Feasibility Study for Developing a Microgrid at the ITHACA AREA WASTE WATER TREATMENT FACILITY to Serve the Ithaca North Energy District

CEE 5910 Final Report

Fall 2015

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ADVISOR'S INTRODUCTION

This report summarizes the findings of a one-semester project analyzing the proposed installation of an electricity microgrid within the city limits of Ithaca, NY. In brief, a microgrid is a system of electricity generators, storage systems, and controls that can be networked with residential and commercial electricity users within the district to generate and distribute power under normal operating conditions, and also function in a stand-alone mode in the event of a region-wide power failure such as occurred during Superstorm Sandy in many parts of New York State in 2012.

The research in the project was carried out by a team of Master of Engineering students from the Engineering Management, Environment and Water Resource Systems, and Systems Engineering programs. As advisor, it has been my responsibility to create the foundation for the launch of the project, mostly during the summer of 2015, by working with partners who also have an interest in it. Many of these partners have been active with the Ithaca Community Energy (ICE) group, which came together to apply for and win a grant from the New York Prize program to study microgrid feasibility. The list of partners includes Dan Ramer, Jose Lozano, and Jim Goodreau at the Ithaca Area Waste Water Treatment Facility (IAWWTF), as well as ICE members Wade Wykstra, Tom Hanna, Anna Kelles, John Bozack, Bruce Abbott, and John Graves. We are grateful for their input, as well as that of Matt Cinadr from Source One of Boston, MA, the firm that has been hired to carry out a more comprehensive feasibility study with the NY Prize funds, who took time to consult with the student team and answer questions arising. Thanks also to Alwyn John from the Ithaca City School District for providing energy consumption data for several schools within the boundary of the proposed microgrid.

This project also benefitted from information gathered from several previous M.Eng. projects advised by me and focused on local issues, including feasibility of the Black Oak wind farm (2010), repurposing of the former Emerson plant on Ithaca's South Hill (2011), repurposing the AES Cayuga power plant on Cayuga Lake to combust biofuels or municipal waste (2012), TCAT fleet energy-efficient bus technology feasibility (Spring 2014), and expanded conversion of waste biomass at IAWWTF (Fall 2014). Interested readers may wish to download project reports similar to this one at www.lightlink.com/francis .

One of the challenges with the project format is that the students must carry out a project that they did not design within the space of a single semester. Not only must they create from the framework that I provide a coherent scope of work, but they must also self-organize the team and execute the project during the course of the semester. No previous background in microgrid systems or related technologies was required to join the team, so students joining have varying degrees of familiarity and must therefore dedicate a substantial fraction of the time in the project researching the state of the technology, especially near the beginning. As advisor, I can report that the team successfully overcame these challenges and met their research objectives, and I am pleased share the results of their work with a wider audience.

In closing, I wish to thank all of the above individuals for their input into the project, as well as any other individuals who contributed and whom I may have overlooked. While this support is gratefully acknowledged, the findings and opinions in this report do not represent official positions of the IAWWTF, Ithaca Community Energy, or Cornell University, and responsibility for any and all errors rests with me as advisor and with the team.

Respectfully submitted,

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ABSTRACT

The city of Ithaca has been identified as an area where a microgrid would reduce both utility and infrastructure costs by the New York Prize's Finger Lakes "Opportunity Zone" (Ramer). Ithaca is seen as a city of concern because of its dependence on the functionality of the Ithaca Area Waste Water Treatment Facility (IAWWTF). If the facility fails, the city would be rendered "uninhabitable" (Ramer). To mitigate this risk, the team was interested in learning how to make the wastewater treatment plant the hub of a new microgrid control system and the new "core distributed energy resource facility" for the North Energy District (Ramer). Because the IAWWTF also treats waste water for nearby municipalities, other communities would suffer if the plant were ever without power. A microgrid would provide a backup source of energy and ensure that priority users, in particular the IAWWTF, would not be left without power if there were an emergency or disruption in the main power grid. To investigate the feasibility of implementation, research was gathered on potential renewable technologies to provide power to the microgrid, and a systems architecture model was developed to evaluate the possible scenarios.

EXECUTIVE SUMMARY

A microgrid is a localized grouping of electrical sources that can operate connected to or in isolation from the centralized grid. Microgrid systems are growing in popularity in response to events that have interrupted power supplied.

Ithaca is an excellent location for a potential microgrid. There is a lot of support for renewable energy in the community, and the location supports many potential renewable technologies. In order to develop a solution for a system, an extensive amount of research was compiled on the available renewable energy technologies.

Two locations were originally considered for the microgrid: the North and South Energy Districts. The South Energy District is based around the Emerson Power Plant, and the North Energy District is based around the Ithaca Area Waste Water Treatment Facility. The North Energy District was chosen as the focus of the microgrid feasibility study.

The required demand for the microgrid was determined by examining the priority and non-priority users of the North Energy District. Priority users consist of local schools and the Ithaca Housing Project, while non-Priority units consist of local residential households in the area. The project assumes a demand peaking factor of 2 and a 15% buffer to account for any changes. On this basis, the microgrid was determined to have a 6 MW energy production requirement.

Solar arrays, biomass, and CHP were determined to be the main technologies that will be incorporated into the Ithaca microgrid. A 2 MW solar array will be installed on the ground around the IAWWTF with a system has a lifetime of 25 years and a capital cost of $4.4 million. In addition, energy from biogas production and natural gas will help to power a combined heat and power (CHP) plant. The CHP design will utilize microturbines and work in combination with fuel cells to produce the remaining 4MW of energy required by the system. Energy storage, which is useful in microgrids to help levelize demand, was also considered. Lithium ion batteries have been selected as the most cost effective, efficient method of storage.

In addition, a systems engineering architecture was utilized to generate the best possible scenarios based on the technologies researched. A set of solutions based on different metrics is

detailed in this this report, which solutions serve as a source for future work as the microgrid project moves forward.

Motivation for Project

Microgrids are gaining popularity in communities around the US. They protect vital infrastructure from losing power in the case of major weather events, and can serve to move communities to 'greener' energy sources. Installing a microgrid in Ithaca would bring the community one step closer to reducing overall emissions as well as protect the city and town against power outages from a variety of extreme weather conditions. Ithaca has been chosen as a contender in the NYSERDA NY Prize feasibility competition for sponsorship of a microgrid installation. With this project, the team examined the feasibility of implementing a microgrid at the Ithaca Area Wastewater Treatment Facility to supplement the work by professionals on the NY Prize project.

Goals of the Project

The goal of the Fall 2015 CEE 5910 project is to establish the feasibility of creating a microgrid to serve the Ithaca area both in times of regular national grid operation and during the event of a natural disaster.

Team member background and team composition

The team is comprised of 11 Masters of Engineering students:

Caitlin Rose McKinley is from Schoharie, NY. She received her undergraduate degree in Environmental Engineering from Cornell University and is now studying to receive her master of Engineering in Engineering Management.

Laura Nielsen is from Endwell, NY. She received her Bachelor's Degree in Mechanical Engineering from Cornell University and is now pursuing her Masters of Engineering in Engineering Management.

Dean Rottau is from Tabernacle, NJ. He received his Bachelor's Degree in Mechanical Engineering from Cornell University and is now completing his Masters of Engineering in Engineering Management.

Isabel Kok is from Irvine, CA. She received her Bachelor's Degree in Mechanical Engineering from Cornell University and is now finishing her Masters of Engineering in Engineering Management.

Geoffrey James is an international student from Indonesia. He received his Bachelor's Degree in Industrial and Systems Engineering from University of Southern California and currently is in process of getting his Masters of Engineering in Engineering Management.

Walter Paleari is from Milan, Italy. He received his Bachelor's Degree in Energy Engineering at Politecnico di Milano and is currently pursuing a Master of Engineering in Systems.

Ravi Patel is pursuing his Master of Engineering in Systems.

Jevon Yu is from Billerica, MA. He received his Bachelor's Degree in Operations Research & Engineering from Cornell University and is now finishing his Masters of Engineering in Engineering Management.

Rahim Gulamaliyev is from Baku, Azerbaijan. He received his Bachelor's Degree in Petroleum Engineering from Azerbaijan State Oil Academy and his Master of Science Degree in Geological Sciences from Cornell University. Currently he is in the process of getting a Masters Degree in Engineering Management.

Lauren Frazier is from Greenville, North Carolina. She likes juggling, taking long walks, and chocolate cake. She completed an environmental engineering degree from Cornell and is now getting a civil engineering masters degree in Environment and Water Resource Systems from Cornell because she loves Ithaca so much.

TEAM STRUCTURE

The team operates under the leadership of Caitlin McKinley from the Engineering Management perspective and Walter Paleari from the Systems Engineering perspective. Jevon Yu and Ravi Patel act as outreach coordinator and Laura Nielsen is responsible for record keeping.

Rather than forming a rigid permanent work structure students take on tasks, individually or collaboratively. After the work is completed, the team comes back as a whole and breaks down the remaining work into tasks again. For example for the Market Survey work was assigned as follows:

- Dean - Microgrid Supported Areas in Ithaca
- Lauren - Microgrid Infrastructure
- Rahim - Solar
- Brian - Wind
- Jevon - Hydropower
- Geoffrey - Biomass
- Caitlin - Wastewater
- Isabel - Combined Heat and Power
- Laura - Geothermal

STAKEHOLDER ANALYSIS

The first step in the systems architecting process is identifying the stakeholders that will influence and in turn be influenced by the System that is being designed. Once the stakeholders have been identified, their needs are then ascertained to determine a list of needs that the system will have meet. Making a list of stakeholders and brainstorming their needs accomplishes this task and the list of stakeholders for this project is shown in Table 1.

List of stakeholders	*Description*	*Type*	*Most Important need*
Priority users	Hospitals, schools, emergency services, first responders etc, services that are vital during blackouts or disasters	Beneficiaries	Clean, stable power, even if uncoupled from main grid
ICE	Group of local politicians, businesspersons, etc., who are interested in setting up a local microgrid.	Problem Stakeholder	Minimum possible cost
Waste water plant	Plant treats waste water from region, already has a system of gas fired micro turbines that generate power. They will be part of the priority users, proposed site of micro-grid.	Stakeholder	Stable power, even if uncoupled from main grid
Regulators	Government regulators	Problem stakeholder	project up to regulations
Local community	Local community who will benefit from the services provided by priority users	Stakeholder	Usage of services provided by priority users
Local government	City and town governments that will benefit from services of priority users in cases of emergencies, also their support will be important in setting project	Stakeholder	Services provided by priority users in case of Emergencies
Suppliers	Businesses that will supply the equipment and raw materials for the	Stakeholder	Business

	project		
External consultants +Cornell	Consultant team from NY state, who are also trying to conduct a feasibility study of micro-grid	Stakeholder	Information
State government	NY State government	Stakeholder	Project report
NYSEG	Local energy provider	Stakeholder	Additional power to augment grid
NGOs	Environmental NGOs	Stakeholder	clean power

Table 1: List of stakeholders and stakeholder needs.

Each of these stakeholders are connected to each other by some value flows. The next step in the process is mapping out the connection between the stakeholders using a stakeholder value network. The stakeholder value network for the microgrid is displayed in Table 2.

Once the connections have been identified, each of them are given a score depending on 2 criteria, Supply Ranking & Intensity of need.

		Intensity		
		L	M	H
Supply ranking	L	0.1	0.2	0.4
	M	0.2	0.4	0.8
	H	0.3	0.5	0.95

Table 2: Scores of value flow based on intensity and supply ranking.

The supply ranking is based on whether or not there were alternative suppliers for the service or function, and intensity maps the urgency of requirement for service or goods exchanged. Therefore the adjacency matrix of the SVN with the value of the flows is displayed in Table 3.

Ref #		Project	Priority users	ICE	Waste water plant	Regulators	Local community	Local government	Suppliers	External consultants +Cornell	State government	NYSEG	NGOs
1	Project	0	0.95	0.95	0.2	0	0.2	0.5	0.4	0	0.1	0.1	0.1
2	Priority users	0	0	0	0	0	0.95	0.4	0	0	0	0	0
3	ICE	0.95	0	0	0	0	0	0	0	0	0.1	0	0
4	Waste water plant	0.95	0	0	0	0	0	0.4	0	0	0	0	0
5	Regulators	0.95	0	0	0	0	0	0	0	0	0	0	0
6	Local community	0.5	0	0.4	0	0	0	0.95	0	0	0	0	0.2
7	Local government	0.2	0	0	0.8	0	0	0	0	0.1	0	0	0
8	Suppliers	0.8	0	0	0	0	0	0	0	0	0	0	0
9	External consultants +Cornell	0.1	0	0	0	0	0	0	0	0	0	0	0
10	State government	0.95	0	0	0	0	0	0	0	0	0	0	0
11	NYSEG	0.2	0	0	0	0	0	0	0	0	0	0	0
12	NGOs	0.2	0	0.1	0	0	0	0.2	0	0	0.1	0	0

Table 3: Stakeholder adjacency matrix with score of value flow.

STAKEHOLDER VALUE NETWORK

The network topology is of a meshed fashion. This describes the complex relationship between the 12 Stakeholders of the network. Since the project affects a fairly large part of Ithaca, the needs, relationships and value networks are very diverse and often interconnected.

There is only one hub in the stakeholder value network: the regulators. The regulators present a problem for this project as they get nothing in return for the licensing and permissions they issue to the project. The network includes 47 loops, containing between 2 & 6 nodes as shown in Figure 1. The green connections represent a low value flow score between 0.1 to 0.4, the orange a medium score between 0.41 and 0.7, and the red a high score between 0.71 and 1. This is reflected in the stakeholder value matrix shown in Table 3. The matrix shows the connections between the stakeholders, much the same way the SVN does. Wherever there is a connection between stakeholders in the stakeholder value network, the value in the corresponding cell in the matrix in Table 3 is non-zero. Conversely, if there is no connection, the value in the matrix is zero.

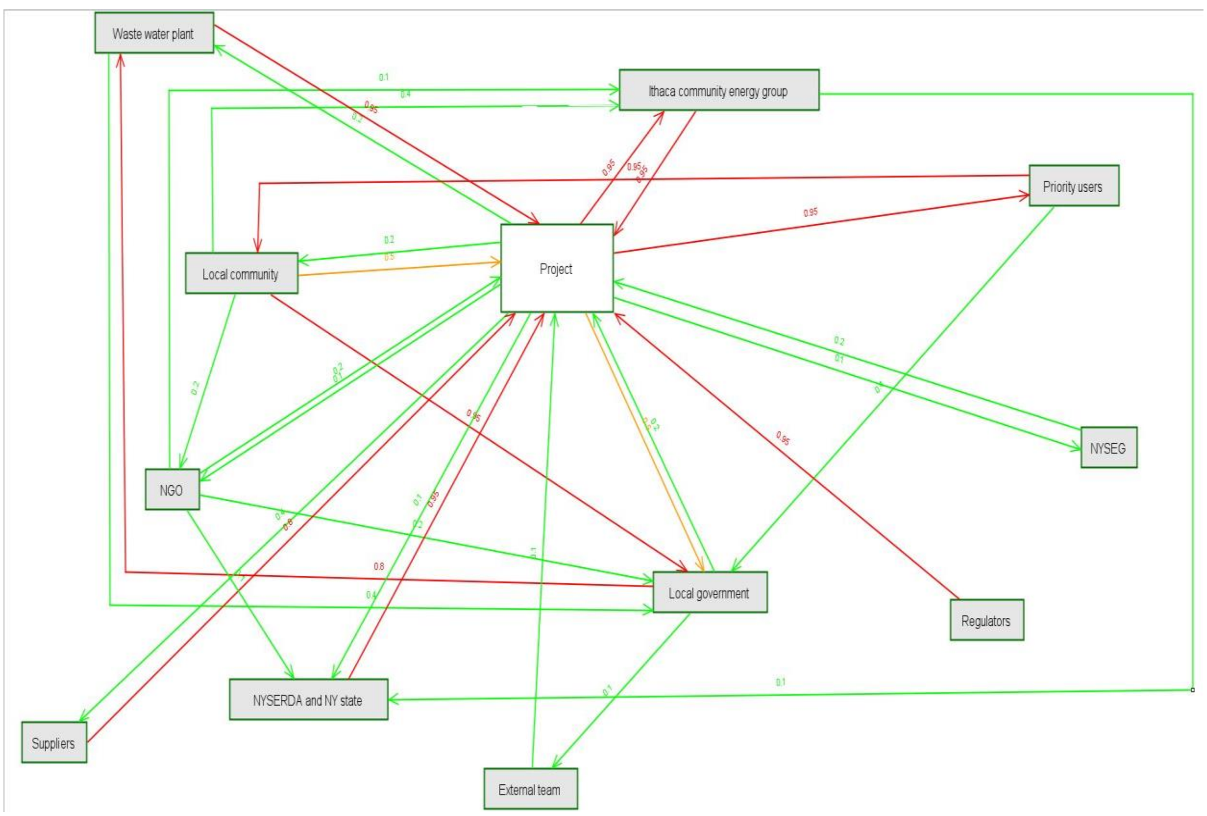


Figure 1: Stakeholder value network.

The loops in the SVN, their nodes, and their values are noted in Table 4. An in-depth search first algorithm in MATLAB enumerated the loops, and then the scores of each loop were calculated by multiplying the scores of all the connections in the loop. (The nodes are displayed in Figure 1 by the reference number used in the Stakeholder matrix i.e. Project = 1.0, Priority users = 2.0 etc.).

Sr #	*Values Loop with nodes listed*	*Scores*	***High value loops***
1	[1.0, 3.0, 1.0],	0.9025	Project – ICE – Project
2	[1.0, 2.0, 6.0, 7.0, 4.0, 1.0],	0.6516	Project – Priority user - Local community – Local gov – Waste water plant – Project
3	[1.0, 2.0, 6.0, 1.0],	0.4512	Project – Priority user - Local community – Project
4	[1.0, 7.0, 4.0, 1.0],	0.38	Project – Local gov – Waste water plant – Project
5	[1.0, 2.0, 6.0, 3.0, 1.0],	0.3429	Project – Priority users – Local community – ICE – Project
6	[1.0, 8.0, 1.0],	0.32	
7	[1.0, 2.0, 7.0, 4.0, 1.0],	0.2888	
8	[1.0, 4.0, 1.0],	0.19	
9	[1.0, 2.0, 6.0, 7.0, 1.0],	0.1715	
10	[1.0, 6.0, 7.0, 4.0, 1.0],	0.1444	
11	[1.0, 6.0, 1.0],	0.1	
12	[1.0, 7.0, 1.0],	0.1	
13	[1.0, 10.0, 1.0],	0.095	
14	[1.0, 3.0, 10.0, 1.0],	0.0902	
15	[1.0, 2.0, 7.0, 1.0],	0.076	
16	[1.0, 6.0, 3.0, 1.0],	0.076	
17	[1.0, 6.0, 7.0, 1.0],	0.038	
18	[1.0, 2.0, 6.0, 12.0, 1.0],	0.0361	
19	[1.0, 2.0, 6.0, 3.0, 10.0, 1.0],	0.0343	
20	[1.0, 2.0, 6.0, 12.0, 7.0, 4.0, 1.0],	0.0274	

Sr #	Values Loop with nodes listed	Scores
30	[1.0, 6.0, 12.0, 1.0],	0.008
31	[1.0, 6.0, 3.0, 10.0, 1.0],	0.0076
32	[1.0, 2.0, 6.0, 12.0, 7.0, 1.0],	0.0072
33	[1.0, 6.0, 12.0, 7.0, 4.0, 1.0],	
34	[1.0, 7.0, 9.0, 1.0],	
35	[1.0, 12.0, 7.0, 1.0],	
36	[1.0, 6.0, 12.0, 3.0, 1.0],	
37	[1.0, 2.0, 7.0, 9.0, 1.0],	
38	[1.0, 6.0, 12.0, 10.0, 1.0],	
39	[1.0, 6.0, 7.0, 9.0, 1.0],	
40	[1.0, 2.0, 6.0, 12.0, 3.0, 10.0, 1.0],	

21	[1.0, 11.0, 1.0],	0.02	*41*	[1.0, 6.0, 12.0, 7.0, 1.0],
22	[1.0, 12.0, 1.0],	0.02	*42*	[1.0, 12.0, 3.0, 10.0, 1.0],
23	[1.0, 2.0, 6.0, 12.0, 3.0, 1.0],	0.0171	*43*	[1.0, 4.0, 7.0, 9.0, 1.0],
24	[1.0, 2.0, 6.0, 12.0, 10.0, 1.0],	0.0171	*44*	[1.0, 6.0, 12.0, 3.0, 10.0, 1.0],
25	[1.0, 4.0, 7.0, 1.0],	0.016	*45*	[1.0, 2.0, 6.0, 12.0, 7.0, 9.0, 1.0]
26	[1.0, 12.0, 7.0, 4.0, 1.0],	0.0152	*46*	[1.0, 12.0, 7.0, 9.0, 1.0],
27	[1.0, 12.0, 3.0, 1.0],	0.0095	*47*	[1.0, 6.0, 12.0, 7.0, 9.0, 1.0],
28	[1.0, 12.0, 10.0, 1.0],	0.0095		
29	[1.0, 2.0, 6.0, 7.0, 9.0, 1.0],	0.0086		

Table 4: Loops in stakeholder value network.

The loop with the highest value is the one that contains only the Project and ICE. This is obvious, as ICE commissioned the project. The give and take between ICE and the project is large, and hence it is a high value loop. The second highest loop contains many stakeholders. This suggests that the value delivery in the system is going to be governed by a complex set of indirect interactions between stakeholders.

The rest of the top five loops with the highest value contain the 3 to 4 highest-level stakeholders, such as the priority users, local community, and the IAWWTF. This shows a large degree of interconnectedness between the stakeholders, where many stakeholder needs can be fulfilled by other stakeholders rather than the system itself.

Once all the value loops were identified, the weighted stakeholder occurrence was calculated by considering all the loops that the stakeholder is part of and normalizing it.

Sr #	*Stakeholder*	*Weighted stakeholder occurrence*
1	Local community	0.4587
2	Priority users	0.4538
3	Local government	0.414
4	waste water plant	0.3655

5	ICE	0.316
6	Suppliers	0.068
7	State government	0.0554
8	NGOs	0.0404
9	External consultants	0.0044
10	NYSEG	0.0042
11	Regulators	0

Table 5: Customer relative importance.

The most important stakeholder is in fact the local community. This suggests that the priority customers should in fact be determined by understanding the needs of the local community. The local government was an unexpected major stakeholder. Before the computation of the stakeholder values, the local government was not viewed as a very important stakeholder. The waste water plant and ICE are both important stakeholders as expected.

Market Research

Microgrid Background

To understand how a microgrid works, one must first understand how the power grid works. The electrical grid consists of a system of transmission and distribution lines and their related facilities to connect providers and consumers of electricity. Because it is difficult to store large amounts of electricity, electricity must mostly be produced at the same time it is being used. Therefore, the grid is always running and connecting the source of electricity with a web of many consumers—homes, businesses, and public systems.

The modern-day grid uses AC (alternating current) technology, which can transmit energy over longer distances than DC (direct current), which was being used up until the 20th century. After World War II, demand for electricity began to grow so electric utilities began to interconnect their transmission systems in order to build larger, jointly owned generating units. Now, three large interconnected systems “separately serve the eastern and western halves of the US and Texas” (U.S. Energy Information Administration) . Today in the US the interconnected systems include approximately 2,000 electric distribution utilities, 300,000 miles of transmission and distribution lines, and 7000 power plants (USEIA). The transmission lines are high-voltage because high-voltage electricity incurs fewer losses through the lines; therefore, a converter is necessary to step down the voltage before it reaches the distribution lines. Those interconnected high voltage transmission lines are collectively known as “the grid.” Utilities may sell the electricity they produce at their own plants, or buy electricity from other sources on the wholesale market.

The microgrid is an alternative to taking energy directly from the main grid. The microgrid functions in a parallel form to the grid, but can also operate independently. To construct a microgrid, there needs to be an available power source, a power management system including inverters to convert electricity to a usable form, an energy storage system such as batteries or thermal storage (depending on the capability of the area), and a utility connection, should the microgrid wish to exchange power with the main grid. The connection happens at a common coupling and can be switched off in case of a main grid failure.

Microgrids are growing more popular in developed countries because they represent a shift towards a more energy independent, sustainable future. They also protect areas from larger grid failure should there be extreme weather conditions or other technological issues. A microgrid that can function without interruption in the instant that the larger grid fails is considered to have "ride-through capability." However, because ride-through capability is expensive on top of the required microgrid investment, most microgrids power done when the larger grid fails, and then power up as soon as possible afterward to run in isolation from the larger grid, usually within a few minutes (Cinadr). During super storm Sandy eight million customers lost power because flooding knocked down transmission lines and substations. A study conducted by the US Department of Energy estimated that "sustained power interruptions", interruptions over 5 minutes, cost the US $26 billion annually (Hayden). Many people also view the microgrid as the upcoming foundation for a futuristic ultimate smart grid, as the microgrid provides intelligent local data with reliability and integration of "distributed energy resources" and "energy storage assets" (Hayden). The microgrid system represents a bottom-up approach and is seen by some as the "answer to our energy crisis" (Kamenetz). The microgrid is going to allow customers control of their energy usage, energy meters, monitoring systems, and energy storage. It will also allow customers to sell energy back to the main grid in times of peak usage, should the customer produce more energy than he/she draws.

Microgrids can technically be powered by any energy source, but the general push has been to incorporate renewable energy sources into the microgrid's capacity. The sources generally considered include solar, wind, geothermal, biomass, and CHP (Combined Heat and Power). These sources, generally dependent on variable conditions, have understandable power quality issues. Solar and wind capacities vary with time of day and season, as well as climate and surrounding area. Therefore, these technologies typically require a backup source should their output fall; these sources may be natural gas generators and fuel cells.

Microgrids have been emerging rapidly in recent years, especially in the Northeast, where unpredictable weather patterns urge energy independence from the main grid. However, one of the most successful case studies is at the University of California San Diego (UCSD), where they have a 42-megawatt system consisting of a 30-MW natural gas CHP plant, 2.8-MW of fuel cells, and 1.2-MW of solar PVs. Through a process called cogeneration, in which one fuel source (in this case natural gas) is used to produce both electricity and heat, the CHP plant saves UCSD $8 million/year in energy costs. Its gas turbines also produce 75% less emissions than conventional power plants (UC San Diego). The fuel cells turn "waste methane gas" from the campus' wastewater treatment plant into electricity without combustion (UC San Diego). In total, the UCSD microgrid supplies 85% of the campus' electricity needs and 95% of its heating and cooling needs.

In July of 2013, Connecticut announced it was building nine small microgrids after the power losses it experienced from Superstorm Sandy. Now it has progressed to the design of 11 projects; the state awarded those projects more than $23 million in state grants. These high initial costs may eventually be offset by the capability to sell excess energy back to the main grid, the environmental benefits, and extra funding as microgrid technology grows more prominent; however, microgrids are an extremely new field with no "familiar ground" (Siemens). Therefore, each new project in forward-thinking states such as Connecticut, California, New York, and New Jersey are being watched, both by advocates and opponents—the latter of which are mostly large utility companies who worry that the existing power supply will be disrupted if consumers start to consume more local energy.

Another existing project to watch is at a community level in Borrego Springs, California. The 4-MW project will include two 1.8 MW diesel generators, a 500 kW battery at the substation, three smaller batteries, 700 kW of rooftop solar PV, and 125 residential network systems (Berkely Lab). This project aligns with the team's study of Ithaca because it is at a community level and incorporates existing infrastructure, including the system of rooftop PVs. The project was awarded $7.5 million of federal funding from the US DOE, and about $6 million more from additional partners.

All information gathered for this project indicates that Ithaca would be an excellent location for a microgrid system. Further research into the technological aspects of a microgrid system will create a clear picture of the potential system.

Microgrid Control System

At the center of the microgrid is the microgrid control system that connects the variety of energy sources powering the grid. Microgrid control systems are typically comprised of both a hardware unit and pre-installed software for operation. Through optimization programming, a microgrid control system integrates various energy sources to optimize power output. The control system has the ability to operate the microgrid independent of the main grid, and it includes switches for choosing which demand customers to serve (priority, non-priority, or both).

For the purposes of this feasibility study, the team has decided to exclude microgrid control systems from the systems architecture model since every iteration on the design must include a control system. To determine which system would be best for the Ithaca microgrid, the team has created a decision matrix to weigh the various product attributes of several current options.

As shown in the decision matrix (Appendix), six different microgrid controls systems units were compared for the team to come to a final recommendation. Control systems evaluated include: Siemens Microgrid Control (basic), Siemens Microgrid Control (advanced), ABB Renewable Microgrid Controller, Grid IQ Microgrid Control System (GE), SEL Microgrid Control Systems, and Spirae BlueFin Microgrid Control Strategy. These control systems were chosen based on their rank in a Google search test; however, it is important to keep in mind that there are other control systems available beyond the brands considered in the decision matrix.

The first attribute of the matrix is local control. This describes a control system that connects the energy sources in "parallel" rather than in "series" so if one source fails the rest of the microgrid can continue to operate. The rating system for the decision matrix shows that a system rated as a 2 under local control means that the operating system of the controller is unknown. Due to manufacturer's lack of familiarity with control systems, some of the desired information for the decision matrix was unknown and therefore has been rated as a 2 on a 1 to 3 scale. The next attribute is island mode, which describes the state of the system when the main national grid fails. If the control system can operate in isolation (or when "islanded"), the microgrid will continue to function. Several elements of forecasting are also included in the decision matrix: weather forecasting, renewable generation forecasting, and load forecasting. A combination of these three forecasts allows the control system to predict future generation and demand levels that the system must meet. The turn key attribute describes whether or not the system is ready to run as soon as purchased, or if extensive installation is necessary. Finally, scalability represents whether the control system can be scaled to operate under various demand and load capacities.

The team decided to give the local control and island mode attributes minimum values of 3 (the highest rating) because these two elements are integral to the system. The purpose of the Ithaca microgrid is to support the community when the national grid fails. To do this, it must be able to switch into island mode whenever an extreme event occurs. Additionally, local control systems increase the reliability of the system significantly, so it does not make sense to consider connected (opposite of local) systems.

The highest weightings were also given to the local control and island mode attributes for the reasons previously stated. The next highest weighted attributes are the load forecast, forecasting renewable generation, and the scalability of the system. Load and renewable generation forecasts can help the control system to optimally meet future demands, so the team decided that this should be ranked as important for the system. Additionally, since the size of the microgrid is subject to change, a scalable model is necessary so the controller does not need to be reexamined for a different sized microgrid design. Turn key was weighted as least important because it has no effect on the actual system operation and it is just a way to reduce installation time.

After combining the attribute ratings and weights, the Grid IQ Microgrid Control System from GE is rated as most desirable for the Ithaca microgrid system. The team has been in contact with members of the GE team to gather additional information on the control system. Until further details of the systems architecture are determined, the cost of the microgrid cannot be determined. However, according to GE representatives it is likely to lie in a range of $0.5 - $1 million.

WWTP

The Ithaca Area Waste Water Treatment Facility (IAWWTF) is at the heart of the microgrid plan. The 2014 Cornell Engineering Management Project Team explored the possibilities for the IAWWTF in relation to power generation. The paper *A Feasibility Study of Energy Production* written by the team is the basis of knowledge for the Waste Water Treatment Plant for this project (Ainslie et al).

The 2014 report explores the potential of several energy sources. The existing infrastructure is the Combined Heat and Power (CHP) turbines, which is reliable and cost effective for the IAWWTF. The plant can currently produce 120,000 to 150,000 cubic feet of biogas per day, which can fuel the CHP turbines and produce over 200 kWh per month. The thermal energy produced by the CHP system is then used to heat the bio-digesters, which need to be maintained at 98°F for 28 days to produce methane. Every one million gallons of wastewater flow per day can produce enough biogas in an anaerobic digester to support 26 kW of electric capacity and 2.4 million Btu per day (MMBtu/day) of thermal energy in a CHP system.

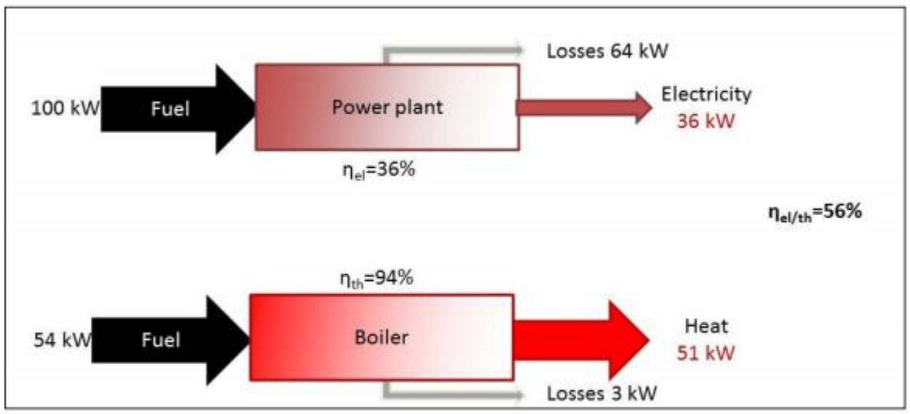
The IAWWTF has been exploring various means of producing electricity, and as part of the initiative they have already implemented a 7.5 kW solar system at their facility. This array is capable of producing 9,210 kWh of electricity per year. Additional electricity produced by the CHP turbines can be used to power the plant and make the plant self-reliant. This allows the plant to avoid a cost of 10.5 cents per kWh, which is currently the price paid to utility companies. Biodiesel production has also been explored, and the TCAT (Tompkins Consolidated Area Transit) system is a possible customer of this project. If 80-gallon biodiesel processors can be used, the price per gallon for production could be reduced making biodiesel more economically attractive.

The 2014 Cornell team generated four scenarios for future energy production at the IAWWTF. The first scenario has the plant producing enough biogas to become self-sufficient. The second scenario is to use the CHP system and solar photovoltaics to produce enough energy to make the IAWWTF self-sufficient, and to produce adequate energy for 300 homes in the proposed Inlet Energy District. The third scenario builds on the second, but incorporates the biodiesel production mentioned earlier. In the fourth scenario, the revenue from the previous scenario is used as the funds for a hydropower investment and to power the plant and residences. More details about the plans can be found in the 2014 report, but the team ultimately recommended scenario 3.

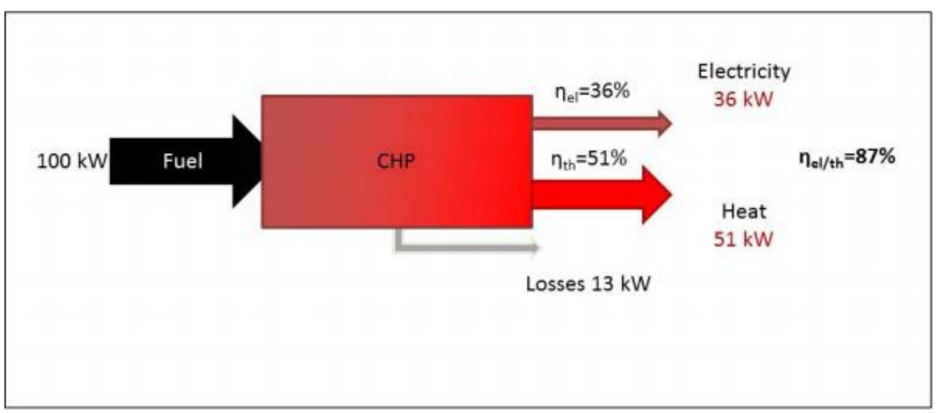
The IAWWTF will be a large part of the Ithaca microgrid, and will be incorporated with the other technologies the team has explored. One example of a successful microgrid project that incorporated a WWTP is at USC San Diego (Johnston). The facility used biogas from their WWTP and their microgrid powers more than 90% of their electrical load and heating and cooling load. Project such as this can serve to help the team consider ways to make the Ithaca microgrid feasible.

COMBINED HEAT AND POWER

CHP, which stands for "Combined Heat and Power," is an efficient and sustainable source of power generation. The idea behind CHP plants is that two products are generated: electricity and heat. In a traditional fossil fuel burning power plant, waste heat generated by the prime mover during electricity generation is lost and cannot be recovered leading to an average power plant efficiency between 25% and 45% (Renac). In the case of the most efficient large, 1 GW or more, combined-cycle natural gas fired plants, efficiencies up to 60% can be achieved (Vanek et al, p.188). However the remaining energy still exits as heat and cannot be used.



Traditional generation of heat and power, efficiencies and energy balances. Source: RENAC.



CHP generation, efficiencies and energy balances. Source: RENAC.

Figure 2: CHP efficiency comparison (Renac).

CHP plants have the ability to increase this efficiency by capturing the waste heat and recovering it for heat or electricity production, depending on the type of cycle the plant utilizes. As shown in Figure 2, a CHP plant combines the two processes of traditional system, which drastically decreases the overall efficiency. The two types of cycles used in a CHP plant are summarized below.

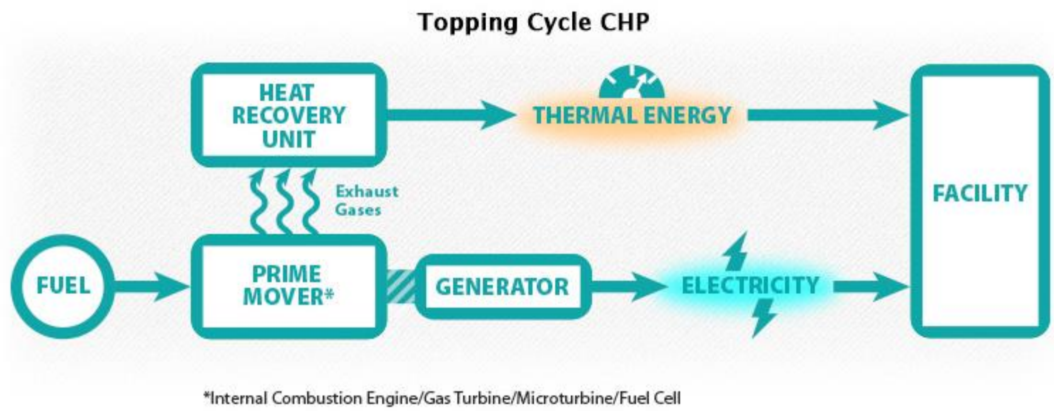


Figure 3: CHP Topping cycle.

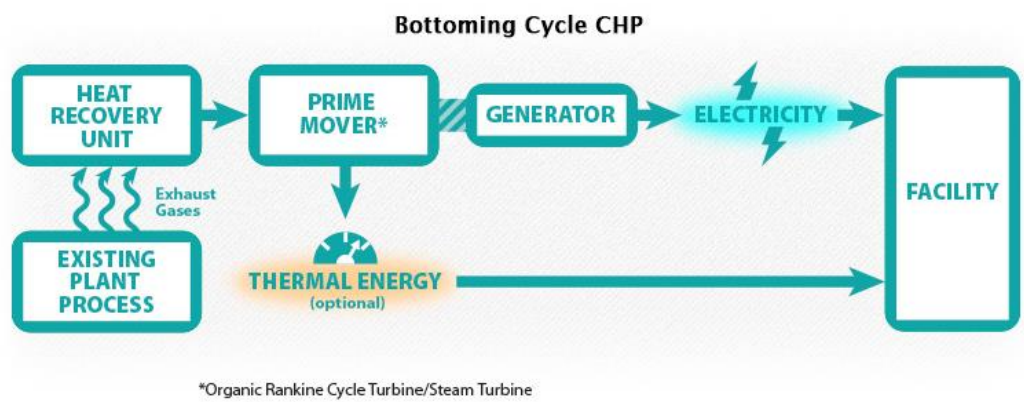


Figure 4: CHP Bottoming cycle ("Combined Heat and Power (CHP)").

In a topping cycle (Figure 3), the production of electricity is the main target and the waste heat is recovered to produce thermal energy or heating. In a bottoming cycle (Figure 4), the focus of the prime mover is to generate thermal energy, and a secondary generator is implemented for electricity production. The team's design is going to focus on the topping cycle because the Ithaca microgrid is primarily an electricity generating system.

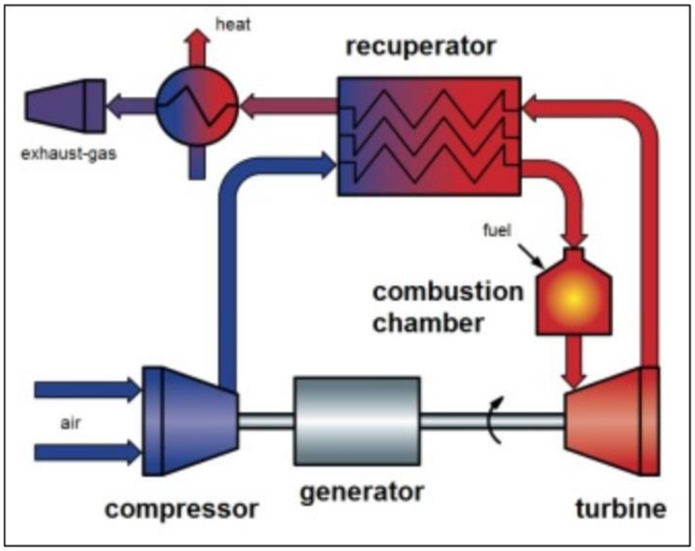
When considering a microgrid in Ithaca, CHP presents itself as a strong contender because CHP plants already power large areas of Ithaca. For example, Cornell University runs the Cornell Combined Heat and Power Plant (CCHPP) that produces the majority of the campus' electric power. Every year the CCHPP generates around 180 million kWh a year. The plant consists of two combustion turbines that combust natural gas to provide the power needed to turn an electric generator. In addition to its ability to provide electricity and heat, CHP systems significantly reduce greenhouse gas emissions. The CCHPP system has a predicted 55% reduction of SO_2 and NOx and a 20% reduction in CO_2. CHP plants are located locally and close to the facility they power to reduce unnecessary spending on transmission lines and other energy transportation methods. Other benefits of using a CHP plant include decreased emissions, a more decentralized energy source, and the opportunity to use biomass as a fuel input.

Because Cornell already runs on their own CHP "grid", a microgrid meant to serve priority user can focus on other important areas of infrastructure and not waste resources powering the large campus. In addition, Energize Ithaca, a company with the mission to power the entire Ithaca area with the energy from a CHP microgrid, has already started much of the prep work for introducing this form of energy production to the public.

A CHP plant is made up of roughly four main parts: a prime mover (the engine), generator, a heat recovery system, and electrical interconnection. There are many different types of prime movers, including gas turbine, microturbine, reciprocating engine, steam turbine, and fuel cells.

Gas Turbine

One of the more efficient prime movers for a CHP system is a gas turbine, which acts in a similar way to a piston-and-cylinder internal combustion engine but runs a continuous combustion process, unlike an ICE in an automobile that varies output greatly depending on load. The air that leaves the cycle through the compressor can be heated by transferring the heat from the high temperature exhaust gases leaving the turbine. Gas turbines provide flexibility as the technology works for both a small and large scale systems, allowing the technology to change with any changing demands of the community. In addition, gas turbines have an average of 30% electrical efficiency and require the use of a cleaner fuel. The Ithaca microgrid CHP system would run on a topping cycle, making electrical power a secondary priority, so 30% efficiency would meet the energy capacity requirements. Also, because the Ithaca community is looking for a sustainable power source, gas turbines would facilitate the transition to cleaner fuels.



A CHP plant scheme with a gas turbine. Source: Enertwin.

5: Gas turbine schematic ("EnerTwin").

Microturbine

A more recent innovation derived from the traditional gas turbine is the microturbine. When used in a CHP system, this type of turbine can reach efficiencies up to 80% (WBDG). Along with the flexibility of being powered by many different types of fuels, microturbines are an extremely powerful and cost effective choice. Other advantages include a smaller number of moving parts, lower maintenance costs due to less parts, compact and lightweight size, and lower emissions. Roughly the size of a refrigerator when in the 25- to 100-kW range, a microturbine typically has output between 25 and 500 kW (WBDG). The components of a microturbine typically consist of a compressor, combustor, turbine, alternator, recuperator (a device that captures waste heat to improve the efficiency of the compressor stage), and generator (Figure 6) (WBDG).

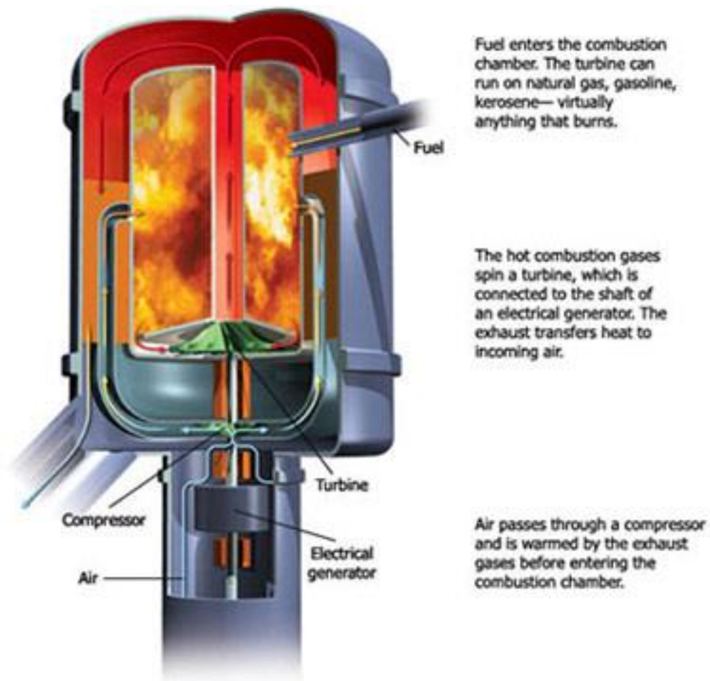


Figure 6: Microturbine schematic (Capehart).

Reciprocating Engine

A reciprocating engine is a heat engine, also called a piston engine, which uses one or more reciprocating pistons to generate rotations from applied pressure. The most common is the internal combustion engine, which is found in cars and other motor vehicles. The engine operates on a four-stroke process: intake, compression, combustion, and exhaust. The fuel and air mix together in the intake compressor, and as the piston moves up and down the mixture becomes combustible with the motion. When the piston reaches the top of the cylinder, there is a spark plug to ignite the fuel and air mixture, and the resulting explosion pushes the piston back downward. Then the exhaust stroke begins, where the exit valve is opened and exhaust gases leave the cylinder to then be used in the generator. The reciprocating engine can operate on natural gas or biomass in CHP plants and will have an electrical efficiency of roughly 40% (Renac).

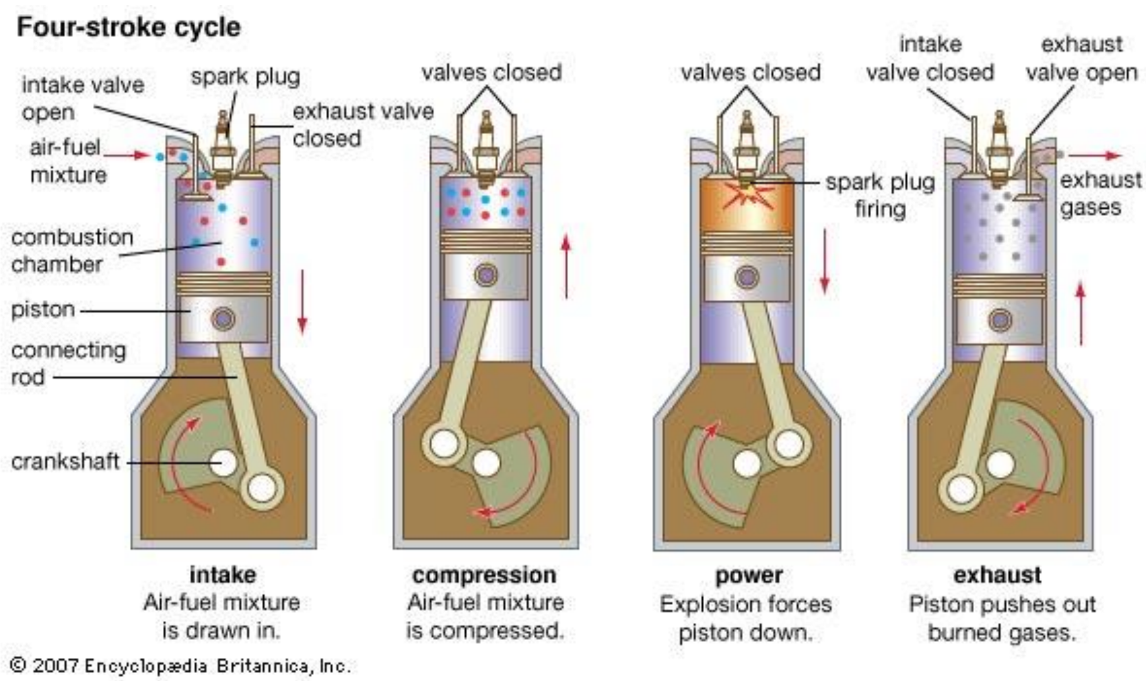


Figure 7: Internal combustion engine cycle (Proctor II).

The reciprocating engine is typically used in CHP plants that are geared towards smaller industrial sites where most of the demand is for hot water heating or other similar lighter load demands.

STEAM TURBINE

Over 80% of the world's electricity is generated by steam turbines driving rotary generators (Electropedia). The steam turbine was first introduced in 1885. A steam turbine has a different setup than other prime movers because a steam boiler as well as a steam generator is necessary to convert the steam into usable energy. The three energy conversions first extract thermal energy from the natural gas, which then raises steam, second turn the thermal energy into kinetic energy in the steam turbine, and third uses the rotary generator to turn the mechanical energy into electrical energy (Electropedia). High-pressure steam enters the turbine and passes through alternately fixed and moving blades that gradually grow larger to allow the steam to expand through the turbine.

Steam turbine use the Rankine cycle, which is a reversible thermodynamic cycle applied to a working fluid in an evaporator (Electropedia). The prime mover's efficiency is based on the maximum Carnot efficiency, which takes into account the input steam temperature and the temperature of the condensed water. A typical steam turbine plant has a condensing unit efficiency of 58%, which can be improved by cogeneration in the CHP. The efficiencies of the other parts of the prime mover - the generator, turbine, boiler, and piping - are all 90% or higher (Rajamani). An advantage of using steam turbines in CHP plants is that they can take a large selection of fuels and produce high-quality steam. However, this does not exactly apply to the Ithaca microgrid design because the team will only be considering two fuels: natural gas and biomass. The main disadvantages of the steam turbine is that it has a slow startup time, high investment costs, and decreasing efficiency with decreasing size of units.

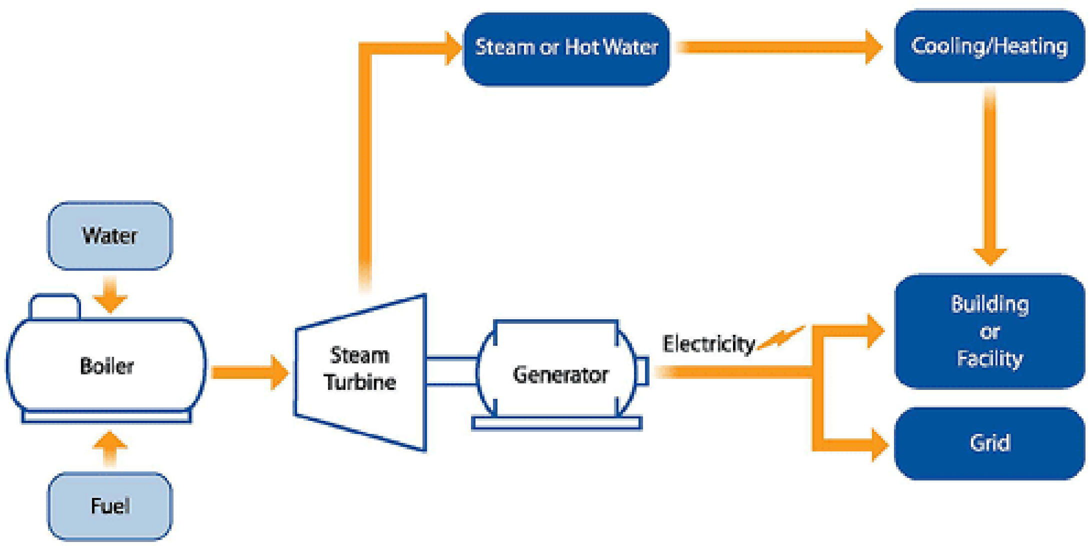


Figure 8: CHP plant with steam turbine ("What is CHP?").

Summary of typical cost and performance characteristics by CHP technology. Source: U.S. Environmental Protection Agency, Combined Heat and Power Partnership – *Catalogue of CHP Technologies* – 2008					
	Steam Turbines	Int. Comb. Engines	Gas Turbines	Micro Turbines	Fuel Cells
Electrical Efficiency	15 – 38%	22 – 40%	22 – 36%	18 – 27%	30 – 63%
Overall Efficiency	80%	70 – 80%	70 – 75%	65 – 75%	55 – 80%
Typical Capacity (MWe)	0.5 – 250	0.01 – 5	0.5 - 250	0.03 – 0.25	0.005 – 0.2
Typical Power-to-Heat Ratio	0.1 – 0.3	0.5 – 1	0.5 – 2	0.4 – 0.7	1 – 2
Part Load Behaviour	ok	ok	poor	ok	good
CHP Installing Costs ($/kWe)	430 – 1,100	1,100 – 2,200	970 – 1,300	2,400 – 3,000	5,000 – 6,500
O&M Costs ($/kWhe)	< 0.005	0.009 – 0.022	0.004 – 0.011	0.012 – 0.025	0.032 – 0.038
Hours to Overhauls	> 50,000	25,000 – 50,000	25,000 – 50,000	20,000 – 40,000	32,000 – 64,000
Start-up Time	1 hr – 1 day	10 sec	10 min – 1 hr	60 sec	3 hr – 2 day
Fuels	All	Natural gas, biogas, propane, landfill gas	Natural gas, biogas, propane, oil	Natural gas, biogas, propane, oil	Hydrogen, natural gas, propane, methanol
Noise	High	High	Moderate	Moderate	Low
Power Density (kW/m²)	> 100	35 – 50	20 – 500	5 – 70	5 – 20

Figure 9: Summary of typical cost and performance characteristics by CHP technology (Renac).

FUEL CELLS

Fuel cells are an electricity generating technology that convert chemical energy from a fuel into electricity ("How Do Fuel Cells Work?"). This is accomplished by two catalysts (an anode and a cathode) with a proton exchange membrane (an electrolyte) between them. The presence of an electrolyte is critical as it permits only the appropriate ions to travel across the membrane. This enables the oxidation-reduction chemical reactions to occur through the movement of positively charges ions between the two sides of the fuel cell. As a result, the negatively charged electrons that are extracted can be used to produce an electrical current. The only exhaust byproducts are water and minimal emissions depending on the type of fuel inputs and reaction.

In order for fuel cells to continue producing energy, there must be a continuous supply of fuel and air in order to sustain the chemical reaction. As long as these inputs are present, electricity can be produced. A variety of fuel inputs can be used including hydrogen, methane, propane, octane, and ammoniac (San Martin). Each of these fuels has a different level of thermodynamic efficiency and produce varying levels of emissions depending on the type of fuel cell.

Since fuel cells do not use combustion to extract power, there are no thermodynamic constraints that are present with many other power producing techniques. This large advantage makes fuel cells more power efficient. Alone, fuel cells can achieve anywhere between 37 to 60% electrical efficiency (San Martin). When combined with heat recovery CHP systems, the total efficiency including heat can be anywhere in the range of 80 to 90%. The lack of combustion also significantly reduces the amount of greenhouse gas emissions that are produced.

Other benefits of fuel cells include the fact that they do not require much physical space, operate quietly, and are highly reliable. Since fuel cells are relatively small in size, they are able to be installed in a greater number of locations, providing power at the point of use and removing any distribution and transmission costs. In terms of reliability, the amount of power produced is not dependent upon the time of day and environmental factors (Carpenter). As long as there is fuel being supplied, energy can be produced. The reliability of fuel cells is also increased by the flexibility of being able to use a variety of fuel inputs. Whenever there is a disruption of supply of a particular fuel, a different fuel type can be used. This is especially helpful during emergency weather situations and power outages.

There are many types of fuel cells that are best suited for a variety of applications, contexts, and scales. Currently the most prevalent types are PEM, AFC, PAFC, MCFC and SOFC. Performance metrics and characteristics for each technology type are listed in Table 6 (Comparison of Fuel Cell Technologies).

Comparison of Fuel Cell Technologies

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Efficiency	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	50-100°C 122-212° typically 80°C	< 1kW–100kW	60% transportation 35% stationary	• Backup power • Portable power • Distributed generation • Transporation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up	• Expensive catalysts • Sensitive to fuel impurities • Low temperature waste heat
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90-100°C 194-212°F	10–100 kW	60%	• Military • Space	• Cathode reaction faster in alkaline electrolyte, leads to high performance • Low cost components	• Sensitive to CO_2 in fuel and air • Electrolyte management
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a matrix	150-200°C 302-392°F	400 kW 100 kW module	40%	• Distributed generation	• Higher temperature enables CHP • Increased tolerance to fuel impurities	• Pt catalyst • Long start up time • Low current and power
Molten Carbonate (MCFC)	Solution of lithium, sodium, and/ or potassium carbonates, soaked in a matrix	600-700°C 1112-1292°F	300 kW-3 MW 300 kW module	45-50%	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP	• High temperature corrosion and breakdown of cell components • Long start up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	700-1000°C 1202-1832°F	1 kW–2 MW	60%	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & CHHP • Hybrid/GT cycle	• High temperature corrosion and breakdown of cell components • High temperature operation requires long start up time and limits

Table 6: Comparison of fuel cell technologies ("Comparison of Fuel Cell Technologies").

Fuel cells are used for a variety of applications from powering vehicles to satellites and space capsules. The more prevalent uses of fuel cells include large-scale installations that provide primary or backup power for commercial, industrial, or residential buildings. Generally, these buildings are located in areas that are more remote and inaccessible, and thus they cannot be connected to the main power grid. Due to this popular and generalized use case of fuel cells, it can be inferred that fuel cells are naturally suited for microgrids. This is due to the highly reliable, flexible, and resilient nature of fuel cells, enabling microgrids to perform more effectively independent of the main grid (Carpenter). Since microgrids usually utilize a wide variety of energy sources, any disruption of one or more of those sources can be offset by the highly predictable and constant production of fuel cell. Renewable energy technologies such as solar, wind, and hydroelectric are also more variable and fluctuating in their power production due to environmental, seasonal, and weather-related factors.

Fuel cell installations for microgrids have been increasing in number in recent years. There have been many successful and cost-saving installations across the country, particularly in the states of California and Connecticut. With the growing number and success of fuel cell companies, there have been more examples of fuel cell integration into microgrid projects. Some of these projects include microgrids at the University of San Diego, University of Bridgeport, San Jose Water Treatment Plant, among many more (Skok). The wide variety of these microgrid implementation projects includes integration with hydrogen, biogas, and wastewater treatment capabilities.

With the incorporation of fuel cells in the Ithaca microgrid, there are a few added benefits. First, it will be able to contribute to a large percentage of the electricity generated. In the spreadsheet model, the fuel cells are projected to achieve 55% efficiency and produce a majority of the electricity. Second, the fuel cells are clean and produce only 520 lbs/MWh of CO_2 emissions. Furthermore, the fuel cells integrate well with the other selected technologies of biogas as a fuel input and CHP for heat recovery. Choosing the fuel cells as the CHP driver over other technologies helps increase total efficiencies to around 80%.

Though the installation and operating costs for fuel cells are greater than those of other renewable technologies, the key metric here is the power-to-heat ratio. Currently there is no plan or ability in the area around the IAWTTF to utilize the remaining exhaust heat being produced for district heating or other uses, although an eventual commercial/residential development with district heating/cooling has been discussed in a preliminary form (Ainslie et al). In order to get the most out of the fuels, it may be more cost-efficient and economical to generate power in the form of electricity rather than heat. This is why the power-to-heat ratio of up to 2 can offset the larger costs of using the fuel cells over those of another CHP driver.

After conducting research on different fuel cell technologies and looking at other installations of microgrids of similar scale, the team recommends the usage of MCFC fuel cells. The leading vendor of MCFC fuel cell solutions currently is FuelCell Energy and they have been targeting the microgrid market with their line of DFC fuel cell stacks. Many of these stacks have successfully been installed and in operation at a large number of locations. Easily scalable, these individual fuel cell stacks can be combined to form a system with a capacity of a few hundred kilowatts to large megawatt farms. FuelCell Energy also has extensive experience in integrating their DFC systems with biogas inputs and CHP applications.

Currently, the largest barrier to the wide adoption of fuel cells is the capital investment costs. A DFC3000 fuel stack costs $2,400/kW and the installation and integration costs brings that amount to about $7,200/kW (Remick). Despite this high capital cost, the levelized cost of energy taking into account the power produced over the system's lifetime is somewhere between $0.12 and $0.13 per kWh. This amount is before any government incentives, grants, or subsidies are applied. Additionally, to help with covering the cost of the fuel cells, FuelCell Energy offers to set up power purchasing agreements. This combined with any other incentives, grants, and subsidies can significantly help lower the total costs.

In the years to come, fuel cell technology will continue to improve in performance and greatly reduce in cost. Over time, these trends will increase the attractiveness of fuel cells as a clean and reliable energy-generating source. As manufacturing costs decrease and economies of scale grow, fuel cells will become more widely adopted. By 2020, the cost per kW for a installation is expected to drop from about $8000/kW to $2100/kW (Spendelow). With federal and state incentives in place, the further cost reductions for adoption and operation will help overcome any financial barriers to adoption. Considering the value and reliability fuel cells provide to microgrids, they are likely to form the backbone of power generation for many of these systems in the future.

Solar

The sun is a tremendous source of renewable and clean energy that can be harnessed to meet energy needs without causing any damage to the environment. Solar power is the conversion of sunlight to electricity, and the mechanism in which the energy is obtained is classified into two types: concentrated solar power (focus a large area of sunlight into narrow beam using mirrors), and photovoltaic (converts light into electricity). The team will focus on photovoltaic (PV) technology in this report because of its application to the microgrid project.

A solar cell is an electric device that converts light energy to electricity by the photovoltaic effect, which is a physical and chemical phenomenon. Solar cells are interconnected by flat wires or metal ribbons and assembled into modules or PV panels. Solar panels produce DC current, which fluctuates with the sunlight's intensity. For commercial applications, DC is converted into AC current using inverters.

There are three main types of solar panels: Mono Crystalline, Polycrystalline, and Thin Film. Their advantages and disadvantages as are discussed below:

1. Mono Crystalline

Mono Crystalline panels are made from silicon ingots, which are cut into cylindrical shapes to be embedded into panels.

Advantages:

- Highest efficiency, as they are made out of high-grade silicon, at 15 to 20%. SunPower produces X-series panels with 21.5% efficiency. SolarCity has recently introduced a panel with 22.05% efficiency, and Panasonic will manufacture 22.5% efficient panels in the near future.
- Requires less space, and produces four times yield as thin films.
- Usually manufacturers provide 25 years warranty and this panel type has the longest lifetime.
- Tend to perform better even in low-light conditions.

Disadvantages:

- Expensive, high costs.
- If the solar panel is partially covered with shade, dirt, or snow, the entire circuit can break down.
- Tend to be more efficient in warm weather, which presents a problem for implementation in the Ithaca area.

2. Polycrystalline

Polycrystalline panels are created by melting raw silicon and pouring it into a square mold, which is cooled and cut into perfectly square wafers.

Advantages:

- Process used to make polycrystalline silicon is simpler and less costly.
- Tend to have slightly lower heat tolerance than monocrystalline solar panels.
- Perform slightly worse than monocrystalline solar panels in high temperatures.

Disadvantages:

- Efficiency of polycrystalline-based solar panels is typically only 13-16%.
- Generally need to cover a larger surface area to output the same electrical power as monocrystalline silicon.

3. Thin Film Solar Panels

Thin Film panels get their name from the thin layers of photovoltaic material that comprise the panel, which are deposited onto a substrate. These panels are known for their performance in harsh environments, where they are susceptible to dust and snow.

Advantages:

- Various types including Amorphous silicon (a-Si), Cadmium telluride (CdTe), Copper indium gallium selenite (CIS/CIGS), Organic photovoltaic cells (OPC).
- Mass-production is simple and can be made flexible.
- High temperatures and shading have less impact on solar panel performance.

Disadvantages:

- Low space-efficiency and generally not very useful for residential applications.
- Thin-film solar panels tend to degrade faster than mono- and polycrystalline solar panels.
- Efficiency is between 7 and 13%.

Swanson's Law is an observation similar to Moore's Law that states that solar cell prices fall 20% for every doubling of industry capacity. The price of silicon PV cells has dropped from $76 in 1977 to $0.70 in 2014, which is over a 100% change.

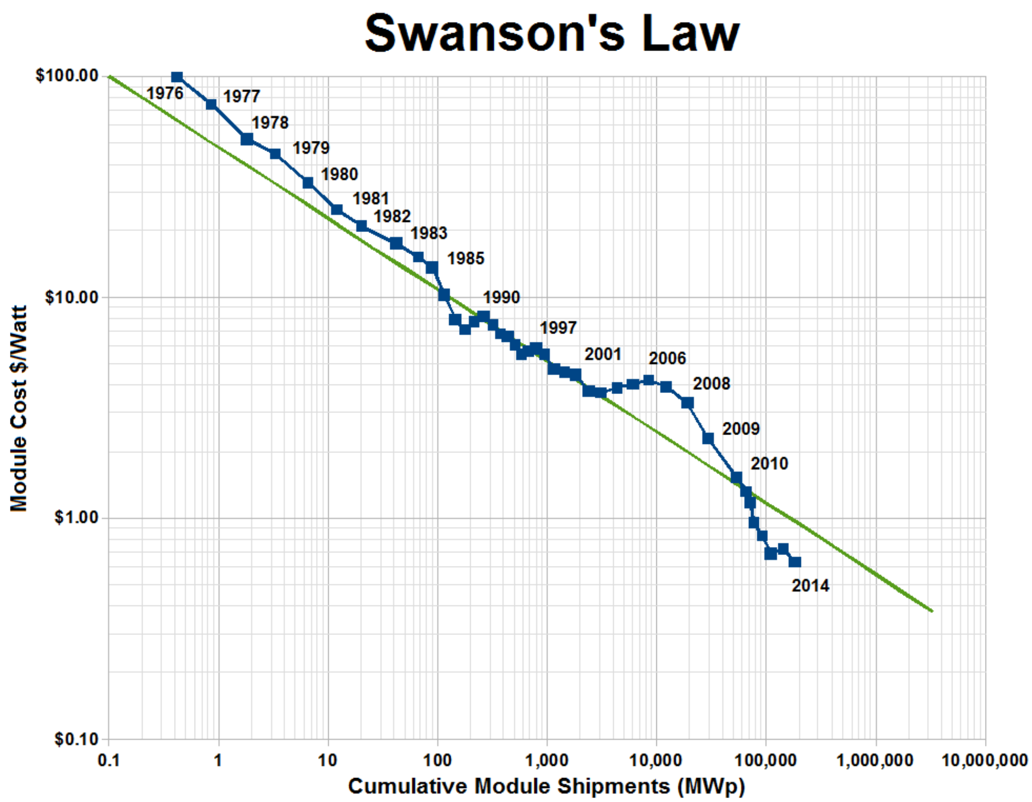
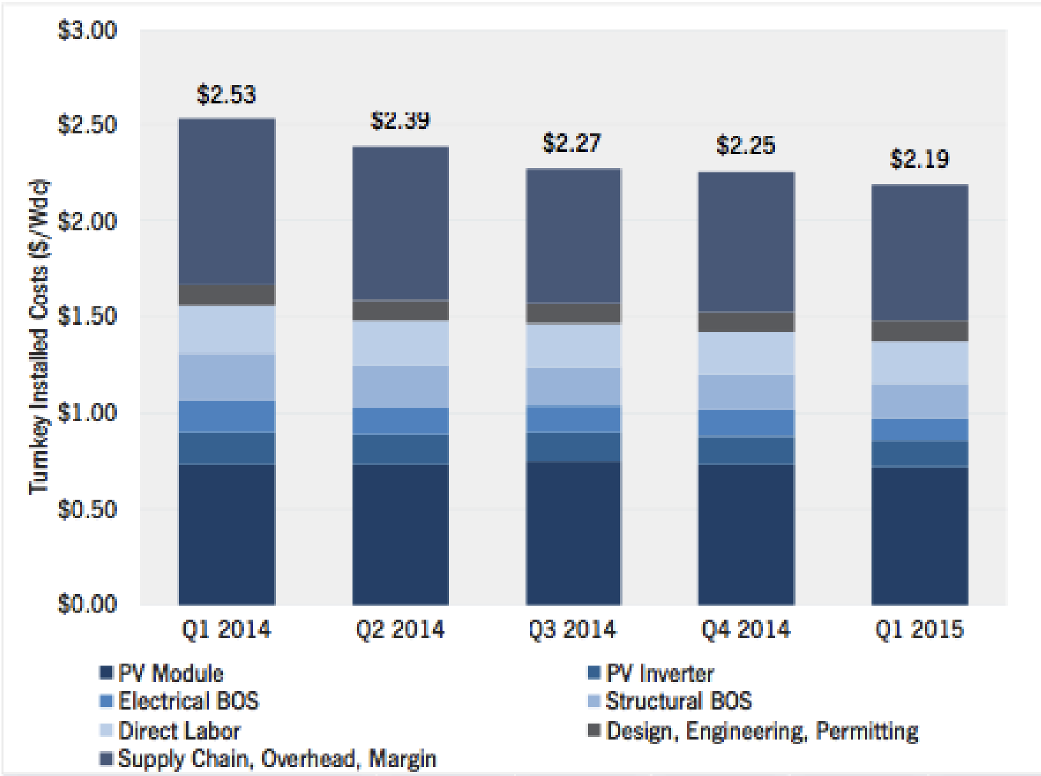


Figure 10: Swanson's Law, solar module cost and shipments ("Swanson's Law").

The installed price of solar systems has been rapidly decreasing as well. As shown in Figure 11, the price of commercial systems has declined from $2.53 in Q1 2014 to $2.19 in Q1 2015 (14% drop in last year only). The cost of panels represents only about the third of the total cost of installing a solar system. The additional costs are associated with electrical components, structural costs, direct labor, permit and interconnection costs, etc.



Non-Residential	Q1 2014	Q2 2014	Q3 2014	Q4 2014	Q1 2015
PV Module	$0.73	$0.73	$0.75	$0.73	$0.72
PV Inverter	$0.17	$0.16	$0.15	$0.15	$0.14
Electrical BOS	$0.16	$0.14	$0.14	$0.14	$0.11
Structural BOS	$0.25	$0.22	$0.20	$0.18	$0.16
Direct Labor	$0.25	$0.23	$0.23	$0.22	$0.22
Design, Engineering, Permitting, Interconnection	$0.11	$0.11	$0.11	$0.10	$0.11
Overhead and Markup	$0.87	$0.80	$0.70	$0.73	$0.71
Turnkey Pricing	$2.53	$2.39	$2.27	$2.25	$2.19
Reported Pricing	$3.70	$3.31	$3.34	$3.43	$3.23

Figure 11: Non- residential turnkey system pricing with breakdown (Kann et al).

Since the roof of the IAWWTF is not appropriate for implementing a solar system, a ground fixed solar system is proposed. According to the team's calculations, a solar system of up to 2 MW in size can be installed on the land surface available, as shown in Figure 12.

Figure 12: Overhead view of the IAWWTF potential solar array placement.

Using the free online calculator PVWatts, which is developed by NREL, the annual production of the proposed system at IAWWTF can be estimated. The weather station in Binghamton, NY located 50.8 miles from was selected as the nearest weather station for the calculator. The calculator assumes that a standard Crystalline Silicon module has a 15% efficiency, DC to AC ratio of 1.1, and an array tilt of 35° to maximize the annual production. The monthly production of the system as well as the solar radiation obtained from PVWatts is presented in Figure 13.

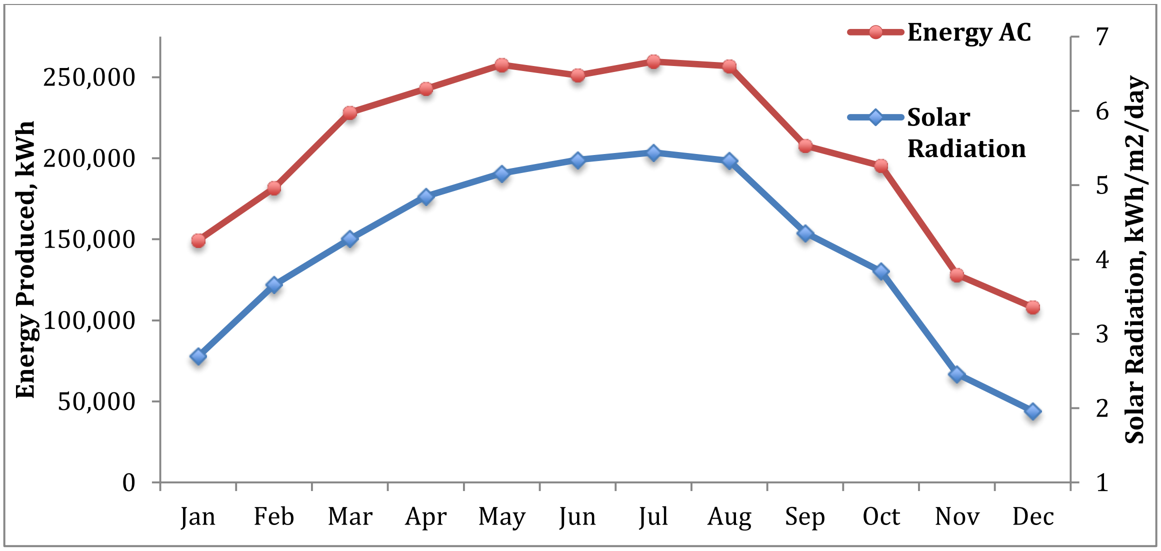


Figure 13: Energy production and solar radiation versus time.

From the above analysis, approximately 2.47 million kWh of energy annually is expected, or a capacity factor of (2.47 MkWh)/(17,520kWh at 100% nameplate capacity) = 14.1%. Additionally, assuming the installation costs of $2.2/kW, a 25 year system lifetime, and an annual operating cost of only $40,000 (2,000kW*$20/kW/yr), a LCOE of about $0.17 per kWh can be expected.

Snyder Road Solar Farm is Cornell University's first large-scale solar energy project and can serve as a good example of a successful solar project in Ithaca. This solar farm went live on September 19, 2014. The farm consists of a 2 MW array of solar panels on 11 acres of Cornell property in the town of Lansing (near the Ithaca Airport). The 8,000+ panel solar system will produce about one percent of Cornell's electricity and reduce university carbon emissions by 0.5% and provide hundreds of thousands of dollars in energy savings to the university.

Other notable projects in Ithaca include the 45.6 kW system at SPCA of Tompkins County. The SPCA projects that the shift to solar power will cut electrical costs by $6,600 dollars every year, resulting in $340,000 saved over the 25-year life of the system. Also, the 31.7 kW grid-connected system at Ithaca Bakery and the current 7.5 kW system at the IAWWTF are good examples.

Wind Power

Wind power works by using turbines to convert wind energy into electrical power. Wind turbines use the force of the wind to spin propeller blades, which in turn rotate electric generators to produce current. Inside the generator a coil of wire moves through an electric field, producing an electric current inside the wire and generating electricity. Electricity generated from wind power is variable at several different timescales: hourly, daily, or seasonally. Instantaneous electrical generation and consumption must remain in balance to maintain grid stability, so this variability can present substantial challenges to incorporating wind power into a microgrid.

Wind power production is difficult to predict because of variability in the wind. There is a 40% chance that power production will change by 10% or more within 5 hours. A good energy storage system is also necessary for implementation. Hydroelectricity complements wind power well because when the wind is blowing strongly, nearby hydroelectric stations can temporarily hold back their water. When the wind drops they can increase production to compensate.

The most common wind turbines are horizontal axis wind turbines with 3 rotating blades. This model extracts the maximum amount of power from the wind. Vertical axis wind turbines are less popular because the power output from wind turbines is largely a result of the rotor diameter. It is significantly easier to have a large rotor diameter on a horizontal axis turbine as opposed to a vertical axis turbine.

Turbines are often designed to specified use, and the largest turbines can produce approximately 2MW under normal (~5m/s) wind conditions.

A description of the different types of wind turbines can be found in Table 7.

Turbine	**Description**
HAWT	The blades of the turbine spin on a horizontal axis, so they need to be pushed out far enough from the base so that high winds won't bend them back into the mast. This type of turbine is typically angled forward into the wind.

Darrieus wind turbine	These wind turbines look a little like whisks with slender curved blades creating a cage-like configuration.
Giromill	This type is like the Darrieus, but with straight blades instead of curved ones.
Savonius wind turbine	This turbine utilizes scoops instead of blades, and relies on drag rather than wind lift. The scoops spin because the wind has less resistance on one side of the scoop than the other. This results in less efficiency, but can be used in areas where cost and reliability are a higher factor for consideration. These types of turbines are often used for ventilation on caravans and buses.
Twisted Savonius	By changing the shape of the scoops to solid blades twisting around the axis, efficiency can be improved by reducing the loss of energy in drag. These are often used in urban wind energy generation where the changing direction can be a problem for a fixed HAWT.

Table 7: Description of various types of wind turbines.

Wind power has a relatively high cost of production. The technology requires a large initial investment. Roughly 80% of the cost is the machinery, the rest is comprised of site preparation and turbine installation. Wind power costs are competitive with other renewable technologies because there is no fuel to purchase and turbines require minimal operating expenses.

Transmission from Black Oak Wind Farm to the microgrid could supply a significant amount of energy production to the Ithaca Microgrid.

Primary Voltage	Lowest Cost ($MM/mile)	Highest Cost ($MM/mile)
230 kV	$0.30	$1.60
345 kV	$0.60	$1.50
500 kV	$1.50	$2.20
765 kV	$2.00	$3.20

Table 8: Cost of high-voltage transmission lines.

Installation cost is primarily determined by the turbine tower height, and overall weight of all turbine parts. Lighter turbines by design are easier to create and install. Much of the initial cost of wind power is ‘tower’. The least expensive tower is a Guyed Tower, for small wind turbines of less than 2kw. Freestanding towers range in height from 12 to 40m. They produce from 3kw to 30kw. Hydraulic towers are the easiest to install but are the highest cost.

Wind turbines typically have low maintenance costs. Proper selection and installation of turbines can reduce maintenance costs. For example, there are several important consideration for installing rooftop turbines. Before installing rooftop wind turbines, the endurance of the roof needs to be tested. The structure, thickness and construction materials of the roof must be checked. The roof must be able to endure the weight of the turbine as well as the dynamic load of the rotating turbine from the turbulent wind. Noise issues must also be considered. Vertical wind turbines are preferential for rooftops, because of lower noise. It can reduce the impact to the normal living environment of the residents. Aesthetic maintenance costs are necessary in order to make the turbine appearance united with the building style.

The Black Oak Wind Farm is a 16.1 MW wind farm proposed in western Tompkins, New York. The farm will contain 7 GE 2.3 MW turbines. Cornell University has agreed to purchase all electricity generated by the proposed Black Oak Wind Farm in Enfield, New York. The farm is expected to generate 45 million kWh annually, according to one study.

Hydroelectric Power

Hydroelectric power generates electricity through the gravitational force from the falling or flow of water. Moving water with a strong enough current is able to turn turbines that are connected to generators to produce electricity. Hydroelectric power has the advantage of being relatively low cost, making it the most widely used form of renewable energy in the world. Furthermore, it can be flexible by adjusting the production level according to energy needs. However, there are concerns of creating a disruption to local ecosystems by interrupting the flow of rivers.

Within Ithaca, there are a few feasible plans and improvements for hydroelectric power. Currently, hydroelectric accounts for 11% of the total electricity produced, and there is potential for this figure to grow (Johnson). By March 2016, the existing water treatment plant will be replaced and hydro-turbines will be added that can generate 343,000 kWh a year (Dennis).

Furthermore, this addition will reduce CO_2 emissions by approximately 118 tons a year and lower the city's utility bills.

Detailed feasibility studies conducted in the 1980s exist that examine the possibility of building two hydroelectric plants in Ithaca: one at Fall Creek and another at Six Mile Creek (Bosak). The construction of a hydroelectric plant at Fall Creek is estimated to produce 6.67 million kWh per year, and a plant at Six Mile Creek is estimated to produce 1.35 million kWh per year. Combined, these two projects would bring in a total of 8.02 million kWh annually and a gross income of $802,000 per year to the city with an estimated payback period of 13 years. The proposed plant at Fall creek is close in distance to the proposed microgrid location at about one mile away from the IAWWTF.

Cornell University has a hydroelectric plant on Fall Creek that has been generating power since 1904 (Franzese). Recent upgrades in 2013 and 2014 have optimized the electric generation to increase production by 1 million kWh per year and reduce greenhouse gas emissions by 450-600 metric tons per year ("Hydroelectric Plant"). These improvements to the plant will help the campus reach its goal to become carbon neutral by 2035. The presence of a hydroelectric plant already on Fall Creek is a testament to the viability and reliability of hydroelectric power in in Ithaca.

Hydropower can be one of best energy sources to run a microgrid power system. The advantage of hydropower is that it is continuous and reliable, thus making it perfect for providing a steady charge to a battery bank. Additionally, during low consumption periods hydro pumping can use produced electricity to pump water back upstream. This essentially acts as a form of energy storage, and hydro pumping is the largest-capacity form of grid energy storage available.

Biomass

Biomass is organic matter that can be burned or decomposed to be used a source of energy. In a way, biomass energy is a form of solar energy since it receives its original energy from the sun via photosynthesis. This solar energy is stored in plants and is available for conversion into usable forms of energy. When burned, plants release carbon dioxide that is absorbed by other plants in the environment; therefore, biomass as an energy source is carbon neutral (Brenchmont).

Biomass energy can be collected in a variety of ways including burning wood, converting waste into energy, collecting methane for biogas, and using energy crops for biofuels. The liquid biofuels, ethanol and biodiesel, are used almost exclusively for transportation; therefore, liquid biofuels will not be considered as a viable source for this microgrid project.

There are several advantages of using biomass as an energy source for the Ithaca microgrid. First, biomass helps eliminates existing waste by converting it to biogas. Second, biomass is carbon neutral and can reduce carbon footprint of the microgrid. Additionally, biomass has the potential to strengthen rural economies, enhance energy security, and minimize the environmental impacts of energy production. Challenges to biopower production include the need for a sufficient feedstock supply, concerns about potential health impacts to nearby communities from the combustion of biomass, and its higher generation costs relative to fossil fuel-based electricity. Additionally, biopower generally requires tax incentives to be competitive with conventional fossil fuel-fired electric generation such as coal and natural gas (Brenchmont).

Solar and wind offer the important advantage of zero fuel cost, but they have higher capital costs and much lower utilization rates because solar only produces electricity when it is sunny and wind when it is windy. The combination of high capital costs and low utilization lead to higher electricity prices. It is true that biomass fuel costs money, it is not free like the wind and sun. However, the lower overall capital costs and a much higher capacity factor of 83% compared to wind and solar which are 35% and 22% respectively leads to a lower total system levelized cost (Ainslie et al).

The main reason why biomass is studied is due to its stability. Similar to fossil fuels, biomass system will continue to produce energy as long as there is enough fuel. It is important to note that a microgrid has to continue delivering power when the main grid is unable to do so. Hence, by having a reliable energy source such as biomass the risk of running out of energy is minimized, which is of utmost importance since a microgrid's reliability cannot be compromised.

Biomass Conversion Technologies for Energy Production

In the context of this document, biomass conversion refers to the process of converting biomass into energy that will in turn be used to generate electricity and/or heat. Different methods work better with different types of biomass. Typically, woody biomass such as wood chips, pellets, and sawdust are combusted or gasified to generate electricity. Very wet wastes, like food, animal and human wastes, are converted into a biogas gas in an anaerobic digester. There are multiple methods to produce biomass energy from these feedstocks. Although there are several new innovations regarding biomass conversion technology, the team only focused on methods that have been proven and widely adopted: combustion, gasification, and anaerobic digestion.

Direct combustion is perhaps the most traditional method of extracting energy from biomass and it is similar to a coal direct combustion system. Industrial biomass combustion facilities can burn many types of biomass feedstocks. Biomass feedstocks are burned in a boiler to produce steam, and the steam turns a turbine, which drives a generator to produce electricity and heat. Because of potential ash build-up (which fouls boilers, reduces efficiency, and increases costs), only certain types of biomass materials are used for direct combustion (Sriram). Although a direct combustion system is attractive, it is not feasible considering that the IAWWTF will be used as the microgrid hub. The usual feedstock used for direct combustions are wood pellets and wood chips which are dry. However, the feedstock for the Ithaca biomass systems is sludge from sewage or food waste, which is often too wet.

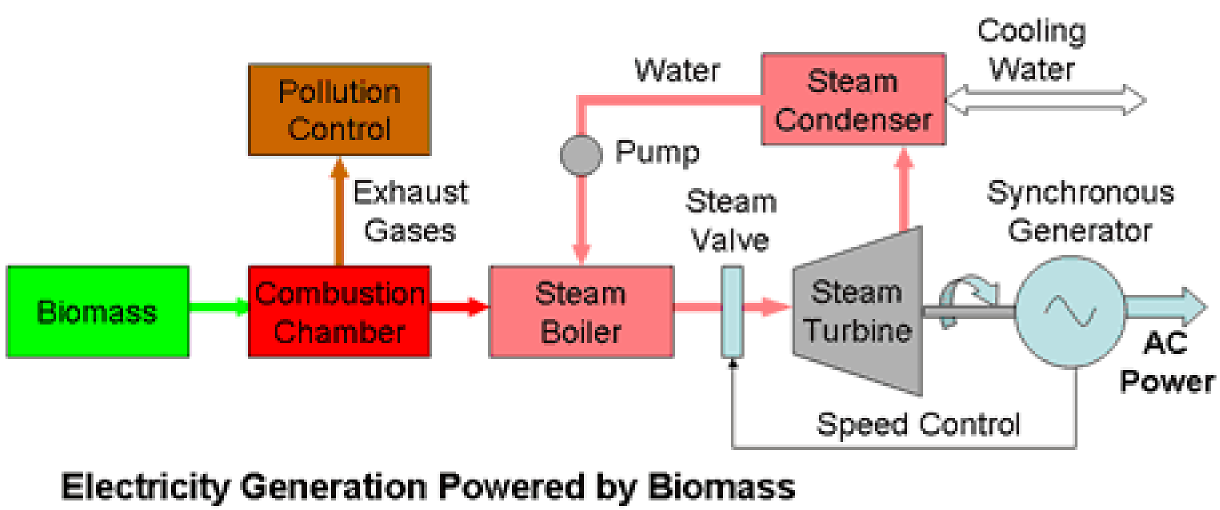


Figure 14: Direct combustion ("Battery and Energy Technologies").

Gasification is a process that exposes a solid fuel to high temperatures and limited oxygen to produce a gaseous fuel commonly known as syngas. Gasification has several advantages over burning solid fuel. It produces a fuel that has had many impurities removed and could therefore cause fewer pollution problems when burnt. Second, it is convenient since one of the product gases, methane, can be treated in a similar way as natural gas and used for the same purposes. Therefore, the syngas can be used as a substitute for natural gas to drive a high-efficiency combined-cycle gas turbine in a CHP system (Sriram). Although gasification is much cleaner than the biomass direct combustion since the syngas output is cleaned and filtered, it is still a relatively new technology and not as reliable as the others.

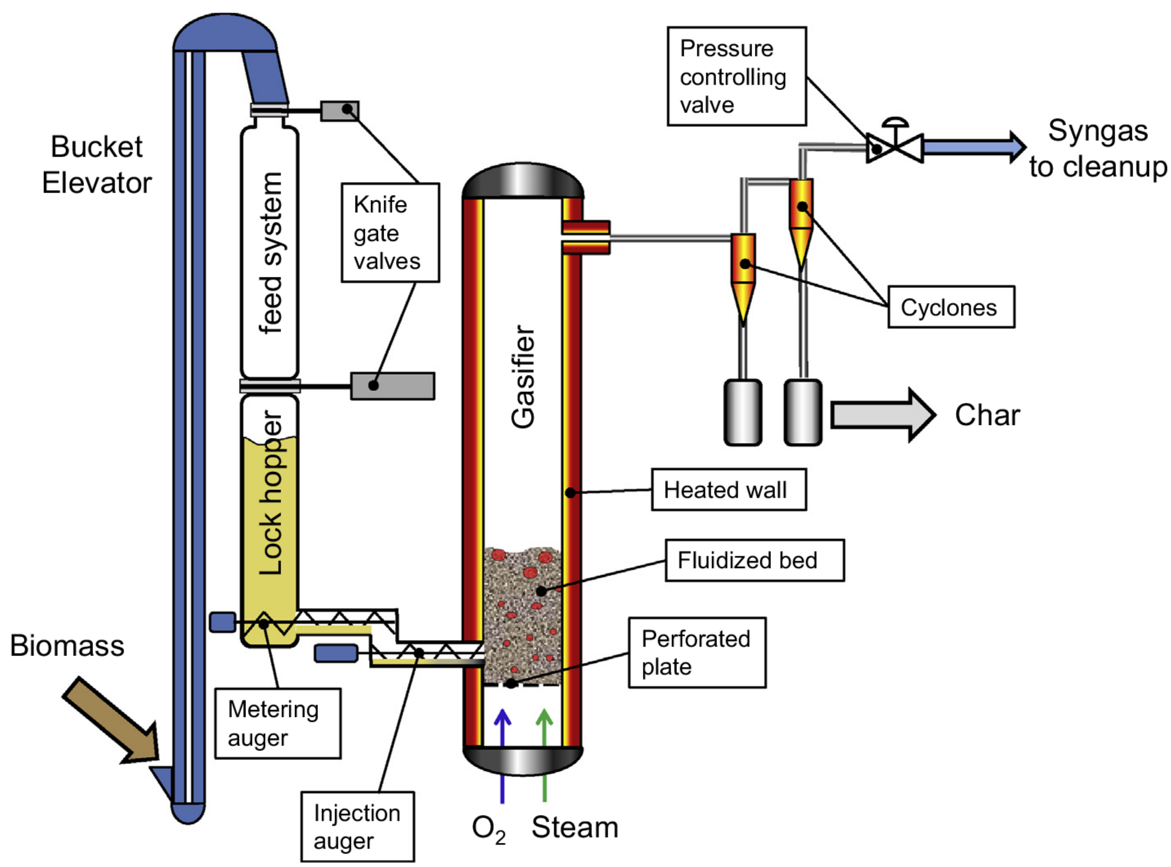


Figure 15: Gasification schematic ("Biomass Gasification and Syngas Cleaning").

Anaerobic Digestion (AD) is a natural biological process where organic material is broken down by bacteria. It takes place in the absence of oxygen. By feeding organic matter such as food waste, animal waste, or human sewage into digester tanks and adding bacteria, emitted gas can be collected and used as an energy source. The biogas produced from the digester is then purified and burned to generate electricity and heat in the CHP system.

A variety of factors affect the digestion rate and biogas production of AD, the most important factor being temperature. Anaerobic bacteria can endure temperatures from below freezing to more than 135°F (57.2°C), but they flourish at temperatures of 98°F (mesophilic) and 130°F (thermophilic). Bacterial activity, and thus biogas production, falls off significantly between temperatures of 103°F and 125°F and gradually between 95°F to 32°F. In order to optimize the digestion process, the digester must be kept at a consistent temperature as rapid fluctuations upset bacterial activity.

Anaerobic digestion of municipal wastewater sludge has been widely practiced since the early 1900s and is the most widely used sludge treatment method. Overall, the process converts about 40 to 60% of the organic solids to methane (CH_4) and carbon dioxide (CO_2). The chemical composition of the gas is 60 to 65% methane, 30 to 35% carbon dioxide, plus small quantities of H_2, N_2, H_2S and H_2O. Of these, methane is the most valuable because it is a hydrocarbon fuel with energy per volume of about 36.5 MJ/m3 in combustion.

The residual organic matter from AD is chemically stable, nearly odorless, and contains significantly reduced levels of pathogens. The suspended solids are also more easily separated from water relative to the incoming sludge or aerobically treated sludge (such as in outdoor ponds). These solids leftover from the anaerobic digestion process are then sent into a nutrient rich biofertilizer and stored in large covered tanks that are ready applied twice a year on farmland in place of fossil fuel derived fertilizers. The waste that cannot be reused for compost is dewatered and made into a dry cake, which is transported to landfill (Energy.gov). One concern is that if the leftover solids from digestion are contaminated with pollutants (heavy metals, organic pesticides, trace amounts of pharmaceuticals, etc.) it may not be possible to apply any of them to land and they may all need to be transported to landfill.

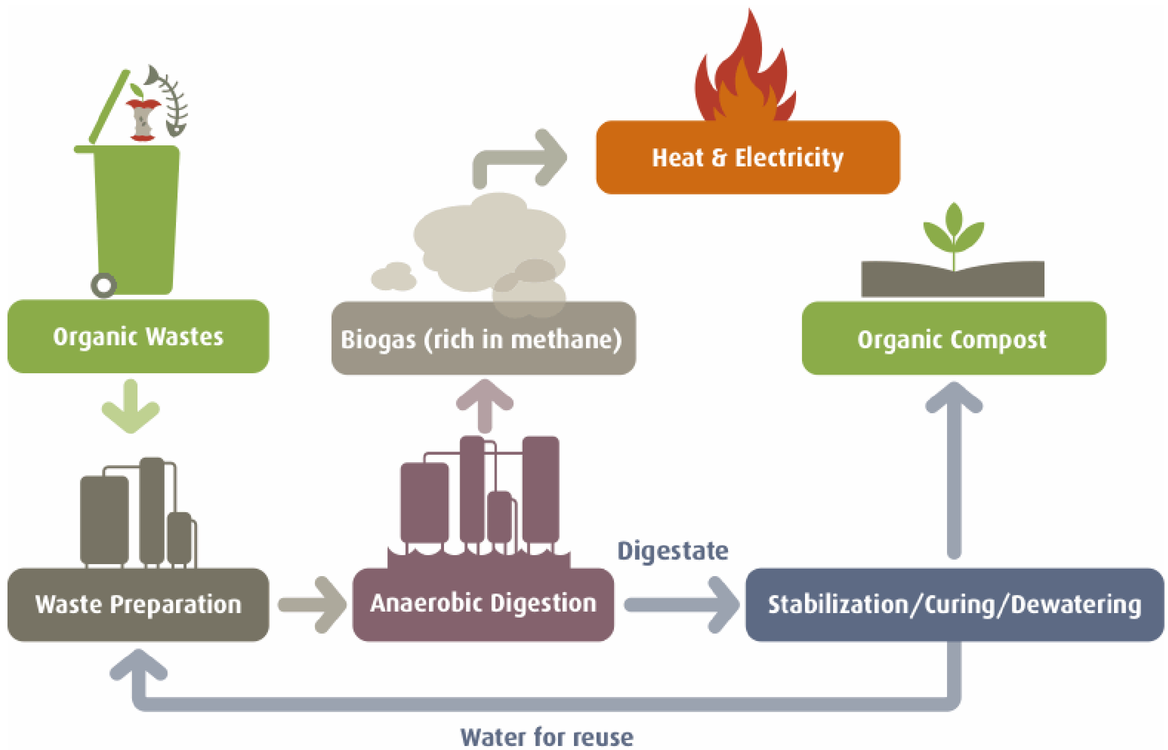


Figure 16: Anaerobic digestion schematic ("Anaerobic Digestion Adoption").

With respect to the Ithaca area, all three biomass technologies are feasible. However, gasification and direct combustion are costly as the necessary systems would need to be build and incorporated into the CHP system. Conversely, Anaerobic Digestion system is already implemented at the IAWWTF, and they have been trying to improve their Anaerobic Digestion system to produce more biogas. Therefore, Anaerobic Digestion is the most feasible technology to use for the Ithaca microgrid.

The IAWWTF processes waste in three different stages: primary, secondary, and tertiary. Waste is a major input to the facility, which flows in through pipeline or via trucks. The primary stage of processing includes gravity settling where the heavy sludge is separated from the wastewater. The wastewater moves to the second stage of activated sludge process. This is the stage where most of the energy produced/purchased is used. In this process, aerobic microorganisms are introduced to the clarified wastewater under constant aeration. The microorganisms assimilate organics in the wastewater, and the heavy sludge with organisms gets separated. In the third stage, chemicals such as ferric chloride and polymers are introduced to separate phosphorous from wastewater. The waste is chlorinated for disinfection and de-chlorinated before entering the pipeline to Cayuga Lake. The waste sludge that gets separated at the three different stages is dewatered and sent to the biodigesters. Anaerobic digestion occurs to reduce the total biomass, and the waste is digested for 28 days at 98°F to produce biogas. The waste sludge is again dewatered and made into a dry cake and transported to landfill.

Basically, while cleaning the wastewater before releasing it into Cayuga Lake, the plant is conveniently able to produce biogas, which it then uses to meet its own energy needs. However, IAWWTF cannot utilize its full capacity because of the limited amount waste that enters the plant for biogas conversion (Blakinger). Based on the data collected in the 2014 team project, the plant is able to produce up to 2.1 mWh/year based on the current waste load. The plant's energy needs are approximately 4 GWh; therefore the biogas produced is only able to satisfy 53% of this value (Ainslie et al). The amount of biomass energy produced is projected below in Table 9.

Project Size and Performance	*Units*	*Input Value*
Generator Nameplate Capacity	*kW*	260
Biogas Consumption per Day	*cubic feet/day*	101,385
Biogas Consumption per Year	*cubic feet/year*	37,005,577
Energy Content per Cubic Foot	*BTU/cubic foot*	600
Energy Content per Year	*MMBTU/year*	22,203
Electrical Conversion Efficiency	*%*	35%
Heat Rate	*BTU/kWh*	9,749
Availability	*%*	92%
Annual Energy Production	***kWh***	**2,095,392**
Project Useful Life	*years*	20

Table 9: Table of the amount of energy produced using regular waste load.

However, there is a hope for a future pilot project to bring more waste from outside town to the IAWWTF. It is predicted that by the time the microgrid project will be realized, the amount of waste that comes into WWTP will increase threefold. Then, the current generator capacity of 260 kW can be upgraded to 780 kW to accommodate the increase in waste load. It is assumed that there will not be any degradation in the biogas production system. The energy content is 600 BTU/cubic foot of gas since the biogas produced using the anaerobic digestion system is composed of 60 to 65% methane. The amount of biomass energy produced using these assumptions is projected below in Table 10.

Project Size and Performance	Units	Input Value
Generator Nameplate Capacity	*kW*	780
Biogas Consumption per Day	*cubic feet/day*	304,155
Biogas Consumption per Year	*cubic feet/year*	111,016,731
Energy Content per Cubic Foot	*BTU/cubic foot*	600
Energy Content per Year	*MMBTU/year*	66,610
Electrical Conversion Efficiency	*%*	35%
Heat Rate	*BTU/kWh*	9,749
Availability	*%*	92%
Annual Energy Production	***kWh***	**6,286,176**
Project Useful Life	*years*	20

Table 10: Table of the amount of energy produced using three times waste load.

When the waste load is increased by three times, it is predicted that the amount of energy produced will exceed 6.2 GWh, which is above the 4 GWh IAWWTF energy requirement. The amount of biogas left could then be used as a fuel in the microgrid CHP system. Additionally, the amount of energy consumed by IAWWTF is predicted to be decreasing, which translates into less biogas consumed to satisfy the IAWWTF energy requirement leaving more available for the microgrid CHP system (Barret). The amount of energy produced in this calculation assumes the maximum supply the system can handle. In reality, the amount of waste coming into the IAWWTF may vary, which reduces the amount biogas produced. However, this should not pose a problem as the CHP system can always operate on extra natural gas when the biogas alone is not sufficient.

GEOTHERMAL

Geothermal energy was explored as an option for providing power to the proposed Ithaca microgrid. Geothermal energy is stored about 6ft below the earth's surface where temperatures do not fluctuate with the changing seasons. A geothermal system takes advantage of this resource by passing fluid filled piping through the ground to either extract or deposit heat into the ground. This energy can be utilized in two ways. The heat energy can be converted into electricity at a power plant if heat from a sufficient depth is accessed so that the temperature is high enough (a.k.a "enhanced geothermal"), or if there is access to steam near the surface, as in "The Geysers" power station in California. Otherwise, the heat energy can be used directly to heat and cool indoor spaces ("Geothermal FAQs"). Since the former generally requires reservoirs of steam or hot water to be effective, it will not be considered as an option for the Ithaca area.

By utilizing the heat energy directly, indoor heating and cooling expenses can be greatly reduced. In the winter, circulated fluid absorbs heat and carries it indoors. An indoor unit then compresses this heat to a higher temperature, and the warm air is then distributed. In the summer, the system reverses by depositing heat into the ground and bringing cooler air into the unit compressor. For the direct use of heat energy, there are two types of systems that can be installed: open-loop and closed-loop ("Frequently Asked Questions regarding Geothermal Systems and Heat Pumps"). Open-loop systems generally use groundwater from a conventional well as a heat sources, whereas a closed-loop system passes fluid through usually horizontally trenched plastic pipe to exchange heat with the environment.

Overall, a direct heat geothermal system requires a geological assessment of the proposed land area, as well as borehole exploration and flow testing (Thermal Energy Partners). The costs for installation are usually in the range of $20k to $25k for a 60,000 BTU heating and cooling load ("Installation").

Based on the previous discussion, the direct heat system is the only geothermal system feasible for the Ithaca area. Therefore, geothermal energy cannot be used to provide power to the microgrid. However, any operating facilities or temperature controlled rooms associated with the operation or housing of the microgrid could be heated and cooled by a geothermal system. Although this would not contribute to the power production of the system, it would reduce the overall system load.

Energy Storage

Energy storage devices are intended to serve as reservoirs for energy when its generation is at a surplus to be discharged by the device at a later time. Energy can be stored in the form of gravitational potential energy, chemical energy, kinetic energy, or electrical potential energy. With an effective control system, storage operates as an intermediary in a microgrid between the supply and demand sources by optimizing the transfer of energy from one side to the other to minimize overall energy losses or maximize profitability.

When attached to a grid, energy storage typically serves one of three functions. The first is supplying energy to users when the grid goes down for a certain period of time. In this configuration, storage mediums are kept fully charged in case of a power outage. Vital systems will be able to run on this stored energy for a fixed period of time until the batteries drain completely. The amount of time that these systems can be supplied power is directly proportional to the total capacity of the storage systems.

The second and more common function is load adjustment and balancing. Storage devices store energy when the grid is producing more electricity than it is consuming. The devices then discharge during peak consumption when the grid has trouble keeping up with demand or to reduce costs. In this scenario, the energy losses due to the efficiency limitations of the storage systems are overcome by the discrepancy between the cost of energy at times of peak and low demand.

Finally, energy storage can be used to levelize the erratic electricity output from certain energy sources such as solar, hydro, and wind power. Unlike traditional sources of energy production, these methods are directly dependent on environmental factors that cannot be controlled and can fluctuate wildly over a short span of time. The large drop in energy production that occurs when a cloud passes between the sun and a solar panel, for example, does not change the continuous instantaneous demand for energy. In order for these technologies to actually contribute usefully to the grid at their rated capacities, energy must be instantaneously stored when generation is at a relative maximum, then released when natural factors prevent the source from generating electricity at its expected average output.

Pumped-hydro energy storage stores energy in the form of gravitational potential energy. When the grid is producing excess electricity, it is used to run pumps that push water from one reservoir up to a reservoir at a higher elevation where it is stored. When additional energy is needed, the water is allowed through the turbines from the higher reservoir to the lower reservoir in order to generate electricity. Pumped hydro systems typically operate with efficiency values between 70% and 85%. One of the largest advantages that pumped hydro has over other methods of energy storage is that it does not suffer efficiency losses as it is scaled larger, unlike batteries. This is one of the reasons that pumped hydro accounts for over 99% of the global installed energy storage capacity, approximately 127,000 MW total. The two major concerns when considering the feasibility of pumped hydro in a microgrid are the potential up-front installation costs and the availability of the necessary environmental factors. Naturally existing reservoirs and height gradients can greatly reduce the costs for pumped hydro, as significant geographical shaping does not have to take place. In order to make pumped water storage effective, either a large height difference or a very large reservoir is needed. With the correct existing geographical features, pumped water hydro can be by far the cheapest energy storage option per kilowatt-hour of capacity.

Another type of hydroelectric energy storage is the use of hydroelectric dams. By varying the flow passing through a dam, one can effectively store energy in gravitational potential. If less water is allowed to pass through the dam when there is low demand, the water level raises higher before the dam. The flow can be increased later, which can increase turbine output during peak demand hours. The advantage of hydroelectric dam energy storage over pumped water storage is that energy is stored and converted identically, but pumped water suffers from pumping losses while damming does not.

Compressed air energy storage is another common method of energy storage where excess electricity is used to compress air and store it. Air can either be stored as a compressed gas, or compressed further and cooled to be stored as a liquid, which reduces necessary storage space. When electricity is needed, a valve is opened, heat is applied, and the expansion of the compressed gas generates electricity as it passes through a turbine. The storage vessel for the air can be a manmade aboveground vessel or an artificial or naturally occurring underground cavern. The availability of a cavern suitable for compressed air storage can drastically reduce the costs necessary for implementation. However, compressed air energy storage has particularly low energy efficiencies, often as low as 60%. This is largely because of the energy inherently lost due to the compressibility of gases. This energy loss is magnified as the volume is scaled up, making compressed air storage effectively useless above certain capacity ranges because as the gas is compressed, heat is generated. As the container space grows, more and more of this heat is lost to the environment.

The final major type of mechanical energy storage that is feasible for use in a microgrid is flywheel storage. A flywheel suspended in a magnetic field is accelerated as excess electricity from the grid is imparted to the motor. Energy is stored as rotational kinetic energy in the rotating flywheel. When the grid requires electricity from the flywheel, the motor functions as a generator by decelerating the flywheel to generate electricity. Flywheel energy storage systems are in their early stages of development, meaning that they have generally high capacity costs. Flywheel systems have high efficiencies, often almost 90%. However, they typically have fairly low capacities and are best employed when directly linked to highly variable power generation systems for short-term load leveling.

Batteries are a type of energy storage device that take in electricity and convert it to chemical energy. When the energy is needed, the battery discharges sending the electricity back into the grid. There are many different types of batteries, which are classified by and differ in function by their chemical composition. Compared to mechanical energy storage systems, batteries have the distinct disadvantage of wearing out and needing to be replaced over a relatively short period of time, while mechanical systems usually only require minimal maintenance. This repeated reinvestment often makes up-front storage costs less than mechanical storage systems, but more expensive over longer time horizons.

Lead-acid batteries are the oldest type of rechargeable battery. They account for 40 to 45% of the total value of all batteries sold worldwide due to their low cost and high surge currents. This gives lead-acid batteries a high power-to-weight ratio, which combined with its low cost makes it an ideal choice as a starter battery for automobiles. Lead-acid batteries have the second-lowest cost per kWh of storage among all types of batteries at roughly $600/kWh. Excessive charging can cause electrolysis, which emits hydrogen and oxygen in a process referred to as “gassing,” and batteries are equipped with vents in order to normalize the pressure buildup. In the event that the vent is damaged or blocked by foreign objects, this gas can build up pressure inside of the battery, which could cause the gases to ignite and explode. While this is something to be cognizant of, it becomes very unlikely when batteries are maintained and stored properly. A system of many lead acid batteries in series is the most common way that batteries are used in a microgrid. Their popularity within microgrids is largely due to their low cost and scalability; however, they must be replaced after three to five years of service.

Lithium-ion batteries are another attractive choice of battery for use in a microgrid. They are currently the cheapest battery available, at around $500/kWh. Additionally, lithium-ion battery technology has been and will continue to progress rapidly. Among other uses, lithium-ion batteries are projected to dominate the rapidly growing market of energy storage for electric vehicles. As electric vehicles boom, lithium-ion battery capabilities will likely increase, paired with a drop in prices. In fact, by 2020, lithium-ion batteries are expected to cost between $100-$200/kWh. This makes the lithium-ion battery by far the cheapest battery available and makes energy storage in general a much more affordable option. One advantage of lithium-ion over other types of batteries is its longevity. Lithium-ion batteries tend to last around ten years, double that of the average lead-acid battery. However, lithium-ion batteries, like lead-acid batteries, do carry a safety risk. Over-charging, short-circuiting, or external damage can cause thermal runaway and cell rupture, which can cause the battery to catch fire causing a chain-reaction by causing adjacent batteries to overheat and fail. This is especially concerning when considering their use in a microgrid setting, where many batteries would be in close proximity to one another. However, there are many safety features on the batteries to prevent these types of events from occurring, and future developments are making lithium-ion batteries even safer.

The third and final type of battery that is commonly used in microgrids is the flow battery. Flow batteries are functionally different from lead-acid and lithium-ion batteries. In flow batteries, the ionic solution is stored outside of the cell, then flows through the cell in order to generate electricity. Flow batteries hold several advantages over traditional electrochemical batteries; they require little maintenance, and unlike lead-acid and especially lithium-ion batteries, they have significant tolerance to overcharging. Additionally, flow batteries scale quite well, which makes them an attractive option for microgrid use. However, flow batteries are very complex compared to more traditional batteries, and are therefore significantly more expensive.

One of the primary motivations for establishing a microgrid in Ithaca is to provide continuous electricity to primary users in the case of a grid failure. Because this microgrid is designed specifically for this functionality, installing energy storage for the same purpose would be redundant. The microgrid is also designed to be able to supply to all priority users, even at peak consumption, with multiple buffers built in to ensure this capability. This means that energy storage is not needed to support priority user demand.

The main way that energy storage devices would be implemented in the North Energy District would be to levelize the output from the solar field. Solar fields become a much more functional and valuable energy source when connected with an appropriately sized energy storage system. Levelizing the output of the microgrid solar field is especially important due to the current expectation that excess energy will be sold back to the main grid. If this were the case, the extra electricity produced during peak hours could be sold back to the main grid for revenue. Without this option, this extra energy will need to be stored so that it is not wasted. There is no universal ratio of solar capacity to storage capacity that works for all systems. After comparing the ratios across several existing microgrids with solar capacity, however, a ratio of 0.8 kilowatts of solar generating capacity to every one kilowatt-hour of energy storage seems to be appropriate given Ithaca's solar potential. Given the 2 MW of solar capacity included in the model, the corresponding storage capacity is 2.5 MWh.

Pumped water hydro, though often the most cost-effective and reliable energy storage solution, is not suitable for storage for the Ithaca microgrid. Despite Ithaca's natural elevation differences and natural reservoirs, there do not appear to be any suitable locations for a pumped water system in the northern energy district. Additionally, the lack of natural underground caverns for compressed air storage makes it too costly of an option for energy storage. The necessary scale of such a system amplifies this. A compressed air system with 2.5 megawatts of capacity would have too significant heat losses due to scaling, resulting in an extremely low system efficiency.

With today's technologies and prices, a system of lithium-ion batteries appears to be the best-suited energy storage solution for the Ithaca microgrid. While lead-acid and lithium-ion batteries are priced very similarly, lead-acid batteries need to be replaced twice as often as lithium-ion batteries. This almost doubles the annual cost of a lead-acid storage system compared to a lithium-ion system. With an anticipated cost of $500/kWh and expected lifespan of 10 years, the annual cost of this storage system would be $125,000 per year.

The anticipated drop in price of lithium-ion batteries by 2020 makes it a much more attractive option for energy storage. Given that the Ithaca microgrid is still in the planning stages, it is reasonable to think that batteries in this price range could eventually be implemented in the initial microgrid installation. Even if these savings are not realized in the initial battery system, when the batteries need to be replaced in around ten years the dramatically-reduced battery prices expected by that point in time will lead to significant cost reductions by choosing lithium-ion. Assuming that lithium-ion battery prices drop to $150/kWh by the time the first installation is purchased, the annual cost of the system drops to $37,500.

There are several factors to be considered for how the batteries would be used within the microgrid. In order to minimize cost and maximize performance and battery lifespan, certain decisions need to be considered when implementing a system of batteries into the microgrid. The first of these is the state in which the batteries are stored and maintained. The factor that can contribute most negatively to the performance and lifespan of lithium-ion batteries is the temperature at which the batteries are stored and discharged. The batteries need to be stored at room temperature in order to minimize capacity losses over time. Additionally, lithium-ion batteries last longer when they are not regularly discharged 100% each time.

PROJECT FRAMING

Initially, the scope of this project included both the North and South Energy District because Ithaca is connected to the grid by two separate substations owned by New York State Electric and Gas (NYSEG). Figure 17 below shows these two substations (City of Ithaca NY Prize 2015).

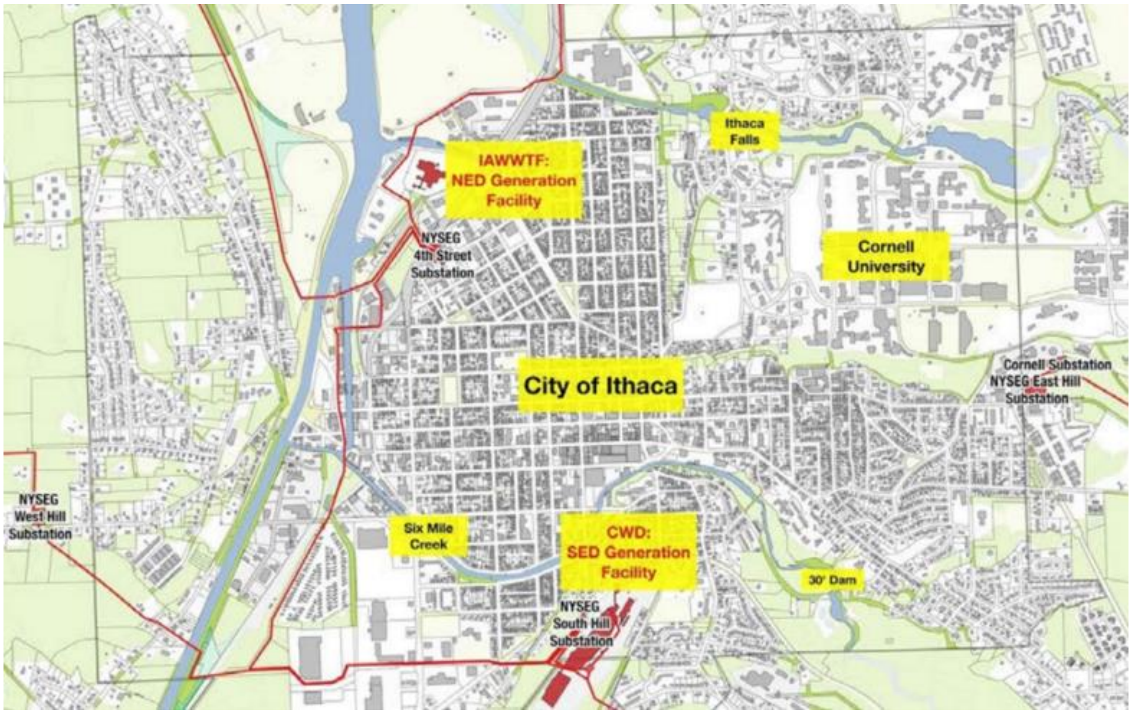


Figure 17: North and South Energy District substations.

This North Energy District (NED) would be based on the IAWWTF and the South Energy District (SED) would be based on the Chain Works District.

The NED energy resources would be located next to the IAWWTF, which treats wastewater from the City of Ithaca, the Town of Ithaca, and the Town of Dryden, as well as trucked waste from a number of other sources. The NY Prize document designated the priority users of the NED as follows: the IAWWTF, the Ithaca High School and Administration Building Complex, Boynton Middle School, Fall Creek Elementary School, and section 8 properties owned by the Ithaca Housing Authority titled the Ithaca Housing Projects. The NY prize document also states that the NED has a residential population of 3,738 in a total of 1,680 households.

The SED would be based at the CWD factory building, which is located adjacent to the second NYSEG substation. It would serve the south end of the city, whose priority users would be South Hill Elementary School, the Ithaca Police Station, the South Hill fire station, the County Mental Health Building, the County Library, the City Water Treatment Plant, Ithaca City Hall, Town of Ithaca Offices, and several residential facilities. The NY prize document also states that the SED has a residential population of approximately 11,822 in a total of 3,885 households, which comprise the non-priority users.

Within the SED there exists more complexity and less advanced infrastructure. Because the NED is closer to being feasible for the plans for the microgrid, the team decided to focus primarily on the North Energy District's users as shown in Figure 18 below.

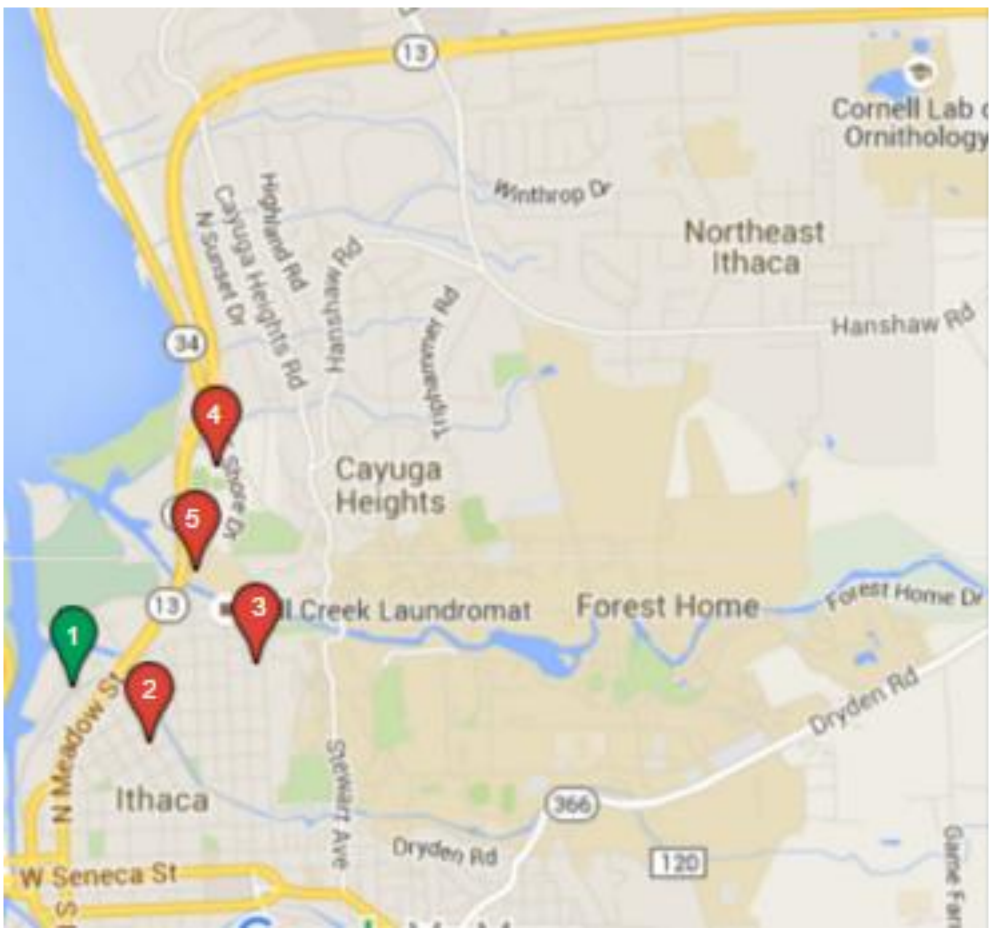


Figure 18: North Energy District priority users: (1) Ithaca Waste Water Treatment Plant (2) Ithaca Housing Project Area (3) Fall Creek Elementary School (4) Boynton Middle School (5) Ithaca High School

DEMAND ANALYSIS

Energy consumers of the North Energy District were divided into primary and secondary users. The NED has a residential population of 3,738 in a total of 1,680 households. The demand capacity was calculated by analyzing the demand of specific priority users. The priority users and their associated energy usage as found by NYSEG are as shown in Table 11.

Priority users	kWh/y	kW
Ithaca HS	3,193,155	365
Boynton MS	1,065,692	122
Fall Creek ES	187,033	21
Ithaca Housing projects	530,000	61
IAWWTF	4,010,400	458
TOTAL	8,986,280	1026

Table 11: Priority users' energy usage in kWh/year and average kW power requirement.

In review of the non-priority users, which represents the 1,680 households of the NED, research shows that the average New York state household uses about 603 kWh per month. This correlates to approximately 7500 kWh a year. Table 12 below shows this calculation for the NED non-priority users.

Non-priority users:	kWh/y	kW
Unit amount	7,500	0.86
Number of units	1,680	1680
Total amount	12,600,000	1438

Table 12: Non-priority users' energy usage ("Ithaca, NY Electricity Rates") in kWh/year and average kW power requirement.

A buffer of 15% was used to account for variations between peak-to-average load demands between users in the team's calculations. Based on Figure 19 below, the demand capacity was calculated using a peaking factor of two since this ratio is slowly rising with time.

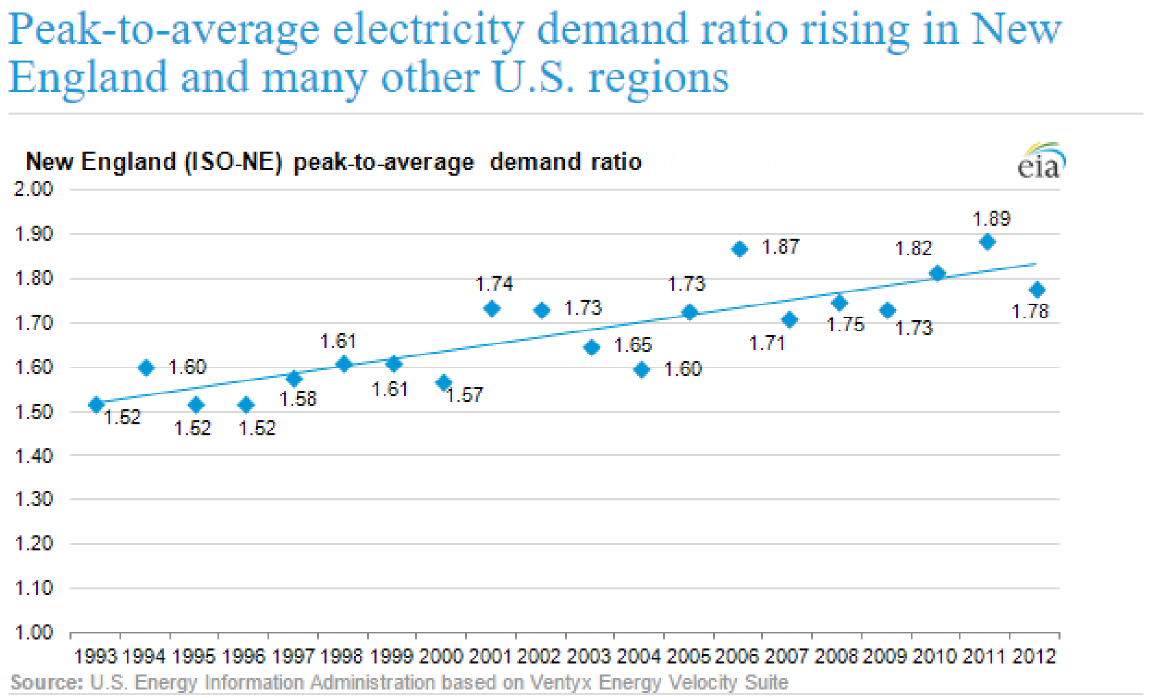


Figure 19: Peak to average load demand in the New England area ("U.S. Energy Information Administration").

The load factor was found for the three ICSD buildings for the past fiscal year (7/1/2014 to 6/30/2015). Ithaca High School, Boynton Middle School, and Fall Creek Elementary School had load factors of 60.96%, 35.20%, and 34.72% respectively. These values show that the ratios for the middle and elementary schools would be greater than the estimated value of 2 used in the team's calculations. However, the 15% buffer should account for these fluctuations.

Capacity calculation:		
Priority users	1026	kW
Non-priority users:	1438	kW
Combined average	2464	kW
Peaking factor	2	
Peak power	4928	kW
Buffer	15%	
Required power	5,668	kW

Figure 20: Capacity calculation.

Quarterly demand capacity for non-priority users and priority users was determined using the average demand per quarter. The Ithaca City School District building was an exception, and the 2014 quarterly demand was used. All other demand values were determined to be 25% of the annual average demand in research.

SYSTEM ARCHITECTURE

CONCEPT SELECTION

After the analysis of the stakeholders and the assessment of their needs, five different concepts for the power production side of the microgrid were generated and one final concept was selected.

1) Solar panels, biogas, and a backup of natural gas. This is the concept currently presented by ICE for the NY Prize application. It contains two renewable resources (solar and biomass) and a more secure, though relatively clean, option (natural gas), which is a very good mix. Furthermore, the waste water plant already owns a bio-digester whose capacity is three times more than the current load.

2) Coal plant. Even if polluting and not particularly suited for a microgrid, a coal power plant was considered among the options mainly because of the very low price of coal.

3) Storage only. This concept considers installing a mix of different types of batteries, flywheels, and possibly a pumped water storage system that will be charged when the microgrid is connected to the national grid and will provide power to the users if disconnected. Therefore, no real power production unit is considered. It is important to note that a storage system is included in all the other concepts, as it is necessary to meet the high frequency variations in the demand. However, in the other concepts the size of the storage will be definitely smaller.

4) Hydroelectric, solar panels, and wind. This concept is entirely based on non-emitting sources. The economics and the availability of power may be compromised by this choice, but emissions need to be considered and this option is worth exploring.

5) Distributed solar panels. In the previous concepts, solar panels were included as part of the central hub, while in this concept the solar panels are not only on the ground surrounding the waste water plant, but also on houses in Ithaca. The PVs installed at the

waste water plant can not meet the entire demand of the North Energy District, but adding more panels can result in a high enough supply of electricity.

Five options are available and many criteria could be used to decide between the choices. Qualitatively, one could think that the first concept is the most feasible and secure, but it may not always be possible to make the best assessment based a qualitative method; hence a quantitative method is used.

The Analytical Hierarchy Process, also known as AHP, is a rigorous method that allows the analyst to decide between different concepts based on multiple criteria without having real estimates of the performance of the concepts in all the criteria. In fact, the AHP is based on pairwise comparison and simply requires comparing each concept to all the other concepts for all the criteria.

The criteria used in the Analytical Hierarchy Process is as follows:

- Availability: this criterion represents the percentage of time the microgrid can supply power over the total time. In emergencies this is particularly important, as without the national grid as a backup there is a need for a stable output of electricity.
- Cost/revenues: Economic feasibility of the project is an important criterion for the stakeholders involved.
- Emissions: given the current attention to climate change and pollution, the emissions of the microgrid plays a significant role. Moreover, the central hub of the grid will be very close to where the local community lives, and they will require a certain standard of environmental sustainability.
- Impact on the landscape: though possibly less important than other criteria, the impact the microgrid will have on the landscape may vary significantly between the different concepts, and will therefore be considered.
- Limitations on maximum capacity: not all sources can produce the same amount of power. This depends mainly on the region (a microgrid in San Diego CA will have more solar energy available than one in Ithaca) for solar, wind and hydropower. Non-renewable sources do not have this problem, so it is important to distinguish between the

concepts based on this parameter. The availability of external supply of the source can be very important and has to be considered.

The AHP confirmed the first impression that the current concept (solar panels, biomass and natural gas) is the most suitable for satisfying the needs of the stakeholders. More details on this method and how it was applied in this study can be found in the appendix.

Problem formulation and enumeration

Once the final concept for the system, in this case the microgrid, has been formalized, the next step in the systems architecture process involves enumerating the different architectures of that system. An architecture can be viewed as a possible configuration that the system can assume.

The enumeration process begins by identifying the main decisions that will affect the system the most. These decisions can be formulated by discerning the main physical forms that will comprise the system (e.g. fuel source, gas turbine, batteries, solar panels, etc.), and studying how they interact and affect each other.

After identifying all the decisions, they can be placed in the form of an array formally known as an architectural array. An architectural array is a mathematical construct, which allows the architect to get all the possible architectures for the system by changing the options for each of the decisions in the array. As an example, consider a system with 3 decisions, each of which has two options: 1 and 0. The architectural array will have three elements each with two options, mathematically represented as [2 2 2]. For this array, any architecture the system can have can be shown by choosing the values of each of the elements or decisions. This system will have 8 possible architectures: 000,100,010,001,110,101,011,111. By coding a system into an architectural array, it is possible to perform many mathematical functions on it, most noteworthy being optimization.

The purpose of enumeration is to understand the possible configurations the system can take and eventually locate the optimal architecture by performing optimization on this architectural array. Enumeration can be achieved in two main ways: partial enumeration or full factorial enumeration. Partial enumeration, as its name suggests, involves enumerating only a part of the total number of possible architectures. This method is useful when the number of architectures is very large (>10^8). The more desirable method of enumeration, full factorial enumeration, involves the enumeration of every possible architecture. While computationally expensive, this method is preferred because unlike partial enumeration, which may leave out possibly optimal architectures, every possible combination is considered.

There are 6 main types of decisions, which are described in more detail in the Appendix. The system being studied only relies on one type: standard form. A standard form decision is one where one option needs to be chosen from a set of N options. Hence, this type of decision can take N possible values; therefore, the total number of possible combinations for a system can be found by identifying all the possible values that each decision can take. In the simplest case, where each of the decisions are independent, i.e. the option selected for one decision will not have any effect on the possible options for any of the others, the total number of architectures can be calculated by multiplying the number of options for each decision. Consider the example of the system with 3 decisions seen earlier. Each decision had two options, and assuming independence, the total number of possible architectures is 2*2*2 = 8.

It is worth noting that due to the multiplicative nature of the calculation, the number of architectures rises very quickly to often unmanageable levels.

Decisions and Options

The main decisions identified for this problem are regarding the technology used, the total size of the grid, and the mix of different sources.

As far as the technologies are concerned, only decisions regarding the gas/biogas technologies were considered. In fact, the team chose to maximize the energy produced by the solar panels a priori. This is for three main reasons:

1. Emissions are a major concern of all the stakeholders and not maximizing the energy produced by this renewable source may have a negative impact on the reputation of this project.

2. There is not much space available for solar panels; therefore their maximization will not have a major impact in terms of total cost of the system.

3. Fixing this parameter reduced the complexity of the model, along with the computational time required to solve the optimization problem.

For the same reasons, the usage of biogas has been maximized. Furthermore, as the waste must be treated anyway it seemed pointless not to use all the biogas generated, especially since it is a carbon net zero process.

Consequently, four options were identified as the most feasible: reciprocating engine, micro-turbine, standard gas turbine, and fuel cells. However, while the first three alternatives are mutually exclusive, it has been decided that the fourth could be combined with one of the first three. This was done because of the inherent differences that exist between the fuel cells and the other options in terms of emissions and costs. Therefore, the following must be decided regarding the gas-fired power production units and their mix:

- Unit used along with the fuel cells, where the options are reciprocating engine, micro-turbine, and standard gas turbine.

- How the energy produced from gas is divided among fuel cells and the unit chosen in the abovementioned decision. This ratio is expressed by the percentage of energy produced by fuel cells out of the total energy produced using biogas and natural gas. It has been decided to split this decision into four decisions, one per quarter of the year, as a good compromise between the complexity of a monthly optimization and the inaccuracy of a yearly optimization.

Eventually, four decisions (one per quarter of the year) were added regarding the energy production. Since it is necessary to meet at least the demand of the priority users, the minimum production of energy per quarter is just enough to meet the priority users demand, while the maximum is the total projected demand of the North Energy District.

Therefore, nine decisions are present and they can be encoded in a 9-entries architectural array. In the table below the decisions, the options and their representations in the array are summarized.

Position in the array	Decision	Number of options	Description
1	Percent of energy produced between the priority users demand and the maximum demand of the NED in quarter 1	11	0=Only priority demand is met 10=All the demand is met
2	Percent of energy produced between the priority users demand and the maxim demand of the NED in quarter 2	11	0=Only priority demand is met 10=All the demand is met
3	Percent of energy produced between the priority users demand and the maxim demand of the NED in quarter 3	11	0=Only priority demand is met 10=All the demand is met
4	Percent of energy produced between the priority users demand and the maxim demand of the NED in quarter 4	11	0=Only priority demand is met 10=All the demand is met
5	Gas power production unit used along with fuel cells	3	0=Reciprocating engine 1=Micro-turbine 2=Standard gas turbine
6	Percent of energy from gas produced by fuel cells in quarter 1	11	0=0% 10=100%
7	Percent of energy from gas produced by fuel cells in quarter 2	11	0=0% 10=100%
8	Percent of energy from gas produced by fuel cells in quarter 3	11	0=0% 10=100%
9	Percent of energy from gas produced by fuel cells in quarter 4	11	0=0% 10=100%

Table 13: Decisions, options, and descriptions for the architectural array.

All the decisions are independent; therefore, the total size of the architectural space is the multiplication of the number of options for each decision.

$$\text{Size of the space} = 11^4 * 3 * 11^4 = 643{,}076{,}643$$

It can be noticed that the architectural space is very large, however, using a Genetic Algorithm it is possible to approximate the optimal solutions fast and very precisely.

TRADESPACE EVALUATION

Once the architectures have been enumerated, a set of metrics needs is used to evaluate the architectures. The metrics need to be chosen such that they are architecturally distinguishable, which means that the value of the metric cannot be the same across all the architectures.

Once the metrics have been determined, a value function needs to be generated such that if one passes the array of a particular architecture through it, the function will give the value of all the metrics for that architecture. The creation of a value function is very important for the optimization function. Once a robust value function has been developed, the architectural tradespace is ready to be optimized.

Generally, the value function and list of architectures are passed through an optimization algorithm, which can generate an optimal set of architectures. There are many different types of algorithms that can perform this optimization. For this particular project, a genetic algorithm was used.

A genetic algorithm (GA) uses evolution as an analogy to pick out the optimal architectures while removing any suboptimal ones. In the GA, the architectural array is considered to be a chromosome, each of the decisions are genes, and the options for the decisions are alleles. As with evolutionary biology, two parent chromosomes are bred to form children with each containing a part of the first and second parent. These chromosomes can undergo random mutations as in genetics.

The whole process starts as an initial population of N architectures. The number of architectures, N, should be greater than or equal to ten times the number of decisions for the optimization to function properly. Then, the factors that determine the ‘fitness’ of an architecture are chosen. This fitness is generally either the maximization (e.g. reliability, or profits) or the minimization (e.g. capital cost, emissions) of the metrics. This fitness is what the algorithm evaluates the architectures on. Once the algorithm has evaluated the architectures based on their fitness, the algorithm first breeds the fittest parents to generate children via a crossover operator. A crossover operator randomly chooses a point in the array where it will break the parent chromosomes and swap the two parts with each other thus creating 2 children. The crossover operator is demonstrated in Figure 21.

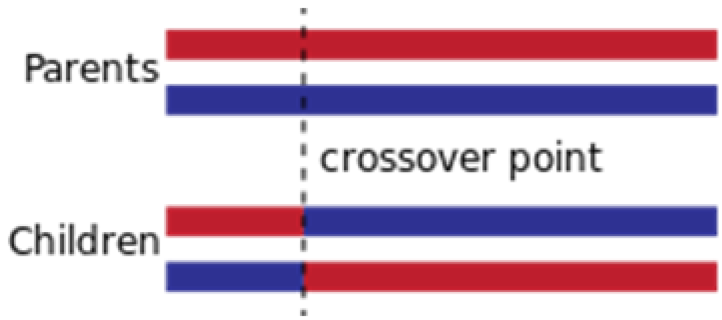


Figure 21: Crossover operator results.

Some of the architectures are mutated slightly in a random fashion. The children then form the second generation and the whole process repeats itself iteratively until the optimal results are obtained. Generally, in a GA the final output will have duplicates as the final set of good architectures are generally less than the initial population. The final set of architectures are those architecture for which no other architecture is better in every metric, i.e. it is better than all the other architectures in at least one metric.

EVALUATION OF METRICS

Three main metrics were identified in order to evaluate the architectures: cost and revenues, CO_2 emissions, and availability. As previously mentioned, having more than one metric leads to a set of optimal non-dominated solutions (the Pareto frontier), as opposed to a single solution.

COST AND REVENUES METRIC

To evaluate the financial aspect of the system, an NPV approach was taken. The main parameters used to compute this metric are shown below, and more details regarding the functions used and how they relate to the architectural array can be found in the Appendix.

- **Initial investment**

The initial investment for the architecture is calculated as the sum of the (fixed) cost of solar panels and the (variable) costs of the gas power production units with the terms in the parenthesis referring to what is variable and what is fixed in the optimization. Since the capacity of solar panels installed is maximized, the cost of the installation is fixed while for the power production units the capacity varies. The investment costs of the storage system was not added as not part of this model.

- **Operational cost and revenues**

The operational costs were calculated by summing the yearly costs of the gas-fired power production units and the solar panels. Once again, as the amount of energy produced by solar panels is fixed, their operational cost will be fixed as well while those of the gas units will change depending on the percentage of fuel cells used and on the total production. Clearly, the operational costs for the gas units include both the cost of the fuel and the operation and maintenance cost.

As far as revenue is concerned, any electricity not purchased from the national grid was considered revenue. This definition of revenue was reached, as the money would remain within the community as a whole, whether it be it the end users in the local community or the operators of the microgrid. Therefore, the yearly savings will be computed as the average cost of electricity in Ithaca into the total production of electricity per year.

- **Demand Model**

All the aforementioned metrics depend strongly on the intensity of the demand; two different approaches were taken. First, a constant demand over a 20-year timespan was assumed, then a stochastic demand model. The latter is a binomial model where each year the demand has a probability of 0.9 of increasing by 5% and a probability of 0.1 of decreasing by 1%. Then a Monte Carlo simulation is used to calculate the expected metric over the timespan. This is a more realistic model, but it increases the complexity of the evaluation function. Therefore, it was possible to use this model only over a timespan of five years and it was decided that only the results from the first model be discussed in this report.

- **Timespan**

  The lifespan of the project was taken as 20 years.

- **Discount rate**

  Given that this project will be mainly funded by the state, a discount rate of 7% has been assumed.

Emissions

Emissions were calculated in a very similar way to the operational costs. However, the system actually starts to emit only if it is producing more energy than that provided by the solar panels (which are completely non-emitting) and needs more fuel than the available biogas (whose carbon emissions follow the cycle of the carbon, and are therefore not considered as a new input of greenhouse gases).

Availability

Availability is defined as the time between failure of the system divided by the sum of the time to failure and the time to repair, and it depends exclusively on the technology used. To avoid unnecessary complexity in the model, only the availabilities of the gas units are considered as they are what differentiates the availability of one architecture from another. Therefore, even if the actual number will not be exact, it will allow a comparison between the architectures.

Furthermore, for some components not included in this model, like the control system, it was almost impossible to find studies regarding the availability, making every estimate very inaccurate.

Therefore, the availability for each architecture is a simple multiplication of the availabilities of the gas units. If all the energy is produced by only one unit (for instance, only fuel cells or only micro-turbine), then the availability is simply the availability of that unit.

Outcome of Genetic Algorithm

The genetic algorithm was performed for a group of 150 architectures; a more in depth analysis of the structure of the genetic algorithm is discussed in the Appendix.

The final output of the genetic algorithm gave a set of 60 architectures that were non-dominated. While the set of 60 architectures is a very large set of optimal architectures, the set was analyzed to make a note of any "good" patterns that emerged by sorting the metrics in order of fitness. This analysis was done for each of the metrics: net present value, total emissions, and availability, and recommendations were made for the final design of the microgrid.

Before exploring the architectures, the decisions and their meanings should be reviewed. The first 4 decisions have to do with the amount of production per quarter. Each of the 4 decisions have 10 options, 0 to 9.0 represents the minimum production, which equals the demand for the priority users (2MW), and 9 represents the demand for the entire north energy district (6MW). Each option represents an increase of 0.4 MW over the previous option. The 5th decision has to do with the type of engine used. There are 3 option for this decision: 0 = reciprocating engine, 1 = micro-turbine, and 2 = Gas turbine. The final 4 decisions represent the amount of fuel cells used for production in each of the 4 quarters: 0 = 0% fuels cells, and 10 = 100% fuel cells.

The following are the architectures that optimize each one of the metrics:

Net present value	Emissions	Availability
10 10 10 10 2 0 0 0 0	0 0 0 0 0 10 10 10 10	0 0 0 0 0 0 0 0 0

Table 14: Optimized architectures for net present value, emissions, and availability.

For the architecture that optimizes net present value, the maximum achievable NPV was found to be about $13.2 million at the end of the timespan of the project. As can be noted from referring to the architecture noted in the table above, the quarterly output is maximizing to 6MW where gas turbines are used and fuel cells are minimized. These three patterns persist for the top ten architectures optimizing NPV. This fact was considered when the final recommendations were being made.

The architecture that optimizes (minimizes) total emissions, as seen in the table, minimizes the amount of production to 2MW and maximizes the amount of fuel cells. It was found that even the cleanest architectures, which minimize the production to the level needed to supply only the priority users, would produce at least 1,500 tons of CO_2 over its entire lifecycle. It was also noted that the architectures that excelled in minimizing emissions had two characteristics: they maximized the use of fuel cells, which produce very low emissions, and they minimize production per quarter to just the amount needed to provide for the priority users. The second is in direct contradiction of the architectures maximizing NPV, which is to be expected.

Finally when considering architectures that maximize availability, the architecture that minimized production used a reciprocating engine and minimized fuel cells. This is logical as reciprocating engines were found to be the most reliable drivers, thus architectures containing them had availability of about 97.3%. It should be noted that this final number is only the availability of the part that is being optimized; the rest of the system has other components whose availability will affect the availability of the entire system.

Final recommendation

Besides the previously mentioned suggested architectures, some general conclusions can be inferred from the results of the algorithm. All the architectures that had high results in the three metrics showed these common features:

- All the architectures with high NPV values always met the demand of the whole North Energy District. This means that the installed capacity should be around 6 MW, as shown in the MS Excel model.

- As far as emissions are concerned, the best solution is to produce only as much energy as the priority users need since the more energy is produced the more CO_2 is emitted. However, a way to reduce emissions but still keep production high is to maximize the energy produced by fuel cells. This seems to be a good balance between minimal production with low emissions and high production with high NPV.

- The architectures with the highest availability proved to be those using the reciprocating engine. As a consequence, it can be seen that there is a tradeoff between availability and emissions.

Note that the model is very sensitive to input data, therefore the three suggested architectures might change with improved data. However, the good features shown by the optimal architectures are not likely to change and should be used as guidelines for the design of the microgrid.

Spreadsheet Model

After gathering research on technologies that could potentially be included in the Ithaca microgrid, a spreadsheet model of the involved costs was constructed based on several assumptions. First, a discount rate of 7% was assumed for each of the technologies. Second, a price of $2.51 per mcf of natural gas was decided upon. This price reflects currently low prices in the natural gas market driven by plentiful supply; prices fell by nearly 50% in the 2009-2012 period, and if the supply were to tighten in the future they might rise again. Finally, no government incentives were assumed, which means that the total cost of the microgrid will be less expensive than the figures presented with the addition of any federal or state subsidies.

Based on their feasibly and costs, the technologies of biogas, solar, CHP, and fuel cells were chosen to be included in the spreadsheet model. Capacity factors, efficiency, availability, capital costs, operating costs, and emission rates for each of the technologies were all considered in the model. For the core of the microgrid, the cost of a microgrid control system and energy storage were included as well.

Three scenarios were considered in the model, and each differs on whether or not CHP and fuel cells are included. These two decision variables greatly affect the performance metrics of costs and emissions.

The amount of solar PV was set at a fixed rate as the number of panels was limited to the available ground area around the IAWWTF. Biogas capacity was set at three times the current capacity based on predicted figures. The biogas produced from the IAWWTF will also be used by the fuel cells to reduce the use of natural gas. Next, an appropriate capacity of fuel cells was selected based on the demand. Depending on the scenario, the remaining amount of demand that needs to be covered will be produced by CHP steam turbines.

	Scenarios		
	No Fuel Cells (1)	CHP & Fuel Cells (2)	No CHP (3)
Solar Production %	11.43%	11.43%	9.57%
Biogas Production %	10.17%	-	-

CHP Production %	78.40%	34.60%	-
Fuel Cell Production %	-	53.97%	90.43%
Annual Production (kWh)	21,586,280	21,586,280	25,768,393
Annual cost (Mil.$)	$3.34	$3.40	$3.67
LCOE per kWh	$ 0.1545	$ 0.1575	$ 0.1425
Annual Emissions (kg CO_2)	9,468,710	6,389,590	5,018,976

Table 15: Three spreadsheet scenario figures.

The fuel cell's capacity was constrained as the fuel cell stacks come in discrete amounts with each of the modules from Fuel Cell Energy. A DFC1500 module was used for the CHP and fuel cells scenario, and a DFC3000 module was used for the scenario that excludes CHP. As a result, an extra 18% of electricity is produced in this scenario causing extra emissions.

Although not shown in Table 15, the scenarios could be extended by adding a storage capacity of 2.5 MWh as discussed above. This addition would entail $150,000 per year of additional costs, or approximately 4 to 5% on top of the annual cost figures shown.

Recommendation and Future Work

Of the three scenarios, the third with just fuel cells is the best having both the lowest LCOE and annual emissions at about 14 cents/kWh and 5 million kg CO_2 emissions. In addition, these metrics produce 18% more electricity than the average required demand, given the discrete amount of fuel cell capacity that can be purchased. Based on the team's calculations, the following amounts of capacity for each of the technologies are recommended.

Technology	Installed Capacity (kW)
Solar	2,000
Biogas	780
Fuel Cells	2,800

Table 16: Recommended installed capacity of each technology for Scenario 3.

Using this model, each of the input parameters can be adjusted with changes in the assumptions and data. As time goes on and more current and accurate figures are collected, the model can be easily adjusted. A more accurate demand model and forecasting can add a more dynamic component of the model with regards to seasonal and even hourly fluctuations in demand. The usage of solar and energy storage would be adjusted the most to accommodate while production of electricity from the fuel cells can be limited. Overall, this model serves to produce a general idea of the costs of the microgrid as well as how much power each technology is contributing. This information can be used to inform what investments are needed and how much economic benefit can be obtained from the microgrid.

Other future work that can be done includes the adaptation of this model for the South Energy District. While those demand figures and energy inputs are still unpredictable at this point, the similar technologies can still be considered and this existing model can be used with some changes.

APPENDIX

MICROGRID CONTROL SYSTEM DECISION MATRIX

	Value								Final Score					
Attributes	Siemans Microgrid Control (Basic)	Siemans Microgrid Control (Advanced)	ABB Renewable Microgrid Controller	Grid IQ Microgrid Control System (GE)	SEL Microgrid Control Systems	Spirae BlueFin Microgrid Control Strategy	**Min Value**	**Weight**	Siemans Microgrid Control (Basic)	Siemans Microgrid Control (Advanced)	ABB Renewable Microgrid Controller	Grid IQ Microgrid Control System (GE)	SEL Microgrid Control Systems	Spirae BlueFin Microgrid Control Strategy
Local Control	2	2	3	3	2	3	3	5	10	10	15	15	10	15
Island Mode	3	3	3	3	3	3	3	5	15	15	15	15	15	15
Weather forecasting	3	3	1	3	1	2		2	6	6	2	6	2	4
Load forecast	1	3	1	3	1	2		3	3	9	3	9	3	6
Turn Key (ready when purchased)	1	1	3	1	1	2		1	1	1	3	1	1	2
Forecasting renewable generation	3	3	1	3	1	2		3	9	9	3	9	3	6
Scalable	2	3	3	2	3	2		3	6	9	9	6	9	6
Score Totals	**15**	**18**	**15**	**18**	**12**	**16**			**50**	**59**	**50**	**61**	**43**	**54**

Table 17: Microgrid control system decision matrix, for further detail please refer to Excel attachment.

ANALYTICAL HIERARCHY PROCESS

DESCRIPTION OF THE PROCESS

The Analytical Hierarchy Process, developed by Saaty in the 1970s, is a process used for complex decision-making when multiple criteria are relevant to the decision. It is based on a pairwise comparison.

A basic outline of the process is as follows:

1. List all the alternatives and the criteria to make the decision.
2. Compute relative weights for the criteria.
3. Compute relative scores for each alternative in each criterion.
4. Compute the total score of each alternative as a weighted sum.
5. Check the consistency of the process.
6. Choose the best alternative.

The pairwise comparisons (both for the criteria and for the alternatives) are developed by building a comparison matrix, as shown below.

Alternative A1   *Alternative A2*   *Alternative A3*

Alternative A1	a_{11}	a_{12}	a_{13}
Alternative A2	a_{21}	a_{22}	a_{23}
Alternative A3	a_{31}	a_{32}	a_{33}

Table 18: Comparison matrix.

a_{ij} represents the relative importance of AlternativeA_i (rows) over AlternativeA_j (columns). It is important to note that the comparison matrix must be reciprocal:

- $a_{ii}=1\ \forall i$
- $a_{ij}=\frac{1}{aji}\ \forall i,j$

As far as the scale is concerned, the values range from 1/9 to 9. The meaning of the scale values is shown in the table below; values from 1/9 to 1 mean that the opposite comparison has the reciprocal value.

The Fundamental Scale for Pairwise Comparisons		
Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
Intensities of 2, 4, 6, and 8 can be used to express intermediate values. Intensities 1.1, 1.2, 1.3, etc. can be used for elements that are very close in importance.		

Table 19: Scale for pairwise comparison.

Once the comparison matrix has been built, it can be shown that the normalized principal eigenvector of the matrix approximates the weights of the alternatives. [See Thomas L. Saaty, Decision-making with the AHP: Why is the principal eigenvector necessary, European Journal of Operational Research, 145 (1), 2003, pp 85-91]. This can be easily done using any engineering tool (e.g. for this report MATLAB has been used; WolframAlpha can also be used).

The next to last step of the process is to compute the total score of each alternative. Let w_i be the weights of the criteria and a_{ij} be the scores for each alternative on each criterion. Then the total scores S_j are:

$$S_j = \sum_{i=1}^{\#criteria} w_i s_{ij} \quad j = 1,2, \dots \#alternatives$$

Before selecting the best alternative it is necessary to control if, in the pairwise comparison, the consistency has been respected. This means that if, for instance, in a certain criterion A_1 was rated better than A_2 and A_2 better than A_3, then A_1 should be rated better than A_3. It is possible to do this control following these steps:

- Compute the principal eigenvalue λ_{max}.
- Define the consistency index CI=(λ_{max}-n)/(n-1) where n is the number of alternatives.
- Normalize the index to take into account that higher n naturally led to higher inconsistency. CR=CI/RI, where RI depends on n following this table.

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0.58	0.9	1.12	1.24	1.41	1.45	1.45	1.49

- If CR>0.1, the comparison matrix is inconsistent; therefore it is necessary to repeat the creation of that matrix.

After this control, the best alternative can be chosen.

The comparison matrix for the criteria and the alternatives for this project are shown below.

Criteria						**Score**
	Availability	Cost	Emissions	Impact landscape	Limitations max power	
Availability	1	3	5	5	9	0.5161

Cost	0.333333333	1	0.5	5	3	0.1636
Emissions	0.2	2	1	6	3	0.2118
Impact on landscape	0.2	0.2	0.166666667	1	2	0.0604
Limitations on max power	0.111111111	0.3333333	0.333333333	0.5	1	0.0481
CR	0.0950					

Availability						**Score**
	Nat gas + PV + biogas	Coal	Storage only	Hydro + PV + Wind	Distributed PV	
Nat gas + PV + biogas	1	1	5	9	9	0.4015
Coal	1	1	5	9	9	0.4015
Storage only	0.2	0.2	1	5	5	0.1249
Hydro + PV + Wind	0.111111111	0.111111	0.2	1	1	0.0360
Distributed PV	0.111111111	0.111111	0.20	1	1	0.0360
CR	0.0380					

Cost						**Score**
	Nat gas + PV + biogas	Coal	Storage only	Hydro + PV + Wind	Distributed PV	
Nat gas + PV + biogas	1	4	6	2	3	0.4597
Coal	0.25	1	1	2	0.5	0.1342
Storage only	0.166666667	1	1	1	1	0.1166
Hydro + PV + Wind	0.5	0.5	1	1	1	0.1329
Distributed PV	0.333333333	2	1	1	1	0.1565
CR	0.0645					

Emissions						**Score**
	Nat gas + PV + biogas	Coal	Storage only	Hydro + PV + Wind	Distributed PV	

Nat gas + PV + biogas	1	5	0.2	0.2	0.2	0.0770
Coal	0.2	1	0.111111111	0.111111111	0.111111111	0.0278
Storage only	5	9	1	1	1	0.2984
Hydro + PV + Wind	5	9	1	1	1	0.2984
Distributed PV	5	9	1	1	1	0.2984
CR	0.0290					

Impact on landscape						**Score**
	Nat gas + PV + biogas	Coal	Storage only	Hydro + PV + Wind	Distributed PV	
Nat gas + PV + biogas	1	6	0.5	5	1	0.2340
Coal	0.166666667	1	0.111111111	0.5	0.2	0.0379
Storage only	2	9	1	9	5	0.5124
Hydro + PV + Wind	0.2	2	0.111111111	1	1	0.0750
Distributed PV	1	5	0.2	1	1	0.1407
CR	0.0600					

Limitations on maximum power						**Score**
	Nat gas + PV + biogas	Coal	Storage only	Hydro + PV + Wind	Distributed PV	
Nat gas + PV + biogas	1	1	4	9	9	0.4014

Coal	1	1	4	9	9	0.4014
Storage only	0.25	0.25	1	3	3	0.1130
Hydro + PV + Wind	0.111111111	0.111111111	0.333333333	1	1	0.0421
Distributed PV	0.111111111	0.111111111	0.333333333	1	1	0.0421
CR	0.0030					

It can be noted that all the comparison matrices respect the consistency condition (CR<0.1). Therefore, the total scores for all the concepts can be computed:

CONCEPT	**SCORE**
NAT GAS + PV + BIOGAS	0.3322
COAL	0.2567
STORAGE ONLY	0.1831
HYDRO + PV + WIND	0.1101
DISTRIBUTED PV	0.1179

Since the score of the first option is the highest it can be considered to be the superior option based on the criteria that have been selected for this analysis.

Decisions

There are 6 canonical classes of decisions:

1. Standard form
2. Down selecting

3. Assigning

4. Permuting

5. Partitioning

6. Connecting

Each type of decision will be considered, and the number of possible combinations of that decision using N elements will be identified.

1. Standard form decision: A standard form decision is the simplest type of decision. One option needs to be chosen for a set of N options. Hence, the number of possible combinations of this decision = N, the number of options.

2. Downselecting decision: A downselecting decision generally involves a yes-no type of decision. If there are N elements for a downselecting decision, each of them can be chosen or not. As an example, consider one is making a sandwich. For the filling there are three options: turkey, ham or bacon. Each of the options can be chosen to be included in the sandwich or not. This is a downselecting decision. This type of decision can be visualized in Figure 22, where the circles are elements, the red box is no, and the green box is yes. The total number of possible combinations of this type of decision = 2^N, where N = number of elements for the decision.

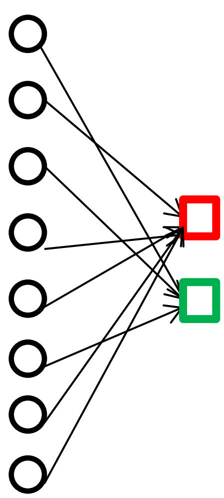


Figure 22: Downselecting decision schematic.

3. Assigning decisions: An assigning decision is a decision when there are N elements from one set, which have to be assigned to M elements from another set. A better way of understanding this is to consider a team of N people who have to complete a set of M tasks. Each of the N people can be assigned to perform any or all of the M tasks. Similarly, there can be more than one person assigned to each task. This type of decision can be visualized by viewing Figure 23. In this figure, the circles are the elements in the left set (people) & the squares are the elements in the right set (tasks). For an Assigning decision with two sets of M & N elements, the total number of options $= 2^{MN}$.

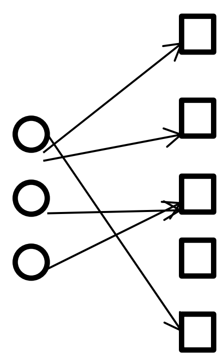


Figure 23: Assigning decisions schematic.

4. Permuting decisions: Permutation has to do with order. A permuting decision is about the number of ways a set of elements can be ordered. Consider 5 people have to enter the room, and only one can enter at a time. This is a simple permuting decision. The number of different values for this decision is given by N!

5. Partitioning decision: This decision deals with how a set of N options can be placed into different teams or partitions. Consider a class of N people that has to be split up into teams containing at least 1 person. Hence, at the two extremes will be 1 team with N people and on the other N teams with 1 person each. The total number of possible ways of partitioning N people into teams is given by a special class of numbers called Bell numbers. Charts to determine these bell numbers can be found online.

6. Connecting decision: A connecting decision, as the name suggests, deals with the number of ways a set of N elements can be connected to each other. Consider a network of N

computers. The computers can be connected to all or at least one to remain in the system. The configurations this network can take are called connecting decisions. Given a set of N elements, the number of values for this type of decision is given by: $2^{\frac{N(N-m)}{k}}, k = \{1,2\}$ depending on whether connections are directed or not, and $m = \{0,1\}$ depending on whether self-connections are allowed or not.

EVALUATION METRICS

The following procedure was followed to compute the costs and revenues:

- The production of electricity per quarter is calculated as the percentage of maximum demand per quarter (expressed in the first four positions of the architectural array).
- The electricity generated using gas is computed as the difference between the electricity produced and the production of solar panels per quarter.
- The cost of the fuel per year is computed as the electricity generated using gas into the cost of the fuel per kWh (if the production is greater than the available biogas, a backup of natural gas will be used).
- The energy produced by gas is split between fuel cells and the other power production unit depending on the decisions in the last four positions of the array. Then the operation and maintenance cost are calculated for both the technologies.
- The yearly costs are the sum of the fuel cost, operation and maintenance costs, and yearly costs of solar panels.
- The yearly revenue is the yearly total production into the cost of electricity.
- The investment is the sum of the capital costs of solar panels and those of the gas fired power production units (which are total production divided by 8760*the capacity factor).

The yearly costs and revenues are computed once per year and then discounted, while the investment is calculated only for the first year. These calculations can be found in the MATLAB function cost.m.

Emissions were calculated exactly like the cost of fuel, taking into account that the emissions of biogas can be considered equal to 0. The calculation of the emissions can be found in the MATLAB function emissions.m.

GENETIC ALGORITHM PARAMETERS

An initial population of 150 architectures was generated as a mix of 6 reference architectures and 144 randomly generated architectures. The reference architectures were chosen to sample the extreme points of the space where good architectures often occur. In the MATLAB function used (mycreationfunc.m) it is also possible to add some deterministically sampled architectures, generated using Orthogonal Arrays. The algorithm was run both with and without those architectures, but as the changes in the result were negligible, it was decided not to include them to improve the readability of the code.

In order to create the next generation, some options have to be set.

- Elite count: the number of elite children that will survive in the next generation. Those are the architectures with the highest fitness in the population and will go into the next generation without changes. The standard MATLAB option has been used, which means that the number of elite children is 2 per iteration.

- Crossover fraction: the percentage of the population (excluding the elite children that were already selected) that will be bred. The standard option has been used, which is 80%. Note that the architectures undergoing the crossover are, once again, selected based on fitness.

The remaining architectures will undergo the mutation.

The algorithm uses the fitness function to rank the architectures based on their metric, and it then chooses the elite children and the crossover population. This function is simply calculating the metrics per architecture and then storing the scores in an array. As shown in the function attached (myfitnessfunc.m), NPV and availability are stored in the array as –NPV and –availability. This was done because the algorithm attempts to minimize the metrics, while NPV and availability must be maximized.

A single point crossover has been used. Therefore the function simply spits the two parents and combines the first section of the first parent with the second section of the second parent and vice-versa.

As far as the crossover point is concerned, this is chosen randomly taking a sample out of a uniform distribution. If the building blocks were known a priori it would be possible to bias the selection in order not to split them; however, since they are unknown, randomly choosing the crossover point is a safe choice. The function is attached, called “myxoverfunc.m”.

The main goal of the mutation function is to introduce a small mutation in the architecture. Therefore, in “mymutationfunc.m” each entry of the array has a probability of 10% to be mutated. This is basically ensuring that at least one bit will be mutated, while keeping the probability that too many bits will be mutated very low.

The number of generations, which means how many iterations the algorithm will perform, was not set a priori. In fact, Matlab implementation of the genetic algorithm has a series of controls to understand when the optimal set is reached. These controls are based on how much an iteration is different from the previous ones and, if the difference is lower than a threshold, they make the algorithm stop. The difference between the generations is represented by different parameters, such as the difference in fitness (which means how good a generation is) and in Pareto spread (which means how diverse in terms of metrics a generation is). It was decided to use the standard options for these controls, which lead to 104 generations.

MATLAB FUNCTIONS

The MATLAB functions mentioned in the report are included here as a reference.

Cost.m

```
%% cost function 4 Ithaca microgrid, by Walter Paleari 11/26/2015
% cost function, computes the NPV of the power production side of the grid
% storage, transimission and control system excluded
% NO UNCERTAIN DEMAND

function NPV=cost(arch, I, year_cost, op_cost, fuel_cost, max_demand, ...
    priority_demand, peak_factor, buffer, CF, solar_prod_per_qt, solar_I, ...
    solar_year_cost, max_biogas, el_price, discount_rate)

%first the operating/yearly cost and investement are calculated for what is
```

```
%variable, then the cost of solar is added

total_production_per_qt=priority_demand+(max_demand-priority_demand).*(...
    (arch(1:4))/10)';
variable_production_per_qt=total_production_per_qt-solar_prod_per_qt;

fuel_cell_percent=(arch(6:9))/10;
fuel_cell_production=variable_production_per_qt.*fuel_cell_percent';
combustion_production=variable_production_per_qt-fuel_cell_production;

fuel_cell_year_production=sum(fuel_cell_production);
combustion_year_production=sum(combustion_production);
fuel_cell_year_cost=year_cost(4)+fuel_cell_year_production*op_cost(4);
combustion_year_cost=year_cost(arch(5)+1)+combustion_year_production*...
    op_cost(arch(5)+1);

variable_production=sum(variable_production_per_qt);
% solar_production=sum(solar_production_per_qt);
if variable_production<=max_biogas
    fuel_year_cost=variable_production*fuel_cost(1);
else
    fuel_year_cost=max_biogas*fuel_cost(1)+(variable_production-max_biogas)...
        *fuel_cost(2);
end


total_year_cost=sum([fuel_cell_year_cost, combustion_year_cost, ...
    fuel_year_cost, solar_year_cost]);

total_production=sum(total_production_per_qt);
total_year_revenues=total_production*el_price;

fuel_cell_capacity_per_qt=fuel_cell_production/(CF(4)*2190);
combustion_capacity_per_qt=combustion_production/(CF(arch(5)+1)*2190);

fuel_cell_capacity=max(fuel_cell_capacity_per_qt)*buffer*peak_factor;
combustion_capacity=max(combustion_capacity_per_qt)*buffer*peak_factor;


investment=solar_I+fuel_cell_capacity*I(4)+combustion_capacity*I(arch(5)+1);
cash_flow=total_year_revenues-total_year_cost;
k=discount_rate;
NPV=-investment;
for t=1:20
    NPV=NPV+cash_flow/(t^k);
end

end
```

emissions.m

```
%% emissions function 4 Ithaca microgrid by Walter Paleari 11/26/2015
% computes the emissions of one arch in gCO2
% NO UNCERTAIN DEMAND

function emissions=emissions(arch, operating_emissions, max_demand,...
    priority_demand, solar_prod_per_qt, max_biogas)

total_production_per_qt=priority_demand+(max_demand-priority_demand).*(...
    (arch(1:4))/10)';
variable_production_per_qt=total_production_per_qt-solar_prod_per_qt;

fuel_cell_percent=(arch(6:9))/10;
fuel_cell_production=variable_production_per_qt.*fuel_cell_percent';
combustion_production=variable_production_per_qt-fuel_cell_production;

fuel_cell_year_production=sum(fuel_cell_production);
combustion_year_production=sum(combustion_production);

variable_production=sum(variable_production_per_qt);
if variable_production<=max_biogas
    emissions=0;
else
    emissions=fuel_cell_year_production*operating_emissions(4)+...
        combustion_year_production*operating_emissions(arch(5)+1);
end

end
```

availability_func.m

```
%% availability function 4 Ithaca microgrid by Walter Paleari 11/26/2015
% computes availability for one architecure

function availability=availability_func(arch)

av_vector=[0.97297
    0.89285
    0.92336];

if sum(arch(6:9))==0
    availability=av_vector(arch(5)+1);

elseif sum(arch(6:9))==40
    availability=0.95;

else
    availability=av_vector(arch(5)+1)*0.95;
```

```
end

end
```

myfitnessfunc.m

```
%% fitness function by Walter Paleari 12/11/15
% calcuates the metrics for 1 architecture and creates a
% vector with them
%NEED TO REDO THE load_parameters function!!!

function fitness=myfitnessfunc(arch)

 [I, year_cost, op_cost, op_emissions, fuel_cost, max_demand,...
    priority_demand, peak_factor, buffer, CF, solar_prod_per_qt,...
    solar_I, solar_year_cost, max_biogas, el_price, discount_rate,...
    cdf, max_paths, priority_paths, Nsample]=load_parameters(1);

% [npv,req,emissions]=level1(arch, I, year_cost, op_cost,...
%     op_emissions, fuel_cost, max_demand, priority_demand, peak_factor,...
%     buffer, CF, solar_prod_per_qt, solar_I, solar_year_cost, max_biogas,...
%     el_price, discount_rate, cdf, max_paths,...
%     priority_paths, Nsample, samples_max, samples_priority);

availability=availability_func(arch);

% fitness=[-npv, req, emissions, -availability];
 npv=cost(arch, I, year_cost, op_cost, fuel_cost, max_demand, ...
    priority_demand, peak_factor, buffer, CF, solar_prod_per_qt, solar_I, ...
    solar_year_cost, max_biogas, el_price, discount_rate);

em=emissions(arch, op_emissions, max_demand,...
    priority_demand, solar_prod_per_qt, max_biogas);

fitness=[-npv, em, -availability];
end
```

mycreationfunc.m

```
%% creation operator by Walter Paleari 12/11/15
% Inputs are:
        % nvars: not used
        % FitnessFcn: not used
        % options: not used
% Output is a matrix with the randomly generated architectures
% As a first draft the initial population will be created as a random
% population of 100 individuals
```

```
% enum_random_standardform is used, maybe fullfact and then a random
% selection will be faster

function [ancestors]=mycreationfunc(Genomelength, FitnessFcn, options)

vec_num_options=[11 11 11 11 3 11 11 11 11];
Ninitialpop=150;

reference=[10 10 10 10 0 10 10 10 10
    0 0 0 0 0 10 10 10 10
    5 5 5 5 0 10 10 10 10
    10 10 10 10 0 0 0 0 0
    0 0 0 0 1 0 0 0 0
    5 5 5 5 2 0 0 0 0];

OA=[];

deterministic=[reference; OA];

Nrandom=Ninitialpop-size(deterministic,1);
random=enum_random_standardform(vec_num_options,Nrandom);
ancestors=[reference; random];

norep=false;
while norep==false
    ancestors=unique(ancestors,'rows');
    if size(ancestors,1)<Ninitialpop
        random=enum_random_standardform(vec_num_options,Nrandom);
        ancestors=[reference; random];
    else
        norep=true;
    end
end

end
```

myxoverfunc.m

```
%% crossover operator by Walter Paleari 12/11/15
% inputs are:
        %who_are_the_parents: vector (logical?) which says which parents have
been
        %chosen by the selection function
        %options: not used
        %nvars: number of decisions
        %FitnessFcn: not used
        %unused: not used (???)
        %thisPopulation: the whole population at that generation, which
```

```
        %means that thisPopulation(parents,:) is the matrix with the
        %parents
% single point crossover
% the point is selected randomly with a uniform probability distribution
% outputs is a matrix with the children
% ONLY WORKS IF NPARENTS IS EVEN (hopefully the algorithm will take care of
% that, but who knows)

function children=myxoverfunc(who_are_the_parents, options, nvars, FitnessFcn,
unused, thisPopulation)

parents=thisPopulation(who_are_the_parents,:);
[Nparents, Ndecisions]=size(parents);
children=zeros(Nparents, Ndecisions); %children matrix is preallocated
                                      %Nparents=Nchildren
parents_index=1; %it goes through all the parents
children_index=1; %it goes through all the children

for i=1:Nparents/2
    %select the parents
    parent1=parents(parents_index,:);
    parents_index=parents_index+1;

    parent2=parents(parents_index,:);
    parents_index=parents_index+1;

    %the point of crossover is randomly selected
    crossover_point=ceil(rand *(Ndecisions-1)); %the actual points of
crossover are Ndecisions-1, crossover is AFTER this point

    %the children come into the world
    child1=[parent1(1:crossover_point) parent2((crossover_point+1):end)];
    child2=[parent2(1:crossover_point) parent1((crossover_point+1):end)];

    %children are stored in the matrix of the new generation
    children_index=2*i;
    children(children_index,:)=child1;
    children(children_index-1,:)=child2;

end
```

mymutationfunc.m

```
%% mutation operator by Walter Paleari 12/11/15
%Inputs are:
        %parents: vector (logical?) which says which parents have been
        %chosen by the selection function for the mutation
        %options: not used
```

```
        %nvars: number of decisions
        %FitnessFcn: not used
        %state: not used (no idea what this is)
        %thisScore: not used
        %thisPopulation: the whole population at that generation, which
        %means that thisPopulation(parents,:) is the matrix with the
        %humans
%outputs is a matrix with the mutants (Nmutants=Nhumans)
%the mutation probability is the probability each single bit is mutated
%given that this subset of the population is expressely selected to be
%mutated the mutation probability will be pretty high (~.1)

function mutants=mymutationfunc(who_are_the_humans,options, nvars, FitnessFcn,
state, thisScore, thisPopulation)

max_values=[10 10 10 10 2 10 10 10 10]; %the max_values the mutants can have
is set

humans=thisPopulation(who_are_the_humans,:); %the matrix with the humans is
set
[Nhumans, Ndecisions]=size(humans);
mutants=humans; %don't know why it might be helpful to keep the humans
p=0.1; %probability of mutation of a single bit


%first loop goes through all the humans
for i=1:Nhumans

    %second loop goes through the decisions in each human
    for j=1:Ndecisions

        %we see if that entry will be mutated
        dice=rand;
        if dice<=p
            mutants(i,j)=randi([0 max_values(j)],1,1);
        end

    end

end

end
```

SPREADSHEET MODEL

Assumptions:

1. 5 priority users as discussed earlier.

2. Non-priority users equivalent to 1,000 households at 5,000 kWh per year.

3. Peak load is 2 times the average load.

4. IAWWTF uses 4 MkWh per year, but can generate 6 MKWh per year total (assuming 3x the current load; net is available for grid).

5. For simplicity ignore solar PV.

6. Assume that biogas fuel cost is $0 because sludge disposal is paid for with tipping fees (net neutral).

Demand and Capacity:

Data

Priority users	kWh/y	kW
Ithaca HS	3,193,155	365
Boynton MS	1,065,692	122
Fall Creek	187,033	21
Ithaca Housing projects	530,000	61
IAWWTF	4,010,400	458
Total	8,986,280	1026

Non-priority users	kWh/y	kW
Unit amount	7,500	0.86
Number of units	1,680	1680
Total amount	12,600,000	1438

Capacity Calculation

Average power:		
Priority users	1026	kW
Non-priority users:	1438	kW
Combined average	2464	kW
Peaking factor	2	
Peak power	4928	kW
Buffer	15%	
Required power	5,668	kW

No fuel cell scenario:

Biogas Energy Production

	kWh/y	kW
IAWWTF demand	4,010,400	458
Availability	91%	
Supply	6,205,584	780.1762115
Net supply to microgrid	2,195,184	322
Required power		2,464
Net after removing biomass		2,142
Total Operating Cost, $/yr	$ 402,409.88	

Control System Cost

Total Capital Cost	$ 1,000,000.00
Annual Capital Cost	$ 94,392.93

CHP

	Capital Cost ($/kW)	Operating Cost ($/kWh)	Emissions (kg/yr)
Reciprocating Engine	$ 1,150.00	$ 0.021	7,995,500
Microturbine	$ 1,000.00	$ 0.017	9,333,037
Gas Turbine	$ 2,250.00	$ 0.011	23,109,669

	Annual Capital Cost	Annual Operating Cost	Total Annual Cost
Reciprocating Engine	$806,623.05	$ 1,366,962.93	$ 2,173,585.98
Microturbine	$ 701,411.34	$ 1,106,589.04	$ 1,808,000.39
Gas Turbine	$1,578,175.52	$ 716,028.20	$ 2,294,203.73

Solar Energy

Installed Capacity, kW	2,000
Capital Cost, $/kW	$ 2,200.00
Total Capital Cost	$ 4,400,000.00
Interest Rate	7%
System Lifetime, yr	25
Annual Capital Cost	$ 377,566.28
Operating cost, $/kW/yr	$ 20.00
Total Operating Cost, $/yr	$ 40,000.00
Annual Production, kWh	2,466,793
LCOE, $/kWh	$ 0.1693

Note: No incentives are assumed

Total Cost Calculation

Total demand (kWh)	21,586,280	21,586,280
Electricity from plant	2,195,184	10.17%
Electricity from solar	2,466,793	11.43%
Net from CHP	16,924,303	78.40%
Efficiency	0.26	
Energy input to CHP	65,093,473	kWh/yr
	216,111	mcf/yr
Natural Gas Cost	$ 2.51	per mcf
Natural Gas Cost per year	$ 542,438.41	
Annual Operating Cost	$ 1,548,998.93	
Annual Capital cost	$ 1,292,543.87	
Total Annual Cost	$ 3,383,981.21	
Lev cost per kWh	**$ 0.1568**	**per kWh**

Annual Emissions (kg CO2)

CHP	9,333,037
Solar	135,674
Total	**9,468,710**

Energy Storage (Lithium-Ion Batteries)

Solar PV to Storage	0.2
Installed Capacity, kW	10000
Cost per kWh	$ 150
Total Storage Costs	$ 1,500,000
System Lifetime, yr	10
Annual Capital Cost	$ 213,566.25

CHP and fuel cells scenario:

Biogas Energy Production

	kWh/y	kW
IAWWTF demand	4,010,400	458
Availability	90.8%	
Supply	6,205,584	780.1762115
Net supply to fuel cells	2,195,184	322
Total Operating Cost, $/yr	$ 402,409.88	

Control System Cost

Total Capital Cost	$ 1,000,000.00
Annual Capital Cost	$ 94,392.93

CHP

	Capital Cost ($/kW)	Operating Cost ($/kWh)	Emissions (kg/yr)
Reciprocating Engine	$ 1,150.00	$ 0.021	3,528,410.26
Microturbine	$ 1,000.00	$ 0.017	4,118,664.77
Gas Turbine	$ 2,250.00	$ 0.011	10,198,286.17
	Annual Capital Cost	Annual Operating Cost	Total Annual Cost
Reciprocating Engine	$355,962.37	$ 603,240.10	$ 959,202.48
Microturbine	$309,532.50	$ 488,337.23	$ 797,869.72
Gas Turbine	$696,448.12	$ 315,982.91	$ 1,012,431.03

Solar Energy

Installed Capacity, kW	2,000
Capital Cost, $/kW	$ 2,200.00
Total Capital Cost	$ 4,400,000.00
Interest Rate	7%
System Lifetime, yr	25
Annual Capital Cost	$ 377,566.28
Operating cost, $/kW/yr	$ 20.00
Total Operating Cost, $/yr	$ 40,000.00
Annual Production, kWh	2,466,793
LCOE, $/kWh	$ 0.1693

Note: No incentives are assumed

Fuel Cells

Installed Capacity, kW	1,400
Total Capital Cost	7,840,000
Interest Rate	7%
System Lifetime, yr	20
Annual Capital Cost	$740,040.54
Fuel Operating Cost	$ 174,611.85
Annual Maintenance Costs	$ 367,920.00
Total Operating Cost, $/yr	$ 542,531.85
Annual Production, kWh	11,650,800
LCOE, $/kWh	$ 0.1101

Note: No incentives are assumed

Fuel Cell Capital Costs

	Cost ($/kW)	Capacity (kW)	Gas Consumption (scfm)	Units
DFC300	$ 3,500	280	39	0
DFC1500	$ 2,400	1,400	181	1
DFC3000	$ 2,300	2,800	362	0

Biogas Install	$ 3,200

Biogas

kW	322
scm	310
Methane %	60

Input Fuel Proportion

Natural Gas	77%
Biogas	23%

Total Cost Calculation

Total demand (kWh)	21,586,280	
Electricity from solar	2,466,793	11.43%
Electricity from fuel cells	11,650,800	53.97%
Net from CHP	7,468,687	34.60%
Efficiency	0.26	
Energy input to CHP	28,725,719	kWh/yr
	95,370	mcf/yr
Natural Gas Cost	$ 2.51	per mcf
Natural Gas Cost per year	$ 239,377.81	
Annual Operating Cost	$ 1,473,278.96	
Annual Capital cost	$ 1,735,098.49	
Total Annual Cost	$ 3,447,755.26	
Lev cost per kWh	**$ 0.1597**	**per kWh**

Annual Emissions (kg CO2)

CHP	4,118,665
Fuel Cells	2,115,277
Solar	135,674
Total	**6,369,615**

Energy Storage (Lithium-Ion Batteries)

Solar PV to Storage	0.2
Installed Capacity, kW	10000
Cost per kWh	$ 150
Total Storage Costs	$ 1,500,000
System Lifetime, yr	10
Cost per Year	$ 213,566.25

No CHP scenario:

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