Residential Wind Turbine Design Decision Support System

Mohammed Almutairi, Anutaj Chahal, James Fritz and Luis Soto
George Mason University, jfritz3, achahal, malmuta5, lsotoalv@maosnlive.gmu.edu

***Abstract*—Residential homeowners in Virginia pay on average $130 every month for electricity and the price is projected to increase in the future by 0.7% per year. In comparison to the rest of the United States, Virginia homeowners pay 14% more than the national average. Further, the variance in monthly bills is $54, causing uncertainty in monthly cash flows for homeowners. Renewable energy systems show potential to reduce costs and variability. Solar panels are in widespread use, except in jurisdictions where they are not allowed for residential purposes (e.g. Virginia) or where there is nonexistent direct sunlight. Solar panels only provide power during daylight hours. Residential wind turbines offer a renewable energy alternative for specific locations where wind is sufficient (e.g. adjacent to large bodies of water) or where there is potential for Venturi effect which amplifies wind magnitude (e.g. urban canyons).**

A Decision Support System (DSS) was developed to assist consumers in the selection of a wind turbine for residential power generation for their specific location and their specific energy needs. A model of wind turbine characteristics: aerodynamics, gearing, tower and control system, as well as Life Cycle Costs, and breakeven point was coupled with a stochastic simulation of local wind profiles. A Multi-Attribute Utility Analysis (MUAT) was used to rank the alternatives.

A case-study for a property in Annapolis, Maryland, showed that using the Aeolos 10kW residential wind turbine would generate 5,298 kW per year. With an initial investment of $24,420, the break-even point is 76 years. Higher coefficients of power, government rebate incentives and possible roof mounting are identified to reduce the break-even time.

INTRODUCTION

Residents find themselves in a cycle with utility providers where they have to pay for electricity regardless of the cost. Power utility companies such as Dominion recommend that customers can only reduce their bills by controlling their energy usage. The factors that are out of the homeowners control are the fuel costs and weather conditions, which are considered as the main drivers of electricity rates.

Power plants rely heavily on fuel sources such as coal and gas to power its operations. Also, peaks in demand during seasons such as summer stress power plants and the electric grid forcing high operational costs.

The average U.S household uses 901 kWh monthly [1]. Since 2001, prices have risen by 2.6% The average retail price of electricity between the state of Virginia and Washington State are illustrated in Figure 1[7].

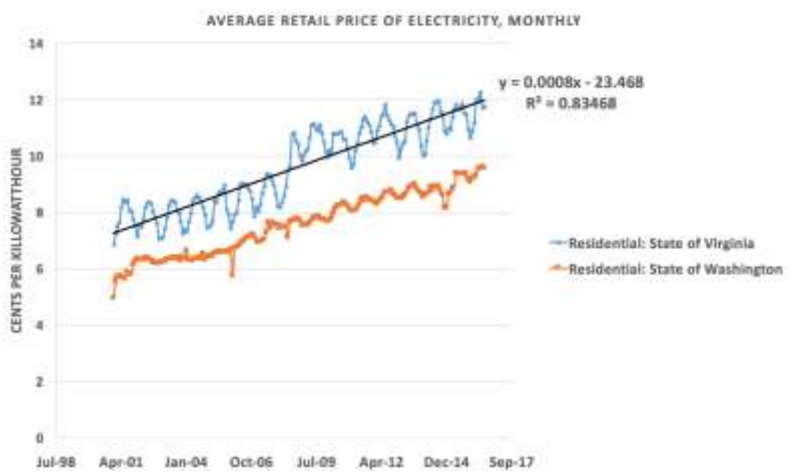

Fig 1. A comparison between Washington state and Virginia in terms of retail prices of electricity.

According to the U.S. Department of Energy, 64.5% of Washington State's energy production comes from renewable sources, which should provide a clear example on how the role of renewable energy help out dissipate the fluctuations of utility bill price.[2]

Virginia has the price fluctuation greater than Washington. This is because the two main drivers of prices are fuel costs and weather conditions. Virginia has more seasonality than Washington state, causing prices to fluctuate more. Figure 2 illustrates a monthly variability on utility prices that causes a financial uncertainty for residents, who want to have a steady utility bill rather than a varying one [8].

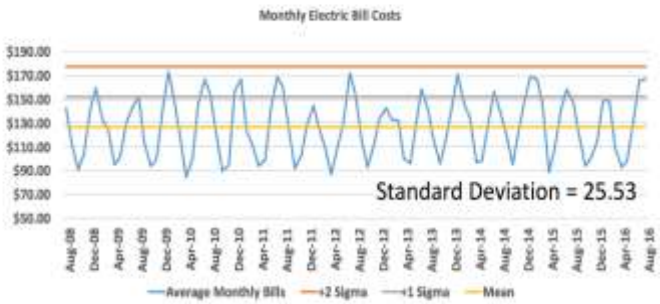

Fig 2. (VA Monthly Electric Bill Costs)

PROBLEM AND NEED STATEMENTS

I. Problem Statement

Residential electricity costs are continuously increasing over the years. There exists a variability in the monthly utility bills because of high peaks of demand of electricity during the summer and winter months with a variance cost of $54. Additionally, according to EIA prices will increase by 18% in the next 23 years in a report that takes six cases into account that includes high and low economic growth, high and low oil prices, and high and low oil and gas resources [1]. The use of fossil fuels which include coal, natural gas and nuclear energy cause climate change. An alternative method of generating energy is through renewable sources (e.g. wind). Currently, the residential wind turbine market is developing and the decision support system could be improved in order to mainly focus on microclimate fixed locations with potential wind power.

II. Need Statement

There is a need for residential wind turbine design decision support system to reduce the cost and variability of utility bills for homeowners. The DSS needs to collect micro-climate data for a specific location and to select the best wind turbine systems to be installed for a given site.

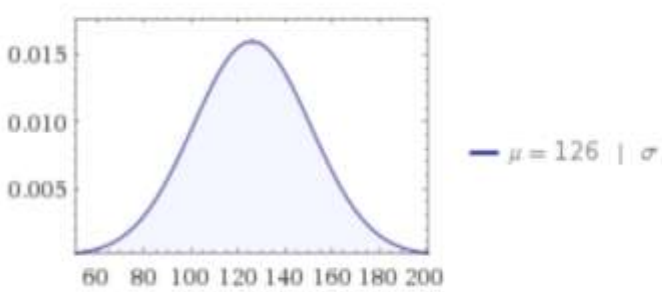

Fig. 3 A distribution that shows the high variance in monthly utility bills for residents in Virginia.

PHYSICAL PROCESS

There are two different types of wind turbines in use, the Horizontal Axis Wind Turbines (HAWT) and the Vertical Axis Wind Turbines (VAWT). In the case of HAWT, rotation of the wind turbine blades is caused by the force of lift being generated by the flow of air over the blades. For VAWT, rotation of the wind turbine is caused by drag which is generated when air flow makes contact with the blades of the wind turbine. The efficiency of HAWTs are much greater than that of VAWTs by 40%, therefore this paper is limited to HAWTs.

I. Components of Wind Turbines

Small wind turbines such as the ones that would be installed in residential areas consist of an odd number of blades which will be explained in detail in the next section. They also have generator which converts rotational mechanical energy into electricity. A drive shaft that is connected to this generator spins which drives the generator and generates electricity. Small wind turbines have a direct drive shaft which does not require a gearbox. This allows for the drive shaft to be connected directly to the generator. The final component is a wind vane which helps keep the wind turbine pointed upwind.

STAKEHOLDER ANALYSIS

Residents

Objective: For residents and small business, wind systems would help in reducing the costs of utility bills and minimize the variability in electricity bill costs.

Tensions: Reliability can be a source of a tension given the fact that there might be some days with minimal wind. Further, in the case of net metering, utility companies might impose excessive requirements on residents who are selling back their energy surplus.

Utility companies

Objectives: The majority of utility companies have a clear goal which is to keep their monopoly and keep providing reliable and safe energy to their customers.

Tensions: A clear tension would be the end of their monopoly since utility companies do not want customers to get their energy from a new competitor (e.g. small scale energy manufacturers).

Virginia State Corporation Commission - Division of Public Utility Regulation (PUR)

Objectives: To regulate just and reasonable rates that would satisfy both the consumer and the utility provider.

Tensions: A tension may rise between PUR board members, who are appointed by state representatives, and the state representatives who receive political donations from utility companies. The pressure from state representatives might make board members hold programs that would encourage renewable energy businesses.

Federal Regulators (EPA, FERC, OSHA)

Objectives: The overall objective is safety among all federal regulators.

Tensions: A possible tension might face federal regulators when there is some uncertainty of residential safety.

Renewable Energy Manufacturers

Objectives: Small and large scale wind turbine manufacturers share the same goal which is to advance their production and increase their profit.

Tension: The highest tension among all stakeholder as shown in Figure 4. is between the small-scale manufacturers and utility companies because utility providers do not wish to share their monopoly and allow customers to generate their own power.

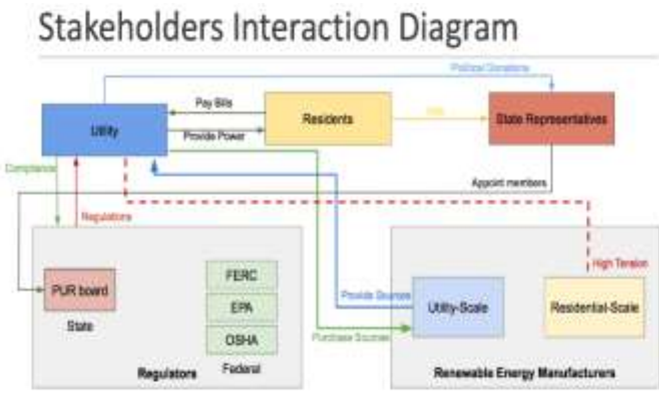

Fig. 4 Stakeholder interaction diagram

RESIDENTIAL WIND TURBINE DESIGN DECISION SUPPORT SYSTEM

A decision support system was designed to find the optimal wind turbine configuration for a specific location. The wind characteristics at that specific location is called a micro-climate.

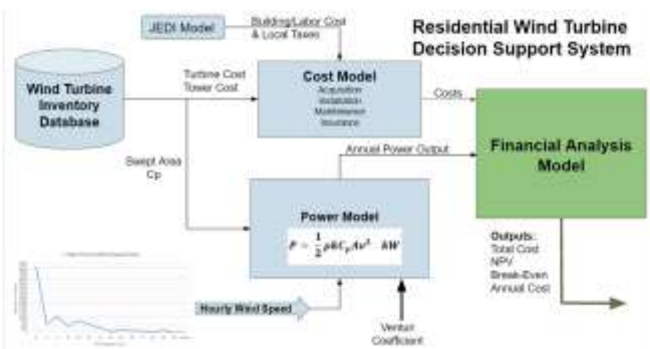

Fig. 5 DSS Input/Output Diagram

The Decision Support System (figure 5) consists of a wind turbine inventory, wind speed data, power model, cost model and a financial analysis model.

The inputs for the DSS are wind speed data that spans a period of one year and also existing wind turbine design and performance characteristics from the wind turbine inventory.

The system uses these inputs to perform an analysis in order to compute annual power output via the power model and calculates the break-even point via the financial analysis model.

The DSS's outputs consist of the total cost of the system including installation, net present value, break-even point and the turbine's annual cost. The second critical component of the system is the analysis component which takes the inputs from the site survey and creates an optimal wind turbine configuration. This configuration will have characteristics consisting of number of blades, dimensions, cost and output. A trade-off analysis is performed on existing turbine configurations stored inventory, based on the characteristics of the optimal turbine configuration. From this analysis, the output is developed. This output consists of the best existing wind turbine configurations, it's specifications, cost, expected annual output and its return on investment.

I. Wind Turbine Inventory

The residential wind turbine inventory consists of 42 turbines and 17 manufactures. These turbines cover the full range of wind turbines from low output turbines to turbines with outputs of 100 kWh. The purpose of doing this it to have the ability for the system to be applied to the entire range of turbines within the small wind turbine market. In the data structure of the wind turbine inventory database, each slot consists of the specifications of that particular turbine such as Manufactures, Country, Model, Blades, Swept Area, Rotor Diameter, Cut-In Speed, Rated Power, Product Life, Max Design, Wind Speed, Tower, Tower Cost, Turbine Cost, and Total Cost can be seen in Figure 6.

Manufactures	Xzeres	Bergey	Aeolos
Country	USA	USA	UK
Model	Skysteam 110	Bergey 7.5 kw	Aeolos 10kw
Blades	3-Blades, upwind	3-blades, upwind	3 glass fiber
Swept Area(m^2)	10.2 m^2	38.5 m^2	50.24 m^2
Rotor Diameter	3.6m	7.0m	8m
Cut-In Speed	2.2m/s	3.1 m/s	6.7 mph
Rated Power	2-kW @ 11m/s	7.5-kw @13m/s	10 kw @ 11m/s
Product Life	20 Years	20 years	30 years
Max Design Wind Speed	63 m/s	53.6 m/s	52 m/s (116.3 mph)
Tower	Monopole self supp	Monopole Tower	Monopole Tower
Tower Cost	$13,919	$12,705	$9,600
Turbine Cost	$15,000	$31,770	$14,820
Total Cost	$28,919	$44,475	$24,420

Fig. 6 Data Structure of Wind Turbine Inventory Database

II. Wind Speed Data

Wind is incredibly variable, therefore capturing the full behavior of the wind at a specific site requires a long period of time. To capture this variability and changes over every season, one year of wind speed data is used for the calculation of annual power output. The variability of one year or more of wind data can be seen in figure 7.

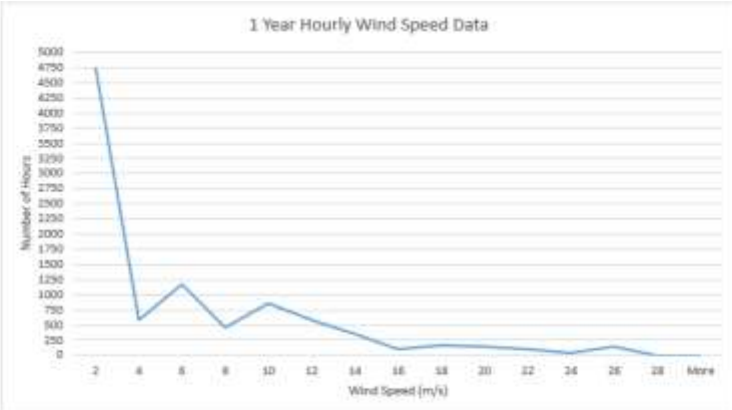

Fig. 7 hourly wind speed data over one year

III. Power Output Model

Within the power model, it is assumed that all wind turbines in the inventory have fixed pitch blade design. The inputs of this model consist of the swept area and Cp from the wind turbine inventory. The output for this model is the annual power output in kW. This is calculated by using the power output equation.

The engineering law for power output of wind turbines is the Kinetic Energy equation. This equation is one half the mass of an object, multiplied by its velocity. Wind is made up of many small particles of are in motion. The wind's mass is represented by many small particles through the use of the Mass Flow Equation. This accurately represents the mass of the air flowing over the blades[3].

Mass flow substitution

$$P = \frac{1}{2}\frac{dm}{dt}v^2 \longrightarrow P = \frac{1}{2}\rho A v^3\, kW$$

□ Air Density = 1.225	kg/m^3
A Swept area =□ * Blade radius^2	m^2
k kiloWatt coefficient	kW
v wind speed	m/s
Cp coefficient of power	

The coefficient of power represents the measure of the wind turbine's efficiency. This is calculated by the following:

$$C_P = \frac{\text{Actual Energy Produced}}{\text{Wind Energy into Turbine}}$$

This coefficient is limited by a concept called Betz limit, that shows that under ideal conditions and maximum rated speed, no wind turbine shall be more efficient than 59.3%[3].

An example power output curve for a wind turbine can be seen in figure 8.

Fig.8 Power output curve

This curve illustrates the three speeds that pertain to the power output of a wind turbine. cut-in speed is the wind speed at which a wind turbine will start spinning and begin to generate electricity. The rated speed is the wind speed at which the wind turbine is generating maximum power output at its max efficiency. The cut-out speed is wind speed at which a wind turbine will stop spinning and generating electricity to prevent damage and failure of components.

In addition to the power output portion of the power model, there is also a concept called the Venturi effect that will be used to increase the overall power output of residential wind turbines. The Venturi effect takes place when air or wind becomes restricted between two object. When the air enters between the two objects, the area in which is contained is reduced therefore causing its velocity to increase. This increase in velocity is what will be increasing the overall power output of the residential wind turbines. This effect is also present when wind travels up steep slope. In this case, the wind's velocity will be greatest at the slope's peak.[9]

IV. Cost Model

Small wind turbine manufacturers provide a fixed acquisition cost to homeowners who are interested in buying a wind turbine system. The price provided only takes into account the cost of the system and the shipping leaving customers with unknown costs such as installation, maintenance, and insurance. The cost model uses data from multiple sources to approximate the total cost of system. In this model a program developed by the National Renewable Energy Laboratory (NREL) called The Jobs and Economic Development Impacts (JEDI) was used. The program helps in evaluating the labor and construction costs, fees associated with permits, and taxes. Along with the JEDI model some assumptions were made based on previous research done by the NREL. To calculate the operation and maintenance costs for a wind turbine system the NREL recommends to assume a fixed cost of 0.007 $/kW produced. The NREL also recommends to assume that the insurance would cost 1% of the total investment cost. An extra cost to the wind turbine system is the addition of a home battery to store unused energy by the wind. Tesla's new product Powerwall II was chosen to be paired with a wind turbine. A cost of a 14 kWh battery was added to each wind turbine. It costs $7000 and it would last for 10 years.

V. Financial Analysis Model

This model is the final output for the user. It will include the final total cost of the system, the net present value of the investment, the breakeven point, and the annual costs over a period of twenty years. The total cost of the system will be derived from the cost model. The net present value will be calculated using the following equation where:

C_t: Net Cash inflow During period t
C_0: Total investment costs
r: Discount rate
t: Number of time periods

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_o$$

Another key function of the Financial Analysis Model is to calculate the break-even point for each turbine in the inventory based on the wind speed data of the specific site. This is done through the calculations in figure 9.

	Equation
Electricity Cost	Previous year rate ($) + (previous year rate ($) * 0.0078)
Maintenance Cost	Electricity Cost ($) * $0.007
Insurance Cost	Turbines Cost ($) * $0.01
Annual Utility Bill	Electricity Cost ($) * Yearly Electricity Usage (kW)
Total Maintenance Cost	Maintenance Cost ($) * Total Power Generated (kW)
Annual Turbine Cost	Maintenance Cost ($) + Insurance Cost ($)
Net Metering Value	Total Power Generatated (kW) * Electricity Cost ($)
Savings	Net Metering Value ($) - Annual Turbine Cost ($)
Break-Even	Saving ($) + Current Break-Even Value ($)

Fig. 9 Equations used for break-even calculation

Annapolis, Maryland and Spotsylvania, Virginia Case Studies

From 1 January 2016 to 31 December 2017, wind speed data was collected for two locations: Annapolis, Maryland and Spotsylvania, Virginia. At each of these sites, wind speed data was logged every hour of every day for one year via weather stations that are mounted about five meters off the ground. This resulted in 8760 wind speed data points. The wind data from both sites was used as inputs for the DSS. For this case study, it was assumed that the turbines would be mounted on sixty foot monopoles. Based on the data from these locations the following results were found.

The average velocity of the wind was 5.45m/s. Based on a cut-in speed of 2.24m/s, the wind profile showed that there was wind with the potential to generate electricity for 32% of the year.

For the Spotsylvania, Virginia site, the average velocity of the wind was 4.58m/s. Based on a cut-in speed of 2.24m/s, the wind profile showed that there was wind with the potential to generate electricity for 26% of the year.

Case Study Analysis

Over the one year time period, it was seen that the Annapolis, MD site had greater wind potential. Figure 10 displays a comparison of annual output at both locations of seven turbines within the inventory.

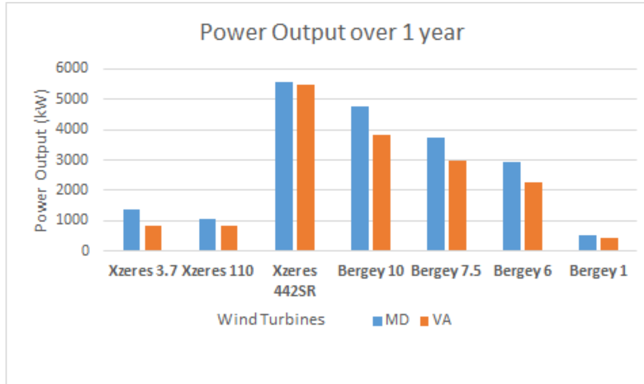

Fig. 10 Wind turbine cost vs annual power output

Based on the results of the case studies, there are characteristics of wind turbines that directly affect overall power output. The first being Cp. The coefficient of power has a large effect on the annual power output therefore having a significant effect on the break-even point and feasibility of these wind turbines.

From the annual output results, the break-even points were calculated. While the results were consistent, they did not show financial feasibility for an average homeowner. In one example the Aeolos 10kW wind turbine was used which has one of the highest efficiencies and lowest cost in the wind turbine inventory. It was found to have a break-even point at seventy-six years. Considering that the life cycle of these turbines is twenty years, we find this to be infeasible.

The solution to this problem is utilizing roof mounting to eliminate the cost of the monopole tower and also applying a federal tax credit of 30%. This tax credit is for 30% of the installed cost of the wind turbine.[6] Although the credit expired on 31 December, 201, it is likely that a similar credit will be available. This yielded a break-even point of twenty-four years.

In addition to utilizing roof mounting and the federal tax credit, increasing the Cp of the Aeolos 10kW turbine reduced its break-even point significantly as well. While this is not realistic because this would require changing the design of the turbine, it does illustrate the effect of using higher efficiency wind turbines. The effects of using a roof mounted option, applying the 30% tax credit and increasing the coefficient of power (Cp) can be seen in figure 11.

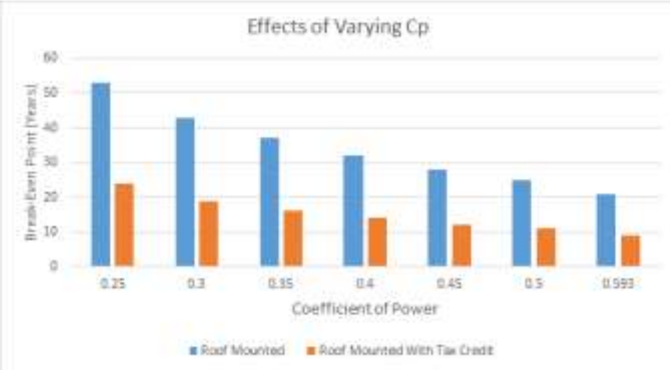

Fig. 11 Effects of Cp Change and Tax Rebate

Applying the government tax credit while using the roof mounted method and not changing the Cp from its original value of 25%, resulted in again a break-even point of 24 years, 52 years less than originally calculated. By then increasing the Cp value from the original value of 25% through a range stopping at Betz limit of 59.3%, a significant reduction in break-even point can be seen.

Conclusion

In conclusion, combining increased Cp values with roof mounted designs that will also be eligible for government tax credits is the best solution. This provides residents with systems that have feasible break-even points closest to being within the twenty-year life-cycle of these wind turbines. The next milestone would be to have residential wind turbine systems with break-even points that are less than ten years. By applying a Venturi effect of 37%, the break-even of the Aeolos 10 kW turbine reduced from twenty-four years to ten years. To reduce the break-even point below ten years, the Venturi effect would have to be greater than 40%. Taking advantage of this the Venturi effect would enable wind turbine owners to increase their power output without increasing their costs.

References

[1] "U.S. Energy Information Administration - EIA - Independent Statistics and Analysis," U.S. Energy Information Administration (EIA) - Data

[2] "Washington State Energy Profile," Washington Profile. [Online]. Available: https://www.eia.gov/state/print.cfm?sid=WA.

[3] Textbook: Wind Turbine technology: principles and design by Adaramola and Acho

[4] For further information - eia.gov." [Online]. Available: http://www.eia.gov/outlooks/aeo/pdf/0383(2015).pdf.

[5] "Virginia SCC," Division of Public Utility Regulation. [Online]. Available: http://www.scc.virginia.gov/pur/index.aspx.

[6] RESIDENTIAL RENEWABLE ENERGY TAX CREDIT by the Department of Energy http://energy.gov/savings/residential-renewable-energy-tax-credit

[7] U.S. Energy Information Administration - EIA - Independent Statistics and Analysis. (n.d.). Retrieved March 28, 2017, from https://www.eia.gov/electricity/data/browser/#/topic/7?agg=0,1&geo=vvvvvvvvvvvvo&endsec=vg&linechart=~ELEC.PRICE.VA-RES.M~ELEC.PRICE.WA-RES.M~~~~&columnchart=ELEC.PRICE.US-ALL.M&map=ELEC.PRICE.US-ALL.M&freq=M&start=200101&end=201412&ctype=linechart<ype=pin&rtype=s&pin=&rse=0&maptype=0

[8] U.S. Energy Information Administration - EIA - Independent Statistics and Analysis. (n.d.). Retrieved March 28, 2017, from https://www.eia.gov/electricity/data/browser/#/topic/5?agg=0,1&geo=00000001&endsec=8&freq=M&start=200101&end=201510&ctype=linechart<ype=pin&rtype=s&pin=&rse=0&maptype=0

[9] "Exploring the Venturi Effect"[Online]. Available: https://www.comsol.com/blogs/exploring-the-venturi-effect/