DEVELOPING A DECISION-MAKING FRAMEWORK FOR A DISTRICT ENERGY SYSTEM MANAGER

by

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Dedicated to my family and friends

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NOMENCLATURE

Acronyms	**Initialisms**
AC	Air Conditioning
ACC/VAV	Air-Cooled Chiller with Variable Air Volume System
AHP	Analytical Hierarchy Process
AHU	Air Handling Unit
ANSI	American National Standards Institute
ASHRAE	American Society of Heating Refrigerating and Air-Conditioning Engineers
BPA	Annual Total Cost Savings
BTU	British Thermal Unit
BTUH	British Thermal Units per Hour
CCHP	Combined Cooling Heating and Power
CHP	Combined Heating and Power
CHW	Chilled Water
CHWS	Chilled Water Supply
CHWR	Chilled Water Return
CHWSR	Chilled Water Supply & Return
CP	Compromise Programming
CW	Condenser Water
CY	Cubic Yard
DAT	Discharge Air Temperature
D.C.	District of Columbia (legislation and rules)
Delta P	Difference in Pressure between two lines
Delta T	Difference in Temperature between two lines
DT	Difference in Temperature (difference between supply and return)
DOE	Department of Energy
E&P	Exploration and Production
EIA	Energy Information Administration
ELECTRE	Elimination and Choice Translating Reality
EPA	Environmental Protection Agency
EUI	Energy Use Index
F	Fahrenheit
FoS	Federation of Systems
GA	Genetic Algorithm
GEO & HP	Geothermal and Heat Pump System
GHG	Greenhouse Gas
GSF	Gross Square Feet

GPM	Gallons per Minute
HCFC	Hydrochlorofluorocarbon
HVAC	Heating Ventilation and Air Conditioning
HDPE	High Density Polyethylene
HR	Human Resources
HZ	Hertz
IAQ	Indoor Air Quality
IDEM	Indiana Department of Environmental Management
IEEE	Institute of Electrical and Electronics Engineers
IND	Indiana
ISO	Independent System Operator
ISO	International Organization of Standardization
Klb	Thousand Pounds
KPI	Key Performance Indicators
KPPH	Thousand Pounds per Hour
kW	KiloWatt
kWh	KiloWatt-Hour
Lb	Pound
LEED	Leadership in Energy and Environmental Design
LNG	Liquified Natural Gas
LP	Linear Programming
MAUT	Multi-Attribute Utility Theory
MBTUH	Million British Thermal Unit per Hour
MCDM	Multi-Criteria Decision-Making
MILP	Mixed Integer Linear Programming
MISO	Midwest Independent System Operator
MW	Megawatt
NLP	Non-Linear Programming
NPV	Net Present Value
NREL	National Renewable Energy Lab
NWCP	Northwest Chiller Plant
O&M	Operations and Maintenance
OAT	Outside Air Temperature
OPI	Operational Performance Indicator
OR	Organizational Research
KW	Kilo Watt
LEMOP	Labor, Equipment, Material, Overhead, & Profit
Lf	Lineal Foot (or Feet)
LTA	Lost Time Accident
N+1	If largest unit goes off-line, demand can still be met with balance

PPA	Power Purchase Agreement
PPE	Personal Protective Equipment
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
PRV	Pressure Reducing Valves
PSIG	Pounds Square Inch Gauge (pressure)
PSO	Particle Swarm Optimization
PV	Photovoltaic
RAR	Repair and Rehabilitation
RECs	Renewable Energy Credits
SCT	South Cooling Tower
SMC	Air Force Space and Missile Command
S&C	Steam and Condensate
S&E	Supply and Expenses
S&W	Salary and Wages
SoS	System of Systems
SoSE	System of Systems Engineering
St. Cond.	Steam Condensate
SWOT	Strength Weakness Opportunity Threat
T	Temperature
TES	Thermal Energy Storage
TG-1	Turbine Generator One
TG-2	Turbine Generator Two
TLV	A Steam Specialist Company
TOPSIS	Technique for Order Preference by Similarity to Ideal Solutions
TVA	Tennessee Valley Authority
US	United States
WCC/VAV	Water Cooled Chiller with Variable Air Volume System
WPM	Weighted Product Method
WSM	Weighted Sum Method

Subscripts Superscripts

Ft^2	Feet squared

ABSTRACT

Managing the highly dynamic and interdependent systems within a district energy system is an intricately complex undertaking. A district energy manager is expected to make decisions that will result in the achievement of the district's goals, often with limited capital and personnel resources. What has been lacking in the tools available to a district energy manager is an established decision-making framework with which to process the complex internal and external variables involved to effectively develop and evaluate options to make successful decisions.

While capitalizing on the experience of seasoned district energy managers and a literature review of current methodologies, this dissertation assesses the strengths, and weaknesses of the methodologies currently available to managers of district energy systems and presents a new and more comprehensive decision-making framework. A system of systems engineering approach is applied, and multiple relevant case studies are analyzed. Procedures for significantly mitigating many of the external risks to a district energy system are developed and documented.

The main contribution of this dissertation is a unique decision-making framework with a holistic approach encompassing the complexity, emergence, and interdependency of district energy subsystems. This framework will aid a district energy manager in making successful decisions which meet the goals of the district.

CHAPTER 1. INTRODUCTION

1.1 Statement of the Problem

A district energy system that produces energy, distributes, and serves a customer is a complex system and the manager of that system frequently has limited capital and personnel resources to meet challenging and diverse goals. The problem is for the district energy manager to utilize the available resources in an effective manner that meets the goals of the institution, which usually include solutions that are congruent with all systems within the district energy system and typically affect environmental, financial, safety, and resilience. The multiple systems within a district energy system may be managed independently but are interdependent, which leads to a higher level of complexity. Ideally, the development of integrated solutions coming from a system of systems approach can prevent unintended consequences and lead to better results in the effort to meet the goals of the institution. The district energy manager's understanding of the issues and where to focus could be greatly facilitated by a better decision-making process than what has been available in the past. Initially, the manager will need to identify the most pressing immediate, mid-term, and long-term issues that require alignment and prioritization. The manager will work through the available options to more effectively manage the system of systems to the goals. There are many management books and scholastic journals on decision-making as well as many articles on coding to optimize power plants and the selection and dispatch of assets. Within the literature review, there was not an overarching list or overview of how to systematically identify the problems faced by a district energy manager or how to consider a more holistic approach. Also missing in the literature is a defined process, framework or considerations for making district energy management system decisions under different scenarios and goals.

Systems within the district may include production, distribution, and demand. There are many subsystems and processes within the district energy system and there may be an incongruency of goals between the major systems. Likewise, there are additional issues and considerations outside of the district energy system that may greatly influence and affect the success of a district energy system. Steps should be taken in those instances to mitigate the external risks.

Engineers design and manage power plants, distribution systems, and buildings. Holistically, district energy systems are interdependent, dynamic, and complex. An engineer with the correct tools in the toolbox, a guiding framework, and the ability and authority as a district energy system manager can bring non-traditional, innovative, and cost-effective guidance and solutions to a district system.

1.2 Motivation

Based on my own experience, and the experience of other managers in district energy systems, I believe there is a need for a decision-making tool to facilitate and enhance a district energy system manager's ability to consistently make effective decisions to meet the goals of the district's owners and stakeholders. Such a tool would be beneficial for someone who is gaining experience in a district energy system and wants to understand and learn how to make decisions in alignment with goals and a mission statement.

Climate change, energy conservation, grid security, emissions, renewable energy, microgrids, carbon tax, economics, and fossil fuels are frequently the focus of headlines in conventional and social media. There is more prevalence and growth of climate strikes, protests and denials of fossil fuel use or distribution systems in the last few years. It is becoming more challenging to have an intellectual debate about the topics and the default for many has been more of a thirty-second sound bite or a 140 to 280-character tweet.

For more than twenty years I have been involved with energy conservation, energy hedging, faculty advising for student environmental groups, energy production, distribution, guest lecturing on power plants/renewable energy, and economic dispatch and optimization of energy systems. I have viewed energy from many roles: student, energy manager, principal energy analyst, strategic energy and data analyst manager, guest lecturer, power plant manager of a district energy system, and energy consultant. A holistic and balanced view is seldom found in articles, journals, or discussions and it does not take much time to see that there is a lot of misleading information being shared that is only partially accurate and carries a bias from an emotional, technical, or economic perspective.

As my focus in this dissertation is the decision-making process in a district energy system, I believe it is important to mention that not only have I witnessed and experienced decisions resulting in mistakes and delays that could have been avoided, I have made some. Additionally, there are times I have successfully taken a novel approach to problems. I was able to look from a different perspective that resulted in a faster, cheaper solution to the immediate problem. Why wasn't that approach taken in the past? The quick answer is that we often default to the traditional problem-solving approach. A solution that has worked in the past will be repeated. For example, if you lose too much pressure on a distribution steam line that extends to the far end of campus, the traditional solution is to increase the size of the steam pipe. That solution is straight forward, but it can be expensive and may take a year to implement. It may not be the best solution in the short-term or long-term. Situations like this call for the type of decision-making framework that is developed in this body of work. I looked at existing decision-making methodologies and approaches to determine if there was an application that is already regularly used in district energy systems. This led to the belief that a new framework or an approach to making decisions needed to be created specifically for district energy systems. My research reveals a combination of recommendations and expands on existing methodologies or processes for future use by managers in district energy management systems.

When I began serving as plant manager on the production side of a combined cooling heating and power (CCHP) facility of a district energy system, I had already spent a number of years working in energy conservation in the distribution and demand side of the same district energy system. Additionally, I had served as the interim manager of the distribution systems that included steam, chilled water, electricity, domestic water, sanitary, and storm sewers. Production, distribution, and demand all had goals to serve and a focus on safety and reliability. But reliability to a production facility is not the same as the reliability to the demand or building users or even for the distribution system, and vice versa.

A district energy system is not a new technology and some have been around for well over a hundred years. District energy systems for electrical production and distribution were some of the first electrical systems in the United States. In 1902, there were 815 city-owned and governed municipal power companies in the United States.

The electrical grid [1] grew as a result of the New Deal (1933), the Rural Electrification Act, Tennessee Valley Authority (TVA), Bonneville Power Authority (BPA), and the proliferation of for-profit investor-owned utilities. At this point, utilities were primarily becoming regulated territorial monopolies. With the exception of the large hydro dams and the nuclear plants in the United States coming on-line in the 1950's, utilities were mostly fired by coal and oil. Fuel cost and fuel flexibility became major issues in the United States in the 1970's when the oil embargoes hit. The nuclear power plant partial meltdown at Three Mile Island in 1979 was the beginning of the end to nuclear plants being built in the United States. Legislation was passed in the United States in the 1970's that limited natural gas as a fuel in power plants.

There has been a significant focus on renewable energy with goals by states, cities, and universities pledging or passing resolutions to be carbon neutral by 2025[2], or 2050 [3] [4] or to achieve a greater than 50% carbon reduction by 2025 to 2050. Some have viable plans to get there but others don't. Many states in the United States have renewable portfolio standards that require a percentage of energy produced in the state to be sourced from renewables. Many take a narrow view of the energy industry and conclude that coal or natural gas use is inherently bad. Those taking this view see pipelines, oil and natural gas companies, and profits from those companies as bad. The same group often categorizes all renewable energy production as good. Progress to "Green the Grid" is happening, but it will not happen overnight. The grid itself in the United States has a problem even without considering the intermittency of adding renewable energy to the grid. In regulated states, new power plants were built only with the approval of the regulating agency and that regulatory agency guaranteed that the utilities' investment into new plants would be fully recovered including a return on equity. If a fossil fueled plant is retired 10 years into a 30-year depreciation cycle, the remaining value of the plant is referred to as a stranded investment and typically will be recovered by the utility from the rate payers.

There is a general misunderstanding of capacity and capacity factor with different methods of producing steam, heat or electricity. For example, let's say that a utility or a company builds a 100-

Megawatt (MW) utility scale (two MW per turbine) wind turbine utility farm, a 100-Megawatt natural gas fired combustion turbine, and a 100-Megawatt solar fixed photovoltaic (PV) farm in the same area in the Midwestern United States. The annual electrical output of the three plants would vary significantly.

- The wind farm would have a capacity factor of 30-35% and produce around 300,000 megawatt-hours of electricity per year.
- The combustion turbine plant would have a capacity factor of 90-95% and produce around 830,000 megawatt-hours of electricity per year.
- The solar farm would have a capacity factor of 15-18% and produce around 155,000 megawatt-hours of electricity per year.

To further exacerbate the issue, the intermittency and challenge in forecasting the hourly output of the PV and wind generation can cause instability in the grid. With investment tax credits, production tax credits, and net metering, wind farms may bid into the grid operator at less than zero cost for their electricity, and that prevents traditional base-loaded coal and even natural gas plants to operate at their peak efficiencies as they are only partially loaded and are unable to cover the variable natural gas or coal fuel costs. Nuclear plants also have difficulty in being competitive in the current market and some have been retired early or are not filing for a renewal of the operating license per the Code of Federal Regulations with the Nuclear Regulatory Commission.[5][6]

The challenges of integrating renewable energy with the electrical distribution grid have been well researched and documented in technical and industry papers. In the last few years, microgrids have also been an area of study and focus. Many district energy systems could be considered microgrids or have a section of the district energy system that they consider a microgrid. Having more components within a microgrid and district energy system frequently provides additional resilience, but also brings complexity and optimization challenges.

Engineers discuss efficiencies and systems and will need to determine where to put the box around the process to determine the resultant inputs and outputs. Specifically, I focused my preliminary work on an overview of a district energy system that includes a combined cooling and heating plant (CCHP) production facility, the distribution of utilities, and demand side consumption. I explore the interdependence between these three components or subsystems. As every district energy system has many externalities that can affect all aspects of the near, middle, or long-term planning and operation, I include those considerations in my study.

This work includes a framework and perspectives from the districts' management goals, that encompasses energy, fuels, economics, finance, engineering, operations optimization, plant management, renewables, risk mitigation, resilience, and safety.

CHAPTER 2. LITERATURE REVIEW

2.1 District Energy Systems

District energy systems come in many shapes and sizes. For my dissertation, I focused primarily on a CCHP that produces steam and chilled water, and also produces a significant portion of the electricity consumed on the district energy system. This CCHP also distributes the electricity, cooling, and heating to the buildings and end users. The end users are included in this system but are not under the direct control of the district energy manager. The framework that I created will work well for all CHP and CCHP plants that include production, distribution, and demand. With simple modifications, the framework model would still work well if the demand is separated from the production and distribution portion. The differentiation of a CHP and CCHP in this situation is that if cooling is neither a product nor a service provided by the district energy system, it will be excluded from consideration by default. This framework can be used even if the district energy system is a thermal system only. The complexity, dynamism and flexible boundaries between the systems of a CHP and CCHP call for this type of framework. This complexity and interplay between the production, distribution, demand, externalities and arbitrage creates more options and opportunity costs when determining the best choice or next choice.

2.1.1 Energy Production

I would first like to focus on the energy production component of the district energy system. There are many inherent advantages to having CHP as discussed in the Environmental Protection Agency's Catalog of CHP Technologies written in 2015 with 2017 edits [7]. *CHP is an efficient and clean approach to generating electric power and useful thermal energy from a single source of fuel.* Alternatively, depending on the type of CHP, there can be a variety of sources of fuel. There are two primary classifications of CHP: a topping cycle and a bottoming cycle. A topping cycle is when electricity is produced initially and the thermal energy coming from the generation of electricity is used to drive equipment, make additional electricity, process steam, produce district heating, produce hot water, or produce chilled water. An example of a topping cycle set-up would be a natural gas fired combustion turbine which produces electricity, coupled with a heat recovery steam generator. A combustion turbine is most cost effective when the minimum demand for steam is sufficient for the entire year to fully utilize the heat from the natural gas combustion at the turbine. Figure 2.1 shows an example of a topping cycle CHP [7] and additional descriptions are available for more information on bottoming and topping cycles [8].

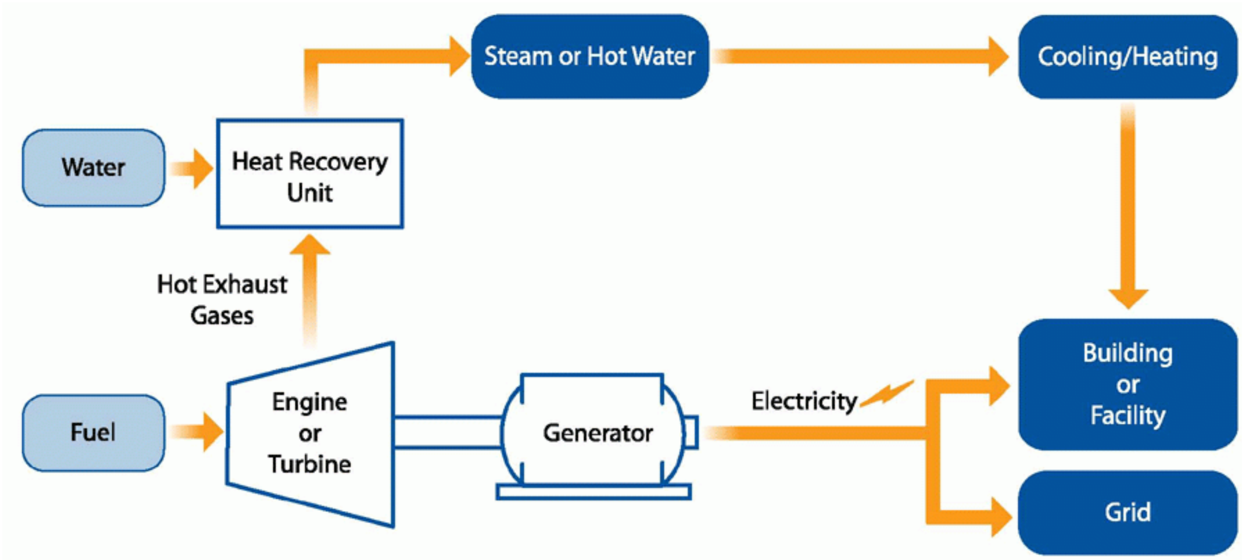

Figure 2.1 Combustion Turbine with Heat Recovery [7]

A bottoming cycle [9] [8] is when steam is first produced by a boiler or some other means and that steam can be used to produce electricity and distribute steam at multiple pressures and temperatures for additional uses. A typical installation may include natural gas or solid fuel boilers to generate the steam. A backpressure steam turbine and/or a condensing steam turbine may be utilized to generate electricity, including reducing steam pressure for further utilization in the facility or distribution system for the building demand. Figure 2.2 shows an example of a bottoming cycle CHP from [7]. Fifty years ago, bottoming cycles were primarily fueled by fuel oil or coal. The last ten years have seen a transition to natural gas as the preferred fuel choice of CHP production.

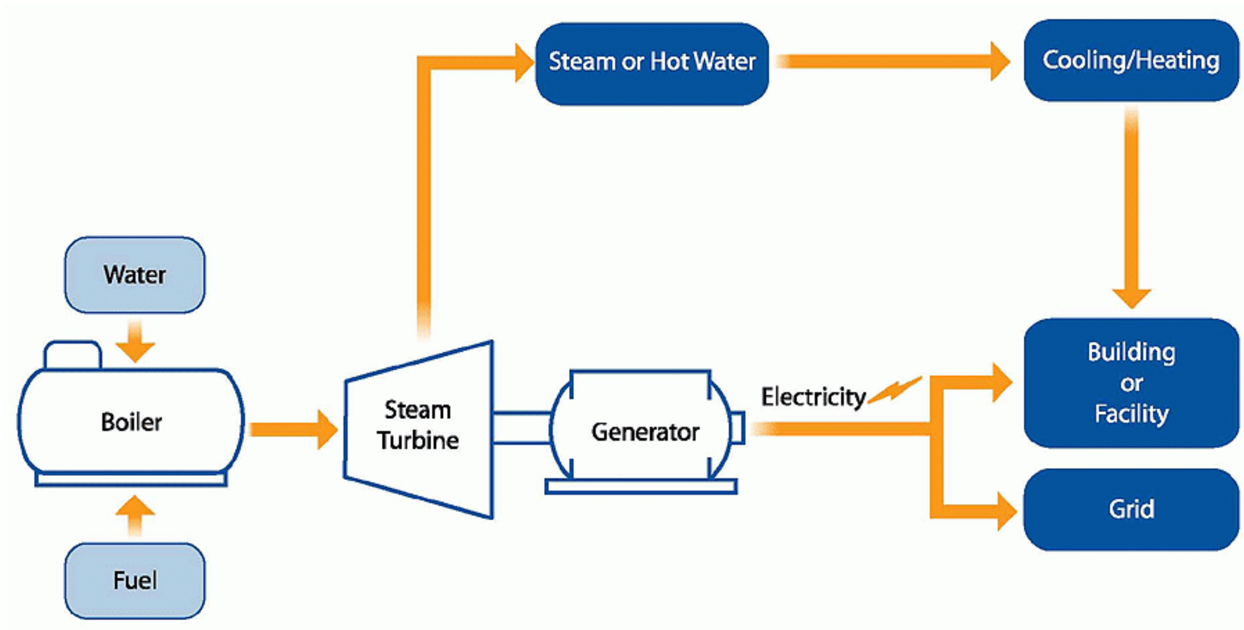

Figure 2.2 Steam Boiler with Steam Turbine [7]

Chilled water production in a CHP and CCHP plant is generated with absorption chillers, electrical centrifugal chillers, or centrifugal chillers driven by steam turbines.

Renewable energy production is becoming more prevalent as costs have dropped significantly over the last several years. The two most significant increases in production capacity in the United States have been in solar (photovoltaic) and wind. Some of this capacity has been added behind the meter on the district energy systems. The balance of the renewable energy generation was imported into the district energy system. Alternatively, renewable energy credits (RECs) or energy may be purchased through a power purchase agreement (PPA).

Energy storage with CHP systems is becoming more prevalent and adds more flexibility in the generation and dispatch of energy. Hot water storage tanks, thermal energy storage of chilled water (or ice), and battery storage for electricity are frequently being incorporated in new CHP designs. Energy storage may be added for several reasons:

- To include peak shaving of energy demand [10]
- As capacity to black start a plant [11]
- As an option to delay new capital for new chillers, boilers or generators [12]
- And for smoother integration of renewable energy production and micro-grid control.[13]

2.1.2 Energy Distribution

On a district energy system, the energy produced will be distributed to the end users through a variety of ways.

2.1.2.1 Energy Distribution – Electrical

Depending on the size of the district, electricity will be distributed through a power distribution center and through a series of underground duct banks, switches or above ground poles and wires. It is usually beneficial for the CHP to discharge at a higher voltage than the customer can use and to install a transformer close to the end user where the voltage is reduced for the customer's use. Then the reduced voltage conductors will be connected to the end user's building switch gear and motor control center.

Electricity storage in batteries has been added to some distribution systems over recent years as battery technology and costs improve.

2.1.2.2. Energy Distribution – Chilled Water

Chilled water may be produced within the main CHP plant and additional satellite chiller plants or chillers around the district energy system. These all may be part of one loop or multiple chilled water loops. These chillers may be driven by the electricity or steam produced by the CHP plant, even if they are not located at the site of the CHP facility, but are within the grid. This is similar to having distributed electrical generation and can have the same benefits.

Chilled water is traditionally distributed from the chiller locations to the end users through a chilled water supply and chilled water return line. Depending on the location, the pipe may be carbon steel (lined or coated) or HDPE (high-density polyethylene). The lines are frequently buried directly in the ground below the frost line. Chilled water plants discharge water from 38^{o} - 50^{o} Fahrenheit, depending on the season, use, and dehumidification requirements. Chilled water plants and pipe sizes are designed around a temperature difference of 10^{o} – 20^{o} Fahrenheit between the chilled water supply and return pipes.

2.1.2.3. Energy Distribution – Hot Water or Steam

Steam or hot water from the production facility is distributed through the district in pipes that may be installed in walkable underground tunnels, half-pipe tunnels or they may be direct buried. Because of the delta T between the steam/hot water and the ground, insulation is required to minimize heat loss. There are many philosophies of best practice with hot thermal distribution for districts which may include:

1. superheated steam in multiple pressures
2. saturated steam systems
3. hot temperature water systems
4. medium temperature water systems

It is important for economic and environmental reasons to return as much of the steam condensate to the CHP for reuse, thus reducing water and chemical usage, and costs.

2.1.3 Energy Demand

The purpose of CHP production and energy distribution is to serve the demand of the district which may include schools, office buildings, hotels, banks, and other commercial or industrial facilities. In some cases, the district energy system is created with a few independent users and additional users either move into the district and choose to be connected to the system due to a favorable value proposition, or the users may have been there and connected to the district energy system later rather than initially. Examples of these public district energy systems are in Seattle [14], Minneapolis [15], Chicago [16], Toronto [17], and Indianapolis [18]. In each case the options available and the value propositions are different. In many of these instances, there is a decoupling of the energy interface between the demand user and production/distribution CHP system where the district energy system supplies the necessary energy to the building and the customer pays for their consumption. The cost of the utilities to the user affects the behavior, energy conservation and impetus to change or economize. In those cases, but dependent on the contract between parties, the district energy system may be required to expand production and distribution to meet additional user demand.

In addition to the public district energy systems mentioned above, there are many systems across the United States where the entire production, distribution, and demand are owned and operated by a single entity. This is common in many universities across the country including Michigan State University [19], University of Texas – Austin [20], Iowa State University [21], and Purdue University [22].

2.1.4 Externalities of the District Energy System

There are many influences outside of the direct control of the district energy system manager. Extreme weather events are the first item that comes to mind in this category. We are not able to control weather, but a district energy manager can mitigate the risk by preparation and redundancy in addition to mitigating the price risk for spikes in prices, whether weather-related or not. There are regulatory and legislative risks that can cause a significant impact to district energy operating budgets. These risks may come from the municipality in which a district resides, or could come from the district governance itself, state or federal government in the case of the United States. Examples could be carbon taxes [23] or a binding resolution setting a maximum allowable carbon footprint by a specific year in the near future. Several of these regulatory [24] and legislative risks could significantly affect the cost of the commodities to operate the plant. In 2005-2006 the United States was relying on importing natural gas and built plants to import liquefied natural gas (LNG) from a number of countries. Then with a combination of directional boring and the fractionation process, exploration and production companies began producing an excess of natural gas. The United States recently became the #1 natural gas producing country in the world and now exports natural gas to other countries. Included in the political platforms of a number of U.S. presidential candidates is a ban on the use of fractionation in the extraction and production of natural gas and oil in the United States. [25] The elimination of fracking oil and natural gas in the next several years has the potential to have a significant negative cost impact to unhedged fuel for district energy systems. Regardless of your opinion on any of these issues, a district energy manager should consider the potential repercussions for these types of issues and develop a pre-emptive strategy.

There are many steps to mitigate some of these commodity fuel risks which include hedging fuel risk, having fuel redundancy by source and type, and even emergency stockpiles.

Most district energy systems are connected to several grids, not the least of which are the electrical grid and the interstate natural gas pipeline grid. As stated in “The Grid” [26], “More than 70% of the grid, transmission lines and transformers are 25 years old; add nine years to that and you have the average age of an American power plant.” Bakke further states that America has the highest number of electricity outage minutes of any developed nation, and that number is increasing. Cyber security is a concern with the potential of foreign entities hacking into the United States’ electric and utility grid. The natural gas interstate pipeline system also could be subject to attack from outside agencies.

The wide adoption of renewables has created additional instability to the aging electrical grid due to the intermittency and inability to forecast renewable output and this variability results in fossil fueled generation operating outside of optimal efficiency ranges.

2.2 Managing and Decision-Making in a District Energy System

There are dozens of scholastic papers about optimizing the production of a power plant based on the most economic dispatch or the most environmentally friendly dispatch of the available equipment. While there are many scholastic research articles on managing energy consumption and demand within individual buildings, I did not find any that focus on the management and general decision-making for normal operations of a district energy system.

2.2.1 Design and Operation of a CHP Distributed Generation

Bracco and Dentici [27] identified a location in Italy as a potential location for designing a distributed energy system. The focus of the work and project was to determine if energy efficiency, costs, and emissions could be improved by adding a district energy system to a growing mixed-use complex. The criteria they used was to compare the costs and environmental benefit of a traditional method of heating and powering four facilities with the costs of developing a hybrid distributed energy system. They then modeled the operation of the proposed distributed generation system. Four diverse end users including a swimming pool facility, school, residential complex with several buildings, and a city hall in the province of Genoa, Italy were included. Their intent for this project was not to build a central facility that would produce the combined thermal and electrical needs, but to have distributed boilers and CHP in each of the four facilities connected with a thermal pipeline. The model defined that the four entities could exchange thermal energy with the other buildings connected in the district but that they were not able to exchange generated electricity. This insured that the surplus electricity generated by any one facility would never go to the electrical grid owned and operated by others. Also, the electricity demand and kWh that could not be generated by the user's own CHP would be purchased from the electric grid. Hourly thermal and electrical load profiles were generated for each building and the thermal pipeline was sized based on the output of the model with each of the boilers optimized by the capacity, load profiles, natural gas fuel costs, and efficiency curves of the equipment. Capital costs to install, own and operate were also considered. The authors used a mixed integer linear programming model and determined that although their model could be more fully developed, it was adequate for the preliminary design phase. The work was performed as a result of Directive 2002/91 of the European Parliament per their requirement to comply with the Kyoto Protocol. The goal was to determine options to design and install distributed thermal and electricity generation in a cost-effective manner. This system as designed for Genoa was very specific and based on the modeling of the energy requirements of the four buildings/complexes for an average climate on a typical day (seasonally). Designing a system for average weather has significant limitations and little resilience. The list of equipment for these facilities included six engines, two gas turbines, and four boilers. The authors did not appear to consider all of the thermal and electrical generation equipment being right-sized and located in one facility and the thermal and electric output distributed to the other locations. The paper stated thermal energy could be exchanged between the four facilities but any excess electricity would be exported to the grid. This is indicative of some of the decisions that are frequently considered as district energy systems grow. For example, if a new building is being proposed and would be located 500 feet past the current distribution energy system, does it make sense to add new infrastructure and connect it to the district energy system or should the local electric and natural gas utilities connect to the building? Bacco and Dentici decided to add a hybrid district energy system instead of a traditional system in their analysis to evaluate potential economic and environmental benefits. The parameters for making that decision are different in almost all cases and may require further analysis depending on the goal. Would the new building 500 feet out of the district include all utilities or only some of the utilities? Are there other new buildings in the master plan that will be added to that same area in the next five years? Does the district energy system have excess capacity now? Where does the capital come from to build the extension? Is this new building a strip mall that may be replaced in ten years, or will it be a critical building in the future of the district energy system? These are all considerations that will be discussed later in the methodology and next steps of my research.

Gu [28] modeled a CCHP system and discussed the challenges of energy management, such as responding to stochastic variations in renewable energy output and load profiles. The publication also discussed the possibility of multiple operational objectives, the coupling with the outside grid, and having a mixture of binary and variable inputs as issues that still require significant refinement. The authors discussed time scale challenges and focused primarily on the short-term, from one minute to one day ahead, and did not focus on long-term planning or issues.

2.2.2 Decision-Making 1900s to Operational Research

Jung [29] argued that neither thought nor observation could be separated from feeling, the source of value judgements. Ackoff [30] discussed the founding of operational research (OR) in the machine age in the 1930's and how OR had gained widespread acceptance in the 1960's. Ackoff further stated that university classes were being taught by academics with no management experience. The academics' work focused on algorithms and theoretical models rather than work on formulation and solving actual management problems or proof of concept of solutions for managers. Researchers in OR in the machine age used a three-step process of taking things apart to understand them and practiced reductionism to break down the issues to the finest element to determine a cause and effect. Ackoff stated this reflected a deterministic view of the universe, and "everything that occurs is taken at the effect of a preceding cause." As the complexity of their models increased, the likelihood of operational researchers creating a functional model decreased. As Ackoff said "the optimal solution of a model is not an optimal solution of a problem unless the model is a perfect representation of the problem, which it never is." Ackoff gave an example in which a management team was given a model to implement but discontinued the use of the model within about six months because of a change in the environment of the system. The researchers did not try to incorporate the changes because they were neither quantifiable nor predictable.

Ackoff moves into a discussion of problem solving and states that, “Managers are not confronted with problems that are independent of each other, but with dynamic situations that consist of complex systems of changing problems that interact with each other.” Additionally, he states that the effective management of these complicated systems is more about planning that requires holistic treatment rather than problem solving. In a paper later that same year, Ackoff [31] worked on the development of academic programs that dealt with complex issues faced by organizations as a whole and not individual problems with the parts. Jackson and Keys [32] discussed a system of systems approach and stated that it was essential that different methodologies be developed that address the variety of problems that exist. Jackson and Keys also stated that systems engineering and systems analysis are similar to OR, and probably best aligned to solve a mechanical unitary problem. They defined a unitary problem as one where all of the decision makers agree on a common set of goals for the whole system and will make their decision accordingly and further stated that unitary problems are considered static in nature. That would be a good coordinated starting point to realize that many problems exist in many contexts and that a variety of solution methodologies will likely be required. Forrester [33] agreed with Ackoff about operational research becoming more academic than practical. In this same journal by Forrester, he discussed the soft OR and the hard OR, where the hard OR included linear programming, Monte Carlo simulation, regression analysis and algorithms. Forrester stated that these mathematical procedures are all “static and linear in character and are not able to capture the dynamic nature of important processes in the real world”. On the other hand, Forrester believes there is a close relationship between systems dynamic and soft OR.

2.2.3 From Operational Research on to System of Systems (SoS)

Maier [34] addressed System of Systems Engineering (SoSE) with a belief that in most cases, the architecture of a SoS would be communications; really more of a set of standards to communicate between the components. His work [35] was originally published in 2003 to develop the concept, foundations, research directions and implications for SoSE. This is the first journal that I found that took the holistic view and merged SoS with Systems Engineering (SE) and stated that it was an evolution of traditional systems engineering. It asserted that this change was required to deal with much more complex systems. Some of the early research in this area involved the military, computer systems and space exploration. The authors stated that academic research and applied practice should be aligned and coupled to be effective in developing the methodologies, processes and techniques to achieve effective SoSE. Table 2.1 begins to delineate the distinctions between SE and SoSE.

Table 2.1.Distinctions between SE and SoSE [36]

Area	**Systems Engineering**	**System of Systems Engineering**
Focus	Single complex system	Multiple integrated complex systems
Objective	Optimization	Satisficing (defined pages 39-40)
Approach	Process	Methodology
Expectation	Solution	Initial response
Problem	Defined	Emergent
Analysis	Technical dominance	Contextual influence dominance
Goals	Unitary	Pluralistic
Boundaries	Fixed	Fluid

Sage and Biemer [37] discussed the concern of the groups involved in engineering SoS, or federation of systems (FoS) about the definition, development, and deployment of a systems engineering process that will enable these systems. This appears to be generally in relation to standards that were being used at the time including military standards, coordination draft by the Air Force Space and Missile Command (SMC), and additional standards from the US Energy Information Association (EIA), Institute of Electronic and Electrical Engineers (IEEE), and International Organization of Standardization (ISO). Table 2.2 furthers the discussion on the requirements of SoSE.

Table 2.2. SoSE Process Requirements [37]

Characteristics of the SoS	**SoSE Process requirements – the process must…**
Operational Independence of the Individual System	1) Provide an enterprise strategic plan. 2) Allow for feedback from SoS operations.
Managerial Independence of the Individual System	3) Develop individual systems separately, ideally in a coordinated way. 4) Be consistent with individual systems in engineering processes. 5) Provide for an integrated SoS acquisition strategy.
Geographical Distribution	6) Allow operational (functional) and system-level architecting. 7) Allow for geographically dispersed system interaction.
Emergent Behavior	8) Provide a set of SoS capstone capability requirements. 9) Validate those capstone capability requirements. 10) Allocate capstone requirements to individual systems. 11) Continually analyze and assess SoS capabilities.
Evolutionary Development	12) Allow for incremental and evolutionary system deployment.
Self-Organization	13) Revise system functionality in response to SoS operations.
Adaptation	14) Develop and continually refine a SoS. 15) Develop and continually refine SoS scenarios.

Sauser and Boardman [38] discussed the management of a system of systems and affirmed that if you believe you have the answers, you have already made the mistake. Early in their journal article they argued that a successful approach to project management for a SoS is predicated on four principles;

- problem demystification,
- legacy assessment,
- state-space solutioning, and
- integration framework.

They introduced five characteristics (Table 2.3) that they believed would be a reasonable set of fundamental building blocks for understanding and managing a SoS. Like Ackoff before, they mentioned in the article that the traditional approach to solving problems has been a reductionism and discovery approach. This is an abbreviation of the table:

Table 2.3. Definitions and Characteristics of SoS [38]

Characteristic	**Definition**
Autonomy	The ability to make independent choices; the right to pursue reasons for being in fulfilling purposes.
Belonging	Happiness found in a secure relationship.
Connectivity	The ability of a system to link with other systems.
Diversity	Noticeably heterogeneity; having distinct or unlike qualities in a group.
Emergence	Appearance of new properties in the course of development or evolution.

McChrystal [39] discussed the problems that the Joint Special Operations Task Force had in 2003 in fighting Al Qaeda in Iraq. A lot of language used in this book is in close alignment with SoSE. McChrystal discussed the dynamic nature of the fighting, the interdependency, the complexity and that while reductionist models are based on planning and prediction, the new environment demands a revised approach. Reductionism is a way to drive for efficiency, but what really is required is to be effective. The authors also addressed “resilience thinking as a burgeoning field that attempts to deal in new ways with the new challenges of complexity.”

SoS and SoSE use in transportation and policy [40] and aerospace design [41] were also discussed. Gorod [42] asserts that when there is a need to solve a problem expeditiously, one looks for a heuristic or a good enough solution. This brings up a particularly relevant term used in Table 2.1. Satisficing [43] as a term was introduced by Nobel Prize Laureate Herbert Simon and indicates that in a complex environment a “best result” can’t always be achieved. An example where this occurs is if a power plant suddenly has an unplanned outage. The requirement is to get the power plant back on-line and producing, and not to form a committee to discuss ways to optimize. Satisficing is proceeding with the first adequate solution.

2.2.4 Multi-Criteria Decision-Making (MCDM)

There is an abundance of scholastic articles on techniques for using MCDM. Some of the articles discussed the aspect of sustainable energy management [44] and gave an overview of how to use MCDM methods including weighted sum method (WSM) [45], weighted product method (WPM) [46], analytical hierarchy process (AHP) [47], preference ranking organization method for enrichment evaluation (PROMETHEE) [48], the elimination and choice translating reality (ELECTRE) [49] [50] the technique for order preference by similarity to ideal solutions (TOPSIS) [51], compromise programming (CP) [52], and multi-attribute utility theory (MAUT) [53] [46].

The classifications of application areas in this research included:

- Renewable energy planning
- Energy resource allocation
- Building energy management
- Transportation energy systems
- Project planning
- Electric utility planning

An energy policy journal article [54] looked at MCDM as applied to evolving strategy development with the nexus of energy and environmental planning and policy development. The authors discussed satisficing techniques and awarding alternative energy supply or demand reduction options pass/fail grades by using conjunctive and disjunctive methods. Options with a passing grade are considered for the MCDM model. An additional scholarly paper [55] looked at the analysis and decision theory aspect of MCDM as a tool for teams to use in the prioritization and funding of research and development projects.

Communication is key in using the powerful methodology of MCDM. MCDM appears to be an excellent tool when considering some aspects of a district energy system with multiple objectives such as fuel, assets, renewable energies, emissions, and cost factors and weighing those with the interests of all of the stakeholders. It appears to be similar to a task force. However, MCDM does not seem to lend itself to include all aspects of what a district energy manager needs to understand. For example, consideration is not given to changing goals and priorities, existing facilities and capacities, dynamic changes to district boundaries or future energy needs.

2.2.5 Decision-Making Using Instinct or Intellect

Boehl [56] considered asset management decisions and frameworks such as MCDM, in addition she discussed intuitive decision-making and decision traps. The author indicated that she was drawing from her academic and professional experiences in the mining and utilities industry. In addition to the consideration of MCDM, decision tree and paired comparison analysis were included. When I looked into the decision traps [57], several of the discussed traps were easy to confirm from my experiences including bias, perpetuating the status quo, optimism, distorting memory, over-confidence, and escalating commitment.

Mitchell [58] worked to explain erratic decisions and the factors that both inhibit and enable managers. When investigating the managers’ abilities in understanding, the authors considered the concept of metacognition. This refers to the conscious reflection about one’s own thinking. In the research, they considered three different hypotheses. The authors concluded that managers using metacognition were less likely to make erratic decisions. Managers in dynamic environments were also less likely to make erratic decisions. Increased comprehensiveness was offered as one probable explanation for the decrease in erratic decisions. Conversely, erratic decisions increased in hostile environments, especially in hostile environments with low dynamism.

2.2.6 Optimization of CHP or CCHP Plants

There are many scholastic articles on the selection and options of components of a CHP and CCHP. There are several scholastic and technical articles on methods to optimize and control these plants once they are in operation with varying goals including cost optimization and the minimization of greenhouse gases (GHG) [27] [59] [21] [28] [60]. Complexity is increasing in government, industry and district energy systems. A multitude of methods has been developed in the district energy production optimization category. Included are linear programming (LP) [25] [61], non-linear programming (NLP), mixed integer linear programming (MILP) [62], genetic algorithms (GA) [63], and particle swarm optimization (PSO) [64]. Research is continuing in this area with combinations of these programming methods and additional spin-offs or hybrid programs. There are commercially available chilled water plant optimization packages for economic dispatch of pumps, chillers, towers, and fans. As the primary focus of my PhD study and literature review was to identify what is currently available and where I can add value to the area of study that is currently not in the literature, I did not focus on the specificity of the output of these models, but rather on how they can best be used in a more holistic approach to managing a district energy system. The focus for the optimization of CHP and CCHP is an effort for the production side only and does not take into consideration the distribution and demand systems. The production side is one system of the SoS and if the focus of a district energy manager is only on the production aspect, opportunities will be missed that taking a holistic view would address. The district energy manager needs to look at the individual components and systems, but also consider the interdependence and varying boundaries between the systems.

2.2.7 National Renewable Energy Labs and REopt

One area of consideration, for example, is to investigate the physical limitations, costs, and how a 5% or 10% renewable energy portfolio could be achieved behind the meter at a Midwestern district energy campus. "Behind the meter" is a common phrase with reference to renewables and micro-grids. To clarify the phrase, the output from a photovoltaic array installed on a building of a master-metered campus would be absorbed into the consumption of the campus and would not register on the meter. It would therefore be “behind the meter”. Alternatively, electricity purchased or imported from a wind or solar farm miles away from the campus would not be from “behind the meter”. National Renewable Energy Labs (NREL) [65] began developing a platform for energy integration and optimization in 2007. Between 2013 and 2014, NREL [66] converted an earlier generation of the REopt tool to a mixed integer linear program to improve the solver and named it REopt. REopt lite is available to use directly while the full REopt tool requires assistance from the NREL staff. These tools are useful in the evaluation of the addition of a renewable energy portfolio behind the meter. The REopt program can model the thermal and electrical energy use at a site, incorporate policy and tariff structures and incentives and determine options and costs. One unique item that my dissertation focuses on addresses the interdependency of the production, distribution, and demand aspect. I contacted NREL and confirmed with the REopt team that [67] “we consider the lumped requirements of the energy needs of a facility so don’t consider any distribution system constraints.” In their desktop model, NREL has done some preliminary work with electrical distribution constraints but nothing on heating or cooling systems. I certainly see REopt lite and the full desktop REopt model as excellent available tools to assist a district energy manager in some aspects, but they are incomplete.

2.2.8 Interviews with District Energy Managers

Outside of good management practices, there was no blueprint or guideline provided to me when I assumed management roles for different subsystems within a district energy system. To make sure that my situation was not unique, I reached out to others that hold or have held similar or more executive roles.

I interviewed four managers from four locations who have worked as district energy managers in multiple roles [68]. Included in these roles are an Assistant Vice President for Utilities and Maintenance, a Director of Utilities and Services, a Director of Engineering and Administration, and a Plant Manager of a CCHP plant. The aggregate of utility experience of these four individuals is over one hundred years in district energy systems in a Midwestern university campus environment.

Some observations from these interviews:

- No one was given a blueprint to follow for making decisions when they became managers.
- All had been involved in utilities that were managed by others, so they were able to see how decisions were made.
- Everyone had at least one experienced utility manager to mentor them or they had a maintenance resource with decades of experience.
- Goals have evolved for many and differed between campuses, including sustainability and greenhouse gas emission goals, keeping utility costs flat, more involvement in master planning, and forecasting and sharing with management when the capacity of systems are overextended.
- Three out of the four institutions generate a significant percentage of their electricity.
- There are some similarities in risk mitigation strategies of fuels and power.

These discussions increased my confidence that I am providing a unique contribution to this field of study while providing important guidance for incoming district energy managers and future opportunities for additional research and refinement of decision-making methodology for district energy managers.

2.3 Summary of Literature Review

In my literature review I identified several existing tools but each of them had limitations in what is required for a district energy manager. Multi-criteria decision-making is a good tool when used to determine the kind of district energy system you want to have or migrate to. MCDM processes are normally used by diverse stakeholders at a very high theoretical level who are either considering a new system or a dramatic change for an existing system. This falls short of what a district energy manager needs to make day-to-day decisions, or even year-to-year decisions on how to operate a system, how to grow, and how to meet goals and mitigate risks. Also included in the literature review was optimization of CCHP, CHP and chiller plants with programming solutions. This too is important but there are already many solutions that are commercially available to district energy managers to optimize chiller plant systems. To me, these are tools in a district energy manager's toolbox and depending on the goals, available capital and internal resources, the district energy manager can select the best product to utilize. Sometimes optimizing the dispatch in the most efficient manner may not be the most effective solution to the problems that the district energy manager faces. The manager needs to consider that the solutions may not be in the production area, but can best be solved in the distribution or the demand part of the systems, or even by dealing with the externalities influencing the system operations. I have confirmed a gap of an existing decision-making methodology based on the literature review and the interviews with other district energy managers. As administration, goals, and mission statements change, district energy managers need to be effective and agile in managing the change, have the ability to refocus, and have or develop a holistic approach to the new paradigm. The erratic decision section of the review addressed the culture and behaviors that help and hinder decisions. This is more of an awareness that a district energy manager should have and to encourage and promote the development of the culture and values necessary to enable other district energy managers to think through options, make good decisions, and develop and tune their abilities. The National Renewable Energy Labs REopt program can be utilized as another tool in the district energy manager's toolbox. It will continue to improve but it will not have all of the answers. REopt can be a helpful tool when determining if a thermal energy storage (TES) tank for chilled water is the best option for the next chilled water asset, but the district energy manager and staff need to already understand where the limits are in the distribution system, where the acceptable locations of the TES would be, and what, if any, obstacles those present to the REopt model.

I am intrigued by the development of systems engineering, system of systems, and systems of systems engineering. I believe there is value in incorporating a SoSE approach as a start to creating a methodology for a district energy manager to mitigate risks, direct focus and determine a logical process for determining the best allocation of resources to meet the institution's goals and mission statement. I believe this is a unique contribution to this industry and field of study.

CHAPTER 3. METHODOLOGY

3.1 Selecting a District Energy Manager

The executive determining the process for hiring a district energy manager needs to decide who should conduct the hiring search, screen candidates, and assist with the interview process. Has the hiring process been vetted out with upper management and is it in alignment with the goals and mission statement? Are the members of the hiring committee diverse enough to give independent, insightful, honest and clear feedback to assist in selecting the correct candidate? All of the guidance and tools for a district energy manager in the balance of this work are consistent and valuable for seasoned district energy managers as well as newly hired managers moving from different engineering roles into this position.

When hiring the new district energy manager, considerations may include: 1) Where is the best fit for the new manager in the organization and should an organizational change be a precedent to the hiring phase or as part of this hiring process? 2) What leadership qualities, professional qualifications, and skills are required or preferred? 3) What is the current status of the district energy system and is there a clear vision of future goals? 4) What are the expectations and timelines of the path forward and the expectations and requirements of a new manager to get there?
The district energy manager will need to assimilate data and information from engineering, operation and maintenance, and economics to determine the best path forward in alignment with the goals.

The selection of a district energy manager is included in this section to provide a true beginning to the knowledge map (Figure 3.1). The top of the knowledge map begins with the process of gaining an understanding of the goals of the administration along with the strengths and weaknesses of the existing staff and the issues that must be addressed. It is logical to include the selection process for hiring new district managers here to create a complete and comprehensive path.

3.2 Knowledge Map, Framework, and Considerations

A variety of case studies and a knowledge map for a new district energy manager will be examined to demonstrate the framework, considerations, and effectiveness of these approaches.

Examples and discussion considered:

- What should be included in a holistic viewpoint and framework for a new district energy manager to succeed?
- If a steam plant on a district energy plant kicks off-line during a polar vortex, what factors should the manager of the system consider? What are the manager’s goals?
    - Is this an operational problem?
    - Is this an economic problem?
    - Is this an engineering problem?
    - What are the considerations and how is the situation resolved?
- When demand is growing within the district energy system, at what point will production be at capacity or distribution capacity? What are the limitations and how are those limitations identified?
    1. Is growth practical, expected, and reasonable?
    2. Is reliance an issue?
    3. Is safety an issue?
    4. Can the growth be offset with other measures?
    5. How will existing stakeholders be affected?
    6. What are the resources to identify a solution?
    7. Are there unintended consequences with those decisions?
    8. Is it expected that new capital will be provided to allow infrastructure to be added to keep up with the demand growth within the district energy system?
    9. Will the district energy management be involved early in the master planning of any development to assure that energy will be available and can be provided at the intended location in conjunction with the growth?

3.3 Overview of District Energy System Management

The knowledge map below in Figure 3.1 was created as a general framework and outline of a methodology for a district energy manager regardless of the specific goals of an organization. To provide a complete knowledge map, the first eight plus nodes are common best management practices and could be found in a number of different management resources. The balance of the knowledge map is engineering focused for a district energy system. Critical to the success of any manager is understanding the goals of management. Safety and resilience are typical goals for a district energy system. Goals can vary greatly from institution to institution and one institution may strive to be the low-cost supplier while another may be striving to achieve an aggressive carbon free target. Regardless of the specific goals for any particular district energy system, the framework still has the necessary elements for success. The framework reflects the importance of the goals beginning at the top with learning the goals of management, and continuing by pulling the staff together with goals and a mission statement. Goals and mission are also pointed out as an overarching goal of system of systems management. For the Midwestern university campus with a CCHP plant that is my specific area of focus, those goals are listed on the right side of the system of systems block on the bottom of Figure 3.1. The goals for this institution are safety, resilience, and student affordability. The additional goal listed is compliance with any environmental permits. The next sections contain more detail on specific areas of Figure 3.1 and clarify those with additional figures later in this document.

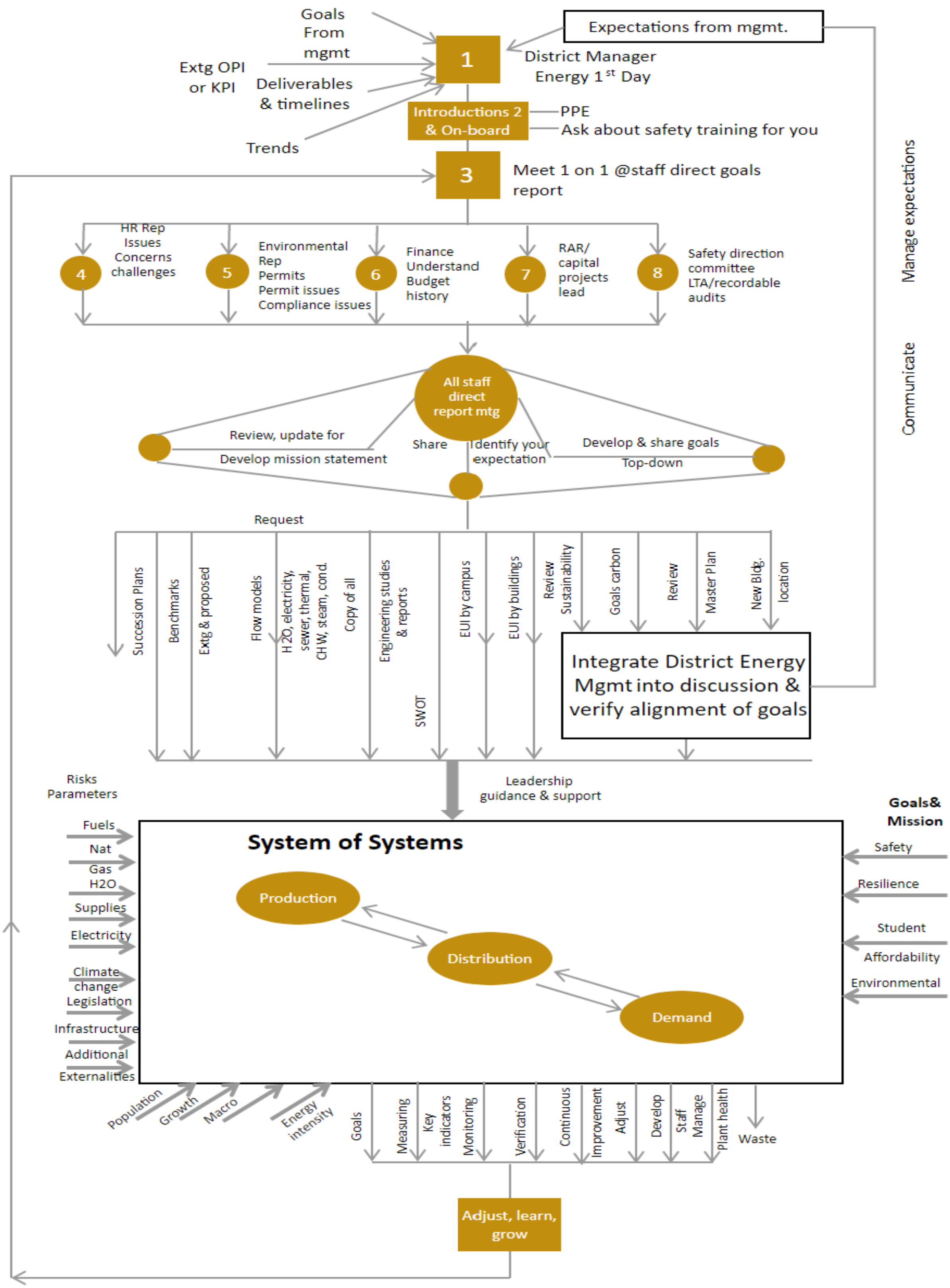

Figure 3.1 Knowledge Map for District Energy Management

3.3.1 District Energy Manager – The First Thirty Days

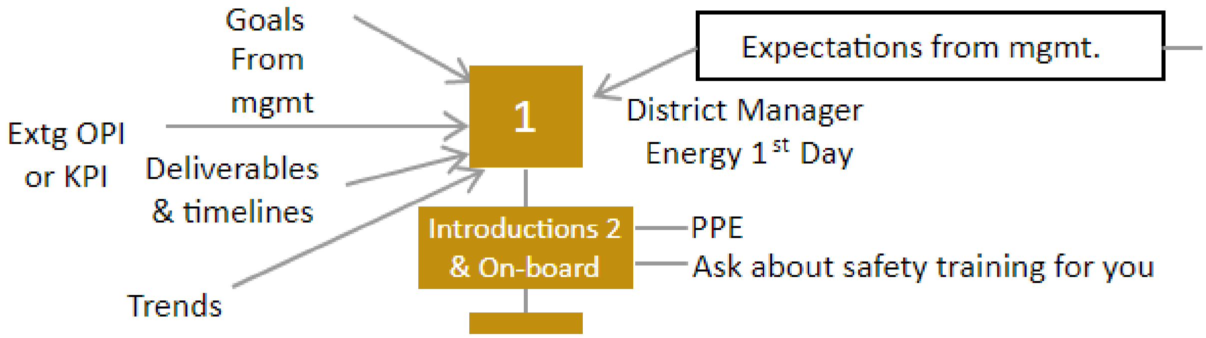

Figure 3.2 Nodes 1 and 2

<u>Node One on Figures 3.1 and 3.2 - District Energy Manager First Day</u>: Whether an internal or external candidate, through the interview process the new district energy manager probably has an understanding of the management goals and may already have those goals clarified and in writing. The success of the district energy manager, the department and organization rely on an alignment of purpose with these goals. Frequently new managers are given a set of expectations which may have succinct deliverables and timelines which should also be a focus in the first thirty days.

As the manager gets acclimated, it is good to get a clear overview of the recent energy system performance. Frequently organizations have established metrics including key performance indicators (KPI) and operational performance indicators (OPI). Additionally, the new manager may want to request any available trends which may include year over year budget performance, unit costs, job vacancies, safety performance, or insurance claims.

<u>Node Two on Figures 3.1 and 3.2 - On-boarding and Introductions:</u> A good early step as the new manager is being onboarded and introduced, is to verify the required safety training and request any needed training while requisitioning all required personal protective equipment. Asking direct reports for some of that information sends a message to all personnel that the new manager is committed to safety.

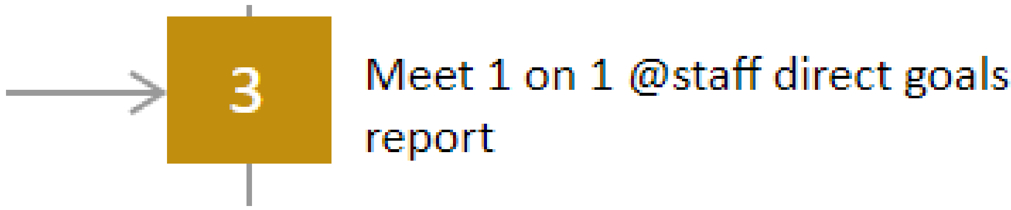

Figure 3.3 Node 3

Node Three on Figures 3.1 and 3.3 - Meet One-on-One with Direct Staff: Meetings with the manager's direct reports should begin by the end of the first week. Learning about the person and empathetic listening are two goals for these meetings. Where is the drive? What are the passions? Why is the person here? Are there issues that are brought up? How are the employee's verbal communication skills? This provides insight into the organization and possible issues.

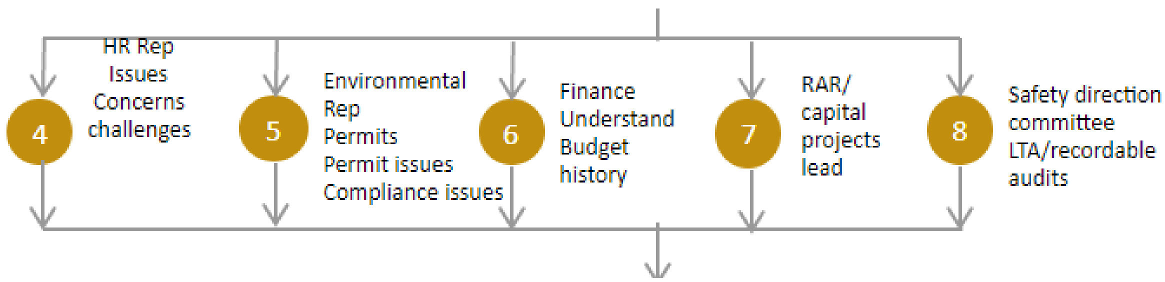

Figure 3.4 Nodes 4, 5, 6, 7 and 8

Node Four on Figures 3.1 and 3.4 - HR Representative Issues, Concerns, and Challenges: After one-on-one meetings with staff, it is a good time to sit down with the human resources (HR) representative for the district energy system. Develop communication expectations with the HR representative. Find out about the outstanding HR issues throughout the district energy system and not only issues with direct reports. Mention any issues that came up during one-on-one meetings that can be shared. HR issues may include new policies, personnel performance, attendance, friction/cooperation, morale, open and unfilled positions, organizational challenges, obstacles to implementation, grievances, changing work conditions, pending or possible retirements or any number of additional issues.

Node Five on Figures 3.1 and 3.4 - Environmental Representative - Permits, Compliance Issues: The environmental representative will be able to bring the manager up to date on any current air, water, waste, or other permits in place, and any issues with any of the permits or compliance. Are there training issues? How does safety fit within the environmental organization or is some of the safety for personnel training handled by another organization? It is appropriate at this meeting to request an emergency call list and to verify who and when to contact for different types of environmental emergencies. Identify staff resources or other resources to communicate with on specific aspects of permits. Also, the recommendation is to learn where these permits are kept, both physically and electronically.

Node Six on Figures 3.1 and 3.4 - Finance Representative - Understand Budget and History: Understanding the financial picture can sometimes be challenging. Management and the trends from Node 1 can provide some insight. Since the new manager most likely did not start on the first day of the fiscal year, the budget was probably already in play. There may be multiple sources of funds for commodity procurement, purchased utilities, custom contracts with suppliers and providers, and sole sources for specific materials. It is important to understand several aspects of the budget. Does the purchased utility budget come from the general fund? Is it based on revenue charged to the end user? How are those rates developed, and by whom? How often are they updated and are they in arrears or forward looking? Is there a contingency budget? What is the overhead mark-up percentage on salary and wages and when or where is that included in the costs? How are capital projects for new equipment, equipment replacement, and repair and rehabilitation handled and managed? Are there procurement strategies in place for any commodities? How are those managed? What is the budget process and who is involved? What are the approval limits and signature requirements?

Node Seven on Figures 3.1 and 3.4 - Repair & Rehabilitation and Capital Projects: District energy systems are usually large enough with significant amounts of equipment and connecting infrastructure that projects, both small and large are either in design or are in construction or both. Some district energy systems have significant maintenance workforces but almost all district energy systems require specialty trades and expertise for certain tasks and roles. What are the requirements for bidding and engineering? How are funds secured to do projects? Who scopes and manages the projects? Who oversees construction? If engineering design expertise is required from an outside firm, how is that firm's contract procured? Have recently completed projects been on time and on budget? What is the approval process for new capital projects and new money? What is the role of the district energy system staff and manager through conceptual design, bid, construction, commissioning and start-up? What is the status of the current projects in design and construction?

Node Eight on Figures 3.1 and 3.4 – Safety, Committees, Training and OSHA Records: Organizational structures can differ significantly from institution to institution. The safety representative may be centrally located or roles and responsibilities may be divided. It may require additional effort to understand the safety resources and expectations both internally and externally. During the district manager's first week there will be some insight as to safety requirements (Node 2). The district energy system safety meeting should be attended to understand the issues being addressed. It would also be good to ask the safety committee about the training that is required for various staff including office staff, energy and plant engineers, managers, maintenance and operations. Procedures including items like lock-out and tag-out, material safety data files, OSHA training verification, contractor job site sign-in and orientation, confined space entry, and burn permits should be reviewed. Is safety a priority?

3.3.2 District Energy Manager – Thirty Days and Beyond

Figure 3.5 All Staff Direct Reporting and Team Building

Team Building and Alignment in Figures 3.1 and 3.5: At this point the district energy manager has made a lot of discoveries, has developed a basic understanding, and has begun to prioritize the next steps for the organization. It is time to enter the next stage of development of the organization. Under nodes 4, 5, 6, 7, and 8 of Figure 3.1, there are four connected nodes that look like a wing of an aircraft or an umbrella. This is the stage for aligning the staff to the common goals. The items in this figure include: a) All-staff direct report meeting, b) Review, update and develop mission statement, c) Share, d) Develop and share goals top down, and e) Identify your expectations. Once the manager's team and direct reports have acknowledged the goals, it is a good time to work together and incorporate the goals into a more comprehensive mission statement. If the upper administration already has a mission statement in place, the district energy manager's organization's mission statement should align with it while reflecting the unique goals of the organization. If others don't have a mission statement, be the first one on the block to have one. Working as a team to create and develop a mission statement is a process that can take a few meetings or months. The mission statement should be published, displayed, and shared with all employees in the system. Everyone now has a better understanding of the requirements we have as individuals and as team members for a common goal and expectations. Additional positive steps that this director brought to the table are not unique. An excellent exercise for understanding the employees and the organization better was for each employee to do an individual SWOT analysis. Employees are tasked with identifying their Strengths and Weaknesses, and either their personal or the organization's Opportunities and Threats. The output of these charts is not for general publication but for a bit of an introspective and to provide points for discussion during one-on-one conversations with direct reports. The opportunities and threats sometimes reveal interesting unknowns that may be completely unfounded and may present an opportunity to provide helpful feedback. Acknowledgement or affirmation may be beneficial for an employee. This development of the mission statement, SWOT analysis, and reviews can take several weeks or months. This is a good time to regroup and for a periodic review of how the district energy system group is doing and how it could improve. Having the district energy manager share goals and expectations is better than having surprises later. This section of Figure 3.1 is not a one time and done event but a continuing and recurring process development for the team's growth and leadership.

Request Information and Determine Current District Energy Status in Figures 3.1 and 3.6:

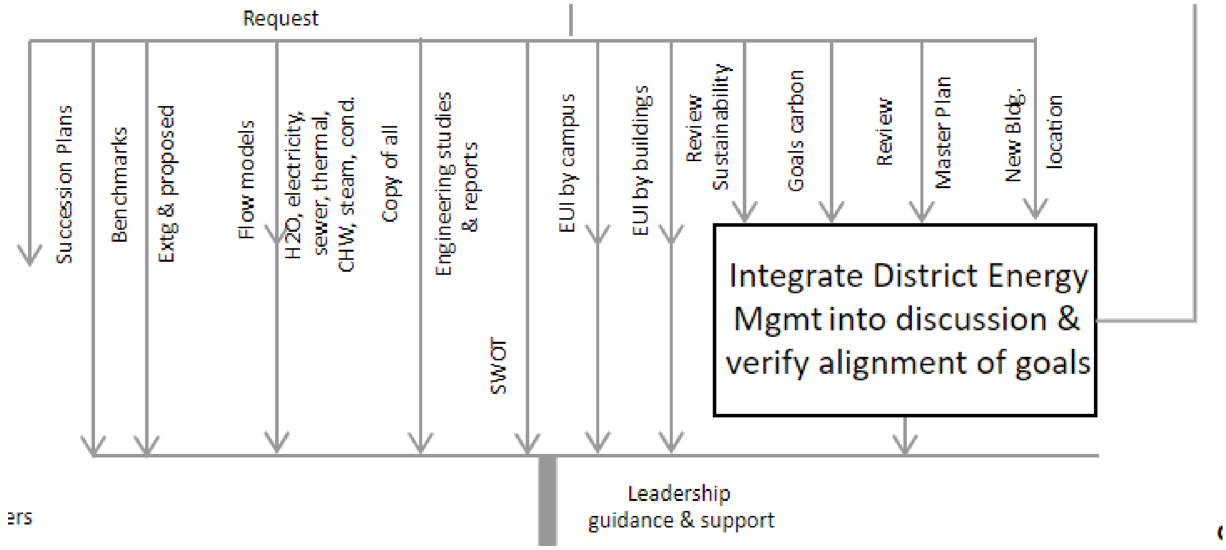

Figure 3.6 Request Flow Models, Benchmarks, and Coordination

It is important for the engineers and managers to have ready access to this data and information that the district has invested to gather. This allows the district energy manager to evaluate options in a system of systems approach and apply the engineering principles required to make effective decisions expeditiously. This next section has over twelve components that are representative of information that may have been gathered but is not always available to all. Many staff members may not even be aware that this information currently exists, and it will be valuable to have a central location for sharing. This information in aggregate should give a pretty thorough analysis of the status of the district energy system. A brief description is written below for each of these items as possible resources that are available.

Succession Plans – This could include the current status of the organization and if future stages of organizational change are in progress. This could also include employees currently scheduled to retire, or those having sufficient years of employment to retire. Plans should include the number of those employees who are in specialized roles and whether the staff being trained for those roles will be ready when the time comes.

Existing and Proposed Benchmarks – Has this district energy system benchmarked itself with similar institutions, whether on a subscription basis, by association, or publicly available measures?

These could be costs per unit of energy, labor costs, fuel diversity, capacity of infrastructure, or goals.

Flow Models: Water, Sewer, Thermal, Chilled Water, and Electricity – Primarily flow models for distribution systems determine the capacity of infrastructure and identify the robustness of the system. Additionally, peak flow issues are typically identified as potential pinch points where in water systems excess water velocity can result in excessive pressure drops and cause erosion and noise issues and premature pipe failures. Electrical systems will also look at transformer and distribution capacities. These flow models are valuable to have in-house and calibrated to enable the consideration of new buildings in the master planning or the possible addition of new customers. The models can be used for the "what if scenario" to answer the question of whether the existing district energy infrastructure can handle the additional load at that location. These flow models are also critical when utilizing a system of systems approach which is discussed at length later in this document.

Engineering Studies and Reports – Many district energy systems have been around for decades and have had significant staff turnover over those years. Previous managers of these district energy systems may have looked at many different scenarios and infrastructure plans or engineered estimates or analyses over the years. It is important to determine what records of past studies and plans are available and that staff members have access to review these for valuable information. Every five to ten years, as a district energy system evolves, a comprehensive energy plan may be developed. Before developing the next plan, it is very helpful to find out what the last plan included and what recommendations and predictions from that plan have come to fruition. This is also a good place to take the step forward as to a possible scoping of the new plan. The previous study might have analyzed options with net present value calculations to look at gas combustion turbines or thermal energy storage or conversion from steam distribution to hot water systems. Maybe that analysis should be done again with new commodity prices and new data from the production and distribution systems. The answers might have changed and could reveal an undiscovered value proposition worth funding.

EUI by Building and EUI by Campus – EUI is an initialism for Energy Use Index which is a benchmark frequently used to compare energy consumption (intensity) by building. The unit of measure is the number of thousands of British thermal units per gross square foot (GSF) per year consumed in the building. A lab building with a lot of required outside air ventilation might have an EUI of 500 Btu/ft^2/year, where a typical classroom or office building might have an EUI of 75 Btu/ft^2/year. Many factors need to be taken into consideration. In an upper Midwestern university, a large percentage of the EUI will be for heating, whereas a similar building in Miami, Florida will have a larger EUI percentage used for cooling. During this last fiscal year in Indiana at a combined cooling, heating, and power plant (CCHP) and campus district energy system, an EUI was calculated based on the metered annual consumption of each building to determine the campus use by utility, and the KBTU by commodities was divided by the GSF of the buildings that were served by steam, chilled water, and electricity for that district energy system. The results were that 48% of the EUI for the campus was for steam to campus, 34% for chilled water, and 18% for electricity. It is important to be consistent when measuring and comparing district energy consumption. The GSF may be different for steam and chilled water and electricity, so the denominator will be different when the GSF is different. It is also a good idea to include the heating degree days and cooling degree days from year to year as this could significantly change the EUI between years. Another consideration is to add new facilities to the GSF when the project construction is deemed significantly complete. If air conditioning is added to an existing non-air-conditioned building, the additional air-conditioned GSF should be added to the existing cooling denominator. Metered energy data by building, when available, makes comparing labs to each other or residence halls to other residences halls possible. LEED building energy models can be compared to the actual energy consumption. This frequently identifies opportunities to investigate buildings that are not performing properly and there may be opportunities to reduce the energy consumption and demand load on the system. Comparing campus EUIs can yield valuable information. Looking at universities with similar climates and technical intensities can help determine the relative health of a district energy system. EUIs can help evaluate the energy demand of its users and indicate whether there may be opportunities for improvement. The usefulness of EUIs when using a system of systems approach will be addressed later in this dissertation.

Review Sustainability, Carbon Goals, Review Master Plan, and New Building Locations – All of these items lead into an area identified in "Integrate district energy management into discussion and verify alignment of goals". For a district energy system to be successful it is critical that a knowledgeable district energy manager or designee be at the table for the discussions of these initiatives. It is important to remember that energy on a district energy system is a demand pull. Chilled water, electricity, and thermal energy will not be produced unless they are needed by the district itself. If the demand for energy is reduced, the demand for production is also reduced, making the system more sustainable and producing less carbon. As noted on the right side of Figure 3.1, there is a loop going back to management to manage expectations and communicate during the development of these plans.

3.3.3 District Energy Manager – System of Systems

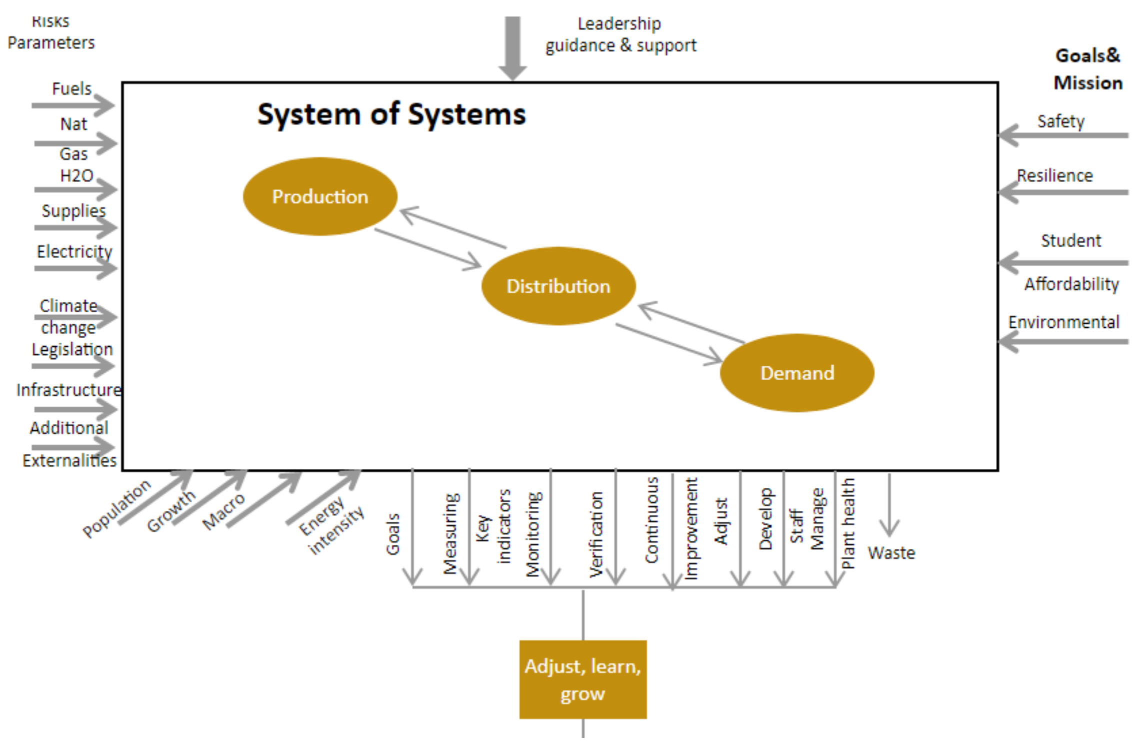

Figure 3.7 System of Systems as Part of the Knowledge Map

At this juncture as denoted on Figures 3.1 and 3.7, moving from the evaluation of the current status into a system of systems management approach requires leadership, guidance and support from the district energy manager.

System of Systems (Figures 3.1 and 3.7) – Over the next several pages I provide an overview of the components of the system of systems approach shown in Figure 3.1 along with showing additional exhibits detailing parameters of the subsystems, interdependence between systems, dynamic boundaries, and externalities that influence the system of systems. These next four figures specifically address the externalities of the SoS, the production, distribution, and demand as to the specific information to gather and consider for this knowledge map. A problem-solving framework is presented in the next chapter on case studies. Following the synopsis of the system of systems components and externalities I explore several case studies that incorporate the system of systems approach into actual issues and opportunities that I have worked with others to explore and solve. The system of systems box on the bottom of Figures 3.1 and 3.7 has three ovals representing the three subsystems within the district energy system; production, distribution, and demand. The list of issues and components that can significantly affect the operation and success of a district energy system is on the left side of the box. We will explore these externalities to the SoS in greater detail.

Externalities and Macroeconomic Affects (left side of SoS box) in Figures 3.1 and 3.7:

Fuels and Natural Gas – Traditionally these are among the two or three highest costs in a district energy system. There are many macroeconomic and political occurrences that can significantly influence these costs. Fuel and natural gas risk mitigation strategies are recommended and those strategies are included in this dissertation. As district energy plants in the United States are typically combined heat and power plants and located in metropolitan areas, natural gas would be considered the primary fuel for the majority of those plants. As natural gas is almost always delivered to the district energy system via natural gas pipeline, and natural gas pipelines are interconnected and similar to the miles of interstate roads in the United States, purchasing or hedging natural gas strategies and hedging processes are unique and will be addressed separately in this document and appendices.

Water and Supplies – Water and chemicals for water treatment including chilled water, boiler feedwater, condenser water and cooling towers are critical for the safety and economical operation of a district energy system. Strategies for procuring the water and chemicals need to be taken into account by the district energy manager. Receiving contaminated condensate back into a CHP or CCHP can be very detrimental to the continued operation of the district energy system and steps must be taken to maintain the integrity and quality control of the system. Any condensate that is not returned to the production facility must be made up with additional water in which case additional chemicals and heating are required which has economic and environmental impacts.

Electricity – If a CHP or CCHP does not produce 100% of the electricity required for the district energy system, the direct price of electricity can significantly affect the budget. Electricity and fuel are typically the two highest purchased utilities that a district energy manager will have on the budget. If the district self-generates a portion of the electricity consumed, price risk mitigation is important so fuel price hedging should be considered. Additionally, the integration of a renewable energy portfolio behind the meter can be a hedge against higher electricity prices.

Climate Change and Legislation – Whether legislation comes from regulatory bodies, state or national legislation, compliance can involve major costs. Additionally, if the district energy manager is taking a long view of the potential effects of weather on the district energy system, considerations should be made to mitigate that risk.

Infrastructure – The integrity of the pipelines, electrical grid, internet, and even highways can certainly influence the ability of the district energy system to perform and be resilient. The definition of infrastructure could be stretched to include the banking industry, capital availability and skilled employees.

Effects from the University but Outside of the District Energy System (these are the diagonal lines at the bottom left of the SoS box) in Figures 3.1 and 3.7:

Population – This refers to population growth on the demand side of the district energy system. It would include the increased energy consumption and peaks due to additional students, faculty, and staff including the addition of summer classes (affects summer cooling and peak demand of chilled water).

Growth – As new buildings are added that consume additional energy, this peak demand will increase. Unless the growth and capacity demand increase are offset with energy conservation measures, growth will result in increased peak demands to serve the district energy system.

Energy Intensity and Macro – As mentioned earlier, there are significant variations of energy consumption between classrooms and laboratory buildings. As the energy intensity increases on campus, the EUI tends to also increase, thus putting additional strain on the production and distribution systems of the district energy system. Energy intensity also increases when fume hoods or process equipment are added to existing buildings or a building without chilled water cooling adds air conditioning.

<u>*Measurements, Benchmarks, and Growth (these are the vertical lines exiting the bottom of the SoS box) in Figures 3.1 and 3.7*</u>*:*

Goals, Measuring Key Indicators, Monitoring, Verification, and Manage Plant Health – Measurements and monitoring by the district energy manager and team need to verify that the goals are being met and measured.

Continuous Improvement, Adjust, Develop Staff – These are steps to confirm that the district energy system team is moving forward, being agile and growing.

<u>*Goals and Mission (right side of SoS box) in Figures 3.1 and 3.7:*</u>

Goals for the Institution: Safety, Resilience, Student Affordability, and Environmental – Safety is the practice of safe operations and being proactive on safety for all stakeholders. Resilience is to reliably operate the district energy system to provide sufficient utilities for the occupants of the facilities for health, comfort, and safety. Student affordability is to be aware of and have a continuous focus on reducing the cost of education for the students. Environmental is to assure compliance with environmental regulations and permits.

The last node on the bottom of Figures 3.1 and 3.7 is to adjust, learn and grow. This node connects back to meeting one-on-one with staff (Node 3), completing the circle and defining the process as continuous and dynamic.

Now to look at the three systems of the district energy system. The descriptions and lists in Figures 3.8, 3.9, and 3.10 for production, distribution, and demand are used to complete the system of systems engineering aspect of the knowledge map (Figure 3.1).

3.3.4 Production

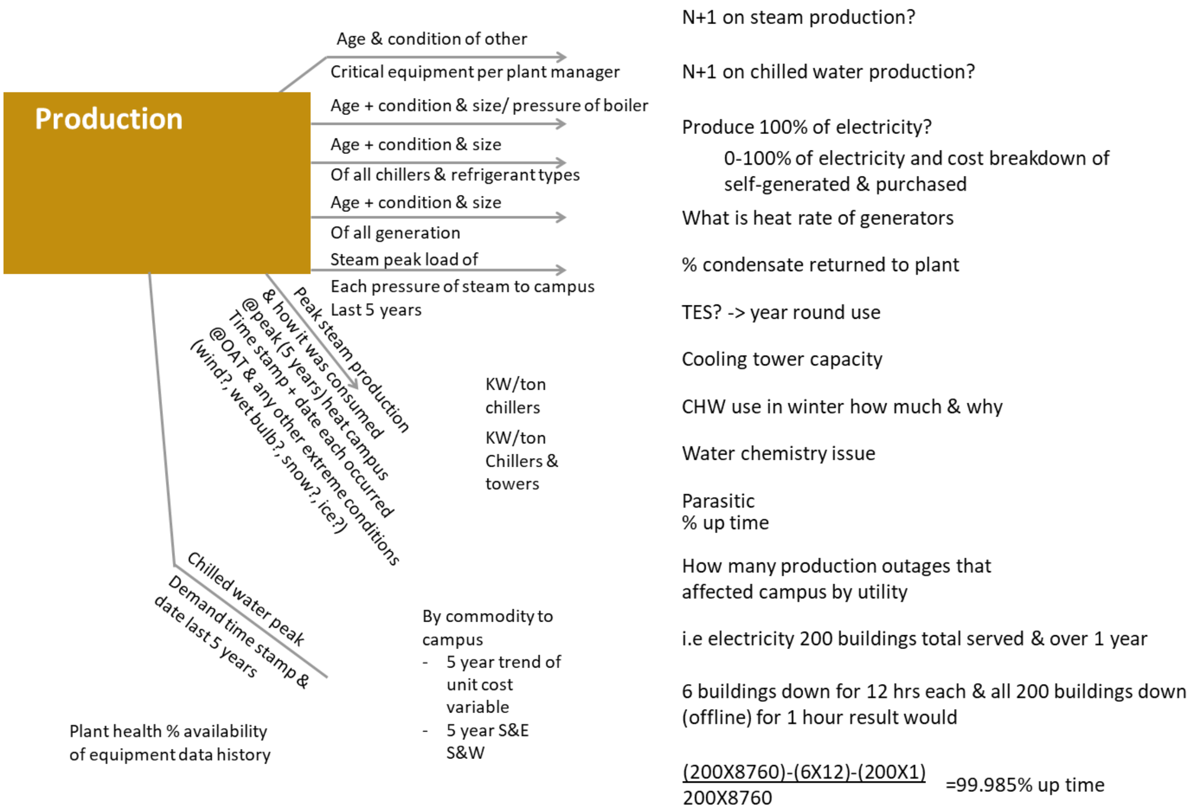

Figure 3.8 Production for the Knowledge Map

The items shown on Figure 3.8 comprise a good first list for determining the level of current maintenance procedures, plant health, and capacity and condition of existing production assets. Everything on the list is self-explanatory for utility engineers and anyone familiar with district energy systems. One term that might not be obvious to all is N+1. As an example, for chillers N+1 means that if the district energy system's largest chiller goes off-line, the district energy system still has enough chillers to meet peak conditions for chilled water demand. In conjunction with the N+1 it is common to review key performance indicators such as "up-time" to verify that customer needs are met. There are additional reliability measures that can be considered as an alternative.

3.3.5 Distribution

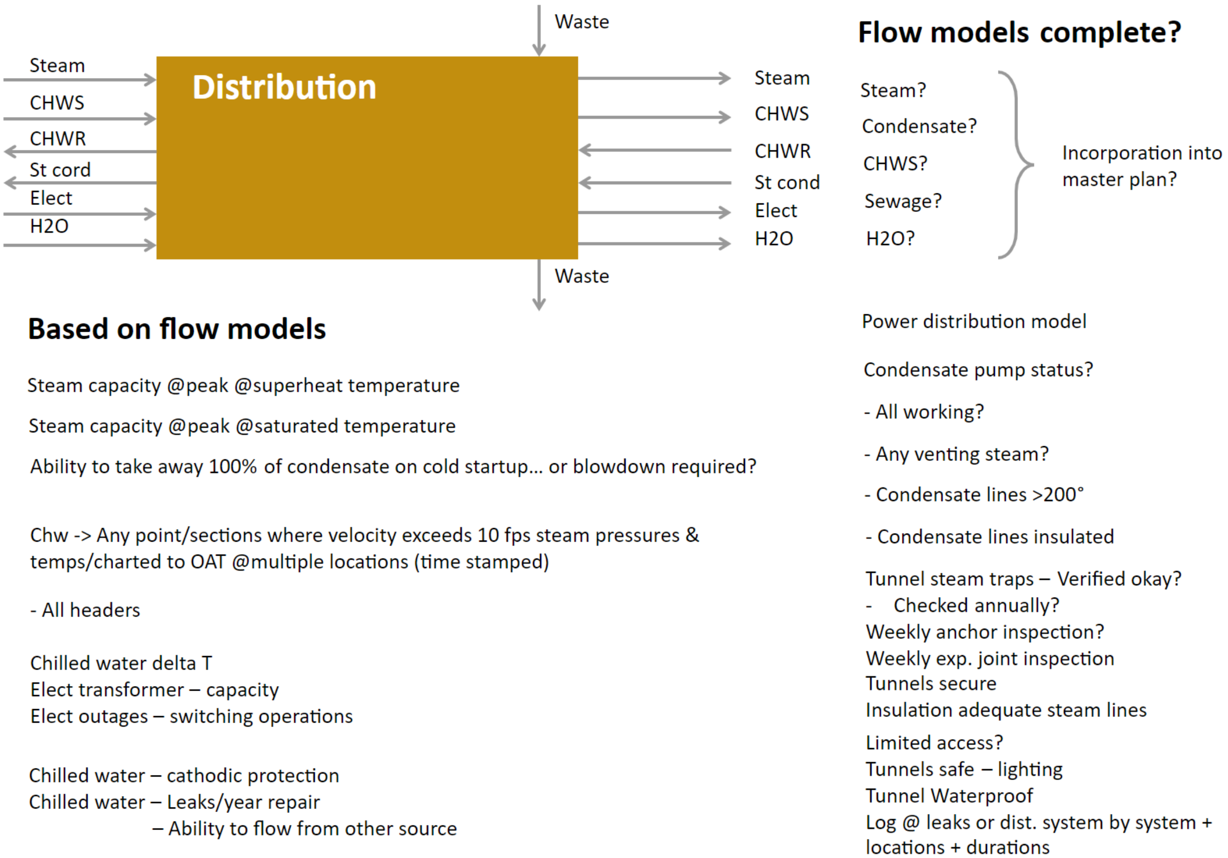

Figure 3.9 Distribution for the Knowledge Map

*Note on chilled water maximum velocity above [69]

The horizontal lines shown going into and out of the distribution box represent the flows coming from the production into the distribution to the demand section of the system. The return flows are also shown. The items shown on Figure 3.9 represent a good first list for determining the degree of current maintenance procedures, capacity issues by commodity, and the safety and security of the distribution infrastructure. As the N+1 criterion is important for the production system, flow models which consider velocities, peaks, and capacities are important for the distribution system. It is also important to maintain the integrity of the distribution system which is addressed in the list above. Some of the information is based on steam and steam condensate for the thermal system delivery on the district energy system. The district energy system manager would know from the process established in Figure 3.1 if the district was served with a steam and condensate system or a hot water distribution system. Additionally, the manager would know which systems are in tunnels or direct bury.

3.3.6 Demand

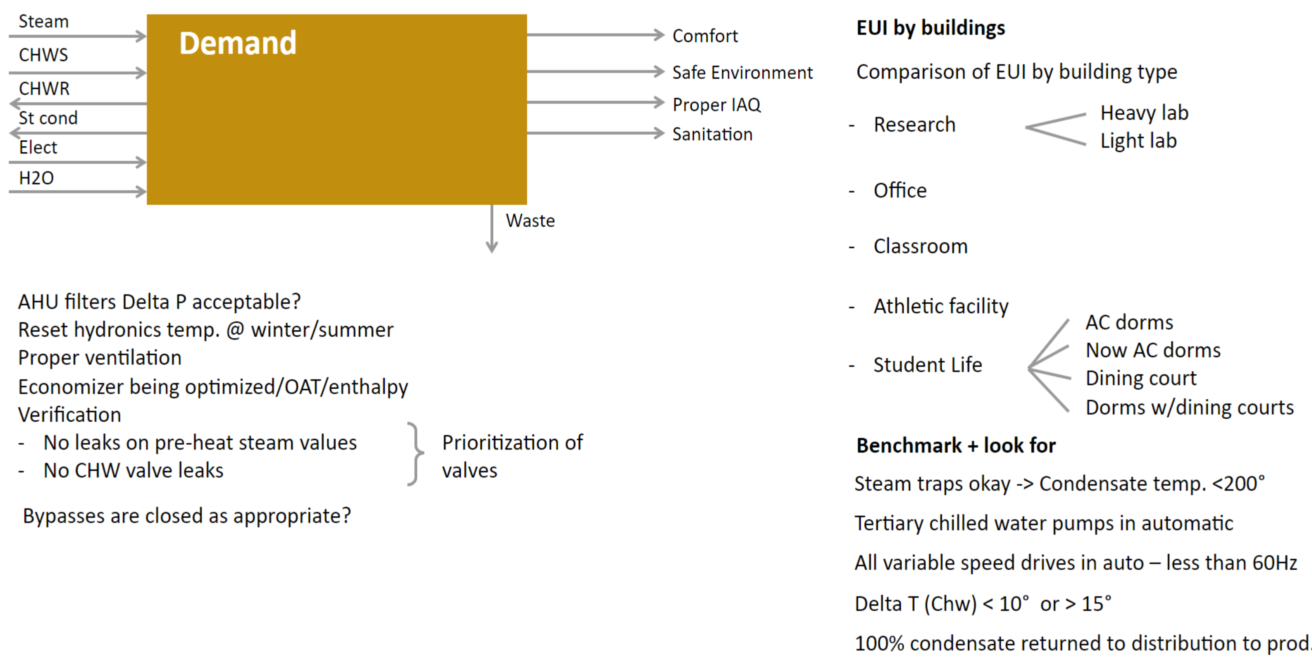

Figure 3.10 Demand for the Knowledge Map

Demand represents the end user in the district energy system. On the left side of the box in Figure 3.10 the utilities that feed the demand are shown. The right side of the box lists the goals to achieve comfort and safe ventilation to the buildings. The demand portion of a district energy system within buildings could include thousands of air handling units, fume hoods, valves, fans, and pumps. The items listed above are high level items for consideration and comprise the information needed to complete a first pass identifying potential opportunities. This work will not get into the details of a building's operation, but rather considers some of the interdependencies between production and distribution and the demand use within these buildings.

3.3.7 Externalities of SoS

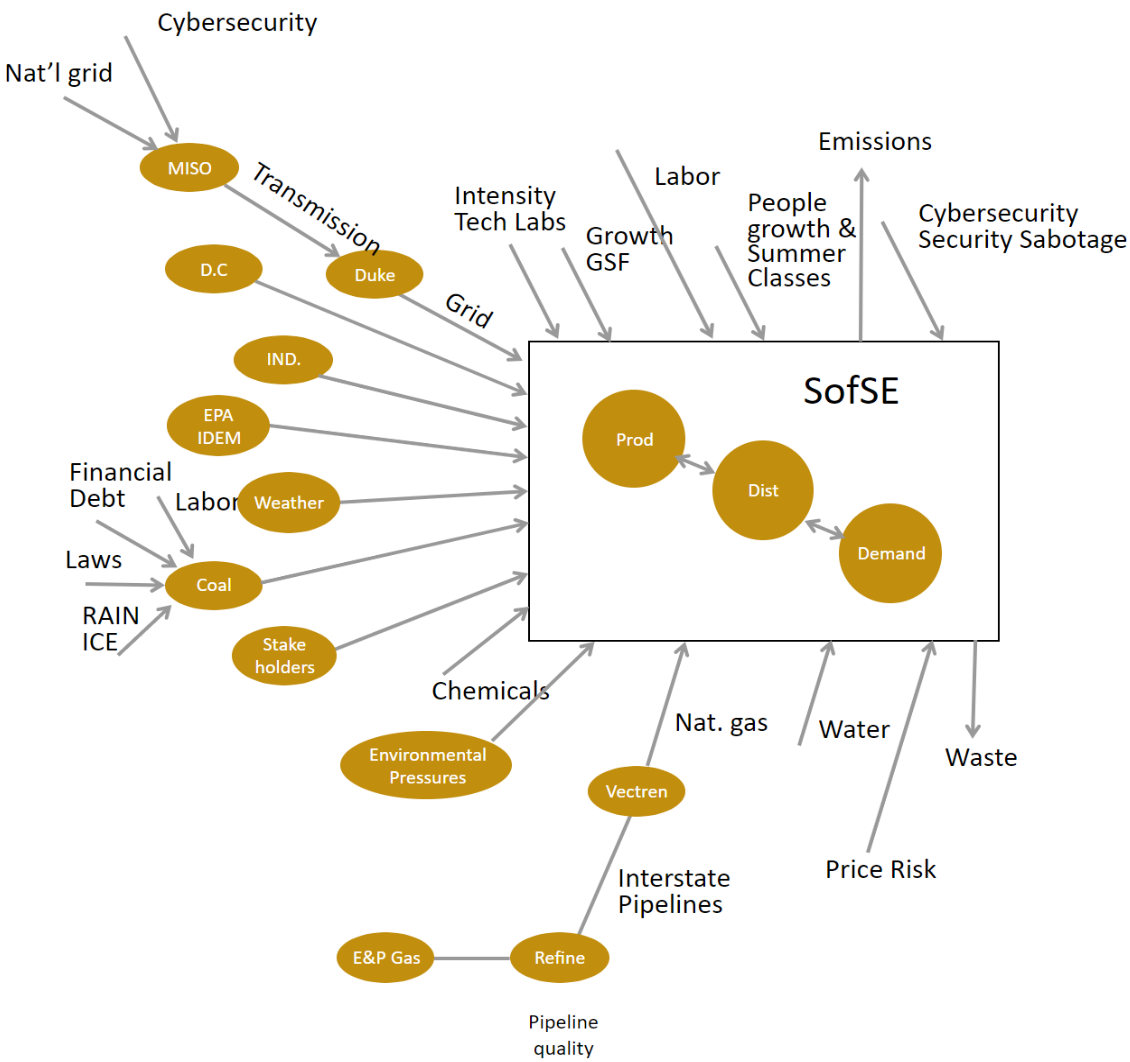

Figure 3.11 Externalities Affecting District Energy System - the Knowledge Map

There are many factors that can apply external pressures to a district energy system and there are some that are internal to the district, but may be out of the district energy manager's control. These items affect energy production costs, demand peaks, energy consumption and resilience.

There are methods to mitigate risk for many of these items and those methods are included in this work.

Many of the largest risks to the district energy system are externalities that affect the system of systems. These risks are shown as part of the knowledge map (Figures 3.1 and 3.7). Recommendations for addressing the many externality risks that can be significantly mitigated are discussed later in this dissertation. Appendix A provides an example of an operational strategy plan which will help to identify externality risks. Appendix B includes strategies for mitigating fuel risks with hedging.

As previously mentioned, my focus is on two categories of externalities. The first externality category is *Effects from the University but Outside of the District Energy System.* These externalities include energy intensity, population, and growth.

The recommended strategy to address these risks is to integrate the district energy management into discussions early and verify the alignment of goals with the master planning group, sustainability group, and the upper administration. Ideally the district energy manager will actively participate in these discussions. This feedback loop, shown in Figure 3.1, includes communication from the district energy manager to those higher in the administration. The knowledge that district energy personnel need to bring to the planning table includes production, distribution, and demand limitations. Specifically, challenges in the flow models, building energy use indices, and benchmarking should be shared. The flow models will identify the pinch points of the distribution system while the energy use indices will help predict the actual energy consumption and peak demand of similar facilities.

If the addition of a high energy building is proposed on an area of campus with a distribution limitation, that issue can be brought up and addressed early. There may be an opportunity to increase the capacity of the distribution system to this location which would be a more traditional approach to address the limitation. Using a system of systems approach, a major capital expansion of the production system might be delayed by adding distributed production to the district energy system by incorporating a base or peaking chiller or boiler in that proposed building's design. Input from the district energy manager may result in alternative options for a better and less capital-intensive building location. As mentioned before, energy demand is a pull from demand to distribution and production. The district energy system only produces energy that is being consumed within the system in real time unless energy storage capabilities have been installed. It is important for administration to understand this conceptually.

Situations like replacing old laboratory buildings with new ones may present themselves during the planning process. In cases like this, there is value in developing a strategy for the timing of the decommissioning of the old lab and encouraging best energy efficient practices in the design of the new building. The district energy manager should present the benefit/cost analysis of lower energy, operational and maintenance costs over the life of the building vs the initial cost of construction. The district energy management team needs to understand the implications of decisions and be there to propose and support the best decisions based in sound engineering and economic practices.

An increase of population may not add any gross square feet of campus but can certainly add load. Adding population density and an increase in building utilization may affect the peak demand for electricity and cooling loads. It may also affect production and/or distribution or even demand if a particular air handling system within a building will not have the capacity to provide sufficient ventilation air or cooling during periods of peak demand. Also specific to population, if residence halls are added and the on-campus population increases, water and sewage demand can be expected to increase as well.

The second group of externalities that I am addressing is the *Externalities and Macroeconomic Affects* as shown in Figures 3.1 and 3.7. Included in this group are fuels, natural gas, water, supplies, electricity, climate change, legislation, infrastructure and additional externalities. A good overall source for determining risk mitigation is the district energy system's insurance company. Normally a district energy system insurance underwriter will want to make at least an annual visit to make a risk assessment. Their reports are valuable and give a fresh perspective on items which may need to be addressed or should at least be considered. They may highlight issues such as maintaining spare parts for major equipment, acquiring additional fire protection or modifying safety procedures or safety forms. It is always good to review the recommendations with the team and management.

The category of fuels includes coal, diesel, fuel oil, and specialty fuels such as biomass or tire-derived fuels. Fuels are commodities and the price has varied significantly over the last 20 years. Environmental permits and manufacturer's recommended fuel specifications may require tight specifications and chemical limitations for fuels. It is best to provide these specifications to the procurement office which should bid the exact fuel requirements to suppliers. A multi-year contract for these fuels with a commitment for the supplier's ability to deliver the volumes upon request within a set number of days is ideal. Storing fuels on-site can be a problem. Coal or biomass should be stored in waterproof containment year-round. Having wet or frozen coal/biomass can cause plugging in boilers and decrease boiler efficiencies. Additionally, district energy managers may not want to keep the inventory on-site for financial accounting reasons. With a multi-year deal it is good to make sure the escalator is reasonable and tied into a published index. In a long-term contract for fuel, be careful on the escalator and make sure that the basis of escalation is reasonable. Also be wary of any fuel riders for delivery, how they are calculated and with what base assumptions. The needed volumes will be based on the operating strategy, the rate of consumption, on-site storage capacity, on-site inventory, and the estimated rate of fuel consumption. Frequently on fuels, it is good to determine the minimum and maximum projected consumption per year for each of the fuels. If the district energy manager has the ability for fuel switching and arbitraging based on the costs of fuel or electricity, it is good to calculate the absolute minimum that may be used in a year. Due to the unplanned availability of an operating asset, the minimum may be at 30% of the normal consumption, but it should be included early in the bid process. The maximum quantity of fuel that may be needed in a year should be determined by looking at worst case scenarios for weather or asset availability. If any of these fuels generate a waste product that will need to be processed, stored, recycled or that requires payment to dispose of, an option with the purchasing contract for handling that waste product should be considered. With trucks delivering the fuel and returning with the waste product, the associated costs may be attractive. The environmental management group should be included in that discussion. Also, fuel flexibility can be an excellent way for risk mitigation and reliability.

Although natural gas is also a fuel, I chose to exclude it from the general fuel category. Many district energy systems' natural gas use has grown significantly over the last twenty years and the monthly expiry of natural gas has ranged from less than $2.00 per decatherm to over $12.00 per dekatherm (1 million BTU) for that time period. Without risk mitigation, the volatility of the commodity can severely crush an annual budget when buying 100,000 dekatherms or 3 million dekatherms of natural gas. Also, I specifically want to single out natural gas to list some procedures I developed and the successful procurement process that I have used since the late 1990's.

An understanding of the local distribution company (LDC) for natural gas is necessary for an understanding of the natural gas market. The LDC is the gas company that owns the pipeline and the meter that goes to the district energy system facility. It is frequently the same LDC that provides the natural gas to the local community. Rate tariffs for state regulated LDCs, are typically published and can provide information on how the rate tariffs are structured for residential, commercial, and industrial applications. There are frequently a variety of natural gas accounts for larger users, like district energy systems, that allow for the delivery of the commodity (natural gas) to the LDC, who will deliver the natural gas to the district energy system's natural gas burner tip(s). The district energy system may have one natural gas meter or hundreds of small meters with a series of pipelines spread over a large geographical area. LDC costs can vary greatly, from 5% of the cost of the utility for the throughput costs and meter costs to a much higher percentage, depending on rate tariffs and the congestion of the areas served by the LDC.

There are many ways of procuring natural gas. The LDC can deliver natural gas, although commodity prices will change with the LDC fuel costs adjustment based on the approved rate tariff. Daily, weekly, or monthly procurement and pricing from a few or several vendors is an option if there is a transport account for purchasing natural gas. This method does not allow for mitigating the risk of the volatility of the commodity for budget surety. This may yield the least expensive cost of natural gas but in a polar vortex scenario with pipeline limitation or freeze-ups it could be the most expensive. This method may be appended with procuring call options where a premium is paid for the possibility of benefitting from softness in the market. The district energy systems that I am most familiar with are risk averse with management preferring to have some budget surety for energy costs. For those cases, I recommend selecting a marketer. I suggest working with the procurement group, as with the fuel commodities, to identify the minimum and maximum volumes by account to include in the marketing package. Internal audit or someone within procurement can help to develop risk procedures that include; fiduciary responsibilities, delineation of duties (hedging, verification of hedges, and invoicing), the ability to use options or forward contracts, hedge approvals, the duration and volumes allowed for hedges, and authorized personnel. There are many details that should be considered and there are consultants specializing in energy procurement. I would encourage developing some simple guidelines for the process, such as layering hedges with forward contracts over sixty months up to a percentage of the total projected volume to be consumed. Determine how these rules will be established and how approvals to hedge will be initiated. I strongly recommend against hedging by committee, as committees are not agile or available when necessary to execute quickly. Alternatively, the individual(s) performing the hedging should proactively request authorization from the administration to hedge up to 60% or 80% of the projected needs based on the budget, beating the last year's budget or a specified target price.

Using fundamental and technical analysis as a tool can be beneficial in mitigating fiscal risk with the hedging of natural gas. When the district energy system generates some or all of their electricity, controlling the fuel input costs is a mitigation strategy to be able to control the cost of generated electricity. It is important to understand the true costs of generation and heat rates. This is another example of utilizing this system of systems approach to evaluate and hedge natural gas, based on the boiler/heat recovery steam generator efficiencies and generator heat rates, and to reduce the electricity cost from the base rate electricity. These strategies are discussed in more detail in Appendices A and B.

Depending on the location in the country or world where the district energy system is located, water issues may vary significantly. A readily available water supply is critical for district energy systems. Whether owned by the district energy system or not, it is important to determine the risks of the water system; potable water, hydronic, boiler feed water, fire protection, chilled water, boiler make-up and condenser water system. With water comes sewage expenses and some district energy systems have sewage costs that are many times greater per one thousand gallons than the variable water cost for the same volume. It is important to determine and understand the costs to understand the risks to serve the customer and to be able to manage a budget. Look for the weak points in capacity and infrastructure. Are there enough water wells? Does the district energy system have a reliable quality control program? Any there any concerns with permits? Is there a sufficient number of interconnections to the distribution system? Are they located properly and can they be isolated? Are there agreements in place to offer mutual aid and assistance with other water or district energy utilities? Are there sufficient water towers for fire protection and system pressurization? Is there adequate source protection for the water? Verify that there are a sufficient number of certified operators, proper training and that a succession plan is in place. Sterilization protocols, training, reporting and safety practices must be in place.

Chemical treatment, refrigerant, spare parts, support equipment like pumps, instrumentation, meters, fans, blowers, valves, air compressors, controlled systems, and limestone for circulating fluidized boilers are all included in the supplies category. I recommend reviewing the report from the district energy system insurance underwriter as a first pass on identifying the risks to see if they identified any critical items that should be in inventory at the site. Secondly, I would identify all essential equipment that is required to serve campus, starting with the boilers or chillers. As was shown in the knowledge map (Figure 3.1), in the production portion of the system of systems engineering approach (Figure 3.8), the current peak demand of each utility of the district energy system needs to be identified. This may include steam (or hot water), chilled water, potable water and electricity. Once those utilities are identified, identify the largest single capacity unit for each of these utilities (such as a boiler for steam, and a chiller for chilled water). In a scenario where the largest unit for any one of these utilities would unexpectedly go off-line on a peak design day, would there be enough capacity with the other production assets to continue to provide 100% of the system's needs? If not, the utility production is at risk. Determine how many additional units (such as tons of cooling capacity or pounds of steam from a boiler, or a well that pumps potable water), it will take to have the N+1 capacity, which is a standard in many district energy systems. With the system of systems engineering approach as I described, an additional chiller or boiler may not be required. Instead, the N+1 redundancy may be achieved by making less expensive and more effective modifications in the distribution or demand area. It is important to have a proper inventory of supplies in place to be able to reliably deliver energy to the customer. As mentioned before, the traditional solution might not always be the best solution.

A district energy system may produce none, some, or all of the district energy system's electricity. Even though the electricity may be produced and supplied from the grid, the district energy system may deliver that electricity to the users in the district energy system. Other district energy systems may produce a significant portion of the electricity used by the system and may also have an agreement with a utility which will supply whatever additional electricity the district energy system needs beyond the self-generated amount. I am not aware of any district energy system that isn't connected in some manner to the rest of the electrical grid. Critical manufacturing, research, or data centers may require redundancy in an electrical feed and even multiple supply sources. Most systems do not have full redundancy, but most critical systems have some back-up generation, uninterrupted power sources (UPS), and/or electrical storage to be able to either keep power on or to bring it back quickly. While it is currently expensive to store electricity, the price of electrical storage is expected to come down as the next generation of battery technology is developed. Some of the currently available electricity storage methods come with less than ideal environmental footprints from sourcing, operating, and ultimate re-use or recycling. These concerns are relevant for lithium ion, lead acid, and many of the rare earth minerals.

Another consideration of risk for electricity is the cost. The cost of the electricity for a kWh (converted to the cost per million BTU) is many times higher than the same cost per million BTU of steam from an efficient boiler. In most cases, reducing carbon or approaching carbon neutrality would involve decarbonizing the electrical grid plus replacing natural gas or other fossil fuel heating with electric heating or at least augmenting geothermal or heat pumps with electricity.
A district energy system having the ability to generate electricity with one or a variety of fuels has the ability to hedge the electricity prices and possibly lower them by hedging the fuels that generate the electricity (topping cycle) or that produce the steam that can generate the electricity in a steam turbine (bottoming cycle).

The district energy manager needs to be aware of risks from the electrical utility that feeds the district energy system and determine the needed redundancy of assets (transformer/switches) and delivery points. Utility reliability and interruptions should be tracked as key performance indicators. The district energy manager needs to make sure that all critical areas have the necessary back-up, and verify that critical users, such as research labs, email systems, payroll, and data centers have all of the electrical back-up in place. Any shortfalls to that back-up should be shared as identified risks with the administration.

Maintenance on the systems should be coordinated with the utility to ensure reliability of operation for both entities and to minimize any risk to either. This will allow each system operator to put the electrical distribution system in the best set-up to mitigate risks and to prevent failures and downtime.

Renewable energy and storage are becoming more attractive and they have become cost effective in many parts of the country. A risk mitigation strategy that should continue being used is keeping current on renewable costs, incentives and subsidies. This information is valuable when determining market costs and choosing the best applications, location and method for renewables whether it is actual generation behind the meter, power purchase agreements, or virtual power purchase agreements.

Climate change, legislation, and even institutional goals are often interwoven. If climate models are reviewed for each area of the country, there is typically a forecast of trends for the next few decades for how the climate is expected to change in a particular region. For example, if significantly more rainfall or precipitation in the late winter and spring seasons is projected and the district energy system has already been subjected to multiple floods over the last few decades, the district energy management should have discussions on what steps can be taken to reduce the risk to the system and add system resilience. There are carbon neutrality goals that have been adopted or considered for district energy systems. It is imperative to the success of a district energy system that the district energy manager is at the table for these discussions to furnish relevant information, costs, and challenges including cost, schedule, management commitment, and possible construction interruptions that would be required to successfully meet these goals.

Legislation could also significantly affect district energy systems. If legislation was passed that taxed carbon at $40 per ton, district energy systems would generally modify operations and the cost structure would certainly change. Similarly, if directional boring and fractionation become illegal, the costs to operate a natural gas plant may change quickly and drastically. Electricity prices in many areas of the country would also change and in most cases, significantly increase. Cooling district energy systems with refrigerant could also change with legislation requiring refrigerant conversions, resulting in significant capital outlays for either new chillers or retrofits to existing chillers and a potential loss of capacity by de-rating a chiller. Refrigerant replacements are expensive and may require service interruptions if scheduled improperly. The cost of a new chilled water plant varies based on several factors but can begin at $2,000 - $4,000 per ton and if a district energy system has to replace a 30,000-ton system, a $60 million cost certainly may lead to consequences based on the phase-out of existing refrigerants and the costs and effectiveness of new refrigerants.

Interstate electrical grids, interstate and international natural gas pipelines, LNG terminals, electricity production (hydro, natural gas, nuclear, coal, and renewable energy), exploration and production (E&P) of oil and natural gas, and independent system operators are all critical pinch points for the United States energy infrastructure. The grid in the United States is old and in need of repair and upgrading. The cybersecurity risk of utilities in the United States is frequently the subject of industry journals and a serious concern of the Department of Homeland Security. Individual district energy systems and independent system operators have performed risk analyses and made strides on securing some systems, but with the interconnection of these systems, weak areas within our complex electrical grids are likely.

Controlling physical access to a district energy system and preventing electronic access from outside of the system requires constantly evolving vigilance. District energy systems need continuous safeguards in place with contractors and employees, on interfaces with the connecting infrastructure, with the pipelines and the quality of the fluids or gases within those pipes, with the electrical grid to verify an ability to isolate from the grid if necessary, and even for the chemicals being purchased and incorporated into the processes.

World trade, weather, import tariffs, tax rates, economics, tax revenue, pandemics, unemployment, educational systems, vendors, products, retirements, new energy delivery systems and terrorism are all externalities that could modify the way business is done. District energy managers need to be able to adapt quickly to changing goals and parameters.

This chapter displayed the knowledge map (Figure 3.1) and described in detail all of the aspects, components, descriptions, and the interface with the other aspects of the knowledge map. The first sections described the importance of understanding the administration goals and the strengths and weaknesses of the existing district energy management staff and where efforts may need to be focused on financial, environmental, human resource issues, safety or capital project issues. This knowledge map recommends a path to align the staff with the management and the goals of the institution. The next section covers the flow models, energy use indices, succession plans and engineering studies. Coordination of the district energy management with master planning, goals, and sustainability are included. The next section delves in each of the four main components for the district energy system and details some of the considerations of the production, distribution, demand, and externalities with the inclusion of the district goals. Both internal and external risk parameters are depicted with descriptions and discussion of the potential risks. A continuous loop is also shown to adjust, learn and grow based on the district energy outputs.

CHAPTER 4. CASE STUDIES

The best way to see the utilization of the framework is to view the applications with case studies. Five cases are discussed in this chapter.

4.1 Case Study One – Power Plant Goes Off-line

On occasion an event occurs that is either external or internal to the district energy system that can cause the entire production to go off-line unexpectedly. Such an event will be used as an example for Case Study One. In early December around 10am, when the temperature was 40 degrees F, a power outage tripped the boilers and the electrical generation and steam production went to zero. Four or five operators were running the plant and the plant manager happened to be walking into the production control room when this occurred.

Questions mentioned in Chapter 3 on methodology came into play. Was this an operational, an economic or engineering issue? What was the role of the district energy manager or the manager of that area (power plant manager)?

Figure 4.1 below is a framework for making decisions for the district energy manager. Starting at the first node, the problem had arisen and the question was whether this was core to the mission. In this case it absolutely was core to the mission as resilience is high on the goal list. The next question to answer was does this issue demand an immediate resolution. The answer was yes. Because this required a fast resolution, satisficing or taking a heuristic approach was the preferred methodology. Three steps are listed. 1) Benchmark goal: get the power plant back on-line as soon as safely possible. 2) Assess options: the operating shift supervisor led the effort to determine how to bring the power plant back on-line despite the presence of the power plant manager in the control room. 3) Select the first option that is good enough: the operations shift supervisor led the effort and directed the operators to bring the plant back on-line. With decades of experience working in the plant, the shift supervisor had the experience required to get the plant operational again. Most of the other operators also had many years of operations experience in the power plant and were cross trained in multiple operation roles. What should the plant manager or district energy manager have done in this situation? The best thing for the plant manager and the district energy manager to do in these situations is to support the operations shift supervisor. The best way to do that is to communicate effectively to others in the organization. In this case study, with the plant manager already present in the control room, that plant manager should immediately contact the district energy manager (the next level up in the chain of command) and continue notifying them of developments until directed otherwise. It is important to have previously prepared a communications plan that is readily available in the file. This plan should identify the responsible parties for the coordination through the chain of command and to media. A short list of additional contacts should be considered for notification in this type of outage. Possible considerations would be to verify that all of the subsystem managers have been notified along with critical customers in the district energy system, which may include fire, police dispatch, or a centralized data center. The other systems in the system of systems will be involved and play their part in the recovery.

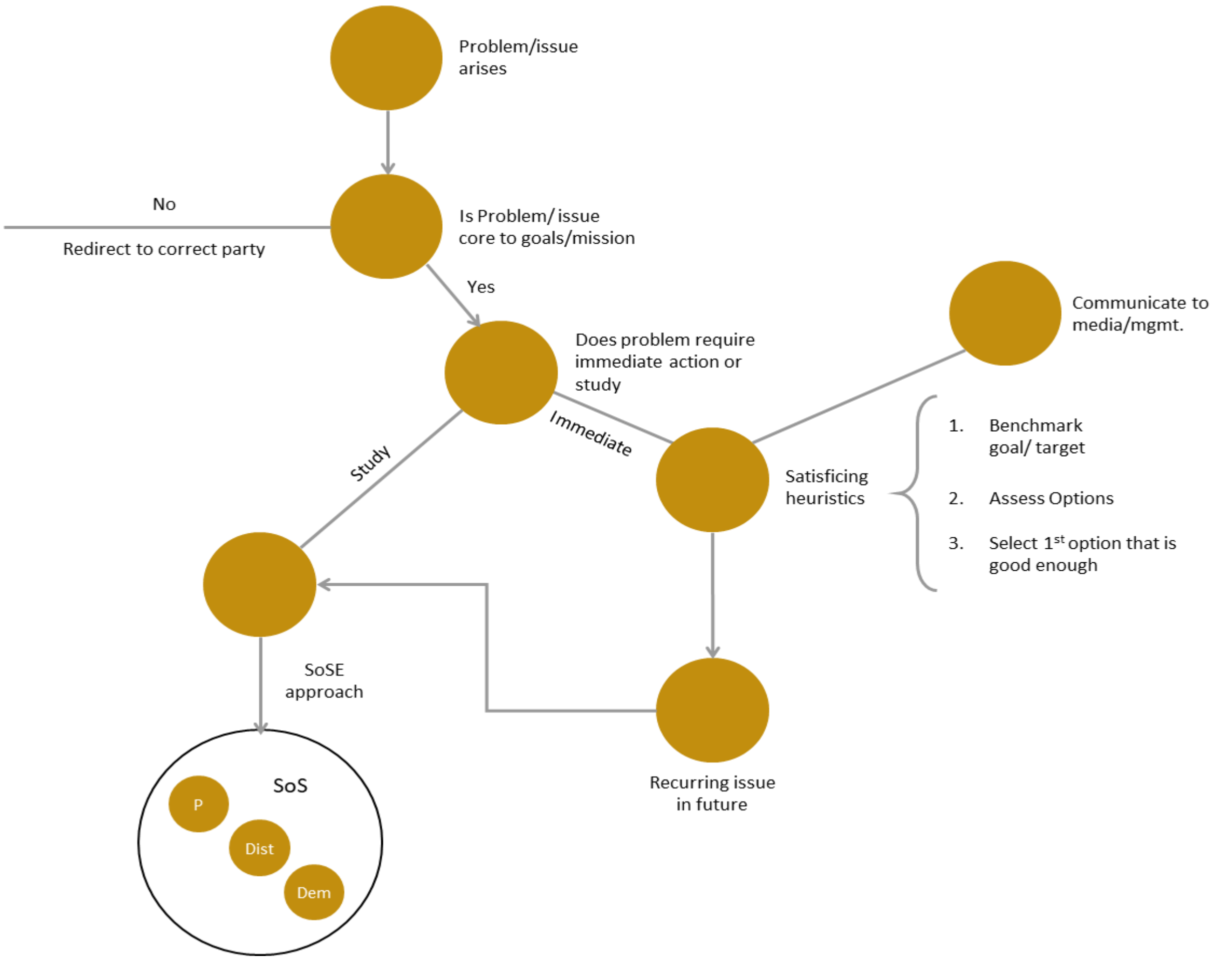

Figure 4.1 Decision Step 1 – General

4.2 Case Study Two – Campus Steam Pressure Drops

Geographically located in a polar vortex, the district energy system was experiencing record low temperatures with frigid wind chills. The campus was fully occupied and the weather was expected to last another two days. The campus had been growing for a number of years, and with this bitterly cold weather the pressure on the 125 psig steam headers to campus at the farthest end of the district from the steam production facility was at 75 psig. When the pressure of that header drops to 75 psig, the pressure reducing valves cannot be depended on to maintain the campus 15 psig header. In addition to building HVAC use, the steam in the district energy system was used for autoclave sterilization, humidification, laundry, dishwashing facilities in food courts, and instantaneous water heater systems for showers and personal hygiene.

Figure 4.1 can once again be used as a framework.

Proceeding through the questions revealed an immediate problem that required resolution. If this happened once and the district continued to grow, it would probably happen again. The district energy manager needed to satisfice an immediate solution while being aware that ultimately a longer-term solution would need to be developed and implemented. A combination of solutions was applied that resolved the problem for this occurrence. The pressure on the steam header exiting the plant was at 121 psig and that was raised to 125 psig. The 125 psig line was significantly superheated and the superheat temperature was lowered to the capacity of the desuperheater. Both of those activities increased the pressure of the header. The pressure drop of the header is always the lowest between 6-9am on weekdays. Part of the reason for that morning dip is because air handling units in academic spaces are scheduled off and are coming back on-line. By pre-heating buildings more during the night, we were basically able to shift some load. Additionally, where possible the perimeter heat remained on during the night and served as thermal storage to reduce the morning peak. There was not one solution that would have solved the entire problem for that polar vortex, but taking the system of systems approach addressed the issue satisfactorily. The proposed longer-term solution will be part of the scope and is reflected in Case Study Five.

As we have already stepped through Figure 4.1 for Case Studies One and Two, it is time to include the district energy goals and more detail in the benefit/cost/timing analysis to evaluate the potential options. These additions and clarifications are included into Figure 4.2.

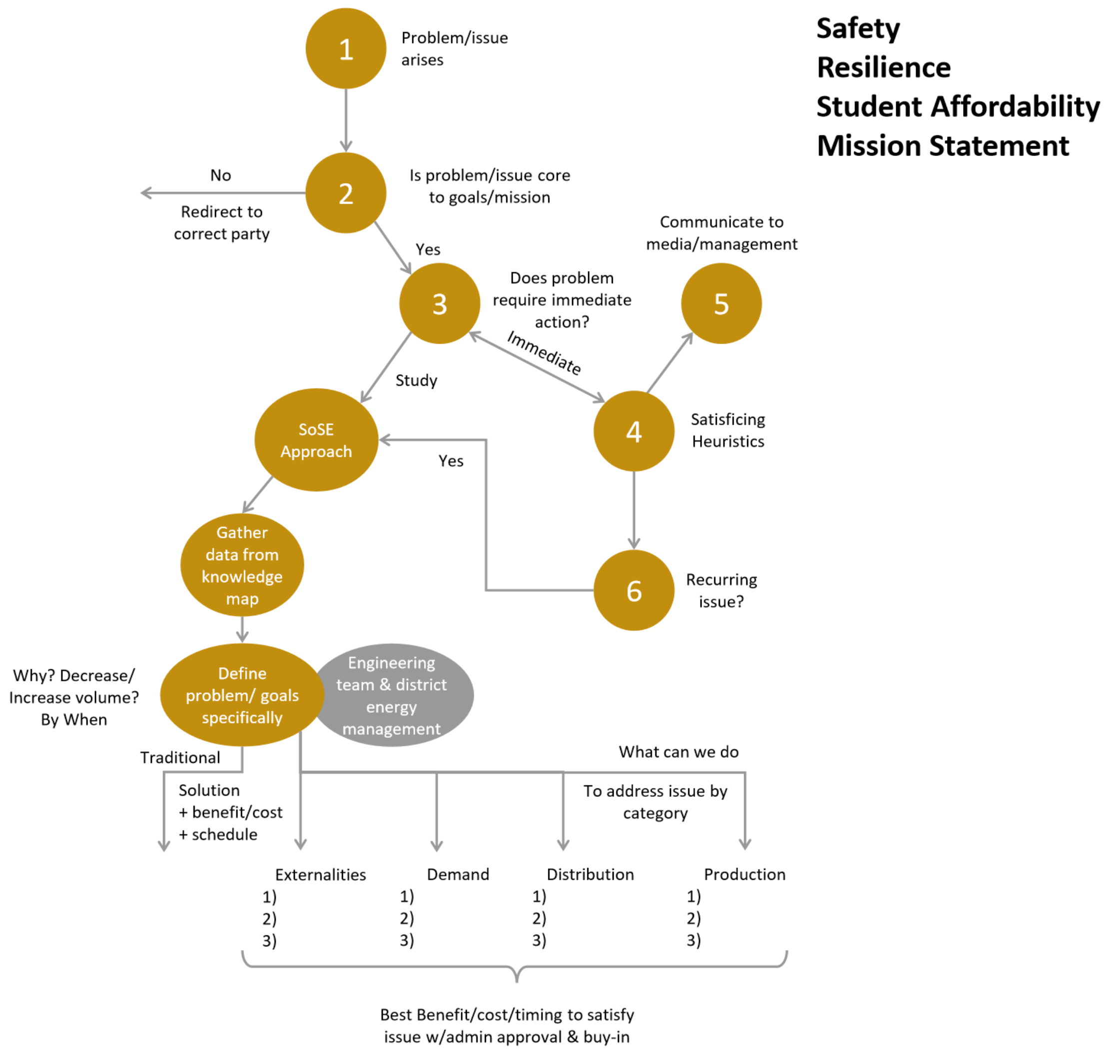

Figure 4.2 Expanded Framework for Decision-Making on District Energy Systems

4.3 Case Study Three – Outlying Building Added to Campus

As a proof of concept, the district energy system utilized in case study three is located several hundred miles west of the district energy system used in the other case studies. This case study utilizes the expanded framework as shown in Figure 4.2.

The parent institution of the district energy system acquired an existing 145,000 gross square foot building. An architectural and engineering firm was involved in building envelope upgrades. Mechanical upgrades were also needed. The owner and district energy system manager determined that this building will be utilized for at least twenty years.

The district energy system at this location has a chilled water central plant and distribution and a steam plant that distributes 35 psig steam to the district at 325 degrees F. This district energy system does not have a combined heat and power plant and purchases all of its electricity from the regional public owned power and electric utility.

The parent institution requested a recommendation on utilities serving this building from the district energy system management. Node 1 of Figure 4.2 is “Issue arises” and the parent institution has asked the question about utilities. Node 2 is “Is problem/issue core to the goals and mission” of this district energy system. As the parent institution of the district energy system has asked the question and this newly acquired building is located in the vicinity of the district energy system, the answer is clearly “yes” and we proceed to Node 3 of Figure 4.2.

Node 3 asks “Does problem require immediate action?”. The parent institution is looking for a recommendation covering a twenty-year period. If an immediate response is not required, the optional path is to “study” the problem using a system of system engineering approach. This request requires some study. To investigate this to make the best decision requires a collection of information from a knowledge map.

For this case study, I looked for information from a knowledge map, and requested very specific information from the current management of the district energy system. The district energy managers and staff furnished the following information based on their knowledge and history:

1. The building is located 1350 feet from the nearest campus steam, chilled water, and electricity (and is across a stream from the district energy system).
2. The location of the building is in an area with available land and real estate in its immediate proximity.
3. The cooling requirement of the building is 4,200 MBTUH.
4. The heating requirement of the building is 3,672 MBTUH.
5. The unit cost charged by the district energy system to customers for utilities is:
    a. Steam $7.40 / klb.
    b. CHW $0.056 / ton-hour

c. Electricity $0.057 / kWh

Note: No demand is charged on these utilities.

6. I requested the district energy system's cost information for the most recent boiler and chilled water additions along with the project costs and capacity of those additions. Based on my own experiences, these costs are reasonable compared to previous estimates and projects that I have done and reviewed.
    a. Boiler – estimated cost to add an 80 kpph boiler producing steam @ 250 psig and 500 degrees F is $6.55 million.
        i. Dividing the dollars by the capacity results in a steam capacity cost of $6,500,000 / 80 kpph = <u>$81,250 per kpph.</u> This will be discussed in more detail in the benefit cost analysis.
    b. Chiller project – installed chiller project including a 2500-ton chiller with chiller pumps, tower pumps, tower, and fan in a new chiller building for a cost of $6.2 million.
        i. Dividing the dollars by the capacity results in a chiller capacity cost of $6,200,000 / 2,500 tons = <u>$2,480 per ton.</u> This will be discussed in more detail in the benefit cost analysis.
7. Steam pressure distributed to campus is 325^0 F and 35 psig which is superheated by 44.4^0 F.
8. The maximum monthly consumption of natural gas to heat the domestic water is 270,000 therms per month.
9. Overall efficiency of chillers, towers, pumping and distribution per year is 0.732 kW / ton.

The information above is the result of my initial data request and the timely and complete responses that I received. The district energy system manager and engineers that I am fortunate to work with at this institution are very knowledgeable about their costs, systems, and efficiencies.

Now that the initial information has been attained from the knowledge map, we go to the next node in Figure 4.2 which is "Define problems/goals specifically" with an adjoining node "Engineering team and district energy management”. In a typical situation the team and management would be working to clearly define the goal and I will serve as that team for this case study.

The specific goal for this is to “Provide the utility recommendations with the best value for this newly acquired 145,000 square foot building.”

The next step in Figure 4.2 Expanded Framework for Decision-Making on District Energy System is to list the traditional solution and alternate solutions that may come from a combination of the production, distribution, demand or externality systems.

As the district energy system management was asked to provide the utility recommendations, a traditional solution would be to connect this building to the chilled water and steam distribution system. This will be the district option. As this case study is a proof of concept of the framework, I will expand the detail for the district energy option to identify some of the estimating considerations for evaluating the benefit and costs. I will furnish a summary of the recommendations.

District option – Obvious challenges to this option include crossing a stream and the potential for additional risks with a traditional steam and chilled water routing being underground. Moving toward a final decision, it is important to keep those risks in consideration as part of the cost/benefit analysis. Using the previously received information, the scope is to connect the building to the existing steam system with a minimum of 1,350 lineal feet of pipe steam via a distribution system and capable of providing 3,672 MBTUH peak.

- Steam at 325 degrees F and 35 psig [70]
    - Has an enthalpy of 1197.31 Btu/lb., so 3,672,000 BTU/hour / 1197.31BTU/lb. = <u>3,067 pounds per hour of steam required</u>
        - This is a stand-alone building and no other further expansion for the campus is expected at or near this site.

- Recommended velocity of superheated steam is 100-200 ft per second [71]. Using TLV steam calculator, a 3" ANSI Schedule 40 pipe at this flow rate and conditions would be 152 feet per second which is in the acceptable range.
    - v = Velocity (ft/sec)
    - ms = Steam flow rate (lb/h)
    - d = Pipe inner diameter (inches)
    - V = Specific Volume (ft^3/lb.)
    - v = Velocity = $((m_s) \times (V)) / (3600\pi(d/24)^2 = 152$ ft/sec.
- Superheated steam has a higher pressure drop than saturated steam due to the increased specific volume of the superheat. With a minimum steam run of 1,350 feet, it is important to verify that the pressure drop would be within an acceptable range with this superheated steam over this distance.
    - Pressure drop with the 3" pipe based on the equivalent length of straight pipe at the prescribed conditions = 25 psi, which is excessive.
        - Recalculation using the TLV calculator with 4" pipe (4.026" inside diameter) results in a steam velocity of 88 ft per second and a pressure loss of 6.71 psi, which is acceptable.

- The required line size for steam has been determined to be at least 4" schedule 40 pipe, and a district energy system would require returning the condensate back to the district energy system.

It is important to appreciate the value of using benefit cost analysis including schedule implications to evaluate options when using this decision -making framework in a system of systems engineering approach. The approach on this case study is to identify the options, then estimate each and determine present values of those options through a twenty-year time frame. The estimate required to establish the preferred option(s) does not require competitive bid estimates but should start with an order of magnitude accuracy of plus or minus 30%. If two options become differentiated as the best options and those options are relatively close, it is best to verify your risks and benefit at the time which may require additional clarification and study.

For this district energy option, I will use the RS Means Cost Data from 2012, convert the estimate from the 2012 US national average to the specific location utilizing Construction Cost Indexes with RS Means data and use that same resource to update the estimate from 2012 costs to January 2020 costs.

RS Means has a combined 6” steam line and 3” condensate line within a 20” case and the cost including labor, equipment, material, overhead and profit (LEMOP). I extrapolated the costs between the 6”/3” size and the 3”/1.5” size and that estimate is $410 per lineal feet. Assuming 100 additional lineal feet would be reasonable for an expansion loop or offset of routing in addition to the original 1350 lineal feet. Based on the frost depth at the location of the district energy system being around 50”, the top of the carrier pipe will be near that 50” depth from the surface. This will also be the case with the chilled water system.

This portion of the steam and condensate (S&C) cost is:

- 2012 US national average
    - Steam and condensate (S&C) line 1,450 lineal feet (lf) x $410 = $594,500.
    - Trenching for S&C carrier pipe 4’ wide, 6’deep 1:1 slope = 1,450 lf x $33.40 = $48,430.
    - Bedding for S&C carrier pipe 1,450 lf x $23.50 = $34,075.
    - Backfill and compaction around carrier pipe 1,450 CY x $54.90 = $79,605.
    - Backfill and compaction above carrier pipe 1,450 CY x $50.15 = $72,717.
    - Stream crossing or bridge $150,000.
    - Drains, vents, inspections and expansion infrastructure $125,000.
    - Subtotal construction costs for steam and condensate = $1,104,327.
    - S&C Engineering and design @ 7% of first costs = $77,303
    - Total S&C first cost construction and engineering = $1,181,630.

The next item to estimate is chilled water. The cooling demand of the additional building is 4,200 MBTUH. 4,200,000 BTUH / 12,000 BTUH per ton = 350 tons

Chiller ton = (GPM x Delta T (F^0)) / 24 – assume 15^0 delta T

350 tons = (GPM x 15) / 24 => GPM = 560 GPM

Using Cameron Hydraulic Data, at the 560 GPM volume, the 6” new steel pipe will have a velocity of 6.21 feet per second velocity and a head loss of 2.00 feet per 100 lineal feet of pipe. Assume the 1,450/100 x 2.00 =29.00 ft of head loss. Going to an 8” line size would drop the 29 ft head loss by around half. Increasing the line size from 6” to 8” will significantly add cost but also future capacity to that end of the district energy system. The assumption now is that the 29 ft of head loss during peak design hours for the district energy system is acceptable and reasonable and if this option is considered further, clarification of future expansion of this site of the district energy system is warranted and verification of the acceptability of the head pressure required.

The portion of this chilled water cost is:

- 2012 US national average
    - Chilled water supply and return (CHWSR) lines = 2 x 1,450 lf x $35.95 = $104,255.
    - Trenching for CHWSR = 4’ wide x 5’ deep x 1,450 lf x $17.91= $25,970.
    - Bedding for CHWSR = 1,450 lf x $30.20 = $43,790.
    - Corrosion wrap on CHWSR = 2 pipes x 1,450 lf x$3.70 = $10,730.
    - Backfill and compaction around CHWSR pipes 1,450 CY x $54.90 = $79,605.
    - Backfill and compaction above CHWSR pipe 1,450 CY x $50.15 = $72,717.
    - CHWSR crossing or bridge $150,000.
    - Drains, vents, inspections and expansion infrastructure $75,000.
    - Subtotal construction costs for chilled water = $562,067.
    - CHWSR Engineering and design @ 7% of first costs = $39,345,
    - Total CHWSR first cost construction and engineering = $600,412.
    - Total CHWSR & S&C first cost construction and engineering = $1,782,042.

Electricity, natural gas (for heating domestic water), potable water, and sewer at this building site will all be evaluated, revitalized, or replaced for all of the options on this case study. There will be no differentiating costs for the installation of the non-HVAC options so they are excluded from this analysis. Normal utility hook-ups are at no cost to the owner as long as commodity throughput charges will pay for the utility investment to serve that facility and this is a large enough facility to warrant that investment by the utility.

The base first cost for this “traditional” option has now been estimated and will be updated later in the study from the 2012 RS Means national average to 2020 cost at the location of this district energy system.

The next step utilizing Figure 4.2 is to identify some alternatives to the traditional approach that will answer the same scope; “Recommend the utility option with the best value for this newly acquired 145,000 square foot building.”. Once these alternative options are selected and confirmed, first costs will be estimated for those additional options.

The selected alternatives to the district energy system direct connection are:

1. Air cooled chiller and variable air volume system (ACC/VAV)
2. Water cooled chiller and variable air volume system (WCC/VAV)
3. Geothermal and heat pump system. (Geo&HP)

Performing a literature review of mechanical HVAC system options prevalent in the geographical area pertaining to this case study I found multiple sources of information that were helpful, including Shonder [72], [73], Battocletti [74], and Martin[75]. Within the literature sources mentioned here, first costs, energy costs, operation and maintenance costs were also discussed. Shonder [72] identified the three systems listed above and also included a water cooled chiller option with a constant volume air system. Constant volume systems are no longer normally included as a reasonable option due to the inefficiencies of those systems. I have excluded that as an option here. This article was published in 2000 and the original costs for these options were based primarily from 1995 numbers but some of the other costs such as operation and maintenance were based on 1999 and 2000 numbers. I have updated all of these numbers to 2020 values for the development of the benefit cost analysis between the base and options.

On Figure 4.2, options to the traditional solution are listed, which include externalities, demand, distribution, and production. The base consideration connecting to the district energy grid dealt with the production and distribution aspect. As this acquired building was scheduled to have upgrades on the building envelope, that demand portion was being addressed outside of this case study. That could also be considered as an externality per Figure 4.2.

The use of the acquired 145,000 square foot building is similar to the four 69,000 square foot buildings studied in Shonder[72] so the costs for the three options will be based per square foot basis. Estimated costs including engineering using 1995 dollars for the options from this literature were used and broken into categories to compare the benefit costs between the traditional and three options.

Here is a summary of the key assumptions, options and summary of the NPV benefit/cost analysis for Case Study Three:

Table 4.1 Case Three Summary of NPV Benefit/Cost Analysis with Inputs

	Key Assumptions / Inputs	
	Inflation	2.50%
	Discount rate	5.00%

	Cost Category	District	ACCVAV	WCCVAV	Geo&HP
1.1	**First Cost & Engineering**	$ 1,866,198	$ 5,483,461	$ 5,654,832	**$ 5,443,300**
1.2	**Maintenance Costs**	$ 142,735	$ 596,178	$ 604,103	**$ 562,574**
1.3	**Energy Costs - District**	$ 4,234,790	$ -	$ -	**$ -**
1.4	**HVAC Electrical Costs**	$ 502,918	$ 535,478	$ 488,625	**$ 528,064**
1.5	**HVAC Natural Gas Costs**	$ -	$ 346,714	$ 348,704	**$ 101,799**
1.6	**Water Costs**	$ -	$ -	$ 29,336	**$ -**
1.7	**Capacity Costs - Infrastructure**	$ 3,225,476	$ -	$ -	**$ -**
	Total	$ 9,972,118	$ 6,961,831	$ 7,125,599	**$ 6,635,738**

District, ACCVAV, WCCVAV, and Geo&HP costs were delineated over seven categories listed above 1.1 through 1.7. A net present value (NPV) calculation was done using Excel with over a 20-year period with the key assumptions on inflation and discount rate. Maintenance costs used in year 1 were from Shonder[72] but were also compared with other literature including Martin[75].

Although the unit maintenance costs were not identical with the two sources, the full NPV relative results regardless of which literature was selected would not have changed the answer.

Each of the four possible solutions were acceptable in providing a full solution to the parent institution's request "Provide the utility recommendations with the best value for this newly acquired 145,000 square foot building." A determination of the best solution was completed by evaluating four options with a benefit/cost analysis using a net present value calculation with each of the options based on a twenty-year occupancy of the newly acquired building. The geothermal and heat pump option has the best present value and is the recommendation to the parent institution.

4.4 Case Study Four

This case study looks into a chilled water system at a higher education campus' district energy system in the Midwestern United States. Currently the chilled water system serves about 14 million gross square feet of space. The gross square feet served by the chilled water system has been expanding, both with new buildings and added cooling in previously non-chilled buildings.
A comprehensive energy management plan was generated in 2010 and many optimization and replacement strategies for the chilled water system from that plan have been implemented. Chilled water meters were installed at each building and provide data including chilled water supply and return temperature and gallons per minute of flow.

A new campus master plan has recently been released requiring additional chilled water capacity to serve new buildings. This case study will be utilizing:

- Figure 4.2 – Expanded Framework for Decision-Making on District Energy Systems,
- Figure 3.1 – Knowledge Map for District Energy Management,
- Figure 3.8 – Production for the Knowledge Map,
- Figure 3.9 – Distribution for the Knowledge Map,
- Figure 3.10 – Demand for the Knowledge Map, and
- Figure 3.11 – Externalities Affecting District Energy Systems, the Knowledge Map.

With the release of the new campus plan, it is necessary for the district energy management to review the current status of the chilled water system, and determine the future chilled water requirements. Utilizing the expanded framework shown in Figure 4.2, we begin with Node 1 “Issue arises”. The issue of meeting additional chilled water needs on campus has presented itself as a result of the new campus master plan. Node 2 of Figure 4.2 directs us to determine whether or not the problem/issue is core to the goals and mission. Since the goals for this campus are currently safety, resilience, and student affordability, the condition of Node 2 is satisfied and we continue to Node 3. Node 3 of Figure 4.2 asks “Does problem require immediate action?” Immediate action is not required. The problem is a long-term planning issue that will require study. That brings us to the SoSE (System of Systems Engineering) Approach node. With the SoSE approach, the following node is “Gather data from the knowledge map”.

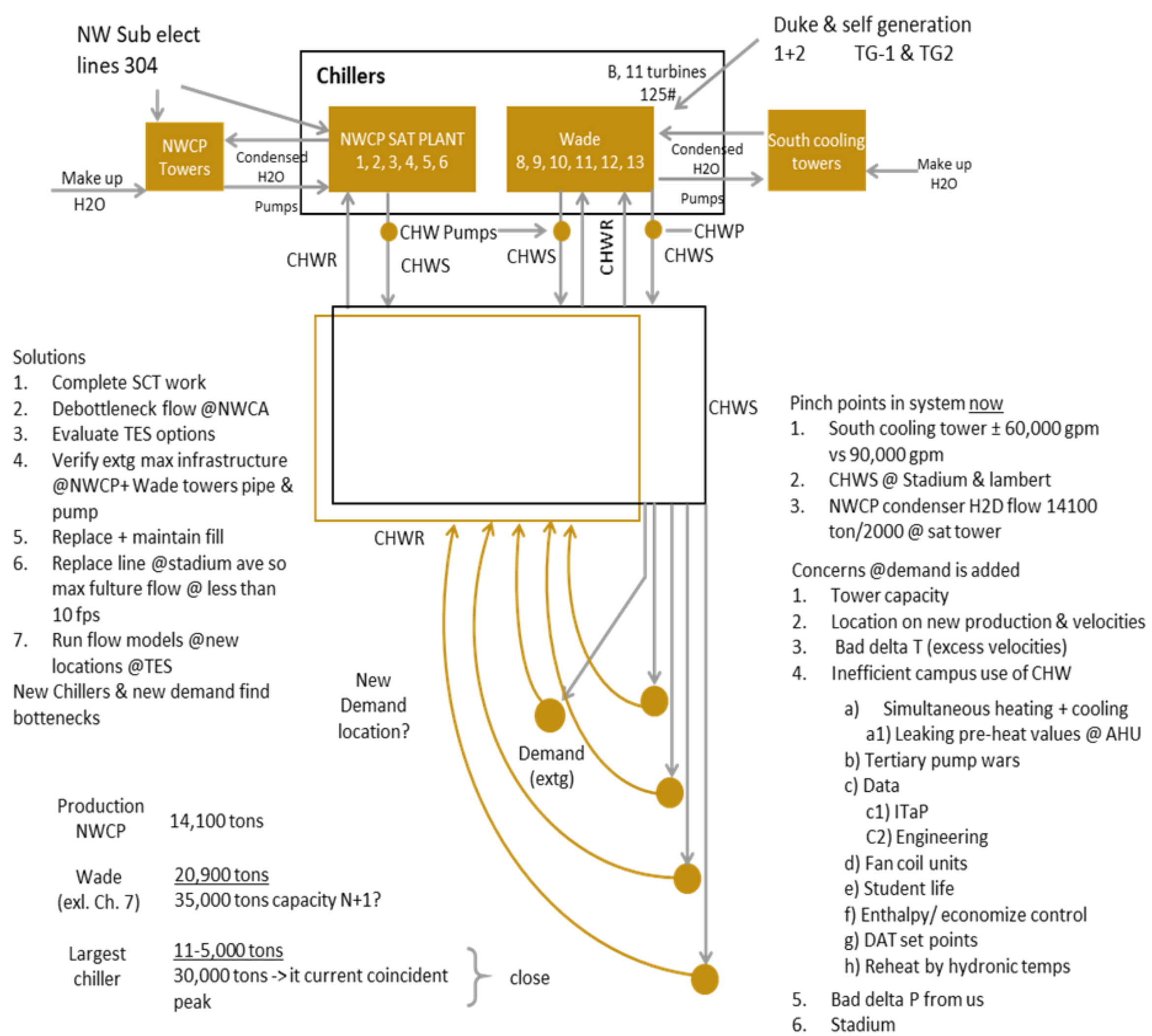

Figure 4.3 Chilled Water Considerations with Knowledge Map

Figure 4.3 is an example of what can be generated when the engineering team and district energy management group discuss the current status of the chilled water system and begin to investigate the specific items as noted before.

Specific items required for this case study include:

1. Proposed buildings with GSF, project completion dates and peak chilled water requirements for each new building (Table 4.2).
2. Chiller campus peaks over the last few years (Table 4.3).
    a. It is interesting to note that the peak chiller hourly load was in August of 2018 and not in 2019 or 2020. Utilities management, engineering, operations, maintenance and building control systems personnel have continued to work on improvements during the growth over the last several years. There are many variables to consider before making conclusions.
3. Current flow models for chilled water distribution and chilled water plant data.
    a. The models are intended to be updated again by 2021/2022 but we have a computer chilled water flow model from a few years ago which allows us to look at potential bottlenecks or excess velocities.
4. Chiller capacity, age, refrigerant, and operation and maintenance cost (Tables 4.4 and 4.5).
    a. The full capacity of the chillers at the main power plant (24,220 tons) plus the full capacity of the satellite chiller plant (14,100 tons) equals 38,320 tons. The campus coincident chilled water peak hourly demand over the last three years was 30,409 tons in August of 2018. With the largest chiller (chiller 11) having a capacity of 5,000 tons, the campus has recently been at N+1 (the peak capacity minus that of the largest chiller). 38,320 - 5,000 = 33,320 tons, which exceeds the current campus coincident demand of 30,409 tons.
    b. 33,320 - 30,409 = 2,911 tons of theoretical N+1 capacity remaining.
5. Verifying the adequacy of the capacity of the condenser system (Tables 4.4 and 4.5).
    a. The chiller capacity of satellite chiller plant is 14,100 tons and the total condenser water design requirement for those chillers is 41,500 gpm.

        i. There is an indication that the condenser water flow is not able to meet the requirement of the chillers running at full capacity. An engineering investigation is ongoing.

   b. The main power plant chiller capacity is 24,220 tons and the total condenser water design requirement is 64,100 gpm.

        i. There was a debottlenecking project for the cooling tower that serves the main power plant and the condenser water flow was intended to be increased to the original design of 90,000 gpm.

            1. Although on the surface view, the cooling tower condenser water flow exceeds the 64,100 gpm requirement of the chillers, there is a steam driven condensing turbine that requires a little over 22,000 gpm while operating. So, at peak chiller capacity, the tower must have the capacity of over 86,000 gpm, assuming there are no condenser water piping restrictions.
            2. Options to increase tower capacity are being evaluated and considered.
            3. An engineering flow model was used to depict the condenser water flow velocity when all of the main power plant chillers are running at full capacity. One section of the carbon steel piping showed a velocity of 12 feet per second during those peak occurrences. Ideally the velocity should remain under 10 feet per second. It is acceptable to exceed this velocity during short time periods but it is important to consider this piping restriction if the intention is to add chilled water capacity and condenser water volume at the main power plant in the future.

6. Energy use index for existing buildings by commodity (chilled water). Data not provided here in detail but used in analysis:
   a. Hourly flows available by building.
   b. Hourly chilled water supply and return temperatures by building.

Table 4.2 Proposed Building GSF, Peak Tonnage, and Building On-Line

Building	Size in GSF	Peak Tons (CHW)	Building On-Line
JA	32,000	**229**	2020
AB	126,000	**832**	2020
ST	111,000	**634**	2020
P3 MS & 3rd St		**596**	2020 / 2021
VM	162,000	**850**	2021
GW	245,000	**1501**	2022
NM	38,000	**80**	2024

Table 4.3 Top Five Peak Hours of Peak Days (one highest peak hour per day)

Date	Peak Hour of Day	Total Campus Tons
August 28, 2018	17:00 to 18:00	30,409
July 16, 2018	16:00 to 17:00	29,947
August 27, 2018	16:00 to 17:00	29,947
July 19, 2019	14:00 to 15:00	28,823
July 18, 2019	16:00 to 17:00	28,715

Table 4.4 Main Power Plant Chiller Information

Chillers	7	8	9	10	11	12	13
Tons	3000	4500	2000	2000	5000	3860	3860
Steam/Elect	Steam	Steam	Elect	Elect	Steam	Elect	Elect
Refrigerant	R22	R22	R123	R123	R134a	R134a	R134a
Installed	1988	1994	2000	2001	1999	2015	2015
O&M $	$$$$	$$$	$$	$$	$$$	$	$
CW GPM	9000	13500	4000	4000	15000	9300	9300

Table 4.5 Satellite Plant Chiller Information

Chillers	1	2	2	4	5	6
Tons	2000	2000	2000	2700	2700	2700
Elect	Elect	Elect	Elect	Elect	Elect	Elect
Refrigerant	R123	R123	R123	R123	R123	R123
Installed	2002	2002	2005	2007	2007	2012
O&M $	$$	$$	$$	$$	$$	$$
CW GPM	6000	6000	6000	7700	7700	8100

Information has been gathered from the knowledge map. Proceeding through the expanded framework for decision-making, we use this information to specifically define the problem and goals in conjunction with the engineering and management team. The specific problem is:

- The campus demand will be exceeding the capacity of the chilled water infrastructure in the next few years.
- Some of the existing chilled water assets are approaching end of useful life.
- Two of the existing chillers use R-22, a hydrochlorofluorocarbon (HCFC). As of January 1, 2020, R-22 is no longer produced in the United States and is banned from import.
- There is limited capital available to address the problem.
- Project approvals, engineering, and construction may take three years.

As a manager and with consideration of my conversations with the engineering, operations, and maintenance department I am defining the specific goal as "<u>Provide a five-year plan, recommendations and considerations for the district energy system chilled water system to meet the district's goals of safety, resilience, and student affordability."</u>

Now that the specific goal is in place, the options for how to proceed need to be considered. The traditional solution to meet the additional demand is to add chiller tonnage. The system of systems engineering (SoSE) approach considers the traditional solution but goes further by looking at the bigger picture and considering all of the other systems. Initially, I will look at the traditional solution. As N+1 is a typical district energy system method to assure reliability or resilience to be able to meet demand, N+1 should be maintained throughout the five-year plan. If that is not feasible, that additional risk should be noted to management. Let's look into other considerations based on the knowledge map and investigation. After the traditional solution is identified, bringing in items from Figures 3.8 (production), 3.9 (distribution), 3.10 (demand) and 3.11 (externalities) will provide a more complete picture from which a five-year plan, recommendations, and considerations can be generated.

The oldest chillers in the district energy system are shown on Table 4.4. According to the ASHRAE Equipment Life Expectancy Chart, well-maintained water-cooled chillers will run for 23 to 25 years. Chiller 7 was installed in 1988 and Chiller 8 was installed in 1994, so both chillers have exceeded their life expectancy. Chillers 7 and 8 are the district energy system's only chillers using

R-22 as a refrigerant. R-22 is no longer produced in the United States and the price is continuing to increase. Additionally, Chiller 7 has been having maintenance issues and is running in 2020 for the first time in over two years. Chiller 8 is a steam driven chiller that is expensive to maintain. Chiller 11 was installed in 1999 and would be the next chiller to be replaced after 7 and 8 based on life expectancy. That removal and replacement should be in the early planning stages now. Connecting the dots between the current campus peaks, the schedule of the new buildings coming on-line, and the retirement and replacement of chillers is required to understand the beginnings of the plan for the next five years.

It is important to think through the concept of peak demand by building and coincident peak demand of campus. The goal of this district energy chilled water system is serving the campus. A specific goal of maintaining N+1 of the campus demand has been stated. As noted in Table 4.3, the peak campus chilled water was in August of 2018. Since 2018 there has been campus growth with more students and more gross square feet of chilled water buildings being added to the chilled water district energy system. How did the peak demand of campus decrease over the last three years with more students and more space to cool? There can be many reasons to consider. The campus has worked to operate more efficiently over the last few years which could be a factor in the peak demand decrease. Additionally, the hot and humid peak days may have occurred in August of 2018 when the campus was fully occupied compared to the other annual peaks. Realistically with the complexity of the campus and a district energy system there are many contributing factors. I recommend continuing to look at the data and updating peaks by building and coincident campus peaks each year. Utilizing hourly peaks as the N+1 basis has worked well over the years.

During a five-year span, seven buildings will be added to campus (Table 4.2). Each building had a peak chilled water demand identified by the engineer of record for the building. As we noted above, when new buildings are added the coincident peak demand does not always record a new coincident peak over the next few years. I recommend looking at individual building peaks verses the campus coincident peak. Will the peak demand by building have a 1:1 effect on the peak coincident campus demand? To determine that answer, we consider that the campus coincident peak occurred on August 28, 2018 at 5-6pm. I selected eight buildings representing three different building classes;

- 3 laboratory buildings,
- 2 student life residential buildings, and
- 3 classroom/office buildings.

Chilled water consumption for each building during the August 28, 2018 coincident peak demand of campus was recorded and listed. The peak one-hour chilled water demand for each year 2018, 2019, and 2020 (up to July, 2020) was recorded for each of the eight buildings. The recorded peak of each building vs. the coincident peak was recorded to determine the relationship between the building design peak and the campus coincident demand. I smoothed the building peak by determining the average peak for each building type over the three years and compared it to the coincident campus peak demand. Results of that analysis indicated that the coincident campus demand peak for each class of building was 93% of the building peak. To clarify, if a new building peak was estimated to be 500 tons by the engineer of record, I would expect that 465 tons (500 x 0.93) would be the contribution of that building to the new coincident peak demand of campus.
I will use the same process to determine the production requirements for the buildings in Table 4.2 and the increase of the annual chilled water campus coincident peak by building excluding changes in weather, population or building operations.

Utilizing the 0.93 factor mentioned above, here is the coincident demand peak increase by year for the next five years (this will be subject to change if additional projects are approved):

- 2020: New buildings = 1,695 tons, coincident campus peak = 1,576 tons.
- 2021: New buildings = 1,446 tons, coincident campus peak = 1,345 tons.
- 2022: New building = 1,501 tons, coincident campus peak = 1,396 tons.
- 2023: No new buildings to be completed.
- 2024: New building = 80 tons, coincident campus peak = 74 tons.

Two buildings have come off-line to facilitate construction in 2020 and their total tons contributing to the campus peak was 121 tons. Those are the only buildings scheduled for decommissioning at this time.

- 30,409 tons @ coincident campus peak – 121 tons = 30,288 tons revised.
- 33,320 tons (N+1 capacity) – 30,288 tons = 3,032 tons (calculated excess N+1 capacity).

Table 4.6 N+1 Status in 5 Years If There are No Chilled Water Capacity Changes

Year	Initial N+1 Tons	Added campus	Balance capacity
2020	3032	1576	+1456
2021	1456	1345	+111
2022	111	1396	-1285
2023	-1285	0	-1285
2024	-1285	-74	-1359

Table 4.6 above assumes that the proposed buildings are added to the district energy system with no additions or deductions in chilled water tonnage, and that the condenser water capacity remains sufficient for the chiller tonnage at full capacity.

In a case like this with multiple issues to address within the specific problem, two or more items may be blended into a traditional solution. The traditional solution in this case:

1. Perform a heat and mass balance of the main power plant's annual operation to determine the benefits, costs, and risks of having steam driven chillers (centrifugal or absorption) verses electric chillers. There may be an economic advantage to having chillers that are driven with 125 PSIG steam. With the additional 125 PSIG steam demand during the summer, additional electricity can be generated with the existing 10 MW backpressure turbine. The back-pressure turbine has a heat rate of less than 4,000 BTU/kw so the cost to produce electricity with this turbine is lower than market costs.
2. Maintenance, operations, refrigerant and future needs should be considered in this analysis for all chillers, cooling towers and associated equipment.

3. Update the existing chilled water engineering flow model to include all new buildings and loads that have been added and will be added through 2024.
    a. Identify distribution bottlenecks with high pressure drops, high flow velocities or inadequate chilled water capacity for all existing and new buildings.
    b. In consideration of potential future growth per the campus master plan and 3a (immediately above), determine potential location(s) for a new satellite chiller plant site.
4. Determine variable condenser water flow through operation ranges 6 – 30 MW of the 30 MW condensing turbine by consulting with the original manufacturer's engineer. This is needed to determine the water capacity of the main power plant condenser system that can be dedicated to the chilled water system.
5. As chillers will be need to be added, verify the condition and capacity of the chilled water supply and return headers entering and leaving each of the existing production facilities. Perform a pinch point analysis to determine the maximum flow capacity in GPM and tons from each existing plant.
6. Add 4,500 to 9,000 tons of cooling.
    a. Install one chiller (minimum 4,500 tons) at the main power plant and install condenser water capacity for a minimum of 1,500 additional tons of cooling, after commissioning is complete and the chiller is operational, then;
        i. Remove the 3,000-ton R-22 chiller (Chiller 7 from Table 4.5).
    b. Install the second chiller (4,500 tons) at the main power plant or at another campus location. As this is the traditional solution, the estimated cost will be based on the installation at the main power plant. After the chiller is installed and commissioned, then;
        i. Remove the 4,500-ton R-22 chiller (Chiller 8 from Table 4.5).

Accomplishing steps one through six above will result in a gain of 1,500 tons of capacity plus the removal of the two R-22 chillers. This meets the forecasted additional tonnage requirements for 2024 as listed on Table 4.6. It is important to keep in mind that other proposed projects may be approved that will add to the additional tonnage required by 2024.

This is the traditional solution. The next step is to determine an estimated cost for this traditional solution. Items one through five of the traditional solution do not require capital but do require engineering focus. The district energy management may choose to perform all of these steps internally or they may choose to augment their staff with outside expertise.

Using historical information for estimating is a good conservative approach for estimating future costs. In 2014 at the main power plant, a large steam driven chiller was removed and two new chillers were installed. There are records of hard costs and soft costs that can be used as the basis of estimating 6.a, 6.a.i, 6.b, and 6.b.i. The location and complexity of the 2014 work can be compared to the present case. In this case the complexity, location, and access are similar. Proceeding with the estimate:

- 6.a – In 2014, two chillers were purchased, installed and commissioned with all auxiliaries including mechanical and electrical gear and control interfaces at the main power plant at a cost of $1,250 per ton. This included engineering, structural modifications to the facility, and connections to the existing cooling tower and condenser water lines.
    - 2014 chiller cost of $1,250 per ton (R.S. Means nearby city cost index of 188.4).
    - 2020 chiller cost conversion (R.S. Means nearby city cost index of 217.7)
    - 2020 => 4500-ton chiller: 4,500 tons x $1,250/ton x (217.7/188.4) = $6.5 million.
- 6.a.i – In 2014, the estimated cost for the removal of Chiller 7 (including engineering) = $187,000.
    - Using the same conversion indices as shown in 6.a; $198,000 x (217.7/188.4) = $230,000.
- 6.b – 2020 => 4,500-ton chiller: same as 6.a = $6.5 million
- 6.b.i – 2020 => Chiller 8 removal (including engineering) = $230,000.

As this may be a series of projects, one may want to consider adding an inflation factor to 6.b and 6.b.i. Even with an immediate approval it may be a year before the chillers are purchased and the project is competitively bid. Some consideration to contingency should be included in the process.

Depending on the timing of the project and construction, the removal of Chiller 7 or 8 may be beneficial before the placement of the new chillers. The goal is to maintain N+1 capacity at all times, so if the demolition and construction could be completed between the months of September and April, all of the chiller capacity would not be needed during those months. There is a location on campus that has chilled water headers installed and available for the direct connection of four 500 - ton air-cooled temporary chillers. It may be cost effective to consider that as an option as the project and schedule is being developed.

Table 4.7 Traditional Solution (2020 dollars)

Item	Description	Tons	Cost
6.a	Add Chiller 14	+4,500	$6,500,000
6.a.i	Remove Chiller 7	-3,000	$230,000
6.b	Add Chiller 15	+4,500	$6,500,000
6.b.i	Remove Chiller 8	-4,500	$230,000
		+1,500	**$13,460,000**

Now that we have an estimated cost of the traditional solution, we can look at alternatives to evaluate benefits, costs, and risks. Taking a system of systems engineering approach as an alternative to the traditional solution may include:

1. Production – Add a new satellite chiller plant on campus.
2. Production – Add distributed chillers on campus to act as base load or peaking chillers.
3. Production – Maintain chiller efficiency, optimize chiller dispatch and optimize the cooling tower systems and condenser flow to the chillers.
4. Distribution – Add a thermal energy storage tank or expand the use of the distribution system for thermal energy storage.
5. Distribution – Verify the programming of all chilled water building pumps to optimize the distribution process flows and eliminate pump wars and chilled water blending at buildings.

6. Demand – Reduce the chilled water peak by building with building optimization and chilled water demand control.
7. Demand – Verify that the chilled water delta T at all buildings meets or exceeds 15° F which will reduce the chilled water flow velocities on the distribution system and reduce pressure losses.
8. Demand – Verify that all of the steam or hot water pre-heat control valves maintain a positive 100% shut-off to prevent peak simultaneous heating and cooling.
9. Externalities – Identify the buildings and chilled water load on campus where chilled water peak demand could be shed completely or reduced based on building utilization, prioritization of needs, or scheduled events.

Often an advantage of using a system of systems engineering approach is a cost-effective combination of solutions.

Using experience along with discussions with engineering, operations, and maintenance, a list similar to the one above can be generated. The next step, using the expanded framework for decision-making (Figure 4.2), involves evaluating the identified options on the basis of benefits, costs and timing to satisfy the issue with administration approval and buy-in.

<u>Production Options</u> - Adding a new satellite chiller plant may cost twice the dollars per ton due to the infrastructure upgrades required for a new location, including the addition of a significant electrical system that may be in the 1 kW per ton capacity range and be equal to or exceed 4,800 volts. Additionally, the distribution system piping should be sized for the full capacity of that chiller plant, even if the current intent is to add 1 or 2 chillers in a satellite plant that will eventually have the capacity of four to six chillers. Assuming the use of water-cooled chillers, cooling tower capacity will have to be installed for the first phase of the chiller implementation but the water source and physical footprint should be established for the balance of the towers that will be required for the full capacity of the satellite facility.

Adding or using distributed chillers on campus can be beneficial. It is best to incorporate new distributed chillers within the design early for any new buildings. The buildings currently in design on the five-year plan are past the logical point where chillers could be incorporated into the building. One site had been identified in the previous five years for adding up to two 2,700-ton chillers in a remote section of the campus which would have been an excellent location in light of the distribution bottlenecks in that area of campus. That location was to be incorporated into the ground floor or basement of a new facility. Currently that proposed expansion in that area of campus has been delayed indefinitely.

The other alternative in this option is to identify any chillers that may be currently distributed on campus. There are two locations served by the chilled water grid that have local chillers in place to augment the existing chilled water systems. One of these chiller locations is at the site of a data center and the other location is at the site where intensive lab research is done. The chilled water capacity in these areas is in the 200 to 400-ton range. As utilities are not currently billed to individual users or buildings, it is recommended that an engineering review of these chillers be done with a dual focus. Firstly, is there a way to better utilize those chillers and have them function more optimally and efficiently with the central chilled water system? Secondly, can additional chillers be added at these sites to augment the capacity of the chilled water system at a more economic cost as a whole than the other alternatives? It could be that adding 400 tons to an existing 400-ton building system can reduce the coincident campus peak by that amount and that the addition of that 400 tons is cost effective when compared to the plant capacity additions. Although it is unrealistic to expect this to solve all of the capacity issues, a solution such as this can assist in the sequencing of capacity additions and demolitions at the main campus plant and be cost effective.

The campus does a very good job of keeping the systems maintained and all tubes are cleaned annually on the chillers and condensers. There are some steps that can be taken on dispatch optimization which should trim the chilled water annual costs but at the coincident peak demand all of the chillers will be operating. Engineering, operations and maintenance are currently evaluating and calibrating all of the instrumentation and flow meters. Engineering is currently conducting a detailed condenser water and cooling tower analysis including an update of the current condenser water flow at both the satellite and chiller plant. This will determine the maximum chiller demand, output, and the coincident condenser demand flow, plus verify the pump curves and the tower capacity.

Distribution Options - Thermal energy storage can be a good alternative to adding chillers to the production of a campus. Reviewing engineering studies, as noted on the knowledge map, we see that adding a chilled water thermal energy storage was studied during the comprehensive energy master plan in 2010. At the most basic level, thermal energy storage systems could be considered a wide spot in the distribution system that allows for charging this chilled water storage at night and distributing it in the day, thus reducing peak demand. An additional benefit is that chillers and towers can also operate more efficiently at night with lower wet bulb temperatures. Also, depending on campus electricity consumption and electrical contracts, hourly electricity prices are typically lower from 10 pm through 6 am. The combination of operating the chillers more efficiently at a lower kWh per ton and the cost of the kilowatt-hours consumed being at two cents per kWh less than during peak cooling electricity costs will bring the operating costs down. Another benefit is that if a chiller trips off-line and there is any kind of delay in meeting the coincident peak demand at that moment with chillers, the thermal energy storage will mask or smooth the demand curve. Thermal energy storage tanks do not have moving parts, require little maintenance and have a low life-cycle cost. Additional pumps will be required to distribute the water. The size and aspect ratio of a tank will allow for thermal stratification of the chilled water tank for effective charging and discharging of the tank. This campus has chilled water demand every hour of the year of at least 4,000 tons. The campus has installed the equipment necessary to produce "free cooling" by not using refrigerant when the outside air temperature is below 40^{o} F. With a thermal energy storage tank, more "free" chilled water could be produced during the winter months to charge the tank at a lower kWh per ton. Using the engineering study from 2011 that evaluated a thermal energy storage (TES) system, it was determined that a 5-million-gallon steel tank would be the ideal size. A tank of this size would have a peak tonnage reduction of 8,000 tons and a storage capacity of 47,000 ton-hours. A location was included and the distribution piping and equipment was estimated in 2011 dollars.

- 5 million-gallon TES tank and piping = $10,000,000 (2011 dollars) with RS Means city index of 173.0.
- 2020 dollars (RS Means city index of 217.7 =>
    - o 2020 dollars => $10,000,000 x (217.7 / 173.0) = $12,584,000.

Adding in $460,000 to remove the R-22 chillers brings the total estimate for this option to <u>$13,044.00</u>. Installing the 5-million-gallon thermal energy storage system would be the equivalent of an 8,000-ton reduction of peak tonnage. The traditional solution recommended adding 9,000 tons of cooling capacity and removing two R-22 chillers (end-of-life) at a total cost of <u>$13,460,000.</u> These two total cost figures reflect first costs only. A more thorough benefit/cost analysis is required. Incorporating the maintenance cost differential between chillers and thermal energy tank storage along with the day to night electricity load curve shift yields an energy and demand combined kWh savings of at least 1.5 cents per kWh. Table 4.8 depicts the advantage of TES over adding chillers based on a 20-year schedule.

Table 4.8 Case Four Summary of NPV Benefit/Cost Analysis with Inputs

	Key Assumptions / Inputs		
	Inflation	2.50%	
	Discount rate	5.00%	
	Cost Category	**Chillers 14 & 15**	**TES**
1.1	**First Cost & Engineering**	$ 11,898,540	$ 12,119,952
1.2	**Maintenance Costs**	$ 334,761	$ 36,421
1.3	**Energy Costs**	$ -	$ (2,383,564)
	Total	$ 12,233,301	$ 9,772,810

Additional distribution opportunities during peak chilled water days mentioned above [76] were part of an email exchange with Dr. Braun and the author early in the summer of 2020. The discussion included precooling campus buildings overnight as another form of thermal storage, and dropping the chilled water production temperature on the chilled water distribution header as an additional way of storing chilled water and shaving peak demand and shifting load.

The campus chilled water production and distribution is based on the distribution head pressure required to give the campus the necessary pressure to operate without building pumps. Many buildings do have chilled water pumps. Ideally, they are only used when an individual building's set-point requires the pumps to generate a building differential pressure. Some building operations have manually placed the pumps in operation which can be problematic since individual chilled water pumps can affect the operation and pressures of the chilled water distribution system in adjoining buildings. These outliers need to be monitored and addressed to avoid “pump wars” between buildings.

Demand Options – Two effective means of eliminating tons of demand are reducing the chilled water demand in buildings and reducing the coincident peak chilled water demand of campus.
If there are relatively high velocities in the chilled water distribution system, such as greater than 10 feet per second with carbon steel for extended periods, it is beneficial to review the delta in temperature (delta T) of the supply and return chilled water headers at that building. The lower the delta T temperature, the less efficiently the building’s chilled water system is being utilized. By increasing the building delta T to more closely align with a design delta T of 15^{o} to 18^{o} Fahrenheit, the velocity and volume of chilled water will be reduced along with the pressure drop in that section of the distribution system. Reducing the delta T at the building is much less expensive than replacing chilled water piping systems with larger pipe sizes.

Another simple demand element in a building that is sometimes ignored is reviewing the steam preheat valves and chilled water valves at the major building air handling units. There are normally enough temperature data points available on the building control system to verify that the steam valves are in good condition. Steam valves should have an absolute isolation so that steam doesn’t preheat the outside air when it is not required. This preheating results in simultaneous heating and cooling which contributes not only to wasting energy at the building, but also directly contributes to the coincident peak demand of chilled water.

There may also be opportunities to shed the chilled water (or steam) load with better scheduling of air handling units, utilization of enthalpy control and economizer optimization.

Externalities Option - There may be buildings with seasonal use or certain venues that could have greatly reduced energy consumption such as for the chilled water for a football stadium in July or steam heating in February. All buildings need to be protected with weatherizing, maintaining proper humidity levels, and ventilation. Many campuses have distributed data centers, department computing labs, or multiple servers that require augmented cooling. These computers and server spaces should be inventoried to verify that efficient equipment is being utilized effectively. Cloud computing, in lieu of these distributed centers may be very cost effective.

Eliminating the need for tons or ton-hours of chilled water can delay the demand for additional future production and distribution capacity. Currently with the Covid-19 pandemic, operations have changed with district energy systems, and heating ventilating and air-conditioning operations. To achieve ventilation and maintain the safety goals, many air handling units are now operating 24 hours a day and 7 days a week to ventilate buildings. This safety need has reduced the ability to pre-cool buildings and reduce outside air based on occupancy.

Currently, depending on the business model, customers may or may not be paying for utilities based on actual costs or demand. If it is currently not being done, an additional externality option is to add direct utility billing to current customers, including a demand component and/or connection fee. This would likely encourage the end user to modify behavior in order to reduce costs by reducing consumption.

This chilled water case study utilized Figure 4.2 Expanded Framework for Decision-Making on District Energy Systems, and Figure 3.1 Knowledge Map for District Energy Management. The specific goal was defined; "Provide a five-year plan, recommendations and considerations for the district energy system chilled water system to meet the district's goals of safety, resilience, and student affordability."

The traditional solution was identified with six steps listed after Table 4.6. The total capital costs for that solution was estimated (in 2020 dollars). Several engineering and investigation steps were included in that six-step solution utilizing information from the knowledge map and these remain part of the recommendation to management.

Using a system of systems engineering approach, nine alternative considerations were identified, including three production options, two distribution options, three demand options, and one option focusing on externalities. Each of those options was discussed and eight of the nine options are viable as facets of a solution. When analyzed, the thermal energy storage option stood out as the best alternative option considering the benefits, costs, and risk present value calculation that was completed. Although the thermal energy storage option does show a significantly better present value than adding chillers based on the twenty-year analysis, a more detailed evaluation of these two options is warranted. The five-year growth plan will probably change and will potentially increase with a recently submitted proposal for a new medical facility. The thermal energy storage option would be the preferred option to add more chiller capacity. After the removal of chillers 7 and 8 in the main power plant, the TES option makes space and condenser water capacity available to easily add two chillers back into the space. A new satellite plant option is still available but would require significantly more capital than adding chillers in the main power plant. The TES option allows more flexibility for the district energy system management in future years.

4.5 Case Study Five – Low Steam Pressure

This case study for a low steam pressure issue that occurs on a 125 psig header at the remote end of a higher education Midwestern campus during polar vortices is in two phases. Phase one covers the years 2011-2012. Phase two covers 2018-2020.

4.5.1 Low Steam Pressure – Phase One (2011-2012)

A comprehensive energy management plan was created in 2011 along with a steam flow model predicting steam pressures and temperatures on campus. The low-pressure conditions on the 125 psig header flow model during a polar vortex matched the actual conditions on campus.
Beginning phase one of this case study, we utilize the expanded framework for decision-making on district energy systems (Figure 4.2) and identify the issue (per Node 1). During winter polar vortex days when the campus is fully occupied, the steam pressure of the 125 psig header at the north end of campus drops to less than 70 psig, which affects the functionality of the pressure reducing system to properly feed equipment and pressure reducing valves that make up the 15 psig steam system used for air handling units. Within this district energy system, the steam is only produced at one location near the south end of campus. Node 2 on the expanded framework for decision-making on district energy systems prompts us to answer the question "Is problem/issue

core to goals/mission?" As this is addressing an optimization strategy for the district's steam system to meet the goals of safety, reliability, and student affordability; yes, this is a core issue. Node 3 of Figure 4.2 is "Does problem require immediate action?" Immediate action is not required, but a solution will be necessary with campus growth. Since study is advisable, we take a System of Systems Engineering approach, as indicated in Figure 4.2, and gather information from the knowledge map.

Information gathered in 2012 is shown below:

1. In July of 2012 the central steam system served 13.9 million gross square feet (GSF) of buildings. Continued growth was planned for campus.
2. Current flow models for steam distribution - Flow models for the 125 psig and 15 psig steam system depicted that there was a drop to 70-75 psig on the 125 psig header at the north end of campus during a polar vortex when the campus was fully occupied. The low-pressure conditions on the 125 psig header flow model during a polar vortex matched actual conditions on campus. At the time we were able to remotely read a pressure gauge at a 125 psig steam pit near this north location. Having the confirmation between the actual reading and the flow model provided us the confidence that the model was accurate. It is important to review and confirm your information from the knowledge map with other sources from the map when available.
3. Capacity of steam production, age, efficiencies, reliability, and N+1 production was available. The campus steam peak demand was approximately 435 thousand pounds per hour of steam and the power plant had a capacity of over 800 thousand pounds per hour of steam. All of the boilers had a capacity of approximately 200 thousand pounds per hour. The commissioning of the four boilers occurred from 1961 to 2010. The boilers were reasonably reliable and had similar efficiencies. A new boiler was being commissioned as the comprehensive master plan was being drafted and the oldest boiler was scheduled to be decommissioned and removed. Pressures and capacity of the new and the old boiler were similar. With the power plant as the only source of steam for heating the campus, the maintenance was done on each boiler during the shoulder months in the Spring and Fall of the year with the intent that all four boilers be available through the winter.

4. Engineering - In our review of engineering studies, we noted a suggestion that reducing the amount of superheat of the steam to campus on the 125 psig line would increase the steam pressure in the header at the north end of campus. Saturated steam at 125 psig is 353 ^{0} F. As the temperature of the steam goes up the velocity of the steam increases, and thus pressure drop increases. The density of steam is the inverse of the steam volume. The specific volume of saturated steam at 125 psig is 3.23 ft^3 per pound, with a density of 0.31 lb/ft^3. The specific volume of superheated 125psig steam at 540 ^{0} F is 4.15 ft^3 per pound, with a density of 0.24 lb/ft^3.

    i. v = Velocity (ft/sec)
    ii. m_s = Steam flow rate (lb/h)
    iii. d = Pipe inner diameter (inches)
    iv. V = Specific Volume (ft^3/lb.)
    v. v = Velocity = $((m_s) \times (V)) / (3600\pi(d/24)^2$
    vi. p = pressure
    vii. d = density = (1 / Volume)
    viii. μ = coefficient of friction
    ix. l = length in feet
    x. g = gravity – 32.2 ft/sec^2
    xi. Δ = delta = change in
    xii. Δ p = $(\mu * l * v^2) / (24d * g * Vol)$
        1. So the pressure drop is proportional to $velocity^2$.
        2. And the pressure drop is linear to (1/Vol), or density.

Dropping the temperature of the superheat steam increases the density of the steam and decreases the delta p (drop in pressure) linearly. We reviewed the engineering information on our existing steam desuperheaters and noted that we could reduce some of the superheat but that the design lower limit was 540 ^{0} F. In the past, we had even been higher than the 540 ^{0} F. Also, the condition of the desuperheater and associated plumbing were in a deteriorating state. Even at 540 ^{0} F on a 125 psig header, 187 ^{0} F of superheat remains.

5. Distribution steam main - The comprehensive energy master plan consultant reported that upsizing the south to north main 125 psig steam header would meet the pressure requirements of campus. The 1260-foot line was in a tunnel.
6. Distribution system - The steam on campus traditionally runs in walkable tunnels. Tunnel inspections are done weekly and inspections of insulation, anchors, expansion joints, and traps are regularly done to verify good condition.
7. Demand – Consider the option of targeting energy use index for existing buildings by commodity (steam).
    a. From the power plant, we knew the steam temperature, pressure and volume going to campus.
    b. We did not have steam or condensate metering in place on campus so we were not sure of Energy Use Indices by building (EUI).
    c. Externalities – Consider alternate solutions such as building shutdowns, infrastructure district changes, peaking distributed boiler, campus steam equipment. Without steam or steam condensate meters installed at individual buildings, there were no readily available metrics to identify the buildings that weren't performing properly. Metered data would have allowed for more targeted solutions but after verifying that steam traps had a low failure rate; our efforts were better utilized in the production and distribution to quantify benefits and costs of solutions.

The next step in our decision-making framework calls for specifically defining the problem and goals. The district energy management and engineering team met with the distribution operations team. We identified the problem as low steam pressure on the north side of campus when the campus was fully occupied during a polar vortex. Furthermore, we determined that the problem would most likely occur on a weekday when classes were being held. Based on their experience, the distribution operations and maintenance group agreed that the building operations problem occurred when our pressure on the 125 psig header dropped to less than 75 psig. Our specific goal was to "<u>maintain the pressure of 75 psig at the north end of campus.</u>"

We agreed that the traditional solution was in the distribution system and to up-size the steam line as noted in Item #5 above. A preliminary estimate for that scope of work was done, funds were identified, and an engineering firm was contracted to be the engineer of record for this project. The estimated full project cost in 2012 for that project was $4.5 million. That was the traditional solution and is the direction that we were proceeding when we start asking if there were alternative solutions, which is the SoSE approach.

Continuing our discussion with our engineering team, operations, and management team we discussed some additional options. We wanted to look for the most cost-effective solutions to improve and assure that sufficient steam pressure is maintained at the north end of campus.
We focused on three of the four areas listed on our expanded framework for decision-making:

1. Production –
    a. Maintaining pressure discharge at power plant at 125 psig.
    b. Lowering the steam temperature to the lowest temperature we could safely do in the winter and monitor the temperature. Coordinating with the distribution group to allow monitoring of the pressure at the header and verification of the system performance at the north end of campus.
2. Distribution – Following up on discussions with engineering, operations and the consultant to identify opportunities for crossovers on campus from the 125 psig to the 15 psig. This would require a structural integrity check of pipe design, slides, guides, anchors and the addition of pressure reducing stations. Crossovers would divert some of the volume from the main header during winter.
3. Demand – Looking at a representative sampling of steam traps in buildings at the north end of campus. If we had a significant number of steam traps that were blowing through, this would be adding to our campus demand volume and excessive blow-through would result in a drop of pressure.
    a. We brought in someone to assist us in steam trap inspection and went through mechanical rooms in the buildings at the north end of campus to inspect the larger steam traps at equipment along with the end of main traps. Some leaking and blocked steam traps were identified on walk throughs of several buildings. A work order was established for the traps that required replacement or repair.
    b. A few of the buildings had hot condensate lines and condensate temperatures of 200^{o} F. These were in residence halls that were occupied and although we

suspected that some of the controls and traps in the individual rooms required maintenance, gaining access to hundreds of individual residence rooms would have been problematic. Summer sports camps were scheduled and attendees were already booked into rooms in these buildings. These camps were a source of income for student life and athletics. If we are unable to find other acceptable and sufficient options to provide an economically feasible solution instead of the traditional solution, we may put in more due diligence to better track these opportunities. Once metering is in place, we could do a better job of targeting specific areas and buildings to provide the best use of capital with a benefit/cost analysis.

c. The steam savings on the traps were marginal for the investment but still contributive to the solution. More demand-side metering would help target buildings and areas that required focus.

With the investigation and preliminary work completed, we took the following multiple steps as having the best benefit/cost potential.

1. Production –
    a. Maintain pressure to campus at 125 psig at power plant – no cost.
    b. Reduce steam temperature at power plant with desuperheaters in cold weather to the capacity and functionality of the desuperheaters – no cost and expected to increase pressure by 4-8 psig at the north end of campus.
        i. Additional benefit of this change is less radiant steam loss from the headers through the year and our engineer estimated that savings at $7,000 per degree per year.
2. Distribution –
    a. Install four crossovers to an adjoining steam project. Estimated cost for addition was less than $400,000 and estimated benefit was between 4-8 psig at the north end of campus. We were unsure if steps 1b and 2a would be directly additive psig benefits.
3. Demand –
    a. Replace or repair steam traps in the survey that were bad. Estimated cost was significantly less than $100,000 and the replacement of leaking steam traps

typically has a simple payback of less than 2 years. We knew that the repair of the traps would benefit our original initiative to maintain the steam pressure, but we did not calculate the direct benefit in the effect on the 125 psig steam header pressure.

Before proceeding in 2012 on the $4.25 million steam main expansion, the district energy system management, engineering and consultant agreed to pause the project and monitor the performance of the 125 psig steam headers during the winter of 2012-2013. The winter of 2012-2013 was reasonably mild and we did not need to open the crossovers and the steps (1 and 3) that were implemented resulted in the steam pressure at the north end of campus remaining over 75 psig at all times. In a follow-up meeting in April of 2013 after review of the data, it was decided to cancel the $4.5 million project. Having the opportunity to open the crossovers in later years gave us confidence that in the five-year plan we would have the ability to serve the north end of campus effectively. The hard costs incurred for these solutions were less than $500,000 and the capital for the canceled project was reinvested in infrastructure.

4.5.2 Low Steam Pressure – Phase Two (2018-2020)

Phase two of this case study deals with the same issue as phase one roughly eight years later. The solutions that were put in place in 2012 satisfied and exceeded the five-year growth plan of the campus. As steam condensate meters were installed, hot condensate was identified in a few of the residence hall buildings and a jointly-funded project by student life and energy and utilities replaced or repaired the steam traps in residence hall rooms during an unoccupied summer session. This resulted in a significant drop of building condensate temperatures. These repairs were identified and completed between 2016 and 2018.

Between 2012 and 2020 the steam system expanded, both with new buildings, building additions, and an increase in campus population. With this campus growth, the steam pressure was close to becoming an issue again in 2018. To repeat the basic background, this campus in the Midwest area of the United States has one steam production facility on the south end of campus and on polar vortex winter days the steam pressure of the 125 psig header at the north end of campus drops near

75 psig, which can become problematic. This phase two is a good real-life example of SoSE (system of systems engineering) and the decision-making framework both iteratively or with a recurring issue.

Proceeding as we did per Node 1 of Figure 4.2; we see that there is a low steam pressure issue on the north end of campus. The continued steps are:

- Node 2 is to answer the question "Is problem/issue core to goals/mission?" Yes, this is a core issue for the district energy management.
- Node 3 of Figure 4.2 is "Does problem require immediate action?" Immediate action is not required, but with continued campus growth, it is likely to require action.
- The System of Systems Engineering approach node of Figure 4.2 directs us to use SoSE. Accordingly, information will be gathered from the knowledge map.

Information gathered in 2018-2019 is shown below:

1. In July of 2019 the central steam system served 15.2 million gross square feet (GSF) of buildings. Many of the 1.3 million gross square feet of buildings added in the last seven years were energy intensive, and the campus and student population had also grown. Continued growth is planned for campus.
2. Current flow models for steam distribution - Flow models for the 125 psig system predicted that steam leaving the power plant at 500 ^{0} F would result in a pressure of 73 psig on the 125 psig header at the north end of campus during a polar vortex when the campus was fully occupied.
3. Capacity of steam production, age, efficiencies, reliability, and N+1 production was available. The campus steam peak demand is approximately 450 thousand pounds per hour of steam and the power plant has a capacity of over 800 thousand pounds per hour of steam. All of the boilers have a capacity of approximately 200 thousand pounds per hour. The commissioning of the four boilers occurred from 1965 to 2011. As mentioned in phase one, the 1961 boiler was decommissioned and a new boiler, commissioned in 2011, is one of the four operating boilers in the plant. The boilers are reasonably reliable and have similar efficiencies. With the power plant as the only source of steam for heating the campus, the maintenance that is done on each boiler

during the shoulder months in the Spring and Fall of the year with the intent that all four boilers be available through the winter.

4. Engineering – As noted in phase one we reviewed the engineering information on our existing steam desuperheaters and noted that we could reduce some of the superheat but that the design lower limit was 540 ^{0}F. Also, the condition of the desuperheater and associated plumbing were in a deteriorating state. In 2018, money was approved for replacement desuperheaters and they were designed to bring the temperature down to 375 ^{0}F (353 ^{0}F is saturated) for the 125 psig header leaving the plant to campus.
5. Distribution steam main - The 2011 comprehensive energy master plan consultant reported that upsizing the south to north main 125 psig steam header would meet the pressure requirements of campus. The 1260-foot line was in a tunnel.
6. Distribution system - The steam lines on campus are traditionally located in walkable tunnels. Tunnel inspections are done weekly and inspections of insulation, anchors, expansion joints, and traps are regularly done to verify good condition.
7. Demand – Consider targeting per the energy use index for existing buildings by commodity (steam).
    a. From the power plant, we meter and collect the data on the steam temperature, pressure and volume going to campus.
    b. 125 psig steam meters have been added at multiple locations on campus including a couple on the north end of campus. Those meters measure steam temperature, pressure and flow.
    c. Condensate meters have been added to 95% of the buildings on the district energy steam grid, so we are now able to see the pounds of condensate being returned and the condensate temperature at the meter which can be an indicator of steam trap quality in the building. We are also able to see trends and outliers with the building operation and compare consumption to similar buildings.
8. Externalities – Consider alternate solutions such as building shutdowns, infrastructure district changes, peaking distributed boiler, and campus steam equipment. Now having more consumption specifics by building, we are better able to target campus demand and look for opportunities by building on this SoSE approach.

Our next step in this case study is to identify the problem specifically and quantify it as shown on Figure 4.2. The district energy management and the engineering team met with the distribution operations team and the power plant management. As in phase one we identified the problem as low steam pressure on the north side of campus when the campus was fully occupied during a polar vortex. This problem would most likely occur on a weekday when classes were in session. Based on their experience, the distribution operations and maintenance group reaffirmed that the building operations problem occurred when our pressure on the 125 psig header dropped to less than 75 psig. Our specific goal was to "maintain the pressure of 75 psig at the north end of campus."

We agreed that the traditional solution was in the distribution system and to up-size the steam line as noted in Item #5 above. That was the traditional solution but with more metering and consumption data, the new desuperheater, and other campus needs, we believed we could identify more cost-effective and alternate solutions, which is the SoSE approach.

Several of the same engineers and operations team involved with the previous work in 2012 were still in place and were familiar with the changes that occurred in the power plant and campus from 2012 to 2020. Having the additional data from metering and an infrastructure option for an apartment complex, and the new desuperheater, the district energy management believed we had good alternatives. As recommended on our expanded framework for decision-making, we used benefit/cost analysis to evaluate these other solutions, and combinations of approaches that would potentially solve our specific problem.

Here is a list with costs for the traditional solution and the alternatives we considered on this phase two project:

1. Cost of the traditional solution of increasing the south to north steam line header from 6" to 12" diameter:
    a. Using RS Means, the cost construction indices for 2012 for the nearest regional city was 180.6. The cost construction indices for 2020 for the same city is 217.7. The updated cost (2020 dollars) is (217.7 / 180.6) x $4.5 million = $5.42 million. This is the cost of achieving our goal using the traditional solution.

2. Improvements in steam production including information on the newly installed and commissioned desuperheaters have been verified, and those revised discharge temperatures can be input into the revised steam model. The cost of the desuperheater project was approximately $625,000. The new desuperheaters at the power plant are able to drop the 125 psig steam headers to 375 ^{0} F. This is a reduction of 175 ^{0} F from the desuperheaters that had just been replaced. Saturation for 125 psig is 353 degrees F, and on a polar vortex day in an occupied campus, there will be a sufficient flow on campus to drop the temperature of the 125 psig steam headers to 375 degrees F. To be conservative and verify, I asked our district utility engineer to run the model dropping from a temperature of 500 ^{0} F from the plant to a new winter level of 400 ^{0} F. As you can see in the first row of data with the font bolded in the top in Table 4.9, the pressure requirements at the north end of campus can be met (as referenced by CQ residence halls).
    a. This information is depicted in Table 4.9 below and shows that dropping the discharge temperature from 500 ^{0} F from the power plant to 400 ^{0} F brings the steam pressure to 78 psig at the north end of campus. That meets our goal of 75 psig at a total cost of $625,000 for the design, purchase, installation and commissioning of the desuperheaters.

Table 4.9 Steam Pressures and Temperatures With/Without Stadium

3. With Both Stadium Feeds On						
Plant Steam Temperature (F)	**CQ North Feed**		**CQ East Feed 1**		**CQ East Feed 2**	
	Pressure (psig)	**Temperature (F)**	**Pressure (psig)**	**Temperature (F)**	**Pressure (psig)**	**Temperature (F)**
400	**78**	**263**	**79**	**339**	**78**	**338**
500	73	307	73	414	73	413
With Stadium East End Feeds Shut off						
Plant Steam Temperature (F)	**CQ North Feed**		**CQ East Feed 1**		**CQ East Feed 2**	
	Pressure (psig)	**Temperature (F)**	**Pressure (psig)**	**Temperature (F)**	**Pressure (psig)**	**Temperature (F)**
400	80	339	80	338	80	264
500	75	310	75	413	75	412
With Stadium West End Feed Shut-off						
Plant Steam Temperature (F)	**CQ North Feed**		**CQ East Feed 1**		**CQ East Feed 2**	
	Pressure (psig)	**Temperature (F)**	**Pressure (psig)**	**Temperature (F)**	**Pressure (psig)**	**Temperature (F)**
400	83	339	83	338	83	339
500	78	275	78	412	78	411
With Both Stadium Feeds Off						
Plant Steam Temperature (F)	**CQ North Feed**		**CQ East Feed 1**		**CQ East Feed 2**	
	Pressure (psig)	**Temperature (F)**	**Pressure (psig)**	**Temperature (F)**	**Pressure (psig)**	**Temperature (F)**
400	84	253	84	339	84	338
500	80	287	80	412	80	411

3. Demand/Externalities (also on Table 4.9) offer some options on building reduction by targeting low use buildings that could be considered for reducing or eliminating loads during a polar vortex.
   a. At the north end of campus, the last consumer of the steam header is a football stadium where six to eight football games are played a year. These home games normally are complete by the end of November. Polar vortices overwhelming happen from December through March and football games are not played at this stadium during those months.
      i. If the stadium was winterized and drained after the last game and the desuperheaters discharged the 125 psig steam at 400 ^{0}F, the north side header pressure would be from 80 – 84 psig depending on whether one or both sides of the stadium were isolated.
4. Distribution – There is a campus apartment complex built in two phases (1947 and 1955) that connects to this same steam header on that section of campus. All of the steam and condensate piping in that area is past its life expectancy per an engineering consultant. Options for this infrastructure upgrade include natural gas. The estimate for this project in 2013 was a hard cost of $3 million including 30% soft costs. Converting that to 2020 cost using RS Means for this area is (217.7/182.7) x $3.0 million = $3.57 million.

As we have already installed and paid for the desuperheaters and determined that we have achieved our goal by lowering the steam temperature to 400 ^{0}F, there isn't a reason to proceed with the other options. Items such as the winterizing of the football stadium and feeding the apartment complex with natural gas are good future options for consideration if the campus continues to grow.

Additional clarifications and options to consider:

a. Besides solving our steam pressure problem at the north side of campus, the desuperheaters were installed for a number of reasons and benefits, such as reducing the radiant steam loss of superheated steam mains during the entire year saving thousands of dollars per degrees per year. Another benefit is reducing the amount of superheat on the 15 psig side of campus after 125 psig/15 psig pressure reducing stations where the superheat may have shortened the life of the seals and seats of steam control valves, causing leaks and simultaneous heating and cooling in air-handling units.

b. A peaking electric driven steam boiler could be added on the north end of campus to only be used when the steam pressure of the 125 psig steam header drops to below 75 psig. These could also be used at the stadium to prevent building freeze-ups if the building was completed winterized.
c. Historically, the steam pressure drop on the header would typically happen between 6am and 10am on a weekday, so control strategies could stagger air handling units on earlier, use the buildings for thermal storage when low ventilation air is needed, or replace steam driven instantaneous potable water heaters with storage tanks for those 4-hour periods during the winter.
d. Eliminate medium pressure equipment that drives the high-pressure campus steam demand such as autoclaves, dishwashers, cooking equipment, dryers and humidifiers.
e. When meters indicate different steam consumption for identical residence halls, a retro-commissioning and optimization of the worse performing building could be completed noting the benefit in steam reduction and cost to perform the work. Once that project is complete there may be a new “best performing” building so it is pretty straight forward to look at economics on the opportunity to retro-commission the others.

The above list is not intended as a complete list of options for future consideration, but if a phase three of this study is needed five years from now, it may be a good place to start the discussion and the investigation on pursuing the non-traditional potential using a system of systems engineering approach.

Case studies one and two used the general framework (Figure 4.1) to reach a satisficing or heuristic “good-enough” conclusion. The remaining case studies used the decision-making framework (Figure 4.2) and described each step going through the framework including the benefit/cost analysis where appropriate. Case study three was a good test of the decision-making framework for in a unique location. Case study four was a master planning scenario that used the framework and provided options with benefit/cost analysis. Case study five demonstrated that the framework can be successful for analysis on a repetitive and iterative case over for several years.

CHAPTER 5. SUMMARY AND RECOMMENDATIONS

5.1 Summary

A literature review was completed for decision-making on district energy systems and augmented with interviews of district energy managers at Midwest universities. Specific to the management of entire district energy systems, neither defined methodology nor frameworks were found in the literature. Although the system of systems approach that evolved from the organizational research field has been introduced to several other areas of focus, it has not included the area of district energy systems. The SoS approach has excellent potential for application in decision-making for district energy systems. This work included the creation of a knowledge map (Figure 3.1) that is a holistic view of managing a district energy system which incorporates a SoS approach within the decision-making framework.

That knowledge map and the decision-making framework of Figure 4.1 and Figure 4.2 were utilized on five case studies in this work. Figure 4.2 is the expanded framework of Figure 4.1 and was utilized in making decisions in case studies three, four, and five.

In case studies one and two we proceeded step by step through the general decision-making framework (Figure 4.1) to address issues that required immediate solutions. We also identified how to use the framework for recurring issues that require long-term planning.

Case study three looked at a different campus district energy system that had added a building outside of the current district energy system footprint. Management wanted to evaluate the best options for connecting utilities to this added building. Options were evaluated and compared based on a present value calculation. A solution was proposed based on this benefit/cost analysis.

Case study four analyzed the chilled water capacity in a district energy system based on the current chilled water peak demand, the projected chilled water loads from building additions identified in the master plan, and the current conditions of the existing chilled water capacity. A traditional solution of adding chillers was compared to options coming from a SoS approach and a benefit/cost analysis was completed. A promising non-traditional solution was proposed for further consideration.

Case study five demonstrated a successful application of the decision-making framework and knowledge map with a two-phase iterative and repetitive process over a ten-year time frame. The problem addressed low-pressure steam headers at a remote section of campus and identified alternative options from the traditional method. Additionally, a future list of solutions was provided for consideration as the campus continues to grow.

The case studies in this dissertation utilized the knowledge map and the decision-making framework with step-by-step explanations of the decisions and the thought processes for those decisions. Multiple specific case studies were carried out to demonstrate the application and flexibility of this methodology.

As mentioned in the introduction of this document, engineers design and manage power plants, distribution systems and buildings. Engineers will design per the scope of the contract, so the district energy management should first determine the best solution before design engineering begins. District energy systems are interdependent, dynamic, and complex. An engineer with the correct tools in the toolbox, a guiding framework, and the ability and authority as a district energy system manager can bring non-traditional, innovative, and cost-effective guidance and solutions to a district energy system. Aspects of system of systems engineering and the items addressed in the case studies, literature review, appendices, the decision-making framework, and knowledge map in this dissertation will contribute to district energy managers making better decisions.

5.2 Recommendations

1. In addition to the knowledge map and decision-making framework, this dissertation also serves as an introduction and overview of items to consider as a manager of a district energy system. It is important to remember that there will be gaps in the available knowledge when solution options are being investigated. Pulling the management and engineering team together to go through the logic of the analysis is important. That is the time to discuss what is known and unknown, and how one can determine or monetize that risk. It may

result in adding a contingency to one of the options or possibly performing a more detailed engineering analysis or testing, which may include soil analysis or non-destructive testing as examples. Frequently an order of magnitude or minimum-maximum dollar range can be determined for these risks and that can be part of the benefit/cost analysis that is used in these case studies.

2. The benefit/cost analysis was performed using an inflation factor of 2.50% and a discount rate of 5.00%. It is important to keep current on energy costs as the base costs or inflation costs are volatile. It is easy to modify or update any of these assumptions based on current market conditions, the district energy management, or as a sensitivity analysis.

Time and resources are important in the evaluation. As an example, if the analysis identifies an option to retro-commission five buildings using a team of eight individuals for eight months per building to save 10% in energy costs, without doing anything to reduce peak demand production, that may not be a viable solution. Additionally, there may only be eight individuals in the district energy system who can perform these tasks, and they may not be available when needed. Some solutions are faster than others, and that is why it is critical to be specific when defining the problem and goals.

I included operation and maintenance costs in the case studies in this dissertation. It is important to include those costs when evaluating options to solve issues that come up in a district energy system.

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

This dissertation has provided a set of tools that can be beneficial to anyone who manages or wants to learn more about managing a district energy system. This dissertation is a useful tool for someone who is starting their career in engineering at a district energy system as well as for individuals in operations, maintenance, finance, or an upper level management position who would benefit from an overview of a district energy system.

In my early research I found an absence of a decision-making blueprint or guide for district energy managers. In the process of completing this work I created, tested, and presented a unique blueprint to aid and improve district energy management.

6.2 Future Work

Tools and processes can always be improved and customized to the needs of a district energy system and that should be considered for future work. Software could be developed specifically for the decision-making framework and also incorporated into the benefit/cost analysis. An expansion into the more sophisticated risk management tools or Monte Carlo simulation may be another possibility.

Additional future work could be incorporating this framework with the National Renewable Energy Lab programs including a carbon tax or an environmental life cycle analysis. Some of the US National Labs work on system engineering and microgrid applications which may be another application for this work.

The decision-making framework, knowledge map, and case studies in this dissertation were based on a specific set of goals. Modifying these goals will not require modification of the framework but may modify the traditional solution and options available to the district energy system and also affect the benefit/cost analysis.

APPENDIX A. OPERATIONAL STRATEGIES (10 YEAR PLAN)

This appendix is an example of the type of issues that may be considered for operating and maintenance plans which can help establish and facilitate hedging strategies.

Operations Strategic Plan and Commodity Procurement Recommendations for Ten Years

These recommendations are subject to change based on weather, equipment, and operational needs.

Operating Schedule - Years One and Two

1. **Base Operation**
    a. Operate natural gas boilers between 120-160 KPPH (thousand pounds per hour).
        i. This is the energy efficient sweet spot.
        ii. Boilers can ramp up and down within these limits as load and steam demand change.
            1. It is not a problem to operate outside of this range, but it will affect economics. The priorities here, in order of importance, are safety, resilience and affordability.
    b. Operate generator 1 (30 MW condensing turbine).
        i. The minimum normal operation of TG-1 will generate 12 MW.
            1. Heat rate improves if extraction is added (if there is demand).
    c. Operate generator 2 (10 MW backpressure turbine).
        i. Continue operation matching maximum generation and extraction to district steam demands.
    d. Solid fuel boiler will be off-line but should be available to run.
        i. Have covered storage loaded with dry solid fuel. The boiler should be prepared to come on-line in case of operational issues such as equipment or polar vortex issues through the months of January – March.
2. **Spring Outage Schedule – Starting Mid-March of Year One**
    a. Year One: It is projected that boiler stack work may take 10 weeks. Spring outage with solid fuel boiler operating will be March, April and May.

b. Year Two: Suggested spring schedule is for solid fuel boiler to operate only in March and April.
c. Bring solid fuel boiler on-line.
    i. Proceed on gas boiler maintenance outages.
    ii. Complete boiler stack work in Year One.
d. Compare natural gas prices to solid fuel (include cash gas, hedge and full solid fuel costs).
    i. If solid fuel is cheaper than natural gas, run that boiler at 120-160 KPPH and keep gas boilers at the low end around 120 KPPH. Solid fuel boiler should be ramped up and down to handle load swings and generation optimization.
        1. While doing this it is important to continue to burn the daily natural gas nomination.
    ii. If natural gas is cheaper than solid fuel, keep solid fuel boiler at lowest operating load at 80-100 KPPH, and operate natural gas boilers at 120-160 KPPH. Ramp the gas boilers up and down to meet load swings and self-generation optimization.
        1. Maintain communication with the operations supervisor and plant manager to verify natural gas nominations are in place.
e. When boiler stack work is complete along with natural gas maintenance outages, bring up boiler and bring down the solid fuel boiler.
    i. In Year One, bring up final gas boiler at completion of maintenance.
f. Take solid fuel boiler off-line.

3. Summer and Early Fall

a. Follow the base operation schedule as shown in #1 above.

4. Fall Operation - Through the End of Years One and Two

a. Bring solid fuel boiler on-line around September 1st and expect to operate until October 31st.
b. After solid fuel boiler is on-line, perform maintenance on remaining gas boilers and other necessary equipment.

c. Operating guidelines for boilers are as noted in item 2d from the spring outage schedule.

d. Solid fuel boiler comes down on November 1st for both years. Operate under base operation guidelines. Goal is to do whatever maintenance is required on solid fuel boiler to make it available to operate if there is an operational need. The plan is to avoid operating the solid fuel boiler until after winter break in early January when the energy demand has increased. Even at that time, it will only be operated if there is a polar vortex, there are equipment problems, or if it can be economically justified as arbitrage.

5. Projected Solid Consumption for These Two Years Will Need to be Estimated

Year Three - the New Boiler Becomes Operational

There will be a new more efficient boiler being commissioned in the district energy system plant. The normal rate of steam received will be 150 KPPH. This additional capacity will add to the flexibility of operating and maintaining the district energy system assets, and will also add redundancy in steam production. This will allow the scheduling of one outage per year per boiler and reduce maintenance and some operational costs for the district energy boilers.

Operating Schedule - Years Three Through Ten

1. January - March Year Three

a. Operate as noted in base operation under operating schedule for Years One and Two with all assets.

2. With the New Boiler On-Line

a. Update operating algorithm monthly on “make or buy” electricity to reflect the purchased steam and new operating parameter.

b. Operate two or three gas boilers to meet load and electricity generation and demand.

c. Schedule gas boiler maintenance outages during shoulder seasons of March and October.

d. Plan on operating solid fuel boiler in March and October.

i. Have solid fuel boiler available to run as needed from November through March of each year with dry solid fuel.

APPENDIX B. RECOMMENDED HEDGING AND PROCUREMENT STRATEGY

This appendix is an example of the type of issues that may be considered for operating and maintenance plans which can help establish and facilitate hedging strategies.

These operation strategies will result in a reduction of solid fuel use, increased consumption of natural gas, and an increase in self-generation of electricity. Current market is attractive to hedge natural gas for several years at or below the current cost of operating the solid fuel boiler.
With the heat rate of the district generators and the future trading prices of natural gas and basis, the district can generate some of the electricity for less than last year's cost.

There are fundamental, economic, and political drivers now that may be driving natural gas prices up in the next several years, which may result in a significant negative impact to an unhedged budget.

Recommendation 1). Identify the local regional natural gas accounts and volumes and understand the natural gas tariff rates. This will help to determine the hedging options available to the district energy system. The present natural gas futures pricing is attractive from a historical perspective and a consideration should be made to buy natural gas forward contracts now to bring hedged levels to 60% for all accounts for 60 months.

Recommendation 2). Request a cost from the solid fuel supplier to store fuel at the supplier site for delivery upon request in tarped trucks. Compare this cost to what it would take to build additional solid fuel storage at the current fuel receiving area.

Recommendation 3). Recommend extending natural gas risk management procedures from 60 months to 120 months range.

Recommendation 4). Evaluate the amount of base purchase electricity every hour of every month based from rate tariff changes and hourly pricing trends.

Recommendation 5). Using a projection model and with assistance of business office, run the models with the suggested operation guidelines for the next 60 months, including in the district energy growth as currently projected. Determine the average steam consumption of campus by month, and add the parasitic historical steam.

Recommendation 6). If there is concern that natural gas cash prices will be cheaper than the current hedged natural gas, investigate purchasing call options (there will be a premium for this) or even consider buying collars (another type of option).

Recommendation 7). Assume all unhedged natural gas may have a $1 or $2 spike per million BTU in the market so keep that amount of monetary reserve in case the market turns. This will not only offset the natural gas but the lost opportunity of hedging self-generation of electricity by the district.

Recommendation 8). Renegotiate solid fuel contract by middle of 2021.

Recommendation 9). Submit semi-annual reports to director of district energy system for management discussion.

Recommendation 10). Consider placing a price trigger 10% above and below the current five-year strip for immediate notification from the marketer to the district energy system for possible execution of a layer, as a dollar cost averaging measure. Consider purchasing natural gas with a trailing stop in a descending natural gas priced market.

Recommendation 11). Continue to receive regular scheduled reports from natural gas marketer to compare hedging strategy to rate tariff and expiry market.

Recommendation 12). On natural gas, hedge basis for two years to volumes hedged on all accounts.

1. **Statement of Purpose** – This section outlines the procedures for the management of natural gas risk for the district energy system campus and the regional systems. The energy to be hedged, may include, but is not limited to natural gas large accounts, natural gas small accounts, unleaded gasoline, diesel fuel, LP gas, coal, and electricity.
2. **Objectives** – The primary risk management objective is to reduce the price volatility of energy for budget surety. The secondary objective is to procure reasonable pricing for the commodity and basis. Reducing the price volatility and procuring the best pricing may be accomplished by using derivative securities (both financial and physical), utilizing forward and futures contracts, spreads, swaps, options, or swaptions.

These procedures will ensure that the energies hedged will only be hedged up to the forecasted consumption of that particular fuel. In some cases when transparency or volume of a specific market is limited, and as deemed appropriate by an energy risk management committee, other representative fuels may be hedged to mitigate risk.

3. **Strategy** – The energy risk management strategy is to look at fuels used by each of the regions and determine price risks and budget impacts associated with each of those of energies. Those energies that have the potential to cause a significant detrimental impact to the budget will be noted for further investigation. Based on that subsequent investigation, if an acceptable means is available to reduce that specific volatility and impact without incurring excessive costs to mitigate that risk, those accounts are deemed appropriate for hedging. Projected energy usage is determined on an annual basis, but updated regularly as needs and projections change. Using macroeconomic analysis with input from marketers, brokers, or energy risk management institutions, hedges will be placed using forward contracts, futures, swaps, options, or swaptions.
4. **Definition of Duties**

Executive Vice President and Treasurer

The executive vice president and treasurer will ensure that the energy risk management procedures are appropriate and effectively implemented. The executive vice president and treasurer will also approve any modifications to these procedures.

Energy Risk Management Committees

Risk Management Committee

The committee will consist of the power plant manager, energy and utility director, director of fiscal affairs, and the energy risk analyst (or similar roles respectively if titles are changed). The responsibility of this committee is to follow the requirements of the energy risk management procedures for all-natural gas accounts, including the main accounts and all other natural gas small accounts that are available to hedge. The fuel risks managed by this committee will include but are not limited to the following: natural gas, LP gas, electricity, and coal (including fuel rider).

Regional District Energy Systems

The main risk management committee will have oversight of the regional district energy system risk management. The energy analyst is to have semi-annual discussions with the utility or physical facilities director of each campus and the account representative for the energy marketer to discuss changes to rate tariffs or region loads. The energy analyst may place hedges at the same levels and with the same permissions as the non- main natural gas accounts. The fuel risks managed by this committee may include, but are not limited to the following: unleaded gasoline, natural gas, LP gas, and electricity.

4. **Scope** – The energy risk management procedures applies to all energy accounts that have been determined to be appropriate for hedging.
5. **Fiduciary Duty** – In seeking to attain the goals of the energy risk management procedures, the risk management committee and its members must act with care, skill, prudence, and diligence under the circumstances then prevailing that a prudent person in like capacity and familiar with such matters would use in the conduct of an enterprise of like character with like aims. All actions and decisions by the committees and its members must be based solely in the interest of the district energy system and owner.

5. Reviews

A. The energy risk management committees will meet at least semi-annually to review current status of risk mitigation program, exposure, budgets, and energy pricing.

B. All hedged transactions and confirmations will be reviewed at least semi-annually.

6. Management Plan Implementation

A. Natural Gas

1) This procedure allows the energy risk management committee to have positions up to the amount of the projected or forecasted amount of natural gas consumption for that particular month. The "futures" or forward contracts are not hedged by the individual gas account (with the exception of the large account at the main plant), but are currently purchased by the aggregated load of all-natural gas accounts for each separate rate tariff for each campus. Each of the three districts will hedge their accounts separately.
2) Each campus will be responsible to publish a semi-annual status report to the director of fiscal affairs and the director of treasury operations. These reports will show the percent hedged by account and by district.
3) Execution of hedges will be made per the direction of the committee; and will either be done by the energy analyst or a designee.
4) The natural gas marketer will manage the forward contract hedges that are made by the district energy system and the marketer. The marketer will also work with information from operations and balance the delivery of the nominated daily natural gas needs to the appropriate delivery point for each district energy system.
5) If an excessive amount of gas has been purchased through the gas marketer, the excess gas may be liquidated by re-selling through the marketer at the discretion of the director of energy and utilities with guidance from energy analyst.
6) The forward purchasing of "natural gas" contracts will be limited to 60 months ahead of the prompt month.
7) The selling of "forward" contracts will be limited to the number of "forward" contracts that have been purchased.
8) The storage of natural gas through the gas marketer may be deemed as an attractive hedge and may be executed by the energy risk management committee at their discretion. The purchase of storage gas that may be acquired will be limited to the amount of gas expected to be burned within 12 months.

9) Other vehicles that may be utilized in hedging risk with natural gas pricing are "options". This could include buying and selling calls and /or puts. These tools are to be used in conjunction with "forward contracts" and will hold to the same requirement that the combination of "forward" contracts, storage, and "options" contracts will not exceed the total rounded up volume of the projected gas burns for that particular month.
10) Depending on the market, the risk management committees may determine that for a particular month, or series of months, that no hedging is recommended, and the natural gas will be required on a daily cash basis.
11) Daily cash gas may be purchased for arbitrage or operational reason at any time.

B. Energy Risk Mitigation other than Natural Gas Accounts

1) Energies included in this category are energies used and paid for by district energy system or regional systems or departments (other than natural gas accounts which is covered in A). This may include mitigating risk for natural gas small accounts, coal, LP gas, fuel oil, electricity, coal, unleaded gasoline, or diesel. This policy allows the risk management committees to have positions up to the amount of the projected or forecasted amount of energy consumption for that particular month of contract, or by looking at price volatility and value at risk.
2) Instruments used to mitigate fuel risk may include either financial or physical derivatives. This may include forward contracts, futures contracts, spreads, swaps, options, or swaptions.
    a. These financial derivatives will be purchased through a contract with either a broker, energy management risk firm, financial institution, or energy marketer. Multiple contracts may be required. Approval of said contract(s) will require the signature of the appropriate financial manager.
    b. The forward purchasing of any hedging instruments or contracts outside of natural gas will be limited to 60 months ahead of the prompt month.
    c. The selling of "futures" contracts will be limited to the number of "future" contracts that are outstanding.

d. The storage of energies may be deemed as an attractive hedge and will be executed by the risk management committees at their discretion.

3) Other vehicles that may be utilized in hedging the risk with energy pricing are "options". This could include buying and selling calls and/or puts. Entering into a collar transaction by buying a call option and selling a put option simultaneously is acceptable under this policy.

Summary

The commodity cost of energies is volatile and these procedures are intended to establish sound methods to mitigate the price volatility risk of energy costs affecting the district energy system.

NATURAL GAS PROCUREMENT PROCEDURES

The energy risk management committee shall develop procedures for managing price risk for procuring natural gas. Other personnel may be added to the group as appropriate. This group will maintain written guidelines for:

- Limitations on the number of forward contracts or the percent of total needs that can be purchased
- Limitations on the number of forward contracts that can be sold
- Limitations on how far forward gas can be traded; and
- Identification of the specific types of instruments that can be utilized (i.e., forward contracts, futures contracts, swaps, options, etc.)

Recommended changes to the procedure shall be reviewed and submitted to the executive vice president and treasurer for approval. These guidelines will also be reviewed, modified, and re-submitted whenever the current market or the needs of the district energy system changes and the committee determines a modification to the existing procedures is required. These written guidelines will be filed with the district energy procurement and / or budget office.

The duties for the natural gas accounts shall be divided among several individuals as follows:

Energy Risk Analyst - Hedging and Procurement Responsibilities

- Ensure procurement of natural gas to meet district energy objectives

- Keep director, appropriate personnel, and energy risk management committee informed on status of purchases
- Enter into appropriate procurement instruments (e.g., forward contracts) when appropriate and in compliance with written procedures
- Ensure written confirmations of trades are generated; and
- Monitor fundamental and technical indicators of energy markets and keep committee informed
- Serve as resource to other personnel on gas and fuel economics
- Notify proper personnel when hedges are being made and for what volumes and costs

District Energy Account Clerk - Invoicing and Payment Responsibilities

- Obtain copies of confirmed hedging activity and confirm with execution
- Obtain report of hedging activity directly from marketer
- Reconcile hedging activity (rates and quantity) to amounts invoiced; and
- Confirm cash gas prices and all fees invoiced are appropriate

Financial Manager for District Energy - Reporting and Reviewing Responsibilities

- Monthly balancing of hedges, nominations with consumption.
- Determine if trading activity complies with written guidelines
- Determine if gains and losses associated with trading are unusual or warrant a further analysis of cost/benefit of activity
- Provide report after review to appropriate levels of management at least semi-annually
- Provide proper disclosure in financial statements in accordance with accounting standards, as deemed appropriate

Main District Energy Office/Operations Manager/Plant Manager

- Predict long range natural gas burn forecasts
- Contact the marketer directly for daily gas nominations and or cash gas for the plant
- Contact the marketer directly if projected consumption will be significantly different than nomination

- Work with pertinent parties at main district, and director of energy & utilities on significant changes to operation plan
- Evaluate operations model and arbitrage opportunities to select best fuel (coal, gas, fuel oil, other)

Regional District Energy Systems

- Director to work with energy analyst to project natural gas needs
- Regional district energy accounting will review hedge confirmation and confirm with marketer
- Regional district will review and approve natural gas invoices to hedge and cash

Requirements of Natural Gas Marketer

The written agreement with gas marketer reflects that the following will be furnished by the marketer

- All trade activity occurring during the month
- Unsettled trades (if any)
- Market reports
- Comparison to rate tariffs
- Guidance on market
- Continued education for district energy management staff

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