An Analysis of WPI's Power Grid in Worcester, Massachusetts

4 March, 2016

A Major Qualifying Project: submitted to the faculty of
WORCESTER POLYTECHNIC INSTITUTE
In partial fulfillment of the Degree of Bachelor of Science

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I. Abstract

This project developed an alterable interactive simulation of the present WPI campus power grid. The simulation accurately represents the voltage, switch gear, breaker ratings, transformer locations, connectivity, and impedance of the actual campus electrical network. This electrical information is overlaid on a three-dimensional Geographical Information System (GIS) model of the campus showing building locations. Simulation results were verified against actual system data. This model will facilitate system studies of campus grid upgrades.

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1 Introduction

A stable power source is critical for an ever increasing amount of day-to-day operations for homes, businesses and institutions. Increases in severity and frequency of natural disasters have amplified the vulnerability of the power grid, in turn putting those who rely on it at risk. For critical facilities that provide shelter, medical services, food, etc. a continuous source of electricity is of even greater importance. Colleges and universities often house thousands of residents who rely on the institution for its services. An outage places these residents in unnecessary and often dangerous predicaments. In these types of cases residents may not be able to depart or receive aid for an extended period of time. With a high energy demand and a dependent population, "keeping the lights on" is an obligation of the institution.

The solution to mitigating the effects of a vulnerable power grid is a concept known as Micro-grids[1]. Micro-grids involve electrical generation and storage of energy on-site at a facility. In the event of grid failure, the micro-grid can ensure that critical energy demands are met. These systems have the opportunity to be applied to numerous college campuses throughout the United States. In particular, at Worcester Polytechnic Institute (WPI) in Worcester, Massachusetts there is inadequate redundancy for the campus in the event of a power grid failure. WPI''s solution for power grid failure is to provide standby fossil-fuel based generators which supply temporary energy to select loads across the campus; these select loads are deemed critical by WPI. The increased potential of prolonged outages which deplete on-site fuel sources is a call for the implementation of a new solution.

To properly assess the efficacy of further on-site generation and redundancy options, an efficient simulation of the WPI power grid is the critical and vital deliverable of this project. Through data collected from existing documentation of the campus and numerous campus walkdowns (see section 3.2.3) with members of the WPI Facilities department, the team designed an operational simulation of WPI's campus in PowerWorld Simulator software. By creating an alterable simulation, the team established an animated model of power flow at WPI as well as a database (within PowerWorld) for specifications of components on the campus grid. Beyond this project, future IQPs, MQPs and institutional projects will now be able to accurately study the feasibility of power grid modifications in a simulated environment before attempting their project implementation.

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[1] A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode. - [1]

2 Background

Increased natural disasters, rising fuel prices, an aging power grid and climate change mitigation efforts have created a growing need for cleaner, more efficient on-site energy generation. This section begins with a review of the fundamentals of a power system, then discusses generation and storage technologies available to implement micro-grids as well as three local Worcester colleges that have successfully implemented micro-grids on their campuses. Finally, the current energy distribution system and known issues of the power grid at Worcester Polytechnic Institute are discussed.

2.1 Fundamentals of the Power Grid

As seen in Figure 1, power in the traditional power grid is generated from a centralized power plant to the loads of the customers. These sources of power typically are remote from the customers and range in the order of megawatts, equivalent to large coal-fired power plants and nuclear power plants. In order to minimize losses, generated power is transported to distribution stations over long distances at high-voltages (less amperage needed for the same loads) then transformed to a smaller voltage to be delivered to end-users by a local utility company. As also shown in Figure 1, certain customers, with greater electrical demands are supplied with higher voltages from the transmission or distribution level.
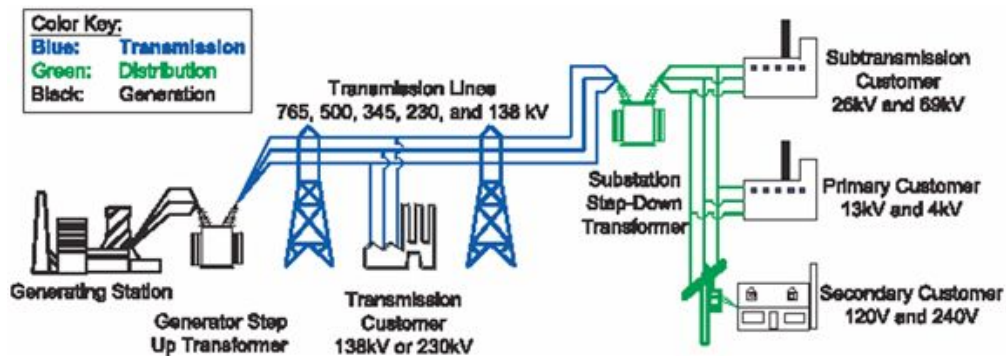
Figure 1 - Electrical Generation, Transmission and Distribution [2]

The fundamental elements of electricity can be compared to the mechanical properties of water flow. Voltage (volts), or potential, is similar to the pressure differential of the water in a pipe. Current (amperes) is comparable to flow rate or in the case of electricity: the amount of electrons moving past a certain point per second. Power (active power) is comparable to the work done at a given moment by the water from the pipe, such as spinning a turbine. Active power is

measured in watts. Energy is a measure of the power delivered over time, measured in joules or watt-seconds.

2.1.1 Multi-Phase Voltages

The most fundamental form of an AC voltage is expressed by the function, for example, as a sine wave:

$$V_{PhaseA} = V_p * \sin((2*60Hz*\pi*t)+0°)$$

V_P is the scalar (magnitude only), peak voltage value of the sine wave in reference to neutral. 60Hz represents the standard for United States AC frequency. The variable "t" represents time, in seconds. In a three phase system, as shown in Figure 5, Phase A is shifted 0° in reference to Phase B and C. Phases B and C are 120° out of phase of the other 2 phases, meaning phase shift values of 120° and 240° respectively.

Multi-phase voltage systems introduce the concepts of line to line voltages (designated as V_{LL}) and line to neutral voltages designated as V_{LN}. A 'line' refers to the conductors attached to the phases in a circuit. V_{LL} voltages are measured across two lines in the system while V_{LN} voltages are measured from a line to the neutral point in the system. A neutral wire serves as a reference point for the voltage of the lines in the circuit and is a return path for the current back to the source.

Phase A can also be represented using the RMS (root mean square) value of the function. The RMS value is equivalent to the DC voltage value that produces the same amount of power in a resistive load. V_{rms} is calculated by taking the square root of the mean average of the square of the voltage from 0° to 360° of the sine wave. V_{rms} is calculated using the following equation: $V_{rms} = V_p / \sqrt{2}$. RMS values allow average power to be calculated for time varying voltage and current. It is important to note that RMS value is not the average value of a sine wave, as the average value of an AC sine wave with a DC offset of 0 is 0 [3].

When transforming three phase voltages, high voltage and low voltage side circuit configurations are a combination of Delta and Wye (see Figure 2 and Figure 3), designated as such for their configuration shapes. The motivation of configuring the high and low side as either Delta or Wye depends on the application of the transformer.

In a delta configuration as seen in Figure 2, the loads are connected between phases A, B and C. The voltage obtained across connected loads is V_{LL}.
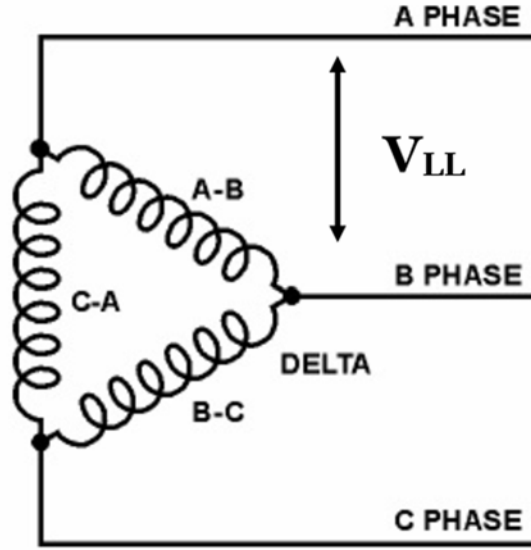
Figure 2 – Delta Circuit Configuration [4]

Wye configurations, as seen in Figure 3, may or may not have a neutral point that is either grounded or not grounded at the common point of connection of all three phases. In this circuit, $V_{LN} = V_{LL} / \sqrt{3}$ and $I_{LN} = I_{LL}$. Wye configurations offer the advantage of being able to deliver multiple voltage levels.
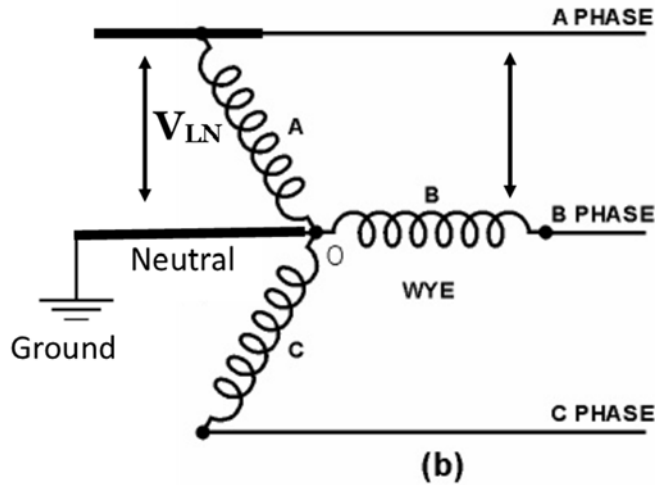
Figure 3 – Wye Circuit Configuration [4]

Four terms refer to 'power': apparent, instantaneous, active and reactive.

$$\underline{\text{Apparent Power}} = V_{rms} * I_{rms}$$

$$\underline{\text{Instantaneous Power}} = V * I$$

$$\underline{\text{Active Power}} = V_{rms} * I_{rms} * \cos(\theta) \; ;$$
$$\underline{\text{Active Power}} = 1/T * \int v(t) * i(t) * dt; \text{ T is the period of time}$$

$$\underline{\text{Reactive Power}} = V_{rms} * I_{rms} * \sin(\theta)$$

Apparent power is the sum of the vectors of the active and reactive power, expressed in Volt-Amperes (VA). More simply, it is the product of the RMS values of current and voltage. The distinction among these types of power are important in a power systems analysis. The heating of a transformer (current flow through the transformer), for instance, is determined from the apparent power being delivered. The power triangle in Figure 4 shows the relationship of active, reactive and apparent power.
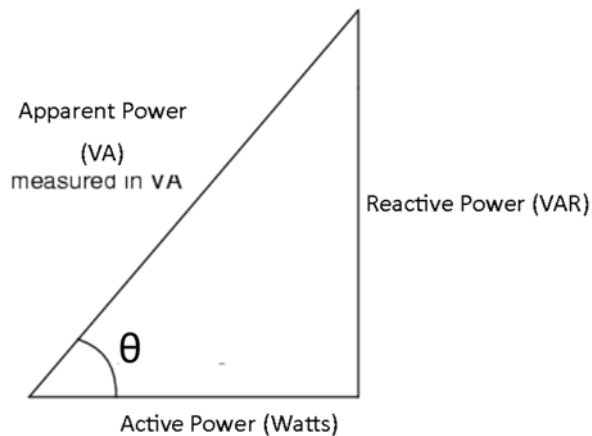
Figure 4 – The Power Triangle [3]

Instantaneous power is the product of the instantaneous values of voltage and current at a given time. Active power is the power dissipated by a resistive load. Power factor, $\cos(\theta)$, is the ratio of active power to apparent power in the circuit. This means a purely resistive load has a power factor of 1. When a circuit contains capacitance or inductance, energy is stored and discharged from these elements introducing reactive power into the circuit, measured in Volt-

Amperes-Reactive (VAR). Purely capacitive and inductive elements consume no active power. A capacitor and inductor each create a ±90° phase shift between voltage and current, the average power of which is 0.

2.1.2 3-Phase Voltages

In commercial and industrial distribution systems such as WPI, three phase voltage grids are used as represented in Figure 5. Phase 1, 2 and 3 are sine waves equal in voltage magnitude. However, the peaks of each voltage phase are off-set by 120° from each other. This results in a voltage greater in magnitude between the phases.
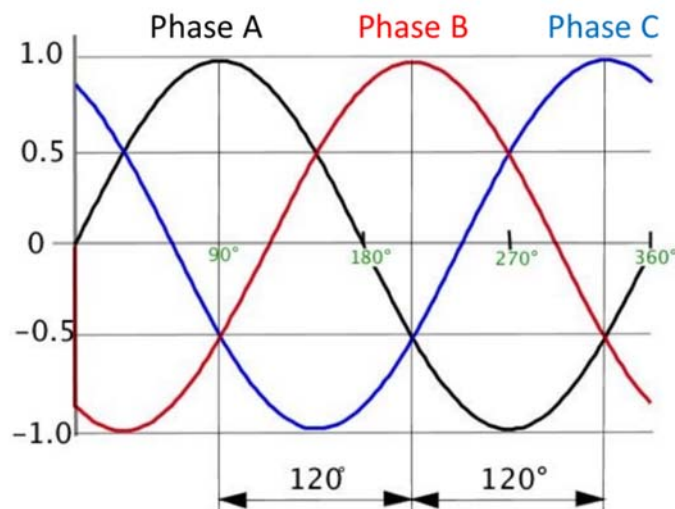
Figure 5 – Three Phase Voltage Graphical Representation [5]

The new voltage derived from phase to phase measurement is the result of the voltage magnitude and phase angle between the two original phasors. A phasor is defined as a vector with a length representing the amplitude of the voltage and an angle between the vector and positive X axis representing the phase voltage.
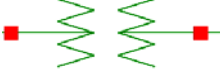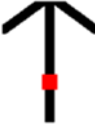
A three phase system has a number of advantages. First, by distributing the load equally on each of the phases there is theoretically no power flow on the neutral wire of the system, as the other phases are used as a return path. The neutral wire is able to have a smaller conductor sizing than in a single phase system. Second, three phase delivers a more consistent amount of power to load devices. This is particularly important in the application of three phase motors where consistent power improves rotational performance and torque. 3-phase power produces a rotating

magnetic field for the motor. In addition, three phase power allows a higher voltage to be obtained from phase to phase.

2.1.3 <u>One-Line Diagrams</u>

A one-line diagram (OLD) is a simplified way of representing a three-phase power system. Each significant electrical element is represented by standardized symbols within a schematic. Within the OLD, only one line represents all three phases; this representation makes it easier for a viewer to understand the power system. An example one-line diagram can be seen in Figure 23 of Section 3.1.2. Table 1 shows the symbols used by the selected simulation software. Each component also includes a circuit breaker to enable/disable the device. In Section 3.4.1, the simulation software is further elaborated upon.

Table 1 – One-Line Diagram Component Symbols

Symbol	Device
	Buses
	Transmission Lines
	Generation
	Transformers
	Loads
	Circuit Breakers

2.1.4 Frequency

The relationship between generation and the load brings in the element of frequency. The alternation of current in the United States power grid (i.e. the number of times, in one second, the current reverses its polarity and return back to its original polarity) is 60 Hz. Most electrical distributors deliver power at a frequency within 0.05 Hz of 60 Hz. This standard is to ensure a balance of generation and load as well as for those devices that use 60 Hz as a reference, such as motor generators connected to the grid [6].

As shown in Figure 6, in an event where generation is less than the load, the frequency drops requiring either load to be shed or increased generation to be activated. Similarly, an excess of generation causes frequency instability issues. Mechanical, regulated generation such as coal-fired power plants automatically account for frequency changes by increasing or decreasing their mechanical output in the event of a drop or rise of frequency respectively [7]. Smaller, on-site points of generation lack the ability to vary electrical output depending on the frequency of the connected grid. This is problematic for ensuring a steady source of power from such generation.
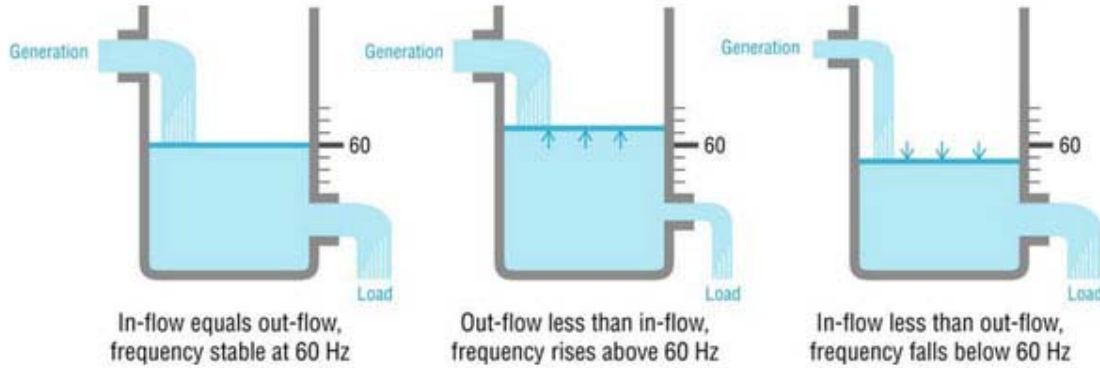
Figure 6 - Frequency Related to Water Flow [8]

2.2 The Need for Resilient Energy

The world's reliance on electricity is a highly visible issue whenever there is a lapse in the electrical supply from the power grid. Component failures, fuel shortages, demand overloads, and damage to the grid from natural disasters can all result in outages that vary in severity. Not only do these outages have long-reaching financial impacts for businesses who can no longer operate but these outages can be catastrophic for facilities and institutions that provide vital services or residence. Figure 7 shows the results of Eaton's Blackout Tracker containing reported blackouts across the U.S. from 2008 to 2014 [9]. These outages vary in severity but have the criteria of any grid failure that impacted customers. From 2013 to 2014 there has been a 12% increase in the number of outages. The figure further exemplifies the stability issues seen with a centralized power grid. Even a short-lasting interruption can damage equipment with voltage instability, repeated power cycling and reboot times of equipment that may not automatically power on after a failure.
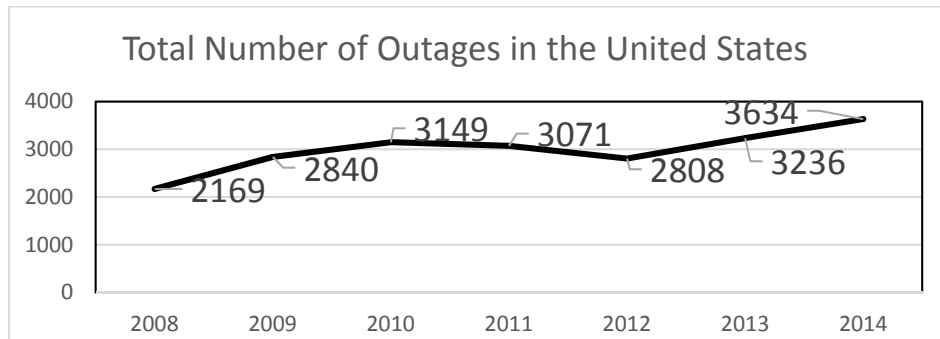
Figure 7 – Power outages in the US since 2008 [9]

2.3 Natural Disasters

Concerns of energy resiliency have become more important in recent years. Since 2010, five major storms have struck Massachusetts [10]. In New England, natural disasters can strike the region at any time of the year. In recent years, Massachusetts has experienced a number of major storms. Some notable examples include hurricanes Sandy and Irene which resulted in coastal flooding and strong winds that carried debris and damaged power lines in the impacted areas. During Hurricane Sandy, nearly 400,000 customers were without power by mid-day on October 29, 2012. By 2pm on November 1, roughly 12,000 customers had not yet been restored. One day later by 5pm, 7,200 customers remained without power [11].

Winterstorm Nemo delivered considerable snowfall and resulted in damaged power lines due to falling tree branches and ice accumulation causing power outages for over 400,000 customers. Local utilities were able to restore 75% of power to customers within 2 days but further outages required nearly a week for restoration. According to local Natural Gas provider NStar, much of the delay was associated to conditions being too dangerous for utility workers to be in [11].

The inherently high fuel costs of fossil fuel-based emergency generators, lost food stores due to inoperable cooling units, damaged electrical distribution systems, idle staff and increased security concerns are just some of the costs incurred [12]. Figure 8 shows the annual cost of power outages per state. The cost for Massachusetts is in the upper tiers for the United States, in excess of $4 billion [13]. This cost reveals the potential benefits and need of energy resiliency investments to ensure power delivery despite grid failure.
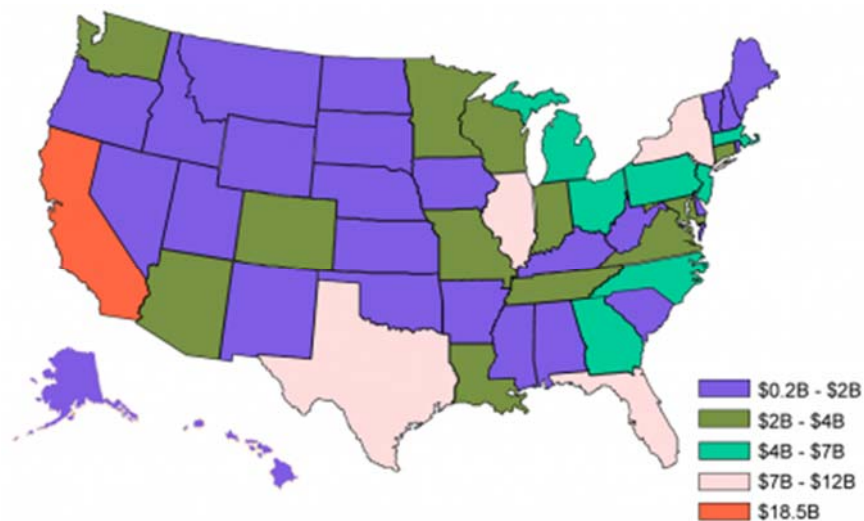
Figure 8 – Annual Business Losses from Electrical Outages [13]

2.4 Traditional Emergency Generation

Historically, the need for resilient energy has been addressed with stand-by generators which power the loads for a customer post- grid failure. Unfortunately, these generators can negatively impact the environment. Stand-by generators typically burn fossil fuels such as diesel fuel or natural gas. Such generators produce greenhouse gases and other harmful emissions from the combustion of fossil fuels that are more potent than other centralized generation sources due to lack of filtering for emission controls [14]. Scientific consensus has linked anthropogenic greenhouse gasses such as the ones emitted from diesel generation to the acceleration of climate change [15]. Additional emissions from diesel generation, such as Sulfur dioxide (SO2) and NOx, are leading contributors to smog and acid rain [16]. With low-efficiency and harmful byproducts, diesel generators do not represent a sustainable back-up method in light of growing grid failures.

Fossil fuel combustion also has an impact on human health. The Massachusetts Department of Environmental Protection states "The air contaminants emitted by engines and turbines can have significant health impacts....Particulate matter, especially the finer-particle-size particulate matter generated by fuel combustion, can cause and contribute to serious respiratory problems" [16]. Due to these health and environmental effects, federal EPA regulations limits emergency stationary combustion engines (excluding portable, propelled or self-propelled motors) to a maximum of 100 hours of operation per year in both testing and emergency use, of which 50 hours can be used for non-emergency situations such as power contribution to the existing grid[17]. Larger, stationary diesel engines in continuous operation must also meet strict criteria such as the use of ultra-low sulfur diesel, annual EPA compliance reports, emission controls and more. For critical sites in New Jersey after Hurricane Sandy, where power was not restored for over a week [18], some facilities depleted their 100 hours due to a single natural disaster.

Diesel generation means a limited supply of energy on-site. During natural disasters, a re-supply of fuel may not be possible due to impassable transportation routes such as roads or bridges. In the aftermath of Hurricane Katrina in 2005, diesel fuel generators of four hospitals went off-line due to fuel depletion and mechanical failure. Since most access roads were flooded or blocked by debris, these critical facilities were unable to refuel inducing evacuations for all four of the sites [19]. The practical issue with the method of on-site diesel generation is that it relies on finite fuel supplies which could become depleted during a prolonged outage unless resources are available for refueling.

The limitations of a centralized power system and the environmental impacts of on-site fossil fuel generation call for a new power grid model. With the additional threat of man-made

and natural disasters increasing in severity, a new model must be resilient to potential grid failure and environmentally sustainable. The solution is distributed generation.

2.5 Distributed Generation Increases Resiliency

Multiple points of generation allow for resiliency of a system. Resiliency is defined as a system's ability to operate effectively in the event a disruption occurs such as a natural disaster or other damages [20]. The significance of a generation source going off-line due to damage from man-made or natural disasters is diminished with multiple power sources connected to the same grid. Figure 9 and Figure 10 contrast the concept of centralized generation with the distributed generation model of multiple sources of generation at various distances from the load. Distributed generation sources implemented with renewable generation further increase the resiliency of a system by eliminating the need for large on-site fuel storage and replenishment. By interconnecting distributed generation, excess power produced can flow back to the grid and thus meet the demands of other customers, depending on the utility provider's regulations.
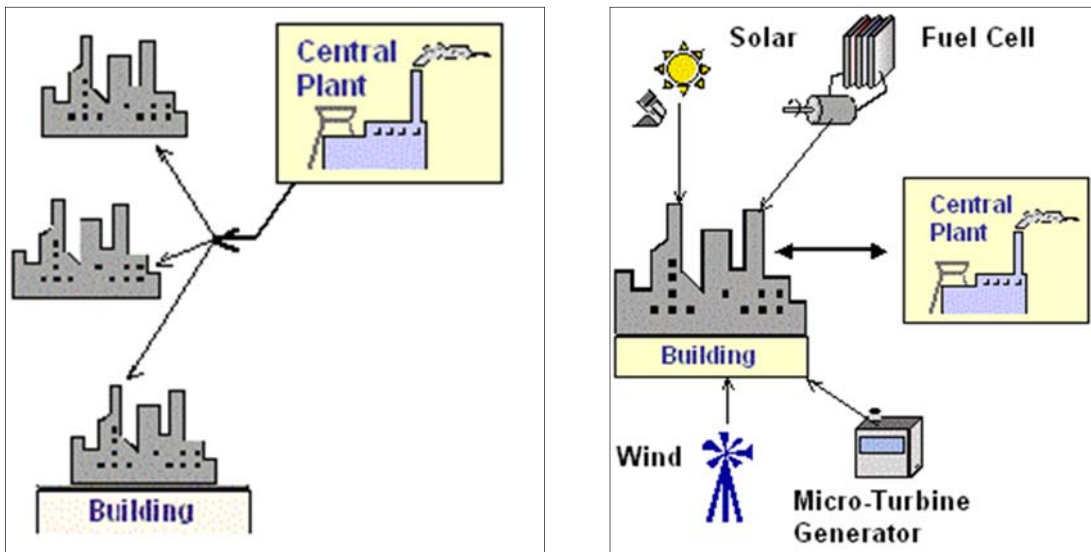
Figure 9 – Centralized Generation Model[21]   Figure 10 – Distributed Generation Model [21]

Micro-grids use distributed generation technologies for on-site generation independent of the power provided by a central plant. Micro-grids vary in scale, and have traditionally been seen in emergency generation (stand-by generation) systems where a grid failure (defined as the ability of the grid to be within a range of variables such as current, voltage and frequency) triggers an isolation of a load that is then powered by a local generator. This is referred to as "islanding". In

the Standards for Interconnection of Distributed Generation, utility provider National Grid defines islanding as:

> "'Islanding' shall mean a situation where electrical power remains in a portion of an electrical power system when the Company's transmission or distribution system has ceased providing power for whatever reason (emergency conditions, maintenance, etc.). Islanding may be intentional, such as when certain segregated loads in an Interconnecting Customer or Customer's premises are provided power by a Facility after being isolated from the Company EPS after a power failure. Unintentional Islanding, especially past the PCC [point of common coupling i.e. interconnection point between the customer and the utility], is to be strictly avoided." [22]

Micro-grids can also incorporate on-site generation that normally produces power and is able to produce power during islanding.

2.5.1 On-Site Generation Integration with the Centralized Power Grid

Fossil-fuel based plants can be called upon to supplement distributed generation in the case of an increased load or decreased generation. Renewable sources produce less consistent power than fossil-fuel generation. For regulatory and economic reasons, the majority of distributed generation is disconnected from the power grid when there is a significant change in a grid variable such as voltage or frequency [23]. This disconnection not only protects the customer's connected loads but also prevents electricity flowing from the on-site generation into a presumably unstable, offline grid. Micro-grids must incorporate proper technology to ensure appropriate islanding takes place as well as adequate generation to supply isolated loads.

2.6 Load Shedding

Load shedding is the disconnection of non-critical loads so as to be able to power critical loads. Installing generation to meet the entire electrical demands within a micro-grid is generally not economically feasible. Instead, the installed generation should be minimally sized to meet the demands of the critical loads only. What constitute as a critical load varies from site-to-site. Refrigeration units and emergency lighting at a local hospital, for example, can be considered critical as they are vital for the function of the health and safety of those which are served by the institution [24].

Renewable, intermittent sources of electricity add the possibility of deficient generation inside the islanded system. When islanding occurs, load prioritization must occur in order to determine the order in which critical loads go offline [25]. For example, a load shedding system may turn off air conditioning in a facility during a power outage and only enable critical loads.

2.6.1 Implementation

The shedding of non-critical loads involves the creation of a second circuit. Alternatively, active load control can automatically power down or reduce the demand of non-critical loads. This active control, for example, can reduce the speed of a ventilation fan to thus reduce its power consumption. In the event of a grid failure and complete reliance on on-site generation, pre-programmed hierarchy of non-critical load shedding can be implemented to remove certain loads from the circuit that are deemed less important than others. Active control can also shed non-critical loads based on certain variables such as voltage and/or frequency. These regulation devices also aid in preventing damages to devices during increased or decreased voltage and instead remove them from the circuit until sufficient power is restored [25].

2.7 Micro-grid Generation Technologies

The simulation provides a tool to simulate future WPI grid enhancements, including Micro-grid generation on the WPI campus. The technologies to implement on-site generation are numerous; however, the primary solutions relative to the Massachusetts region and applicable to the WPI campus are Combined Heat and Power (CHP), Solar Photovoltaic, and Fuel Cells. Other generation technologies, such as wind power, solar thermal and biomass will not be considered for the purpose of this paper due to land/height requirements, regional availability of solar energy and long-term maintenance, respectively. These generation technologies come with advantages and disadvantages in terms of power production, initial cost and integration. No singular piece of technology is the end-all solution for on-site generation; it is a mixture of various renewables that create a resilient system.

2.7.1 Combined Heat and Power

CHP involves using the waste heat from an electricity-producing unit to help meet the user's thermal energy needs. Figure 11 shows the functionality of a CHP system and the overall energy efficiency of the process. By capturing the waste heat and using it for other purposes such as space heating or cooling, the overall efficiency of the combined heat and electrical production is increased up to 85% and more of the fuel's energy contents are conserved in contrast to that

energy being released in the surrounding environment [7]. CHP represents a unique system in that it is a source of energy management and generation. Capturing waste heat from CHP systems as opposed to separate electrical and heat generation systems can reduce energy demands for an installation by as much as 40% [7].
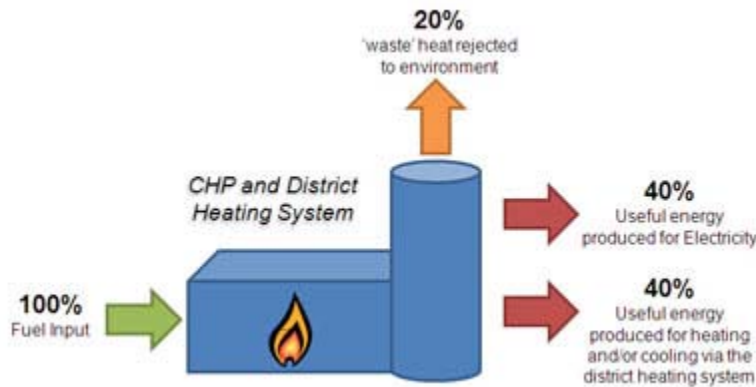
Figure 11 - Combined Heat and Power System [26]

Instead of using waste heat to meet hot water and heating demands, combined cycle uses the waste heat from electrical generation to power a secondary system, such as the spinning of a turbine to produce more electricity. Excess production when load is reduced is controlled through reducing the amount of fuel intake, with less energy needed to maintain the generator's speed. However, without a grid as backup power there is no supplement for an underrated CHP system. For many users the need for their facility to become an electrical island in the event of a power outage, i.e. a load independent of the larger grid, outweighs the substantial capital investment. [27]

Under the Green Communities Act's Alternative Energy Portfolio, CHP was allowed to be researched and implemented for its useful thermal generation despite its reliance on fossil fuels[28]. Massachusetts currently contains 12 facilities with integrated CHP. The largest of these systems is serving the Longwood Medical Campus in Boston, rated at 47.5 MW (megawatts) of power output. Currently, high electricity prices and low natural gas prices allow for a 58% savings in cost per kW (kilowatt) when generating on-site using CHP. In order to run most efficiently, CHP requires high pressure natural gas, a resource not available in all sections of Massachusetts including portions of Boston. Without the availability of high-pressure natural gas, the return on investments for end-users diminishes, requiring additional financial incentives for installations [26].

2.7.2 Solar Photovoltaics

Solar electric or photovoltaic (PV) systems work by converting the energy of the sun to electrical generation. PV is able to be scaled to the direct loads it will be supplying as individual panels are rated in maximum wattage output and can be added to or removed from a system. Traditional PV modules have no mechanical parts, are relatively resistant to extreme weather, and are adaptable in their installation locations ranging from ground to roof mounting. All of these factors increase PV's maximum time between failure.

PV systems may be in either grid-connected or off-grid configurations. In grid-connected systems, the output of the PV is supplied to the load alongside the grid's power. Off-grid systems output to the load and excess capacity is stored in batteries or not utilized. Grid-connected modules that are installed on the load-side of the utility meter face the issue of having to ensure an automatic islanding of the circuit, as a PV module will continue to produce electricity during a blackout. Grid-connected modules installed on the line-side of the meter (between the utility and the customer) allow the customer to sell the power produced by the modules to the utility company. However, in the event of a grid failure, most photovoltaic systems are required to disconnect from the grid for safety reasons thus no longer producing power. This means they cannot provide emergency power to the customer as well. Independent systems are not able to sell their excess power to the utility and generally must purchase expensive batteries that last 5 years if heavily utilized and 10 years if only utilized on occasion. [7]

2.7.2.1 Solar Output

Massachusetts has a relatively low amount of sun available throughout the year, with sun light averaging ~7 hours per day depending on the season. To gauge the efficiency of any electrical generation, capacity factor is used. Capacity factor is the ratio of potential (rated) output of the photovoltaic modules to the module's actual output in a given year. Boston's capacity factor is 17% using an axis-tracking system (PV modules that automatically align to the sun) and 15% with horizontal installations. This means, on average, customers in the Massachusetts region are able to obtain 17% of the rated output of their purchased PV modules. [7]

2.7.3 Fuel Cells

Fuel cells convert chemical energy (most commonly from Natural Gas) into electrical energy by combining oxygen and hydrogen using electrodes and across an electrolyte [29]. The products of this conversion are water, meaning the usual combustion products of carbon-dioxide, sulfur, methane, etc. are not emitted. Figure 12 illustrates the contrast in fuel cells versus conventional

combustion. Fuel cells have a much higher efficiency as they are not converting chemical energy to heat to drive a mechanical motion. Efficiencies as high as 65% can be seen with fuel cells.

When using the waste heat from fuel cells to drive another cycle or meet a thermal load, efficiencies can be as high as 80% [7]. With no vibrations, fuel cells can be placed close to the load with minimal line losses from distribution and transmission. Maintenance is also diminished on fuel cells with no charge or discharging actions and no moving parts.
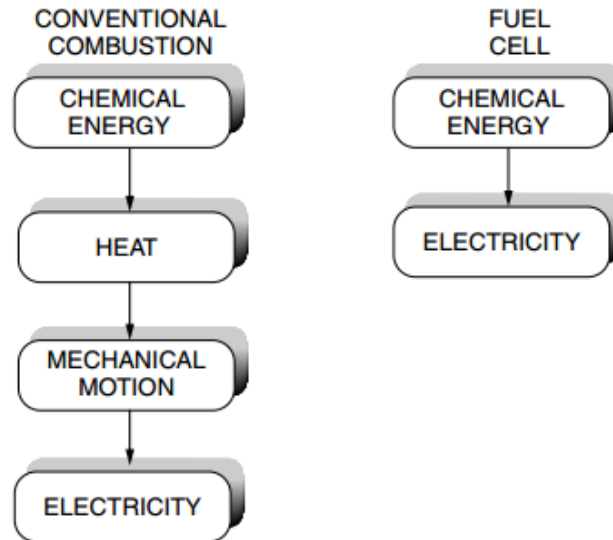
Figure 12 - Fuel Cell vs Conventional Combustion [7]

2.8 Micro-grid Storage Technologies

Storage options provide power to a Micro-grid load when generation is no longer producing power. Most commonly this is useful for wind and solar generation where generation is not consistent throughout a day and thus needs to be stored when produced. Like generation, storage should be sized to meet the critical demands of a Micro-grid over the maximum time period the generation may not be in operation or until the local facility can receive external assistance.

2.8.1 Battery Storage

The incorporation of on-site batteries allows a cycle of depletion and charging to occur at times where generation is unavailable. Inverters are often incorporated in battery storage systems to allow alternating current devices to use the direct current produced by the batteries. The inverter also allows an alternating current source in the same circuit to charge the batteries. SolarCity, partnering with Tesla, has released a battery suitable for residential applications.

Figure 13 and Figure 14 show the operations of these batteries with a photovoltaic system in the event of a grid failure.
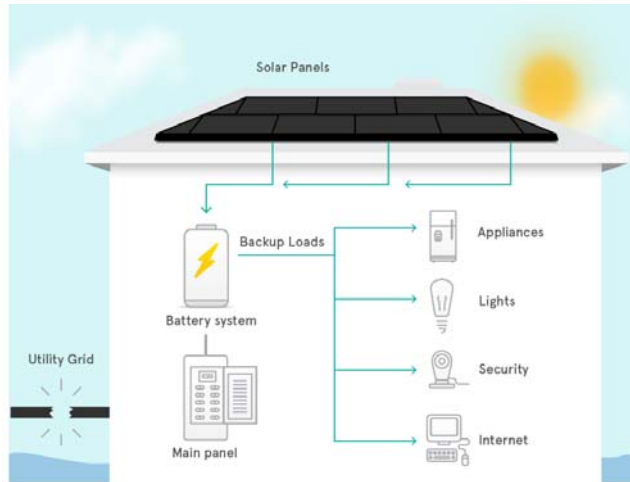
Figure 13 - SolarCity Residential Backup Batteries with Photovoltaics Daylight Operation [30]

During daylight hours when sunlight is available, the photovoltaic systems charge the battery while providing power to the loads. When the source is no longer able to produce power at nighttime in Figure 14, the batteries discharge their stored power to the loads. A battery storage system with renewables allows a repeated cycle of charging and depletion provided the correct weather conditions.
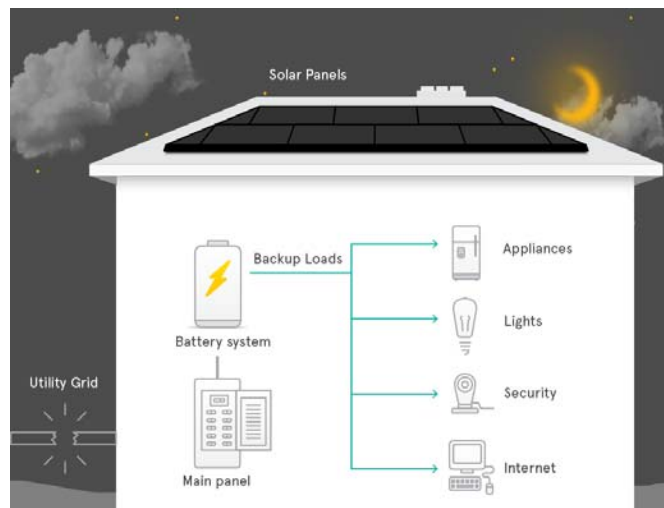
Figure 14 - SolarCity Residential Backup Batteries with Photovoltaics at Nighttime [30]

Battery storage systems work with commercial and industrial applications as well by increasing the storage capability of the batteries to match the higher demands.

2.8.1.1 Design Considerations

Traditional lead-acid batteries found in automobiles are designed to provide short bursts of high electric current and are unsuitable for applications requiring any appreciable usage of the batteries' capacity. Instead, lead-antimony also known as deep-cycle batteries are used. Deep-cycle batteries have a lifetime of approximately ten years when only drained to 25% of their capacity and five years when drained to 50% of their capacity. Lead-based batteries are temperature sensitive as well, with variances of room temperature increasing or decreasing the discharge rate. For every 10° Celsius above 25° Celsius, the lifespan of the battery is decreased by half [7]. This requires facilities to ensure a level of climate control for battery installations, potentially using critical square footage within a facility. The relatively low energy-density of lead-based systems is problematic in this realm.

2.8.1.2 Lithium-Ion

Lithium-ion batteries represent a system with greater energy density, five times that of lead-acid [7]. In Massachusetts, a company called A123 Energy Solutions [31] has developed a Grid Storage Solution that incorporates a large array of lithium-ion batteries, frequency regulation and power conversion contained inside freight-container-like units. An example of such units can be seen in Figure 15. Lithium-Ion storage systems have a charge/discharge efficiency of around 80%.

Figure 15 - Battery Bank of Grid Storage Solution [31]

The containers are able to operate in temperatures from -30° to 50° Celsius and can be purchased in lengths from 20 feet to 53 feet with varying storage capacity depending on the needs of the consumer [32]. The application of these systems allows for easy integration with a building's current system. All aspects of the batteries can be monitored and controlled remotely. In addition, the incorporation of power regulation and conversion in one system saves on installation costs and creates ease for future upgrades as the system is not directly installed into the facility.

2.8.2 Flywheels

Flywheels work by storing electric energy as mechanical energy. When the flywheel is charging and an electric current is applied (connected to a generation source such as the existing grid) the internal generator acts as a motor, absorbing rotational energy from the torque applied to it. When the current is no longer present, the inertia of the rotor applies torque to a generator which induces a current that generates electricity. Flywheels are versatile in their applications.

Flywheel systems range from three kW to one MW in size [33]. Vacuum-sealed installations and magnetic levitation of the internal mass (as opposed to the traditional friction bearings) means less friction for the system when rotating, resulting in efficiency measures of up to 90%. Installations cost on average $330/kWh in contrast to lithium-ion battery installations of $500/kwh. If the rotor is suspended magnetically, flywheels have a theoretically indefinite lifespan provided proper routine maintenance occurs. This gives flywheels another advantage over lithium-ion batteries with a five to ten year lifespan [34].

The disadvantage of flywheels is their low energy capacity as Fly Wheels are intended to provide immediate sources of power within a system. A lithium-ion battery may have an energy density (kilowatt-hour per kilogram) of 0.128 where a flywheel for electric power backup is around 0.043 [35]. One example of providing an immediate source of power is during a micro-grid's transition from grid-connected to islanding where there may be a delay in on-site generation to turn on and produce power. This requires a generator with high power but low energy.

2.8.2.1 Installation Examples

Beacon Power has installed two large-scale flywheel systems in the United States [33]. In 2010, a system was installed in California to store the energy from a wind turbine. The system was integrated with the wind turbine with much success. Another installation took place in Stephentown, New York. A 20 MW frequency-regulation plant was installed with 200 flywheels in order to supplement peak loads on the local grid. Both projects have proved successful and show the feasibility of flywheels.

2.8.3 Thermal Storage

Thermal storage operates on the principle of raising the temperature of a substance in order to store energy within it or, in contrast, storing a chilled substance for later use in a thermal cycle. Figure 16 outlines the latter with particular benefits in the application of air conditioning by performing the cooling process at nighttime (lower ambient temperatures thus higher efficiency) and outside of peak electricity rate hours. Once the chilled water is stored, it can be used to in the air conditioning process without the need of the chillers. [36]

Applications of molten salt work in a similar way. In applications of solar thermal collectors, sunlight is used to heat the molten salt that is then stored in insulated vessels. When there is no longer sunlight, the molten salt is used to create steam that then drives mechanical motion to produce electricity. In times of grid failure, thermal storage allows energy production outside of the times when a renewable source may be able to generate. In situations where there is a grid failure and a limited supply of fuel for generation, thermal storage increases the efficiency by allowing the generation source to operate when conditions are most optimal.
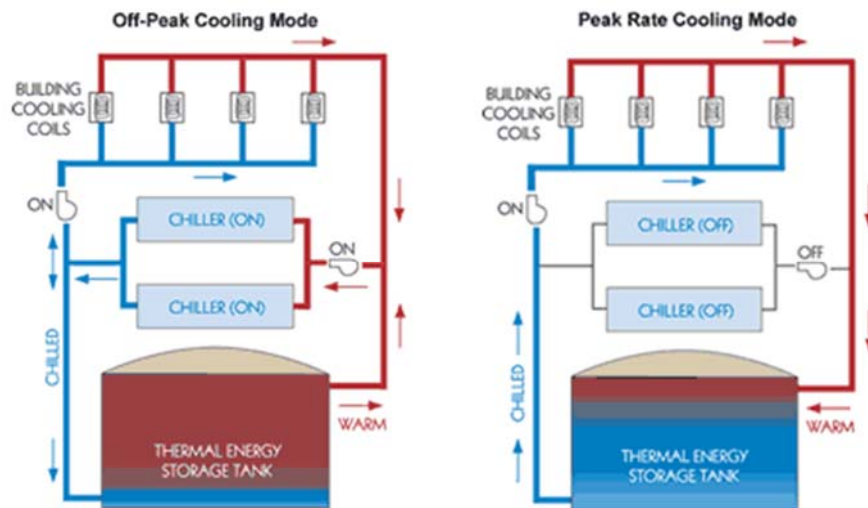
Figure 16 – Ice Storage Air Conditioning [37]

2.9 Financial Benefits of On-Site Generation

2.9.1 Types of modules

The biggest cost derived from the use of solar panels is the initial cost of the module and the installation. Due to the low efficiency of solar power technologies producing a relatively small amount of power, a large array of modules may be needed. For example, a solar system using 6% efficient 500 watt panels will take up twice as much area as a system using 12% efficient panels of

the same wattage. Currently, 21% efficiency is the highest rated solar technology available for commercial use.

There are several types of solar technologies that have been developed. Crystalline panels, which are the most common type of PV panel, come in two varieties: monocrystalline and polycrystalline, both of which are capable of being 20% efficient. Crystalline solar panels are highly reliable and usually come with a 25-year warranty. Crystalline solar panel arrays are most common for residential use.

Another type of solar technology are thin film modules. These modules are very inexpensive but can be inefficient. The lifespan of the thin film modules is often questionable and their efficiency only goes up to 10%. However, they are extremely versatile. They are light weight, can be made microscopically thin, are flexible, and do not require a lot of material to fabricate. Due to their cost effective property, most research and advancement have been invested in making thin film modules more durable and efficient.

Finally, building integrated photovoltaics (BIPV) are designed to look like a part of a roof. They are created to be the same size as the roof shingles. Compared to the above modules, they are less efficient and more expensive. To optimize their function, they are best used on large roof space in very sunny areas [38].

2.9.2 Average cost and factors

In order to determine PV's installation cost to cover part or all of a user's electric load, these following questions need to be answered: How many kilowatt hours are used per month? How much roof area is available to install modules? How many sun hours does that location get per day? Finally, how much money is willing to be invested in the installation and module cost process? According to Figure 17 which illustrates the solar insolation for the United States, Massachusetts gets about 4.0 kWh/m² per day.
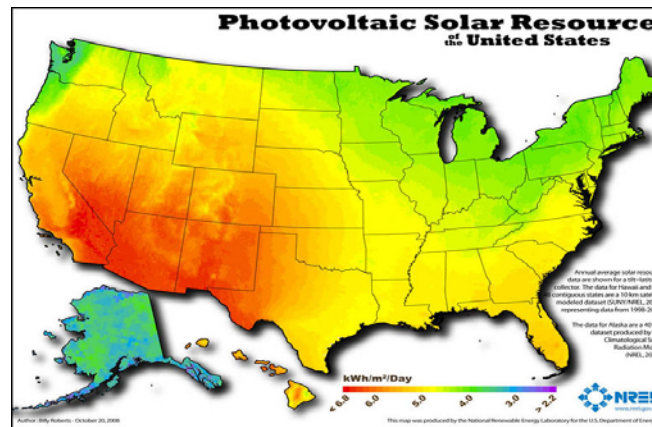
Figure 17 - Photovoltaic Solar Resource of the United States [39]

2.9.3 Financial incentive programs

The US federal government offer business and residential tax incentives and rebates from the purchase and installation of solar panels. Massachusetts alone has a variety of financing options for residents and businesses looking to invest in solar renewables. These options include direct ownership, solar leases, and power purchase agreement (PPA) contracts [28].

The upfront cost of installation and unit purchase can be offset by the following:

- Federal Tax Credit – A 30% federal Investment Tax Credit (ITC) for qualified residential and commercial projects.

- Massachusetts Personal Income Tax Credit – The lesser of 15% of the total cost of the PV system or $1,000, for qualified clean energy projects

- Modified Accelerated Cost Recovery System (MACRS) - Accelerated depreciation is available for eligible commercial projects [38]

Long term costs and incentives can include avoided electricity costs, solar renewable energy certificates, and net metering.

After the initial installation and equipment fee, solar energy does not add to greenhouse emissions, acid rain, or smog. With the increasing technology and dedication to making solar panels more efficient, the cost of solar panels has decreased in the past few years. Solar panels require maintenance over time, but offer a viable solution for businesses or residents looking to save money and reduce their carbon footprint [28].

2.9.4 CHP

Massachusetts offers incentives for CHP systems. The GREEN Communities Grant Program provides funding for municipalities to pursue installations of CHP systems. The conditions for eligibility include developing a plan to reduce energy use by 20% below a determined baseline within 5 years. Since June 2010, the program had approximately $7 million to award for these programs [40].

2.10 Case Studies

To both increase resiliency and lessen energy costs, a number of college and universities have implemented micro-grid solutions. In particular, University of Hartford, University of Connecticut and Clark University have successfully designed on-campus generation allowing them to isolate from the larger centralized grid while still maintaining a power source. These examples are beneficial to study for their selection of critical loads and on-site generation in similar climates.

2.10.1 University of Connecticut (UConn)

Through financial assistance from the Connecticut Department of Energy and Environmental Protection's micro-grid Program, UConn was able to create a micro-grid using existing fuel cells and a 6.6 kW photovoltaic array. Previously, there was no system in place to allow the grid-tied generation to remain online during a grid outage. The fuel cells provide sufficient thermal and electrical generation to supply staging areas, electrical vehicle charging stations, kitchens and space heating for UConn's Depot Campus. [41]

The micro-grid is dual-purpose serving as an educational resource for engineering students researching such designs. Figure 18 shows an overview of the micro-grid's generation sources and critical loads present. The electrical charging station allows UConn's fleet of emergency vehicles to operate without access to gasoline. The gasifier on-campus is primarily for education purposes but allows bio-waste to be converted into usable gas for the fuel cells. While the PureCell fuel cell traditionally runs on grid-provided Natural Gas, it can also run on anaerobic digestion.
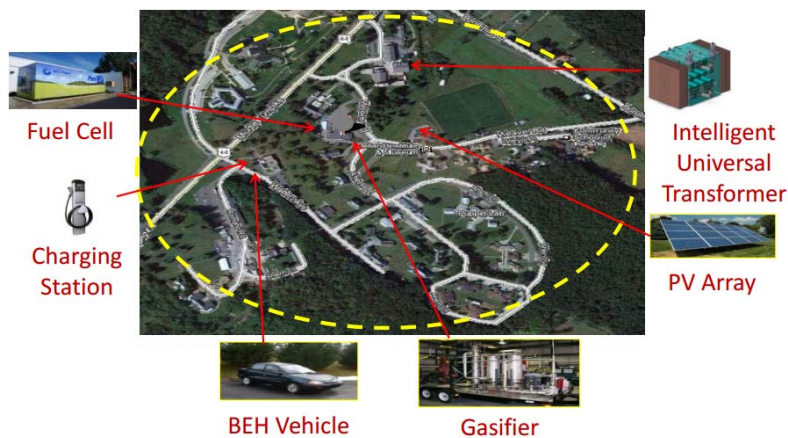
Figure 18 – UConn Micro-grid Overview [41]

2.10.2   Clark University

Clark University in Worcester, Massachusetts supplies a majority of its electrical and thermal load for main campus buildings and residence halls using a natural gas 2.0 MW cogeneration system, renovated in January 2013 (see Figure 19).

Figure 19 - Clark Universities 2MW Diesel Engine

During the summer months, the heat supplied solely by cogeneration allows the university to suspend operations of its existing three high pressure steam boilers. Waste heat from the generator's exhaust and envelope is recovered and converted to steam and delivered through the campus' steam grid. In certain years, the system was able to provide up to 90% of Clark's electrical demand. Cogeneration is able to meet such large electrical demands through energy reduction measures taken across campus that reduced the overall electrical demand. [42]

2.10.3   University of Hartford (UHartford)

The University of Hartford recently completed a micro-grid project to connect all campus buildings to emergency diesel generators. The primary goal of the project was to ensure all residence halls were connected to these emergency generators so as to maintain residential living during a prolonged power outage. Funding for this project came from the Connecticut Department of Energy & Environmental Protection's same micro-grid initiative that allowed University of Connecticut to incorporate their micro-grid.

2.11 Potential Project Discussion

Following the theme of resiliency and micro-grid incorporation at WPI, the team had multiple options for the focus of the project. Table 2 outlines the goals of these potential projects and the advantages/disadvantages of pursuing each. These potential projects are composed of subjects recommended by WPI Facilities, Professor John Orr and the team itself. Primarily, the team placed emphasis in selection on the educational value of the project (ensuring it was sufficiently challenging) and the usefulness of the project to the WPI community after completion.

The determination of creating a software simulation of the power system of WPI's campus came about as the team believed the project solved an immediate issue at WPI. The project also creates a stepping stone for future WPI energy projects (student or institution led). To further the usefulness of the simulation, load information from data accessed through both WPI's networked electrical meters and National Grid billing information was imported into the simulation.

Potential Project	Goals	Advantages/Disadvantages
Co-gen installation at Recreation Center	**Primary Goals:** o Provide 100% of Rec Center's thermal loads through Co-gen o Reduce WPI's net-energy costs & consumption. o Provide engineer calculation for design implementation. **Secondary Goals:** o Create an education resource for students to learnCHP operations.	+ Meets an immediate demand on campus + Increases efficiency of thermal generation for Rec Center pool - Possibility of not being implemented due to a number of factors thus negating a majority of the project - Limited academic scope - Similar projects done by National Grid staff and during WPI lectures
WPI electrical distribution software simulation using PowerWorld	**Primary Goals:** o Simulate interconnection, transformers, wires, lump loads and protection. o Create a tutorial for future users of the simulation to modify it. o Provide a stepping stone for future renewable generation. **Secondary Goals:** o Asses potential on-site generation installation at WPI and recommend generation type & tie-in location	+ Allows future IQP/MQP/Facilities projects to focus their research on incorporating generation into existing network + Provide groundwork for redundancy analysis of existing generation and grid-provided electricity. + Solves an immediate problem too of lack of WPI grid analysis
100% on-site generation to power WPI central campus loads	**Primary Goals:** o Design generation to meet 100% of WPI's electrical load o Reduce long-term energy costs o Increase outage resiliency at WPI **Secondary Goals:** o Lower WPI's carbon foot print through Renewables	+ Reduces WPI's carbon footprint & long-term energy costs + Allow WPI to serve as a model for other institutions - High implementation cost, may not be implemented - Broad in scope, may require greater time frame than available
Analysis of redundancy between substations	**Primary Goals:** o Analyze WPI electrical sources to determine source interconnection feasability in order to reduce power outage time due to failure of Park Ave substation (planned & unplanned outages) **Secondary Goals:** (None)	+ Less operation interruption time - Limited in scope, may be simple fix and thus not educational - Scope limitations also mean if it is not feasible project utility is null

Table 2 - Potential Project Comparison

2.11.1 <u>Simulation Tool Selection</u>

In choosing a simulation tool to model the campus power grid, the team had four primary criteria the simulation tool needed to meet:

1. Ease of Use - The software should have a relatively quick learning curve before. This is due to the time scope of the project as well as ease of use for stake holders in the simulation. An overly complex software would hinder future use.

2. Affordability – The software should be at a cost feasible for the institution to occur for a Major Qualifying Project.

3. Geographic Capabilities – In order to most accurately simulate the campus, the software should be able to incorporate geographical coordinates (longitude and latitude) of grid components.

4. Incorporate Static & Transient Loads – The software should be able to simulate electrical loads based off the user's input in both static and time transient inputs.

With these criteria in mind, the software that was selected was PowerWorld Simulator. Since PowerWorld is used in WPI Electrical Engineering courses, the team was familiar with its operation thus mitigating the initial learning curve of the application. In addition, the software was readily available through an educational license on the WPI servers. PowerWorld offers the feature of overlaying electrical components on a latitude and longitude map. As explained later in this report, this feature allows the importation of the campus' layout from Google Earth Pro (a free software) into the simulation. Finally, the software tool can simulate active and reactive loads through a static value or values that change over time, inputted in a spreadsheet format.

2.12 2015 WPI Power Grid Analysis

Electricity provided to WPI is first obtained through an energy purchasing consultant, Power Options. Power Options advised WPI to use Direct Energy as an electricity generation broker in order to find a cost-effective rate. The generated power is sourced from various generators in and out of the Massachusetts region. The below table, provided by WPI Facilities, shows the breakdown of the fuel types used to generate the electricity WPI consumed in 2014. Overall in 2014, 59% of Massachusetts's power was generated from natural gas while 9.5% was generated using coal [43].

Table 3 – Fuel Sources for WPI's Electricity

Fuel Type	Fuel %
Biomass	2.05%
Coal	4.86%
Diesel	1.07%
Digester Gas	0.03%
Efficient Resource (Maine)	0.54%
Fuel Cell	0.17%
Hydroelectric/Hydropower	6.73%
Jet	0.03%
Landfill Gas	0.58%
Municipal Solid Waste	1.17%
Natural Gas	36.49%
Nuclear	32.87%
Oil	7.20%
Solar Photovoltaic	0.70%
Trash-to-Energy	2.08%
Wind	1.77%
Wood	1.66%

National Grid (NG) utility company, WPI's electricity distributor ensures power reaches campus from the source(s) of generation (see Figure 20).
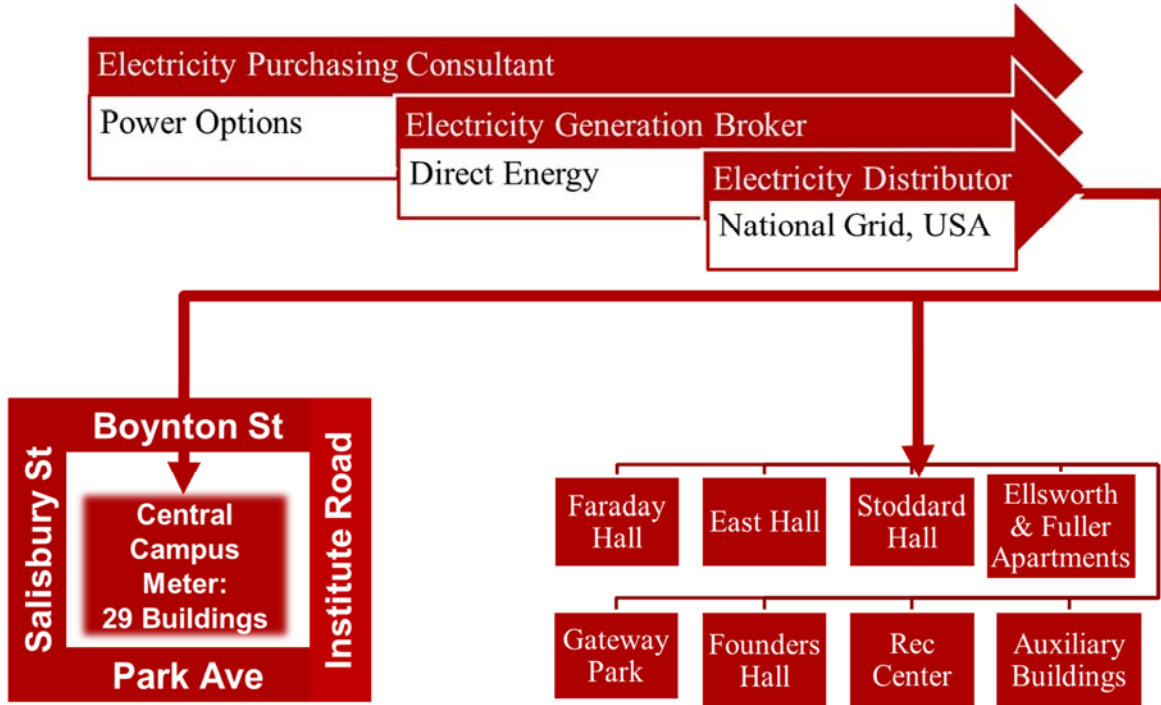
Figure 20 – WPI Electrical Distribution Flow chart

The energy for the main campus is received through two substations. The entirety of WPI's campus is broken up into sections; the buildings located in the area between Institute, Park Avenue, Salisbury & Boynton are all centrally metered at the WPI Powerhouse located in the center of campus. This meter can be found in the basement of the Powerhouse (see Figure 21). As it pertains to this study, Founders Hall, East Hall, Ellsworth, Fuller, Stoddard Hall, Gateway Park & the Sports and Recreation Center are connected directly to National Grid's service and metered separately. Through various meetings, and information derived from the WPI IQP Report "Monitoring Electricity Consumption on the WPI Campus" [44] this information was obtained to provide a broad outline for the way WPI's power grid is segmented.

Figure 21 - WPI Powerhouse elcetrical sub-meter

2.12.1 E-mon Demon Smart Meters

E-mon Demon smart meters (EDSM) (see Figure 22) have been installed on various buildings at WPI. For a full list of buildings, see Table 4.   Software capabilities that come with these meters can inform the WPI community on the energy usage of metered buildings. Usage reports play a fundamental role in determining where energy consumption can be decreased on WPI's campus and the effectiveness of energy reduction measures. Upon meeting with Robert Durning (October 14, 2015), Manager of Energy Efficiency at GreenerU, the team was able to ascertain the capabilities of the EDSM's for the analysis of the campus power grid.

The EDSMs send their load data to the data aggregation software every 15 minutes seven days a week. This software records instantaneous voltage, current and kilowatts for all EDSM's then stores the data on a private WPI network that is isolated for security reasons. Although the data is made available to specific project groups, it was not convenient in this format. GreenerU uses a data analysis software 'Skyspark' (a comprehensive suite for analysis of energy resources including electrical demand, consumption and cost) to view the data in graphical format.

Table 4 – E-Mon D-Mon Buildings

List of WPI Buildings with E-Mon D-Mon Meters
Alden Hall, Atwater Kent, Boynton Hall, Rubin Campus Center, Daniels Hall Gateway, Goddard Hall, Gordon Library, Harrington Auditorium, Higgins Labs Morgan Hall, Olin Hall, Sports & Recreation Center, Riley Hall, Salisbury Labs, Stratton Hall, Washburn Labs

Figure 22 - E-mon Demon Smart Meters WPI Powerhouse

2.12.2   Existing Generation & Emergency Generators on Campus

Cogeneration, as the name suggests, is the systematic generation of two forms of useful energy from a thermodynamic cycle, usually power and heat [45]. The two Tecogen systems

located at Gateway generate power and heat that offsets 30% of the building's electrical energy usage [46]. The CHP system is also controlling ambient temperature and humidity. Beyond cogeneration at Gateway, fourteen emergency generators are also located at WPI, eight of which use oil as a fuel type and six of which use natural gas. These emergency generators operate as stand-by, meaning (outside of regular testing) they do not run unless needed for backup power.

3 Design Approach

3.1 Introduction

This project's goal was to develop a simulation of the present WPI campus power grid to provide existing and new projects with an essential stepping stone in the process of bringing them from planning stages to reality. The team organized the project around four main objectives:

1. Collecting campus electrical data from respective stakeholders.

2. Developed a geographic system on which to overlay electrical components.

3. Imported available campus electrical data into the simulation and verified the accuracy of component ratings and campus power flow.

4. Created a user-friendly tutorial for future IQPs, MQPs, internal projects to manipulate the simulation.

3.2 Objective 1: Analyzing the WPI Power Grid

3.2.1 Obtaining Existing One-Line Diagrams

To complete the first objective, existing One-Line Diagrams (OLDs) were obtained from WPI Facilities. The most recent OLDs were part of an on-going update project by external consultant Fischbach & Moore (F&M) and existed in Adobe PDF format. These diagrams were a combination of diagrams completed by Coughlin Electric in 2007 and present updates made by F&M. In order to maintain the security of the documents, the diagrams were uploaded to WPI's SharePoint server for selected user access and team collaboration. An example diagram of Faraday Residence Hall can be seen in Figure 23. With these diagrams, the team compiled a list of primary buildings on campus to simulate. Notably, these were: academic buildings, residence halls and campus-event spaces.

Due to the complexity and ambiguity of the diagrams after the electrical service entered the building, it was also decided to simulate up to the main distribution of a building. Components after the main distribution panel would only be included to show the connection point of generation.

These diagrams provided key component ratings:

- Physical location of components

- Transformer maximum kVA

- Transformer high and low side voltage levels

- Circuit breaker ratings

- Delineation between utility-owned and WPI-owned property
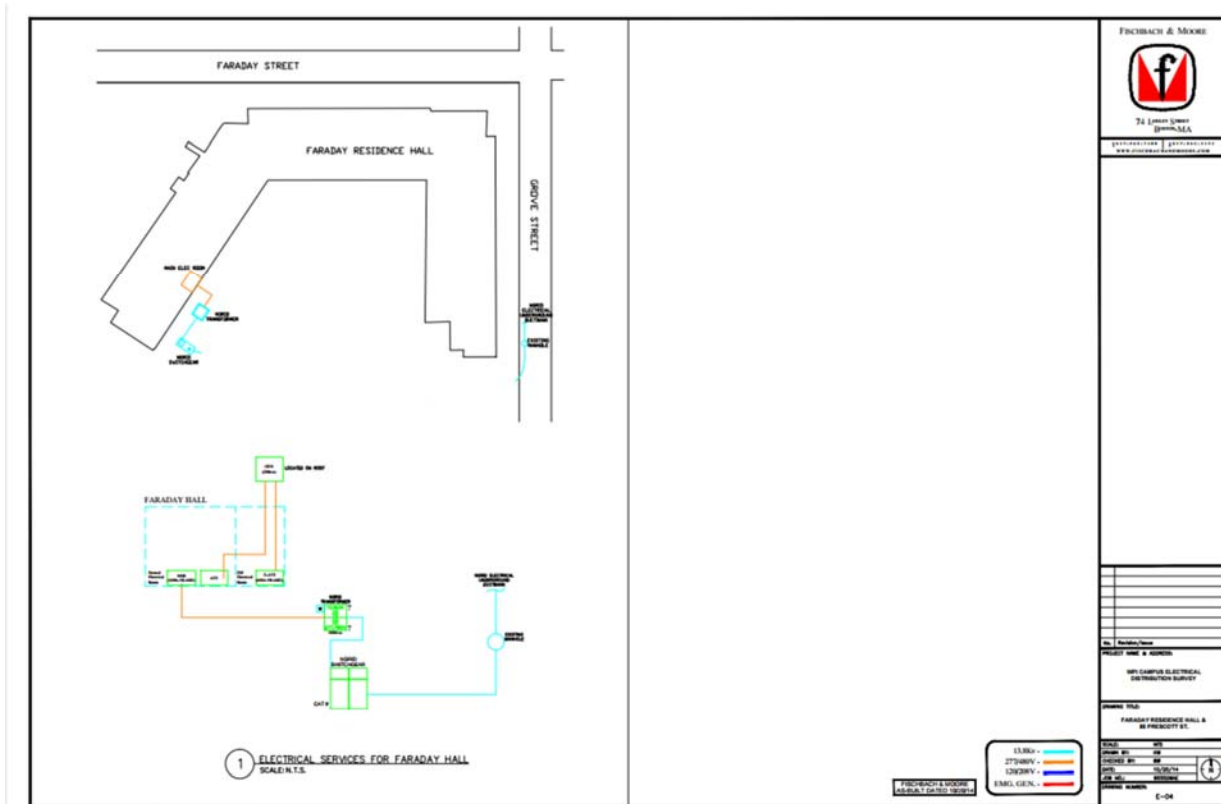
Figure 23 – Fischbach & Moore One-Line Diagrams

These new diagrams, however, were generally lacking:

- Physical location of distribution cables

- Transformer impedance ratings (WPI or National Grid-owned).

- Various component ratings, designated by "??" in their place.

- Various interconnection points of emergency generation.

To go forward with the simulation, it was necessary to obtain these values through other means.

3.2.2 National Grid Meeting

A number of WPI buildings not centrally located on-campus derive their power from a direct connection to the campus electrical provider, National Grid. The team met with Andrea Gossage, a member of National Grid's Community & Customer Management as well as distribution engineer Nathan Walsh at the Sustainability Hub in Worcester, MA. From this meeting, the team was able to obtain the ratings of the transformers owned by National Grid. The ratings provided included: maximum kVA, high and low side voltages, and positive/zero-sequence impedance ratings in ohm values and per-unit values.

3.2.3 Campus Walkdowns

In order to gain a physical understanding of the campus grid and to verify component ratings from the F&M diagrams, walkdowns[2] with WPI Facilities members were scheduled to clarify certain aspects. Ultimately these walkdowns clarified a number of discrepancies in the documentation; discrepancies which were noted for the F&M designers to review.

3.2.4 Generator Ratings

The team obtained information on campus emergency generators from WPI Facilities. The information obtained included the fuel source of the generator, maximum rated output power, and the manufacturer. Discrepancies were noted between the F&M diagrams and WPI Facilities' records and later clarified in the campus walkdowns.

3.2.5 Load Profiles

In order to model the power consumed by various buildings within the simulation, electrical load data was obtained from two primary sources. First, for buildings with E-Mon D-Mon smart meters monitoring electrical consumption, GreenerU provided the team with data from each meter at 15-minute intervals throughout 2015. This data was not complete; meters were

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[2] Walkdowns are methodical, on-site, visual visits of a campus or facility electrical equipment. [47]

integrated into the campus network at different points and some meters went off-line for a large period of time.

Second, for those buildings provided power directly from the power grid, monthly National Grid utility bills were used. The team was provided with a spreadsheet of kW usage per month per building for the 2014 fiscal year.

3.3 Objective 2: Develop a Geographical Overlay

3.3.1 Google Earth & Geographical Information System (GIS)

Since PowerWorld Simulator is able to import latitude and longitude data from shape files, the team decided to use Google Earth Pro to outline the campus and export individual areas. A larger overlay of the campus was imported to ensure proper mapping, followed by individual buildings. Shape files function by each point of the building containing a specific latitude, longitude and height data point.

3.4 Objective 3: Import the Data into PowerWorld

3.4.1 PowerWorld Fundamentals

PowerWorld Simulator uses a traditional One-Line Diagram combined with animations and powerful calculation tools to implement an all-in-one solution of data management, simulations and visual representations. The core aspects of PowerWorld are the mathematical simulation for power flow.

Each component created can be given custom parameters by the user, but begin as "drag-and-drop" functionality. This allows the user to visually create the simulated electric grid. These components are illustrated in Figure 24.
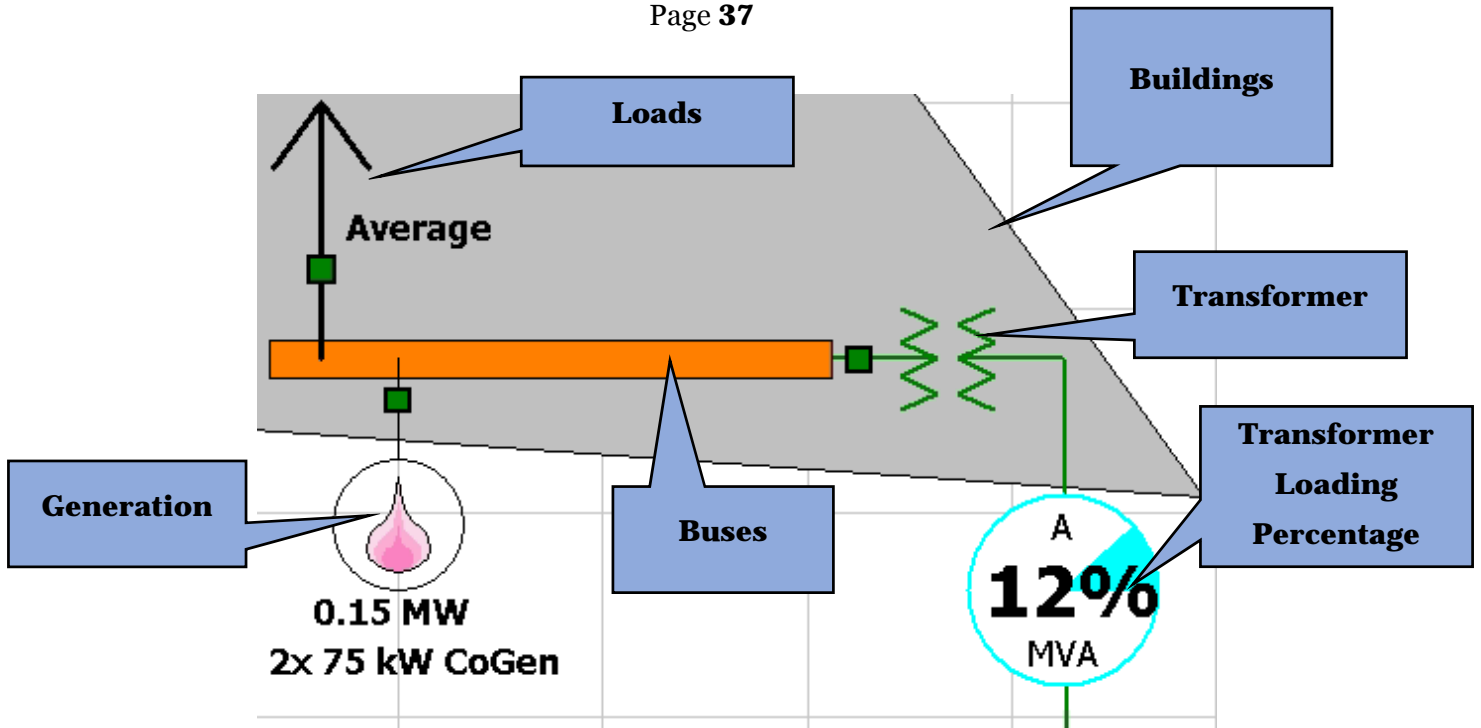
Figure 24 – PowerWorld Fundamentals Example

Table 5 – PowerWorld Components List

Buses	A point of interconnection for other components at the same voltage potential.
Transmission Lines	A common voltage wire connected between components. A single transmission line represents three phase power flow.
Generation	Source of power flow, can either be given a maximum power output or "slack" mode to match its output to the given load.
Transformers	Voltage changes from bus to bus included with a pie chart to display percentage of maximum power output transformer is producing.
Loads	Megawatt and/or reactive power draw from a bus
Circuit Breakers	Can be toggled to show open or closed, thus enabling/disabling device. These are automatically placed with each new component.

3.4.2 PowerWorld Enhanced License

The initial educational trial version of PowerWorld which the team was provided, has a bus limit of 40 per simulation. In order to simulate the campus' buildings and points of connection for emergency/on-site generation, the team needed a greater bus limit due to reaching the maximum of 40 early in the simulation design. To accommodate this, the team obtained the educational license for PowerWorld through WPI's Electrical Engineering department. The

license was installed on a local computer in Atwater Kent which the team used Windows Remote Desktop to access.

3.5 Objective 4: Tutorial

To ensure that future users of the simulation are able to manipulate it properly, the team created a brief tutorial incorporating screen captures for users to follow alongside the simulation. The tutorial covered each step, from logging into the server to performing fault analysis studies. The tutorial video file resides on both the PowerWorld serve as well as in the Appendix.

4 Project Implementation

4.1 Geographical Information System

After selecting the buildings to include in the simulation, meter billing addresses were obtained from WPI Facilities and National Grid (see Appendix A). It is important to note a majority of buildings are attached to the meter for 183 West Street, the central campus electrical meter. Within Google Earth, roof space of each building was individually traced as a polygon to represent its footprint. Figure 25 shows the yellow polygons traced for various buildings. Google Earth also includes the functionality for a 3D trace of each building to incorporate its height. However, this was not implemented for this project due to complexity and varying inaccuracy from building to building.

Figure 25 – Google Earth Shape Files

Shape files exported from Google Earth needed to be converted into ".shp" files to be imported into PowerWorld. To do this, a free service at MyGeoData.com was used. MyGeoData has the capability to specify latitude and longitude map projections for North America as well as specifications for polygon shape output. Figure 26 shows the conversion of Alden Hall's shapefile.
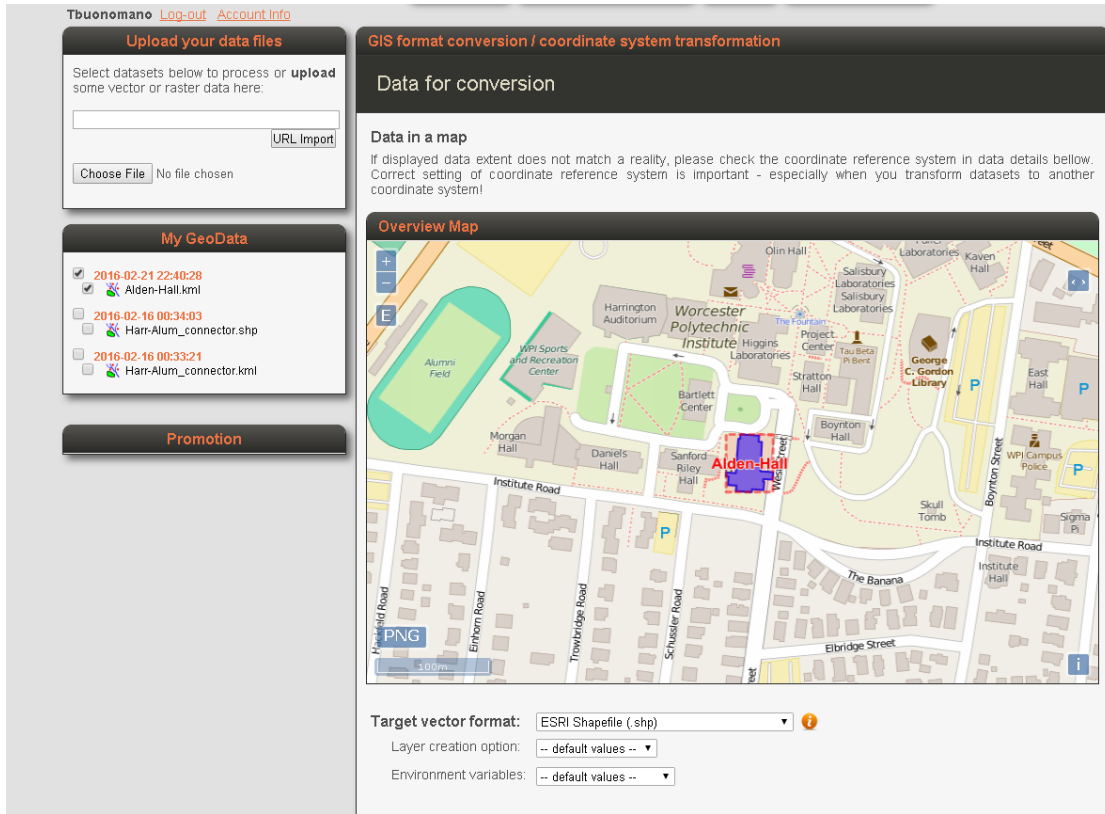
Figure 26 – MyGeoData.com Shape File Conversion

Each shape file was imported into PowerWorld with a magnification of 100,000 in order for the building sizes to be proportional to the overlaid component sizes (see Figure 27).
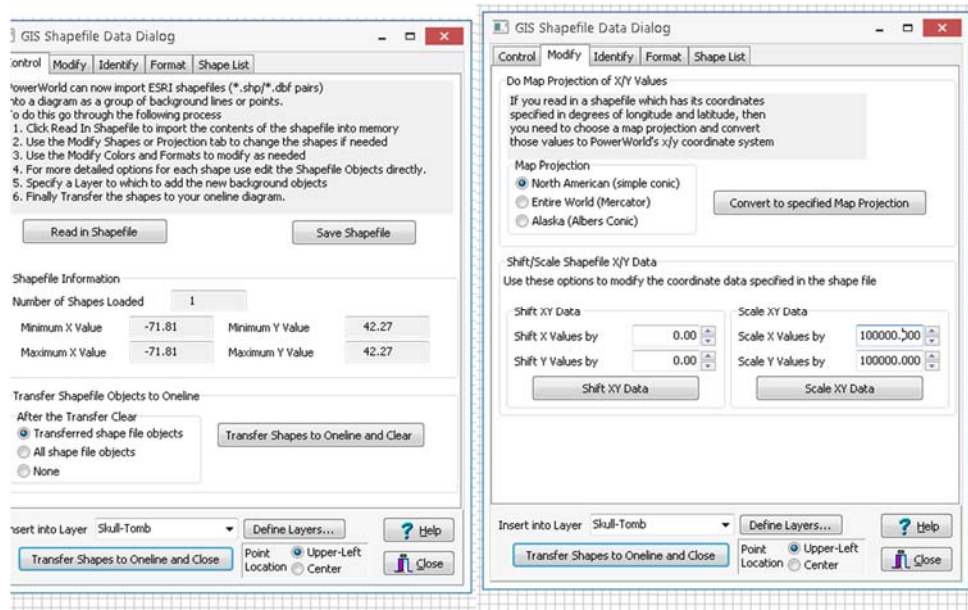
Figure 27 – GIS Import: Modify and Control Tab
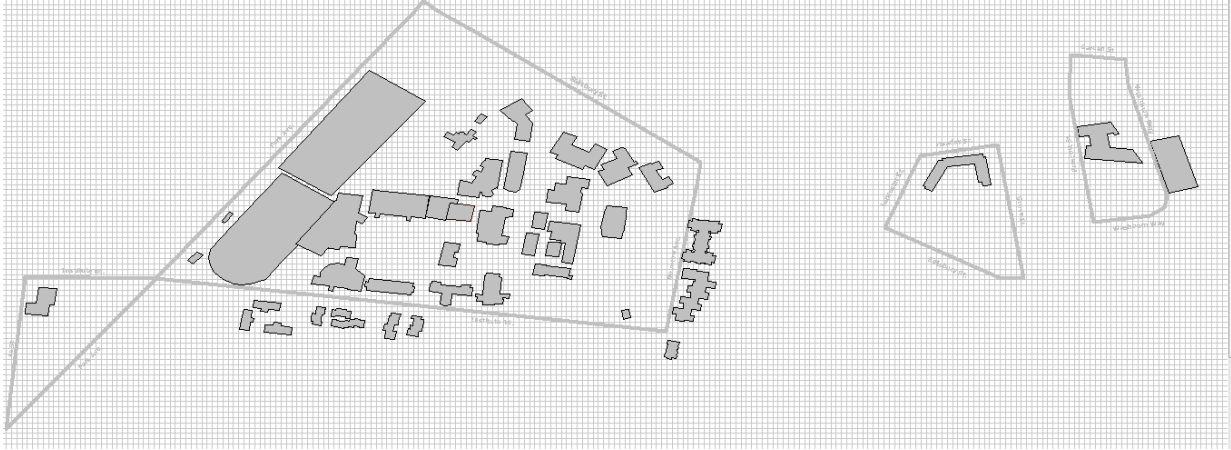
Figure 28 – Imported Building Shapes

Figure 28 shows the PowerWorld simulation with the imported buildings, football field, Park Avenue Garage and border streets. This aerial view shows the areas of Gateway, central campus, Faraday and the WPI Facilities Lee Street office.

4.2 Master Bus List

To create the simulation, the team compiled the collected data to form a Master Bus List found in Appendix B. This spreadsheet identifies each building simulated as a Bus in PowerWorld included with this are the ratings of the transformer connected to the bus, generation at the bus and the high/low voltage circuit breaker ratings.

4.3 One-Line Formatting

Before inserting components over the campus map, the "Default Drawing" settings of the simulation were modified to automatically color components based on the magnitude of the voltage. Figure 29 shows the Default Drawing settings found under the Drawing tab. Using the color legend in Figure 30, buses, transformers, generators and transmission lines will automatically be colored upon insertion.
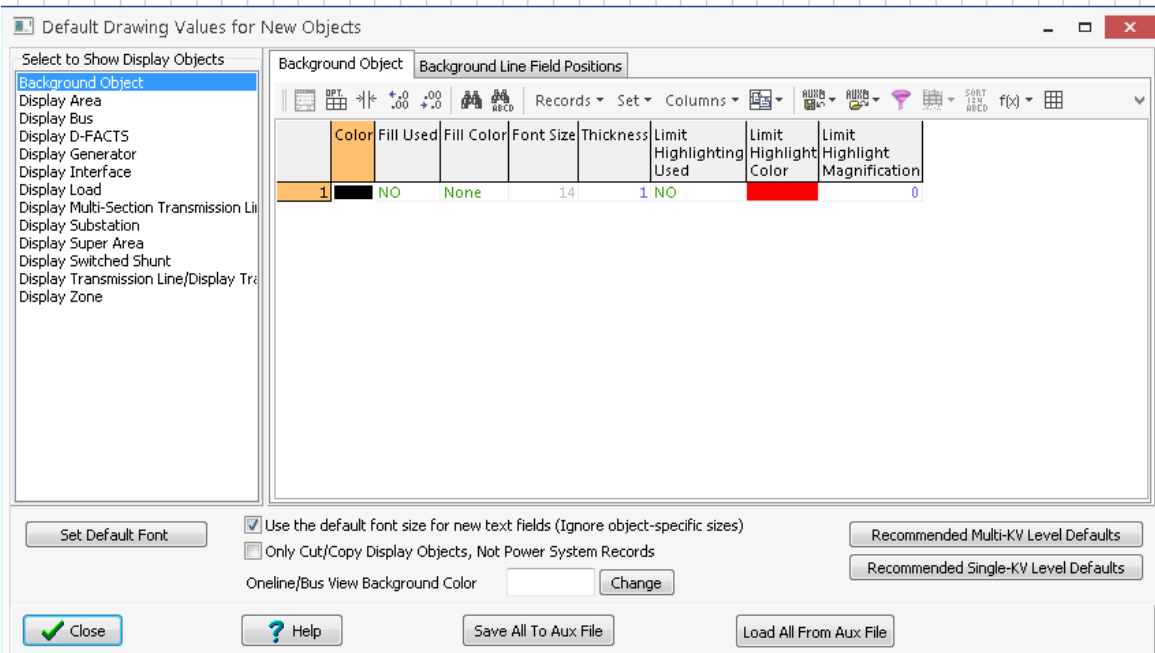
Figure 29 – "Default Drawing" window in PowerWorld
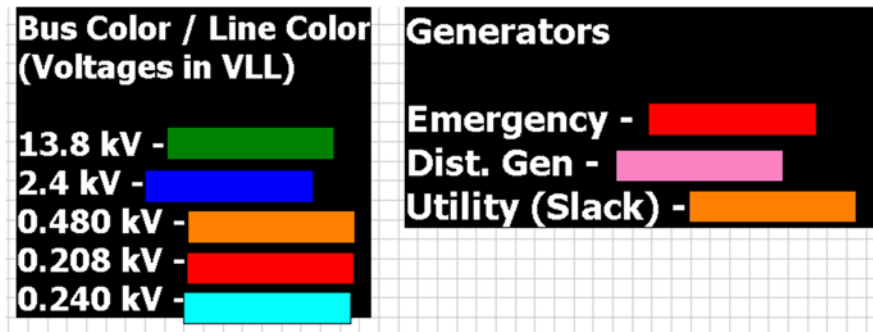
Figure 30 – One-Line Color Key

4.4 MVA Limits

A key parameter within the simulation for transmission lines and transformers is the MVA[3] rating of the component. In this simulation, transformer MVA limits were inputted from specifications on the F&M diagrams as well as information obtained from National Grid. The values obtained from National Grid were converted to kVA.

Within PowerWorld different types of lines can be drawn. Pertinent to this simulation are transformer lines and transmission lines. If two busses have already been made and their ratings properly inputted, then a transformer line can be drawn and placed between the busses. Doing

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[3] [MVA] is the unit Mega volt-amperes. A unit of VA describes apparent power, designated as "S" which gives a direct indication of heating and it is used as a rating unit of power equipment.

this will automatically set up the voltages for the transformer line. However, all other parameters require manual input. In the case of transformer MVA limits, these limits could be manually inputted from documentation that the team received from National Grid. However, when a transmission line is placed between two buses a nominal voltage for the transmission line is determined by PowerWorld as the same as the bus voltage that the transmission line is connected to. It is key to understand that this is not a MVA limit for the line.

The reason behind this in depth look at MVA ratings is due to PowerWorld's functionality with 'circuit breakers'. "Circuit breakers are used to indicate status of lines and transformers (not true breaker representation). Location of a circuit breaker on the line does not matter. Typically, one is placed at each end, automatically." [48]   The way that the team alleviated this setback of a circuit breaker that did not function as a circuit breaker was to set MVA limits for the transmission lines that were drawn. During a simulation if PowerWorld determines that a MVA rating for a line has been reached, the simulation will show an overload on the line with red power flow errors alerting the user.

For this simulation a MVA limit is needed for the A, B and C phase parameters in PowerWorld (see Figure 31 for example of MVA limits inputted). An MVA limit has to be calculated for PowerWorld, it is not a value that the software will actually generate based off of bus parameters. This formula is used to find apparent power (which is the MVA limit in the simulation):

$$S = \sqrt{P^2 + Q^2}$$

Description of variables:

S = Apparent Power, P = Active Power, Q = Reactive Power

To calculate transmission line MVA limits for the team's simulation the following formula was used:

$$T_L VA \; limit = BusV_{L-L} * I_{CB} * \sqrt{3}$$
$$= S \, [VA]$$
$$[MVA] = S \, [VA] * 10^{-6}$$

Description of variables:

$$T_L VA \; limit = Transmission \; line \; voltage \; ampre \; limit$$
$$S \, [VA] = Apparent \; Powerin \; voltage \; amperes$$
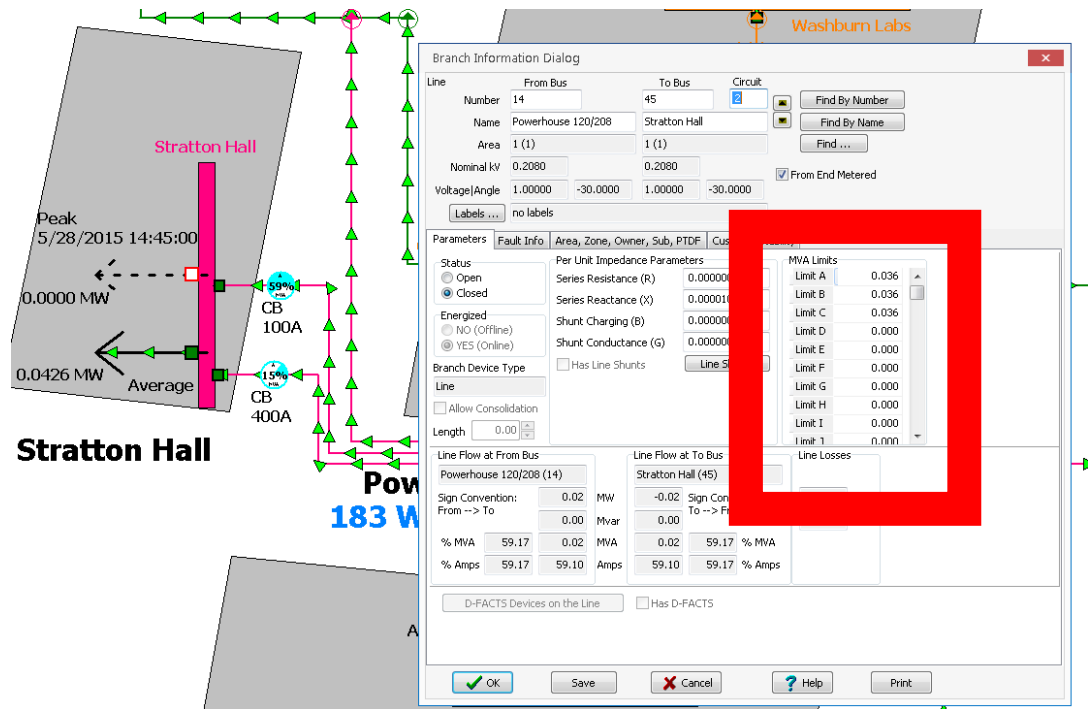
Figure 31 – MVA Limit Example

As an example, the below equations calculate the MVA limit specifically for the line in Figure 31:

$$T_L VA\ limit = BusV_{L-L} * I_{CB} * \sqrt{3}$$
$$= 208V * 100A * \sqrt{3}$$
$$= 36026.7\ [VA] * \ 10^{-6}$$
$$= 0.036027\ [MVA]$$

4.5 Layers

Inputted components into the simulation were placed into pre-selected layers that can be toggled on or off for the users to see. A list of the layers can be found in the "Screen Layers" window. By specifying a conditional zoom as well as Low & High zoom levels, a layer's size can remain static on the viewer's screen while other components are enhanced. The advantage of layering components is that the user can display the components that are currently being selected. In addition, for security purposes, groups of components can be hidden from simulations. With all but the GIS layers disabled, the simulation serves as a GIS tool for campus. The list can be seen in Figure 32.

Figure 32 – Screen Layers Window

4.6 Load Calculations

PowerWorld accepts load data in the forms of watts [W] and reactive power [VAR] (see Figure 33).

Figure 33 – Load Options

The data available to the team was instantaneous kW usage from the E-Mon D-Mon electrical meters (where applicable) and the kW-hours from monthly National Grid bills. From these data were derived two separate values. The resulting calculations can be found in Appendix C: Load Data.

E-Mon D-Mon kW;

$$(\boldsymbol{Average}\ MW\ Load) = \frac{(\ \sum [\![kW\ readings\ )]\!]}{\#\ of\ kW\ readings * 1000}$$

$$(Peak\ MW\ Load) = \frac{Highest\ kW\ reading}{1000}$$

National Grid Monthly Electric Bills kWh:

$$(\boldsymbol{Average}\ MW\ Load) = \frac{(\ \sum [\![kWh\ readings\ )]\!]}{\#\ of\ khW\ readings * 24hrs * 30days * 1000}$$

$$(\boldsymbol{Peak}\ MW\ Load) = \frac{Highest\ kWh\ reading}{24hrs * 30days * 1000}$$

The disadvantage to the calculations for kWh is that the peak values are largely neglected, as kWh readings are an average of kW usage over time. Therefore, average and peak values derived will be lower than actual usage. However, with the lack of sub-meters to provide real-time usage information and further access to electric bills the data obtained was the most accurate the team could calculate.

4.7 Simulation Layout
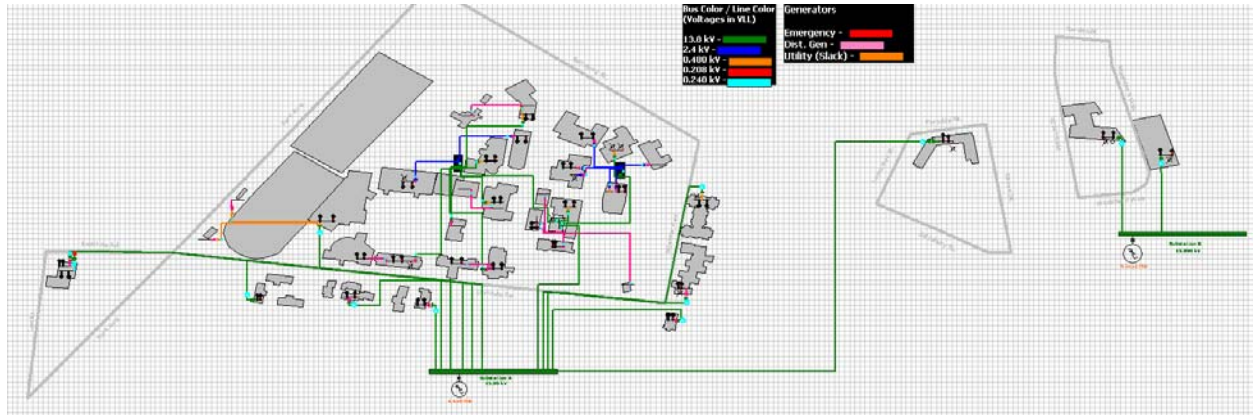
Figure 34 – Overview of Simulation

The one-line diagram begins with Substation A and Substation B. These two substations supply power to all simulated buildings accordingly, the delineation of which was provided by National Grid. Generators are connected to these substations that meet the demand on the substation, aka "slack" generators. This represents the power grid beyond WPI.
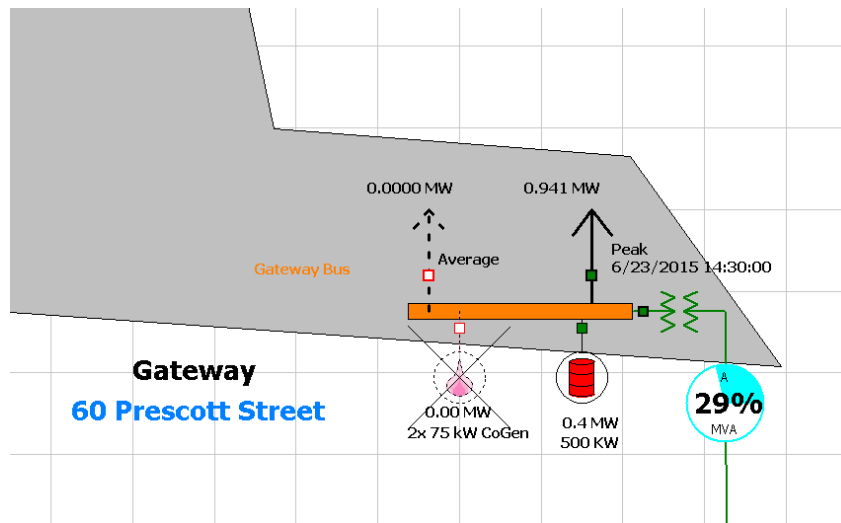
Figure 35 – View of simulated building components

From the two substations, power is delivered to a "bus" at each building representing the main distribution panel for that building. A bus can include load information for peak and average values and generation connected to that bus. For peak MW values, the time the peak was

measured is also displayed. For E-Mon D-Mon readings, there is a date and time stamp whereas National Grid electric bills have a month and year stamp.

Per-unit impedance parameters were entered for all National Grid-owned transformers as well as the per-phase A, B and C MVA limits corresponding to the kVA rating of the transformer. In addition, all known transformers were specified as Delta-Wye configurations with a 30° phase shift from high to low voltage.

For all WPI-owned transformers, due to the deficit of information, the lowest impedance values were used on transformers where documentation was not found and where nameplates were inaccessible for the team. A Delta-Wye and 30° phase shift was also assumed as this is common for most step-down transformers.

Figure 36 – Transformer Parameters

Through the use of "Model Explorer" under the "Case Information" tab, all components in the simulation can be viewed and modified in a spreadsheet type format. This allows mass changes to be made easily, such as closing or opening a circuit breaker to allow for a generator to be 'on/off'

or bus renaming. The Model Explorer function demonstrates the ability for the simulation to serve not just as a visual representation but as a database as well.

Using the "Custom" tab under each component allows custom floating points, integers and string values to be entered as well as an open-response box for notes. In this simulation, for instance, one custom string for all Generators was designated as "Gen. Manufacturer". All known manufacture values accompany each generator, as well as the "Fuel Type" (Natural Gas or Oil).
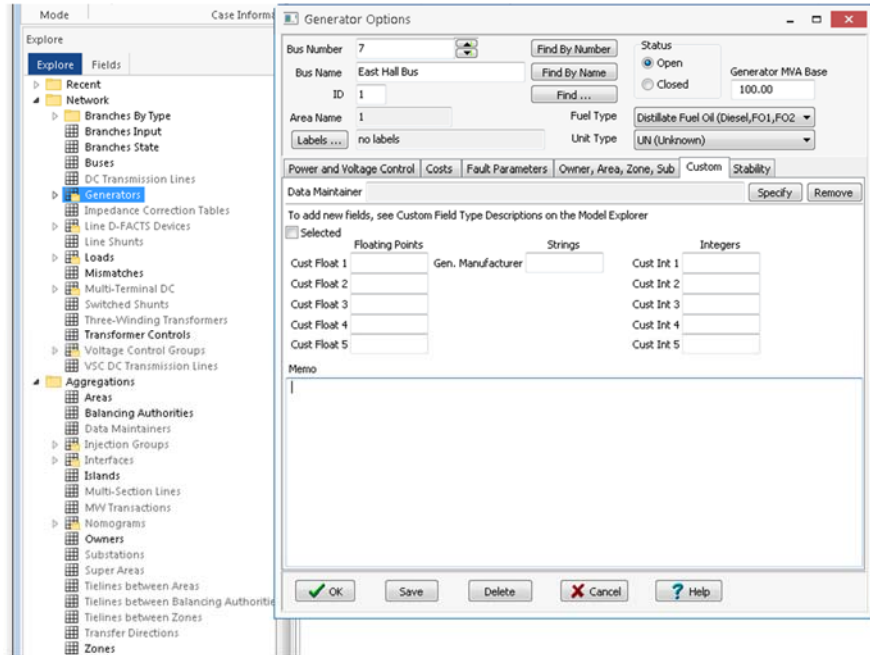
Figure 37 – Custom Tab on Generator Options

The connections to each bus in the simulation can also be viewed in a one-line format, as seen in Figure 38. The Transformer loading, incoming and outgoing connections are shown.
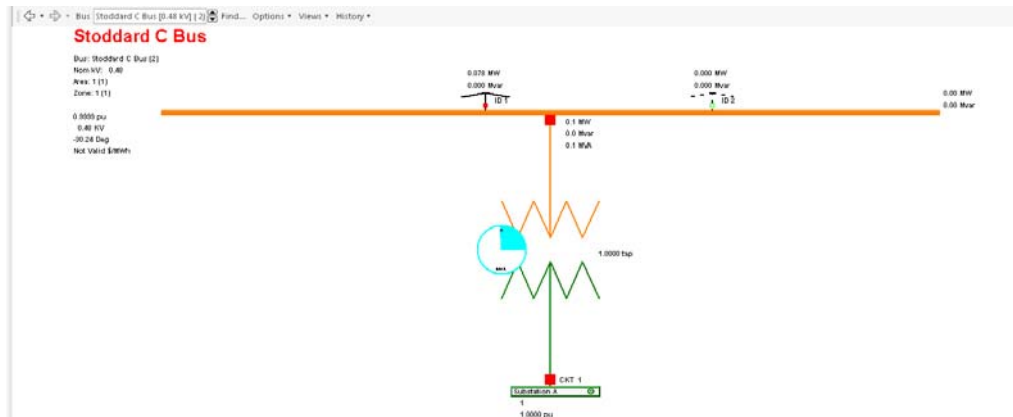
Figure 38 – Bus Views

4.8   **Simulation Access**

The simulation is stored on a remote desktop server housed in Atwater Kent at WPI, named 'powerworld1.wpi.edu'. This server includes a license for the education license of PowerWorld allowing over 40 buses, thus the simulation must be accessed here. In particular, the simulation can be found by navigating to the root of C:\ Drive, under the folder 'Private_PowerGrid_Analysis_MQP2015-2016'.

The remote desktop server uses WPI Admin credentials for access. Individual WPI user accounts can be given access through Professor John Orr (orr@wpi.edu). The directory of the simulation files also requires specific administrative access right granted by Professor Orr this directory is stored on a public share of the remote desktop with the potential for other, non-authorized users to have access. For a step-by-step tutorial of modifying the simulation, see Appendix D: PowerWorld Tutorial. A document in Adobe PDF format of this tutorial is also available in the simulation directory on the remote desktop server.

5   Results & Examples

This projects' main starting goal was the development of a simulation that could accurately represent the WPI campus, not only to represent campus in a precise component parameter manner but also in proper geographical format. The end goal was to have any person be able to look at the simulation, recognize that it was WPI's campus, then be able to understand that power was being transferred from a geographic location of Point A to another location of Point B. However, the simulation has many other capabilities, relevant to this section, they are unnecessary to discuss in depth.

Throughout this section select examples of the simulation will be portrayed. Examples will go over key points of the simulation to give the reader a better understanding of its capabilities. The pertinence of this is to demonstrate the underlying factors of the simulation that hold useful information that otherwise might go unnoticed.

5.1 Visual Representation of Power Flow on Campus

A simplistic way to understand if the developed simulation is functioning is to test and see if there is power flow. Within PowerWorld this is a straightforward test. At the top of the software window click 'Run Mode' and in the 3rd section of that tab select the green circular play button. This will cause arrows to appear in your simulation like the ones shown in Figure 39.
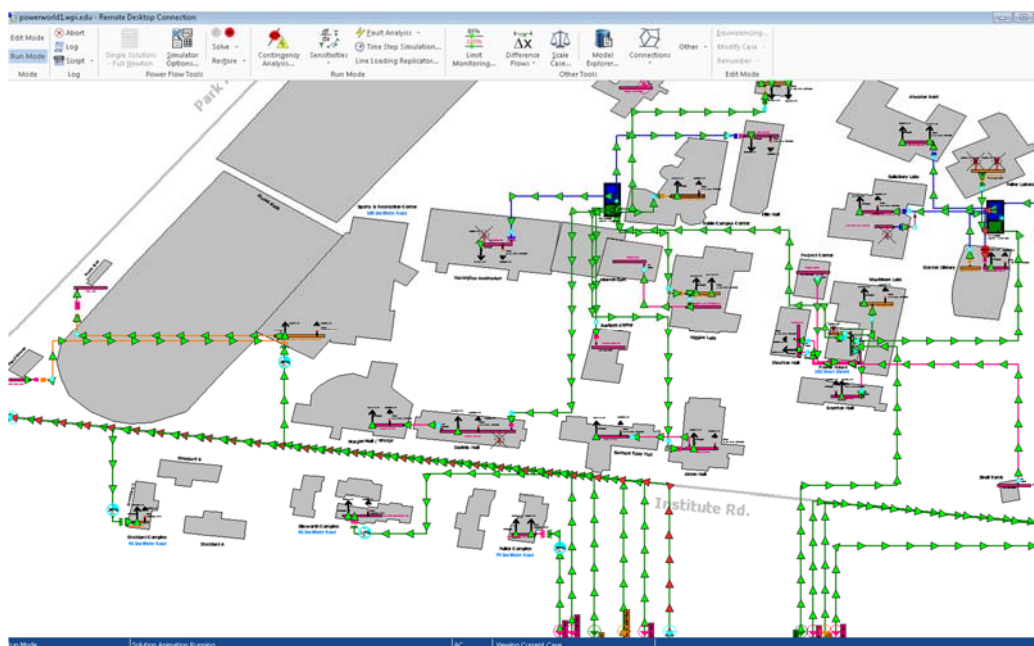
Figure 39 – Representation of Power Flow

5.2 Emergency Generation & Potential for On-Site Generation

It is expected and ideal that most facilities, commercial buildings, and college campuses are equipped for power-failures; this requires the implementation of emergency generation. WPI is currently not completely equipped or prepared for an emergency power failure; only certain portions of campus are ready to handle a major power failure. The access to on-site emergency generation will alleviate the need for outsourcing in the case of an extreme power failure.

In Figure 40, Faraday Hall is depicted representing emergency generation with a natural gas fuel source. To know if the emergency generator is on in this image is a simple check. Typically power flows in via the transformer line, but as it is shown, the transformer line is currently disconnected by its circuit breaker to the bus. This allows for the emergency generators circuit breaker to be turned on thus enabling the average load to be powered through Faraday's emergency generator. To check proper functionality, the direction of the arrows in the figure are oriented in such a manner that they are 'flowing' from the emergency generator through the bus and to the average load. That ensures that the explanation here is in fact correct.
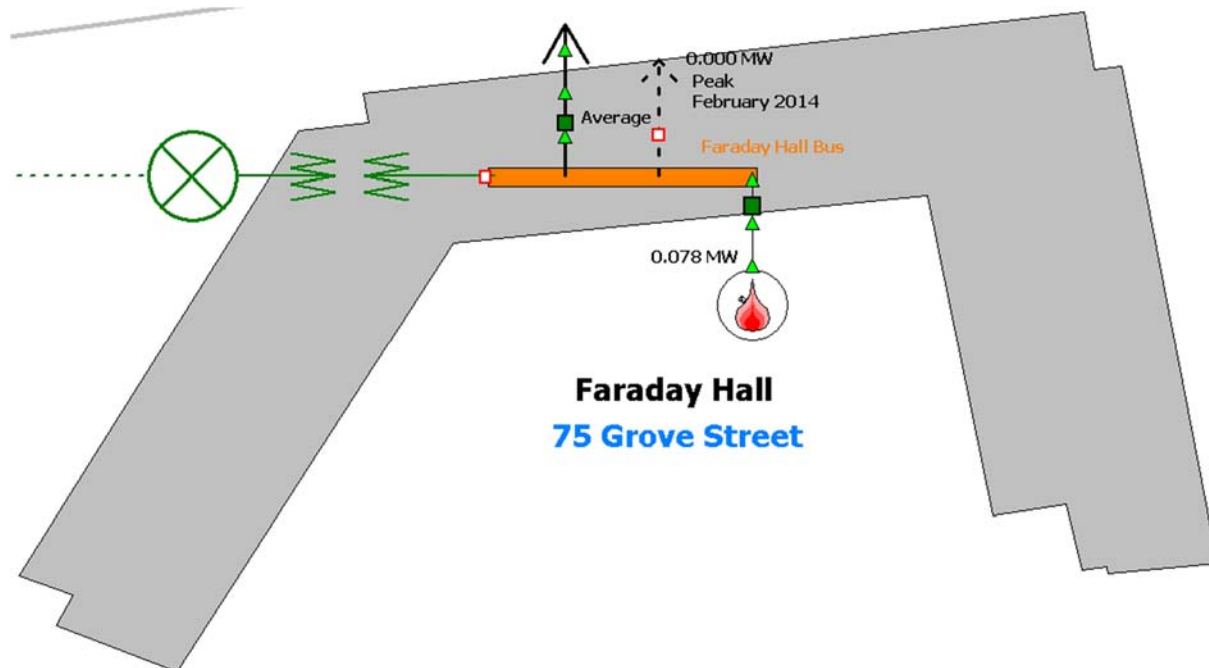
Figure 40 - Faraday Hall Emergency Generation

5.3 Transformer & Circuit Breaker Loading

Within the PowerWorld simulation it is a fairly uncomplicated process to manipulate a transformer. Once two busses have been placed and their voltages set, a transformer line can be drawn connecting the busses. This is done by putting the simulation in 'Edit Mode' then selecting the draw tab at the top of the window. In the 3rd section click on Network. Once a drop down menu appears click on 'Transformer'. To place the transformer, select the first bus it will be connected to then double click on the second bus. The line will be drawn after this step and the drawn transformer parameter window will appear to make edits to.

In Figure 41, an example of a transformers is shown at the upper center of the image. Here 'Transformer loading' is being demonstrated. There are two circles with percentage ratings enclosed within them. The one on the left displays '16%', which means that the transformer it is connected to is loaded with 16% of the MVA that it can handle. While the transformer on the right is at '106%', which means that this transformer is currently overloaded. When this happens the simulation will change the circle color to red to notify the user of the potential hazard.
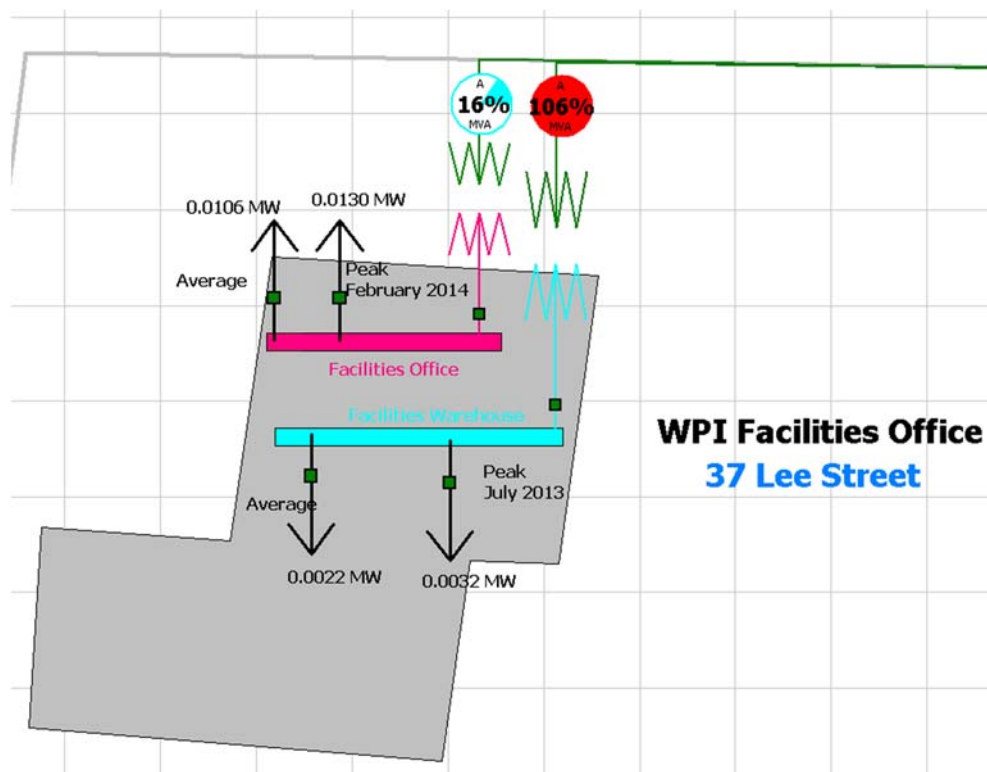
Figure 41 - Transformer Loading

Figure 42 is an effective representation of circuit breaker loading. At the Stratton Hall bus, there are two lines connecting Stratton to the 120/208 Power House transformer. Each of these

lines has a circuit breaker percentile load gauge. Within the simulation the first circuit breaker is at a 59% which means that at the point in time when the screen shot was taken that circuit breaker had a 59% load on it out of the 100A it can handle. It can be deduced that 59A are currently on that specific line through the equation listed below:

$$I_L = I_t * I_\%$$
$$= 100A * 59\%$$
$$I_L = 59A$$

The same can be said for the 400 A line:

$$I_L = I_t * I_\%$$
$$I_L = 400A * 15\%$$
$$I_L = 60A$$
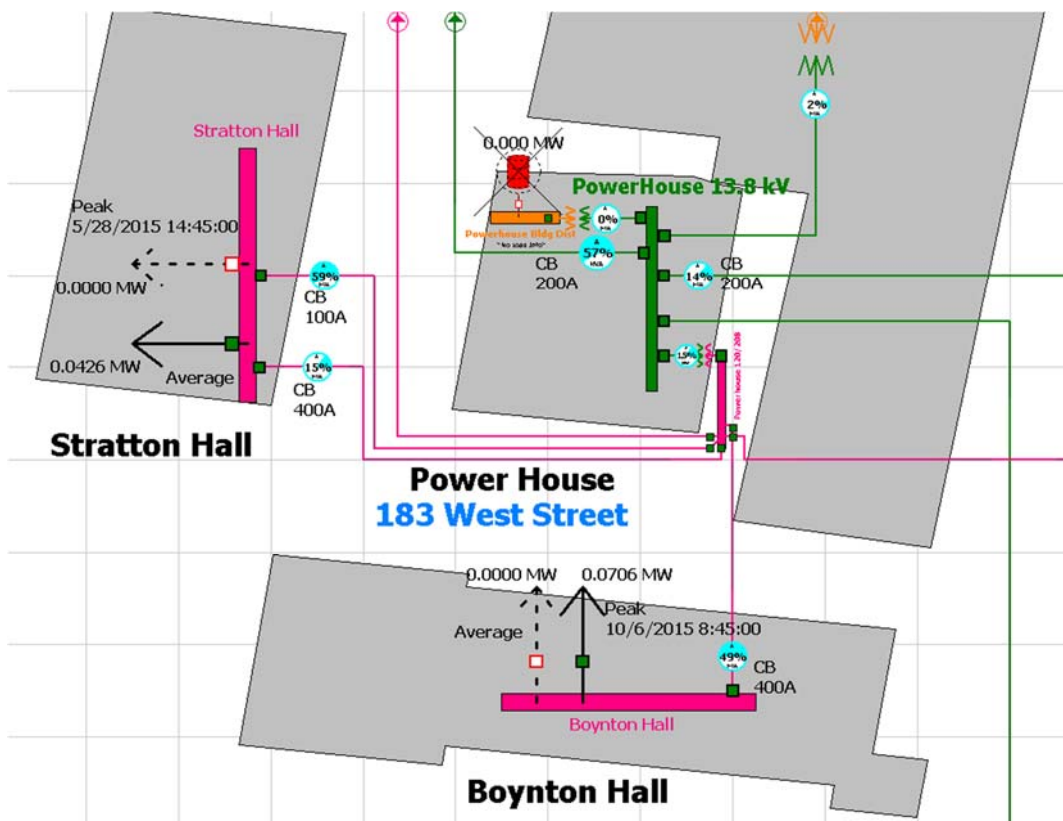
Figure 42 – Circuit Breaker Loading

6 Future Enhancements

6.1 Data Acquisition & Processing

By coupling the simulation with Eco-Screen software provided by Automated Logic, load usage could be demonstrated in real-time. Automated Logic is a company that provides software which enables their customers to manage energy consumption and display that consumption in a public dashboard. In a given building, power consumption could be displayed, where the amount of power being used for a certain room or device, pending on the accuracy of the display, would be shown in real-time. This application would be significant for the WPI campus because the community would become more conscious about their power consumption; ideally making adjustments to their lifestyles to reduce use.

By displaying power consumption and on-site generation in real-time, such as in the below figure, people are able to witness the main consumptions on campus. The team foresees this application being best used in a residence hall where a large amount of the campus power consumption occurs. In addition to making residents more aware about their consumption, this project could be used as a competition tool where halls compete to see who has the lowest power consumption after a certain period of time. Not only does this help the campus with power costs, but it instills positive sustainability practices in the WPI community.
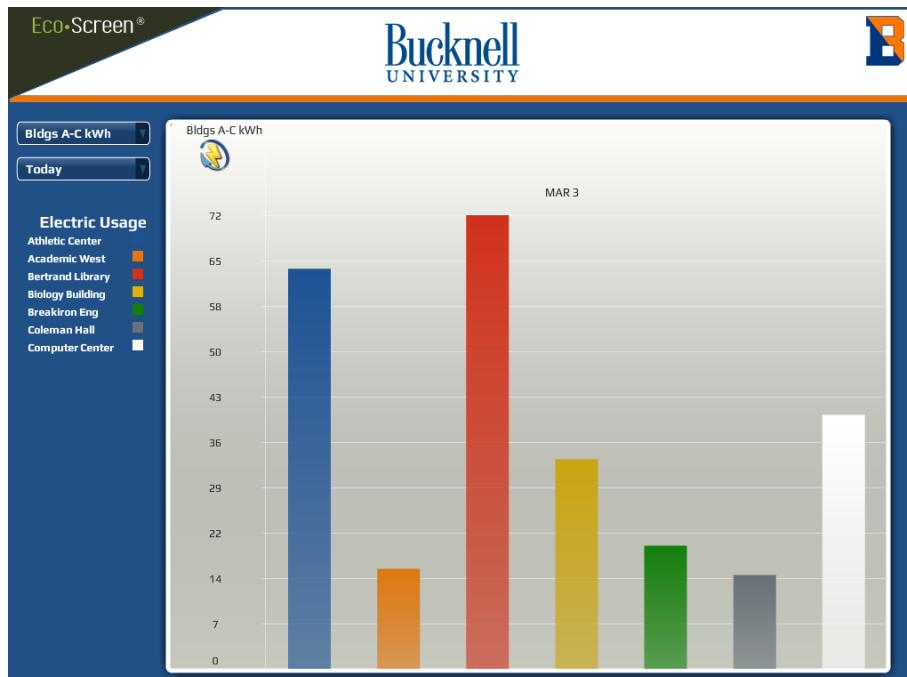
Figure 43 – Example of an Automated Logic's Eco-Screen public dashboard [49]

6.2 Additional On-Site generation

This software simulation of WPI's energy grid allows future campus projects to easily simulate the implementation of on-site generation. With the use of the team's tutorial on PowerWorld, authorized users will be able to easily manipulate the simulation. It will be possible to see the possibility of new generation technologies on campus and what loads they will offset. This simulation is a stepping stone for feasibility studies of CHP or renewable power generation. It will allow campus engineers or future MQP participants to easily simulate the implementation of a renewable system. With further manipulation in PowerWorld, users are also able to calculate the cost of power for a certain amount of time. With this feature, power consumption with current practices can be compared to renewable implementation and the cost savings can be presented in a valid method.

6.3 Transformer Loading

With the accuracy of the simulation, WPI Facilities is able to see the loading on transformers across campus. This is not only useful for daily operations but for planning new loads to be supported by an existing transformer. A transformer that is reaching its peak capabilities will visually alert staff to take action.

6.4 Stepping Stone for Projects

This simulation is a stepping stone for future projects pertaining to the WPI power grid. It will enable past projects to be further enhanced that may have previously not had the access to a simulation software and database. In addition, future IQP or MQP projects at WPI concerning the electrical power grid can utilize the simulation to bypass the issues of having to use paper copies of the grid. The easy access and accessibility to this simulation will speed up the process for many power related projects to come.

6.5 Arc Flash Study

With further enhancement of the simulation by adding conduit sizes, lengths, and locations, it will be easier to conduct an arc flash study by giving engineers simplified access to component ratings. Arc Flash studies allow those working on WPI electrical equipment to determine the proper PPE (personal protective equipment) for the task at hand.

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6.6 Transmission & Manhole Importation

Fischbach & Moore is continuing a project on the update of WPI Facilities' records of the physical location of underground wires on campus. In addition, the project includes information on each manhole and the wires that are inputs and outputs to that manhole. With this project nearing completion, the transmission lines and buses in the simulation can be re-arranged to reflect the location and depth of the real-world wires. Through importing shapes in the simulation and the "Memo" function, manhole locations and descriptions can be overlaid.

Figure 44 – Example manhole layout as part of F&M project

6.7 Facilities Use

This simulation will enhance the capabilities of the WPI Facilities department to convey future projects and connect education with campus operation. WPI Facilities already plays a major role in advising and providing resources to student projects on-campus and this simulation would further that relationship.

7   Conclusion

This project was a comprehensive simulation of the WPI campus power grid in order to assess the feasibility of on-campus generation. The team began by analyzing the latest WPI power grid one-line diagrams and viewing the grid layout in-person in order to determine what project deliverable would most benefit WPI. In addition, the team also researched other college campuses that had alternative, on-site generation resources already implemented. With this data, the team determined that there was a deficit of available resources on the state of the WPI power grid for both educational use and institutional projects

The overall objective of this project was to design an accurate simulation of the WPI power grid to serve as an educational resource for the WPI community, be a dynamic database for campus electrical components and allow the simulation of potential projects. In order to achieve this, the team used Google Earth Pro to create a Geographical Information System that accurately mapped out the WPI campus in PowerWorld. Once completed, existing one-line diagrams were modeled in the software with supplementary data from National Grid and nameplate data from the components themselves. At the completion of modeling the campus electrical layout, the simulation was able to accurately display WPI campus power flow.

Further enhancements for the simulation are outlined in Section 6. With the mapping capabilities of PowerWorld, the precise geographical location of transmission lines on-campus can be inputted into the simulation. In addition, further load data from the addition of future E-Mon D-Mon meters will allow a more accurate simulation of campus electrical usage. Finally, if WPI implements Automated Logics' public dashboard for the WPI community to view, this simulation can be integrated with the dashboard for a virtual simulation of real-time power flow.

Appendix A: List of WPI Buildings Included in the Study

Building	Meter Address
Alden Hall (Auditorium, Classrooms)	183 West St.
Alumni Gym (Gym, Offices, Pool)	183 West St.
Atwater Kent (Classrooms, Labs)	183 West St.
Bartlett Center (Admissions, Financial Aid)	183 West St.
Boynton Hall (Offices, Administration)	183 West St.
Campus Center (Offices, Meeting Rooms, Dining)	183 West St.
Daniels Hall (Residence Halls, Offices)	183 West St.
Fuller Labs (Classrooms, Auditorium)	183 West St.
Goddard Hall (Classrooms, Labs, Offices)	183 West St.
Gordon Library (Library, Meeting Rooms)	183 West St.
Harrington Auditorium (Gymnasium, Classrooms)	183 West St.
Higgins House (Offices, Food Service, Meeting Rooms)	183 West St.
Higgins House Garage (Storage, Offices)	183 West St.
Higgins Labs (Classrooms, Labs)	183 West St.
Kaven Hall (Classrooms, Labs)	183 West St.
Morgan Daniels Wedge (Meeting Rooms)	183 West St.
Morgan Hall (Residence Hall, Offices, Food Service)	183 West St.
Olin Hall (Classrooms)	183 West St.
Powerhouse (Boiler Room)	183 West St.
Project Center (Offices, Classrooms)	183 West St.
Salisbury Labs (Classrooms, Labs)	183 West St.
Sanford Riley Hall (Residence Hall, Administration)	183 West St.
Skull Tomb (Meeting Place)	183 West St.
Stratton Hall (Classrooms, Offices, Physical Plant Workshops, Storerooms)	183 West St.

Washburn (Classrooms, Labs)	183 West St.
Field House (Storage)	100 Institute Road
Press Box / Bleachers (Press Box)	100 Institute Road
East Hall (Dorm)	30 Boynton Street
Ellsworth Apartments (Dorm)	85 Institute Road
Faraday Hall (Dorm)	75 Grove Street
Founders Hall (Dorm)	26 Boynton Street
Fuller Apartments (Dorm)	79 Institute Road
Gateway (Life Sciences/BioMed Center)	60 Prescott Street
Gateway Parking Garage	31 Garden Street, 60 Prescott Street Unit #1, Unit #2
Institute Hall (Dorm)	12 Boynton Street
Sports & Rec Center	100 Institute Road
Stoddard Hall (Dorm)	95 Institute Road
Stoddard A	
WPI Facilities	37 Lee Street

Appendix B: Master Bus List

Abbreviation Key:

ATS – Automatic Transfer Switch   NO – Normally Open

NG – Natural Gas   NC – Normally Closed

MSB – Main Switch Board

OneLine	Area	Bus #	Circuit #	Bus Name	From Bus #	Voltage (kV L-L)	Transformer kVA	Lowest CB Rating (A)	MVA Limit (Trans. Line)	Emergency Generator	Emergency Gen. Connection
	Substation A	1	1	Substation A		13.800					
E02	Stoddard	2	1	Stoddard A, B, C	1	0.480	300	1200 LS			
	Fuller Apartments	3	1	Fuller Apartments	1	0.208	300	600 LS			
	Ellsworth Apartments	4	1	Ellsworth Apartments	1	0.208	300	1200 LS			
	Institute Hall	5	1	Institute Hall	1	0.208	150	600 LS			
	Founders Hall	6	1	Founders Hall	1	0.208	300	2000 LS to 1600 Dist		115kW NG	ATS to Dist.
E03	East Hall	7	1	East Hall	1	0.480	750	2500 LS		150kW OIL	ATS to MSB | ATS to Emerg. Room
E04	Faraday Hall	8	1	Faraday Hall	1	0.480	1000	1600 LS		250kW NG	ATS to 1600A MSB | E-ATS to 600A
	Substation B	9	1	Substation B		13.800					
E05	Gateway	10	1	Gateway	9	0.480	2000	??		500kW	ATS to MSB | ATS to Emerg. Room
										2x 75kW Co Gen	200A NC Switch to MSB
	Gateway	11	1	Gateway Parking Garage	9	0.480	300	400 MM SwitchBoard & (100, 125, 100) Main Elec Room		125kW OIL	125A to MM Switchboard

E06	Sports & Rec Center	12	1	Sports & Recreation Center	1	0.480	1500	2000 LS		TBD	TBD
E01	Power House	39	1	Powerhouse 13.8kV SB	1	13.800					
		13	1	Power House Bldg Dist	39	0.480	1500	200 HS, 800 LS		400kW OIL	TS to MSB
		14	1	Power House *Feeds: Boynton Hall, Skull Tomb, Project Center, Stratton Hall (2), Power House	39	0.208	750	200 HS, 2000 LS			
	West - 2.4kVA Sub	15	1	West - 2.4kVA Sub Station *Feeds Olin, Harrington, Field House	41	2.400	2000	150 HS			
	West - 13.8kv sub	41	1	West - 13.8V Sub Station	39	13.800		200 HS	4.7748		
	Olin Hall	16	1	Olin Hall	15	0.208	300	1200 LS			
	Harrington	17	1	Harrington Auditorium	15	0.208	500	??		15kW	TS to 300A Emerg. Room
	Campus Center	18	1	Rubin Campus Center	41	0.480	1500	80 HS, 100 LS			
	Bartlett	19	1	Bartlett Center	41	0.480	300	10? HS, 400 LS			
	Goddard Hall	20	1	Goddard Hall Main	41	0.480	1500	200 HS		60kW NG	
		49	1	Goddard Hall Building Dist	20	0.208	300	200 LS	0.071968		
	Higgins House	21	1	Higgins House	20	0.208					
	Higgins Labs	22	1	Higgins Labs MAIN	41	0.480	1500	100 HS, 2500 LS			
		23	1	Higgins Labs Building Dist	22	0.208	750	2500 HS, 2000 LS			
	Alden Hall	24	1	Alden Hall	41	0.208	500	50 HS, 1600 LS			

Sanford Riley Hall	42	1	Riley Hall	24	0.208		50 HS, 600 LS	0.215904		
Daniels Hall	25	1	Daniels Hall	41	0.208	1000	50 HS, 4000 LS		80kW	TS to 300A Emerg. Room
Morgan Hall	43	1	Morgan Hall	25	0.208	1000	50 HS	1.43936	*Emergency Battery System*	Battery to 100 A Emerg. Room
Washburn Labs	26	1	Washburn	39	0.480	1000	200 HS, 1200 LS			
Fuller Labs	27	1	Fuller Labs	40	0.480	2000	200 HS, 4000 LS		200kW	TS to MSB
		1							50kW	TS to MSB
East - 2.4kV Sub	28	1	East - 2.4kV Sub *Feeds Gordon Library, Atwater Kent, Salisbury Labs & Kaven Hall	40	2.400	2000				
East 13.8kv Sub	40	1	East - 13.8kV Sub Station	39	13.800		200 HS	4.7748		
Atwater Kent	29	1	Atwater Kent	28	0.208	750	200 HS, 2000 LS			
Salisbury Labs	30	1	Salisbury Labs MAIN	28	0.208	500	300 HS, 1600 LS			
	31	1	Salisbury Labs GEN	28	0.208	750	300 HS, 1600 LS		125kW	TS to 4000A Emerg. Room
Kaven Hall	32	1	Kaven Hall	28	0.208	300	80 HS, 600 LS			
Gordon Library	33	1	Gordon Library A	28	0.480	750	200 HS, 1000 LS			
	34	1	Gordon Library B	28	0.208	150	200 HS, 1600 LS			
Field House	35	1	Field House	1	?	?	?			

	Press Box	36	1	Press Box	1	?	?	?		
	Boynton Hall	44	1	Boynton Hall	14			400 LS	0.143936	
	Stratton Hall	45	1	Stratton Hall	14	0.208		400 LS	0.143936	
			2					100 LS	0.035984	
	Project Center	46	1	Project Center	14			200 LS	0.071968	
	Alumni Gym	47	1	Alumni Gym	23	0.208		400	0.143936	
	Skull Tomb	48	1	Skull Tomb	14	0.208		100 LS	0.035984	
- NO OLD -	Facilities Office	37	1	Facilities Office	1	0.208	150			
		38	1	Facilities Warehouse	1	0.240	50			

Appendix C: Load Data per Building

BUILDING	METER ADDRESS	Average Load (kWh/month)	Average Load (kW)	Average Load (MW)	Period	Data Points	Source	Peak (kWh/month)	Peak (kW)	Peak (MW)	Time of Peak kW
1. Alden Hall (Auditorium, Classrooms)	183 West St.	-	80.14	0.08014	January 1st:12am to Nov 2: 9:45pm	6197	Greener U	-	176.03	0.17603	9/29/2015 18:45:00
2. Alumni Gym (Gym, Offices, Pool)		-		0.00000	-		Greener U	-		0.00000	
3. Alumni Gym Extension (Locker Rooms, Offices)		-		0.00000			Greener U	-		0.00000	
4. Atwater Kent (Classrooms, Labs)		-	89.88	0.08988	January 1st:12am to Nov 2: 9:45pm	6199	Greener U	-	142.74	0.14274	5/5/2015 14:45:00
5. Bartlett Center (Admissions, Financial Aid)		-	MISSING	#VALUE!	MISSING	MISSING		-	MISSING	#VALUE!	MISSING
6. Boynton Hall (Offices, Administration)		-	28.24	0.02824	January 1st:12am to Nov 2: 9:45pm	6857	Greener U	-	70.59	0.07059	10/6/2015 8:45:00
7. Campus Center (Offices, Meeting Rooms, Dining)		-	202.36	0.20236	January 1st:12am to Nov 2: 9:45pm	5325	Greener U	-	506.31	0.50631	9/9/2015 12:45:00
8. Daniels Hall (Residence		-	205.04	0.20504	January 1st:12am to Nov 2: 9:45pm	5706	Greener U	-	661.81	0.66181	9/9/2015 11:45:00

Halls, Offices)												
9. Fuller Labs (Classrooms, Auditorium)		-	MISSING	#VALUE!	MISSING	MISSING	MISSING	-	MISSING	#VALUE!	MISSING
10. Goddard Hall (Classrooms, Labs, Offices)		-	283.21	0.28321	January 1st:12am to Nov 2: 9:45pm	4852	Greener U	-	564.56	0.56456	7/30/2015 10:45:00
11. Gordon Library (Library, Meeting Rooms)		-	285.70	0.28570	January 1st:12am to Nov 2: 9:45pm	5793	Greener U	-	492.22	0.49222	8/18/2015 14:45:00
12. Harrington Auditorium (Gymnasium , Classrooms)		-	115.16	0.11516	January 1st:12am to Nov 2: 9:45pm	6197	Greener U	-	203.84	0.20384	8/26/2015 13:45:00
13. Higgins House (Offices, Food Service, Meeting Rooms)		-	MISSING	#VALUE!	MISSING	MISSING		-	MISSING	#VALUE!	MISSING
14. Higgins House Garage (Storage, Offices)		-	MISSING	#VALUE!	MISSING	MISSING	MISSING	-	MISSING	#VALUE!	MISSING
15. Higgins Labs (Classrooms, Labs)		-	254.91	0.25491	January 1st:12am to Nov 2: 9:45pm	5325	Greener U	-	721.25	0.72125	7/28/2015 15:45:00
16. Kaven Hall (Classrooms, Labs)		-	MISSING	#VALUE!	MISSING	MISSING	MISSING	-	MISSING	#VALUE!	MISSING

17. Morgan Daniels Wedge (Meeting Rooms)			-	MISSING	#VALUE!	MISSING	MISSING	MISSING	-	MISSING	#VALUE!	MISSING
18. Morgan Hall (Residence Hall, Offices, Food Service)			-	227.71	0.22771	January 1st:12am to Nov 2: 9:45pm	6195	Greener U	-	509.09	0.50909	9/3/2015 17:45:00
19. Olin Hall (Classrooms)			-	68.21	0.06821	January 1st:12am to Nov 2: 9:45pm	6198	Greener U	-	162.41	0.16241	9/8/2015 14:45:00
20. Powerhouse (Boiler Room)			-	MISSING	#VALUE!	MISSING	MISSING	MISSING	-	MISSING	#VALUE!	MISSING
21. Project Center (Offices, Classrooms)			-	MISSING	#VALUE!	MISSING	MISSING	MISSING	-	MISSING	#VALUE!	MISSING
22. Salisbury Labs (Classrooms, Labs)			-	129.48	0.12948	January 1st:12am to Nov 2: 9:45pm	6198	Greener U	-	371.38	0.37138	9/8/2015 13:45:00
23. Sanford Riley Hall (Residence Hall, Administrati on)			-	17.12	0.01712	January 1st:12am to Nov 2: 9:45pm	5711	Greener U	-	47.27	0.04727	9/29/2015 18:45:00
24. Skull Tomb (Meeting Place)			-	MISSING	#VALUE!	MISSING	MISSING	MISSING	-	MISSING	#VALUE!	MISSING
25. Stratton Hall (Classrooms, Offices, Physical Plant			-	42.58	0.04258	January 1st:12am to Nov 2: 9:45pm	6199	Greener U	-	221.16	0.22116	5/28/2015 14:45:00

Workshops, Storerooms)											
26. Washburn (Classrooms, Labs)		-	19.06	0.01906	January 1st:12am to Nov 2: 9:45pm	6194	Greener U	-	37.41	0.03741	4/9/2015 15:45:00
27. Field House (Storage)		-	MISSING	#VALUE!	MISSING	MISSING		-	MISSING	#VALUE!	MISSING
28. Football Field Garage (Storage)		-		0.00000	MISSING	MISSING	MISSING	-	MISSING	#VALUE!	MISSING
29. Press Box / Bleachers (Press Box)		-	MISSING	#VALUE!	MISSING	MISSING	MISSING	-	MISSING	#VALUE!	MISSING
East Hall (Dorm)	30 Boynton Street	95266.67000	132.31	0.13231	July '13 - June '14	12	Monthly NG Bills	116600.00000	161.944	0.16194	July 2013
Ellsworth Apartments (Dorm)	85 Institute Road	25143.33000	34.92	0.03492	July '13 - June '14	12	Monthly NG Bills	60320.00000	83.778	0.08378	February 2014
Faraday Hall (Dorm)	75 Grove Street	56480.00000	78.44	0.07844	September '13 - June '14 (New Construction)	10	Monthly NG Bills	80000.00000	111.111	0.11111	February 2014
Founders Hall (Dorm)	26 Boynton Street	59800.00000	83.06	0.08306	July '13 - June '14	12	Monthly NG Bills	80000.00000	111.111	0.11111	February 2014
Fuller Apartments (Dorm)	79 Institute Road	24630.00000	34.21	0.03421	July '13 - June '14	12	Monthly NG Bills	59560.00000	82.722	0.08272	February 2014
Gateway (Life Sciences/Bio Med Center)	60 Prescott Street	-	381.15	0.38115	January 1st:12am to Nov 2: 9:45pm	17112	Greener U	941.04000	1.307	0.00131	6/23/2015 14:30:00
Gateway Parking Garage	31 Garden Street, 60 Prescott Street Unit #1, Unit #2	17212.50000	23.91	0.02391	July '13 - June '14	12	Monthly NG Bills	24800.00000	34.444	0.03444	March 2014

| Institute Hall (Dorm)	12 Boynton Street	10014.55000	13.91	0.01391	August '13 - June '14	11	Monthly NG Bills	13520.00000	18.778	0.01878	December 2013
Sports & Rec Center	100 Institute Road	276366.67000	383.84	0.38384	July '13 - June '14	12	Monthly NG Bills	317000.00000	440.278	0.44028	December 2013
Stoddard Hall (Dorm)	95 Institute Road	55933.33000	77.69	0.07769	July '13 - June '14	12	Monthly NG Bills	122000.00000	169.444	0.16944	February 2014
WPI Facilities A (New Meter - Rear of Bldg)	37 Lee Street	7594.08000	10.55	0.01055	July '13 - June '14	12	Monthly NG Bills	9392.00000	13.044	0.01304	February 2014
WPI Facilities B (Warehouse Meter)		1557.17000	2.16	0.00216	July '13 - June '14	12	Monthly NG Bills	2277.00000	3.163	0.00316	July 2013

Appendix D: PowerWorld Simulator Tutorial

Table of Contents:

A) **Accessing the Simulation:**

i. Contact Professor John Orr for access rights to the Remote Desktop Server 'powerworld1.wpi.edu' and administrative rights to the simulation folder.

ii. Open "Remote Desktop" on any Windows computer. Enter 'powerworld1.wpi.edu' in the 'computer' field.
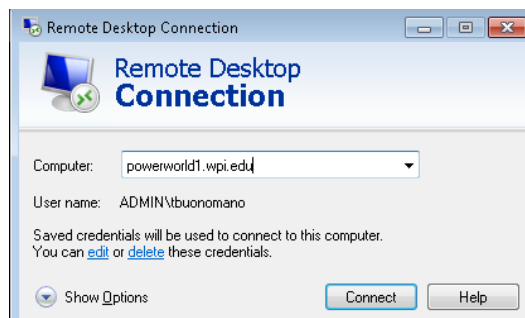
1.

iii. When prompted for credentials, in the username field enter "ADMIN*yourusername*" and in the password field enter your WPI password.

iv. Once logged into the remote server, click 'Start', then 'Computer'. Enter the 'Windows (C)' drive. Then enter the folder 'Private_PowerGrid_Analysis_MQP2015-2016'.

v. In this remote directory, there are several files and folders

1. Backups - contains an extra copy of the simulation in the event of corruption.

2. MouseJiggle.exe – program to prevent an automatic timeout of the remote server by automatically moving the user's mouse.

3. ".pwb" and ".pwd" file extensions – The file that contains the simulation is 'Simulation_MQP_2015-2016_CompletedBy_TPB_RPM_AMC.pwb'. Click this to open the simulation. The '.pwd' file is the oneline diagram information containing a list of the electrical components and their properties without any custom settings or GIS information. This file is necessary for the simulation to run and must remain in the same directory.

B) <u>**Preparing the Simulation**</u>

i. Once the simulation is opened, choose 'Edit Mode' and then save the file to begin editing using the floppy disk icon on the top-left of the window.

1.
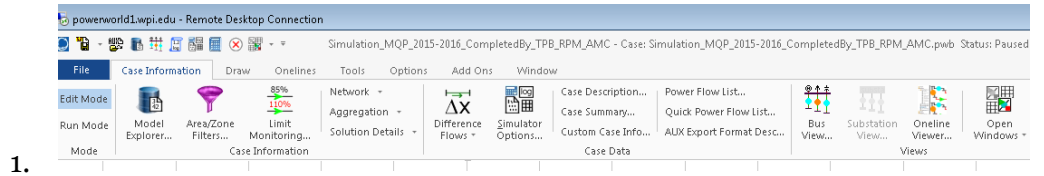
C) <u>**Viewing Options**</u>

i. The software allows both a virtual and spreadsheet view of the components included in the simulation. For a list view, choose 'Model Explorer' under the 'Case Information' tab. Model Explorer allows a spreadsheet view of all buses, transformers, generation and their values.

1.
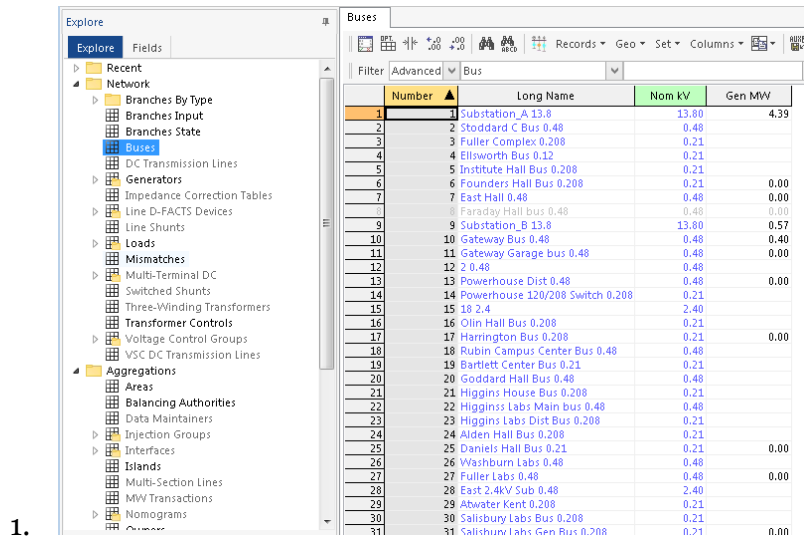
ii. Similarly, 'Onelines' tab -> 'Bus View' shows schematics of each bus and the what is connected to and from that bus.
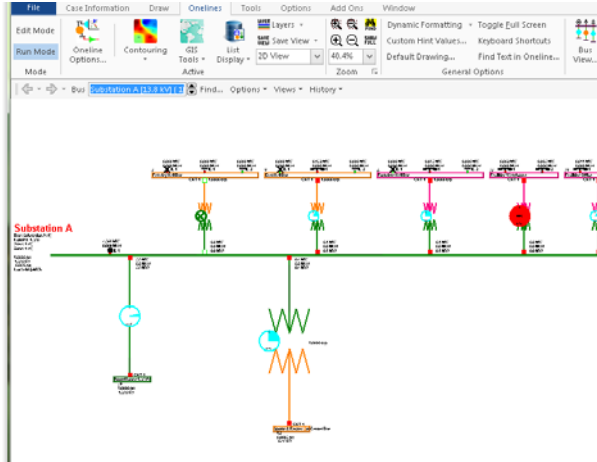
1.

iii. In the left-hand 'Explore' column, 'Custom Field Descriptions' window under 'Case Information and Auxiliary', the user can define custom variables as part of each component in the simulation. These variables can be in string, integer or floating point format and allow an easy way to attach non-standard data to components, such as year of purchase.

iv. Alternatively, components can be viewed in respect to their physical location on the overlay of the campus map. To do so, visit the 'Draw' tab and adjust the 'Zoom' settings.
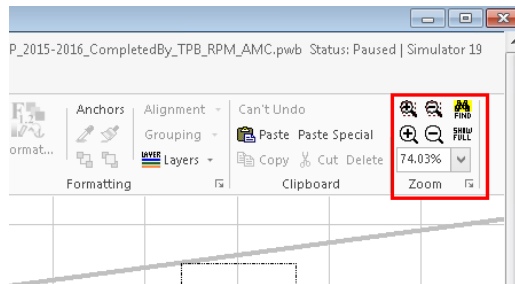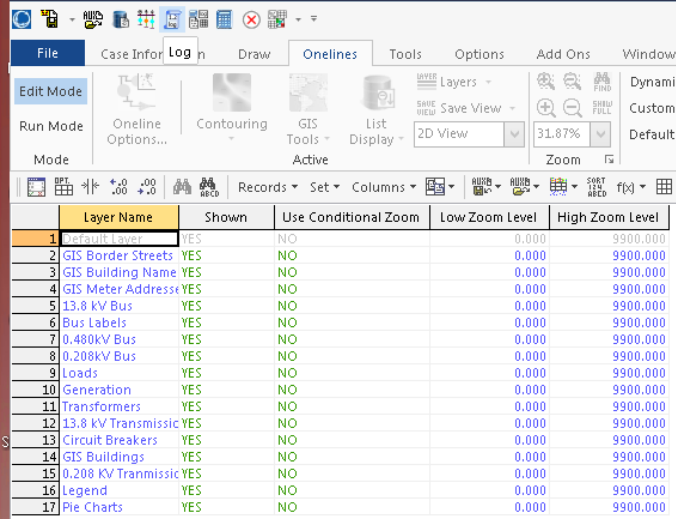

1.

D) **Layers**

i. In order to selectively view components, components are placed in 'Layers' within the simulation. Layers can be shown/hidden depending on what the user is trying to view.

ii. To choose a layer, navigate to the 'Draw' tab and click on 'Layers'. By default, new components are placed in the Default Layer. See Section G of the tutorial to change a component's layer.

iii. A list of all layers can be seen by choosing 'Define Layer'.

1.

E) <u>**Inserting a New Building**</u>

    i. In order to insert a new building, the building's rooftop must be traced using Google Earth Pro. This is free to download for all with a '.edu' email address.

   ii. Once in Google Earth, navigate to the desired building. In the left-hand column, right-click 'Temporary Places' and click 'Polygon'.


1.
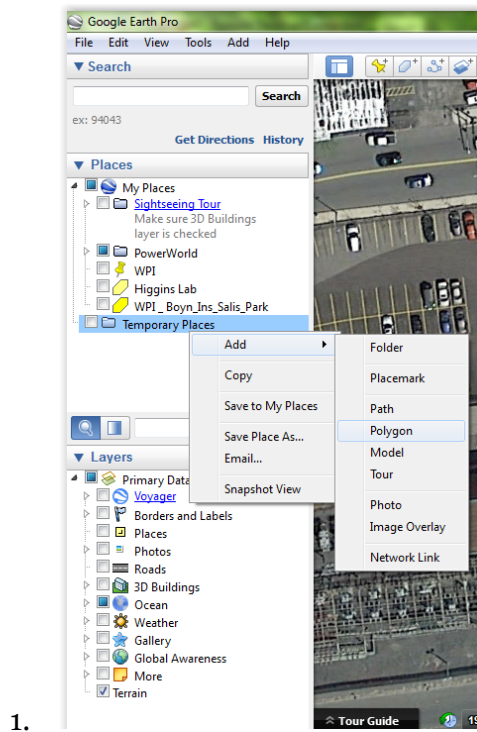
  iii. This will bring up a property window the polygon. Do NOT click 'OK', but instead navigate the cursor to a corner of the roof top. Click once, and this will create the first point of the polygon. Continue to make points around each edge of the rooftop.
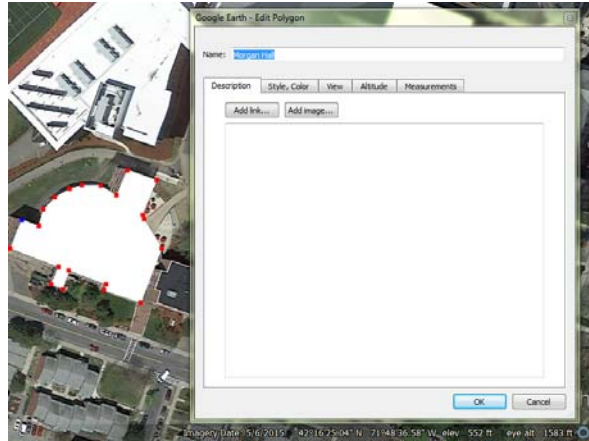
1.

iv. Once the trace is complete, title the building in the 'Name' field and then press 'OK'.

v. Right-click on the newly created shape in the left-hand column, and choose 'Save Place As...'. Then save the shape as a '.kml' file.

vi. Visit http://converter.mygeodata.eu/. In the left-hand column, upload the '.kml' file.

vii. The trace will now be shown on a map. Under the converter settings, change 'Layer Creation Option' to SHPT and POLYGON and press 'Convert Now'.
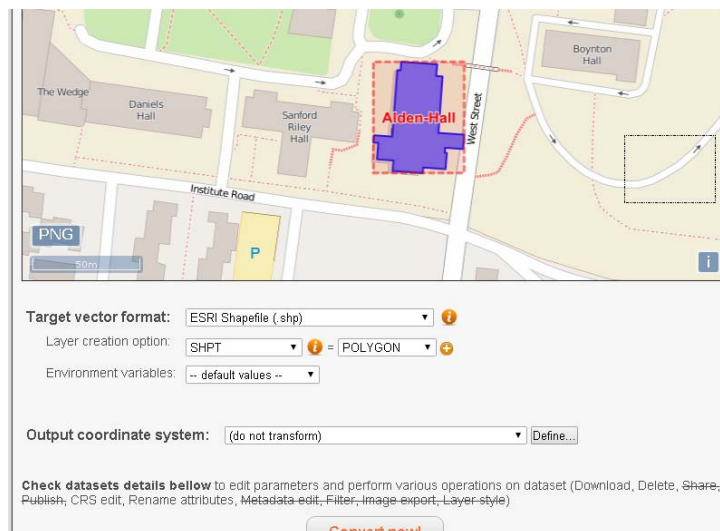
1.

viii. Open PowerWorld and navigate to 'Draw' tab -> 'Background' -> 'Insert GIS Data from Shapefile'.

ix. In the new window, choose 'Read from Shapefile' and navigate to the file exported from MyGeoData.

x. Go to 'Modify' -> 'Scale XY Data' and enter 100,000 for both for X and Y values. Then click 'Scale XY Data'.

xi. On the bottom of the window 'Insert into Layer'-> 'GIS Buildings'. Then choose 'Transfer Shapes to OneLine and Close'. The imported building will be automatically positioned based on its latitude and longitude.

F) <u>**Inserting Components**</u>

i. Navigate to 'Draw' tab. Choose 'Network' and select the component you wish to insert into the simulation.

ii. Each component includes a 'Custom' tab in the property window to input custom numeric variables, strings or paragraph-style memos.

iii. 'Draw' tab -> 'Default Drawing' has the fill and line colors of each component specified based on the voltage set by the user, meaning inserted components will automatically match the color key overlaid on the map.

   1. **Buses**

      a. Use to represent a point of common voltage, i.e. a main distribution panel or switch gear. Drag the shape to the desired size. In the property window, enter the nominal voltage of the bus and assign the bus a number. Set the per-unit voltage to 1.

   2. **Transformers**

      a. Connect the transformer between two buses or a bus and a load, ensuring that you single click at each grid corner when creating the transformer line to allow greater control later. In the property window, voltages are automatically configured but input is required for the per unit impedance parameters.

      b. Enter the 'Phase Shift' in the 'Transformer Control' tab, typically 30 degrees for Delta/Wye transformers.

      c. Enter the transformer configuration (Delta, Wye, etc.) in the 'Fault Info' tab as well as zero sequence impedance parameters.

      d. The 'Display' tab allows you to choose whether the device is 'Anchored' to another component, choose the thickness of the wire, and specify the number of symbol segments, i.e. resolution of the wire's symbols.

   3. **Transmission Line**

      a. Use to connect two components of equal nominal voltage. Per unit impedance parameters are required for insertion.

      b. The 'Display' tab allows you to choose whether the device is 'Anchored' to another component, choose the thickness of

the wire, and specify the number of symbol segments, i.e. resolution of the wire's symbols.

c. In the 'Parameters' tab, any transmission line can be converted into a transformer.

4. **Generator**

a. Connect a generator to a bus. Choosing 'Slack' in the property windows will negate any power rating of the generator, with the generator's output matching the load of the bus. This is useful for modeling substations.

b. Enter a 'MW Setpoint', 'Min.' and 'Max.' MW values for the generator, typically found on the generator's name plate.

c. The generator property window includes a custom field under 'Custom' tab to input the generator manufacturer.

d. Under 'Power and Voltage Control' -> 'Wind Control Mode' choose 'Constant Power Factor' and input the generator's power factor. A 0.90 power factor was assumed for most generation unless otherwise specified.

e. By specifying 'Fuel Type' and 'Rotor Shape', the type of generator can easily be seen on the campus map, i.e. Natural Gas or Diesel.

5. **Loads**

a. Loads are specified with MW or MVAR values and attached to a bus or transformer. In this simulation, peak and average load values are attached to each bus. A text box is manually inserted next to each load in order to specify average or peak.

6. **Text or Shapes**

a. Navigate to 'Draw' tab and choose 'Background'. Users can input images, shapes, text boxes, memo texts directly onto the simulation. This allows easy communication from one user to another and greater specificity of each component.

7. **Line Flow Pie Charts**

a. 'Draw' tab -> 'Pies/Gauges' -> 'Line/Transformer Flow Pie Chart'. Specify the to and from bus the pie chart is monitoring. Check 'Always Show Value (percent)' and 'Style'-> 'Total power (MVA)' to view the level of loading.

b. By default, pie charts are inserted with each transformer and transmission line.

G) **Formatting Components**

i. Select a component, 'Draw' tab -> 'Format'. The format window will allow you to specify the layer in which the component resides, the fill and outline color, and order of appearance. In this simulation, the 'Stack Level' of all buildings are set to 'Base' while all components are set to 'Top'.

ii. In the 'Display/Size' tab, users can choose whether to prevent an object from moving by making it 'Immobile'.

1.
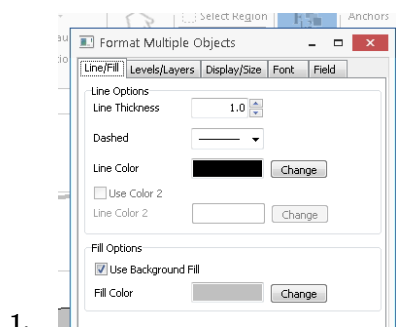
H) **Visual Power Flow Simulation**

i. To view power flow within the simulation, choose 'Run Mode'. The navigate to 'Tools' tab and click the green arrow. The animated arrows shown on the map point in the direction of the power flow. To toggle a component on/off, click on a circuit breaker in series with the component.

ii. Components with loads greater than their specified limits in the simulation can be viewed at 'Tools' tab -> 'Limit Monitoring'

1. In the 'Limit Monitoring' window, choose 'Violating Elements' under 'Elements to show' to view all overly loaded elements.

a.
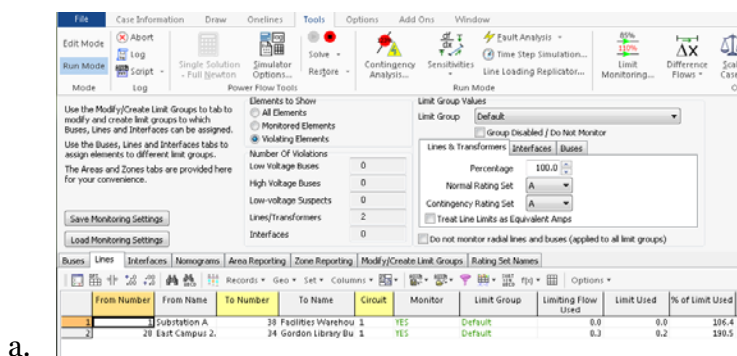
I) **Additional Resources**

i. For an interactive video tutorial, visit:
https://www.youtube.com/watch?v=q4De02324Ck

ii. For in-depth tutorial on analyses available in PowerWorld, visit:
http://www.powerworld.com/knowledge-base-term/tutorial

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