points as an EMM. This will allow for pre-chilling of the building and with the addition of forecasting and can help avoid unnecessarily high billed demand.
Demand Modeling

While the SGUD’s approach for *billed consumption* is acceptable, the current method for *billed demand* needs an overhaul. Billed consumption is fairly straightforward to calculate by using probabilities and allowing for the canceling out of any noise (i.e., error) at individual times when taken over a 29-day billing period. Unfortunately, this is not the case with billed demand. Because billed demand is a maximum (not an average) value, it is affected by the amount of “noise” between the estimated and actual energy consumption during the billing period and any noise cannot be canceled out by averaging. As a result, the most practical method for quantifying billed demand is to accurately quantify the noise in the power estimate.

The noise is likely closely related to the probabilities that certain devices are being used. Because these probabilities are already being quantified for the PIUs, the noise for the demand model should not be difficult to determine. It should be as simple...
as determining the probable billed demand within certain tolerances. This will provide more accurate billing algorithms and quantify the savings from EMMs more accurately.

![Diagram](image)

**Figure 89: SCUD and Bmod with Demand Function**

**App Interface**

In order to get information to students and have them respond to energy events, it has always been the goal of the smart grid team to provide a simple web interface for students to use in the development of apps. In order to accommodate this new type of usage, a new mechanism for requesting data will be developed to insure that the server is not overloaded with requests which would render SGUD useless to everyone. In addition, care will have to be taken to ensure that users are only allowed to access certain data. While privacy is not a large concern at the moment, it is probable that as SGUD is brought online in residence halls, privacy will become a larger concern.
Solar Radiation Forecasting

Solar radiation forecasting is one of the next steps for the SGUD approach to building modeling. While temperature forecasts can be found easily, solar radiation forecasts are significantly more difficult to acquire. They are vitally important for the statistical HVAC method and must be present if an accurate HVAC electrical forecast is to be made.

The sun moves in a very predictable path through the day, which can easily be determined from various calculators. However, the cloud cover is much more difficult to forecast, resulting in a major source of uncertainty in a solar radiation forecast. Currently the SGUD team has two possible methods for cloud cover and solar radiation forecasting.

Cloud Cover Percent is a very simple and somewhat inaccurate method of calculating solar radiation. Many weather services provide a percentage of the sky that is covered by clouds or cloud cover percent. The cloud cover percent would be used to assume that the sunlight is blocked for “X” percent of the time during an interval (X
being the *cloud cover percent*). This method is simple and easy to implement. It will probably work well on extremely sunny or extremely cloudy days, but will have challenges on days when there are mixed clouds. For example, if 10% of the sky is covered by clouds, but those clouds are entirely blocking the sun, this method produces a result of 90% sunny, when the actual results are 0% sunny.

**Numerical Weather Prediction (NWP)** is a method of forecasting weather by dividing the earth into “pixels.” These data can be calculated in up to 15-minute intervals (in the continental United States) and provide information on cloud cover. Because the sun is in a known position in the sky and the clouds are also in a known position (in the NWP forecast) the direct and global solar radiation can be calculated. There are two main challenges for this method. First, the numerical weather prediction model runs are stored in very large files and are difficult to access. Second, it is unclear if the cloud forecasts are currently accurate enough to prove significantly more useful data than the cloud cover percent method. Regardless of which solar radiation forecast is selected, the function will be added to SGUD in the manner shown in Figure 91.

![Diagram](diagram.png)

**Figure 91:** SGUD after solar radiation
**SGUD’s Building Model after Novel functions**

After all of the novel functions are added to the SGUD system, it will operate in the manner described in Figure 92.

![Figure 92: SCUD with All Novel Functions](image)

### 8.2 Improvements

The SGUD building model requires improvements to the current functions in addition to the previously mentioned novel functions. These improvements typically either make SGUD’s building model more accurate, faster or add new functionality. These changes don’t require any fundamental additions to the SGUD approach, but typically require a modification of the previous calculations or operations.

**Speed Improvement**

The slow speed of SGUD’s building model and the server is a constant issue for the SGUD team. It has made most of the technical work unnecessarily time consuming.
and hindering progress. If the SGUD approach is to be successful, it must be able to perform a one-year analysis (at 15-minute intervals) in less than one minute.

**Situation planning**

Initially, it was the SGUD team’s goal for the model to simulate ECMs in buildings, but it quickly became apparent that the versatility of the model allows for many more possibilities. There has been interest in using the SGUD building model to help the University with event planning in order to determine the full energy and financial impacts of specific events. For example, putting on a concert during a hot summer day may appear financially viable, but if that concert sets the billed demand for the month and/or the year, it can end up reducing the financial benefits by thousands of dollars.

**Real Time Prices**

An RTP structure has yet to be implemented into the SGUD model. A mock real time billing structure should be added to the model to compare the rates that will be paid using the standard billing structure to those in a RTP billing structure. This will need to be coordinated with either the local utility or some other source where information about wholesale rates can be found.

**Pollution Values**

The pollution values currently used in the pollution algorithms are simple pollution estimates taken over an entire year. This is acceptable for a basic understanding, but it would be more useful to know the percentage of the campus’ electricity being provided by various resources (coal, wind, solar, natural gas, etc.) and to
use lifecycle analyses (of each energy source) to determine the campus pollution footprint in real time. A good source for information may be located at the following site 
http://www.nrel.gov/analysis/sustain_lcah.html. This means that pollution will likely be less when wind power plants and natural gas plants are providing a large portion of the power, but when coal plants are the primary source of electric generation, there will be significantly more pollution per unit power. This real time pollution information will help inform customers about their pollution footprint in a more useful way.

**Device Review**

Currently, the watts (on) for most devices come from a variety of sources. While most of these sources’ values seem reasonable, there are some values which call into question the reliability of all of the data. The American Council for an Energy-Efficient Economy lists the wattage consumed by a video game console as 24 watts [55]. This may have been correct for old game consoles, but modern game consoles consume significantly more energy [56]. Because the SGUD approach relies heavily on the electricity consumption of devices, it would be wise for the SGUD team to develop a standard for testing the electricity usage of devices under a variety of conditions. This would allow the University of Denver to maintain a reliable, up to date and comprehensive database of devices which would also serve to help the SGUD team understand how/why devices consume energy. Currently much of the device information comes from numerous sources [57,58,59,60,61,62].
Privacy

Privacy is a major concern in modern times and with the continual infiltration of technology into people’s lives the very nature of privacy is in a state of flux. With the advent of electronics and the internet, more data can be gathered and stored than ever before and it is still unclear how these data will be used. Privacy advocates have already expressed concern that smart grid data could be improperly or unethically used without appropriate laws and regulations [63]. At the same time, this information is necessary to a smart grid in order to accurately forecast energy consumption and determine what to charge customers in an RTP billing structure.

The federal government has already begun to collect a lot of data from smart meters without clear regulations about what data can be stored and how it can be used. “EIA will significantly expand its collection of AMI-related data collection beginning in 2011 to improve the breadth and timeliness of its information on AMI. EIA revised its Form EIA-826, ‘Monthly Electric Sales and Revenue with State Distributions Report’ to collect monthly, by state and sector, the number of Advanced Meter Reading (AMR) and AMI meters installed, as well as the energy served through AMI meters. These revisions may improve the ability of interested parties to monitor and assess AMI deployment and utilization in the United States” [24]. The fact that the government is already “collecting” the energy served through AMI meters indicates that they may already have a database of user’s electricity usage without the end consumer even being aware or consenting to the storage or use of their electricity consumption information.
An example of data being stored without sufficient security was found by the SGUD team at the University of Denver smart meter provider. One of the smart meter services that are in use on the University of Denver campus is supposed to be accessed only by individuals with a username and password for the site. While trying to download these data directly to the database, it was discovered by the SGUD team that the historical data from more than 2,000 different meters could be accessed by anyone with a moderate technical prowess. Without clear regulations on how smart grid data will be used, customers’ data may be used without their knowledge and consent.

**Database Query Efficiency**

SGUD’s building model currently has the ability to calculate electricity use and electrical bills for an entire year, but the data warehouse is too slow to support this type of calculation. With upgrades to the data warehouse and SGUD’s building model, it should be possible to calculate an entire year worth of electrical and financial data for different simulations, resulting in near instantaneous financial calculations for a wide range of scenarios such as changing class schedules, efficiency measures and renewable energy. This will greatly expand the SGUD team’s ability to quantify potential savings and reduce the University of Denver’s electricity bills.

**Energy Bill Variability**

The multipliers on a customer’s energy bill can change from month to month. For example, there is one separate demand charge for winter and one for summer, the electricity commodity adjustment changes with the market and most rates change when a new rate case is made. This variability is not currently implemented within the SGUD
billing algorithm. In order for this model to be as accurate as possible, an entire year of variable bill multipliers should be implemented within the billing algorithm.

**Code Interaction Efficiency**

The interactions between different elements in SGUD’s building model are somewhat cumbersome resulting in many workarounds to perform basic tasks. Modifications to the interactions would greatly increase the SGUD team’s ability to analyze data in new ways, increase the accuracy of the model and make results more easily available to students for research.

**Elevator Function**

SGUD’s building model lacks the ability to estimate the electrical load due to the elevator within Olin Hall. The elevator load acts differently than most electrical loads within the building which have already been modeled. The estimated electrical usage of the elevator is likely the result of a changing number of occupants on floor’s above the first floor. The elevator is not likely to experience heavy use during class periods because most occupants are likely in class and not leaving, but it is highly probable that after class, the elevator would experience much heavier use. The smart grid team must investigate this further in order to determine the best way to implement elevators within the SGUD building model.

**Feed Failure**

Currently, there is no way (in the code) of knowing if a feed is providing incorrect results. While it is obvious to observers that a temperature of zero degrees F in the summer is the result of bad data, the model has no way of knowing this. Resolving this
issue will require a thorough review of the feeds and modifications to the data warehouse. This will help ensure the accuracy of the SGUD building model’s results.

**PIU Calibration**

The model is using PIUs which are based upon the assumption that they are being used all the time when activities are in session and never on when they are not. In reality this is not the case, some devices are in use during scheduled activities and some are left on after activities are complete. These PIUs will need to be fine-tuned. The circuit level meters that have already been purchased and installed will primarily be used for this purpose. In cases where circuit level measurement is not adequate, device level meters will be required. This will help the SGUD approach become more accurate and ease the process of expanding it to the next building.

**Discovering Unknown Loads/Activities**

Currently the building model is underestimating the consumption of the building by roughly 10% even with the assumption that all loads are on when activities are present. This may indicate that unscheduled activities are common in Olin Hall, there are loads in the building which are not accounted for, or there is some other phenomena causing underestimations. Discovering these unknown load/activities will help the model accurately estimate consumption and improve overall results.
Chapter 9: CONCLUSION

There are many challenges for the modern electricity grid. The three most important challenges are: 1) it is currently designed to accommodate peak demand that may occur for a few hours per year 2) customers typically do not respond to price signals and 3) the generation (supply) and consumption (demand) must always be equal for the electrical grid to continue to function. These challenges have forced regulators to create a faux supply and demand market which is based on cumbersome regulations, inefficient investment and monopolies.

These three challenges have also created an economically inefficient predict and supply market. In order to improve overall social welfare, reduce the average price of power, and allow for more renewables like solar and wind, the electrical grid must be adapted to accept a supply and demand market or smart grid with appropriate market clearing prices passed through to customers.

Customers have traditionally turned to regulators and utility companies in the hopes that they would create a smart grid, but both of these entities have major disincentives to create one. This has been the single largest barrier to the creation of a functional smart grid to date. This paper proposes a new method of smart grid development which informs the customer about their energy usage so that they can make smarter choices and implement cost effective smart technologies which will have the
maximum impact. This proposed system builds a smart grid from the bottom up rather than previous top down approaches that often required smart meters for every customer and would often not provide good financial returns.

Previous attempts at a bottom up approach to a smart grid have failed because they often did not address a specific financial need for customers. That is to say, these systems costs more, usually a great deal more, than the investor would receive back in benefits. The SGUD approach makes a financial case for specific Energy Modification Measures (EMMs) in the current predict and supply electricity market, while providing the infrastructure and knowledge required for a smart grid which is based on a supply and demand market.

This bottom up approach is accomplished by using a building model that combines deterministic and statistical methods to accurately forecast electricity use. The core principle of this model is that it tells customers WHY they are consuming electricity, while previous approaches simply tell customers THAT they are consuming electricity. Initially, this building model is used to provide investors accurate, reliable and cheap information about EMM’s. Some of these EMM recommendations will require smart meters, sensors and control mechanisms that will form the backbone of a smart building/campus.

Once enough smart building/campus’ are brought online, the system operators will have the tools to begin a transition to a supply and demand market. Once this transition begins, a smart grid will be inevitable.
The SGUD approach has proposed one method of marrying deterministic and statistical methods in order to lay the framework for a smart building. While there are still improvements that need to be made, the SGUD approach shows that it is possible to estimate electricity consumption down to the device level accurately without a large and expensive sensor network. This is a major leap forward for a bottom up approach to providing the infrastructure required for a smart grid and has vast potential for the development of supply and demand market.
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Appendix A: DEFINITIONS AND ACRONYMS

Definitions

**Bus** – the physical connection point between transmission lines, generators and distribution lines on the electrical grid

**Consumption** – the quantity of electrical energy consumed typically measured in kilo-Watt-hours (kWh)

**Capacity factor** – the actual electrical production over the rated power times the hours in a year

\[
\text{Capacity Factor} = \frac{\text{Energy Produced(\text{yr})}}{\frac{365 \times \text{Rated Power}}{8760}}
\]  
(11.1)

**Database** – a structured collection of data; also known as data warehouse

**Distribution** – refers to the low voltage networks which deliver power locally from the transmission network to the consumers

**Economically efficient** – producing the maximum amount of a good or service while minimizing the use of resources

**Energy** – power integrated over time

**Fracking** – hydraulic fracturing of rock in order to extract resources usually oil or natural gas

**Generation/generators** – refers to electrical generators on the grid; also referred to as a plant

**Grid** – the electrical network which generates, transmits and distributes electricity

**Load** – a device or series of devices to which power is being delivered

**Power** – the instantaneous electrical draw

**Reasonable/fair rate of return** – a rate of return provided to investors of utility companies usually comparable with low risk investments available in the market

**Regressand** – the dependent variable used in linear regression

**Regressor** – an independent variable used in linear regression

**Renewable energy** – electrical energy which is derived from renewable resource such as the wind, the sun, or flowing water
**Smart grid** – a future electrical network which has a large amount of communication, measurement and two-way power flows

**Smart meter** – a device which communicates with both utilities and customers and is capable of measuring electrical consumption each hour or a smaller time interval, also known as Advanced Metering Infrastructure (AMI) or Advanced Meters

**Temperature set point** – the temperature which a heating/cooling system is attempting to maintain

**Transmission** – refers to the high voltage network of power lines on the electrical grid

**Nomenclature**

AMI – Advanced Metering Infrastructure (AKA Smart Meters or Advanced Meters)

CFL – Compact Florescent Lamp

DLC – Direct Load Control

eGRID – Emissions & Generation Resource Integrated Database

EMM – Energy Modification Measures

EPA – Environmental Protection Agency

GUI – Graphical User Interface

HVAC – Heating Ventilation and Air Conditioning

I&C – Interruptible and Curtailable load

IRR – Internal Rate of Return

kW – Kilo Watt

kWh – Kilo Watt Hour

NREL – National Renewable Energy Laboratory

PIU – Probability in Use

RTP – Real Time Pricing

SGUD – Smart Grid at the University of Denver

SQL – Search Query Language

TOU – Time of Use (Rates)