MODEL FOR VALUATING DECENTRALIZED ENERGY PRODUCTION

A Master's Thesis

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MODEL FOR VALUATING DECENTRALIZED ENERGY PRODUCTION

The Institute of Economics and Social Sciences
of
Bilkent University

by

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In Partial Fulfillment of the Requirements for the Degree of
MASTER OF ARTS

in

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ANKARA

October 2008

I certify that I have read this thesis and have found that it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Arts in Economics.

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ABSTRACT

MODEL FOR VALUATING DECENTRALIZED ENERGY PRODUCTION

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The purpose of this thesis is to assess decentralized production technologies in an economical framework. Throughout the thesis, technological aspects such as smart metering or connectivity issues are ignored. All assumptions are based on specification sheets by the producers of the technologies to provide an impartial assessment.

Pricing schemes for buying from the grid and selling to the grid are based on dynamic markets, like Amsterdam Power Exchange and Title Transfer Facility. Although these markets are for large scale trading, they provide a good basis for constructing future scenarios where electricity and gas are bought on variable prices rather than fixed prices.

Model constructed to evaluate different technologies finds the optimal production given the technologies and prices for the period. Optimal production clearly defines an upper bound on the value of the technology as any other production increases the cost of heat and electricity of the household.

In retrospect, model establishes a best case scenario for the value of such systems from an economical perspective. Technological, regulatory, and marketing aspects are not explored in this study. Only economical viability of the technologies is explored. In summary, it is common for individuals to make misinformed or wrong decisions. Effects of marketing etc. can be studied, but my belief based on this study is that these devices are not economically viable and their environmental benefits are questionable.

Key Words: Energy, Valuation, Decentralized, Optimization, Combined Heat and Power, Renewable energy generation, Sustainable Development.

ÖZET

DAĞINIK ENERJİ ÜRETİMİNİN DEĞERLENDİRİLMESİ İÇİN MODEL

Cider, Muammer

Yüksek Lisans, Ekonomi Bölümü

Tez Yöneticisi: Yrd. Doç. Dr. Taner Yiğit

Ekim 2008

Bu tezin amacı dağınık enerji üretim sistemlerinin kullanılabilirliğini ekonomik bağlamda incelemektir. Tezin tamamında, teknolojik veya lojistik özellikler dikkate alınmamıştır. Tezin tarafsızlığını koruması amacıyla kullanılan bütün spesifikasyonlar üreticilerin kendi dökümanlarından alınmıştır. Tez boyunca varsayılan enerji piyasası dinamik bir market olarak kabul edilmiştir. Günümüzde bu tip piyasalar genel olarak büyük ölçekli borsalarda işlem görmektedir, ancak küçük ölçekli kullanıcılar için böyle bir piyasa bulunmadığı için, piyasa durumlarının oluşturulması bu marketlerden esinlenerek yaratılmışır.

Değişik teknolojileri değerlendirmek için kullanılan model, piyasa fiyatları ve teknolojilerin verimliliğini kullanarak optimal değer bulmayı amaçlar. Bu optimal değer ekonomik olarak teknoloji için olabilecek en iyi değeri verecektir. Bunun sebebi açıktır, herhangi başka kullanım evin enerji harcamasını arttıracaktır.

Araştırma için baz alınan ülke Hollanda olarak belirlenmiştiri bunun sebebi gerekli bilgilerin bu ülke için kolay erişilebilir olmasıdır. Araştırmanın sonuçları Hollanda için bu teknolojilerin şimdiki duruma yeterli bir iyileştirme sağlıyamadığı yönündedir.

Bunun sebepleri tezin geri kalan kısmında detaylandırılmıştır fakat en önemli nokta Hollanda'daki ev enerji veriminin yüksek olmasıdır.

Kısaca, model teknolojiler için olabilecek en iyi şekilde ekonomik bir analiz yapar. Teknolojik, regulasyon gibi etkenleri ele almadan sadece ekonomik bir analiz yapar. İnsanların ekonomik olarak yanlış kabul edilebilecek yatırımlar yaptığı bir gerçektir. Bu sebeple tekrar belirtmek isterim ki bu tez sadece teknolojilerin olası finansal gelirini inceler.

Anahtar Kelimeler: Enerji, Dağınık, Optimizasyon, Isı ve Güç, Yenilenebilir Enerji Üretimi, Sürdürülebilir Kalkınma.

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I would like to thank my family from the bottom of my heart for their relentless support through the whole process.

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CHAPTER I

INTRODUCTION

Heat and electricity are two of the most important components of modern life. Until now people relied on utility companies to provide these two necessities of modern life; however, several emerging technologies are promising to change this arrangement. It is claimed that small scale energy production technologies have reached efficiencies to rival the existing centralized energy production plants.

Current outlook on fuel and energy prices start to show the effects of dwindling supply on fossil fuels, and the considerable increase in demand from developing nations. Increased cost of energy resources demand that we extract maximal value from these commodities, increasing overall energy efficiency is a definite improvement in this venue.

There seems to be room for improvement, current installed technology in households with a HR-Boiler convert about 95% of the available energy in natural gas to useable heat energy. Electricity on the other hand, is a completely different issue; for example Dutch electricity production and transport is only 40% efficient, this efficiency drops down to 25-30% for Turkey. This means 60-70% of the energy is lost from resource to usable electricity.

Purpose of this paper is to construct a framework to evaluate viability of emerging technologies in decentralized energy production. It is important to establish what individuals will base their decisions upon. People hardly ever consider the bigger picture when making decisions, countless taught experiments show that one’s economic benefits will govern his/her decision over the public benefits. Tragedy of the commons (Hardin, 1968) is a well established taught experiment having its roots back in the days of Socrates. Brief result of the article is, individual maximize their own gains, common resources that are unregulated and freely available will not be considered. In the case of energy production, environmental impact is this common resource. It is safe to assume individuals will try to maximize their own utility by minimizing energy cost of the household.

This paper evaluates emerging technologies on a purely economical sense. It is my belief that any significant concern for environment will be fueled by economical incentives, such as emissions penalties, any adjustment on this regard will be done in the pricing.

It is also important to establish how wide spread use of decentralized production will affect pricing schemes. It is the expert opinion that current pricing schemes will not work with a market saturated by decentralized production, thus markets are assumed behave more like a commodity market. Luckily examples of these exist in large scale; all market behavior is modeled after these large scale implementations.

Economical viability of these technologies will ultimately determine their impact on the market. If these technologies do not prove to be viable economically, it is unlikely that they have an impact on the market. There might be several occurrences; however, it is my belief that any significant impact must be fueled by economic motives.

CHAPTER II

MODEL OVERVIEW

In order to determine the value of a production system, one has to model the behavior of the system for various inputs. In the case of production systems the valuation can be done by assuming the best possible utilization of the production unit for the given set of inputs.

Assumption of optimality is both necessary and logical; underlying decisions for operating a production system is likely to include too many decisions for the end-user. Under this supposition it is only logical to assume an automated system will be making these decisions instead of the end-user. Optimal decision will be made with the purpose of minimizing overall cost of energy, regardless of the user.

The model is divided into three parts; namely:

1. Production optimization.
2. Electricity and heat demand models.
3. Electricity and gas price models.

The value of the system is determined by the production optimization part using deterministic values from the demand and prices.

Overall, the working of the system can be summarized in the following figure.

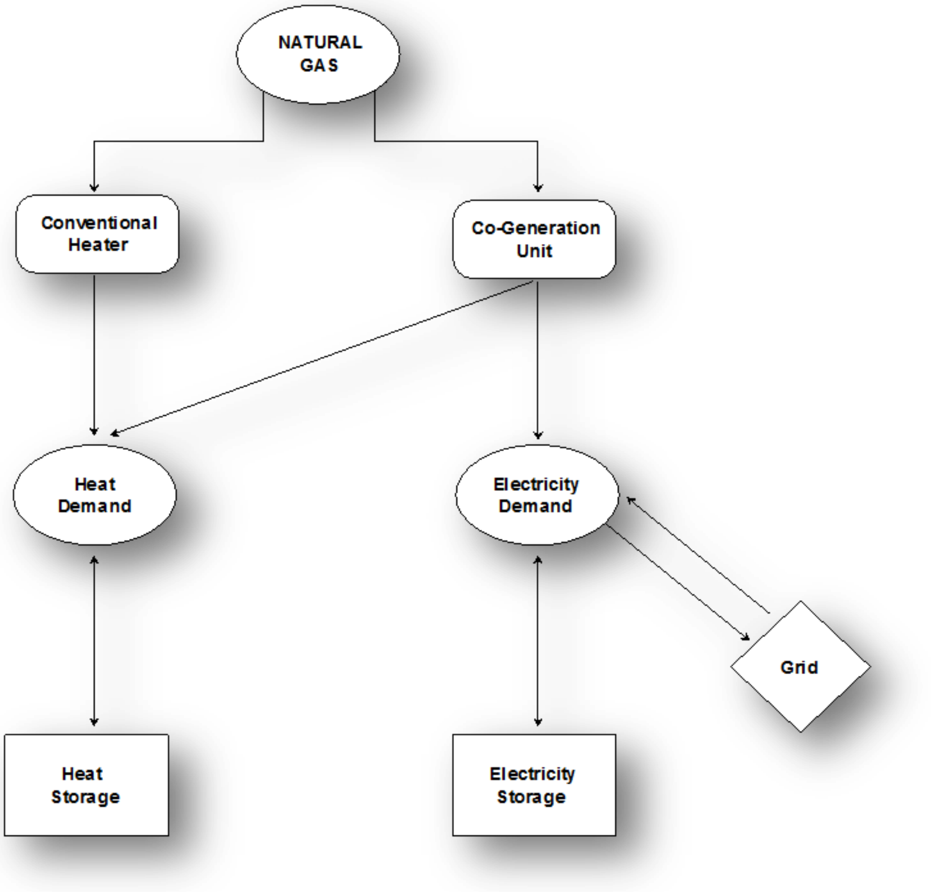

Figure 1: Model Overview

The production model encompasses decisions made for production from the cogeneration device and the conventional heater as well as the storage interactions. Demands, grid prices (electricity buy and sell prices) and natural gas are deterministic inputs to the production system.

2.1 Price Models

The main purpose of the price model is to model the electricity grid price and the natural gas price, so that a stochastic model can be constructed. This stochastic model can then be used to create scenarios for electricity and gas prices in the future, with specified trends.

Some important properties of the price models are:

- The price model uses historical data to construct a stochastic model.
- Model assumes an Ornstein-Uhlenbeck process as the basis for random movement of prices.
- Price models uses trend of the future as input and generates scenarios based on the future annual values, it does not attempt to model future trend of prices.
- Movements on the pricing curves are based on historical prices.

2.2 Demand Models

In addition to the price models, demands for electricity and heat also play an important role in determining the value of any technology; these variables are not generated. In the model these variables are exogenous, i.e. simply taken as given.

Slight manipulation on these variables might be required to model different technologies such as solar panels or micro-wind turbines. Demand growth (electricity) and reduction (heat) in the future is taken into account, using external documents as reference sources.

2.3 Production Model

The production model determines the optimal production from the cogeneration device and the conventional heater. Optimal decision parameters are calculated using the demands and outputs of the price model. In the figure, the production model encompasses all but the demand, grid and natural gas. Details of the Production model are discussed further in upcoming chapters.

Some important properties of the production model are:

- Model uses deterministic inputs.
- Different devices are modeled by specifying different efficiencies and capacities.
- Heat and electricity can be turned off.
- Optimization period is defined by the length of the input.

2.4 Valuation methodology

The value of a technology should be determined by analyzing the negative cash flow generated by the device and comparing it to the negative cash flow generated by the base case. The base case for testing technologies should be no co-generation device and a high efficiency boiler. Net present value of the negative cash flows should be aggregated over the analysis period of the device to find total cost of energy over this period. This value can then be compared to the base case total cost of energy. Additional costs such as maintenance costs over the analysis period should be accounted for in the analysis.

CHAPTER III

DEMAND

Energy demand is an important aspect of the system that plays an important role in the total value of the system. Only heat and electricity demand are taken into account within the model. Heat demand is not further subdivided into hot water needs and spatial heating to prevent further assumptions.

Electricity and heat demand are assumed to be inelastic; this choice was made to avoid cross-interaction with prices. Although not entirely true, this assumption holds for the most part, as altering the daily routine such as showering in the morning or washing the dishes at night are very minor compared to overall energy expenditure.

3.1 Electricity Demand

Electricity demand should be deterministic input to the model, as such percentile values for expenditure must be scaled to annual consumption levels, to account for this change demand forecast curves are scaled to the annual average for EU households, estimated at 3500 $kWh/year$ (EnergyNed, 2007). It is estimated that electricity consumption will experience a steady increase of 1.3% over the next decade, after 2016 electricity demand is expected to stay constant through the rest of the analysis period.

Usually the annual demand follows a U shape with minimal electricity consumption during the summer; this is not the case for nations that rely heavily on air-conditioning; the seasonality effect can easily be seen in the figure below.

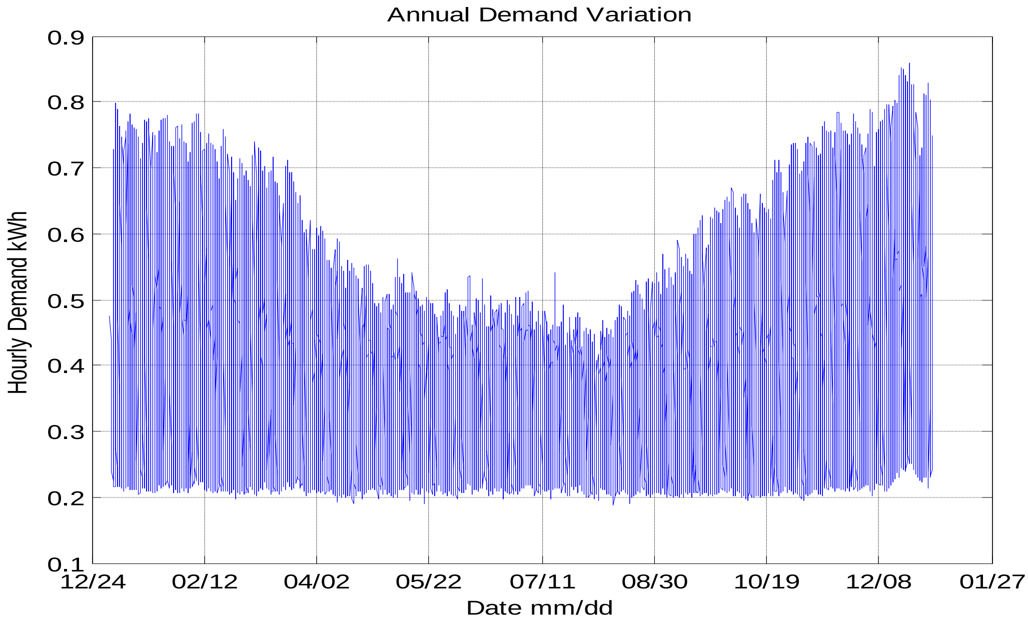

Figure 2: Annual Demand Variation

Note that regardless of the season, there is significant hourly and daily variation within the demand, which is best illustrated in this figure. One can easily identify the peak hours when the users are home and off-peak hours when the users are either sleeping or out of the house.

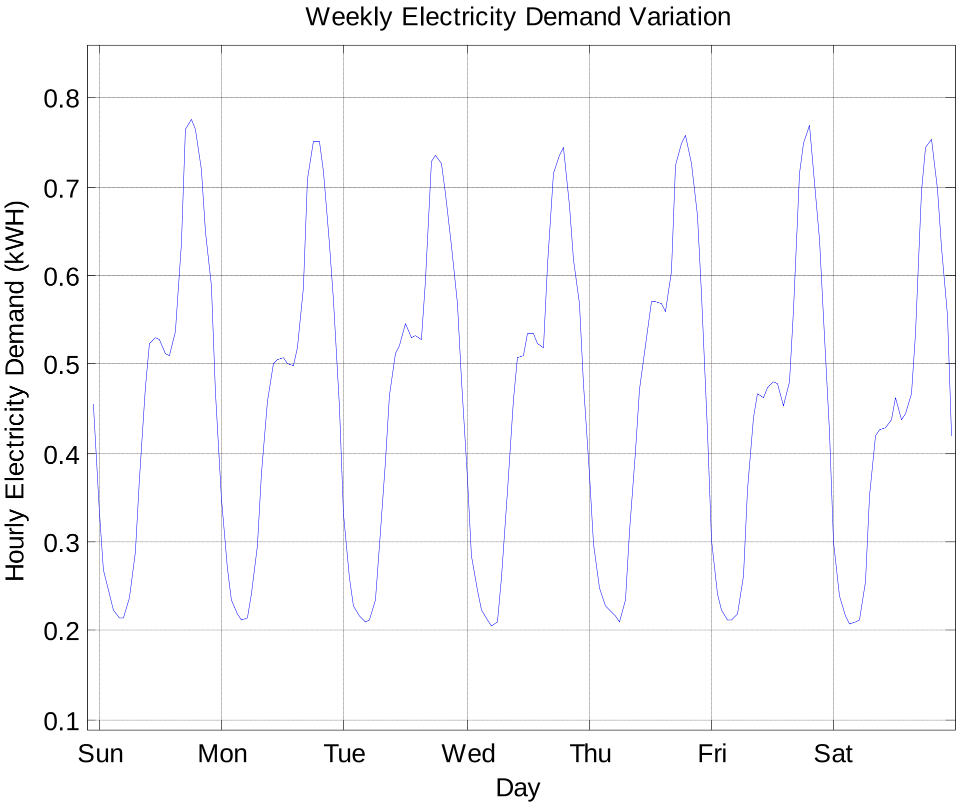

Figure 3: Hourly Electricity Demand Variation

Electricity demand can be manipulated to account for solar or wind generation to model these devices. This is done by first forecasting production from the device and then simply subtracting this amount from the electricity demand. When there is excess production, demand will be negative fortunately the model can account for negative demand, simply selling it to the grid or if possible storing it.

The model is tested under the demand scenarios shown above. This demand profile is taken from measurements over a year from a single household.

3.2 Heat Demand

Unlike electricity demand, heat demand cannot be measured directly. Several approaches were employed to determine heat demand of a residential house, control room data and natural gas demand were the most successful attempts at modeling the heat demand.

Heat demand was modeled after the natural gas demand curves, currently 97% of the overall natural gas demand is for heating (EnergyNed, 2007), either hot water or spatial, 3% of the gas usage accounts for cooking. This assumption was later confirmed by the control room data, control room data could not be used to create the demand profile. Control room data was missing data from the winter months, which are the most important days for heat demand. A simple correlation between control room data and natural gas demand data, gives a correlation coefficient of 0.95, further confirming the close relation between heat and gas demand.

Similar to the electricity demand, heat demand also exhibits seasonal and weekly behavior. Figure 4 depicts the annual change in heat demand, heat demand during the summer months are attributed to hot water demand of a household.

Weekly heat demand variation is depicted in Figure 5; showering needs in the morning can easily be identified by the spike occurrence during the morning hours.

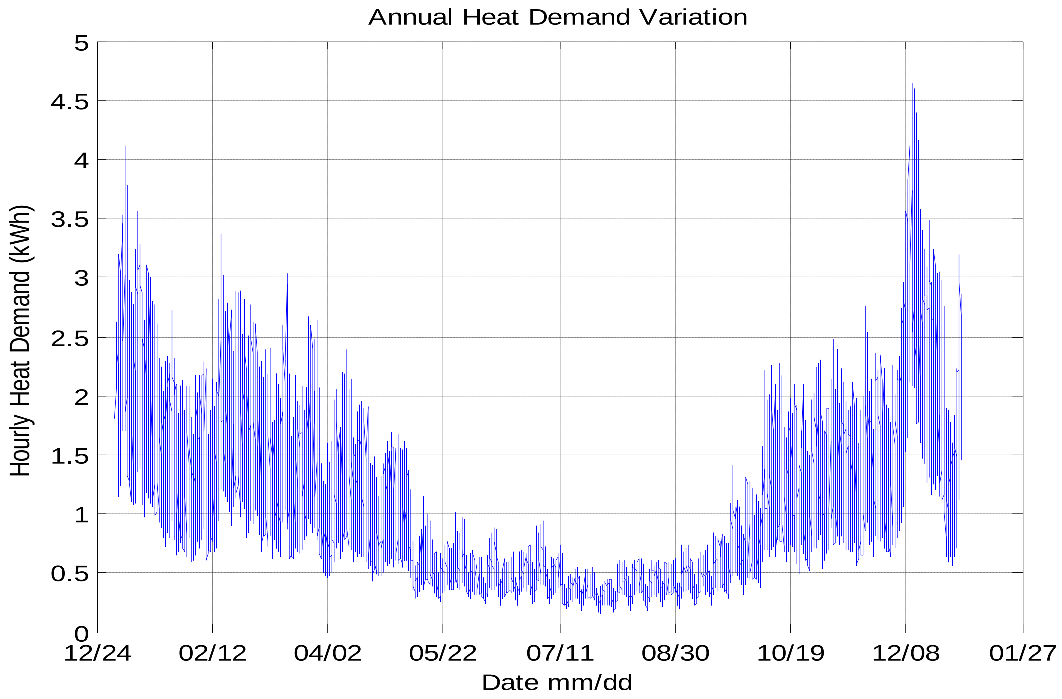

Figure 4: Annual Heat Demand Variation

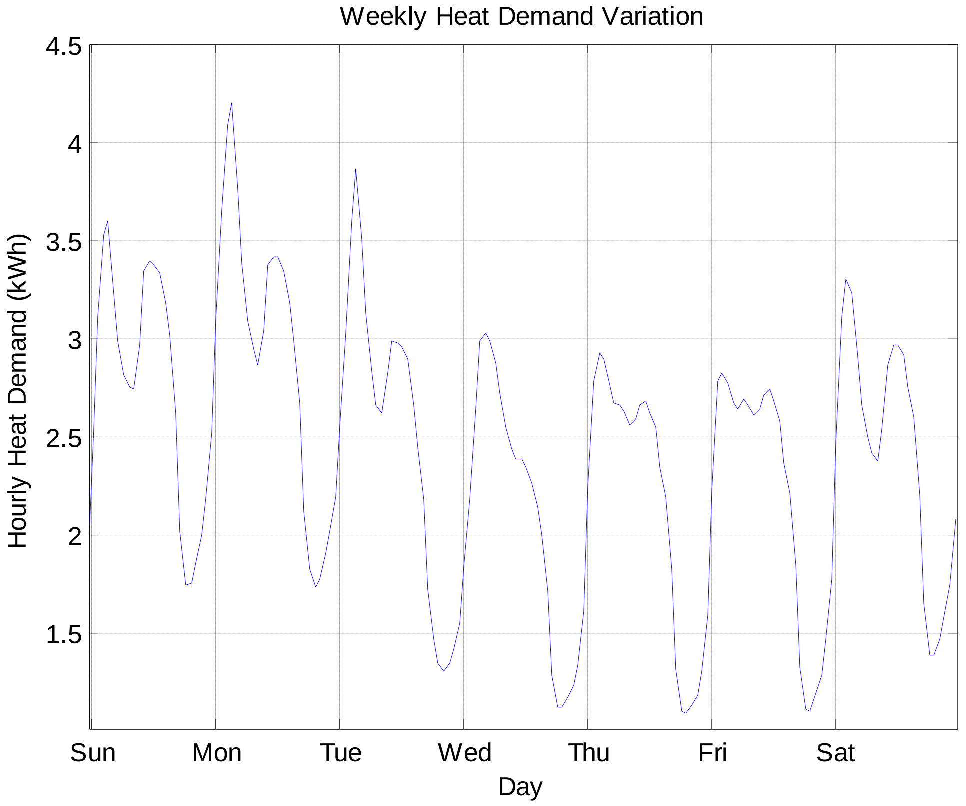

Figure 5: Weekly Heat Demand Variation

Heat demand is assumed to remain constant in a residential house during the analysis period (2010-2020). Main differentiator for heat demand is insulation and efficiency of the boiler. Due to the fact that efficiency of the boiler is accounted for within the model only differentiator is insulator. Heat demand has shown a significant decrease at the start of the 21st century but has been stagnant for the last five years (Energy Information Administration, 2007).

3.3 Possible Extensions

The model can further be extended to include behavioral interaction between demands and prices; modularity of the model eases the adaptation of this extension. Current implementation of the model disregards any behavioral implication of high prices, in layman's terms the demand is taken as purely inelastic regardless of the prices.

Deterministic nature of the demand and optimization model do not allow any other type of input, however this functionality can easily be implemented deterministically, since the prices and demand are generated prior to passing them into the optimization model.

CHAPTER IV

PRICING AND STIMULATION

The production model uses deterministic inputs to determine the optimal production scheme that satisfies demand. A reasonable assumption would be to have the output of the pricing model to be deterministic. However, pricing model is stochastic. Making the model stochastic was necessary to ensure that generated scenarios used to valuate different devices were truly random.

Forward curves are used as the basis for generating pricing scenarios of commodities. Forward curves lack the short term behavior that spot markets entail. In order to construct a realistic pricing scenario both the long term and the short term behavior must be accounted for. This is done by modeling short term behavior on historical spot markets and leveling them to the forward curve levels.

Natural gas prices and electricity commodity prices are the outputs of the pricing model that is used in the production optimization model. Natural gas is the fuel for all of the devices analyzed in this study that use some form of fuel and as such it is an important determinant for the value of these devices. Electricity price is the price at which this commodity can be bought or excess production can be sold to the market. It too is a very important driver for value as it plays a significant role in determining when and how much to produce with the CHP unit.

There are two distinct way of generating scenarios for the price of a commodity in a given period, the first one is constructing a complete model from the ground up. This involves determining factors that affect the commodity price and build the model for that commodity accounting for these factors. The second way of constructing scenarios involves a “blind approach”, looking at the historical data and analyzing the data as is, without constructing a complete model from scratch.

Historically, constructing robust models for natural gas prices and electricity prices have been notoriously hard (Brown & Yucel, 2007). Numerous papers were written on the subject, there are no models that have warranted universal acceptance for these commodities.

The energy crisis, has only added fuel to the fire that is forecasting energy commodities. In order to generate scenarios, a mid-way approach was employed. Several approaches were tried to construct these scenarios, at the end only one of these methods was satisfactory both mathematically and rationally.

Predicting the future course of prices is beyond the scope of this thesis. Natural gas prices are known to be tedious to predict, as they are coupled with crude oil, fuel oil and other energy commodity prices, and increasingly dependent on supply. Publicly available forecasts from third parties are used for calculations. These forecasts however do not encompass the dynamic movement that the market faces in the real world; they are a single average value for the whole year.

The production model uses hourly prices for electricity and gas to determine the optimal production scheme to use. Historical movements are a good starting point for modeling this dynamic behavior of the prices.

4.1 Properties of Electricity Spot Prices

There are several very important points that cannot be overlooked when constructing movements from market prices. Historical data for electricity prices for a residential house is contractual in nature (one price per quarter).

- Although dynamic market is an hourly market, each hour behaves as a different commodity; this is mainly due to the fact that electricity prices are mostly driven by demand and electricity cannot be stored effectively.
- Electricity prices of different hours are different commodities, but there is a strong correlation between movements.
- Electricity and gas prices might be interlinked; a spike in gas price might drive electricity prices higher.
- Gas and electricity prices exhibit historical mean reversion until 2002, over the period 2002-2008 gas price behavior has shifted towards an increasing trend.
- There is seasonality of prices.

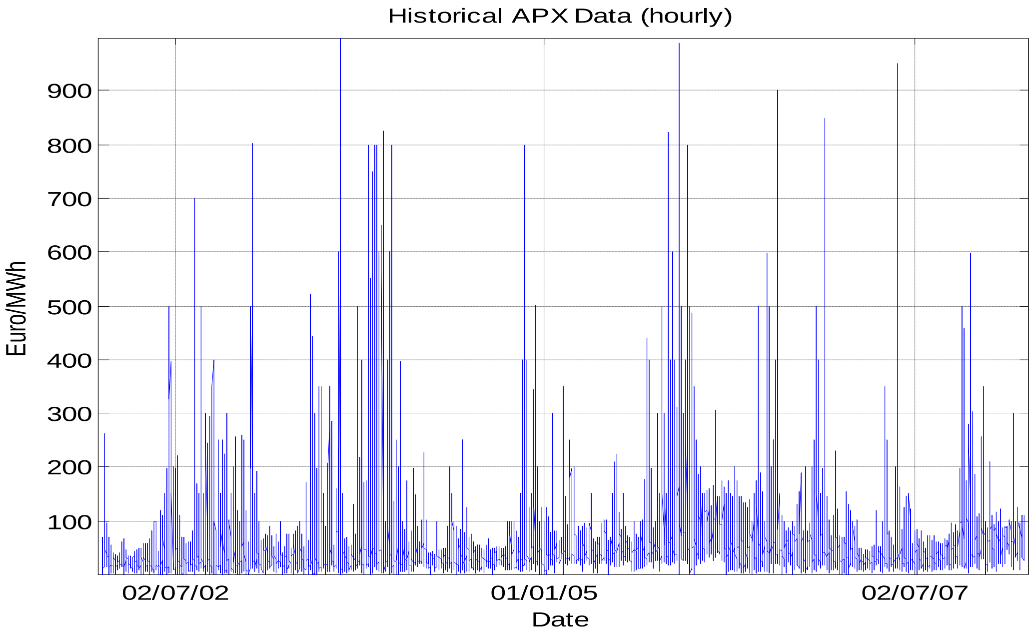

Figure 6: Historical Electricity Spot price data

Historical Electricity spot price data is shown in the figure, this general shape is what we aspire to have at the end of the simulation.

4.2 Employed Methods

It has been a daunting task to construct pricing scenarios that are both mathematically sound and intuitively acceptable. Several different methods were used to generate these scenarios. This section details different methods that failed and one that succeeded.

4.2.1 Historical Sampling

Most logical course of action to construct a dynamic model dependent on historical movements is historical sampling. Idea behind this is simple; pick a day in the historical data that has the same seasonal properties with the forecasted day until you have a complete series that spans 2010-2020.

Due to random picking of days, changes in the prices instead of the prices itself must be used.

4.2.2 *Methodology*

In order to prevent a general trend from emerging, data must be free of all annual trends; trend is removed by fitting linear lines through each year and subtracting it from the data. This was accomplished by spline toolbox in MATLAB; spline toolbox can employ several methods to fit different kind's constructs onto a data series (Mathworks, 2007). In order to have a linear fit with 3 different trends, order of 2 is used for the fit, which defines a linear line and since the historical data is 3 years for gas and 6 years for electricity custom knot points relating to start, end and each January 1st in the data are used.

Sampling is done on the de-trended data, each week is put into a bin with similar properties and a random sample is chosen from the respective bin corresponding to the day that is constructed. Weeks are sampled to preserve spike and seasonal behavior. Trend for the future dates are constructed from forecasted values, a running multiplication on the trend is then performed by the sampled values to reach a final scenario.

Due to multiplication of changes the resulting scenario may have extreme peaks and areas of little to no activity. Historical sampling fails to provide neither a mathematical model nor an intuitive result.

4.2.3 Mixture Models

In quantitative finance, there are several accepted models for pricing commodities. None of these models seems to give respectable results for current state of energy prices. An idea that was employed to create a stochastic model for prices was using a Ornstein-Uhlenbeck model with jumps dictated by a distribution from 2 Gaussian distribution, each of which account for different aspect of the pricing.

Although this model provided some intuitively acceptable results, mathematics behind Ornstein-Uhlenbeck process does not support mixture models for stochasticity.

4.2.4 Ornstein-Uhlenbeck Model with Correlated Jumps

Simplicity usually yields the best results, however accounting for different aspects of energy prices usually makes simple approaches impossible. Keeping the model simple while accounting for the four facts stated above was the challenge of this approach, however resulting model is both intuitively satisfying and mathematically sound.

As this is the pricing scenario model used to create the test cases, methodology will be explained exhaustively.

4.3 Methodology

Starting off with the problem of the link between electricity price and natural gas prices, one has to reach a theoretical consensus if a spike in one of these markets affects the other market. The Chi-Square Independence Test is generally used to determine links between two data sets and if anomalies between them are independent of each other or not. Performing the test shows that there is no significant evidence that a spike in one market has an effect on the other one. Thus, gas pricing model and electricity pricing model can be constructed separately.

Both electricity and gas prices exhibit significant seasonality. In addition to seasonality electricity also exhibits significant day movements. This problem is tackled by removing these seasonality effect with regressing on dummy variables and taking the error term as the base movement. In the case of electricity the regression involves daily dummy variables as well as seasonal dummy variables.

Over the course of the last 5 years energy prices have gone up significantly, mainly due to unrest at the regions producing these commodities. The rise in these prices has also driven up electricity prices. Forecasted levels already take these into account and project a likely path that the prices would follow, so it is imperative that this behavior is removed from the prices. Spline toolbox is used to fit lines for each half-year, fitted line is removed to get rid of this behavior.

The Chi-Square test performed on the electricity and gas prices showed that there was no significant evidence of spike interaction between these markets. This fact is not true for electricity prices for different hours; electricity prices for each hour behave as individual commodities with significant correlation among each other. This relationship between hourly historical prices is replicated with the stochastic model; generated scenarios have the same correlation between different hours. An important point to note here is that correlation between these components has to be derived, as the historical correlation is between different $S_t's$ but correlation between $\Delta\omega_t's$ is required for simulation purposes.

Mathematically speaking, pricing model for gas and electricity follow the general Ornstein-Uhlenbeck process:

$$\partial S_t = \lambda(\mu - S_t) + \sigma \partial \omega_t$$

Undoubtedly simulation cannot be done on continuous time, discrete time representation of the Ornstein-Uhlenbeck process is:

$$\Delta S_t = \lambda(\mu - S_t) + \sigma \Delta \omega_t$$

Scientifically speaking the parameters for mean-reversion rate, the mean and volatility have to be estimated from the historical data, this can be done using a least squares regression(van den Berg, Calibrating the Ornstein-Uhlenbeck Model, 2007).

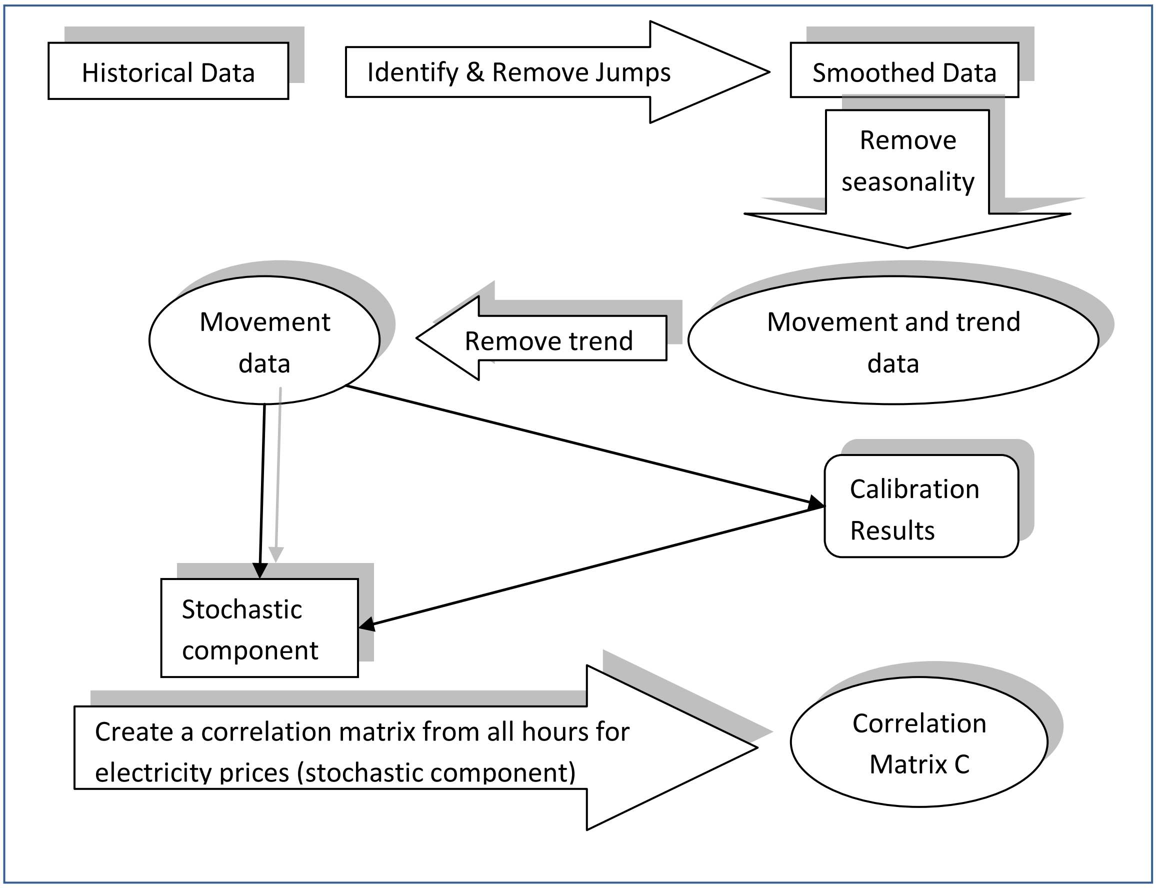

Figure 7: Calculating Correlation of Electricity Price Movements

The correlation matrix C is then used to create 24 correlated series with correlations between them equal to the correlation matrix C. This is done using the Cholesky decomposition of the correlation matrix; the resulting matrix can be used to generate correlated series from uncorrelated series by a simple multiplication (van den Berg, Generating Correlated Random Numbers, 2007). Figure 7 illustrates this process.

Natural gas price fundamentals are calculated in a similar manner, since there is only one series of data for natural gas prices, the correlation matrix is not calculated and the generated data uses a random series of normally distributed random numbers, in line with Ornstein-Uhlenbeck literature. Figure 8 illustrates the generation of scenarios, the stochastic component for gas is not correlated with any other variable, thus can be generated separately, and the electricity prices' stochasticity is generated using the method described above. Note that the average seasonality has to be removed as this is already accounted for in the generated trend.

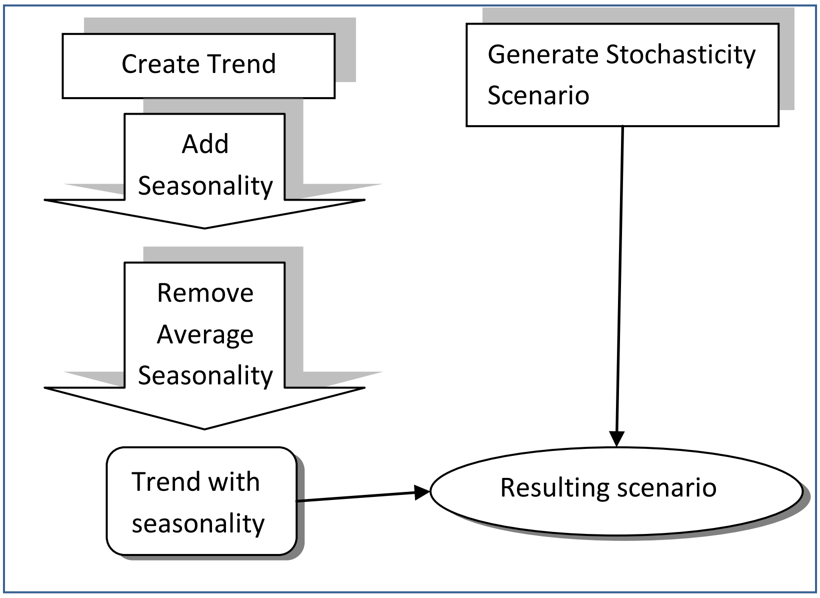

Figure 8: Generation of Scenarios

4.4 Generated Scenarios

There are six different forward curves, which are on an annual basis, since these lack monthly variation (seasonality); seasonal variation has to be added manually. Trend is created from the forward curves; average adjusted seasonality[1] is added to this trend to account for seasonal variation. Finally, random noise, modeled from historical data, is added to create resulting market pricing scenario. The base case is illustrated below, note that this price is *not* the consumer adjusted price, rather the true market price, these levels will have to be adjusted before passed into the production model. Figure 9 illustrates a generated scenario under this simulation scheme.

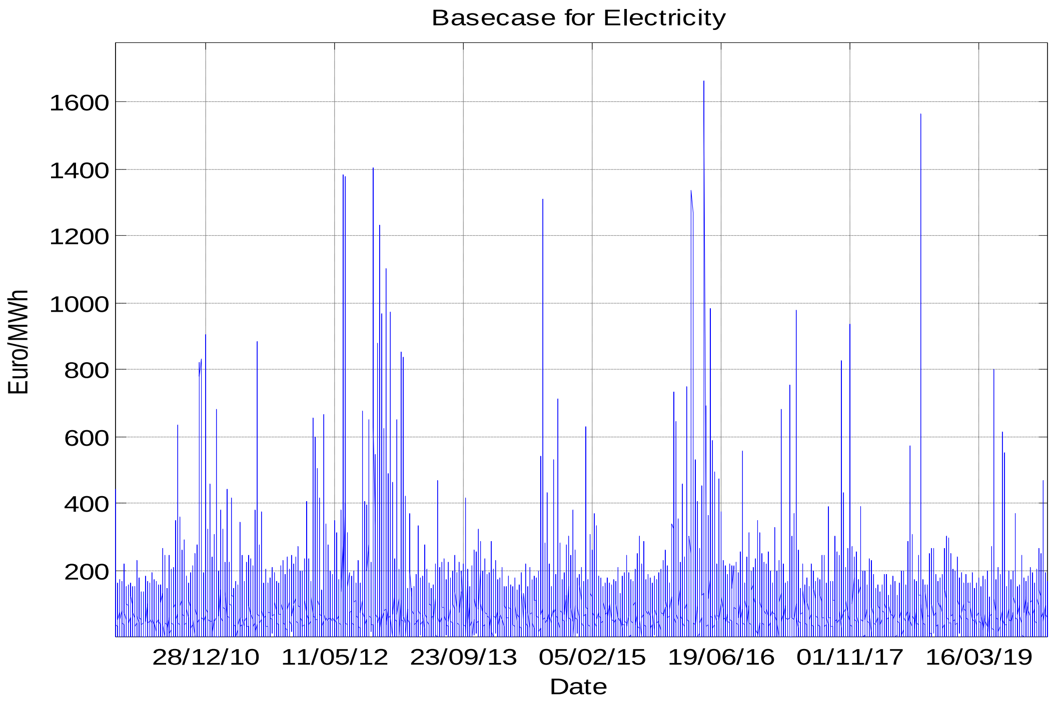

Figure 9: Generated Base Case Scenario

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[1] Average seasonality is set to zero; this is done to normalize seasonality to zero since average seasonality is accounted for in the forward curves.

The historical gas prices have also been contractual in nature for natural gas, it is the expert opinion that this pricing scheme cannot be maintained with increasing demand due to production at decentralized locations, as such market prices are a good historical base to simulate short term behavior of future scenarios.

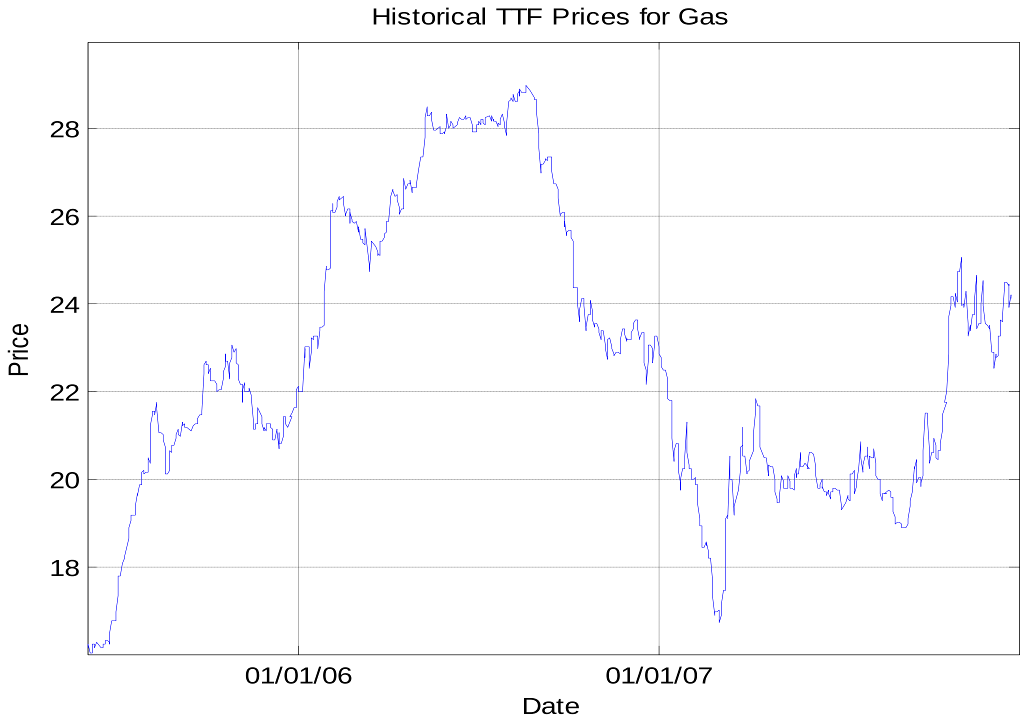

Figure 10: Historical Gas Spot Prices

4.5 Market Prices to Consumer Levels

Market prices are only a part of the total price for electricity, taxation and delivery costs usually drive prices up. One beneficial property of taxes and delivery prices is that they are linear with respect to the amount delivered, as the fixed cost of connection is usually taken care of during contracting. This fact means that one can scale up or down the price and conserve the taxation and delivery costs inherent in the price.

Currently natural gas contract price for residential homes are calculated over fuel oil averages over a six month period that is lagged two months. Pricing scheme is changed completely, so the new consumer adjusted price has to be established from the market prices.

Over the last few years, fuel oil index prices are being adjusted to match the market. This fact presents a unique opportunity for calculating consumer adjusted price. Appendix A shows the details of the calculation of the consumer adjusted price from the current customer prices.

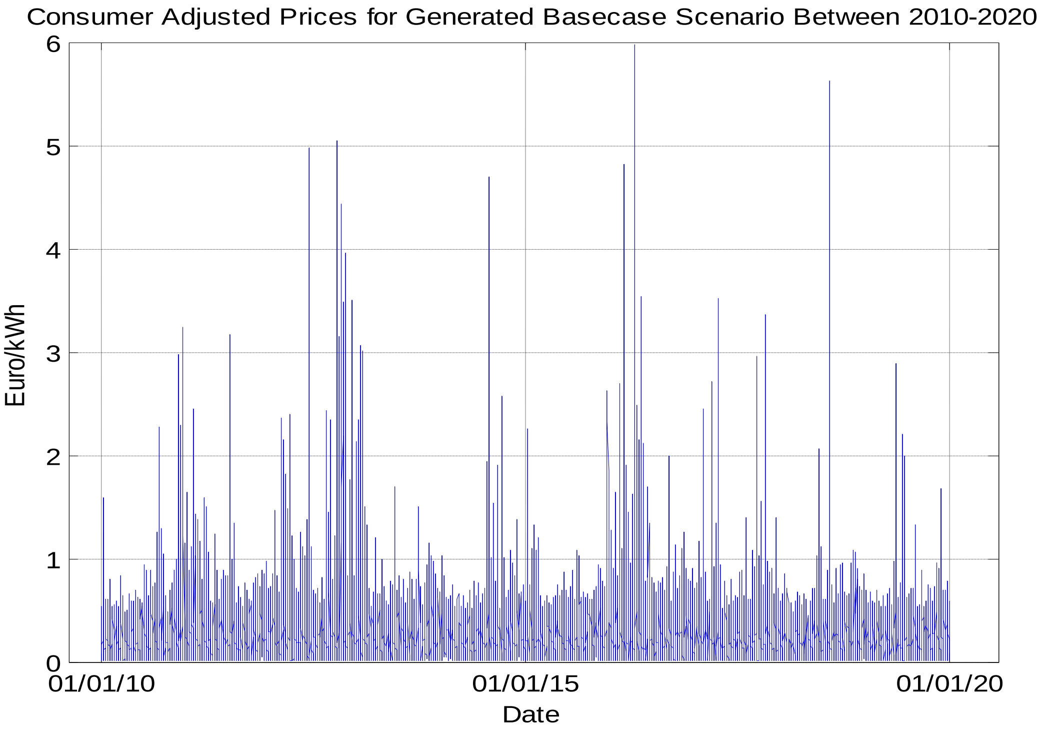

Figure 11: Generated Consumer Price Scenario for Electricity

A generated scenario for the base case gas scenario is illustrated in Figure 11. The consumer adjusted levels are again different from this figure; the consumer adjusted levels are illustrated in Figure 13.

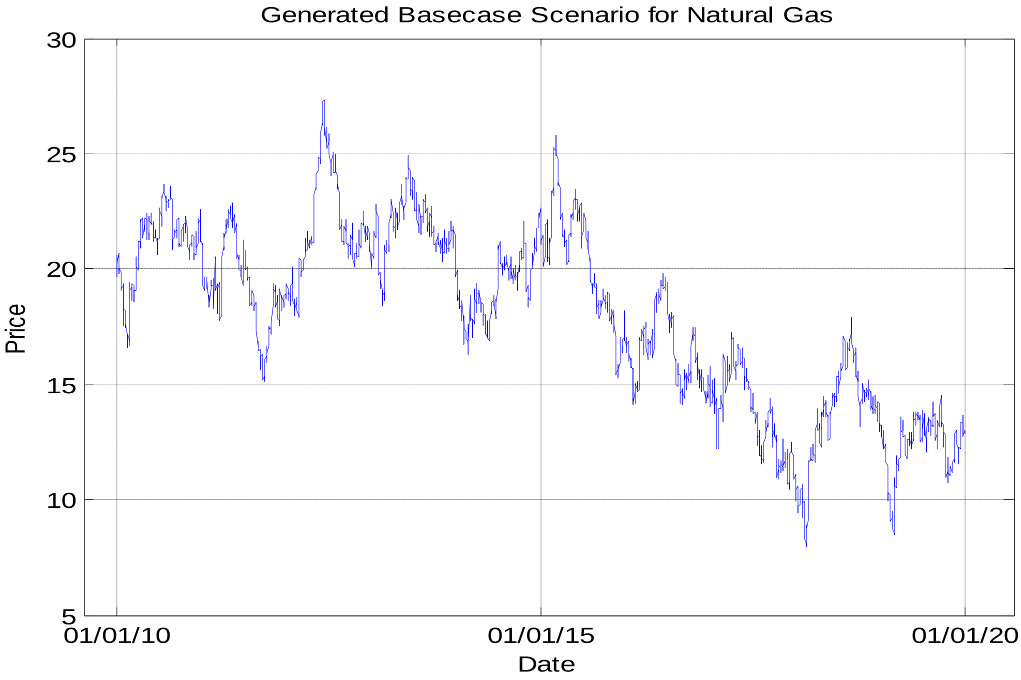

Figure 12: Generated Base Case Scenario for Natural Gas

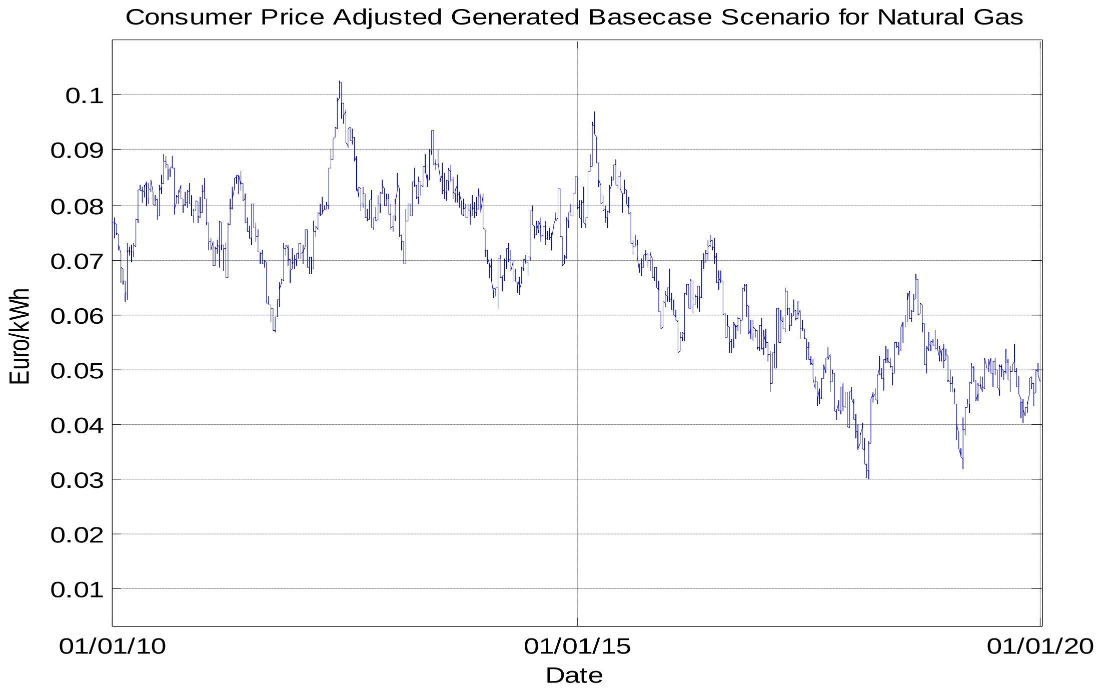

Figure 1: Consumer Adjusted Scenario

The difference from the historical market case arises from the fact that gas prices are mainly dominated by the general trend combined with seasonality.

This difference between the two can be identified easily by a visual inspection. The electricity market prices are much more dynamic, whereas natural gas market prices follow a more mellow movement throughout the year.

CHAPTER V

OPTIMIZATION MODEL

5.1 Why use optimal values?

Introduction of different decentralized technologies will undoubtedly increase the number of decisions that need to be made on a regular basis. Today, residents choose to either turn on or turn off a device. This however will change with these new technologies, at the most basic level when one turns on his/her TV, where should the electricity come from? Produce with the CHP or buy from the grid.

This dramatic increase in decisions that need to be made for household will require some kind of automation; the most logical extension to that is that these decisions will be done with the goal of minimizing cost.

The optimal decision with the goal of minimizing costs gives the best possible value for these devices. The optimal decision is an overestimation of the value of the system, but it clearly defines the upper-bounds for the values of the technologies.

Optimal decision will give the best possible generation scheme to minimize cost, in other words maximize value. Choosing the optimal value as the basis for considering the value also prevents possible criticism that might arise from additional assumptions that would be required to determine the underlying behavior.

In conclusion, although it is highly unlikely that the individuals would utilize the optimal production scheme to satisfy their individual demands; optimal behavior is the best possible utilization of the system. If the value generated under these decisions does not reconcile the investment, it simply never will.

5.2 Finding the Optimum

The optimum can be calculated with a Linear Programming (LP) method, as will be shown later on; The ‘Simplex’ algorithm is used to determine optimal production conditions with the inputs (Schrijver, 1998). As with all complex LP problems, the solution is attained using a computer.

Linear programming problems involve the optimization of a linear objective function (cost) subject to equality and inequality constraints. Although some of the variables in the optimization function in this case may not be linear, any non-linearity is handled outside the optimization. This is one of the facts forcing deterministic input to the production function.

Mathematically speaking one can informally define the problem as:

$Min\ Cost$

$subject\ to: Electricity\ Supply\ \geq Electricity\ Demand$

$Heat\ Supply\ \geq Heat\ Demand$

Unfortunately; mathematical definition of the problem requires quite a lot more constraints and complex definitions. In order to define the problem mathematically one needs to establish the notation beforehand. The following definitions are used in the mathematical definition:

The notation used below can be confusing due to the sheer number of terms and variations; however there is a simple logic behind all the notations used below, and it is quite intuitive.

Terms P, Cap, V, S and eff refer to Capacity (kW[2]), Volume (kWh), Storage (kWh), and efficiency, respectively. Prices follow a different notation but it is quite easily deducted G is for gas, b is for buying from grid and s is for selling to grid.

For scripts:

Capital letters G, H, T, and S refer to Generator, Heater, Transfer and Storage respectively.

Lower case letters e, h, g, in, out, bought, and sold refer to electricity, heat, grid, in to storage, out of storage, buy from grid and sell to grid respectively.

Units: Throughout this paper units are assumed to be in kW for power, kWh for energy and storage, prices are in €/kWh with a time step of 60 minutes or 1 hour.

Inputs to the model as mentioned in earlier chapters have the notation:

$D_e(t)$: Electricity demand.

$D_h(t)$: Heat demand.

$P_G(t)$: Price of natural gas.

$P_b(t)$: Electricity price if bought from grid.

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[2] Capacity is measured in watts, but due to hourly optimization some sections might use kWh as the unit.

$P_s(t)$: Electricity price if sold to grid.

S_{in}: Initial storage.

These variables are taken as exogenous; any interaction between them should be accounted for beforehand, and only real values must be passed to the production model to prevent any non-linearity.

Formally speaking the LP is; a similar LP approach that was used for minimizing environmental impact of large scale buildings (Osman & Ries, 2006):

$$minimize \sum_t P_g(t) * V_e(t) + P_g(t) * V_h(t) + P_b(t) * V_e^{bought}(t) - P_s(t) * eff_T^G * V_e^{sold}(t)$$

$Subject\ to$:

Demand matching

$$D_e(t) \le eff_G^e * V_e(t) + eff_T^G * V_{eb}(t) - V_{es}(t) + eff_T^e * S_{out}^e(t) - S_{in}^e(t) \quad \forall t$$

$$D_h(t) \le eff_G^h * V_e(t) + eff_H^h * V_h(t) + eff_T^h * S_{out}^h(t) - S_{in}^h(t) \quad \forall t$$

Capacity constraints $0 \le V_e(t) \le Cap_G \quad \forall t$

$$0 \le V_h(t) \le Cap_H \quad \forall t$$

$$0 \le S_{in}^e(t), S_{out}^e(t) \le Cap_T^e \quad \forall t$$

$$0 \le S_{in}^h(t), S_{out}^h(t) \le Cap_T^h \quad \forall t$$

$$0 \le V_e^{bought}(t) \le Cap_T^g \quad \forall t$$

$$0 \le V_e^{sold}(t) \le Cap_T^g \quad \forall t$$

Storage constraints

$$0 \le S_i^e + eff_T^e * \sum_{\tau=1}^{t} S_{in}^e(\tau) - \sum_{\tau=1}^{t} S_{out}^e(\tau) \le Cap_S^e \quad \forall t$$

$$0 \le S_i^h + eff_T^h * \sum_{\tau=1}^{t} S_{in}^h(\tau) - \sum_{\tau=1}^{t} S_{out}^h(\tau) \le Cap_S^h \quad \forall t$$

In words, the optimization problem can be narrated. Minimize cost, while generating enough supply to satisfy electricity and heat demand, while not exceeding production capabilities of the devices and not over-utilizing storage capabilities.

Different efficiencies and capacities can be used to define different technologies. A Simple example would be the stirling engine and the Ceres Fuel Cell, setting efficiency and capacity variables as the 3rd column of Table 1 will give the setup for the WhisperGen stirling engine with no storage capabilities, whereas setting efficiencies and capacities as the last column of the table gives the setup of a Ceres fuel cell with 5 kWh of heat storage and no electricity storage capabilities. Both setups include a High-efficiency boiler (HR), although this can be turned off in the model, it is unlikely that a household would be without at least a backup heat generation device.

Table 1: Capacity and Efficiency Table

Term	**Definition**	**WhisperGen Stirling Engine**	**Ceres Fuel Cell**
eff_G^h	Heat Efficiency of CHP	0,81	0,60
eff_G^e	Electrical Efficiency of CHP	0,09	0,20
eff_H^h	Hear Efficiency of HR	0,95	0,95
eff_T^G	Transfer Efficiency from Grid	0,90	0,90
eff_T^e	Storage Efficiency for Electricity	0,70	0,70
Cap_G	Input Capacity of CHP	12	1,6
Cap_H	Input Capacity of HR	8	8
Cap_T^e	Capacity to Transfer Electricity to Storage	0	0,5
Cap_T^h	Capacity to Transfer Heat to Storage	0	0,8
Cap_T^g	Capacity to transfer Electricity from/to the Grid	2	2
Cap_S^h	Capacity of Storage for Heat	0	5
Cap_S^e	Capacity of Storage for Electricity	0	0

Heat storage defined for the Ceres in the table is a 5 kWh storage tank, with up to 0.5 kWh Wh of energy transferable every hour. Transferring heat energy would result in 20% of energy to be lost. Transferring heat from storage will also result in a loss of 20% of the heat transferred.

5.2.1 Limitations

Due to the deterministic nature of the model, every point in time is considered as a decision parameter. This has the implication that there are 8 decision variables per hour adding up to 192 decision variables per day, with an optimization interval of 10 years it is impossible to have a single optimization for the whole period.

Computer and programming limitations, limit the total number of days that can be optimized at once. A work around is to optimize on a monthly basis. Optimization is done on a single month and storage values are carried on to the next month, and then the optimization is done on the following month.

This limitation is negligible, as the necessary inputs are carried over to next optimization sequence.

5.2.2 Model Validation

The constructed model has no built in validation. In order to do a complete validation of the results a new model has to be constructed. However, interpretation of the results gives a good indication on the validity of the model.

The results from the model appear to be intuitively correct. Several examples are:

- A high price in electricity and a low price in gas, triggers over-production of heat. While the HR is offline, the cogeneration unit is active when the cost of production is offset by the profit acquired by selling.
- A low price of electricity in the summer, triggers minimal production levels from the cogeneration unit, while keeping the HR offline.

- If the buy price is below the sell price, the system will exploit the market by buying and selling to the same market.
- Heat and electricity demand are matched exactly most of the time, electricity supply is never over demand, since excess is sold to the market.
- Heat supply may be more than demand, when the price situation is right for overproduction.
- Control run on a household with current setup[3] of pricing and consumption levels[4], gives approximately the same cost for energy calculated by hand.
- Installing a CHP in to a household as an additional technology never increases the energy cost of the house.

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[3] No Cogeneration unit, pricing scheme same as residential tariff in 2008.

[4] 3500 kWh of electricity consumption, 9600 kWh of heat consumption.

CHAPTER VI

TECHNOLOGIES

The world is driven towards a more energy conscious behavior as energy needs are increasing more and more everyday; yet energy resources are dwindling. Several technologies with the goal of alleviating this problem are emerging into the market, decentralized production are one of these technologies, that strive to decrease overall consumption of fossil fuels through increasing efficiency, or producing with renewable energy sources.

The model can be adapted to encompass several emerging technologies, although each technology is unique in its own way, the model is flexible enough to accommodate most of the emerging technologies. Main limitations of the model can be listed as:

- The model assumes there are up to two distinct generation devices.
- There can be no negative flow on any of the internal transfer mechanisms.
- There are only two storage “tanks”, one for heat and one for electricity, hot water and hot air are indistinguishable internally.

The design of the model is to maximize flexibility without compromising from quality. As such, the model has no limitations on demand values, electricity demand might be negative, this allows modeling of perpetual generation[5] devices where the demand of the residence is low and production is high.

The technologies below are some of the emerging technologies that are going to have a growing impact on the market in the next decade. There are two main types of generation devices, perpetual generation devices and cogeneration devices.

6.1 Perpetual Generation Devices

Perpetual generation devices work without input or manipulation from the end-user. After installation, energy is generated dependent only on the environmental factors. Solar panels' generation depends on the irradiation, whereas a wind turbines generation is dependent on the wind speed.

6.1.1 Solar Panels

Solar panels generate electricity if there is sunlight present. Turning them off is possible but not the usual practice as they have no marginal cost of production. Expected production can be taken off the electricity demand, should the electricity demand fall below zero, model will correct this by increasing the amount it sells to the market.

On the modeling side solar panels can be incorporated into any other system, as there is no decision to be made on how much electricity it would produce. Taking the production off of demand is sufficient to model solar panels and no further

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[5] Perpetual generation: This term simply refers to technologies that run without inputs that can be bought, sold or manipulated.

assumptions have to be made. Amount produced can be approximated from irradiation levels taken from the Schipol meteorology station; however this implementation will ignore irradiation effects on electricity demand; during sunny day’s electricity consumption is significantly less than a cloudy day.

6.1.2 Wind Turbines

Like solar panels, wind turbines can be modeled by subtracting production of these devices from the electricity demand.

From the modeling side, wind turbines are not much different from solar panels. Production from solar panels depends on the irradiation, whereas production from wind turbines depends on wind speed. Like solar panel production, wind turbine production can be subtracted from demand to model the behavior.

6.2 Cogeneration Devices

The model accounts for up to one cogeneration device in the residence and another conventional heating component, for replacement devices – cogeneration device replaces conventional heating component, conventional heater can be disabled by setting intake capacity to zero and production efficiency to zero.

Cogeneration devices use natural gas as the energy source, and output both heat and electricity energy, the decision to turn on/off the device is done such that total energy cost of the house is minimal.

There are several emerging technologies that are going to enter the market in the coming years, below are some of these devices. The model cannot accommodate two or more cogeneration devices; although adding another cogeneration device is not difficult; it will almost double the number of decision variables. Theoretically converting the model to accommodate two or more cogeneration devices is easy, however it will significantly decrease optimization period due to the increased number of decision variables.

6.2.1 Stirling Engines

Stirling engines are a replacement technology to conventional heaters. Depending on the scenario conventional heating device can be disabled as described in the previous section. Stirling engines have high heat output and low electricity output. Modeled stirling engine is essentially a HR-boiler with stirling engine attached to it; electricity production can be turned off at will.

6.2.1.1 Modeling Side

The modeling side is not complicated, adjusting efficiencies and capacities are enough to model this layout. The efficiencies for the WhisperGen Stirling engine are used in the tests.

6.2.2 Fuel Cells

Fuel cells are not a replacement technology as their heat output is considerably lower than the heat demand of a residence. Coupled with a high efficiency boiler, these devices supply the heat demand of the house, electricity is supplied both from the grid and the fuel cell.

6.2.2.1 Modeling

Modeling this system is simply a matter of adjusting efficiencies to specifications of the devices used.

6.3 Additional Design Components

Heat and electricity storage are also incorporated in the model, although not tested as standalone products, they are tested with different setups to explore their usefulness for the different devices.

6.3.1 Electricity Storage

Design of the model contains an electricity storage component, today no viable technology exists to store electricity effectively but it is incorporated nonetheless. Electricity storage is tested on a 5 kWh capacity device with 90% storage efficiency. Although this setup is not realistic it gives an idea on the general utilization of the storage in combination with any of the devices.

6.3.2 Heat Storage

The heat storage component is not complicated. Due to linearity of the optimization problem; any heat loss has to be taken into account outside the model. This assumption is not ideal however, with carefully designing the external factors its effects can be minimized. Decreasing stored energy between optimization periods is the simplest and most effective solution to this problem.

It is essential for the designer to decide when and how to account for heat loss, seasonal and daily storage systems have very different properties and behaviors. Heat storage estimates are based on a rather large hot water tank, 210 liter hot water tank was used as the specifics when the heat storage is activated, this device is assumed to have 80% efficiency, and in other words 80% of the heat stored can be used at a later time.

6.4 Tested Technologies

It is important to establish the brand of the cogeneration device as it might affect the results greatly. Comparing different devices are like comparing automobiles, specifying the type is not enough on its own. Different brands yield different results, although both BMW and Toyota might have SUV’s, their emphasis are different. BMW might focus on performance, whereas Toyota might focus on efficiency.

6.4.1 WhisperGen Stirling Engine (on-grid)

The WhisperGen stirling engine is the foremost market ready stirling engine entering the Dutch market today. Combined efficiencies are reported to be at 95% almost at par with high efficiency boilers. Most of the WhisperGen's energy output is in the form of heat, electricity output is only 15% of the total efficiency.

6.4.2 Ceres Fuel Cell (Alpha Unit)

The Ceres Fuel Cell is one of the fuel cells with a promised combined efficiency of 80%. Its main advantage is that it can be turned on and off without degrading the fuel cell stack. The energy output with minimal heat production is 60% electricity and 20% heat(CeresPower, 2008).

6.4.3 CFCL Fuel Cell (Net~Gen)

The CFCL Fuel Cell is another fuel cell company that promises a combined efficiency of 80%(Ceramic Fuel Cells Ltd., 2008), although current levels do not achieve this level of efficiency. Tests are conducted on promised efficiencies. CFCL energy output is evenly divided with equal production on heat and electricity.

6.4.4 AVA Solar Inc. Solar Panel

Solar panels come in a variety of flavors, although conversion efficiencies of $\sim 40\%$ are achieved by researchers, they usually come at a much higher cost than less efficient counterparts. For the purposes of this thesis AVA Solar Inc. panels are tested. AVA estimates a cost of 1€/ Watt, efficiency is reported at$\sim 15\%$.(AVA Solar, 2008)

In layman's terms, for a $6\,m^2$AVA solar panel peak production is 1 kWh at peak solar insolation at 22nd of June for 2010.

6.4.5 Bergey Micro Wind Turbine (Bergey XL.1)

Wind turbines range in shapes, sizes and implementation, for the purposes of this test the Bergey Micro Wind Turbines are tested, which seem to be the most applicable for a household. Production capability is reported as 1000 Watts at 11 m/s(Bergey Wind Power, 2008). Wind energy is a relatively different technology, with non-linear relations with wind speed. Details of the production with Bergey XL.1 are in the Appendix.

The wind turbine is modeled by first estimating a wind speed profile for the target period, than a simple lookup is performed on the values calculated in appendix B.

Table 2: Summary Table

Brand	**Type**	**Capacity**	**Electrical Efficiency**	**Heat Efficiency**	**Cost**
WhisperGen	**Stirling Engine**	12 kWh	9%	81%	4500€
CFCL	**Fuel Cell**	2,5 kWh	40%	40%	10000€
Ceres	**Fuel Cell**	1,7 kWh	60%	20%	10000€
	HR-Boiler	11 kWh	0%	95%	2000€[6]
Bergey	**Wind Turbine**	1,5 kWh	n/a	n/a	1700€[7]

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[6] Note that lifetime of these devices are assumed to be 20 years.

[7] Does not include tower installation, tower installation costs another 1000€.

AVA Solar	**PV Cells**	1 kWh[8]	15%	n/a	1000€

This table summarizes efficiencies, prices, and capacities of the different technologies examined. Note that Cost of the device has no bearing on the analysis; cost is used after the analysis to explore feasibility of these devices, with mass production and improvements in technology these prices are expected to decline for most of the devices.

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[8] Capacity can be scaled to any specification as the capacity depends linearly on the installed amount of solar panels.

CHAPTER VII

SCENARIOS

Value of decentralized energy production devices vary greatly with different pricing and market conditions. In order to draw concrete results these cases have to be examined in detail, and identify important points that affect the value of decentralized production.

Throughout this analysis, Ceres FC is reported unless noted otherwise, other device analysis can be found in the appendix. Following table is an exhaustive list of scenarios and setups for which the simulation is run. These scenarios are chosen with the goal of identifying factors that might affect the value of decentralized production units. Running every scenario combination shifts the focus from important parts of the analysis, and is very repetitive.

Scenarios are chosen specifically to identify different behaviors, for example variation on base case electricity with natural gas scenarios illustrate the effect of natural gas price on the overall value of the system. Similarly, having a high CO_2 penalty case with low natural gas price illustrates the effect of high electricity price with significantly reduced in-house production.

Table 3: Scenarios

Electricity Case	Natural Gas Case	Setup
Base case	High	Heat Storage
Base case	High	No Storage
Base case	Base case	Heat Storage
Base case	Base case	No Storage
Base case	Base case	Electricity Storage
Base case	Low	Heat Storage
Base case	Low	No Storage
High CO2	Low	Heat Storage
High CO2	Low	No Storage
Low CO2	High	Heat Storage
Low CO2	High	No Storage
High Fuel	High	Heat Storage
High Fuel	High	No Storage
Low Fuel	Low	Heat Storage
Low Fuel	Low	No Storage
High Renewable	High	Heat Storage
High Renewable	High	No Storage
High Renewable	Base case	Heat Storage
High Renewable	Base case	No Storage
High Renewable	Low	Heat Storage
High Renewable	Low	No Storage

Demand variation is also taken into account; each of these cases is run for both regular demand profile and high air-conditions use during summer.

Stochasticity of the model allows an unlimited number of scenarios to be constructed; scenarios are generated for each technology separately. Although scenarios are unique for each device, a baseline case is run on each scenario (no production capabilities, single HR boiler and grid electricity) to investigate the added value of a production device.

Generated natural gas price scenarios for Ceres Fuel Cell under normal demand are illustrated in Figure 14Figure .

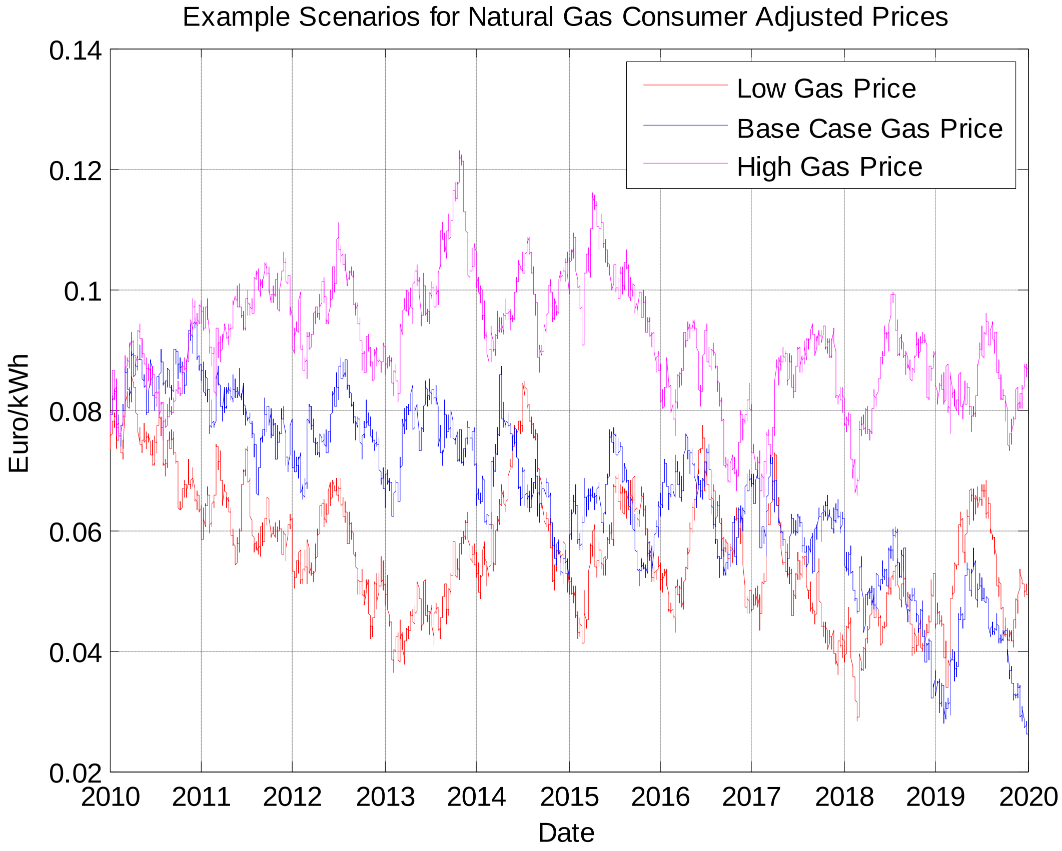

Figure 14: Natural Gas Scenario for Ceres Fuel Cell

Electricity pricing scenarios are generated in a similar manner, plotting all scenarios for electricity prices is redundant. Figure 15 illustrates three different setups for electricity prices. All electricity scenarios will share the same spike behavior; this is done to ensure that results are comparable to each other. Spikes constitute a significant variation in value, if they are randomized for each scenario, the resulting scenarios would not be comparable to each other.

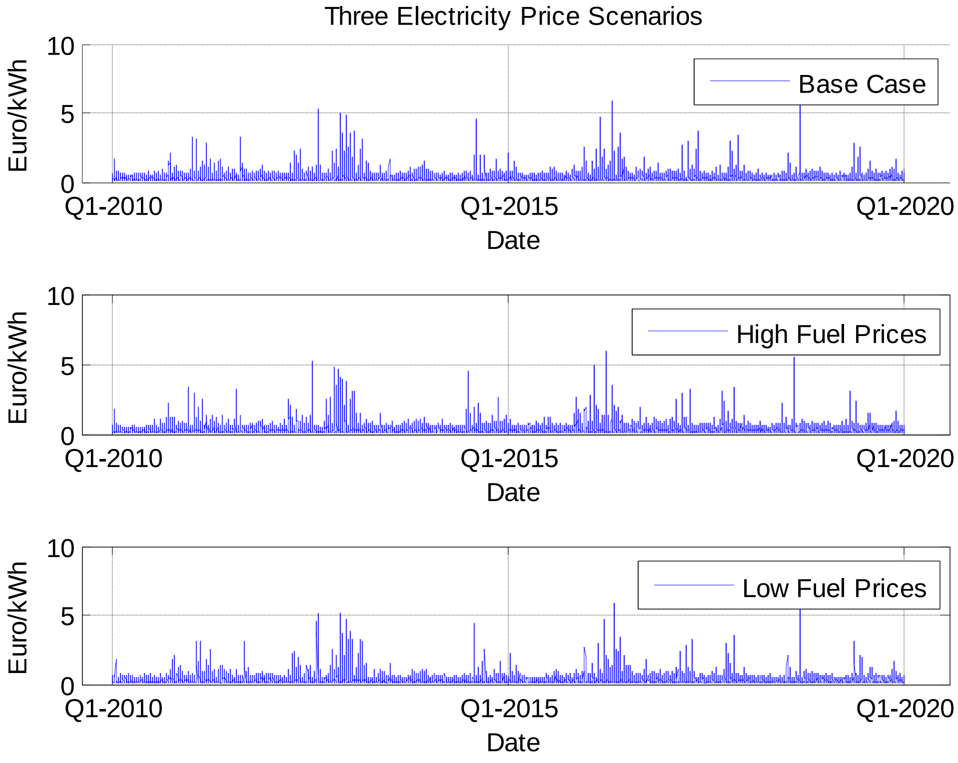

Figure 15: Electricity Price Scenarios for Ceres Fuel Cell

Each device is evaluated with a combination of these scenarios;

Table details these combinations of scenarios. Each of the devices is evaluated under these scenarios and added value is measured by reference to the baseline case, which is the HR-boiler with no CHP case. Demand also plays an important role in determining the value of these systems, as such all calculations are repeated for the high demand case.

7.1 Normal Electricity Demand

Plotting all 21 cases hinders the ability to analyze the cases as the graphs are littered with lines. Creating bounds rather than plotting every case in order to demonstrate the importance of the scenarios enables the reader to grasp the change in value of these systems.

Figure 17 illustrates the maximum and minimum costs for energy for the baseline case; this is calculated over the scenarios for Ceres Fuel Cell. The figure illustrates the bounds with CHP under the same scenarios; negative cost can be interpreted as making a profit by selling electricity to the market.

It is important to note that figures depict energy costs; they do not include the initial investment cost. Cost of energy includes every cost related to energy cost of a household, such as natural gas and electricity bought and sold to the grid. Energy cost of a household can be calculated by:

$$\begin{aligned}&Cost\ of\ Energy = \\ &Natural\ Gas\ Cost + Cost\ of\ Electricity\ Bought - Profit\ from\ Electricity\ Sold\end{aligned}$$

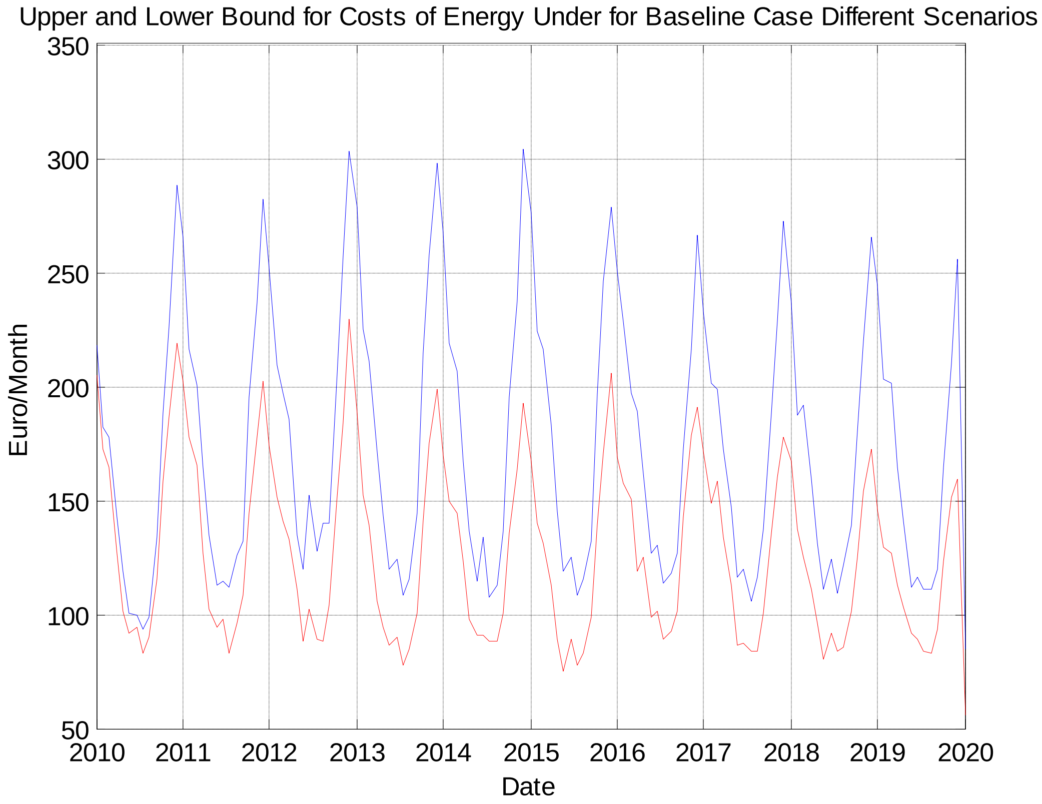

Figure 16: Upper and Lower Bound for Cost of Energy for no CHP

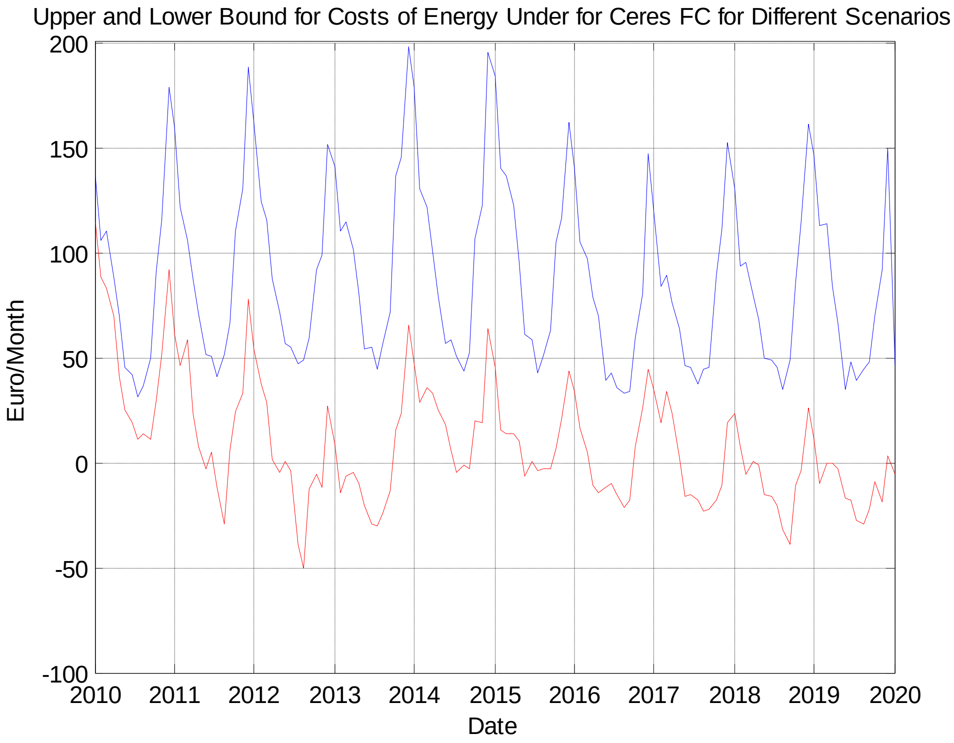

Figure 17: Upper and Lower Bound for Cost of Energy for Ceres FC

It is evident from figure 17 that different scenarios do have significant effect on the negative cash flow generated, and thus in the value of the system. Figure 17 shows that this effect is even more so with a CHP device installed.

7.1.1 Effect of Gas Prices

First 7 scenarios give a good indication on the variation of value with respect to changing natural gas prices, to see this effect one has to look for the variation in negative cash flow under the gas price scenarios in Figure 19 and electricity price Scenario in Figure 18.

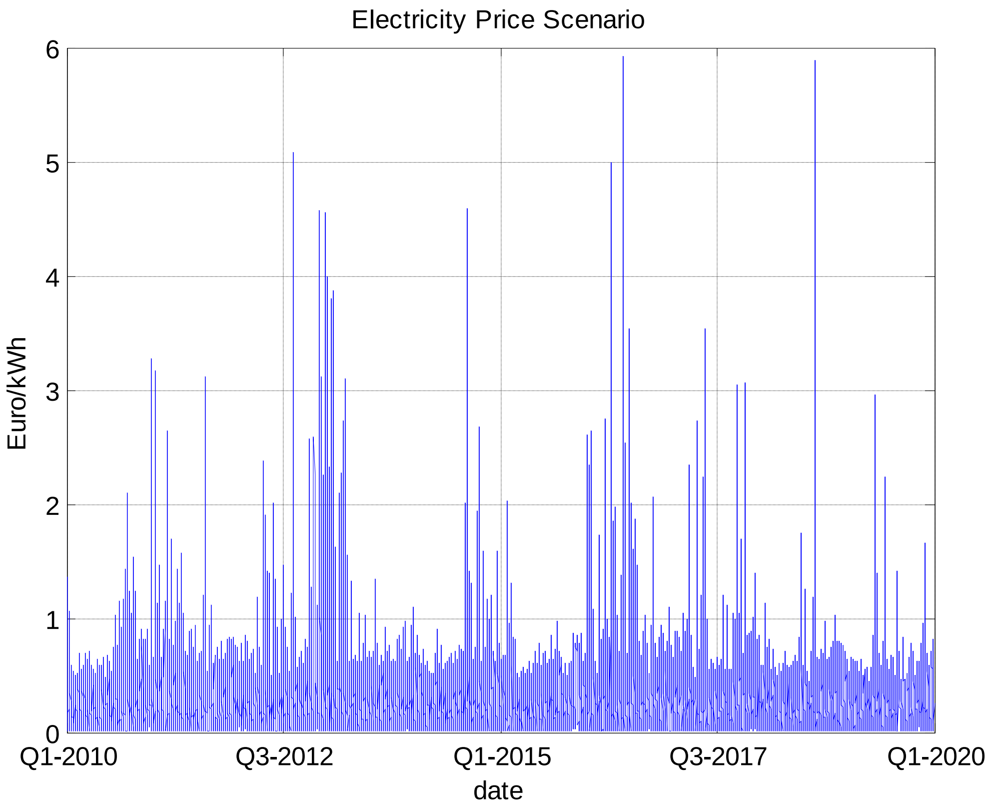

Figure 18: Base Case Electricity Scenario for Ceres FC

Corresponding cash flow variance is illustrated in Figure 19 for a regular household and for a Ceres FC household in Figure 18. It is easy to see that variation in gas prices have a much larger impact on a Ceres FC household than a regular household.

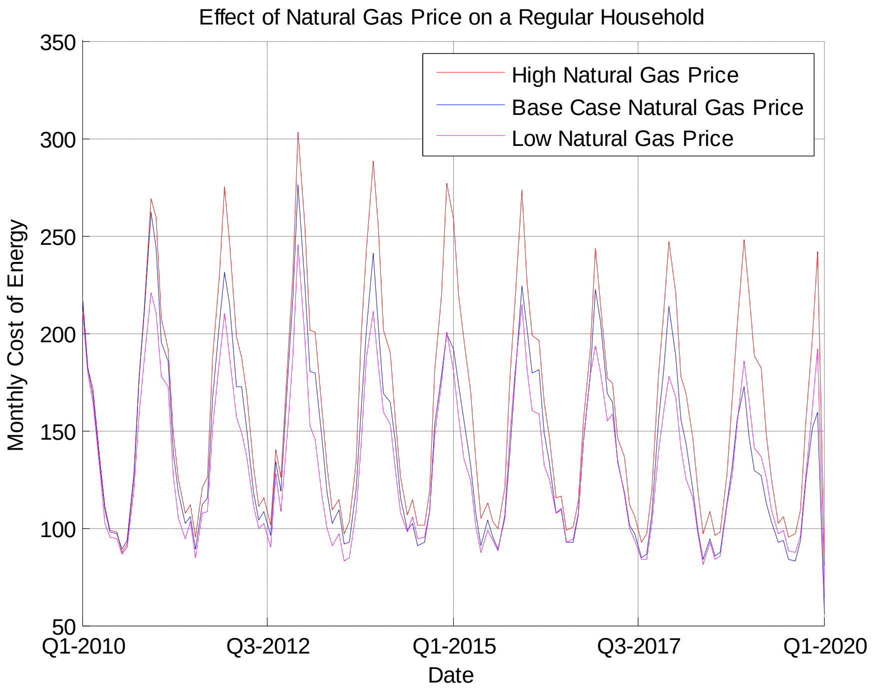

Figure 19: Negative Cash Flow Variance under Different Natural Gas pricing Scenarios

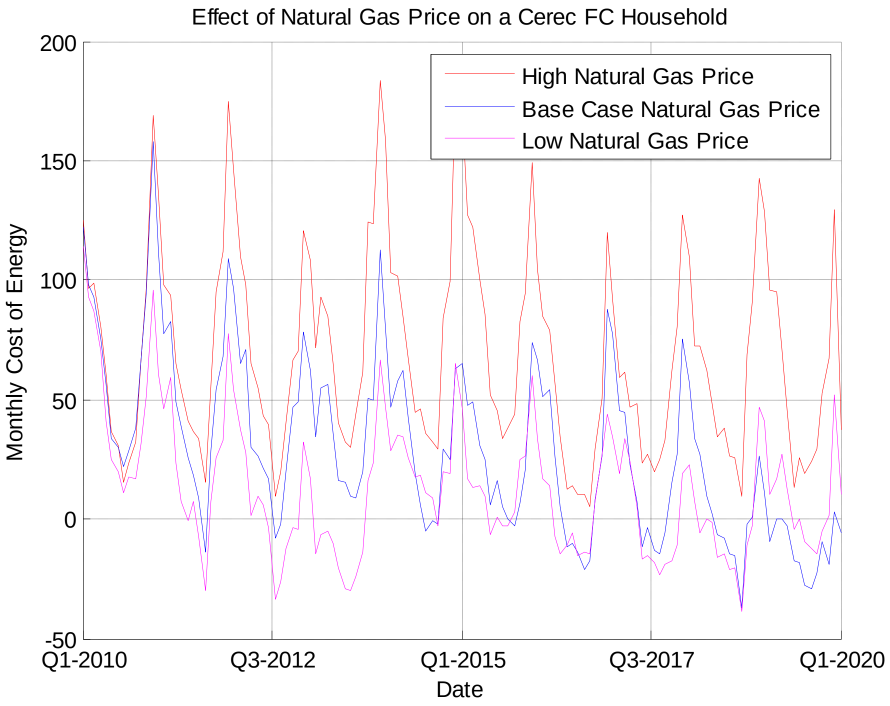

Figure 20: Negative Cash Flow Variance under Different Natural Gas pricing Scenarios for Ceres FC

7.1.2 Effect of Electricity Price

Electricity prices are generally dominated by random movement more than the actual trend. However, the effect of the price of electricity is still a very important factor in the overall value of the system. In order to capture this effect, keeping natural gas price scenario constant and varying the electricity scenario is the best way to reveal the effects of the electricity price on total value.

Fixing natural gas price scenario to high, and looking at the base case, low CO_2 emission penalty, high fuel, and high renewable case should reveal the effect of electricity price on the cash flow.

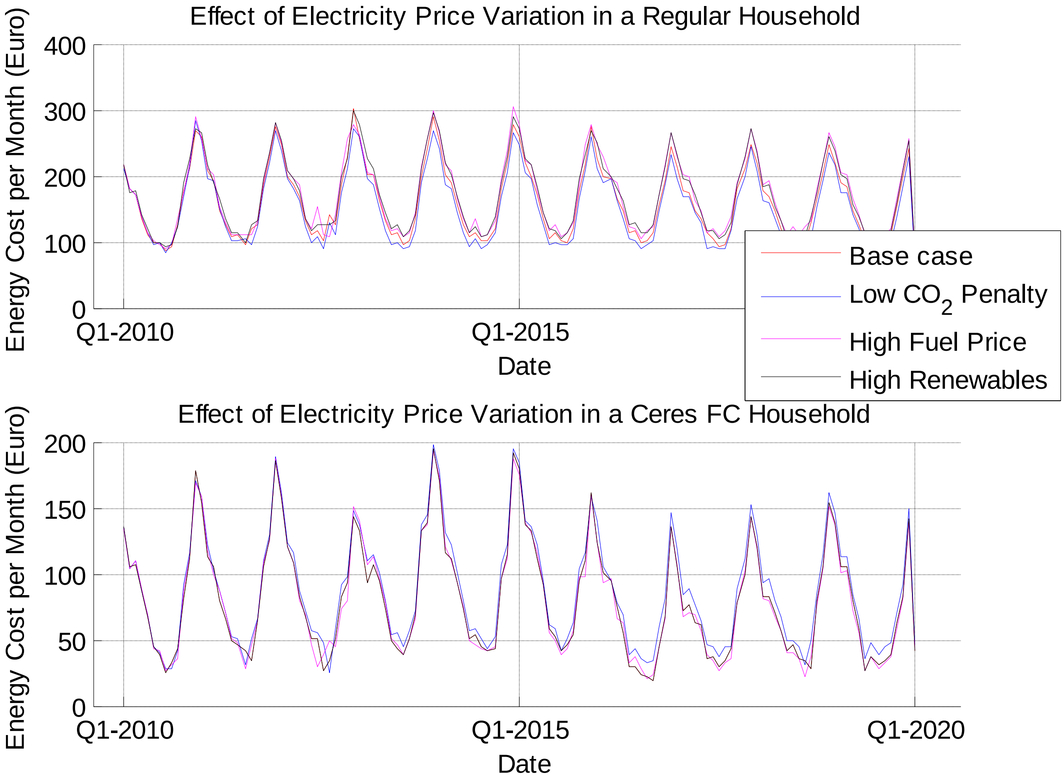

Figure 21: Effect of Electricity Price Variation

Contrary to natural gas price variation, electricity price variation has less effect on Ceres FC, compared to regular household, although still lesser than regular household variation in value is somewhat larger during summer months for Ceres FC, this is most likely caused by the limited production due to smaller demand during summer months. This is to be expected, as more production capability is installed in a house, that household is more “hedged” to variations in electricity prices. Figure 21 illustrates this effect, lower graphs’ (Ceres FC household) variation is much less than the upper graphs’.

7.1.3 Effect of the Spark Spread

Effect of the spark spread can be summarized as the difference in levels of electricity price and natural gas price. Inherently these prices are different however, what is meant by spread is the difference between two cases such as *high natural gas* and *low electricity* price and *low natural gas* and *high electricity* price.

In order to clarify, setups with both electricity and natural gas price scenarios having the same trend will be similar scenarios. Setups with electricity and natural gas scenarios with different trends will be dissimilar scenarios. Figures 22 and 23 illustrate the effects of similar scenarios and dissimilar scenarios respectively.

Convergence in Figure 22 suggests that when setups are similar, level of individual scenarios are not important, without a difference between electricity and gas price trends, savings are almost the same between *high* case and the *low* case.

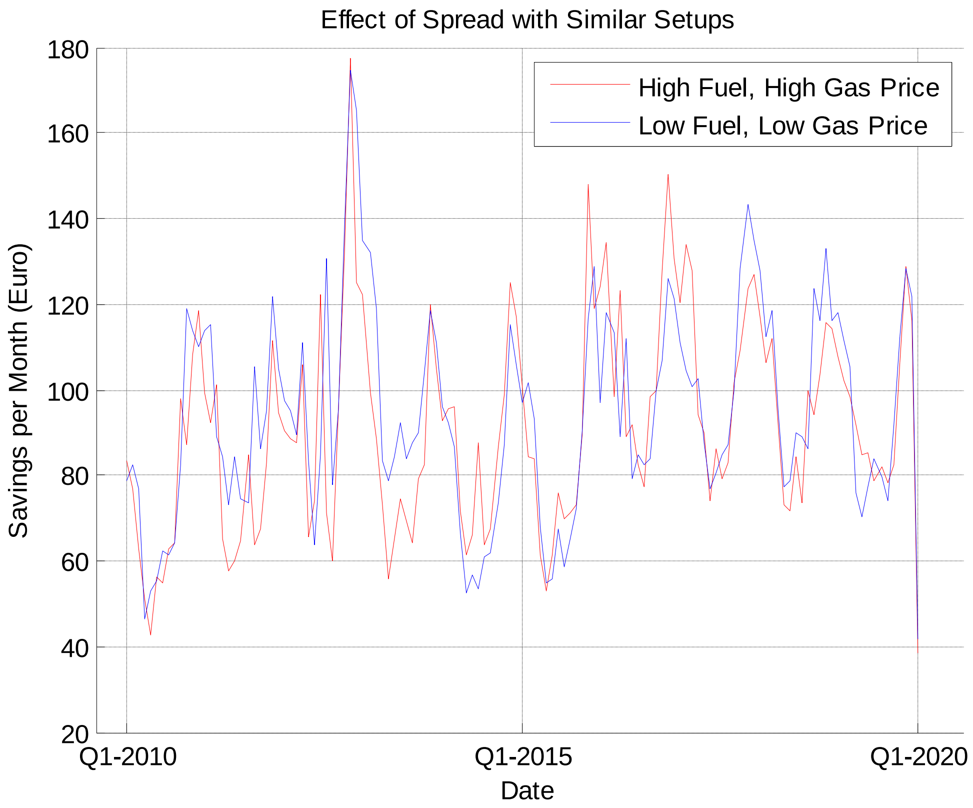

Figure 22: Similar Spread Scenarios

Intertwined graph Figure suggests that, if electricity and gas scenarios are in sync, overall level has little effect. This does not mean that it has no effect; still savings will be higher on the *low gas price* case.

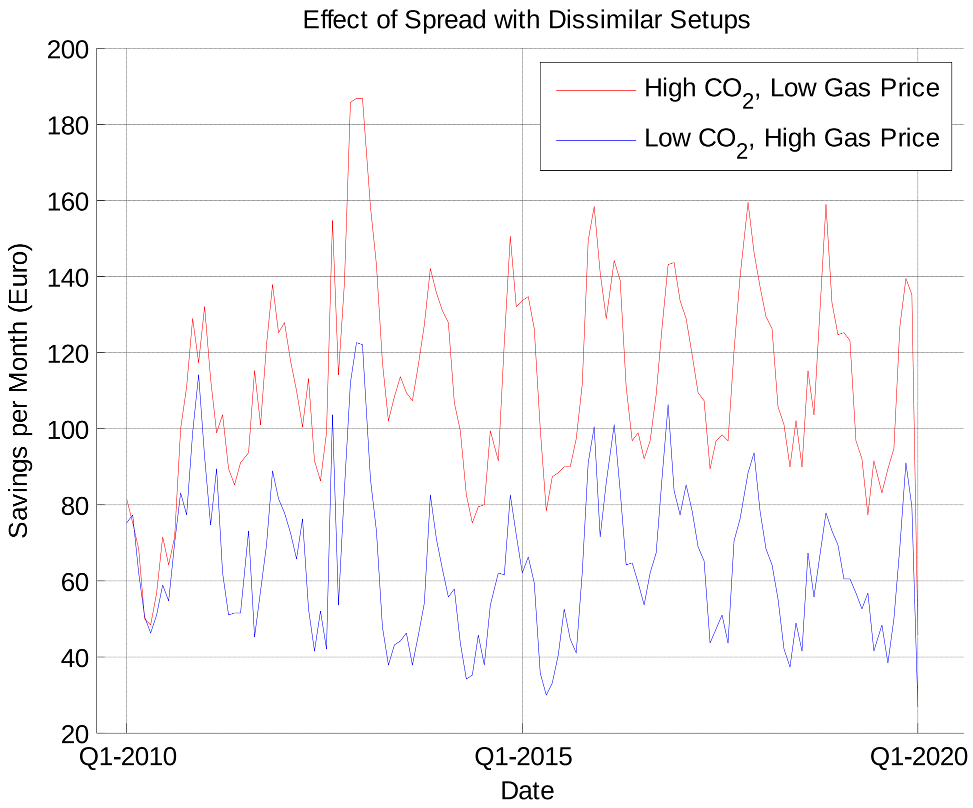

Figure 23: Dissimilar Spread Scenarios

Divergence in Figure 23 suggest that when there is a dissimilar setup, savings will be significantly more on the case with *low natural gas* price setup. In other words, natural gas price will dominate the value of the system, regardless of the electricity price setup.

7.1.4 Summary

Ceres FC is among the most promising technology among all CHP technologies; however it still fails to become a viable investment in any standards. High risk to return ratio, significant upfront investment and no prospect for profit makes Ceres FC an abysmal investment.

CHAPTER VIII

RESULTS

Plots generated for this section use *base case* for both electricity and natural gas prices unless noted otherwise. This is done to keep number of plots to a manageable level, contrary to previous section; results from every generation device are reported under their respective sections.

8.1 Ceres Fuel Cell

It would be redundant to plot all of the cases for production, however it might be useful to demonstrate the difference in supply for a case where electricity storage and production is enabled and a case where only production is enabled, no CHP case is trivial as all of the electricity is supplied from the grid. Figure 24 illustrates different sources used to match the electricity demand of a household with Ceres FC during winter months, summer months do not exhibit a different behavior due to high electricity/heat ratio of Ceres FC.

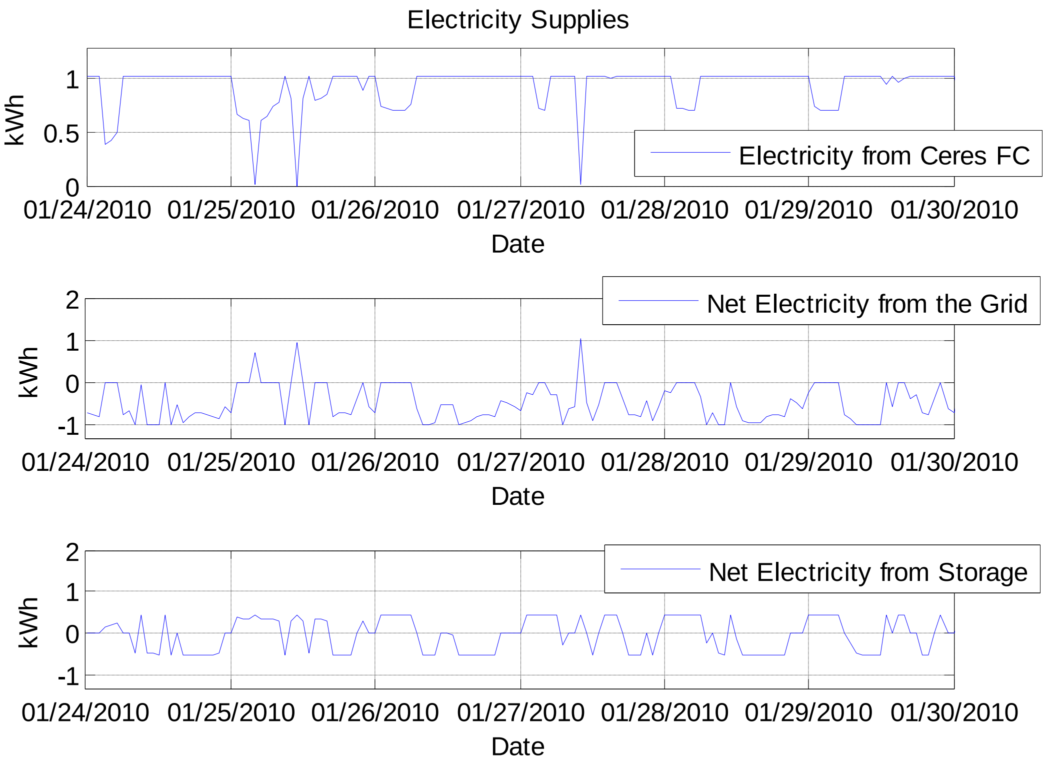

Figure 24: Electricity Supplies for Ceres CHP with Electricity Storage

Looking at Figure 24, one can easily verify that electricity supply is at least matched throughout. Due to high number of data points plotting over the whole period does not provide intelligible graphs. It is important to see the seasonal variation in utilization of a CHP, Figure 27 depicts this variation. It is clear that, although heat and electricity demand play an important role in the utilization of a CHP they are not the only factors that affect the utilization of the CHP. This can easily be identified in utilization difference between July and May.

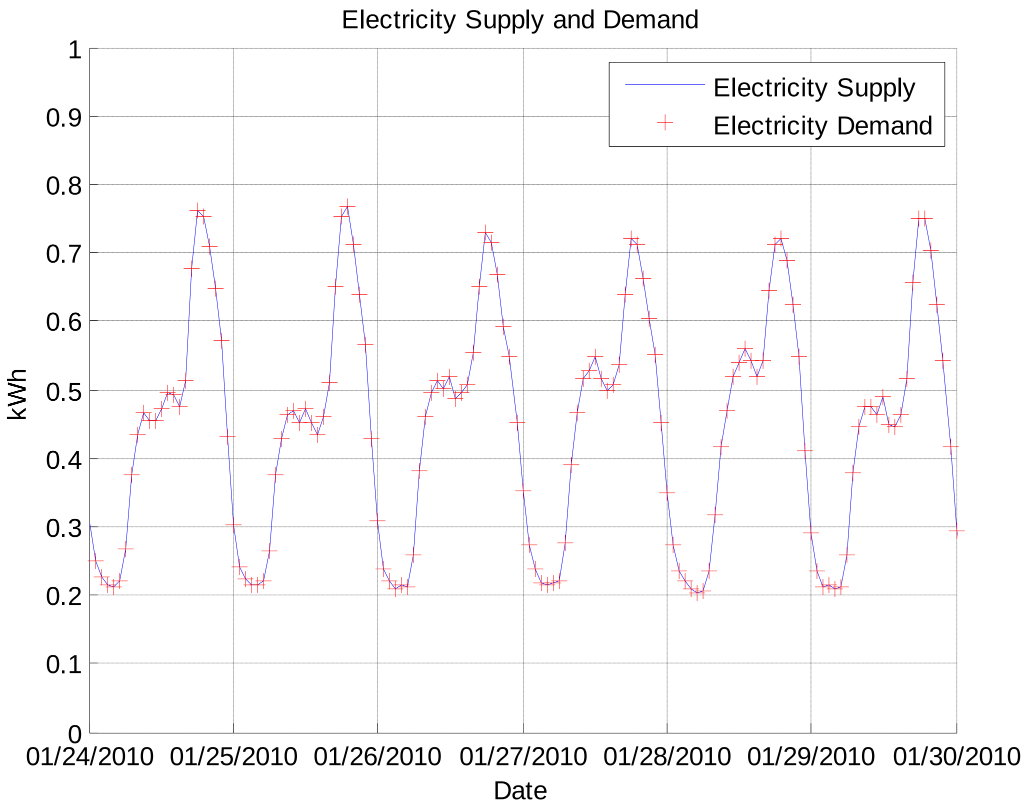

Figure 25: Supply and Demand

Similarly, heat supply is also matched to demand, heat supplies are depicted in Figure 25Figure . Heat storage is hardly ever used; this is mainly due to deterministic nature of heat demand and low efficiency of storage.

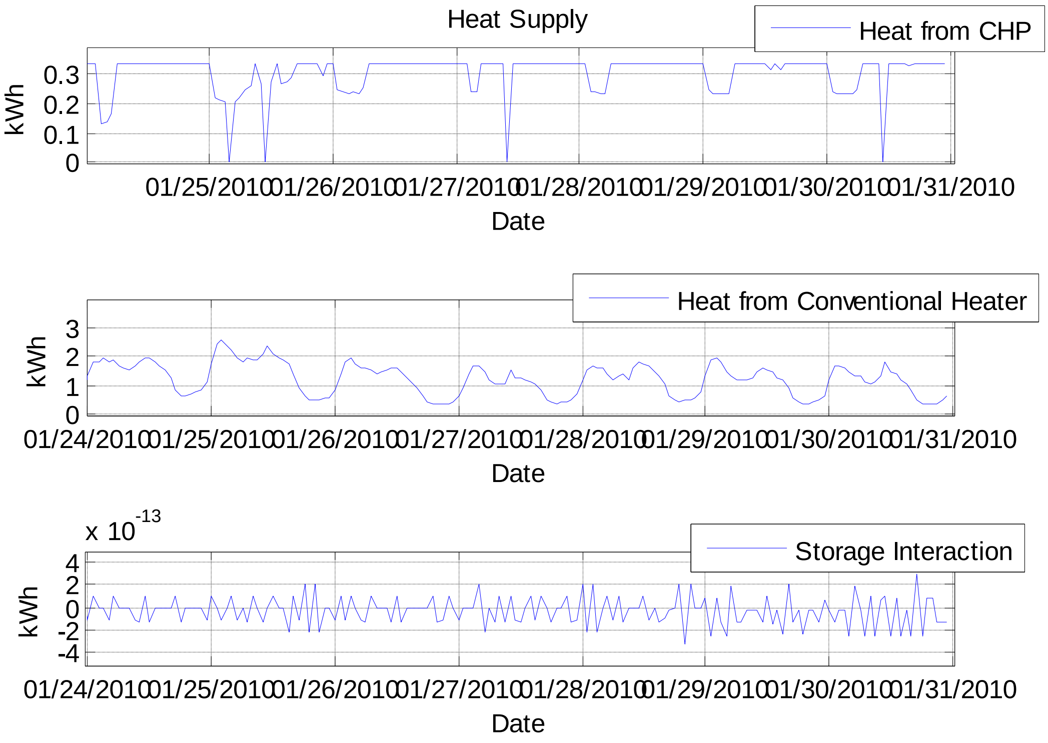

Figure 26: Ceres Heat Supplies

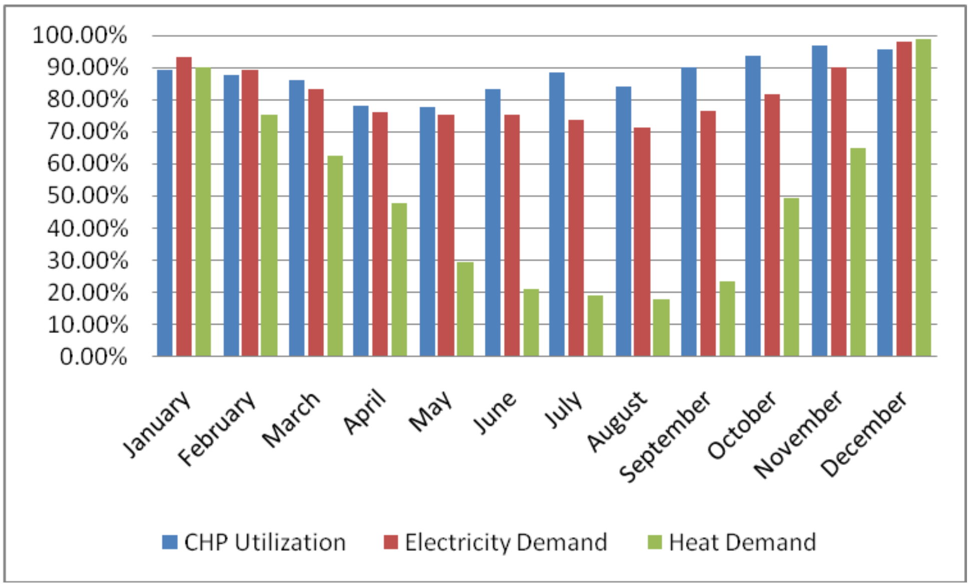

Figure 27: Seasonal Variation in Ceres FC Utilization for Normal Demand

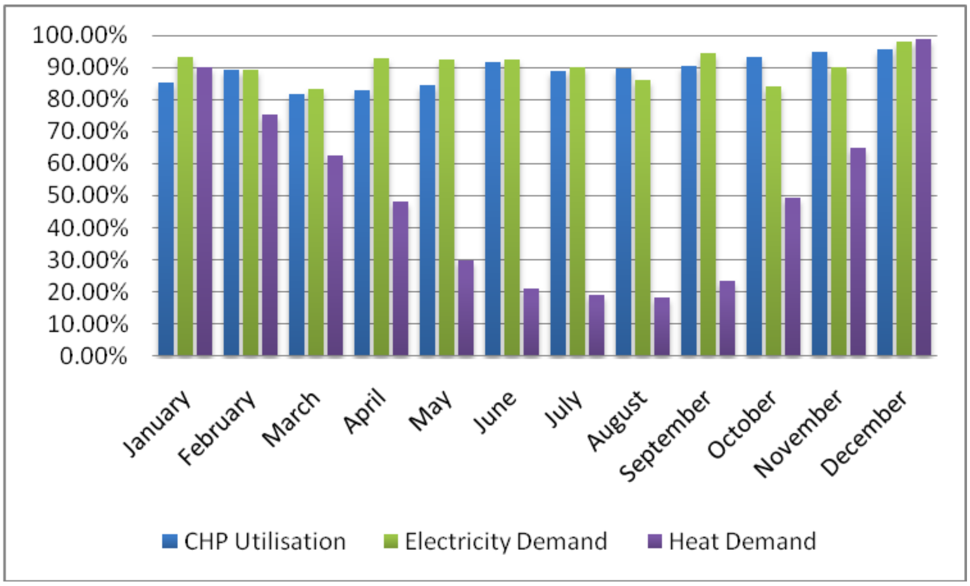

Figure 28: CHP Utilization[9] for Ceres FC with High Demand

8.1.1 Summary

Utilization of the Ceres FC in both normal and high demand cases seems to be similar. Utilization increases during summer months for the high demand, since production is rarely limited by excess heat production.

Ceres FC is among the most promising CHP technologies; however it still is long way from being a viable investment. Operating at an average of 85% capacity, Ceres FC fails to recover initial investment in almost all of the scenarios. Current outlook on energy prices is not in the favor of Ceres FC either, since value is maximized when gas prices are low contrary to current outlook.

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[9] CHP Utilization: Percentage of total capacity of the CHP used.

8.2 CFCL Fuel Cell

Compared to the Ceres FC, CFCL FC has a more balanced electricity/heat ratio, this results in a more restricted production due to excess heat during summer months. In the winter months, electricity production is also limited compared to Ceres FC. This is due to the fact that produced electricity is more expensive compared to Ceres FC, whereas heat is cheaper however, there is a cheaper alternative for heat, which is the conventional heater.

Electricity production scheme with electricity storage enabled is illustrated below.

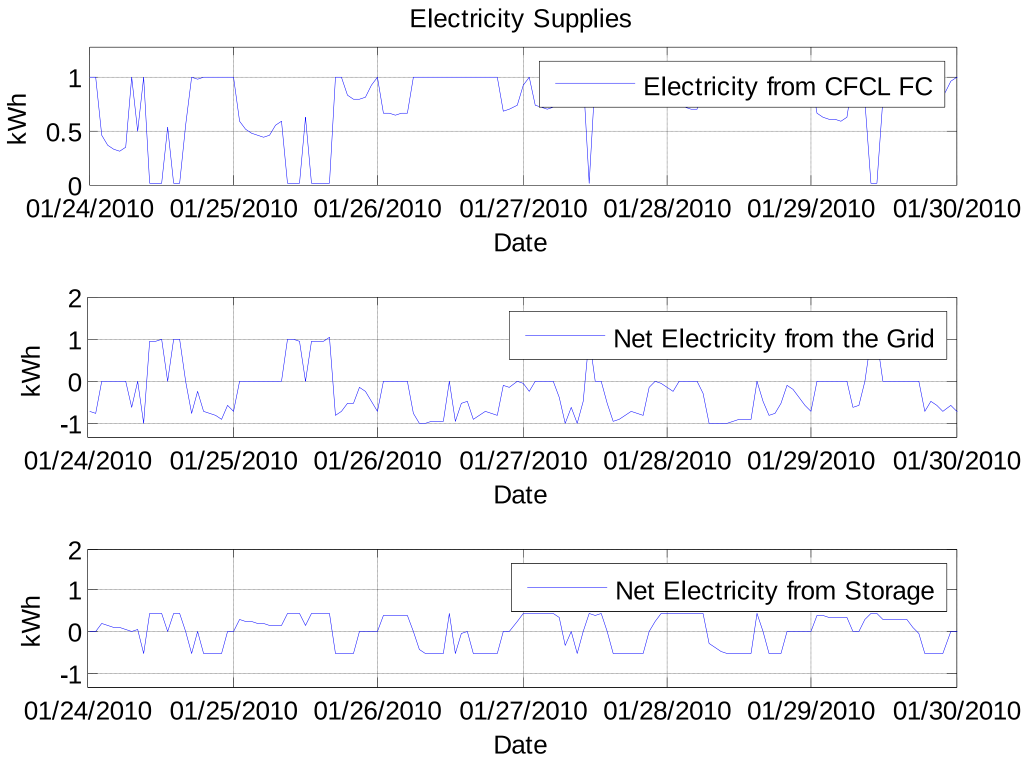

Figure 29: Electricity Production

Heat and electricity demand are matched exactly as Ceres FC, no excess production occurs due to high electricity price and low gas price with any of the scenarios. Utilization under normal electricity demand is depicted in Figure 27. Note that CHP utilization is very limited during summer months.

In the summer months there are several occurrences where heat is wasted blue spikes in Figure 30 are these occurrences. Enabling storage only delays the problem, Figure 31 shows that although spikes through the week are prevented, these spikes occur at the end of the week.

Heat production with storage enabled is shown in Figure 31.

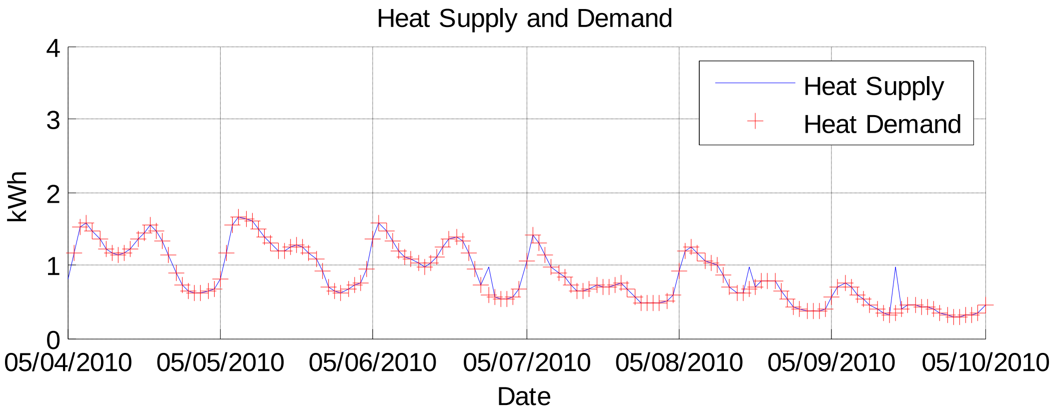

Figure 30: Heat Supply and Demand for High Electricity Demand

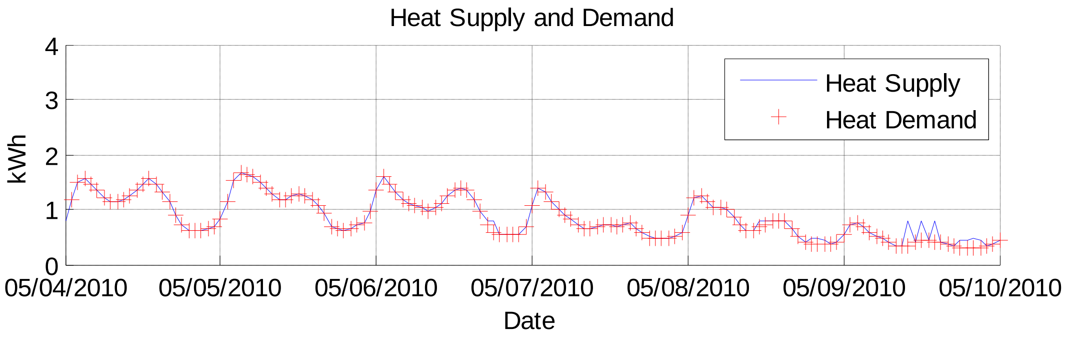

Figure 31: Heat Supply and Demand for High Electricity Demand with Heat Storage

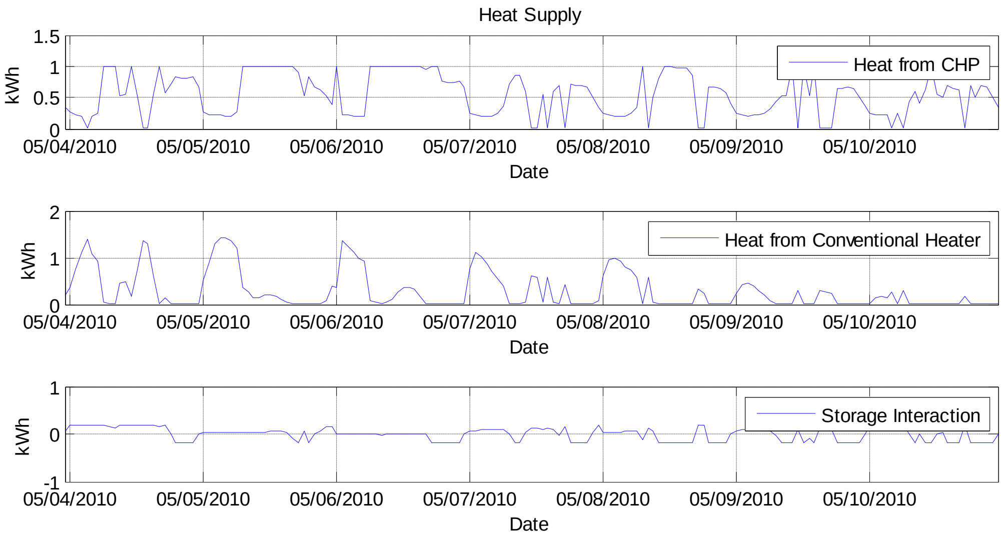

Figure 32: Heat Production for High Electricity Demand with Heat Storage

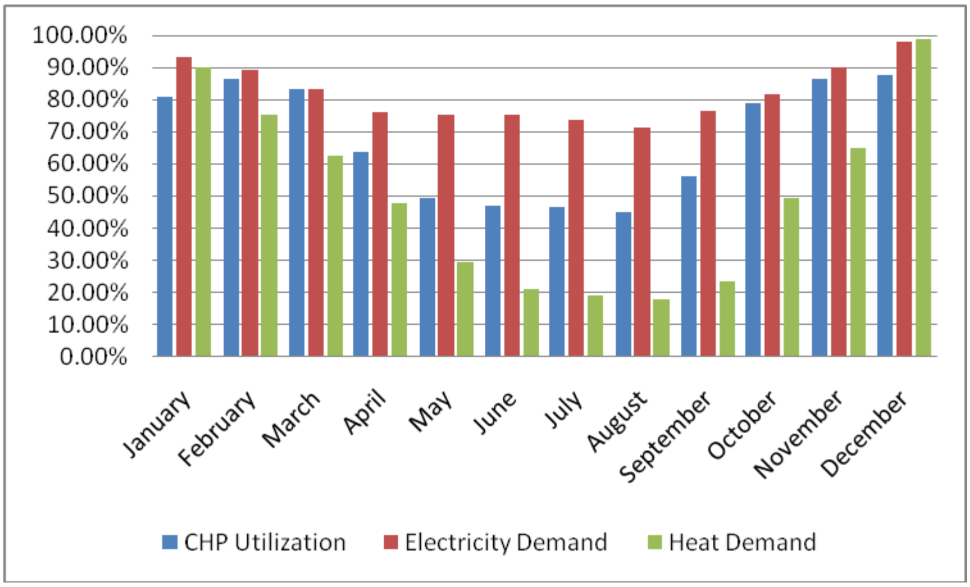

Figure 33: CFCL FC Utilization under Normal Demand

Figure 34 shows that utilization increases during summer months under high electricity demand, note that there is excess heat produced during these months.

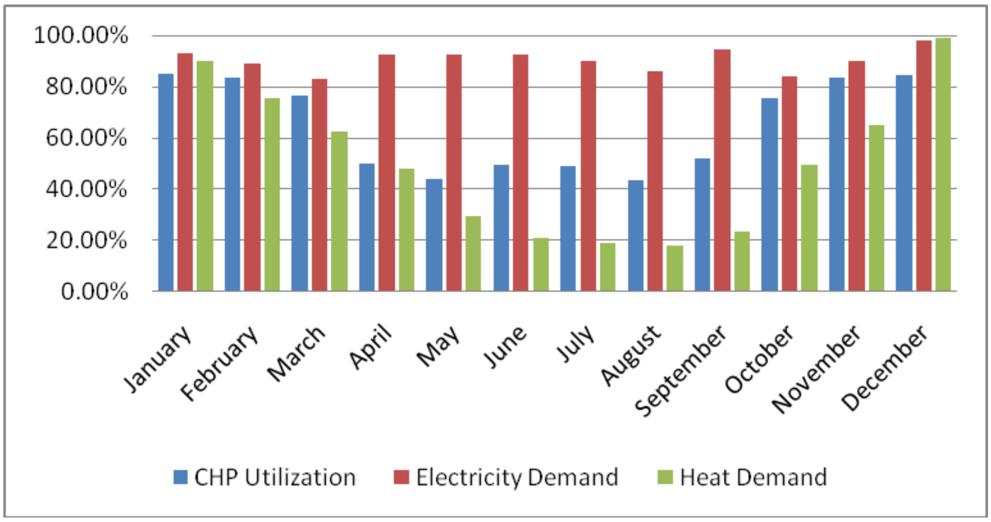

Figure 34: CFCL FC Utilization under High Demand

8.2.1 Summary

CFCL fails to recover initial investment cost under all scenarios both with normal and high electricity demand. Note that this simulation does not take into account the ramping constraints CFCL has, unlike Ceres CFCL cannot be turned on or off at will, doing so will degrade the stack. This further reduces the value of this fuel cell.

Utilization average is 62.4 % for normal demand case and 67.8 % for high demand case; implication of this is that running this device continually is not optimal. Even with actively managing production, this device does not recover initial investment over its lifetime.

Under no circumstance, CFCL FC recovers the initial investment, in most of the cases there is significant loss.

8.3 WhisperGen Stirling Engine

Stirling engine concept is thought of as a replacement technology to conventional heaters. It can be run on two modes of operation, both as a conventional heater and a stirling engine. Electricity produced by the stirling engine is very minor compared to heat it produces, both logic and simulation suggest that its production would be scaled to heat demand.

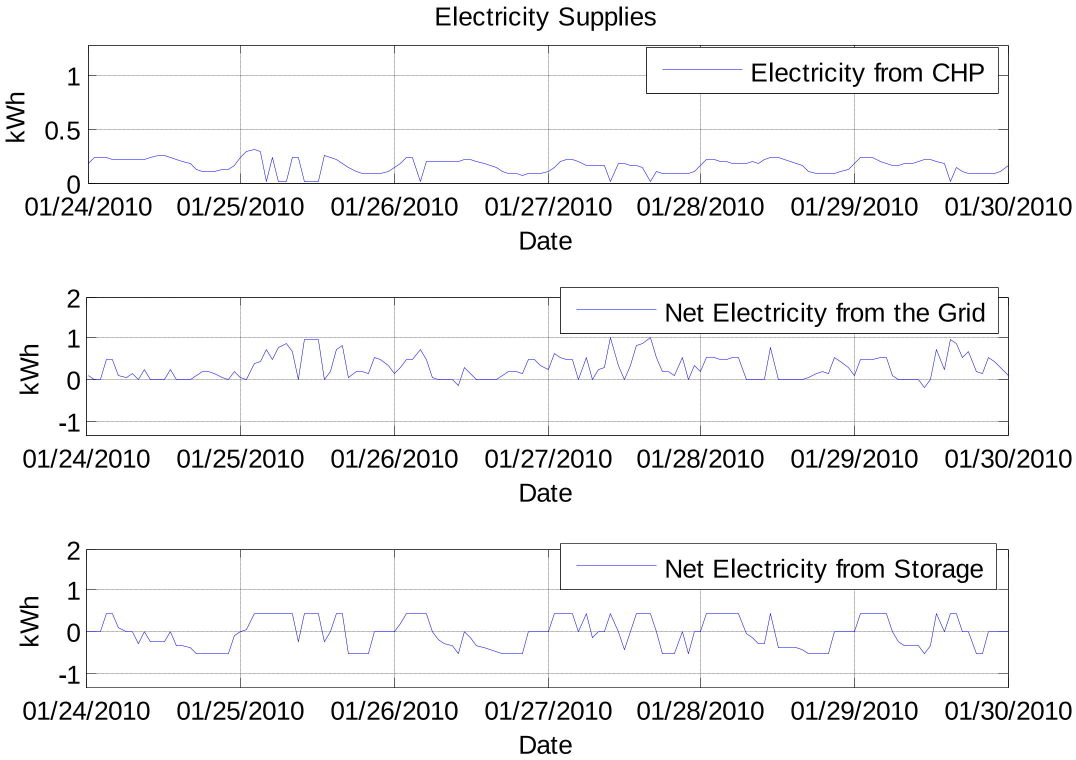

Figure 35: Electricity Supply with WhisperGen SE

Figure 35 illustrates scaling to heat demand over a week, although the capacity to produce electricity is 1 kW per hour this capacity is never utilized even in January, where there is plenty of heat demand.

Figure 36 gives a good indication of production scaling due to demand, compared to Figure 37Figure , one can see that utilization levels does not change although demand in summer months are significantly different between two cases.

It follows from the previous result that, unless electricity prices spike to levels that are close to 20 €/kWh SE will not overproduce to provide the electricity demand instead of the grid.

It is not surprising to see that stirling engine fails to recover initial investment cost; two facts play an important role. Stirling engine utilization levels are much lower than capacity, SE production is scaled to heat demand. Heat and electricity demand does depend on each other, correlation coefficient between heat and electricity demand is very low -0.0786 which corresponds to a correlation of 7.86%.

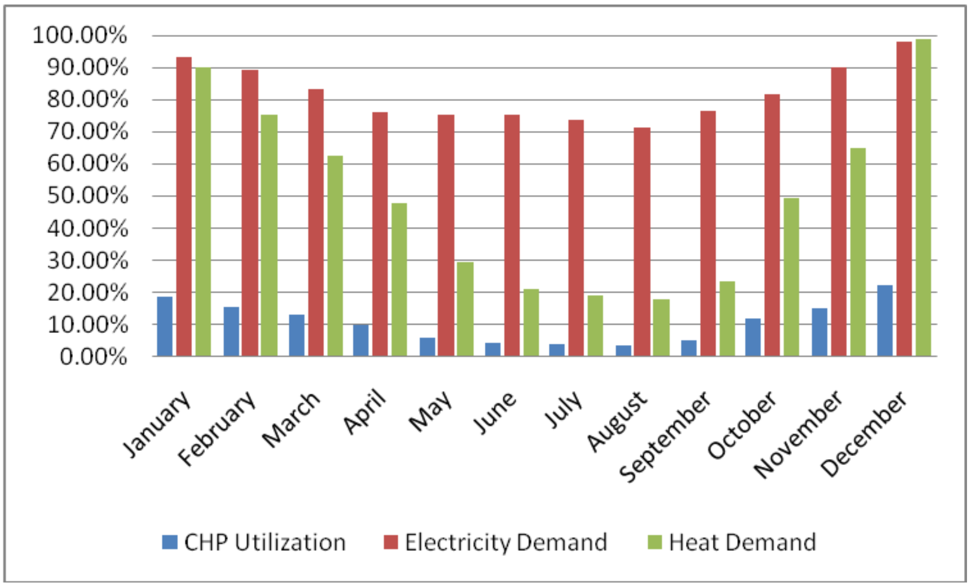

Figure 36: WhisperGen Utilization under Normal Demand

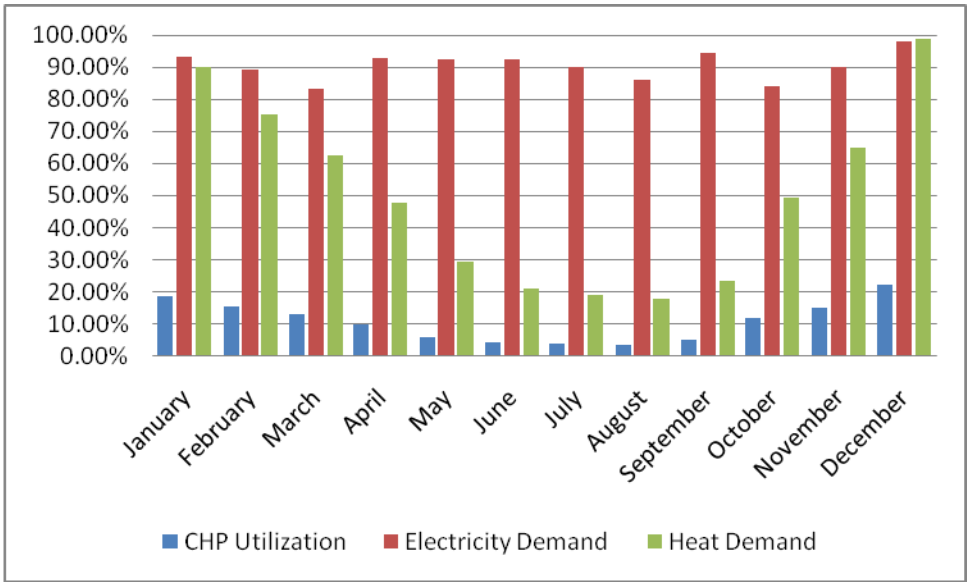

Figure 37: **WhisperGen Utilization under High Demand**

8.3.1 Summary

Stirling engines are the worst performers among all of the CHP units. They fail to recover investment in all cases for both demand profiles. Their only advantage compared to fuel cell systems is they can be classified as replacement for conventional heaters. This implies their cost is drastically lower. However, stirling engines provide only marginal gains over regular HR-boiler setup for households.

Even with efficiencies reaching 95% stirling engines *will not* be a viable investment under any scenario. Stirling engines should be avoided in all foreseeable scenarios. Demise of stirling engines comes from the inherent marginal improvement from HR-boilers, 9% electrical efficiency has negligible effects on energy costs. Their CO_2 savings are a matter of debate. It seems highly unlikely that they would yield any substantial CO_2 savings.

8.4 AVA Solar Inc. Solar Panel

Passive generation technologies such as solar panels and micro-wind turbines have very simple production behaviors. Their production does not depend on demand and their production has no marginal cost. These two characteristics allow them to be modeled in a rather simple way. Their production can be subtracted from electricity demand. Model has no problem handling excess (negative) demand; it can choose to store or simply sell it back to the grid.

Unlike CHPs, passive generation devices have no utilization levels as they are utilized as much as possible. Calculation of energy production from the solar panel is detailed in the figure.

8.4.1 Summary

Solar panels, if produced and mounted cheap enough are a viable technology. Major drawback of solar panels is the fact that they produce maximum electricity when the demand for electricity is minimal, such as summer times; this in turn decreases the value of the system. This effect can be seen by comparing cost savings in normal demand case and high demand case.

Generation is the same for both demand profiles, as mentioned earlier production from these devices does not depend on the demand. However, more of the electricity produced can be utilized within the household in the high demand case. This is expected to create extra value in high demand case. It can be concluded that the energy is generated at sub-optimal times in both cases for efficient utilization.

8.5 Bergey XL Wind Turbine

Wind turbines are very similar in modeling and evaluation to solar panels, production from the wind turbine is modeled and subtracted from demand. Optimization model is then run on this new demand and regular pricing schemes.

Calculation of wind power generation is detailed in

8.5.1 Summary

Wind turbine at a relatively windy spot will generate the most value/price over all other technologies. However, it is important to mention that wind turbines are usually too noisy or big to employ in cities or densely populated areas. There are a couple of interesting implementations utilizing wind power, feasibility of these technologies are a whole other area of research.

On the economical side, wind power technologies are the most promising of all decentralized generation, it must be noted that this is only the case with sellback capabilities. Other pricing schemes are not explored in this paper.

CHAPTER IX

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The Model is based on the optimal production scheme for a set of demands and prices. Implication of using optimal production scheme is: no other solution for the specified system can have a better result in terms of minimizing cost than the current one. Therefore, it is safe to say optimal production scheme provides a lower bound for cost, which in turn is an upper bound for the value of technology in question.

In this paper, five technologies have been explored in detail: Ceres Fuel Cell, CFCL Fuel Cell, WhisperGen Stirling Engine, Solar Panel, and Wind Turbine. These five technologies can be further divided into two subgroups, namely: Combined heat and power and perpetual generation units. None of the CHPs recover the initial investment cost on their ten year lifetime, given that this study explores their upper bound in value it is very unlikely that these technologies would perform better in reality.

9.1 Gas Prices

Study results suggest that natural gas prices strongly influence the value of CHP systems; effect of the price of natural gas is directly proportional with the devices electrical/heat ratio. Higher the electrical/heat ratio, higher the effect of natural gas would be. In all cases high natural gas prices translate into lower value of the system.

Perpetual generation devices do not behave like the CHP systems; their value is independent of natural gas price. Their value solely depends on their capacity, production scheme[10] and upfront investment. In ideal conditions, perpetual generation devices recover the initial investment cost and even turn profit in the ten year period.

9.2 Electricity Prices

Electricity prices have a minor effect on CHPs compared to gas prices, CHPs provide a sort of hedging effect on changing electricity prices. This hedging effect is due to the electricity production capabilities of households, when electricity prices are high they can choose to produce in-house. Contrary to gas prices, low electricity prices translate into low value gained from CHPs in general.

Electricity price does affect perpetual generation devices, same way as the CHPs. Low electricity price yields low value for these devices. This is explained simply by the fact when electricity prices are high, then electricity generated by these devices has higher value.

9.3 Utilization

Utilization depicts the realized potential of CHP systems; utilization does not apply to perpetual generation systems. Utilization levels give a good indication of value, simply by empirical results. A low utilization level corresponds to low returns, such

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[10] Production scheme: Production of electricity by hours.

as stirling engines. Stirling engines have very low utilization levels (under 5% of capacity in summer, 20% in winter) and also very low returns on investment.

9.4 Results

Important results of the study can be summarized in following points:

- Electricity energy produced in-house is more valuable than heat (stirling engines vs. fuel cells).
- Low electricity/heat ratio leads to production scaling to heat demand (stirling engines).
- Heat storage does have some value combined with CHPs.
- Low electricity/heat ratio leads to lowered utilization in summer months.
- Higher demand in summer decreases value of low electricity/heat ratio devices.
- Higher demand in summer increases value of high electricity/heat ratio devices.
- Natural gas price is the most important driver of value for CHPs.
- CHPs have a hedging effect against electricity prices, depending on electricity/heat ratio. Higher ratios lead to better hedging.

9.5 Summary

In retrospect, CHP devices fail to be viable investments. The three most important reasons why CHPs are not viable investments are listed below:

- High upfront investment costs.
- Value indexed to natural gas price.
- Technological limitations.

High upfront investment costs are the most likely issue to be resolved in the near future, unless the upfront investment is reduced to 60% of current levels these technologies will not generate value. One of the biggest problems with CHPs is their dependence on natural gas; this study assumes risk department curves from February, 2008. Prices depicted in the fundamental analysis are very low compared to upcoming analysis. Increasing gas prices will drive the value of these devices further down.

Technological limitations are not explored in this study; however, it is worthwhile to mention inherent technological limitations will have additional negative impact on the value of these systems. CFCL fuel cell for example cannot be turned on and off without degrading the stack, these kinds of effects are ignored for this study.

Perpetual generation devices are viable only if they can reach the advertised levels in terms of efficiency and reliability. It is important to note that solar panels and wind turbines may not applicable to urban environments. Spatial requirements and noise produced; particularly with wind turbines are not compatible with high population density.

It is my belief that CHPs are not the answer to energy needs manufacturers claim them to be. Although this study is performed on advertised levels; test units of the proposed technologies fail to reach advertised levels, their dependence on natural gas prices for value both work against CHPs with the current energy situation around the world.

From a purely economical stand point CHPs *will not* generate value to installed households. Simply because they cannot recover initial investment cost. Perpetual generation devices will add value to installed households, provided there is ample supply of the resource they use present at the installed location (wind or sun) and there is a feasible location for the device.

A simple calculation concerning overall efficiency of households seems to support these results. Dutch electricity production and transport has efficiency around 40%, and a regular Dutch household has a 95% efficient HR-boiler installed for heating purposes. Assuming a 2.8-to-1 ratio[11] of heat to electricity in terms of demand yields an overall efficiency of 76.5%. Combined efficiency of CHPs is 80% for fuel cells, these households also have a HR-boiler with 95% efficiency, depending on utilization levels the overall energy efficiency of the house will be between 80-90%. A regular household spends about 1600 € annually for heating and electricity, clearly an improvement of 3.5-10% will not justify a 10,000 € investment.

9.6 Conclusions

In conclusion, none of the combined heat and power units recovers their initial investment costs even using the upper bound for value. Ceres FC performs the best out of all technologies, stirling engines the worst. Cases where these technologies generate value are scenarios with low gas prices, which will become obsolete with the upcoming fundamental analysis.

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[11] Annual heat requirement is 9800 kWh and Annual electricity requirement is 3500 kWh.

It is my belief that CHPs do not provide enough of an improvement to justify the investment costs. Only value that can be gained from these devices is through transfer of value[12].

As a rule of thumb, technologies with higher electricity/heat ratio are preferable to other technologies with comparable total efficiencies. For example, Ceres FC is preferable to CFCL FC even CFCL FC is preferable to WhisperGen Stirling Engine. However, none of these devices produce enough value to justify the initial investment.

Results of the study are conclusive with the stated assumptions. It is my belief that decentralized energy production should be limited to renewable sources such as wind and solar power. Stirling engines should be avoided as they are poor investments, their impact to market will be limited regardless of their penetration into the market due to their low electricity/heat ratio.

Fuel cell based technologies are also poor investments; they can have a significant impact on the market with high enough numbers. However, lack of economical feasibility of these technologies is likely to prevent widespread use.

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[12] Transfer of surplus, either from consumer to producer surplus or producer to consumer surplus.

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APPENDIX A

CONSUMER ADJUSTED PRICE

Consumers usually experience a different price than the day-ahead market price. This makes linear scaling to determine future taxation tricky. Calculation of the tax adjusted customer price is given below

$\boldsymbol{P_C}$: Customer price 2nd Quarter of 2008.

$\boldsymbol{P_{TTF}}$: Gas spot price average over a 6 month period that has 2 months lagged. (Calculated 2nd Quarter price)

$\boldsymbol{P_{Market}(t)}$: Market price in the forecasted period.

$\boldsymbol{P_{Adjusted}}$: Consumer adjusted price.

As with electricity prices relationship between P_C and P_{TTF} is linear. Thus same linearity can be extended to P_{Market} for calculating $P_{Adjusted}$.

Formally;

$$P_{Adjusted}^{Gas} = P_{Market}^{Gas} \frac{P_C^{Gas}}{P_{TTF}}$$

Electricity prices follow a similar path, however as there is no set scheme for pricing contract electricity from spot market, a linear transformation is assumed from the average spot price over the whole quarter.

$$P^{e}_{Adjusted} = P^{e}_{Market}\frac{P^{e}_{C}}{P_{APX}}$$

Where;

P_{APX}: Average Spot price of 1st Quarter.

APPENDIX B

WIND AND SOLAR GENERATION

Wind Power Generation

Wind power generation is non-linear with respect to wind speed. Bergey XL.1 is reported to produce 1000 Watts at 11 m/s wind speed. Combined with the power coefficient a figure in kWh can be deducted from the wind speed.

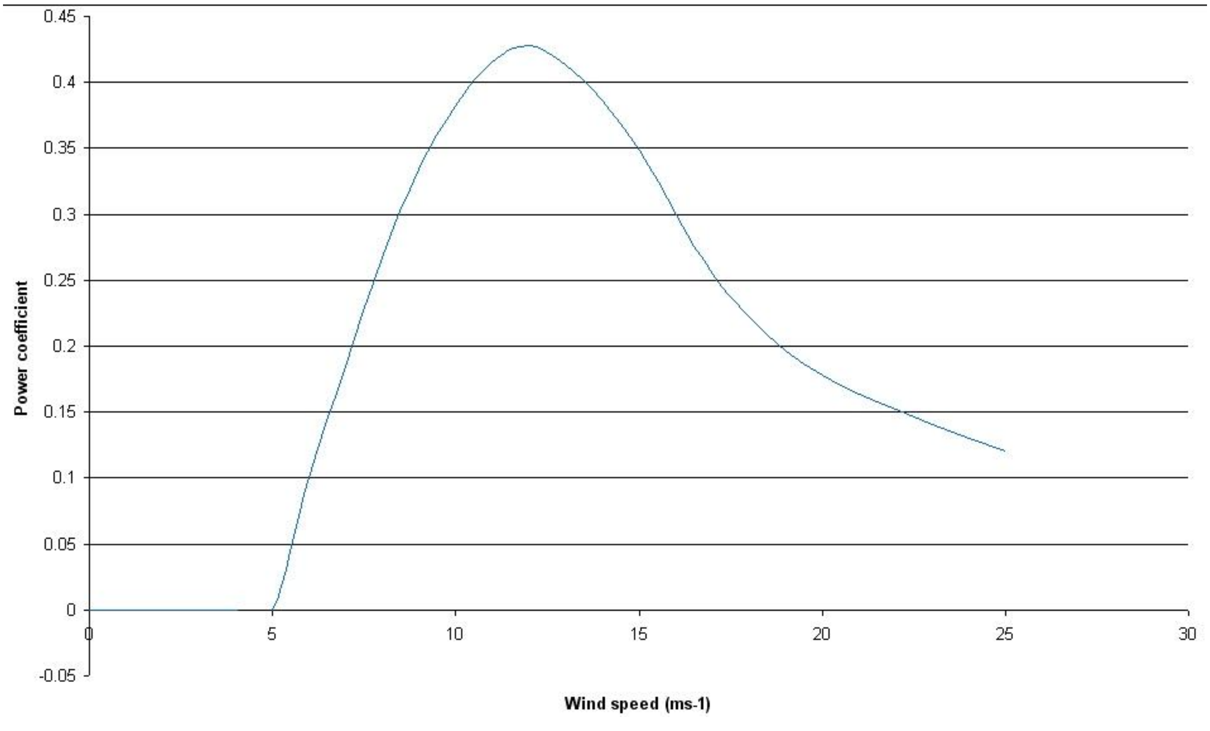

Figure 38: Wind Speed vs. Power Coefficient (Iowa Energy Center, 2006)

Figure 38 gives the percentage of energy that can be extracted from the wind. Combined with the energy density and production capability of 1000 Watts at 11 m/s we get, Figure 38 might be misleading as it suggests peak production at 11 m/s, however correct interpretation is peak efficiency at 11 m/s. Due to this fact production does not peak at 11 m/s, as high speed wind carrier more energy than a lower speeds, although percentage of the extracted energy is less than the slower speeds, more energy is extracted overall.

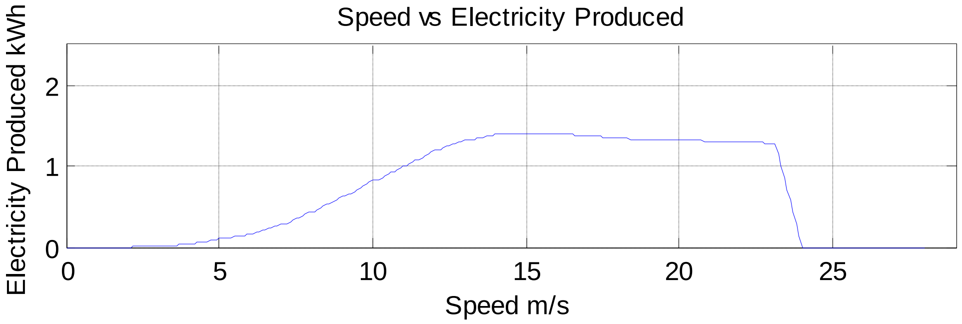

Figure 39: Energy Produced vs. wind Speed

Table 4: Energy Output Values

Wind Speed (m/s)	Energy Output (kWatt)
1	0.000
2	0.000
3	0.005
4	0.038
5	0.101
6	0.162
7	0.279
8	0.441

9	0.624
10	0.820
11	1.000
12	1.200
13	1.315
14	1.392
15	1.394
16	1.396
17	1.374
18	1.338
19	1.333
20	1.329
21	1.306
22	1.295
23	1.284
24	0.000
25	0.000
26	0.000
27	0.000
28	0.000

Main values for energy output are reported in Table 4 and other values are estimated using this table.

Solar Generation

Unlike wind power, solar generation is linear with respect to solar radiation. Solar radiation is measured in $^{kWh}/_{m^2}$. Solar insolation for a PV-Cell[13] optimally inclined over a sample year is depicted in Figure 40. Note that this is not the amount generated by this particular cell.

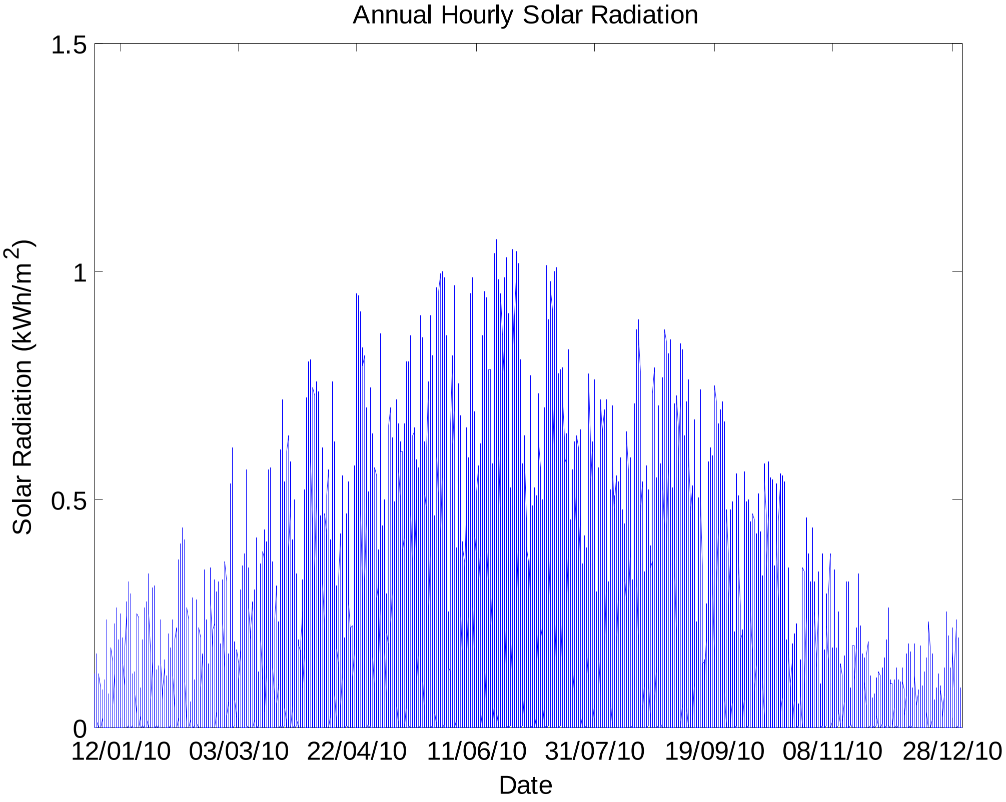

Figure 40: Hourly Solar Insulation

Throughout this paper, it is assumed that installed solar panel is a 6 m^2AVA solar panel. Production from this solar panel over a sample year is illustrated in Figure 41.

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[13] PV-Cell: Photovoltaic Cell

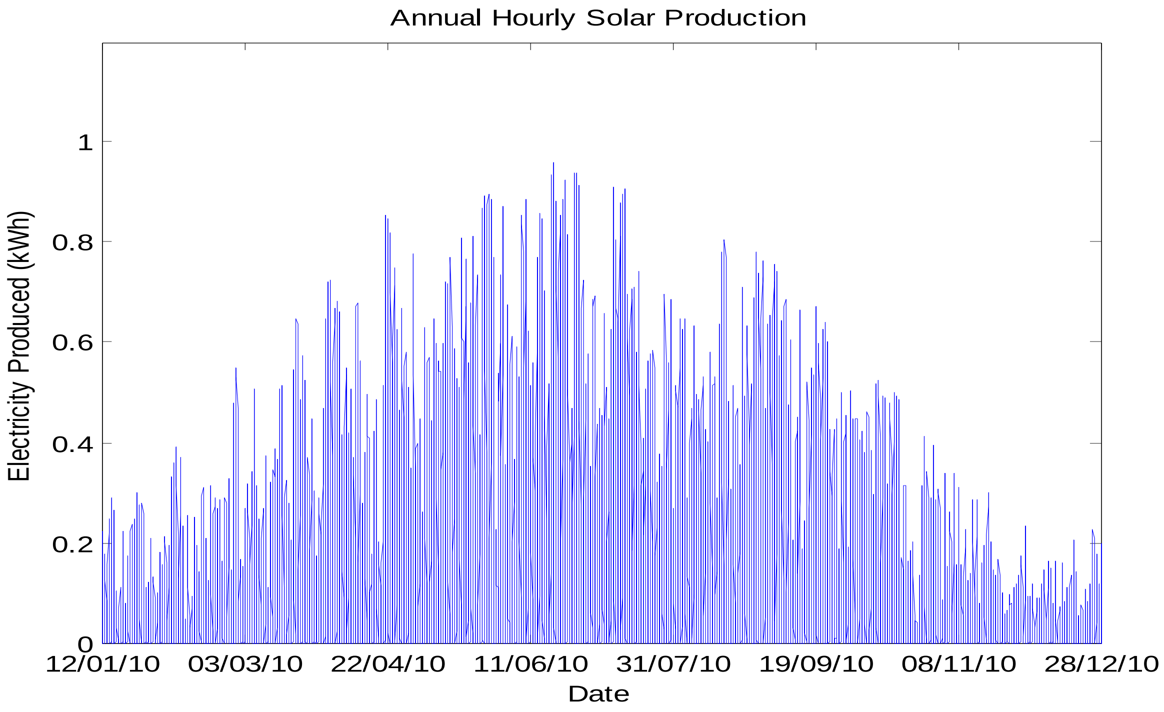

Figure 41: Production from a 6m^2 AVA Solar Panel