EBC
Energy in Buildings and Communities Programme

International Energy Agency

Energy Master Planning for Resilient Public Communities – Pilot Studies

Energy in Buildings and Communities Technology Collaboration Programme

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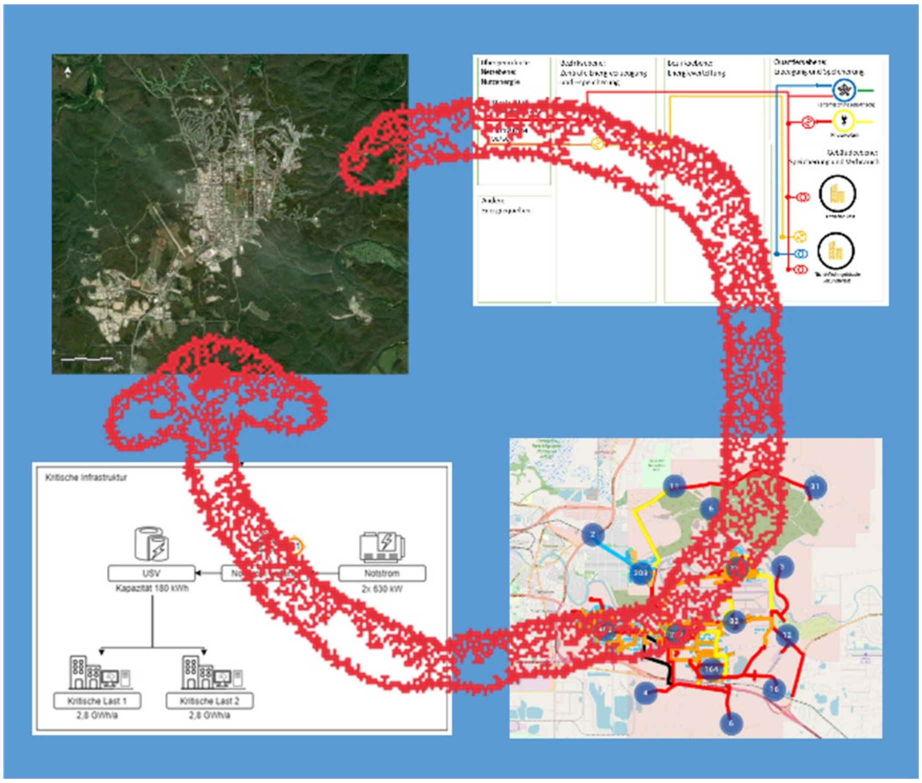

iea Energy Technology Network

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International Energy Agency

Energy Master Planning for Resilient Public Communities – Pilot Studies

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Preface

THE INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA) was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international cooperation among the 29 IEA participating countries and to increase energy security through energy research, development, and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

THE IEA ENERGY IN BUILDINGS AND COMMUNITIES PROGRAMME

The IEA coordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes. The mission of the IEA Energy in Buildings and Communities (IEA EBC) Programme is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities through innovation and research. (Until March 2013, the IEA EBC Programme was known as the IEA Energy in Buildings and Community Systems Programme, ECBCS.)

The R&D strategies of the IEA EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshops. These R&D strategies aim to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy efficient technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five areas of focus for R&D activities:

- Integrated planning and building design
- Building energy systems
- Building envelope
- Community scale methods
- Real building energy use.

THE EXECUTIVE COMMITTEE

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)

Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1 – User Interfaces and System Integration (*)
Annex 17: BEMS 2 – Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modeling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi-Zone Air Flow Modeling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)

Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air-Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting – Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost-Effective Energy and CO_2 Emissions Optimization in Building Renovation
Annex 57: Evaluation of Embodied Energy and CO_2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterization Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings
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Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Public Communities
Annex 74: Energy Endeavour
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76 / SHC Task 59 Renovating Historic Buildings Towards Zero Energy
Annex 77 / SHC Task 61 Integrated Solutions for Daylighting and Electric Lighting
Annex 78 Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
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Annex 85 Indirect Evaporative Cooling

Annex 86 Energy Efficient Indoor Air Quality Management in Residential Buildings
Annex 87 Energy and Indoor Environmental Quality Performance of Personalized Environmental Control Systems

Working Group – Energy Efficiency in Educational Buildings (*)
Working Group – Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group – Annex 36 Extension: The Energy Concept Adviser (*)
Working Group – HVAC Energy Calculation Methodologies for Non-residential Buildings

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Executive Summary

Human life on earth strongly depends on **buildings and infrastructure** and their **provision with energy, water, and other resources**. This is the case in everyday life, and even more so in the "Black **Sky**" regime, which considers disruptive events like natural catastrophes.

Existing energy systems usually still rely on fossil fuels for supply of **critical functions** in case of energy outage. These **emergency generation** systems exist in parallel to normal everyday "Blue Sky" systems and do not add to everyday efficiency and diversity of supply.

Best practices from around the world prove that **holistic energy systems** based on renewable and local sources can **provide for resilience** without relying on fossil fuels. Holistic Energy Master Planning is the key to identifying those cost-effective solutions of energy systems that depend on climate zone, density of energy users, and local resources.

In contrast to a single building approach, **holistic Energy Master Planning** considers buildings together with their supply systems. It does not so much concentrate on the building level, but rather **considers functions of buildings and components of energy systems at all levels**, from single building to whole community. Critical functions and resilience to threats play an important role, primarily on the community level.

The holistic planning method creates a **synergetic approach to diversified building cluster portfolio**, which allows for the storage and further use of a wide range of energy streams that would otherwise be wasted, and thus can contribute to **close resource and energy loops**.

So, if holistic Energy Master Planning is so much better than a segregated approach, why isn't it used in everyday planning? The main reason is the high complexity that results from (1) many buildings, (2) many stakeholders to be addressed, (3) different fields of expertise that need to be considered, from renewable sources over building efficiency and building services to critical functions and threats.

However, new work done in IEA EBC Annex 73, in which international experts from different countries and fields of expertise cooperated to create a **methodology for holistic Energy Master Planning**, considers such different parameters as critical functions, building efficiency, storage, energy system architecture and local resources. The developed methodology **provides a structure** for holistic Energy Master Planning and helps to consider the necessary issues in the proper sequential order. It results in an implementation strategy which – depending on the defined targets – will lead to a **synergetic system that is highly efficient, that has low environmental impact, and that is resilient to identified threats**.

One important element of the planning methodology is a **method to quantify resilience**, which was established by the project team and is described in the Energy Master Planning toward Net Zero Energy Resilient Public Communities Guide (Guide 2021). The methodology allows for evaluation of both the ability of a system to absorb the impact of a disruption (robustness), and its ability to recover.

The holistic energy master planning methodology and its supporting tools have been **tested in six pilot projects** by teams from Austria, Canada, Denmark, Germany, and the USA. This book provides an overview of the pilot studies, lists the tools developed and available to Resilience Energy Master Planning, and describes the Resilience inclusive master planning process. This document provides detailed descriptions of pilot studies that illustrate the many benefits of the methodology and its associated tools.

Foreword

Resilient energy systems are those that can **adapt to changing conditions** and **recover rapidly from disruptions**, including deliberate attacks, accidents, and naturally occurring threats. These systems are especially important for such **critical infrastructures** as **urgent care centers, water treatment plants, data centers**, etc. For this reason, it is important to assess a community's ability to absorb and recover from rapid changes to the energy supply system. The IEA Annex 73 project developed a **seven-step process** for planning the transition to a resilient and synergetic energy and resource system (Figure 3-1), which is described in detail in the Guide (2021). This holistic Energy Master Planning Process was used in the pilot studies described in this document.

Chapter 1 gives an overview of the pilot studies presented in the book. Chapter 2 lists the tools developed and available to Resilience Energy Master Planning. Chapter 3 describes the Resilience Inclusive Master Planning Process. Chapter 4 gives an insight into the metrics and requirements of resilience. Chapter 5 contains a description of the pilot studies. Finally, Chapter 6 summarizes lessons learned during the creation and testing of the Resilience Energy Master Planning Process, in the form of Frequently Asked Questions.

CHAPTER 1. PILOT STUDY OVERVIEW

This work applied the holistic Annex 73-developed Energy Master Planning Process, which includes planning for resilience, to a set of public building communities. The goal of the application was to test and further improve the developed process and its supporting tools, like the software tool for quantification of resilience.

The process was applied to six test areas, two military installations (USA), a university (AT), two city quarters (CDN, DE), and one larger region (DK). The test areas are in the United States, Canada, Austria, and Germany.

A review of the pilot studies reveals certain **cultural and organizational differences** in dealing with resilience and energy management. Differences also arise from varying levels stakeholder involvement and property shares, and from the laws in the host countries that pertain to renewable sources, reliability of local energy systems, identified threats, energy prices, and forms of supplied energy. Moreover, local climate conditions define the needs that buildings must provide. Nevertheless, the **studies** all **share the same systematic approach**, which is closely associated with a holistic view of buildings and supply systems, and which focuses on resilience.

The pilot studies described in this report are described in:

- Fort Leonard Wood (USA) – Section 5.1
- Fort Wainwright (USA) – Section 5.2
- JKU Campus in Linz (AT) – Section 5.3
- Lachine East (CDN) – Section 5.4
- Rosensteinviertel in Stuttgart (DE) – Section 5.5
- Vestforbrænding, Denmark (DK) – Section 5.6

CHAPTER 2. TOOLS FOR HOLISTIC RESILIENCE ENERGY MASTER PLANNING

The goal of Annex 73 was to develop guidelines and tools that support planning of Net Zero Energy Resilient Public Communities and that are easy to understand and execute. The specific objectives of Annex 73 were to:

- Collect, analyze, and document information about best practice community-wide energy master planning processes, and to determine how those processes can be improved
- Develop energy, cost, and resilience targets and constraints
- Develop a database of power and thermal energy generation, distribution and storage technologies, and system architectures
- Develop guidance for energy master planning for Net Zero Energy Resilient Public Communities
- Collect and describe business and financial aspects and legal requirements and constraints that can be used to implement energy master plans for public communities in participating countries
- Integrate the targets, constraints, enhanced system architectures, the technology database, and resilience analysis into an interactive modeling and optimization tool.

An outcome of the project was the creation of manifold results that constitute the basis for the holistic Energy Master Planning Process. Descriptions of the most important of these results may be found (cost free) at the following locations:

- **Website** with information on the Annex 73 cooperation and results https://annex73.iea-ebc.org/
- *Energy Master Planning toward Net Zero Energy Resilient Public Communities* ***Guide*** (referred to hereafter simply as the "Guide"), which details the Resilience Energy Master Planning Process and provides background knowledge on all fields that are covered. https://annex73.iea-ebc.org/Data/publications/EMP_GUIDE_20211026.pdf
- The *Energy Master Planning for Resilient Public Communities – Case Studies* (referred to as the "**Book of Case Studies"**) presents and summarizes cases of energy master planning, many of which are best practice examples of energy master planning. The documentation of Case Studies is one important source of information used to develop the holistic Energy Master Planning Process. An analysis shows that these processes follow different methods and goals, and that they consider resilience in many distinct ways. https://annex73.iea-ebc.org/Data/publications/Annex73-Book-of-Case-Studies-HR.pdf
- The Annex 73 **Technology Database** holds a wealth of information pertaining to thermal energy generation, distribution, and storage technologies, and to energy system architectures, which may be downloaded via: https://annex73.iea-ebc.org/publications
- The Energy Resilience of Interacting Networks **(ERIN) tool** is a calculation tool that implements the methods to quantify resilience. ERIN allows users to model energy and resource flows, and interruptions to those flows due to component failure or shortage of supply. Chapter 5 of the Guide also describes other tools that can be used to quantify resilience and to calculate efficiency of energy systems.

    - Download the ERIN software tool from BIGLADDERSOFTWARE at: https://annex73.iea-ebc.org/publications
    - User Guide: https://annex73.iea-ebc.org/Data/publications/user-guide.pdf
- Two additional guides that focus on planning for Resilient Thermal Energy Systems in demanding climate zones are also available:
    - *Guide for Resilient Thermal Energy Systems Design in Cold and Arctic Climates*. https://annex73.iea-ebc.org/
    - *Guide for Resilient Thermal Energy Systems Design in Hot and Humid Climate*. https://annex73.iea-ebc.org/

CHAPTER 3. ENERGY RESILIENCE PLANNING PROCESS

3.1. Seven-Step Process

The **first step** of the resilience planning process is to identify the location and its key characteristics. While military installations often cover a large area, most of the infrastructure is consolidated into a relatively small area. This presents these communities with a relatively low-cost opportunity for ensuring resilient energy systems for critical infrastructure. Since most of the buildings are in close proximity to each other, increasing energy availability and reducing recovery time is relatively easy during an emergency scenario.

For military installations, it might be straightforward to focus on threats. However, civilian communities like universities, towns, or cities, provide a broad range of functionality in everyday life. While educational campuses do not usually group critical functions into just one zone, educational and scientific communities have a clear mission and host critical processes that strongly depend on technical appliances, like data servers. Therefore, civilian communities can be addressed using the same approach.

The **second step** is to determine the design basis threats and impacts. For each site in each study, buildings of interest were identified based on the nature of that building's mission, and on how well they represented the various resilience goals.

Step three of the resilience planning process is to evaluate the Baseline. The Baseline simulation serves to establish the current "as is" scenario of the site evaluated. Through the Baseline, existing deficiencies can be identified.

The **fourth step** calls for the design and analysis of the Base Case scenario for resilience. These will include future blue sky scenarios and scenarios that account for the previously identified design basis threats. For example, if a relevant threat to a site includes flooding, then a flood scenario that adds fragilities to generators, fuel transportation, switches, etc., would be created.

After the Base Case scenarios have been created and analyzed, **step five** assesses alternatives. This may include more efficient future technology or strategies employed to mitigate the impact of threats depending on the scope of the study. **Step six** then compares these solutions so the most appropriate strategy may be carried forward to **step seven** for implementation.

3.2. ERIN Tool for Quantification of Resilience

Several **metrics** are used to quantify resilience, including but not limited to Robustness, Recovery Time, Availability, and Quality. Robustness is a system's ability to absorb and recover from shocks to the system. The time between the occurrence of a disruption and system recovery is referred to as "downtime." Different types of loads will have a requirement for different amounts of Maximum Single Event Downtime (MaxSEDT), which allows energy managers to prioritize loads depending on the amount of energy availability. Recovery time is the time for a system to transition from “down” to “up.” Depending on the type of event, specific systems may take longer to fully recover than others, which is why it is an important metric to quantify. Energy availability refers to the amount of energy that can be supplied to a load, typically in the form of distributed energy resources. The term “energy quality” is generally used to qualify the output of electrical energy systems, and commonly refers to the power factor of the overall electrical system, which makes energy quality a relevant metric when large capacity inductive loads are being used. Since it is not always feasible to have the ability to produce large amounts of reactive power, it is important to understand the power quality capabilities for a given energy system.

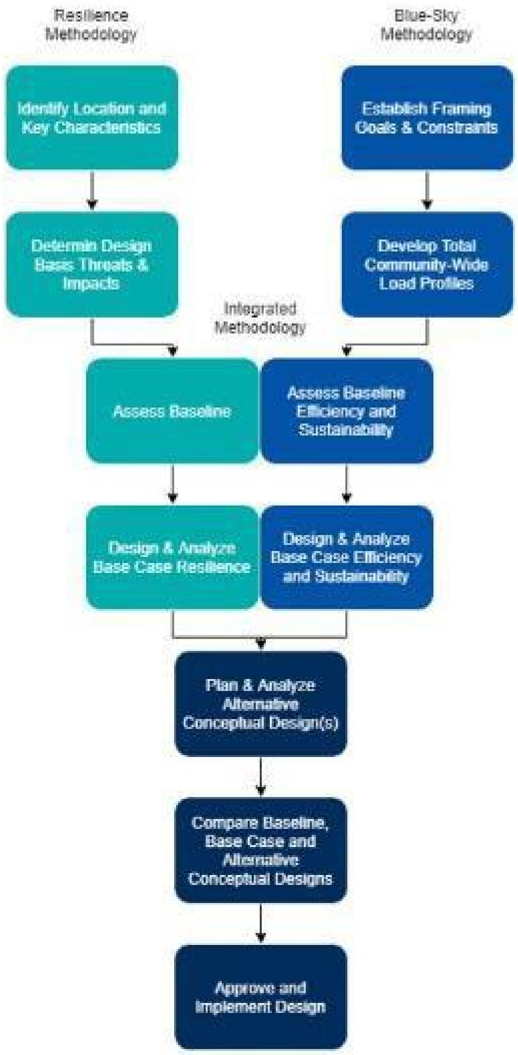


Figure 3-1. Resilience planning process developed by the 2021 IEA Annex 73 Guide. An alternative visual description is found at Fig. 6-1.

The ERIN tool simulates energy flows through a district energy system composed of an interacting network of components. Key features are that the tool

- accounts for both reliability (failure and repair) and resilience to various scenarios (design basis threats).
- models topology and interaction between an open-ended number of energy networks.
- provides key energy usage, resilience, and reliability metrics for the modeler/planner.

A model may be built within the ERIN tool in two ways. In the first method, the user creates a manual input file using the TOML (Tom's Obvious Minimal Language) format. The TOML file is split up into different sections: buildings and their load files, simulation details, components, energy sources, the fuel system, distributions, failure modes, networks, and scenarios. Although manual creation of an ERIN input file is simple enough for very small networks (Figures 3-2 and 3-3), it quickly becomes infeasible when working with hundreds of buildings and complex networks. Study 1 (Fort Leonard Wood, section 5.1) demonstrated this version of the tool.

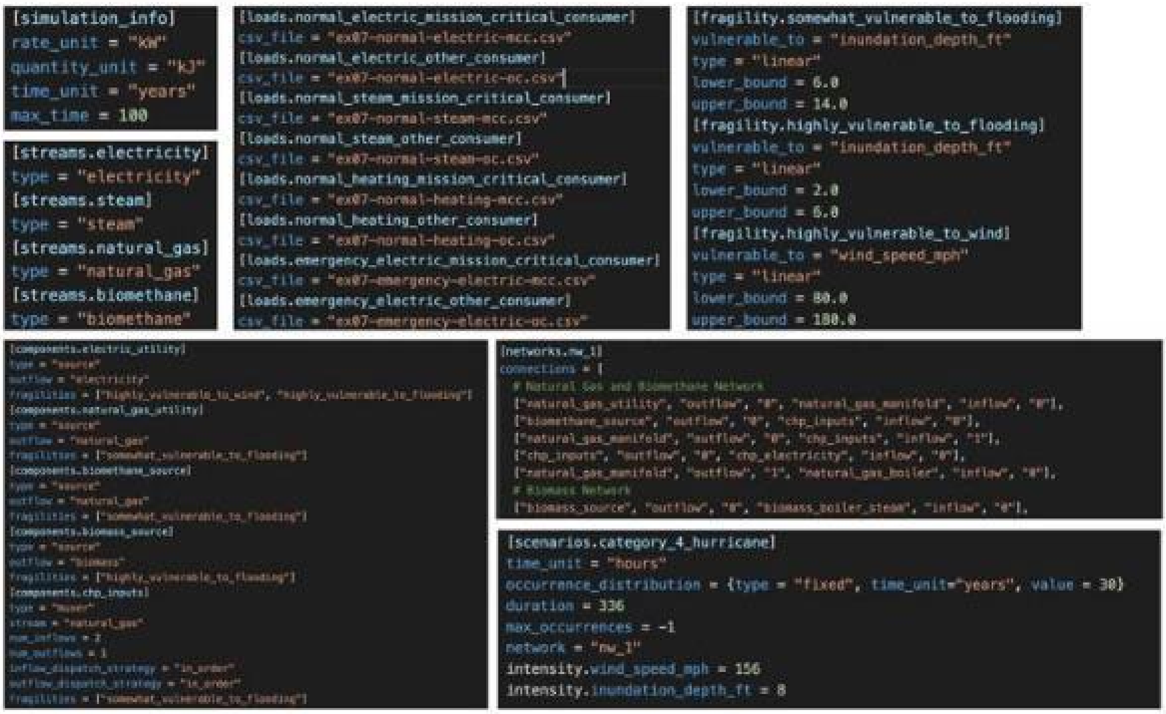


Figure 3-2. An example of a TOML file that the ERIN tool uses as an input in a standalone application.

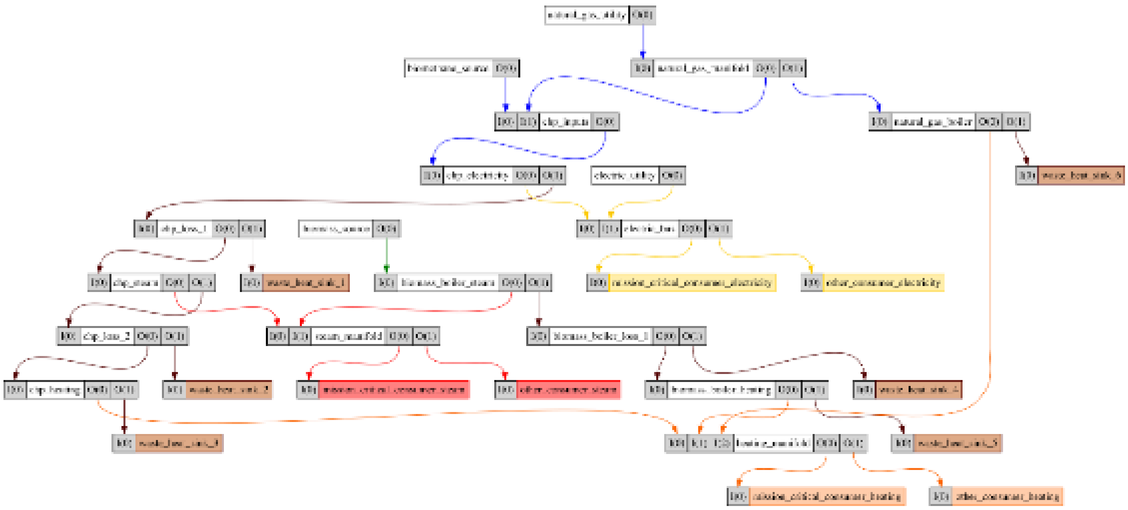


Figure 3-3. The Energy Resilience Simulation Tool can generate customized maps of interconnection points.

The second method involves creating the model using the System Master Planning Tool (SMPL) user interface. This interface simplifies the process by creating a user-friendly workflow for the construction of the TOML file. The TOML file creation is hidden from the user, as are most of the inner workings of ERIN. This increases the usability of the program, as building the TOML file requires specialized expertise and can be both tedious and error prone. The user interface first prompts the user to create a model, after which it initializes a Blue Sky scenario and creates a network. Blue Sky Scenarios are used as a Baseline for comparison with other scenarios; they allow the user to perform an initial assessment of whether the goal requirement metrics are achieved. The user interface enables the user to place model components (electrical and thermal loads, equipment, and sources, defined below) on a map. The user then connects the components in interacting networks of energy streams, from source, through equipment, to loads. For example, coal flows through a transportation network to a coal pile, where it is then converted to steam. The steam network flows to turbine generators, where it is converted to electricity and distributed through an electrical network. The steam also flows through a steam network to building loads where it provides the buildings with heat. The user may also define failure modes representing a stochastic model of reliability and fragility modes that represent components' vulnerability to natural and manmade events. SMPL creates an ERIN input file, runs the simulations, then extracts and displays results. Results include metrics such as MaxSEDT, energy availability (EA), and energy robustness (ER) (described in more detail below). This version of the tool is demonstrated in the second study (Fort Wainwright, USA, section 5.2).

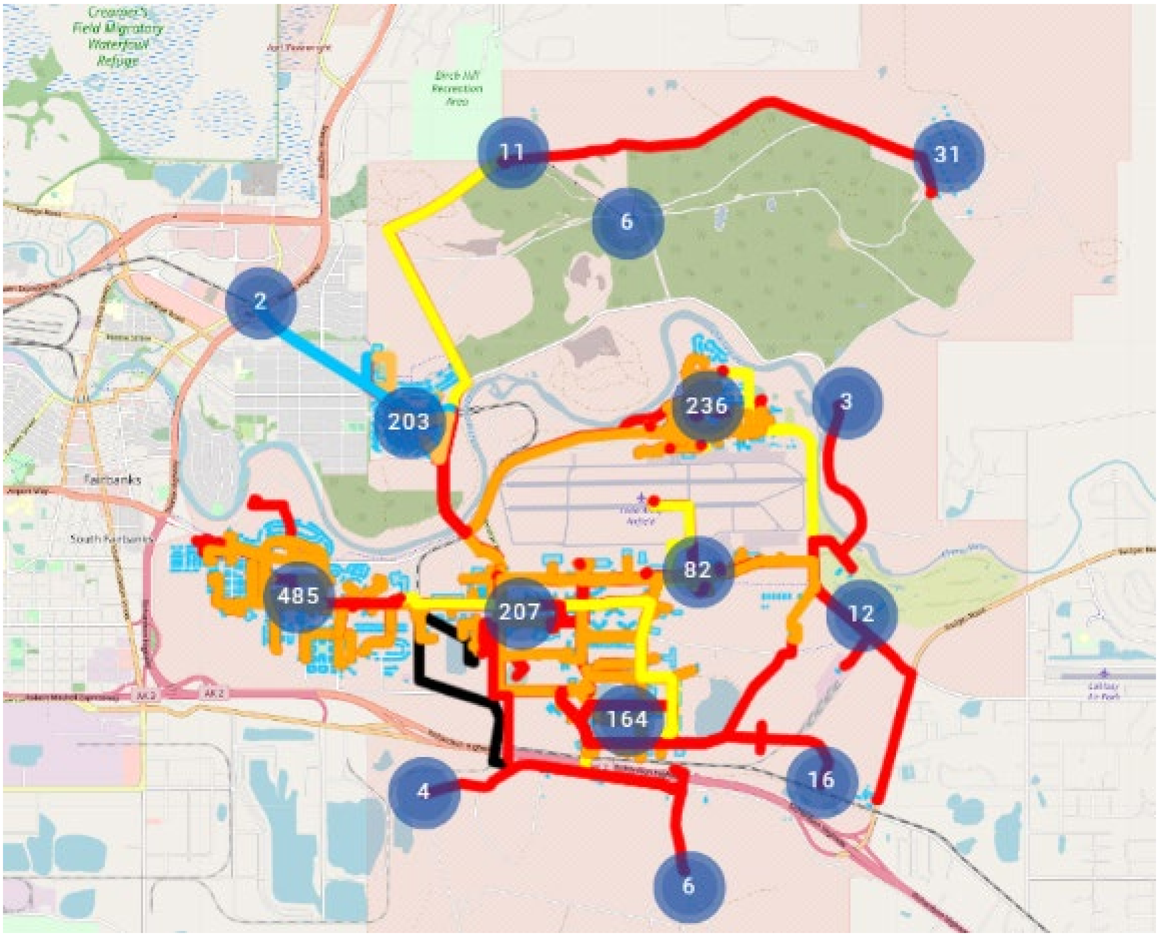
Model Elements. As described above, components are classified as sources, equipment, and loads. Once all components are created, they can be connected to form a network, and assigned scenarios, failure modes, and fragilities. Network connections are associated with the output of one or more components and with the input of one or more other components. Connections represent the flow of an energy "stream," which is a generalization of a specific flow of energy (e.g., electricity, steam, hot water, natural gas, etc.). Short definitions of each element follow:

- *Source:* The origin of an energy stream, such as a coal mine, electric utility, natural gas utility, or fuel depot. Sources also represent renewable resources, such as wind and solar energy.
- *Equipment:* The equipment element can be further broken down into the subtypes of *pass-through*, *converter,* and *"muxer."*
  - *Pass-through:* This allows a stream to flow through without making changes to it. It has one inlet and one outlet, and is used for assigning capacities to an energy stream
  - *Converter:* Changes the stream from one type to another. An example would be a boiler, which converts a stream of coal into steam
  - *"Muxer":* Used for splitting or combining streams. A muxer has multiple inlets and outlets depending on the desired output
- *Loads:* A representation of the energy a facility or group of facilities requests from the network. Loads may be defined by EnergyPlus™ simulations run in SMPL and then imported into ERIN.
- *Scenario:* An instance of the model for a particular set of circumstances where fragilities are assigned. The user sets parameters for duration, probability of occurrence, and intensities (e.g., maximum wind speed).
- *Failure Modes:* Used to represent the reliability of a component. They consist of a failure distribution and a repair distribution (discussed in more detail in a later section).
- *Fragilities: Used* to establish vulnerability to a specific event outside of usual wear on a component. When exceeded, a component can no longer withstand the event and will fail.
- After basic components are defined, energy flows can be drawn in by hand through the user interface. Each flow is color-coded to allow for a clear distinction between the flows that form an energy network. Figure 3-4 shows an example of what these networks look like within the user interface, in which:
  - Redlines represent electric flow
  - Black lines represent coal flow
  - Orange lines represent steam flow
  - Yellow lines represent diesel flow
  - Blue pins represent sources, loads, and equipment.

Within a single model, it is possible to either use the throughput of the same network or to assign different networks by scenario. For example, a scenario that models an emergency might switch to a secondary network that supplies only a select few buildings. While only one network was used in the Fort Wainwright model, this provides a useful feature for future investigation.

Defining and Assigning Reliabilities. Reliabilities were developed for pieces of equipment by assigning a "Failure Distribution" and a "Repair Distribution." These distributions represent a Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) for model components. Various types of distributions were used, including

- *Weibull* – A type of continuous probability distribution
- *Fixe*d – A fixed value, will always return the same number
- Normal – Asymmetric probability.



Note: Circles containing a number represent a group of loads to be broken out when "zoomed in" on.

Figure 3-4. An example set of networks within ERIN.

Weibull distributions were developed for failure distributions to predict when each piece of equipment might fail due to normal wear and tear. Equipment age had to be considered while developing Weibull distributions for reliabilities. Without setting an appropriate offset, all equipment is assumed to be starting from an age of zero and is likely to experience failures at the same time as similar equipment. Consider the arbitrary failure distribution example shown in Figure 3-5.

Because all equipment of the same type uses the same MTBF to determine the scale of the failure distribution, they all reach a near-certain probability of failure in this example around 1200 hours of operation. However, if we now consider a piece of equipment at the same time that began operating 500 hours sooner, we see that it will now reach a near-certain probability of failure at around 700 hours from the time of simulation initiation because its age has been accounted for (Figure 3-6). This provides a more accurate picture of expected equipment failure.

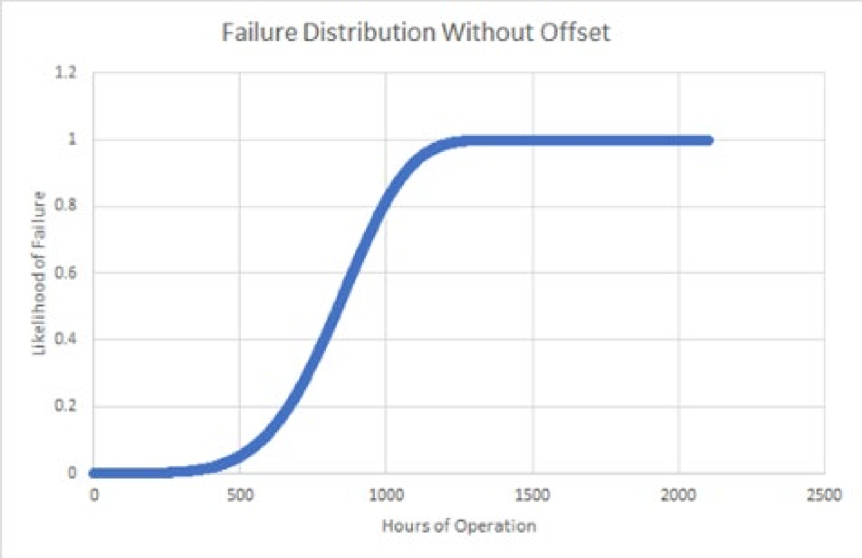


Figure 3-5. Failure Distribution without Offset.

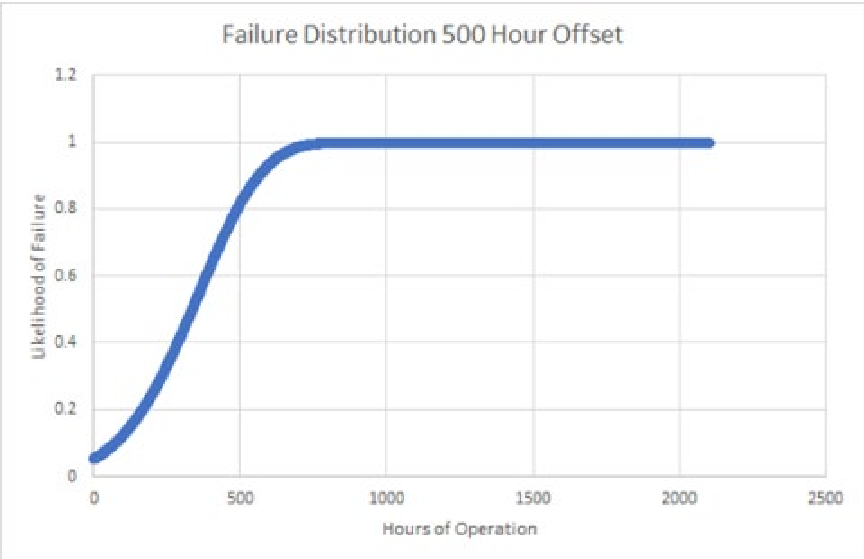


Figure 3-6. Failure Distribution 500-hour Offset.

The logged lifetime hours of equipment were used as a starting point to determine offset. MTBF was determined using U.S. Army Technical Manual (TM) 5-698-1 (HQDA 2007) as reference.

When Weibull distributions were not appropriate, normal or fixed distributions were used for both reliabilities and repair distributions. For a fixed distribution, equipment was always repaired at the same interval. That is, if the distribution were set to 48, the repair always occurred after 48 hours. For the normal distribution, repairs or failure often occurred around the mean, with a standard deviation set for a variance on either side of the mean.

Threats. When analyzing resilience, one must understand the specific threats that require increased resilience. At a base level, three types of threats exist: natural, unintentional and technological, and manmade. Threats most applicable to a particular site will vary based on environment, mission, etc. Design basis threats can be singular or multiple compound threats, and therefore provide the most useful data when resilience modeling.

To avoid running many threat scenarios, it is helpful to consider the effect of each threat on the thermal and electric distribution systems. Such threats as a wildfire may disrupt the connection to the grid and leave the installation with only onsite generation capabilities. However, the same effect may be caused by earthquakes, floods, or any number of threats. Thus, it may be unnecessary to model each threat individually since all these threats will require a similar response. Table 3-1 lists various example threats categorized by their effects on installation operations.

Table 3-1. Threats by operations outcome.

Off-Base Power Loss	On Base Power Loss	Steam Loss	Transportation Disruption
• Earthquake • Wildfire • Flood	• Earthquake • Wildfire • Cyber-attack	• Earthquake • Wildfire • Cyber-attack	• Earthquake • Wildfire • Flood • Fuel shortage

Creating Scenarios and Fragilities. The categories presented as examples in Table 3-1 (column headings) serve as the basis for the scenarios used during the study. While this manner of threat modeling simplifies the process, it is important to not discount individual threats entirely. Especially unique threats may require specific repair and failure distributions or fragilities that warrant a distinct modeled scenario.

As mentioned, when creating scenarios, the user must assign the duration, probability of occurrence, and intensities. The probability of occurrence is governed by the occurrence distribution. In the example scenario created in the standalone application (Figure 3-7) and in the integrated application (Figure 3-8), this is set to “immediately” so the event will occur at the beginning of the simulation. The user may also choose to not have reliabilities calculated for every scenario. The example shown in Figure 3-8 has the reliability option toggled “on” so that normal equipment failure may still occur during the scenario. Finally, the user must define the intensity of the scenario. This may include how fast wind blows during a storm or how high-water levels rise during a flood. In the scenario described in Figures 3-7 and 3-8, which models a cyber-attack, the intensity is set as “cyber_attack_sophistication.”

Once these parameters are set, fragilities must be established by setting repair distribution, vulnerability, and upper and lower bounds. Intensities of scenarios can then be compared to these upper and lower bounds to determine if there is a chance that a particular piece of equipment will fail.

In the example shown in Figures 3-9 and 3-10, a cyber-attack with a sophistication of less than 50 would not be enough to cause a disruption. Any attack with a sophistication between 50 and 65 will have an increased probability of causing failure as the sophistication increases. The previously defined cyber-attack has a sophistication of 70. Because this exceeds the upper bound of the fragility, any pieces of equipment assigned this fragility have a certain chance of failure.

```
# Scenarios
[scenarios.blue_sky]
id = 1
time_unit = "hours"
occurrence_distribution = "immediately"
duration = 8760
max_occurrences = 1
calculate_reliability = true
network = "normal_operations"

[scenarios.cyber_attack]
id = 2
time_unit = "hours"
occurrence_distribution = "immediately"
duration = 300
max_occurrences = 1
calculate_reliability = true
network = "normal_operations"
intensity.cyber_attack_sophistication = 70.0
```

Figure 3-7. Defining a scenario for ERIN as a standalone application.

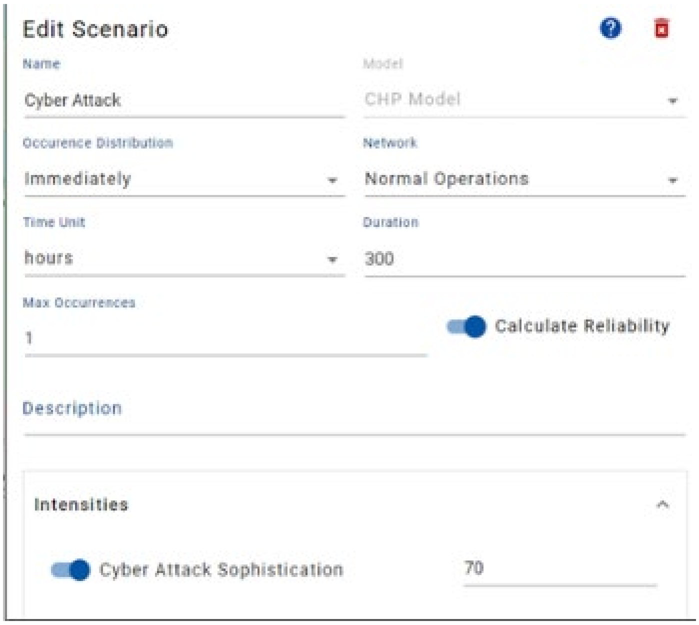


Figure 3-8. Creating a Scenario in ERIN User Interface.

```
# Fragility Modes
[fragility_mode.cyber_attack]
id = 1
fragility_curve = "cyber_attack"
repair_dist = "cyber_repair"

# Fragility Curves
[fragility_curve.cyber_attack]
id = 1
vulnerable_to = "cyber_attack_sophistication"
type = "linear"
lower_bound = 50.0
upper_bound = 65.0
```

Figure 3-9. Defining a Fragility for ERIN as a standalone application

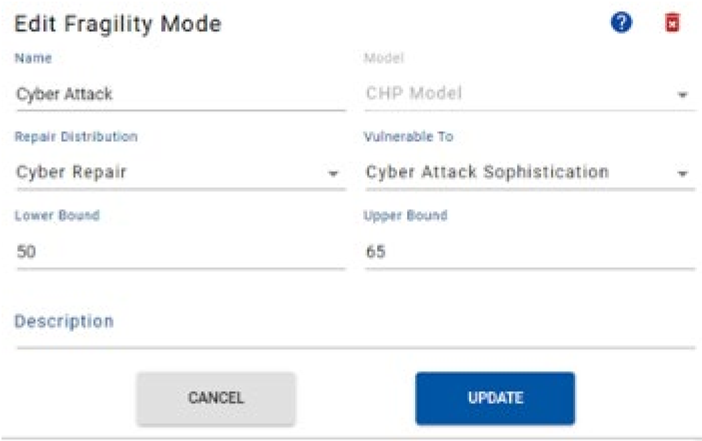


Figure 3-10. Creating a Fragility mode ERIN User Interface.

CHAPTER 4. METRICS AND REQUIREMENTS OF RESILIENCE

It is important to first define the term “resilience” in this context to determine a particular site’s ability to adapt to and recover from an interruption in energy supply. The following metrics as defined in the Annex 73 *Energy Master Planning for Resilient Public Communities Guide* were used to quantify resiliency:

- *Energy System Robustness (ER)* – the percentage of mission energy load served, i.e., the ability to absorb the impact of disruption
- *Energy Availability (EA)* – the percentage of time missions served, which is a measure of the readiness of a system/component to perform its required function
- *Maximum Single Event Downtime (MaxSEDT)* – how long the process can be maintained, how long the building remains habitable, or how long the thermal environment shall be maintained above the sustainability threshold.

Using these metrics, it is possible to assign numerical values to resilience.

4.1. Electric Metrics and Requirements

Requirements for electric resilience were established using the data in Table 4-1 (from the Annex 73 *Energy Master Planning Guide for Resilient Public Communities*). Using the scheme outlined in Table 4-1, each facility is assigned a metric of low, moderate, significant, or high, and is then assigned a level of primary or secondary, based on the mission. The resilience sub-metric, which ranged from low (0) to high (4), can then be used to assign a further level of granularity. Table 4-1 then outlines acceptable levels of EA and downtime based on the facility’s category. Thus, a primary facility with a moderate resilience metric and a low resilience sub-metric must maintain an EA of 0.99 or higher and a MaxSEDT of no more than 302 minutes to be considered sufficiently resilient.

4.2. Thermal Metrics and Requirements

Thermal resilience exists on two levels. The first level is the habitability threshold, which refers to the building’s ability to maintain a temperature that can support human life. A habitable state is defined as one that maintains or exceeds a temperature of 16 °C (60 °F). The second level of resilience is the sustainability threshold or the point below which the building will start to experience damage due to freezing water and sewer pipes, freezing fire suppression systems, the inability to protect sensitive content/equipment, or the start of mold growth during an extended loss of conditioning capabilities. The sustainability threshold is defined as 4 °C (40 °F). Thus, in the context of thermal resilience, Max Single Event Down Time is defined in terms of how long a building can maintain the process of being habitable or sustainable. A parametric analysis of indoor air temperature decay using EnergyPlus™ based energy models was presented in the Guide for Resilient Thermal Energy Systems Design in Cold and Arctic Climates.

Table 4-1. Recommended resilience requirements to power systems serving mission-critical facilities (Guide 2021).

Resilience Metric	Facility Level	Resilience Sub-Metric	Category	Degraded State Availability	Acceptable Average Weekly Downtime (Minutes)	Maximum Single Event Downtime (Minutes)
Low	Primary	Low	LP/1	0.92	806.4	2,419
		Moderate	LP/1+	0.95	504	1,500
	Secondary	Low	LS/0	0.9	1008	3,024
		Moderate	LS/0+	0.92	806.4	2,419
Moderate	Primary	Low	MP/2	0.99	100.8	302
		Moderate	MP/2+	0.995	50.4	150
	Secondary	Low	MS/1	0.95	504	1,500
		Moderate	MS/1+	0.99	100.8	302
Significant	Primary	Moderate	SP/3	0.999	10.08	30
		Significant	SP/3+	0.9995	5.04	15
	Secondary	Moderate	MS/2	0.95	504	1,500
		Significant	MS/2+	0.99	100.8	302
High	Primary	Significant	HP/4	0.9999	1.008	3
		High	HP/4+	0.99999	0.1008	0.3
	Secondary	Significant	HS/3	0.9995	5.04	15
		High	HS/3+	0.9999	1.008	3

P = Primary Facility / Mission
S = Secondary Facility / Mission
L = Low Resilience Metric
M = Moderate Resilience Metric
S = Significant Resilience Metric
H = High Resilience Metric

+ = Highest 10% of a Specific Resilience Metric Range
0 = Resilience Metric Range – Lowest Resilience Metric Range
1 = Resilience Metric Range – Scaled 0 to 4, with 4 the highest level of resilience metric
2 = Resilience Metric Range – Scaled 0 to 4, with 4 the highest level of resilience metric
3 = Resilience Metric Range – Scaled 0 to 4, with 4 the highest level of resilience metric
4 = Resilience Metric Range – Highest Resilience Metric Range

This analysis showed that buildings with high mass were significantly more thermally resilient than frame-based counterparts. Additionally, higher building airtightness and thermal insulation contributed to an increased level of thermal resiliency. The data in Table 4-2 (from the Guide) provide insight into the maximum time to repair a facility at various temperatures for both habitability and sustainability by providing thermal decay test (TDT) downtimes and Outdoor Dry Bulb (ODB) temperatures. These numbers can be used to inform the maximum acceptable downtimes regarding thermal resiliency. For example, a frame building of typical construction would remain habitable for only 1 hour with an ODB of -29 °C (-20 °F) during a loss of heating capabilities. For the purposes of analysis, the thermal resilience metric set for this case study was for all buildings to remain sustainable in the event of an outage. If a higher level of resilience is desired, the threshold may instead be set as the habitability threshold.

Table 4-2. Maximum Allowable Downtime (time to repair) for Different Building Parameters and Outside air temperatures (Guide 2021).

Building Parameters	Temp ODB	Mass Building			Frame Building		
		Typical/Post 1980	Low Efficiency	High Efficiency	Typical/Post 1980	Low Efficiency	High Efficiency
Walls R-value, °F·ft^2·hr/Btu ([m^2·K]/W)		20.5 (3.6)	40 (7.0)	50 (8.8)	20.5 (3.6)	40 (7.0)	50 (8.8)
Roof R-value, °F·ft^2·hr/Btu, ([m^2·K]/W)		31.5 (5.5)	45 (7.9)	60 (10.6)	31.5 (5.5)	45 (7.9)	60 (10.6)
Air Leakage, cfm/ft2 at 0.3 in. w.g. (L/s.m2 @75Pa)		0.4 (2)	0.25 (1.25)	0.15 (0.75)	0.4 (2)	0.25 (1.25)	0.15 (0.75)
Window (R-value, °F ft^2·hr/Btu, U value, W/[m^2·K])		Double Pane; R = 1.78 / U = 0.56	Double Pane; R= 3.34 / U=0.3	Triple Pane; R= 5.25 / U=.19	Double Pane; R = 1.78 / U = 0.56	Double Pane; R= 3.34 / U=0.3	Triple Pane; R= 5.25 / U=0.19
MaxSEDT Hab. (60°F/15.6 °C)	-60 °F -51.1 °C	< 1 hour	2 hours	5 hours	<< 1 hour	1 hour	2 hours
MaxSEDT Sust. (40°F/4.4 °C)		9 hours	28 hours	41 hours	4 hours	14 hours	21 hours
MaxSEDT Hab. (60°F/15.6 °C)	-40 °F -40 °C	1 hour	3 hours	10 hours	< 1 hour	2 hours	4 hours
MaxSEDT Sust. (40°F/4.4 °C)		20 hours	36 hours	51 hours	10 hours	18 hours	24 hours
MaxSEDT Hab. (60°F/15.6 °C)	-20 °F -28.9°C	2 hours	6 hours	15 hours	1 hour	3 hours	6 hours
MaxSEDT Sust. (40°F/4.4 °C)		31 hours	46 hours	60 hours	15 hours	22 hours	28 hours
MaxSEDT Hab. (60°F/15.6 °C)	0 °F -17.8 °C	3 hours	13 hours	29 hours	2 hours	5 hours	9 hours
MaxSEDT Sust. (40°F/4.4 °C)		43 hours	59 hours	90 hours	21 hours	28 hours	33 hours
MaxSEDT Hab. (60°F/15.6 °C)	20 °F -6.7 °C	10 hours	28 hours	45 hours	3 hours	8 hours	15 hours
MaxSEDT Sust. (40°F/4.4 °C)		60 hours	78 hours	95 hours	28 hours	35 hours	40 hours
MaxSEDT Hab. (60°F/15.6 °C)	40 °F 4.4 °C	29 hours	54 hours	72 hours	8 hours	17 hours	23 hours
MaxSEDT Sust. (40°F/4.4 °C)		93 hours	112 hours	123 hours	41 hours	47 hours	50 hours

Chapter 5. PILOT STUDIES

5.1. Fort Leonard Wood (USA)

5.1.1. Introduction

The case study at Fort Leonard Wood, MO demonstrates an integrated approach to energy master planning at a military installation the size of a small city. The combination of aging infrastructure with natural and manmade events pose an increasing threat to cities, university campuses, and military installations. Resilient energy and thermal systems for mission-critical facilities and operations have primarily focused on generators as a backup source in case of a Black Sky (worst case scenario) event. The purpose of this study was to evaluate a holistic system – integrating resilience, efficiency, and sustainability factors – to determine scenarios that support installation master planning at Fort Leonard Wood (Figure 5-1).

Figure 5-1. Aerial view of Fort Leonard Wood, MO (ESRI 2021).

The ERIN modeling tool simulates energy flows through a district energy system composed of an interacting network of components. This tool provides increased resilience analysis to the System Master Planning Tool (SMPL), which on its own would only forecast present and future energy usage. With the additional resilience capabilities of ERIN, equipment reliabilities and threat vulnerabilities are factors that provide a broader determination of site resilience. After the initial analysis was conducted, this case study primarily used ERIN to determine the most economically feasible approach to resilience.

5.1.2. Key Characteristics and Threats

The installation studied is in the Missouri Ozarks, south of the City of Saint Robert, where dramatic shifts in weather are considered the norm. Hot, humid, rainy summers follow very cold, sometimes snowy winters. The temperature typically varies between -3 °C and 32 °C (26 °F and 89 °F) throughout the year and is cloudy most of the time. Major natural threats to Fort Leonard Wood include severe weather events throughout the year, and the primary driver for infrastructure outages across the area is severe weather (storms). The National Oceanic and Atmospheric Administration (NOAA) tracks storm events by county (Table 5-1). In combination with data collected by NOAA, the leading cause of power outages is thunderstorms (hail, wind, tornadoes, and lightning). Winter weather can cause transportation issues and severe ice storms can result in significant damage to electric distribution (broken and fallen power lines). Other hazards of concern include potential flooding along with low-lying areas; extreme temperatures that cause high demand on electric or gas systems, which can potentially strain the infrastructure; and earthquakes. Although there is a small possibility of earthquakes, a major earthquake on the New Madrid fault (up to 8.6 magnitude) could cause moderate damage to well-constructed buildings at Fort Leonard Wood.

Table 5-1. Pulaski County, Missouri total natural hazard events since 1996 (NOAA Storm Events Database).

Hazard Type	Pulaski County No. of Occurrences
High Winds	118
Hail	148
Flooding	89
Winter Weather	31
Extreme Temperatures	17
Earthquakes	0

Manmade risks include bombings, active shooters, and threats to cyber security. Threats could lead to power and communication outages, weakened or blocked supply systems, and mass casualty events. These threats could also compromise the availability of locational resources (e.g., district chilled and hot water, steam, water, electricity grid, natural gas pipeline, liquid fuel) or cause a loss of energy supply (e.g., power and gas supply, renewable sources, energy alternatives).

5.1.3. Total Installation Load Profiles

Fort Leonard Wood has a total of 17 mission-critical facilities and a few thousand facilities listed non-critical that are used for support functions. Mission-critical facilities are facilities that are critical to the main missions of the installation, and may include control rooms and server rooms. The Fort Leonard Wood 2020 Installation Energy and Water Plan (IEWP) assessed the Baseline for the operating conditions of both energy and water systems for the entire installation with an emphasis on mission-critical facilities. The Baseline is defined as the current energy (and water) consumption profile. It includes cooling, heating, electrical energy usage, and operating costs.

Overall, the IEWP assessed three main cantonment areas: Specker Central Plant connected-facilities, South Plant connected-facilities, and all remaining facilities (Table 5-2). This information was obtained through actual usage data based on utility bills and consumption reports and verified through available metered data.

Table 5-2. Generated output from SMPL of three main cantonment areas (Fort Leonard Wood 2020 IEWP).

Group Name	Specker	South Plant	Remaining Buildings
Number of Facilities	45	20	2,313
Number of Mission-Critical Facilities	0	0	17
[Conditioned Area (sq ft [m$^{2]}$)	684,450 [63,587]	695,156 [64,582]	14,750,441 [1,370,361]
Ground Coverage (sq ft [m^2])	2,917,875 [271,079]	5,885,484 [5,885]	1,497,480,576 [139120498]
Total Electrical Load (kWh/year)]	8,102,292	7,481,180	150,946,624
Total Space Heating Load (kWh/year)	7,096,755	7,362,242	113,407,544
Total Domestic Hot Water (DHW) Load (kWh/year)	2,633,544	1,637,438	25,506,904
Total Cooling Load (kWh/year)	4,872,712	3,305,807	68,687,800
Total Electrical Peak (kW)	1,493	1,567	32,693
Total Cooling Peak (kW)	6,067	5,079	102,516
Total Space Heating Peak (kW)	7,275	10,403	177,760

The data in Table 5-2 defines the three areas of interest based on facilities currently connected to two separate central plants, as shown in Figure 5-3. When the IEWP team calculated the three areas of cantonment, two locations – Specker and South Plant — included two of the central plants. The IEWP did not break down other areas of the cantonment or evaluate their proximity to mission-critical facilities. There are mission-critical facilities near to the Specker area and South Plant, but the mission-critical facilities are not currently connected to those two plants, and thus were considered separately. There are also mission-critical facilities that are not near any current central plant.

There are currently five government-owned central energy plants located at Fort Leonard Wood. These include two high temperature hot water and chilled water plants (Specker and

South Plant), which serve approximately 65 buildings. A steam and chiller plant serves the hospital and a central chiller plant serves 15 facilities on the west side of cantonment. Finally, a steam and chilled water plant serves the four-building complex on the north side of cantonment. There is no other onsite generation.

5.1.4. Establishing the Baseline

Of all energy resources currently used at Fort Leonard Wood, the top four consumption types were identified in the IEWP: heating consumption (42%), interior equipment (22%), cooling (13%), and interior lighting (11%). In 2020, Fort Leonard Wood consumed a total of 35,177 MWh of electricity and 797,695 MMBtu of natural gas. There are two current suppliers of electricity and natural gas, Sho-ME Power and Omega Gas. Table 5-3 lists the average cost for electricity at Fort Leonard Wood. Figure 5-2 shows the highest consumption of electricity occurring in the summer months at this particular installation. The maximum peak demand for natural gas is 6,000 MCFD, with one entry point for delivery. The rate structure is tiered with an average of $2.66 per dekatherm.

Table 5-3. Average cost per kilowatt hour of electricity at Fort Leonard Wood.

		2016-2017	2017-2018	2018-2019
Energy	Base	$0.08/kWh	$0.04527/kWh	$0.04527/kWh
Demand	Base	$5.82/kWh	$12.975/kWh	$12.975/kWh
	Peak	$4.25/kWh	$6.00/kWh	$7.50/kWh

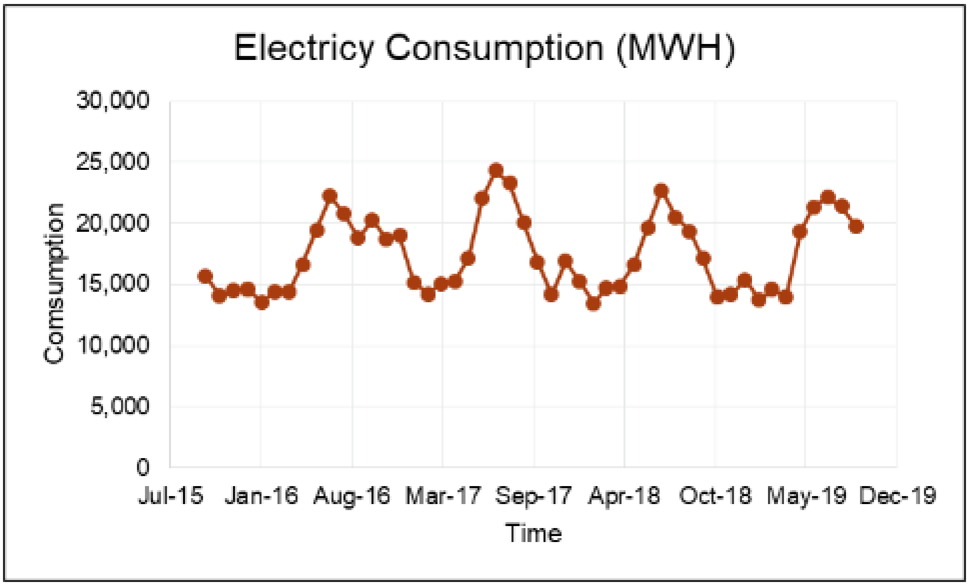


Figure 5-2. Army Energy and Water Reporting System (AEWRS) data from Fort Leonard Wood, 2015 to 2019.

Out of the 17 facilities deemed to be mission-critical at Fort Leonard Wood, 13 use generators for backup power. These generators range from 8 to 36 years in age. Most are diesel generators, and two are natural gas. In 2020, fuel oil consumption was at 7,000 gallons used for backup generation, backup for central plant boiler fuel, and other purposes. There is also a propane air injection system used for backup. This is supplied locally as needed in the form of 13 tanks (30,000 gallons in size). The propane is consumed at the building level and is piped directly from those storage tanks, which are located near the buildings they serve. Propane consumption in 2020 was 1.06 million gallons for general heating, water heating, and backup generation for buildings within the cantonment area that is not connected to natural gas distribution lines, and for buildings located further away on the training ranges.

Besides 90 kW of solar power, there are no large-scale renewable energy resources currently used at Fort Leonard Wood, but when evaluating the consumption of energy and thermal systems, alternative solutions may include the following benefits:

- Increased energy supply security
- Reduced economic disruptions caused by volatile energy prices
- Realization of local economic advantages by capitalizing on local/regional investments in energy conservation or renewables
- Improvement and modernization of local infrastructure.

After considering the energy resources currently used (Baseline) the next step in the determination of resilience is to evaluate the systems for Black Sky (emergency) situations. After determining the total energy usage and priority load of each mission-critical facility, and the heating, ventilating, and air-conditioning (HVAC) and electrical systems serving each, the non-critical facilities in nearby locations should also be assessed. Maximum down time for mission-critical facilities and the associated thermal and electric energy quality must also be determined.

5.1.5. Establishing the Base Case

According to IEA Annex 73, a seven-step process should be considered when assessing resilience (including robustness, recovery, time, availability, and quality). The Base Case or "business as usual" alternative includes all existing and already planned facilities. Facilities planned for demolition in the Baseline are not included. The Baseline models of buildings and energy systems are adjusted to reflect all planned construction or modifications. The Base Case also includes primary energy usage and energy costs with categories similar to the Baseline (Guide 2021). Planned facilities at Fort Leonard Wood include a new hospital, blood processing center, fire station, and a school for up to 10,000 students.

Table 5-4. Mission-critical facilities at Fort Leonard Wood listing location (cluster or out of range of cluster), type of mission-critical facility, and characterization of emergency backup generation/storage.

Mission Critical Facility #	Cluster Area or Out of Range (OR)	Operations (O) or Life & Safety (LS)	Onsite Backup Generation & Energy Storage Equipment Characterization
1	1	LS	Diesel generator x4, 920 kW each 1983 install date

Mission Critical Facility #	Cluster Area or Out of Range (OR)	Operations (O) or Life & Safety (LS)	Onsite Backup Generation & Energy Storage Equipment Characterization
2	OR	LS	Diesel generator x1, 40 kW 112-gallon tank 1984 install date
3	3	O	Diesel generator x2, 45 kW each 306-gallon tank 2004 install date
4	OR	O	Diesel generator x1, 750 kW each 1390-gallon tank 2017 install date
5	OR	LS	Diesel generator x1, 750 kW each 1390-gallon tank 2017 install date
6	1	O	Diesel generator x2, 880 kW each 2006-gallon tank 2013 install date
7	1	O	Shares with Facility # 6
8	1	O	Diesel generator x1, 600 kW each 1206-gallon tank 1998 install date
9	2	O	None
10	2	O	Natural Gas generator x 2, 2080 kW each uninterruptible power supply (UPS) for mission-critical equipment 2012 install date
11	2	O	Shares with Facility # 10
12	OR	O	None
13	2	LS	Diesel generator x 1, 100 kW each 349-gallon tank UPS for mission-critical equipment 2000 install date
14	OR	LS	Diesel generator x1, 350 kW each 1887-gallon tank 2003 install date
15	OR	LS	None
16	OR	LS	None
17	2	LS	Diesel generator x1, 18 kW each 171-gallon tank 2000 install date

When establishing the Base Case, four major areas were identified within the Fort Leonard Wood cantonment. Determining these Base Case areas included detailed discussions with installation stakeholders to ensure that the outcomes would align with the installation's vision, goals, and mission. Some of the mission-critical facilities were out of range of the cantonment or were not near enough to other facilities that would benefit from resource enhancement (Table

5-4 and Figure 5-3). Four elements were considered to achieve the optimum balance for the entire energy system, based on energy delivered and lost: energy generation, energy distribution, energy storage, and energy demand. Distribution strategies under consideration included 100% centralized energy supply solutions, completely decentralized solutions, or a combination of clusters of buildings connected to nearby central energy plants and buildings having individual decentralized energy systems (none currently at Fort Leonard Wood).

The IEWP noted that there is no dedicated supply of fuel for backup generators at Fort Leonard Wood. Generators at mission-critical facilities receive fuel from the main diesel storage area. Installation personnel indicated that it was difficult to ensure backup fuel supply since they must share diesel with other consumers, including large trucks. Flooding also poses a threat to fueling since access to distribution could be limited. The IEWP estimated that most of the backup generators could run 2 to 5 days at half a load with internal storage tanks. Approximately 133,000 gal of fuel would be needed to run at full capacity for 14 days and approximately 69,500 gal at half capacity for 14 days.

5.1.6. Alternative Scenarios and Economic Analysis

The research team for this integrated analysis considered four primary clusters within Fort Leonard Wood's cantonment rather than the three segregations determined by the IEWP. This restructured analysis considered currently used mission-critical facilities in proximity to other high-traffic facilities, along with potential strategic locations for future planned buildings. It also considered energy conservation – the potential to reduce energy consumption and increase thermal storage. Four major energy system elements were considered: energy generation, energy distribution, energy storage, and energy demand (Güssing 2011). Ultimately, based on several factors specific to Fort Leonard Wood's location, mission, primary threats, and other factors, a combined heat and power (CHP) system and thermal storage were prioritized. The four clusters analyzed include:

- North Cluster (Area 1): four mission-critical facilities
- West Cluster (Area 2): four mission-critical facilities
- South Cluster (Area 3): one mission-critical facility
- Combined West and South Cluster (Areas 2 and 3): five mission-critical facilities.

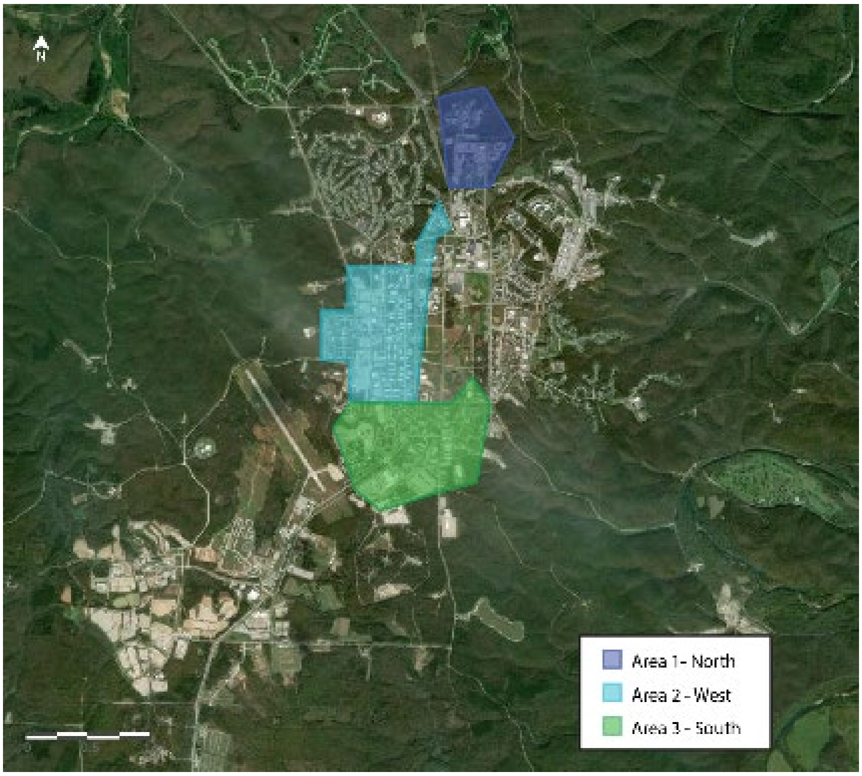


Figure 5-3. Cantonment areas at Fort Leonard Wood analyzed by cluster and proximity to mission-critical facilities.

North Cluster (Area 1)

The first area considered four mission-critical facilities and 27 total buildings, including instructional and hotel buildings. There is also construction taking place within the cluster that includes a new hospital. The down selection analyzed the economic viability of the mission-critical facilities-only, swapping out the old hospital with the new (including upgrades). The second alternative included those same mission-critical facilities with nearby instructional and hotel buildings. Figure 5-4 illustrates the cluster and the proximity of buildings and Table 5-5 lists the load profile of selected buildings.

Figure 5-4. Conceptual representation of North Cluster of buildings.

Table 5-5. North Cluster building load profile.

Parameter	Measure
Number of Facilities	27
Number of mission critical (MC) Facilities	4
Conditioned Area (sq ft [m^2])	887,665 [82467]
Ground Coverage (sq ft [m^2])	2,389,574 [221,999]
Total Electrical Load (kWh/yr)	8,941,625
Total Space Heating Load (kWh/yr)	4,500,598
Total DHW Load (kWh/yr)	1,052,214
Total Heating Load (kWh/yr/sq ft)	2.32
Total Cooling Load (kWh/yr/sq ft)	1.95
Total Electrical Peak (kW)	2,005
Total Cooling Peak (kW)	6,473
Total Space Heating Peak (kW)	8,658

Return on Investment (ROI) for North Cluster, Alternative 1

While stakeholders emphasized that none of the mission-critical facilities were necessarily prioritized over any others since each serves a very specific function, the North Cluster considered both operations (e.g., critical communication facilities, government operations, etc.)

and life and safety (e.g., hospitals, electrical power and water systems, fire stations, etc.) facilities. The current plans for the new hospital include plans for a dedicated heat plant and backup emergency generators similar to the previous arrangement. This first alternative considered sharing a CHP to generate both electricity and steam for the hospital and nearby mission-critical operations-only. This area has high electricity demand and sufficient heat demand so that, by considering the CHP, fuel usage could be more efficiently generated. The CHP would be collocated, serving all mission-critical facilities instead of only the hospital. It would offer supplemental backup electricity and use the district hot water heating system, including thermal storage, to supply heat. Table 5-6 lists the ROI parameters and calculation for North Cluster, Alternative 1.

Table 5-6. ROI for North Cluster, Alternative 1.

Parameter	Measure
Electrical Generation Capacity	0.25 MW
Thermal Generation Capacity	0.375 MW
Initial Investment	$1,457,030
Recurring Costs	$101,971/year
Electrical Energy Savings	$137,794/year
Thermal Energy Savings	$35,072/year
Cost Savings	$70,895/year
ROI	20.55 years

ROI for North Cluster, Alternative 2

The second alternative for the North Cluster considered not only the mission-critical facilities as described in the first alternative, but it also included nearby support buildings such as the hotels and instructional buildings. The CHP and thermal storage would have a much larger capacity and increased investment, but the payback time is similar (Table 5-7).

Table 5-7. ROI for North Cluster, Alternative 2.

Parameter	Measure
Electrical Generation Capacity	1 MW
Thermal Generation Capacity	1.5 MW
Initial Investment	$7,228,498
Recurring Costs	$313,347/year
Electrical Energy Savings	$551,178/year
Thermal Energy Savings	$140,288/year
Cost Savings	$378,119/year
ROI	19.11 Years

West Cluster (Area 2)

The second area considered the proximity between the mission-critical facilities and other types of buildings, primarily newly constructed and/or planned dorm-style military barracks (Figure 5-5 and Table 5-8). This scenario included the need for an expanded distribution system to the newer barracks, or alternately, only the inclusion of the current electrical and thermal connections with the older, already established buildings.

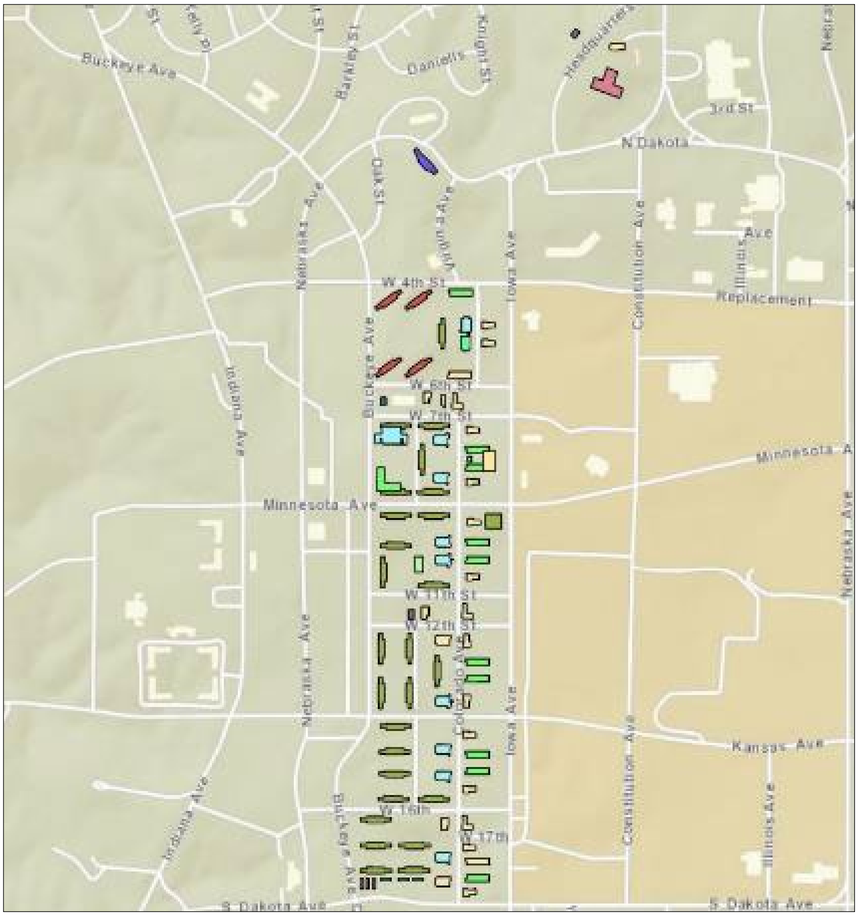


Figure 5-5. Conceptual representation of West Cluster of buildings.

Table 5-8. West Cluster building load profile.

Parameter	Measure
Number of Facilities	92
Number of MC Facilities	5
Conditioned Area (sq ft [m^2])	12,564,201 [1167252]
Ground Coverage (sq ft [m^2])	26,167,432 [2431034]
Total Electrical Load (kWh/year)	21,870,402
Total Space Heating Load (kWh/year)	7,792,985

Parameter	Measure
Total DHW Load (kWh/year)	14,541,565
Total Heating Load (kWh/year/sq ft)	2.36
Total Cooling Load (kWh/year/sq ft)	1.16
Total Electrical Peak (kW)	4,868
Total Cooling Peak (kW)	19,753
Total Space Heating Peak (kW)	22,484

ROI for West Cluster, Alternative 1

The first alternative analyzed costs associated with current infrastructure in place. The size of the CHP was limited by the amount of thermal energy requested during normal operations. In general, the larger the generator, the greater the energy efficiency and the greater the investment return. This assumes that the CHP is loaded at its optimal capacity throughout the course of the year. When factoring in storage, the optimal energy production can be sized to meet the average load (Table 5-9).

Table 5-9. ROI for West Cluster, Alternative 2.

Parameter	Measure
Electrical Generation Capacity	3 MW
Thermal Generation Capacity	4.5 MW
Initial Investment	$18,411,750
Recurring Costs	$940,042/year
Electrical Energy Savings	$1,653,536/year
Thermal Energy Savings	$420,866/year
Cost Savings	$1,134,360/year
ROI	16.25 Years

ROI for West Cluster, Alternative 2

The second alternative analyzed the potential to increase the load served by expanding distribution to a potential new barracks complex. This would increase the average load enough to increase the size of the CHP and to thereby increase its gross return. However, due to the costs associated with the additional thermal distribution, this increased CHP size reduced the ROI by less than a year (Table 5-10).

Table 5-10. ROI for West Cluster, Alternative 2, including expanded distribution to a potential new barracks complex.

Parameter	Measure
Electrical Generation Capacity	4 MW
Thermal Generation Capacity	6 MW
Initial Investment	$23,727,200
Recurring Costs	$1,253,388/year
Electrical Energy Savings	$2,204,714/year

Parameter	Measure
Thermal Energy Savings	$561,155/year
Cost Savings	$1,512,481/year
ROI	15.69 years

South Cluster (Area 3)

The south cluster contained only one mission-critical facility and 21 buildings in total (Figure 5-6 and Table 5-11). Some of the buildings were dorm-style military barracks and maintenance facilities.

Figure 5-6. Conceptual representation of South Cluster of buildings.

Table 5-11. South Cluster building load profile.

Parameter	Measure
Number of Facilities	21
Number of MC Facilities	1
Conditioned Area (sq ft [m^2])	768,504 [71396]
Ground Coverage (sq ft [m^2])	6,447,796 [599020]
Total Electrical Load (kWh/year)	8,504,804

Parameter	Measure
Total Space Heating Load (kWh/year)	7,518,787
Total DHW Load (kWh/year)	1,688,778
Total Heating Load (kWh/year/sq ft)	3,680,623
Total Cooling Load (kWh/year/sq ft)	1.43
Total Electrical Peak (kW)	0.57
Total Cooling Peak (kW)	1,826
Total Space Heating Peak (kW)	5,554

ROI for South Cluster, Alternative 1

The first alternative considered a relatively small CHP consolidated near the southern portion of campus. This presented a unique opportunity to capitalize on existing thermal distribution infrastructure. This resulted in a 13.85 year ROI (Table 5-12).

Table 5-12. ROI for South Cluster, Alternative 1.

Parameter	Measure
Electrical Generation Capacity	1 MW
Thermal Generation Capacity	1.5 MW
Initial Investment	$5,237,987
Recurring Costs	$313,347/year
Electrical Energy Savings	$551,178/year
Thermal Energy Savings	$140,288/year
Cost Savings	$378,119/year
ROI	13.85 years

ROI for South Cluster, Alternative 2

The second alternative considered a similar approach to alternative 1, with a proposed expansion to a barracks complex. This justified an increase in CHP capacity, but also slightly increased distribution costs. While the distribution costs did increase, leveraging the existing thermal distribution infrastructure had significant impacts on the cost projections (Table 5-13).

Table 5-13. ROI for South Cluster, Alternative 2.

Parameter	Measure
Electrical Generation Capacity	2 MW
Thermal Generation Capacity	3 MW
Initial Investment	$9,261,634
Recurring Costs	$626,694/year
Electrical Energy Savings	$1,102,357/year
Thermal Energy Savings	$280,577/year
Cost Savings	$756,240/year
ROI	12.25 Years

Combined West and South Cluster (Areas 2 and 3)

Connecting five total mission-critical facilities and a total of 113 buildings (Figure 5-7 and Table 5-14) in the larger cluster of buildings in the combined west and south of the installation would improve energy supply to more remote mission-critical facilities and may prove cost effective during normal operations.

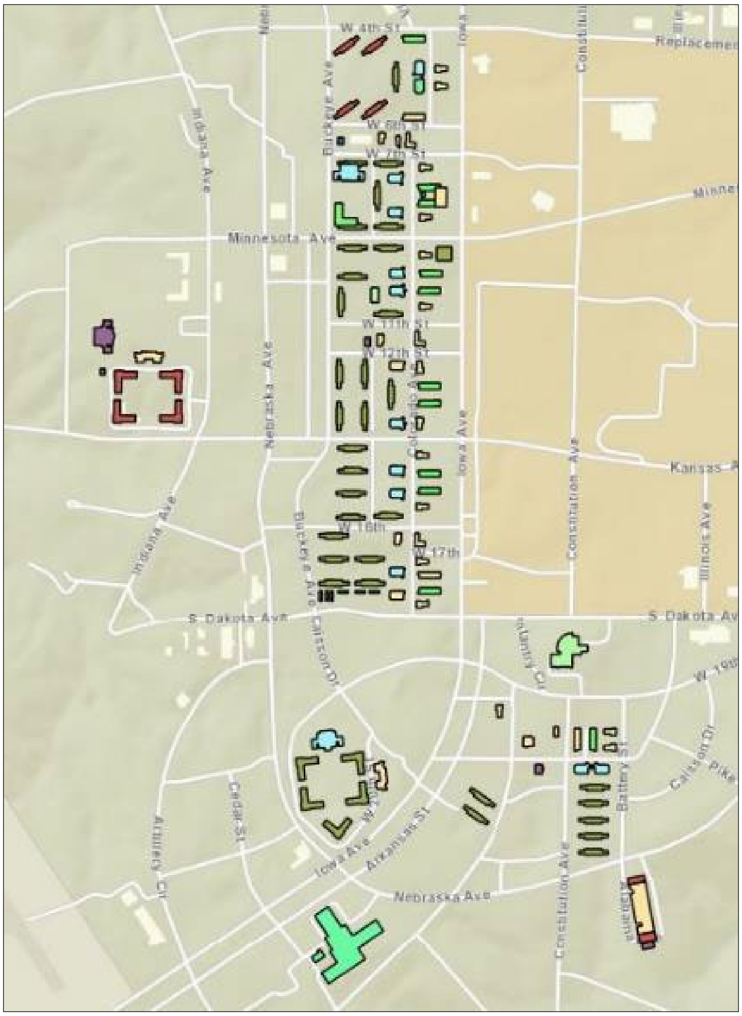


Figure 5-7. Conceptual representation of combined West and South Cluster of buildings.

Table 5-14. West and South Cluster building load profile.

Parameter	Measure
Number of Facilities	113
Number of MC Facilities	6
Conditioned Area (sq ft [m^2])	13,332,705 [1238648]
Ground Coverage (sq ft [m^2])	32,615,228 [3030054]
Total Electrical Load (kWh/year)	30,375,206
Total Space Heating Load (kWh/year)	15,311,772

Parameter	Measure
Total DHW Load (kWh/year)	16,230,343
Total Heating Load (kWh/year/sq ft)	3,680,625
Total Cooling Load (kWh/yr/sq ft)	3
Total Electrical Peak (kW)	4,869
Total Cooling Peak (kW)	21,579
Total Space Heating Peak (kW)	28,038

ROI for Combined Cluster, Alternative (No Other Considered)

This alternative considers the combination of the western and southern clusters. Increasing the CHP and thermal storage size further reduces the ROI to 11.5 years (Table 5-15). This would leverage both existing infrastructure and the development of new infrastructure.

Table 5-15. ROI for Combined Cluster Alternative.

Parameter	Measure
Electrical Generation Capacity	6 MW
Thermal Generation Capacity	9 MW
Initial Investment	$26,427,234
Recurring Costs	$1,852,304/year
Electrical Energy Savings	$3,310,000/year
Thermal Energy Savings	$840,000/year
Cost Savings	$2,297,696/year
ROI	11.5 years

Resilience Analysis and Comparison of Alternatives to Baseline and Base Case

Fort Leonard Wood serves as a good representation of a small community with critical infrastructure susceptible to naturally occurring and manmade threats. The scope of this pilot study was to model the electrical resilience of four buildings while evaluating the costs/benefits of increasing power production capabilities to specific areas. There are several methods to quantifying resilience; this study focused primarily on the EA metric since the basis of the study focuses on increasing power production in localized areas. While ER may be a more comprehensive metric, electrical failures often happen instantaneously, meaning that ER and recovery time become the same value. EA can be calculated by dividing the energy achieved by the energy requested over a specific period. For example, the desired result would be that all the energy requested is supplied, giving an EA of 1. If half of the energy that was requested were supplied, the EA would be 0.5. For the blue and Black Sky scenarios in this study a period of 8760 hours (1 year) and 300 hours (12.5 days) were used, respectively.

Baseline Comparison for North Cluster, Alternative 1 Scenario

The Baseline approach assessed only power supplied by the local utility company. For modeling purposes, the source was represented by the “Transmission” variable (Figure 5-8). This represented everything upstream from Fort Leonard Wood’s main substation or outside of Fort Leonard Wood’s area of responsibility. The main substation represents the distribution from the source to the load, and each building (A, B, C, and D) represents the system load.

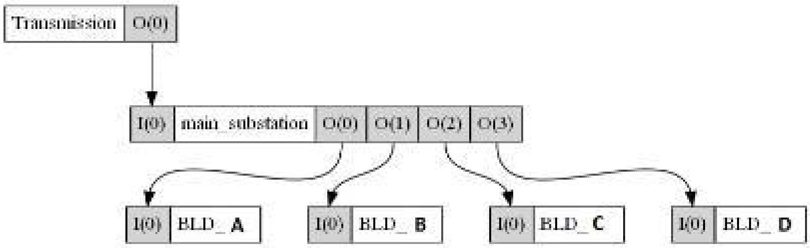


Figure 5-8. Network ports for Baseline resilience analysis.

While this model is not a holistic representation of Fort Leonard Woods electrical distribution system, it allows for a simplified picture of the mission essential electrical grid in a community. The failure rates during the Blue Sky scenario used a Weibull distribution, which considers lifecycle in determining the probability of failure. The MTTR for the electrical system was set at a fixed time of 24 hours, which would be similar to a real-life reliability target that a utility company would be compelled to achieve (Table 5-16). During the Black Sky scenario, a “severe” flood was modeled. While modeling severity is relative and somewhat subjective, it allows for different components of the overall system to be set to fail at specific levels of severity. For example, most of the electrical transmission for the state of Missouri is overhead distribution, which may be less susceptible to flooding events than a substation located near a river system or in a valley. This is not to say that flooding would not cause a transmission system to fail, but rather that the time to repair transmission systems would generally be less than the time to repair a transformer at a substation.

Table 5-16. Baseline electric facilities not meeting requirements during Blue Sky conditions.

Building No.	Gen?	Acceptable MaxSEDT (hours)	Acceptable EA	Model MaxSEDT (Hours)	Model EA	Model ER
A	N	0.005	0.99999	24	0.997	0.994
B	N	0.25	0.9995	24	0.997	0.997
C	N	0.05	0.9999	24	0.997	0.996
D	N	0.05	0.9999	24	0.997	0.994

Under Blue Sky conditions with no redundancy in place, the loads were not served according to the minimum acceptable standards, resulting in a disruption to the mission. Under Black Sky scenarios these results would become much worse (Table 5-17).

Table 5-17. Baseline electric facilities not meeting requirements during Black Sky conditions.

Building No.	Gen?	Acceptable MaxSEDT (hours)	Acceptable EA	Model MaxSEDT (Hours)	Model EA	Model ER
A	N	0.005	0.99999	77	0.743	0.726
B	N	0.25	0.9995	77	0.743	0.729
C	N	0.05	0.9999	77	0.743	0.788
D	N	0.05	0.9999	77	0.743	0.712

The biggest risk with the Baseline approach is that the loads will be subjected to a single point of failure. Despite the transmission (source) being modeled as more resilient to flooding events than the substation, the load was without power for as long as the substation was out of commission. To avoid this single point of failure, a simple approach is to supply backup generators to individual facilities. This approach was evaluated for the Base Case scenario.

Base Case Comparison for North Cluster, Alternative 1 Scenario

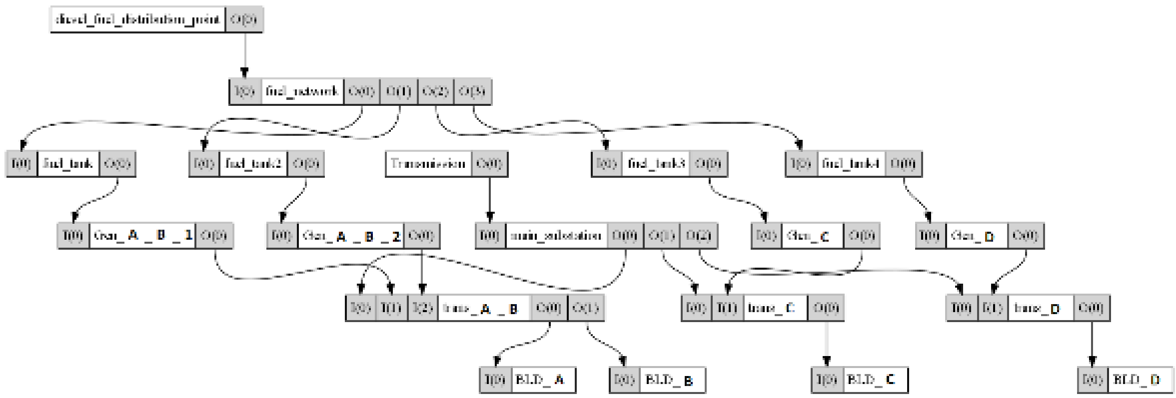


Figure 5-9. Network ports for Base Case resilience analysis.

The Base Case implemented a simple approach to improving resilience by placing backup generators at each individual building (Figure 5-9). With Buildings A and B being the exception, these generators were sized to meet the specific peak demand of their respective buildings and did not share power between buildings. Buildings A and B are collocated with each other and share two generators. This provides an additional layer of resilience for these two buildings by providing redundancy in that, if one of the generators fails, the other can supply both loads outside of peak demand times.

The failure rates were modeled as the same as the Baseline approach, with MTTR being 24 hours during blue sky scenarios and a "severe" flooding event during the Black Sky scenario (Table 5-18). Similar to the utility power source, the backup generators were susceptible to regular outages and were assigned specific failure thresholds for flooding events. Generator C was rated for a severe flooding event, while Generators A and B were not. The susceptibility for generator D was set such that the probability of failure increased (but was not certain) during a "severe" flooding event. The reasoning behind this was to account for differences in elevation and proximity to water sources with respect to generator placement.

Table 5-18. Base Case electric facilities not meeting requirements during Black Sky conditions.

Building No.	Gen?	Acceptable MaxSEDT (hours)	Acceptable EA	Model MaxSEDT (Hours)	Model EA	Model ER
A	Y	0.005	0.99999	7.97	0.973	0.990
B	Y	0.25	0.9995	7.97	0.973	0.979
C	Y	0.05	0.9999	0	1	1
D	Y	0.05	0.9999	9.73	0.968	1

The results from the Base Case scenario demonstrate the value, in terms of improved resilience, that backup generators provide. While the source and distribution still experienced outages during blue sky scenarios (Table 5-19), the backup generators were able to supply the load during the outage. Despite being given specific downtimes (maintenance, failures, etc.), it is very unlikely that these occurrences will coincide with a utility power outage, meaning that, during normal conditions, the loads are served 100% of the time.

Table 5-19. Base Case electric facilities not meeting requirements during Blue Sky conditions.

Building Number	Gen?	Acceptable MaxSEDT (hours)	Acceptable EA	Model MaxSEDT (Hours)	Model EA	Model ER
A	Y	0.005	0.99999	0	1	1
B	Y	0.25	0.9995	0	1	1
C	Y	0.05	0.9999	0	1	1
D	Y	0.05	0.9999	0	1	1

During Black Sky conditions, these systems may be just as susceptible to failure as fixed utility infrastructure. The main difference is that failures on smaller energy infrastructure will have a shorter recovery time than failures on larger systems (Table 5-18). Furthermore, it is easier to take steps on a smaller/mobile infrastructure to remediate the sources of failures. Adding backup generators allowed the system to maintain loads at their desired state during the blue sky scenarios and to reduce the single event downtime by nearly a factor of 10 during the Black Sky event. This can be further improved by developing a simplified microgrid for this specific cluster of buildings that would increase the overall power production of the cluster and use a control strategy to island these four buildings during a disaster event.

Future Case for North Cluster, Alternative 1 Scenario

The third and final approach is to outline alternative/conceptual designs. While backup generators improve resilience sufficiently during Blue Sky conditions, improvements should still be made during Black Sky events. Backup generators typically provide power only during emergency situations. This approach would integrate a larger, high-efficiency CHP plant that would deliver power to the grid, reducing the ROI during normal operations (Figure 5-10). During emergency situations, this generator could island itself from the main grid and deliver power directly to mission essential buildings, adding another layer of resilience.

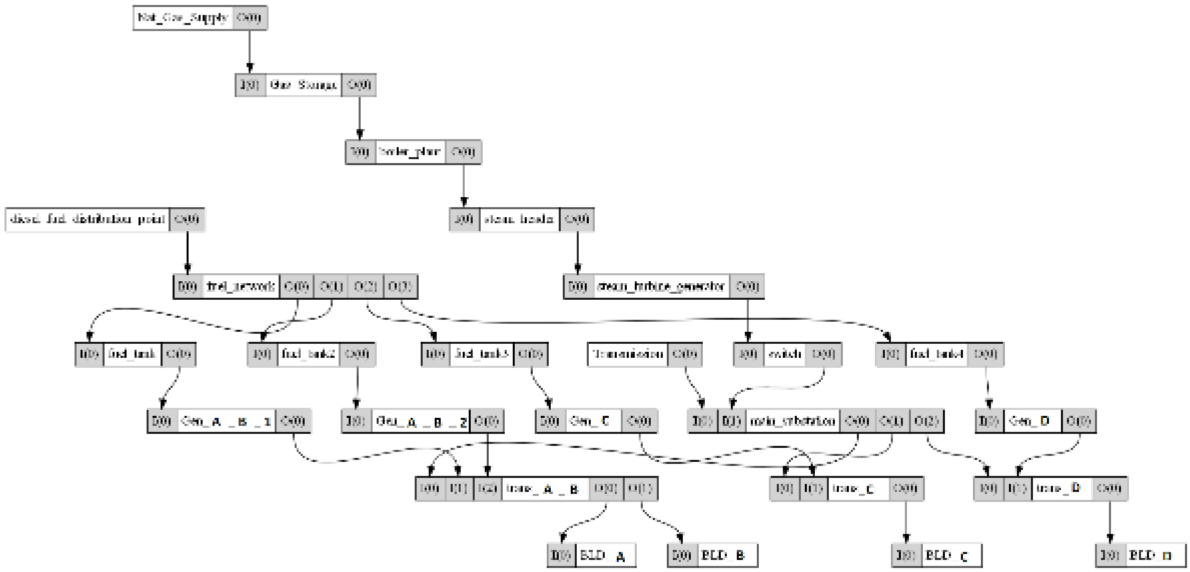


Figure 5-10. Network ports for a future case resilience analysis.

The failure rates and Black Sky event were identical to the Baseline and Base Case approach. This assumed that, since the CHP plant would require a significant investment into energy infrastructure, it would be placed, designed, and rated for natural disaster events, and would be rated for the modeled flooding severity.

Since the CHP and distribution systems were rated for the simulated natural disaster event, none of the loads lost power during either the Blue Sky or Black Sky events (Tables 5-20 and 5-21). This provided the small cluster of buildings with an additional layer of resilience during emergency scenarios. During normal operations, the CHP can produce power as a peaking generator, reducing the ROI for resilient energy systems.

Table 5-20. Base Case electric facilities not meeting requirements during Blue Sky conditions.

Building No.	Gen?	Acceptable MaxSEDT (hours)	Acceptable EA	Model MaxSEDT (Hours)	Model EA	Model ER
A	Y	0.005	0.99999	0	1	1
B	Y	0.25	0.9995	0	1	1
C	Y	0.05	0.9999	0	1	1
D	Y	0.05	0.9999	0	1	1

Table 5-21. Base Case electric facilities not meeting requirements during Black Sky conditions.

Building No	Gen?	Acceptable MaxSEDT (hours)	Acceptable EA	Model MaxSEDT (Hours)	Model EA	Model ER
A	Y	0.005	0.99999	0	1	1
B	Y	0.25	0.9995	0	1	1
C	Y	0.05	0.9999	0	1	1
D	Y	0.05	0.9999	0	1	1

5.1.7. Implementation of Design Recommendations

The actual implementation of design recommendations may be challenging due to the long-term nature of the project. At military installations, it is common for decision-makers such as installation commanders to have short-term assignments. Ideally, any project they are initiating would see completion within 1-5 years. A way to meet both short- and long-term energy master planning goals is to ensure that all short-term projects fit into the long-term roadmap (e.g., achieving net zero emissions by 2045 requires that all new buildings constructed after 2025 be net zero). At this installation, the stakeholders did not wish to pursue combining the hospital with other nearby mission-critical facilities since contracts for the construction of the hospital were well underway and this change departed significantly from already established plans. Additionally, the goal to construct a new hospital as a standalone project that did not originally coordinate well with a full master plan that included longer-term installation energy resilience measures. As long as the hospital had sufficient building-level backup, this was considered sufficient in meeting resilience goals for mission-critical facilities. This illustrates why it is crucial to consider the whole installation (or whole campus/community) rather than simply to consider individual buildings (Guide 2021). In the long run, it could benefit multiple building types, including both mission-critical and support functions.

5.1.8. Conclusion

To simplify the Fort Leonard Wood study and test the durability of the ERIN resilience tool, only one cluster was deeply analyzed with ERIN. As mentioned, the total budget and installation goals from stakeholders must be considered. Recommended alternatives to the Baseline may vary by system architecture and components and may include energy conversion, storage options, or various distribution technologies for meeting long-term energy goals. Ultimately, the ideal solution will consider stakeholder needs, budgetary constraints, and a thorough threat analysis. This study sought to demonstrate that a thorough analysis at the installation master planning level can lead to an integrated approach that includes resilience, efficiency, and sustainability that support the entire community.

5.2. Fort Wainwright (USA)

5.2.1. Introduction

The case study at Fort Wainwright, AK sought to demonstrate resilience modeling for a large-scale site in an arctic climate. This study used the integrated ERIN module within SMPL 2, which allowed a graphical user interface (GUI) to be used in the development of the model. Because the study at Fort Wainwright was over a large scale, including hundreds of individual buildings and building groups, the GUI enabled a more manageable modeling experience. When models become large in scale, TOML files quickly become difficult to organize and debug. Furthermore, network maps such as that shown in Figure 5-10 become messy and hard to follow. The adaptability of ERIN as a standalone or integrated app allows the tool the suit the needs of a particular study.

Locations and Characteristics

Fort Wainwright is located in interior Alaska in the Tanana River Valley basin. The installation spans both sides of the Chena River near its confluence with the Tanana River. Wide seasonal temperature variations are common in this area with summer temperatures averaging between 10 °C and 21 °C (50 °F and 70 °F) and winter temperatures averaging between-26 °C and -43°C (-15 °F and -45 °F).

Building Overview

The study conducted at Fort Wainwright was a large scale effort that modeled most onsite facilities. To present data efficiently, seven representative facilities were selected. These facilities were chosen due to their variety in construction (mass vs. frame), resilience goals, and standby generation capabilities.

Design Basis Threats

As discussed, threats can be organized to facilitate modeling by the effects they produce. The technique was employed during the Fort Wainwright study to create four scenarios, a Baseline and three threat scenarios:

- Baseline (Blue Sky/Business as usual)
- Offsite Electrical Outage (Threat Scenario)
- Onsite Electrical Outage (Threat Scenario)
- Onsite Powerhouse Failure (Threat Scenario).

Baseline

This scenario lasted 1 year (8760 hours). Once the Baseline simulation is finished running, facilities must be evaluated for their resilience against the resilience goals for each facility.

During the Baseline simulation period, almost all facilities met the required resilience metrics for electricity. Only one facility failed to meet the needed level of resilience (Table 5-22).

Table 5-22. Baseline Electric Facilities Not Meeting Requirements.

Building No.	Gen?	Acceptable MaxSEDT (hours)	Acceptable EA	Model MaxSEDT (Hours)	Model EA	Model ER
IONL	N	0.25	0.9995	0.9	0.999897	0.999893
LMCN	Y	8.4	0.95	0	1	1
SVPF	Y	0.005	0.99999	0	1	1
CNXN	Y	25	0.95	0	1	1
GSQP	N	8.4	0.95	0.9	0.999897	0.999893
GGJN	N	0.25	0.9995	0	1	1
ALOT	N	50.4	0.9	0.9	0.999897	0.999893

While multiple facilities are affected by an electrical outage, Facility IONL is the only facility to fail the maximum acceptable downtime metric. Facilities GSPQ and ALOT both experienced outages of the same duration as IONL. However, these facilities have lower resilience requirements than IONL, and are therefore able to meet the prescribed metrics for their facility type. The source of these downtimes was ascribed to several failures of a turbine at the central heating and power plant (CHPP). These failures involve the assigned reliability and maintenance of the turbine. Figure 5-11 shows a sample from within ERIN of the data produced for the turbine that may help the user visualize and compare the requested energy from a load or piece of equipment to what it is able to achieve. Figure 5-11 shows two of the previously mentioned outages. Before the first outage, only a solid line is seen, indicating that the amount of electricity requested from the turbine is being met as the solid "achieved" line is drawn over the dashed "requested" line. After June 12th, the solid line dips but the dashed line it overdrew remains the same, showing an outage of the turbine. This occurred again for a longer duration around June 22nd.

Figure 5-11. Sample turbine outages.

More outages occur during the Baseline, ranging in duration from 4 hours to as long as 13½ hours. During these times, the electrical provider is able to pick up the loads that the turbine no longer covers, which allows facilities to resume operation with minimal interruption. The longest outage, of 13.47-hour duration, occurs in early June. The installation can plan for this regular seasonal summer turbine maintenance to mitigate the effects of the outage during the lag between power supplied by the turbine and power supplied by the utility. However, since all facilities, with the exception of IONL, perform well, it appears Fort Wainwright would be resilient to this type of theoretical outage. If deemed necessary, further mitigation for IONL may include installation of a generator or quick connects so that mobile generation may be brought in. Some improvements may also be made with continued maintenance activities. Maintaining resilience is just as important as taking steps to reach a resilient state. For the Baseline, maintenance of resilience is both desired and appropriate. Maintenance of a resilient state includes regular preventive maintenance, testing of equipment, and consistent refresh of fuel in standby generators and tanks to avoid fuel spoilage.

Resiliency of the thermal portion of the Baseline depends on outdoor temperatures. The resilience metrics section above describes habitability and sustainability recovery times for different types of facilities at various temperatures. Facilities in the Fort Wainwright study were evaluated at the sustainability point (-40 °C [-40 °F]). These acceptable downtimes were then compared to those experienced by facilities during simulation. When one of these downtimes is exceeded by the downtime experienced by the facility, it is flagged in red. Because both electricity and steam are provided by the same turbine, the origin of the outage can be traced back to the turbine once again. The same maximum downtime of 13.47 hours is seen across several facilities. Table 5-23 lists a sampling of the facilities experiencing outage.

Table 5-23. Baseline thermal facilities.

Facility ID	MaxSEDT Experienced (Hours)	MaxSEDT for Sustainability at Outdoor Dry Bulb (ODB) Temperature (Hours)				
		-40 °C (-40 °F)	-29 °C (-20 °F)	-18 °C (0 °F)	-7 °C (20 °F)	4 °C (40 °F)
IONL	13.4717	18	22	28	35	47
LMCN	13.4717	36	46	59	78	112
SVPF	13.4717	36	46	59	78	112
CNXN	13.4717	18	22	28	35	47
GSQP	13.4717	18	22	28	35	47
GGJN	13.4717	18	22	28	35	47
ALOT	13.4717	10	15	21	28	41

While facility ALOT is the only one within the sample to miss the resilience requirements, it represents how 36% of facilities performed. An outage of this duration means that many facilities like ALOT will not remain sustainable when outdoor temperatures drop to -40 °C (-40 °F) or lower. These include facilities with a lower mass or frame construction type. Because the outage of longest duration occurs in June when outdoor temperatures are unlikely to reach this level, the outage is less cause for concern.

Another outage of 11 hour duration occurs in late March. Once again because outdoor temperatures are unlikely to reach -40 °C (-40 °F) or lower during this time of year, facilities will be able to endure such an outage. Two more outages of 11 hour duration are seen, one in September and the other in November. While temperature averages in these months do not typically fall as low as -40°C (-40°F), outages in typically cooler months may indicate some need for remediation. However, because more than one turbine is present onsite and failure is only seen in one, it may be possible to transfer steam generation while the necessary repairs are made. For times when multiple turbines are down or when a short outage would threaten the facility's sustainability, portable boilers may provide support to those facilities requiring it.

Offsite Electrical Outage

This scenario models the loss of power from the utility provider, making the installation fully dependent on onsite generation to meet electric needs of facilities. The scenario lasted for 400 hours. Table 5-24 lists results for the sample building group. At the beginning of the scenario, the connection to the electric utility is severed.

Table 5-24. Offsite outage electrical results.

Facility ID	Gen?	Acceptable MaxSEDT (Hours)	Acceptable Energy Availability (EA)	Model MaxSEDT (Hours)	Model EA	Model ER
IONL	N	0.25	0.9995	14	0.65	0.65625
LMCN	Y	8.4	0.95	1	0.952217	0.992228
SVPF	Y	0.005	0.99999	0	1	1
CNXN	Y	25	0.95	0	1	1
GSQP	N	8.4	0.95	13	0.716147	0.729262
GGJN	N	0.25	0.9995	0	1	1
ALOT	N	50.4	0.9	7	0.728647	0.733173

Some buildings never experience any outage at all. These tend to be those buildings that either have a backup generator, such as SVPF and CNCX, or very small loads that are easily handled by onsite generation capabilities. As the scenario progresses, buildings that have outages begin to either fully or partially meet the requested load as the larger turbine at the CHPP comes online and is able to supply more facilities. Even with the full generation capacity of the CHPP, not all loads can be satisfied for the duration of the utility provider outage. IONL, GSPQ, and ALOT all miss at least one resilience requirement. Figure 5-12, which shows the requested vs. achieved loads for Facility IONL, provides a good representation of how most buildings performed during this outage. While some power is received, there is simply not enough capacity to meet peaks, which causes several outages.

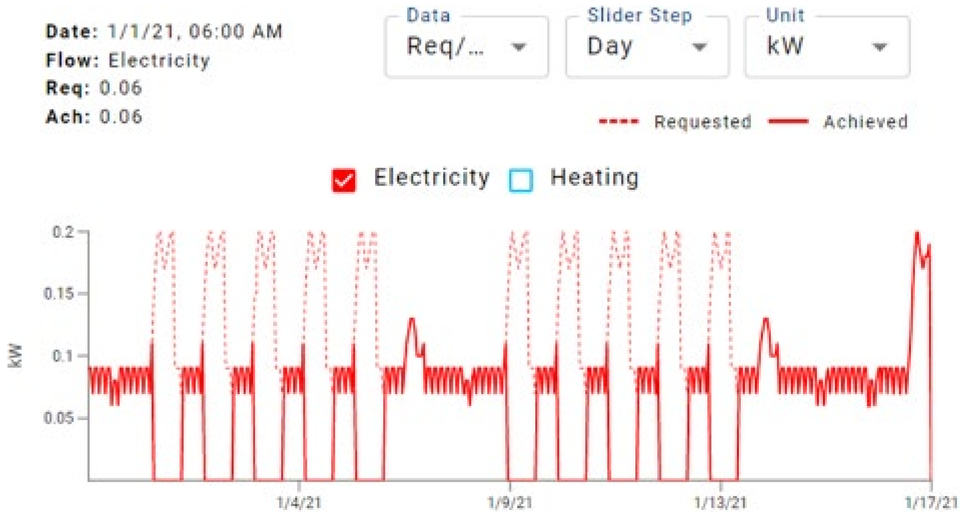


Figure 5-12. Facility IONL cannot meet loads during times of peak consumption.

Facilities IONL and GSPQ fail both the MaxSEDT and EA metrics while ALOT fails only the ES metric. This is because while no single outage is long enough to cause a failure in the MaxSEDT category, the sum total of the multiple outages lowers the percentage of the mission time served to an unacceptable level.

Thermal results for this scenario proved unremarkable. There were no major thermal outages and all facilities met the required metrics for the duration of the event.

Onsite Electrical Outage

The onsite electrical outage scenario simulated a situation in which all capabilities to distribute electricity on site were lost. The scenario lasted 400 hours in total. Of note during this scenario is the failure of even those facilities to meet resilience requirements (Table 5-25). Facility SVPF is the only facility in the sample to maintain a fully powered state.

Table 5-25. Electric Results for on base distribution outage.

Facility ID	Gen?	Acceptable MaxSEDT (Hours)	Acceptable EA	Model MaxSEDT (Hours)	Model EA	Model ER
IONL	N	0.25	0.9995	307	0.2325	0.240385
LMCN	Y	8.4	0.95	9	0.777217	0.973197
SVPF	Y	0.005	0.99999	0	1	1
CNXN	Y	25	0.95	307	0.2325	0.264149
GSQP	N	8.4	0.95	307	0.2325	0.240385
GGJN	N	0.25	0.9995	307	0.2325	0.240385
ALOT	N	50.4	0.9	307	0.2325	0.240385

When evaluating facility CNXN, it became apparent that while the facility does receive support from its onsite generator for the duration of the event; the generator is only able to supply a small portion of what is requested (Figure 5-13). This causes the facility to be considered "down" since the requested load is never met before support from the CHPP and the electric utility is restored. In the previous scenario, support from the CHPP allows the generator to cover the peaks and satisfy the requested load, but on its own, the generator cannot supply the whole facility. If more support is desired, the facility may require more permanent generation capacity or quick connects so that mobile generation can be brought in as needed in times of emergency.

Figure 5-13. Facility CNXN requested vs. achieved.

Facility LMCN faces the same problem, however to a much lesser extent (Figure 5-14). Once again, if more support is desired, additional standby generation or mobile generation capabilities may prove useful for this facility.

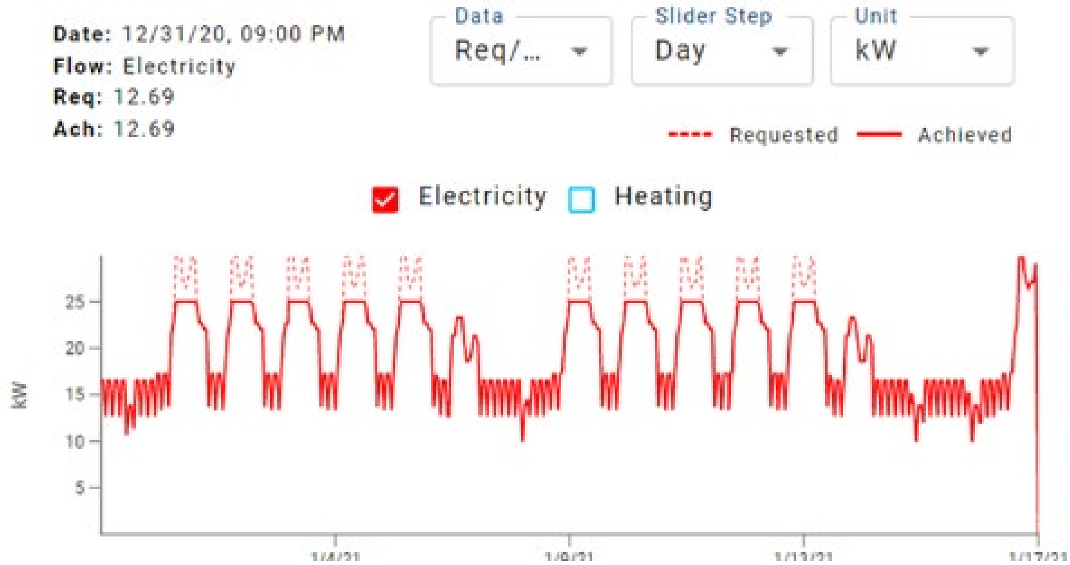


Figure 5-14. Facility LMCN cannot get enough power to cover peaks.

Because the outage is so widespread, it may be impractical to install enough quick connects and store enough mobile generators to support all onsite facilities and not just those with higher resilience requirements. Looped electrical systems or microgrids may help to mitigate this type of outage; however, it is important to assess the benefits of these types of solutions vs. their cost. Economic analysis did not play a major role in this study and may prove an interesting future study. Management of an outage of this magnitude is more important and relocation of missions and people may become necessary.

Thermal results for this scenario proved unremarkable (Table 5-26). There were no major thermal outages, and all facilities met the required metrics or the duration of the scenario.

Table 5-26. Thermal results for the Offsite Electrical Outage scenario.

Facility ID	MaxSEDT Experienced (Hours)	MaxSEDT for Sustainability at ODB Temperature (Hours)				
		-40 °C (-40 °F)	-29 °C (-20 °F)	-18 °C (0 °F)	-7 °C (20 °F)	4 °C (40 °F)
IONL	0	18	22	28	35	47
LMCN	0	36	46	59	78	112
SVPF	0	36	46	59	78	112
CNXN	0	18	22	28	35	47
GSQP	0	18	22	28	35	47
GGJN	0	18	22	28	35	47
ALOT	0	10	15	21	28	41

Onsite Powerhouse Failure

The final scenario models a case in which the CHPP is taken offline. This removed the installation's capability to produce both power and steam on site. Electric distribution capabilities and connection with the electric utility provider were left intact (Table 5-27), thus facilities experienced little to no disruption in electricity as the utility was quickly able to increase supply to make up for what would have been produced on site.

Table 5-27. Powerhouse outage electrical results.

Facility ID	Gen?	Acceptable MaxSEDT (Hours)	Acceptable EA	Model MaxSEDT (Hours)	Model EA	Model ER
IONL	N	0.25	0.9995	0	1	1
LMCN	Y	8.4	0.95	0	1	1
SVPF	Y	0.005	0.99999	0	1	1
CNXN	Y	25	0.95	0	1	1
GSQP	N	8.4	0.95	0	1	1
GGJN	N	0.25	0.9995	0	1	1
ALOT	N	50.4	0.9	0	1	1

During the steam outage, facilities are left without access to steam for periods of 278 hours. Outage times of this duration pose a threat to both facility habitability and sustainability. Sustainment of human life is essential in the event of this type of occurrence. All facilities with access to steam are affected by this outage, with those with more massive construction (higher thermal mass) able to maintain internal temperature for longer periods than other facilities with more lightweight construction (Table 5-28). Figure 5-15 provides a useful visual of the achieved vs. requested heating loads.

Relocation of inhabitants or portable boilers provides potential ways to mitigate vulnerability. As previously stated, long thermal outages are of less concern during periods of mild weather, when outdoor air temperatures are warmer. Having designated cold shelters on site may also prove a valuable solution. These shelters may employ space heaters or other electric sources of heating to evacuate to so that the connection with GVEA or backup generators may be used to help in sustaining life while the CHPP is incapacitated.

Table 5-28. Powerhouse outage thermal results.

Facility ID	MaxSEDT Experienced (Hours)	MaxSEDT for Sustainability at ODB Temperature (Hours)				
		-40 °C (-40 °F)	-29 °C (-20 °F)	-18 °C (0 °F)	-7 °C (20 °F)	4 °C (40 °F)
IONL	278	18	22	28	35	47
LMCN	278	36	46	59	78	112
SVPF	278	36	46	59	78	112
CNXN	278	18	22	28	35	47
GSQP	278	18	22	28	35	47
GGJN	278	18	22	28	35	47
ALOT	278	10	15	21	28	41

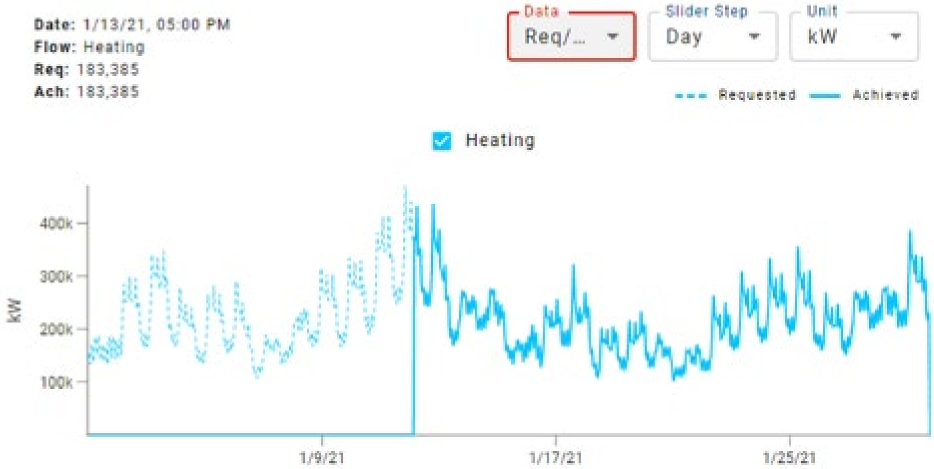


Figure 5-15. Boiler Plant Loads Requested vs. achieved.

Planning For Alternatives

Once the vulnerabilities of a site are identified, mitigation strategies can be tested to help gauge their effectiveness with respect to a particular vulnerability. In general, ERIN allows multiple strategies to be explored quickly to aid in decision making.

The onsite powerhouse failure caused a widespread outage of heat; all facilities in the analysis sample lost both thermal habitability and sustainability while access to electricity remained largely unaffected. To combat the loss of heating, a diesel portable boiler was added to the model. Because backup generators already run with diesel, using a diesel boiler may allow for easier integration into refueling schedules during a long event duration.

With the addition of a portable boiler, the electric results remain unchanged. This is expected since the utility is able to provide increased support and redundancy even when onsite generation is not possible. However, the additional boiler provides a considerable benefit in terms of improving the facility's thermal resilience (Table 5-29).

Table 5-29. After Adding a portable boiler, facilities are able to maintain a habitable environment.

Facility ID	MaxSEDT Experienced (Hours)	MaxSEDT for Sustainability at ODB Temperature (Hours)				
		-40 °C (-40 °F)	-29 °C (-20 °F)	-18 °C (0 °F)	-7 °C (20 °F)	4 °C (40 °F)
IONL	0	18	22	28	35	47
LMCN	0	36	46	59	78	112
SVPF	0	36	46	59	78	112
CNXN	0	18	22	28	35	47
GSQP	0	18	22	28	35	47
GGJN	0	18	22	28	35	47
ALOT	0	10	15	21	28	41

Previously, all facilities listed in Table 5-29 experienced outages of 278 hours. However, with the redundancy of a portable diesel boiler, facilities are now able to avoid losing heat and meet resilience goals. Figures 5-16 and 5-17 show this redundancy.

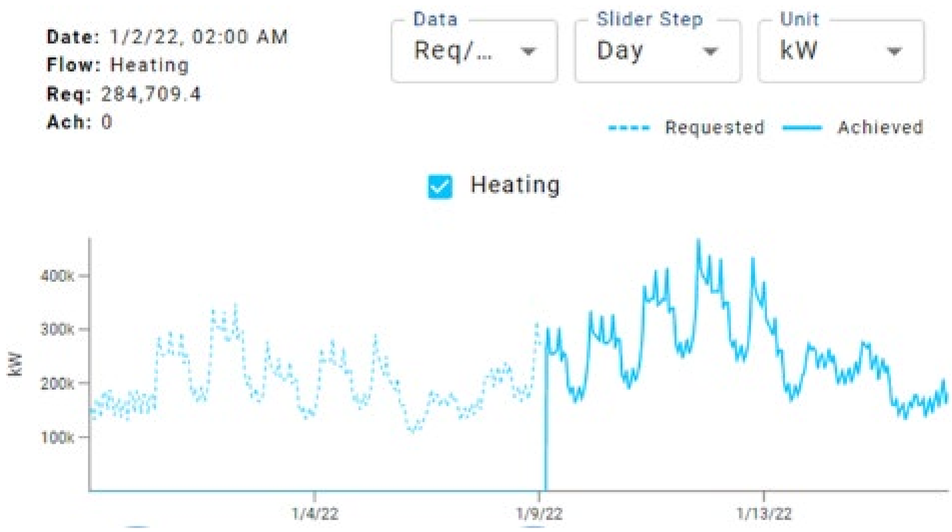


Figure 5-16. Boiler Plant still undergoes outage.

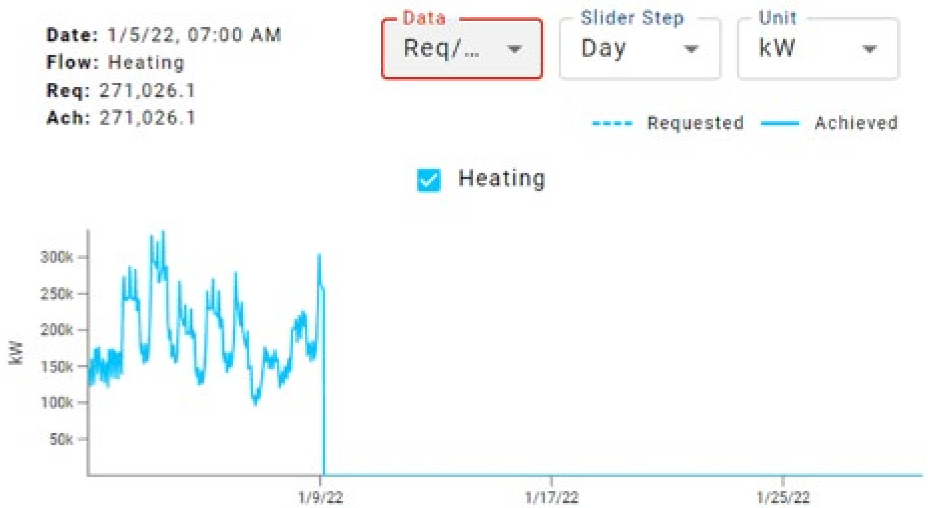


Figure 5-17. Portable Boiler Picks up load during event.

A comparison of Figures 5-16 and 5-17 reveals that the portable boiler meets the load that the powerhouse is unable to supply. The added layer of redundancy from a separate source of heat helps to increase resilience. Now that the solution has been shown to be effective and has been prescreened by ERIN, it merits further investigation; next steps such as economic analysis can be used to determine practicality of the solution vs. other strategies.

Conclusions

The ERIN tool is a useful part of the resilience toolkit. In both standalone and integrated applications, ERIN lets the user rapidly model and adjust during the resilience and master planning process. The two case studies presented provide useful insight into how the capabilities of ERIN can be applied. The four modeled scenarios at Fort Wainwright revealed steps the installation can take to withstand and respond to threats.

A final part of this study involved adding supplementary resilience measures to the powerhouse failure scenario in the form of a portable boiler. This scenario captured ERIN's ability to evaluate the effectiveness and applicability of mitigation strategies. This study also shows how the integrated user interface within SMPL 2 allows for the creation of much larger studies by more easily manipulating data and creating easily understood charts and graphs. Directly viewing the requested and achieved energy for a facility allows for a quicker diagnosis of the cause of an outage so the planning process can continue efficiently.

5.3. JKU (Johannes Kepler Universität) Campus in Linz (AT)

The methodology developed in Annex 73 was applied in 2021 to the JKU university campus in Austria. The methodology, results, and conclusion are described in a master thesis (Schiehl 2021). This section summarizes process and main findings. Currently, the campus relies heavily on energy from the power grid and a district heating network. Only a small part of waste heat from processes and cooling is used. Critical functions like low temperature cold in laboratories and supply of servers are secured by backup diesel generators. This study investigated the effects of building refurbishment and whether a photovoltaic (PV) plant plus electric storage will allow for 100% renewable power supply and increased resilience of the whole campus.

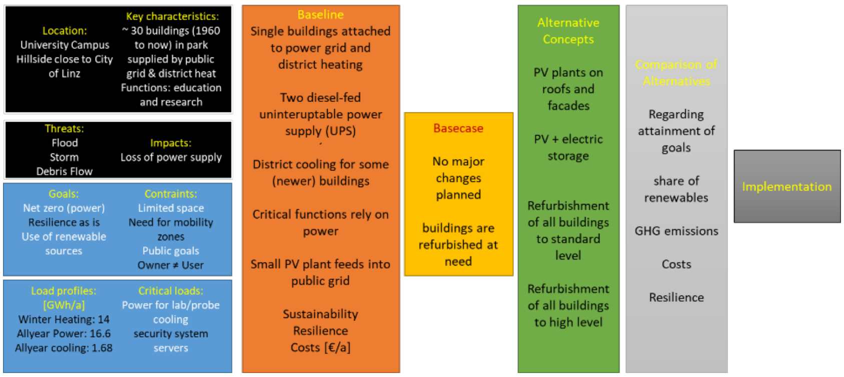


Figure 5-18. Overview of Process and outcome for JKU campus

5.3.1. Resilience Methodology

In the first step, the JKU university campus in upper Austria was defined as the object of study. The JKU campus consists of around 26 buildings located at the campus site around an artificial lake. Most of the buildings have concrete facades with large windows; some are up-to-date high-efficiency buildings; and there is one castle (over 300 years old). Most of the buildings were built after 1970. Other buildings that belong to the university but do not reside on campus were not included in the study.

A schedule for the master planning process was developed. The main stakeholders were identified, informed about the project, and asked for information as well as their interests and intentions regarding JKU campus. The existing energy system was identified, including system boundaries, heating and cooling supply, electricity grid, central facilities, and the distribution system on site.

The public building owners (BIG) provided building energy certificates; the university gave insight into energy consumption, supply system, and critical functions. Figure Table 5-18 shows the energy system in the scheme developed by IEA EBC Annex 73 Operating Agents (Guide 2021) for the Energy Master Plan.

The JKU campus is supplied by regional electric and heat systems. Some newer buildings are provided with district cooling, the cold water is created by the public energy provider using refrigerating machines on the campus. Heat is distributed via a high-temperature water-based system since many of the buildings require high temperature heat.

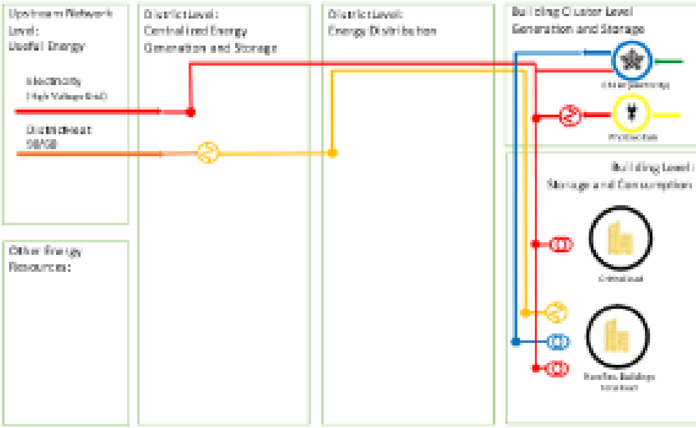


Figure 5-19. Resilience process after disturbance to the system (representation by Anna Schiehl).

The supply was analyzed, including local components and emergency power sources. Areas with increased requirements were identified as critical areas or infrastructure. In addition to identifying the critical infrastructure, it is necessary to know the given system's redundancy and potential hedging components.

Scenarios were developed to enable the assessment of resilience under threat conditions. Threats to the site were identified and the hazard potential was analyzed. The potential hazards were assessed and evaluated in a matrix according to frequency and severity of impact. The selected threats are summarized in different future (Black Sky) scenarios, in which the identified threats occur depending on their probability.

The scenario development identified the relevant failure risks of the power system. The scenarios represent realistic forecasts based on the following steps.

- Investigation of past power outages and reasons
- Listing the frequency and impact of the events
- Quantification of the data
- Development of the scenarios according to the following scheme.

In addition to the Blue Sky (without extreme weather events) scenario, three Black Sky scenarios were identified and investigated

- Scenario 1: Flood
- Scenario 2: Storm
- Scenario 3: Debris flow.

5.3.2. Blue Sky Methodology

The constraints and objectives for the planning process were analyzed simultaneously. The site was inspected. JKU announced internal campus goals and information on the current state of the campus, including plans for the future, was obtained. JKU has expressed a desire to reach a zero-carbon balance by 2030. Public goals for buildings were combined with the goals expressed by JKU to produce the set of goals listed in Table 5-30. Energy performance certificates for the buildings and information on energy consumption (heating, cooling, electricity) were provided. Aerial photos from the GIS databases DORIS (Upper Austrian GIS database) made it possible to determine the topography and to query official permits, property rights, and environmental influences at the site.

By identifying legal or local framework conditions, certain measures in the energy system can be excluded or preferred. An analysis of the legal regulations and framework conditions at different local levels was done and goals were defined.

Table 5-30. Goals defined for JKU Campus

Goals	Quantitative goals
Reduction of CO_2	by 37.5%
Increase renewable share of electricity	to 100%
Reduction of energy-related energy costs	by 25%
Reduction of heat input per m^2	by 1% per year
Implementation of exclusively renewable energy sources	
Increase resilience	
Use of innovative planning tools for resilience calculation	
Increase resilience through storage integration in at least one scenario	

Load profiles were developed for the quantitative analysis of sustainability and resilience of the energy supply. The investigated energy network covers consumption of three energy types, heating, cooling, and electricity.

The thermal storage capacity of the buildings was checked to ensure that it was sufficient in relation to thermal losses to avoid possible damage caused by a short-term supply interruption in the heating network. Therefore, the heat supply was not included in the resilience calculation and no-load profile was created. The heating energy demand is however considered in the calculation of sustainability and energy costs.

Cooling is generated by a cooling unit at the site and is electricity dependent. Therefore, no cooling profile was created, but the generation energy has been included in the electricity analysis.

The amount of energy purchased and its allocation according to the type of energy (heat, cooling, electricity) was analyzed. Table 5-31 lists the identified consumption loads by type.

Table 5-31. Baseline Energy consumption of JKU Campus.

Energy Type	Consumption Baseline (kWh/year)
Electricity	16,600,000
Attributed to critical functions	5,518,800
Heat	14,000,000
Cooling	1,680,000

As stated, the heat supply can be interrupted for some hours (at least) without significant loss of comfort, and for more than a few days without EXposing THE buildings to negative effects. Depending on the load to be served, this can also be the case for electric supply. In fact, three different types of loads can be identified, which can then be treated according to their priority.

Longer-Term Interruptible Loads

This includes loads that can cope with longer-term interruptions without negative effects. The loads do not require a replacement energy supply in case of damage and can resume their function without negative effects even after a longer period of non-supply. This is a secondary load. Examples here are household appliances without a continuous power supply or buildings that can be operated for several days without conditioning.

Short-Term Interruptible Loads

Loads that require a backup power supply are assigned to this category. However, short-term interruptions have no negative influence on the function. Depending on the load, a certain period of time can be bridged. Cold rooms or rooms with certain temperature conditions, for example, can maintain the desired temperature even if there is no active energy supply for a short time.

Non-Interruptible Loads (Uninterruptible Loads)

Consumers that require non-interruptible load are defined by their need for a continuous guaranteed energy supply. Even a brief interruption causes the function to be impaired and negative effects to occur. Most of the time, these areas have an uninterruptible power supply (UPS) unit, e.g., servers, data centers, digital control rooms, etc.

Figure 5-20 shows the scheme of a local energy supply that distinguishes the three categories. In the normal state, all loads are covered by the central energy supplier. In the event of a supply interruption, the loads that are not essential for emergency operation are not maintained. In Austria, electricity consumers can designate specific loads as interruptible in exchange for a lower price. This possibility is used by energy intensive industries and private heating systems (night-storage heaters).

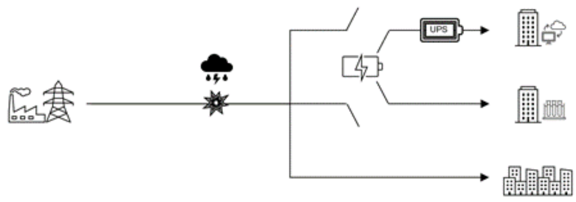


Figure 5-20. Scheme of an energy supply with supply interruption

Baseline and Variants

Detailed information on the existing energy system was obtained in the previous steps. In this step, the baseline resilience, sustainability, and efficiency are analyzed and assessed.

The sustainability and efficiency of the energy system are calculated under normal conditions, i.e., in the Blue Sky scenario.

To evaluate the results of the scenarios, quantitative comparison parameters or metrics are defined, which define how to measure share of renewables or greenhouse gas (GHG) emissions.

The goal of the Resilience Energy Master Planning is to find solutions for energy supply that increase resilience and sustainability.

The variants described in the following sections were investigated as JKU campus energy supply systems. Other measures were considered in a pre-analysis phase but were not further examined.

Baseline

The baseline is the current initial situation. The information gathered in the previous steps was consolidated to describe the current status. The baseline situation was simulated under the influence of the defined scenarios to determine the resilience.

Base Case

The Base Case describes the future state of the object of investigation and is considered the basis for further planning. In this study, no Base Case exists because the campus was recently renovated and no significant changes are planned.

Variant 1 - Additional Photovoltaic System

This is a variant in which an expansion of the PV system on site by 4MWp is analyzed. By integrating additional PV modules, the renewable share of the power supply is increased and the dependence on the utility grid is reduced. The PV system is designed to produce the share of power that is now gained from non-renewable fuels, about one quarter. This scenario would use most roofs and also some building facades.

Variant 2 - Additional Photovoltaic System and Storage Unit

In the second variant, the energy system is expanded to supplement the PV system with a means of storage. The storage system enables increased resilience and self-sufficiency in the campus power supply. The storage is sized to cover a critical functions demand for 24 hrs, which is 7.5 MWh.

Variant 3 - Renovation According to OIB

In this variant, the thermal renovation of the buildings to OIB (Österreichisches Institut für Bautechnik [Austrian Institute for Structural Engineering]) standards was investigated. The OIB is a guideline of the Austrian Institute for Building Technology (hereafter called the "OIB Guideline") and specifies requirements for buildings. The improvement of the building envelopes by an average 36% has an impact on heat and cooling demand and energy efficiency.

Variant 4 - Ambitious Renovation

In Variant 4, the effects of ambitious thermal renovations are analyzed. Potential energy savings through these measures to improve the building envelope were estimated to be around 54%, based on the status of the buildings. This would reduce the heating energy needed to supply the campus.

Comparison

In step 6, the variants are compared to the baseline and the Base Case. The resilience, efficiency, and sustainability parameters of the different system variants are calculated. The results were evaluated and compared to the goals defined in the first part of the process (Table 5-30). Basing on the results, measures can be chosen to fulfill the defined criteria and reach or approximate the goals.

Resilience

Figure 5-21 shows the results for energy availability for interruptible loads in Variants 1 and 2 and the baseline, for the scenarios chosen previously in the Black Sky part of the process.

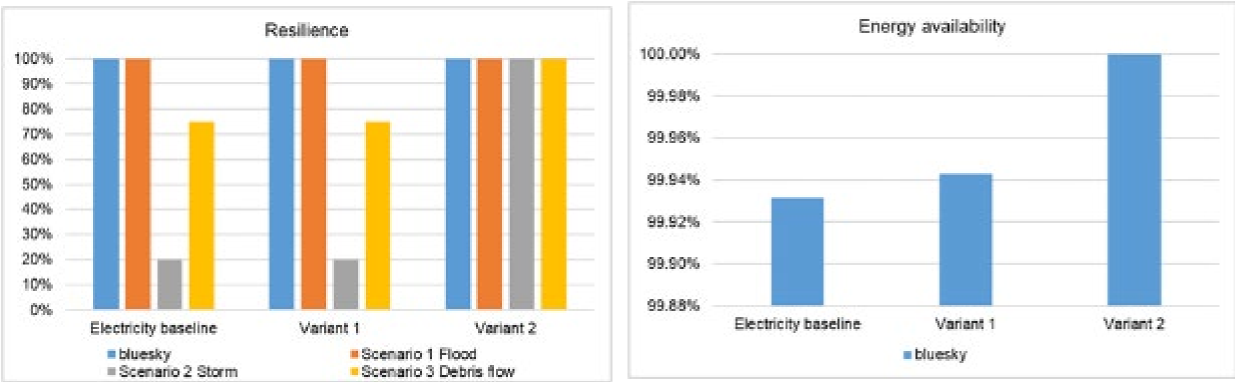


Figure 5-21. Energy availability of secondary load under influence of specific scenario (left) and energy availability of critical loads in Blue Sky scenario (right)

Resilience of the critical loads is not shown, as they are continuously served due to redundant supply chains and UPS components and thus reach 100% in each scenario. The deviation from 100% energy availability in the Blue Sky scenario is small and can be attributed to the probability of simultaneous failure of all sources.

Table 5-32 shows that the power system in Variant 2, in which a PV system is combined to a storage unit, has no interruptions. The system has a resilience of 100% in the simulation and can always maintain its functions. In all variants, high resilience was observed under the influence of scenario 1 (flood). The longest interruptions were observed under Scenario 2 (storm). Under the influence of storms an outage leads to an energy availability of around 20%, whereas in the case of a mudslide, three quarters of the load is covered. In the flood and Blue Sky scenario, the system has a coverage rate of almost 100%.

Under detailed consideration of the variants in the Blue Sky scenario, the energy availability differs (Figure 5-21). Baseline and Variant 1 show a similar reaction to the disturbances described in Scenarios 2 and 3 (right side of Figure 5-21).

In the existing energy system (baseline), most identified critical functions are collected and served by two UPSs. The data in Table 5-32 indicate the resilience achieved for the examined scenarios in the baseline.

The integration of an additional storage facility for electricity is expected to significantly increase resilience of non-critical functions, but only if there is a corresponding micro grid infrastructure. This can be observed in Figure 5-21 (left), which shows that Variant 2 alone, which includes the electricity storage, leads to almost 100% resilience for the electricity supply of the whole system. If the critical infrastructure is protected by UPS components, as is the design at the JKU campus, the resilience of critical functions is already at a high qualitative standard and does not require any immediate improvement.

The resilience goals of the study at the JKU campus Linz were achieved and did not deteriorate in any of the examined variants. The increase in resilience was examined and confirmed in

Variants 1 and 2. There was no quantitative target regarding this improvement. To quantify resilience, the ERIN simulation tool from Big Ladder Software was used and applied to a simplified models for the energy systems of Variants 1 and 2.

Energy storage was also shown to increase self-consumption of the local PV power, thus increasing the flexibility of the system. The increase in flexibility was another one of the goals formulated for the study and is an important parameter of the smart readiness indicator (SMI), which is being introduced in Europe and which promotes a buildings' ability to support and balance energy grids.

Table 5-32. Resilience values for baseline under influence of specific scenario.

Scenario Designation		Energy Availability *[%]*		Maximum Downtime *[hrs/duration]*		Unserved Load [kWh/Duration]		Energy Consumption *[kWh/Duration]*
		Secondary Load	Critical Load	Secondary Load	Critical Load	Secondary Load	Critical Load	Total Load
Blue Sky		99,9315	100	5	0	1 385	0	16,598,439
Black Sky	Scenario 1 Flood	100	100	0	0	0	0	551,916
	Scenario 2 Storm	20	100	12	0	192 608	0	123,752
	Scenario 3 Debris flow	75	100	24	0	231 020	0	995,461

Sustainability

An average two-person household (approx. 3,000 kWh/a) in Austria emits almost 800 kg of CO_2 through annual electricity consumption. In an apartment with a floor area of 60 m^2 (646 ft^2), this corresponds to emissions of around 13 kg/m^{2}a (Umweltbundesamt.at 2021). The CO_2 emissions in Figure 5-22 exceed the average of the listed household in every variant.

In addition to the assessment according to OIB guideline 6, CO_2 emissions are assessed with regard to the requirements of the klima:aktiv (2020, p. 16) initiative. Refurbishments must reach a limit value of 21 kg/m^{2}BGF. Thermal measures are not sufficient to comply with the required limit value; only by integrating the photovoltaic system is it mathematically possible to fall below 21 kg/m^{2}BGFa.

The renewable share of heat and electricity supply is assessed by different methods. The renewable share of the electricity supply increases due to the integration of the photovoltaic system. Figure 5-22 shows the increase in the non-fossil share in Variants 1 and 2 to 100%. According to the Austrian mix, the electricity supply is thus completely made up of renewable energy in the balance.

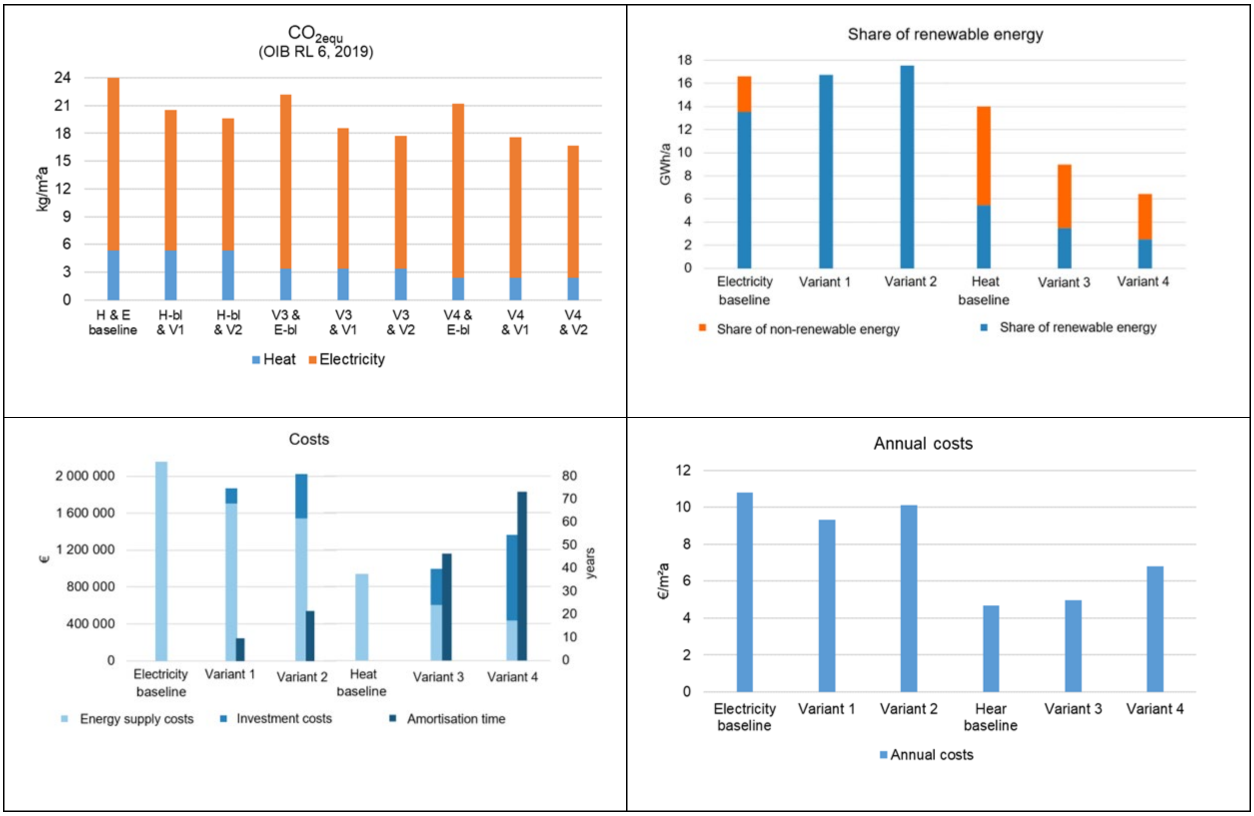


Figure 5-22. Comparison of Blue Sky metrics (GHG emissions, share of renewables, and Costs) for all variants with the baseline, considering consumption of heat and electricity.

In the heat supply, the share of renewables does not change, as the purchased district heating comes from the higher-level grid and its composition is considered unchangeable, but the absolute amount of renewable energy decreases proportionally to the required heat energy. Through the thermal refurbishment in Variants 3 and 4, the total heat consumption is reduced and thus the requirement for non-renewable heat shrinks. Variant 3 requires almost 36% less heat energy than the baseline state. A reduction to less than half of the original heat consumption is theoretically viable with ambitious refurbishment (Variant 4).

The goals defined a reduction in CO_2 emissions of around 37.5%. None of the variants reaches such a high percentage reduction. The maximum reduction is shown by the combination of Variant 2 and Variant 4 (PV plus ambitious refurbishment) with around 31% in comparison to the baseline. The specified 37.5% could not be achieved by any of the proposed measures. The decisive factor is the system's dependence on the higher-level grid. The energy purchased, including its composition and environmental impact, is determined by the regionally available energy production and is consumed at the site. To achieve the goal, measures are required from the energy providers in the higher-level energy supply. An alternative would be the local renewable production of heat and power from a renewable source, e.g., a biomass CHP.

The envisaged increase of the renewable share is possible by supporting the central electricity generation through the photovoltaic system on site. The generated PV power can achieve the share of non-renewable power that is delivered through the public power grid. Thus, a renewable share of 100% for electricity can be achieved, as required in the goals. The goal of implementing exclusively renewable energy sources was met in every variant and was thus achieved. As shown in Figure 5-22, the heat input can also be decreased. The defined target of reducing heat use by 1% per year cannot be determined by the chosen calculation method. The total reduction through the measures cannot be measured over time and does not show the reduction per year. This goal is only possible by doing an annual analysis and by monitoring heat consumption. The difficulty is to allocate the reduction to the set of measures in practice. For this reason, it cannot be determined whether the project study can achieve this target.

Costs

Figure 5-22 (lower left) shows the costs of the measures. Variant 1 shows a reduction in costs of over 2.5€ per m^2 through the use of the electricity produced by the PV system. With the integration of the storage in Variant 2, the expenses increase due to the high purchase costs. Variant 3 increases the costs compared to the baseline from around 4.70€ to around 5.00€ per m^2. This corresponds to an annual increase of around 60 000€. In Variant 4, the annual costs per m^2 even rise to about 6.80€, which means an annual increase of about 400,000€ compared to the baseline. The thermal refurbishment increases the running costs due to the high investment costs of the materials. Even when combining the variants, only Variants 1 and 2 have a cost-reducing effect that compensates for the increased expenses of Variants 3 and 4.

Figure 5-22 shows the share of the type of costs. In Variants 1 and 2, the energy supply costs have decreased due to the measures implemented. Variant 1 shows an annual reduction of around 19%, and Variant 2 shows an annual reduction of 24%. In both variants, the energy supply costs including the investment costs are lower than the baseline costs. In Variant 2 it can be seen that the total costs are somewhat higher than in Variant 1 due to the higher investment costs. The high-cost reduction leads to short payback periods (ROI) of around 9 years (Variant 1) and 20 years (Variant 2). The 2022 price level of around 0.3 €/kWh of power reduces the ROI to less than 3 years (Variant 1) and 16 years (Variant 2). The ROI as percentage on the yearly return of investments is 37% for only PV and 6% for PV plus storage. The ROI values for all variants are summarized in Table 5-34.

The energy procurement costs are reduced in Variants 3 and 4 due to the thermal refurbishment. In an average year, the reduction amounts to around 36% in Variant 3 and more than half of the baseline costs in Variant 4. Nevertheless, the investment costs are so high that the total costs of the variants are higher than the original costs. The ROI is therefore longer than the assumed term of 40 years. So even though Variants 3 and 4 meet the specified energy cost reduction goals, the ROI is still very long. With the 2022 prize level for energy, the ROI is reduced to 10 years for the standard retrofit (Variant 3) and 16 years for high-level retrofit (Variant 4). The ROI as percentage on the yearly return of investments is 10% for the retrofit and 6% for high-level retrofit in Variant 4.

The reduction in energy procurement costs of 25% is not achieved by Variant 1 (19%) or Variant 2 (24%). However, the total costs are still lower than in the baseline situation due to the low investment costs.

The numbers related to costs must be seen as relative, since the recent rise in power and heat costs caused by the war in Ukraine has had a strong effect on economic calculations, and since PV systems are now expected to generate much higher savings. Refurbishment measures on buildings are expected to pay back much faster if energy prices also remain high.

Table 5-33. Sustainability and cost parameters.

		Energy Consumption (kWh/m^2a)	Renewable share (%)	CO_2 Emissions (kg/m^2a)	Annual costs (€/a)
Electricity	baseline	83	81	18.8	10.79
	Variant 1	83	100	15.2	9.33
	Variant 2	83	100	14.3	10.12
Heat	baseline	70	39	5.3	4.69
	Variant 3	45	39	3.4	4.96
	Variant 4	32	39	2.4	6.79

Table 5-34. Return on Investments for prizes before 2022 and actual prizes in 2022 (Heat and Power 0.3 €/kWh).

Variant	ROI [%]	ROI 2022 [%]	ROI [years]	ROI 2022 [years]
Heat baseline	0	0	0	0
Variant 3 (standard retrofit)	2	10	46.4	10.4
Variant 4 (high-level retrofit)	1	6	73.1	16.3
Power baseline	0	0	0	0
Variant 1 (PV)	11	37	8.9	2.7
Variant 2 (PV+storage)	5	6	19.5	16.3

Conclusions

The Johannes Kepler University campus in Linz (AT) has an area of ~200,000 m2, with a specific consumption of electric energy of 83 kWh/m2a and 70 kWh/m^2a of heat from district heating. Most of the buildings were constructed after 1960 and have facades of concrete and glass. Buildings constructed between 1960 and 1990 frequently have poor thermal insulation and tend to overheat.

In this study, the resilience master planning method was applied to the campus. Four variants of modernization were examined for their effects relative to the status quo or baseline situations. Calculations showed that all variants, including renewable energy generation, energy storage, and building envelope refurbishment have positive effects on GHG emissions and share of renewables. Ambitious refurbishment does not completely pay back in energy savings, but all other measures are cost effective, even more so with the higher energy prices seen in the first quarter of 2022.

Resilience

In terms of resilience, the existing system in its current state has a very high level of safety from failure. Note that a guarantee of 100% resilience is not in fact possible. The critical functions can be maintained continuously in the simulation and the loads can be covered throughout the duration of an event. Interruptions of a few hours per year may occur in the secondary load, which are to be considered acceptable. To achieve almost 100% energy availability in the outage scenario, the integration of onsite energy generation (e.g., photovoltaic system) and a storage system is necessary.

Sustainability

The target reduction of 37.5% for CO_2 cannot be achieved with any of the examined variants, nor with a combination of them. A considerable reduction of greenhouse gas emissions can only be achieved by integrating a photovoltaic system with refurbishment.

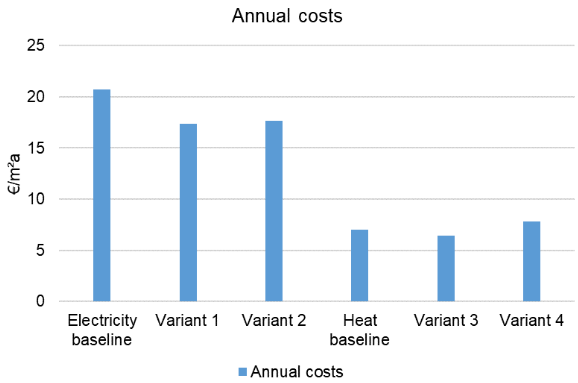


Figure 5-23. Annual costs including investment (lifetime 40 years) with Energy Costs of Q1 2022.

An increase of the renewable share is possible by combining PV electricity and storage. With a PV system of around 4 MWp, 100% of the electricity can be attributed to renewable energy sources if the onsite renewable generation is calculated to replace the non-renewable part of grid power.

The reduction in heat consumption only changes the absolute amount and not the percentage share since the provided district heat has a fixed composition of renewable and non-renewable sources. More than half of the original heat energy can be saved by the ambitious refurbishment in Variant 4. The thermal refurbishment according to the OIB guideline (Variant 3) brings about savings of about one-third.

To improve sustainability, a site would have to set a goal to significantly reduce CO_2 emissions. A combination of efficiency measures in buildings and equipment and onsite generation and storage is necessary to comply with Austrian standards for renovation and new buildings.

Cost Efficiency

PV generation and storage (Variants 1 and 2) both showed positive balances even with the low-energy prices seen before 2022. Also, the refurbishment to OIB level has a positive balance but with a much larger payback period, almost 40 years. Both measures lead to cost savings in energy procurement costs.

Total annual costs including investment costs and the costs to own PV electricity generation are lower than costs of the initial (baseline) state. The reduction in heat consumption associated with the refurbishment measures of Variants 3 and 4 lowers the annual energy costs. The total annual costs increase for ambitious refurbishment due to the high investment costs; from an economic point of view, these are not recommended unless there is a possibility of additional funding. However, if heat prices rise faster than building costs, an ambitious refurbishment could be economically advantageous, even without consideration of improved comfort.

The cost consideration is an essential factor in the assessment of the variants. Measures to substitute electricity with renewable sources are recommended in any case. By integrating the measures, a reduction in the annual energy procurement costs is possible. From an economic point of view, thermal refurbishment is only recommended if other factors (legal requirements, PR effect, end of lifetime of façade components, etc.) make the change necessary. However, high energy costs or the rising uncertainty of heat supply could change the economic drivers.

We have not considered the follow-up costs of unserved loads since there is a very high probability that critical loads can now be covered even in the baseline scenario. However, this depends on the availability of fossil fuels for UPS. Nevertheless, in practice (2022) we highly recommend that follow-up costs of unserved loads also be included in the calculation, which would further confirm alternative solutions.

Variant 1 considers installation of large PV panels on the roofs and facades (around 4MWp); this is recommended for its positive ecological, economic, and energetic effects. It can contribute to a smart JKU campus, increase resilience, and add to the energy flexibility of the campus. It can also help to achieve savings in energy procurement and to reduce the payback period.

Energy efficiency measures for buildings and equipment are also highly recommended, especially when repair or replacement are already needed.

5.4. Lachine-Est (CDN)

This section describes an energy system resilience assessment of the Lachine-Est case study (Rasoulian 2021), which describes a method to compare the reliability, availability, and resilience of energy systems considering sustainability and zero energy district goals is proposed. In this resilience assessment, Rasoulian implemented the suggested methodology in the IEA EBC Annex 73.

5.4.1. Location and Characteristics

Montreal is located in the southwest of Quebec province, with freezing, snowy, windy winters. Over the course of a year, the temperature fluctuations in Montreal are between -13 to 26 °C (9 to 79 °F) (climate-data.org. 2022). The cold climate in Canada results in an average space heating demand in residential buildings that is 61.6% of the total energy demand (NRCan 2022).

Figure 5-24. Lachine-Est eco-quartier location in Montreal.

Lachine-Est is located in the former Dominion Bridge industrial area southwest of Montreal. The location includes two heritage buildings that must be preserved. The design goal is to build a sustainable, zero-carbon emission urban district with high-efficient buildings such as schools, a medical center, a civic center, and residential dwellings.

5.4.2. Buildings and Energy System Design Overview

The case study site Lachine-Est contains six building complexes with different user types: healthcare, commercial, residential, and office facilities. The resilience assessment of the Lachine project considered only space heating demand. Table 5-35 lists each building's use type. The data in Table 5-36 summarize the building's specifications and heating demand. The buildings' design considered high-efficiency materials to meet the project's sustainability goals.

Table 5-35. Use types of buildings.

Building ID	No. of Floors	Floor area (m^2)	Use Type
Building A	9	13,637	First floor Commercial / 2 to 9 residential
Building B	6	5,174	First floor health care facilities / 2 to 6 residential
Building C	9	5,469	First floor offices and commercial / 2 to 9 residential
Building D	6	7,882	First three floors civic center / 3 to 6 educational & cultural institute
Building E	2	5,890	First floor Commercial / second floor residential
Building F	9	1,690	First floor offices / 2 to 9 residential

Table 5-36. Buildings specifications.

Specifications\Building ID	Building A	Building B	Building C	Building D	Building E	Building F
Number of floors	9	6	9	6	2	9
Total floor area (sq m)	122,737	31,044	49,224	47,292	11,782	15,210
Total space heating load (KWh/year)	8,249,180	1,460,777	3,785,383	4,113,954	930,336	1,300,850
Peak space heating demand (kW)	5161	1000	2331	2411	516	786
Specific heating (kWh/sqm/year)	67	47	77	87	79	86

The energy system is designed based on the load curve of the buildings. In the baseline design, a district heating network that consists of a heat production unit and distribution network supplies the demand. The heat production unit consists of 14 ground source heat pumps (GSHP), a boiler with 4000 kW capacity, and thermal energy storage with 190 m^3 (6710 ft^2) capacity. The GSHPs are sized to provide 60% of the peak demand; the rest comes from boiler and storage. The electricity input for the energy system is provided by Hydro-Québec, and the boiler is connected to the natural gas network of the city. In Figure 5-25 the daily heating demand is shown with an orange line. The gray and yellow parts in the stacked chart show the heat pumps heat output, and the boiler and thermal energy storage output, respectively.

Table 5-37. Energy system design specifications

Specifications\ Building ID	Building A	Building B	Building C	Building D	Building E	Building F	Central
Total space heating load (kWh/year)	8,249,180	1,460,777	3,785,383	4,113,954	930,336	1,300,850	19,840,483
Peak space heating demand (kW)	5161.51	999.67	2331.39	2411.21	516.14	785.88	1282
Number of heat pumps in operation	6	1	3	4	1	1	14
Heat pump SCOP	2.22	2.25	2.23	2.2	2.23	2.22	2.22
Thermal energy storage capacity (m^3)	80	15	37	40	10	13	190

5.4.3. Design Basis Threats

In Quebec, more than 80% of households use electricity for heating (Hydro Quebec 2019). In this climate, providing reliable space heating for the buildings is a primary concern. The resilience assessment of this project aims to evaluate the energy system's robustness, i.e., its ability to provide the critical demand in case of a major power outage. This research set the Black Sky scenario as an offsite major power outage that lasts 30 hours, during which time critical demand must be prioritized over normal everyday (Blue Sky) demand. Section 5.4.5 details critical demand calculations.

5.4.4. Baseline and Alternative Scenarios

The Baseline is the current state of the Lachine project; everything mentioned previously is included in the baseline. Any further investigation and scenarios are built based on the baseline. The following sections describe two alternative design scenarios.

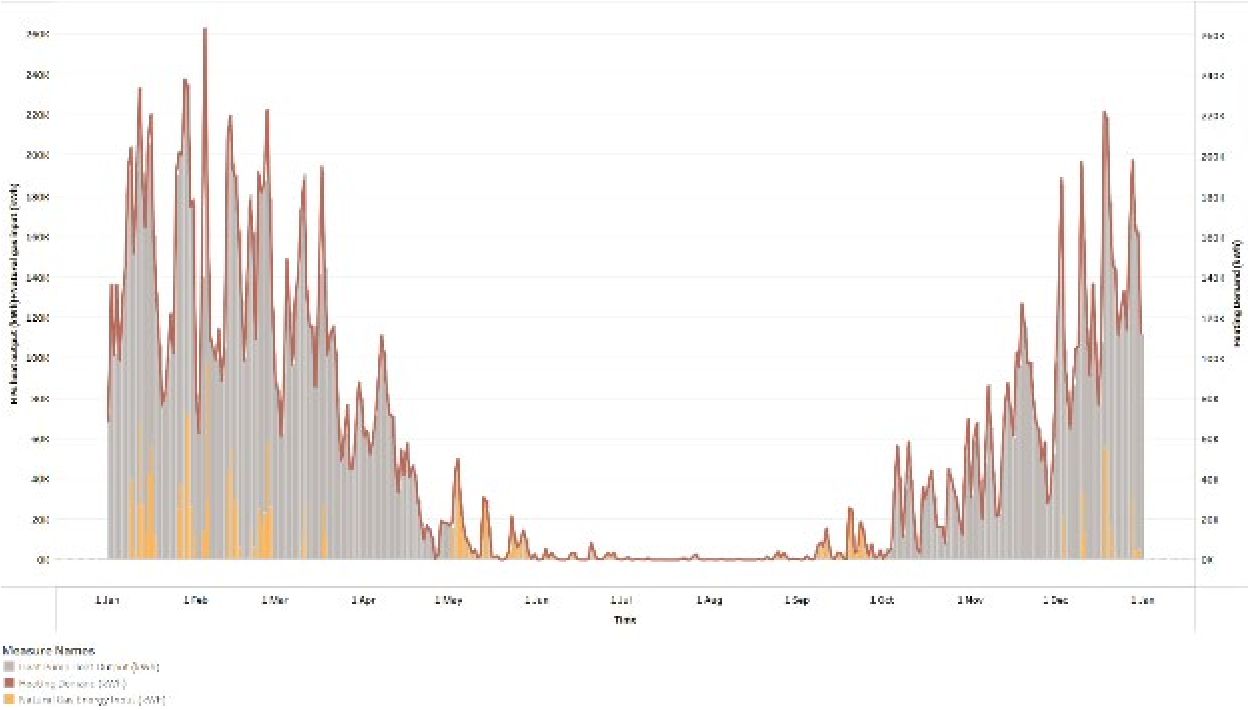


Figure 5-25. Heating demand vs. supply in the baseline design.

Alternative one includes a decentralized ground source heat pump with a gas boiler as backup. In this design, a GSHP unit and a gas boiler were considered for each building. Unlike the baseline, no thermal energy storage (TES) was considered in this design.

Alternative two includes decentralized GSHPs with photovoltaic and thermal storage.

This scenario relies solely on electricity to provide heating demand. Adding PV panels on the rooftops of the buildings increases the renewable share of the electricity and reduces the dependence on other energy sources.

5.4.5. Resilience Analysis and Comparison

The load curve in the Black Sky scenario differs from that of the business-as-usual demand. In a time of disruption, the goal is to keep the spaces above the habitable thresholds. Based on the *Energy Master Planning toward Net Zero Energy Resilient Public Communities Guide* (Guide 2021) and the data listed in Table 5-39, the maximum allowable downtime for the buildings similar to the Lachine area is 29 hours (high-efficiency mass buildings, -17.8 °C [0 °F]). Facilities in the Lachine area have multiple use types, and in case of a disruption, the level of criticality of these use types plays an important role. Unified Facilities Criteria Document (UFC) 3-540-01 (NAVFAC 2014) defines uninterruptable, essential, and nonessential loads. Essential loads include HVAC loads to vital facilities such as hospitals, which need to be supplied constantly, but may be able to endure a short disruption without severe consequences. One example of an essential load in the Lachine area is that which serves the medical center and healthcare facilities in Building B. Table 5-38 briefly lists the criticality levels of loads associated with different types of facilities, in which medical centers are considered highly critical facilities, served by essential loads.

Table 5-38. Criticality level of different loads.

Low	Medium	Significant	High
Offices, housing	Commercial, civic centers	Warehouses, educational institutes	Medical centers

The critical load in each building is a portion of the day-to-day demand. Coefficients are defined based on the hour of the day and main occupants' type. For instance, Building E's first and second floors are commercial and residential. If a disruptive event happens during the day, most residential occupants would be elsewhere, i.e., at work, school, etc. At the same time, the commercial floor is open to the inhabitants. Therefore, the commercial floor's share of critical demand during the day is higher than the residential. This point is reflected in the critical demand calculation by assigning coefficients based on time categories: (1) between 8:00 a.m. and 4:59 p.m. and (2) between 5:00 p.m. and 7:59 a.m.

An offsite power outage was modeled to investigate the system's resilience in the time of a threat. The duration of this scenario was 30 hours, beginning at 6:00 a.m., February 2. Table 5-39 lists the energy availability (EA), model MaxSEDT, and energy robustness (ER) of this scenario (Figure 5-26). The model MaxSEDT is 30 hours, equal to the power outage duration. ER is the amount of the demand that is provided by the supply. The amount of day-to-day demand and critical demand for the same buildings are distinguished by the coefficients. EA is the duration of time when the supply is available to provide the critical load. The only critical load in this study is the space heating load. In the day-to-day operation of the baseline and the alternative one, the heat pump, boiler, and TES supply the demand simultaneously. In case of a power outage, the heat pumps will not be functional, but boilers are available to provide the demand. However, design alternative two solely relies on electricity to produce space heating (combination of hydroelectric [HP] and PV electricity generation). Since solar energy is not available all day long, the EA of alternative two is less than the other two designs.

Table 5-39. The results of baseline, and alternative scenarios under the Black Sky condition.

Scenario	Building ID	Acceptable MaxSEDT (hours)	Acceptable Energy Availability (EA)	Model MaxSEDT (Hours)	Model EA	Model ER
Baseline	Baseline	29	0.99	30	1	0.6486
Alternative design 1	Bldg. A	29	0.999	30	1	0.6887
	Bldg. B	29	0.99	30	1	0.5209
	Bldg. C	29	0.99	30	1	0.6601
	Bldg. D	13	0.99	30	1	0.6616
	Bldg. E	13	0.99	30	1	0.6697
	Bldg. F	29	0.99	30	1	0.709
Alternative design 2	Bldg. A	29	0.99	30	0.4	0.2614
	Bldg. B	29	0.999	30	0.4	0.4246
	Bldg. C	29	0.99	30	0.4	0.2134

Scenario	Building ID	Acceptable MaxSEDT (hours)	Acceptable Energy Availability (EA)	Model MaxSEDT (Hours)	Model EA	Model ER
	Bldg. D	13	0.99	30	0.4	0.2514
	Bldg. E	13	0.99	30	0.4	0.89
	Bldg. F	29	0.99	30	0.4	0.1911

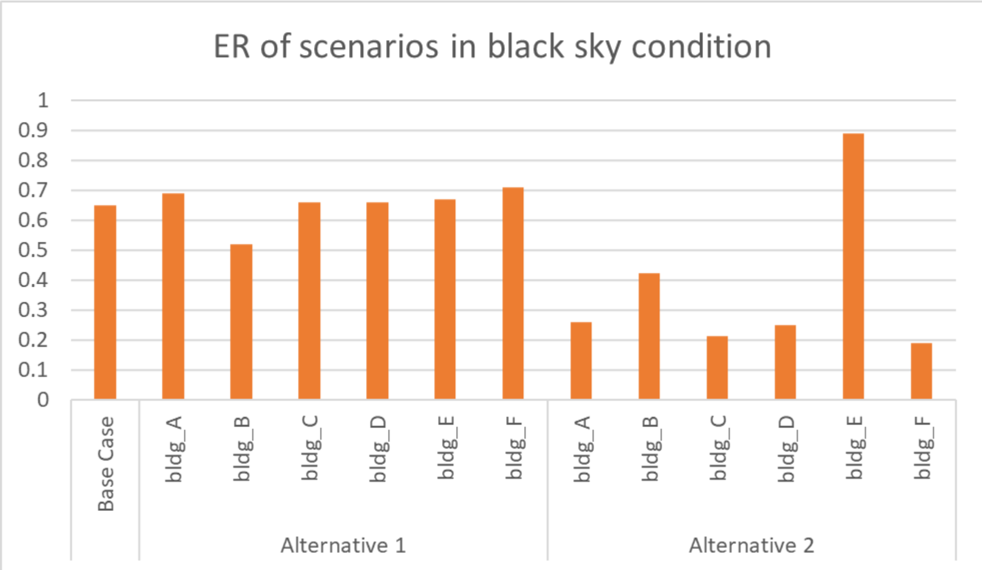


Figure 5-26. ER scenarios in Black Sky conditions.

In the business-as-usual condition, all the designs can provide the load. Table 5-39 shows the results of the Black Sky condition. The data in Table 5-39 indicate that high-efficiency mass buildings can provide a habitable level of temperature for 29 hours after the disruption. Except for the heritage buildings (D and E), all other buildings are included in this category. In both the baseline and Alternative 1 scenario, a gas boiler is sized to provide 40% of the space heating demand. In case of a power outage, the critical demand is less than the day-to-day demand. Therefore, boilers can cover more than 50% of the demand in each building. Figure 5-26 shows the amount of critical load covered by the TES, boiler, and PV panels. In the second alternative system, ER and EA are less than the two other designs. In Black Sky condition, the solar energy availability is 12 hours in power outage duration. Therefore, EA in all buildings is equal to 0.4. For the same reason, this scenario provides less critical demand, as reflected in the ER column in Table 5-39. Figures 5-27 and 5-28 show the cumulative demand and supply for all the buildings in Alternatives 1 and 2 scenarios before and after the power outage.

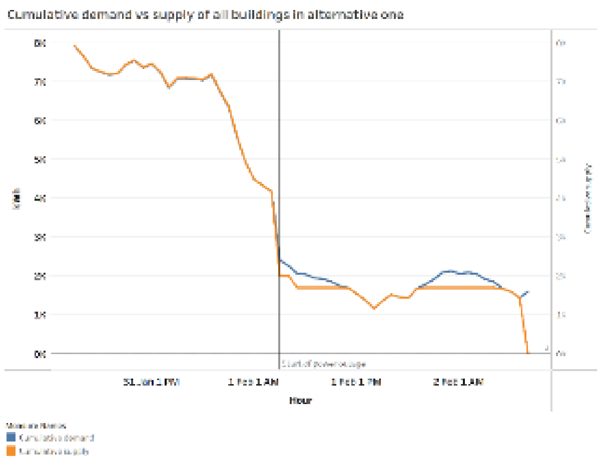


Figure 5-27. Demand vs supply in alternative one.

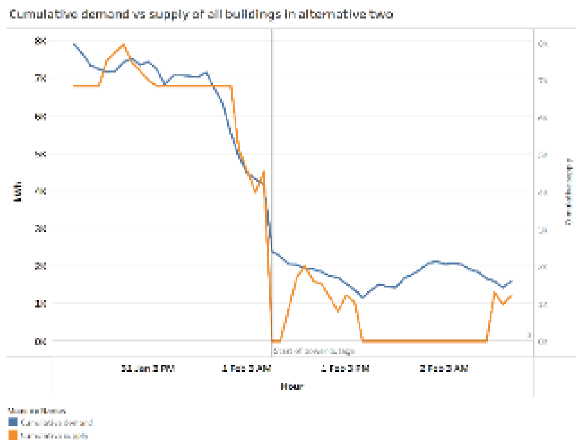


Figure 5-28. Demand vs supply in alternative two.

5.4.6. Conclusion

The IEA Annex 73 energy system resilience assessment method was implemented in the Lachine-Est site case study. Two alternative designs were proposed (rather than the energy system's baseline design), and results revealed that the second alternative design which contains decentral GSHP, PV, and TES had the lowest energy robustness and availability. Adding a gas boiler to critical buildings might improve the feasibility of this design. The baseline and Alternative 1 yielded similar results in which energy availability was 100%.

5.5. Rosensteinviertel in Stuttgart (DE)

5.5.1. Introduction

The planned Rosensteinquartier is located in the city center of Stuttgart, Germany. The quarter will be built where the present tracks of the railway lead to the Central Station. In course of the major infrastructure project Stuttgart21 (new construction of an underground railway station that will replace the existing over-ground station) all tracks leading to and coming from the new station will be underground. When the tracks are removed from the ground level, the resulting vacant area (owned by the City of Stuttgart) will become available for construction.

The newly built city quarter will be surrounded by green spaces from the large Rosensteinpark and by other new city quarters that will be constructed on other parts of the cleared area. The new construction for the Rosensteinquartier has to meet several requirements of the City of Stuttgart. Green, free, and surface water areas should be well-balanced in a mixed residential (min. 4,600 households) and non-residential structure with some special-use buildings like a concert hall, museum, and a civic center. Also, public spaces like schools, sport halls, outdoor sporting areas, and such social institutions like childcare and retirement homes should be included in the developing plan. The official City of Stuttgart requirements statement (FAZ 2022) expresses its vision as:

> *The vision for 2050 is the development towards a climate-neutral state capital. To this end, the city's long-term climate protection goals of "reducing greenhouse gas emissions by 95%" and "halving final energy consumption" by 2050 (compared to the base year 1990) must be achieved. A future-oriented energy concept must therefore be developed for the Rosensteinquartier, which will contribute significantly to achieving these goals. The city is striving to achieve the plus energy level and thus a climate-neutral urban quarter. The energy demand of the future development, which is necessary despite the highest energy requirements, is to be covered primarily by energy from renewable sources available at the location or in the immediate vicinity. If it is not possible to cover the entire energy demand in the area, the necessary residual heat can be obtained via the district heating network. The prerequisite, however, is that the energy balance of the neighborhood and the district heating are climate neutral. The realization of fossil energy generation plants is to be excluded in the new neighborhood.*

In the first phase of the project, an open competition was held in which more than 50 international urban planning consultancies took part. At the end of November 2018, 11 offices and their concepts were selected, and the submitters were asked to more concretely develop their designs in the second phase of the competition, which ended in March 2019. Of the eleven candidates, three were selected as winners to present their detailed concepts, which must then pass through the municipal council for further adaptation and refinement.

The beginning of the construction is highly dependent on the completion of the Stuttgart21 project, which is currently planned for late 2025.

The entire area is subdivided into several smaller quarters with different characteristics and main usages. This analysis focuses specifically on the "Rosensteinviertel," which is the triangular shaped quarter in between the Rosensteinpark and the curved green space shown in Figure 5-29 (mid-center).

Based on the explanations and the geometries of the winning design, a 3D CityGML model of the Rosensteinviertel was created at HFT Stuttgart and published under the CC BY 4.0 license[1]. The areas of the individual uses were also taken from the award text. Fifty percent of the areas for commercial and offices were added as secondary uses to residential buildings, and 50% were assumed to be entirely non-residential. The school and museum buildings are also considered entirely non-residential.

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[1] https://transfer.hft-stuttgart.de/gitlab/rushikesh.padsala/rosensteinquartier

Source: www.asp-stuttgart.de/portfolio-items/internationaler-wettbewerbrosenstein-stuttgart

Figure 5-29. Visualization of the first place in the second stage of the design competition.

5.5.2. Simulation of Heating and Electricity Demand

Based on the previously described CityGML model of the neighborhood, SimStadt was used to calculate the heat demand of each building. In addition, DHWcalc (Jordan, Vajen 2005) was used to create hourly profiles for the domestic hot water demand for a total of 350 residential buildings. Two archetype buildings were defined, with eight and 15 households per building, respectively. The hot water demand for the non-residential buildings was distributed based on the occupancy density in $P/m^{2,}$ and on the usage times over the year and over the day.

Profiles for space heating, domestic hot water (DHW) (Weiler and Eicker 2019), household electricity (Koehler et al. 2021), and electricity for mobility and rooftop PV electricity generation (Eicker et al. 2014) were calculated on a single building level and aggregated to district profiles.

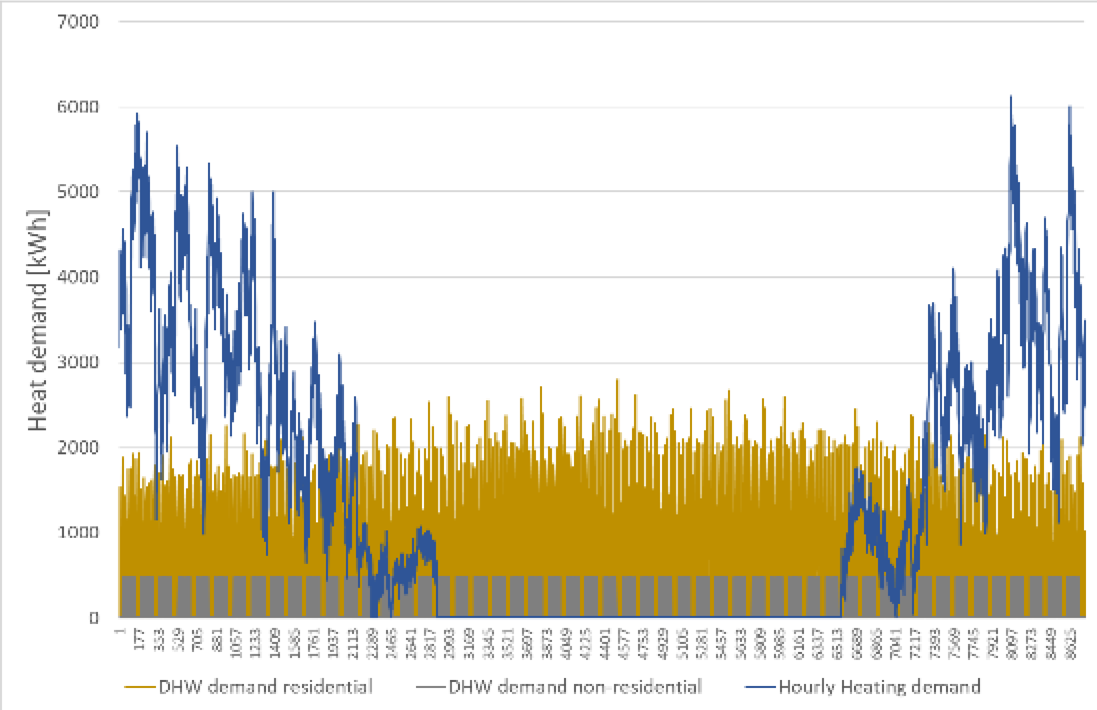

Figure 5-30. Simulation of the heating and domestic hot water (DHW) demand for the case study.

5.5.3. PV Potential Calculation

The calculation of the photovoltaic potential for rooftop installations for each roof surface is based on the previously described CityGML file and their mapping of roof shape and orientation. Additionally, local weather data is considered to calculate monthly and hourly PV electricity production.

Results show a considerable technical potential for rooftop PV installation, however, compared with the large electricity and heating demand of the (at least) five-story buildings, the generated electricity would not be sufficient to satisfy both electricity and heating demand. Therefore, an electricity-based heating solution does not seem favorable.

5.5.4. Resilience Planning and Choice of Heating System

Based on sustainable heat supply systems for a zero-carbon future, a qualitative methodology was developed to select possible supply technologies for sustainable districts based on the individual framework conditions and constraints, which are usually already available at the beginning of the planning process. Possible restrictions for the different supply variants can be spatial as well as geological or strategic and legal parameters.

The restrictions are defined based on general planning practice and expert knowledge. These framework conditions are queried via a checklist, shown as a flow chart Figure 5-31, which shows a cutout of the complete flow chart that comprises a total of 16 different technology options. Figure 5-31 shows an example for a part of district heating and gas-based technologies. For district heating and gas networks, the distance between the existing network and potential building connections is relevant. If the distance is greater than 500 m (1640 ft), the possibility of an extension or new construction of the network is reconsidered. If it is determined that the distance is sufficiently close, the remaining lifetime of the existing network, its available capacity and temperature level are then calculated.

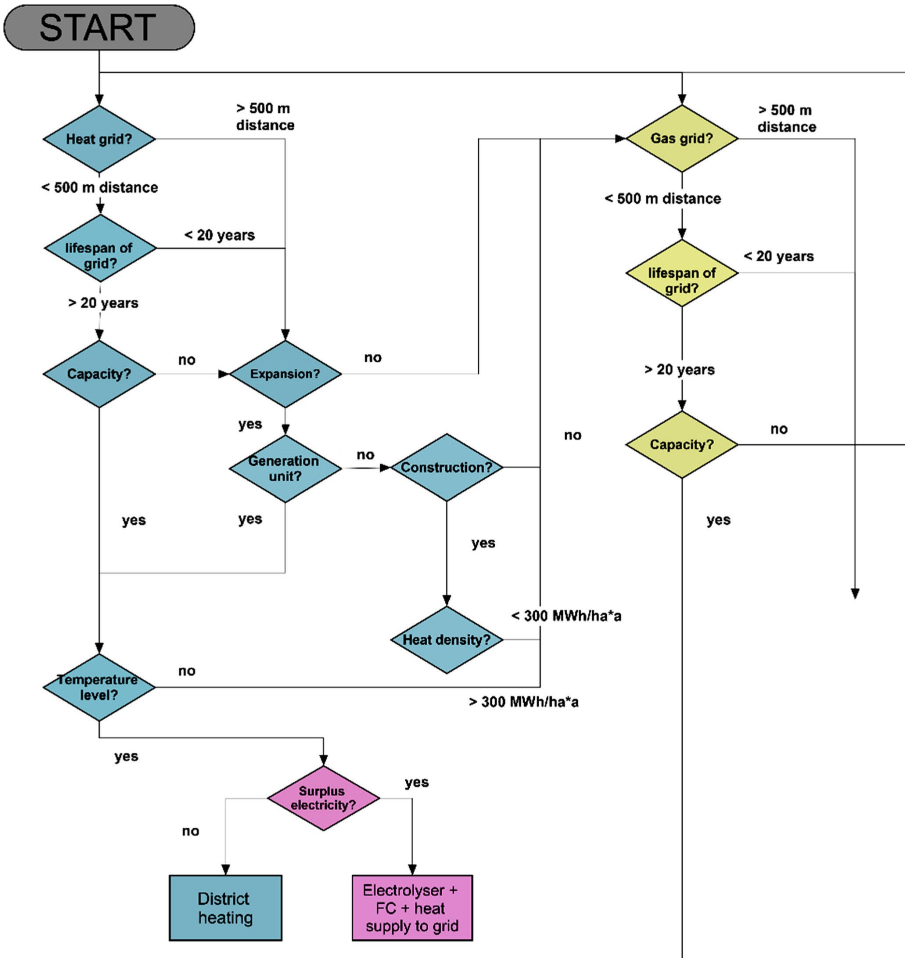

Figure 5-31. Cut-out of flowchart to reduce choices for heat supply variants.

Generally, the questions in the flowchart apply to both the district and building level, depending on whether the technology is designed as a central or decentral system. For example, if heat pump technology (with water or soil as energy source) is considered, the same restrictions regarding water protection or soil conditions will apply regardless of whether the resulting system is comprised of one central or several decentral systems. Based on the information provided, individual technologies can be selected or excluded for the area under investigation.

On the basis of the information in the submitted designs and the regional circumstances, the possible supply system solutions were narrowed down with the help of the described flow chart. Since the energy supply from fossil sources is not allowed and the existing nearby district heating network is only intended to cover any residual heat demand, these energy sources are not suitable. However, there is a gas and district heating network and an electricity network available in immediate proximity to the new development area. Due to the high heat density (approx. 130 MWh/ha*a), the construction of a new local heating network for the distribution of heat is economically possible. Since the target temperature of the heating flow in the low-energy buildings is below 45 °C (113 °F), a supply via heat pumps is a basic option. According to local geological maps, no conditions speak against the installation of ground collectors or ground probes although they must be examined closely. Furthermore, maps of the municipal drainage office show that there is a sewer in the immediate vicinity of the planned neighborhood, which must be considered. Since the goal in this centrally located inner-city neighborhood is to efficiently use the limited available space, a biomass system with a large storage facility would be unrealistic.

After considering these conditions, centralized heat generation and distribution through a local heating network was chosen for this analysis. The heat will be generated by several biogas CHP units and peak-load gas boilers, which are also operated with biogas. This configuration will make it possible to meet the climate-neutral urban district goal of the City of Stuttgart.

There are no particular threats to the infrastructure such as flood, storm, etc. that warrant special resilience measures. Also, there are no critical loads (no hospitals or data centers). Therefore, no special measures regarding resilience are needed except a backup connection between the new district heating network and an existing nearby network. Since several CHPs and gas boilers are needed to satisfy the large demand and subsequent peak load of this quarter, a backup is always necessary to accommodate maintenance or repair activities, especially in mid- or off-peak load times. Additionally, several thermal storage tanks are installed throughout the network to ensure a non-interrupted supply of heat to all buildings.

5.5.5. Dimensioning and Simulation of Heating Supply System

This section details a model of a CHP system that includes several CHPs, peak-load boilers, and thermal storage (Figure 5-32). The model also includes the necessary controls and considers all inputs and outputs on an hourly level. If the storage content is sufficient to satisfy the demand, then that demand will be covered directly by the storage without activating the CHPs or the gas boilers. If demand outstrips the current storage content, the remaining required heat is provided either by one or several of the CHP units, the gas boilers, or by both, depending on the required amount.

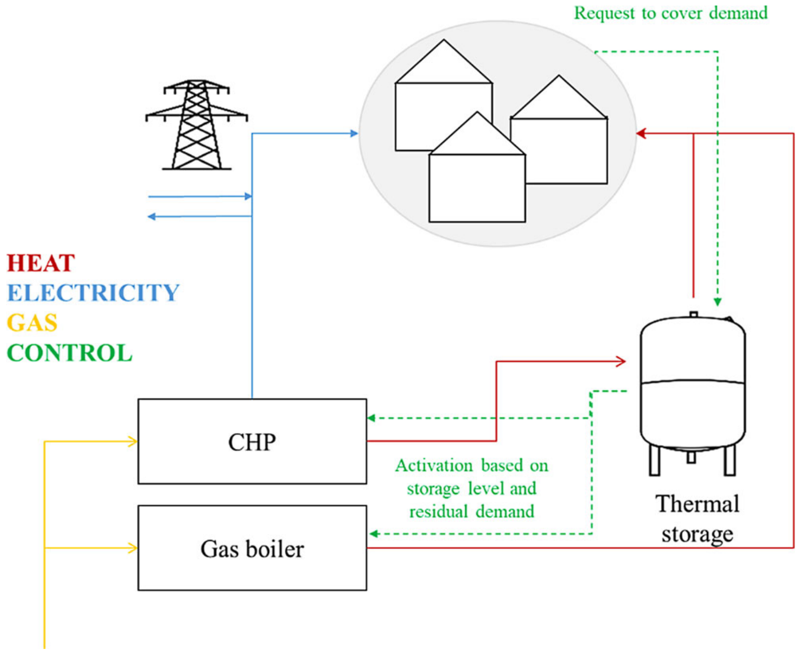

Figure 5-32. System schema of CHP and gas boiler system.

The operation of the individual CHP units is controlled according to the demand so that the units can be flexibly switched on and off individually. In addition, the model considers the modulation range of the CHP units. Consequently, each CHP can be operated flexibly in a range between minimum and maximum capacity. If the demand is below this minimum capacity, the CHP unit remains off.

Based on the demand, the generators are dimensioned based on a rule-based logic. The peak load P_{peak} is 8,364 kWh and it is assumed that 40% of the peak load is covered by the CHP units and the rest by several gas boilers. Table 5-40 lists the components chosen for this system.

Table 5-40. System dimensioning of CHP and gas boiler.

	Share of P_{peak} (%)	P_{target} (kW)	Number of units	P_{target} for each unit (kW)
CHP	40	3,389	3	1,130
Gas boiler	60	5,084	20	254

The target value P_{target} is calculated from the peak load and from the share of that load that the respective component covers. Specifying a number of units results in P_{target} for each unit. It is assumed that all CHP units (and all gas boilers) have the same installed capacity.

Figure 5-33 shows the annual load duration curve of the total demand in gray, the annual duration curves of the cumulative heat generation by CHP units (in blue) and gas boilers (in orange). The operating hours are, for CHP 1 (7,778 hrs), for CHP 2 (4,603 hrs) and for CHP 3 (3,078 hrs). The 20 gas boilers adapt flexibly to the residual demand, which means that at least one of the boilers is in operation for 6,000 hours of the year.

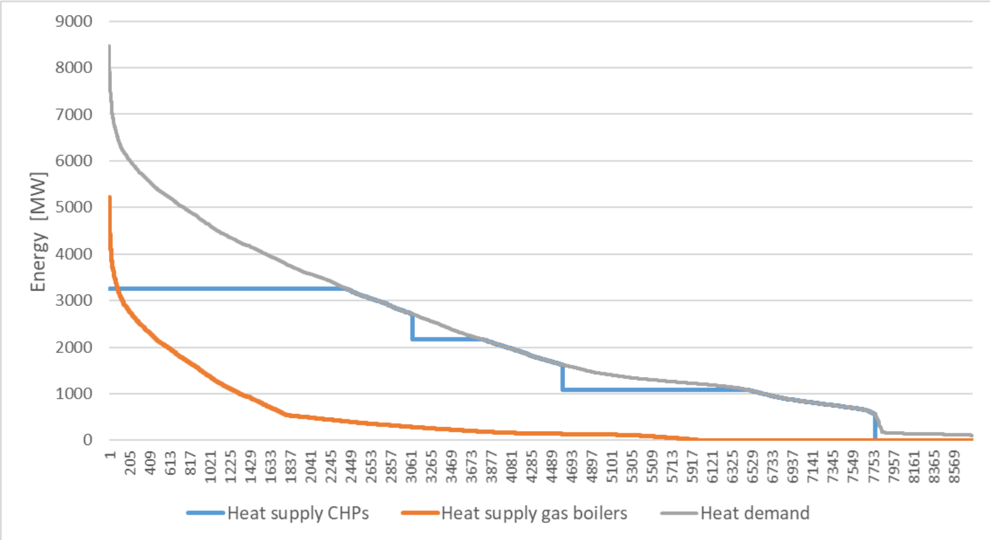

Figure 5-33. Annual load duration curves for total heat demand (gray), heat generation of the CHPs (blue) and heat generation of the gas boilers (orange).

5.5.6. Conclusion

Based on the requirements of the City of Stuttgart and on a consideration of local area boundary conditions, energy demands, and energy generation potentials, a central system consisting of three CHP units and several gas boilers distributed in the quarter and operated with bio gas was chosen as supply system. Considering the low risk for threats in the city quarter, this system will be highly resilient because of the backup connection to the nearby existing district heating network, and because the system is not limited to only one large CHP and gas boiler, but includes several units distributed throughout the area.

5.6. Six Local Communities Supplied by Vestforbrænding, Denmark (DK)

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5.6.1. Introduction

Vestforbrænding is a district heating and waste management company jointly owned by 19 municipalities in the Greater Copenhagen area and northern suburbs of Copenhagen. Vestforbrænding is responsible for the waste management for recycling materials and energy for the 19 municipalities and for supply of district heating in six of these municipalities. Vestforbrænding also delivers surplus heat to the Greater Copenhagen heat transmission system, which is owned by CTR and VEKS.

Vestforbrænding, which supplies heat in six of the municipalities, is also responsible for recycling both resources and energy from waste for the 19 owner municipalities. Vestforbrænding has cost-effectively increased the supply of district heating from 300 to 900 GWh to large buildings in the past 15 years, and any remaining heat is sold to the two transmission companies, CTR and VEKS. In accordance with the Danish Energy Policy, Vestforbrænding has proposed extending the district heating further up to 1,600 GWh in Heat Plan 2030, to reduce dependency on fossil gas and to increase the use of waste heat and wind energy. The plan demonstrates that, compared to individual heat pumps, district heating will be cost effective for both consumers and the society as a whole.

Resiliency has been a **driver**, both for Danish Energy Policy and for the actions related to energy system configurations undertaken by many municipalities. In 1976, Danish Energy Policy aimed to reduce dependency on imported oil. In 2006, the direction of the Danish Energy Policy shifted to achieving independence from fossil fuels for climate reasons. In 2021, steps were taken to speed up the conversion from fossil imported gas to wind and other renewable energy sources.

District heating has been a cornerstone to meet these objectives since district heating precludes the cost-effective use of multiple heat sources in urban areas, such as efficient heat sources like CHP, waste heat, along with fluctuating sources like wind energy. Acting on behalf of consumers, Vestforbrænding has taken an important step in this green transition with its Heat Plan 2030. At the local level, Vestforbrænding has considered resiliency by providing backup capacity to critical consumers and districts. Vestforbrænding and the Greater Copenhagen district heating system are also presented as cases in the Annex73 book of cases.

Since its waste incineration plant was established in 1970 at an old landfill area, Vestforbrænding has been a frontrunner in using waste as an energy resource. This development has taken place in several steps:

1. **Step 1.** In 1970, Vestforbrænding invested in a district heating system that supplies a new hospital and large social housing areas near the plant. The network distributed superheated water (up to 165 °C [329 °F]) to supply process industries and an absorption heat pump at the hospital.
2. **Step 2.** As a reaction to the energy crises of 1973 and 1979, the heat network (hot water network up to 110 °C) was extended to supply heat to large buildings in the area.
3. **Step 3.** While Vestforbrænding could have further extended its own network to the northern suburbs, this heat market was reserved for natural gas due to the national energy policy in 1979. The strong focus of the national energy policy was to increase resiliency at the national level to reduce dependence on fossil fuels from the Organization of the Petroleum Exporting Countries (OPEC) and to replace oil as quickly as possible with Danish natural gas and large district heating systems using efficient surplus heat (CHP from large CHP plant and waste for energy plants). Accordingly, Vestforbrænding left the northern suburbs to meet their energy needs using natural gas, and instead delivered all surplus heat that could not be used in its own network to the Greater Copenhagen district heating system (CTR and VEKS). Thereby Vestforbrænding delivered part of the baseload in this huge system that supplies energy to buildings with more than 70 million m^2 (2,472 ft^2) of heated floor area.

The Heat Supply Act of 1979 formed the legal framework for heat supply planning with its aim to develop the most cost-effective heat supply at the national level, designed to preserve the environment. The Heat Supply Act regulated the competition between gas grids and district heating grids. Because the price of gas was low, there was little additional market for district heating. A second energy policy objective was to ensure payback of the large investment in the gas infrastructure.

In 2006, the Danish Energy Policy took a dramatic new direction in response to evidence of climate change. A solid majority in the Danish Parliament favored the policy, which states that should become independence from fossil fuels by 2050. By 2006, the new Danish gas infrastructure had paid back so there was no reason at that time to give gas the first priority.

This was the starting point for **step 4**. Vestforbrænding elaborated two business plans in 2006 and 2009, which demonstrated that it would be a very good business case for Vestforbrænding, for the heat consumers, and for the society to extend the district heating from 300 GWh to 900 GWh by replacing gas boilers in mainly large buildings in the northern suburbs (but not in one-family houses). This system development had also strong focus on resiliency by ensuring fuel flexibility and spare capacity.

To increase the efficiency and supply these markets, the waste incineration plants were extended with flue gas condensation and large gas fueled peak boilers. New peak boiler plants were located at strategic sites to maintain capacity for 24 hours even in cases of serious plant and/or pipe breakdowns.

These plans were almost completed in 2020, when there were more opportunities for extending the district heating in combination with large heat pumps based on local heat sources from industries, datacenters, district cooling and wastewater. Vestforbrænding elaborated an internal Energy Plan 2035, which demonstrated that it would be possible to replace all the remaining gas boilers in one-family house areas with the available capacity from existing and new plants located at strategic sites while still maintaining resiliency and capacity in the existing network. However, this measure was determined to be cost ineffective due to low prices of gas and CO_2.

In 2021, the Parliament agreed to speed up the projected green transition by 2050 by cost-effectively harvesting the huge potential for waste heat in the heating sector. This plan would specifically replace individual natural gas boilers with district heating or individual heat pumps, to promote independence from imported natural gas and to reduce climate gas emissions as quickly as possible and not later than 2030.

Based on the analysis in the Energy Plan 2035 business plan, Vestforbrænding elaborated **Heat Plan 2030** in cooperation with the six municipalities. In March 2022, the board of Vestforbrænding started **step 5** by approving this plan as a basis for investing 6 billion DKK (Danish Krone, or $863,328,000) in a sustainable and resilient heat supply.

Vestforbrænding will implement the plan in the years by proposing elaborate detailed project proposals for distribution networks and production plans, and by submitting these plans to the municipalities for their assessment and approval in accordance with the Heat Supply Act. When approved, these project documents will be legally binding and will replace the previous approved heat plans. The approved planning documents allow the district heating company to establish the proposed networks and production plants. The geographic information on the new district heating zone will be submitted to the national data plan, which informs the public about the status of the heat supply in each area. Meanwhile, the energy crises and extreme energy prices that occurred during the winter of 2021/22 have sped up the planning process.

Besides Heat Plan 2030, Vestforbrænding has several other remarkable activities that support the green transition, among them carbon capture, extraction of metals from fly ash, and the creation of an information center designed to inform around 30,000 visitors annually (mainly school classes) about recycling materials and energy.

According to **Heat Plan 2030**, Vestforbrænding will invest 6 billion DKK in the next 8 years by extending the district heating distribution and production to supply the remaining 30,000 buildings in the urban areas around Vestforbrænding.

The heat plan is to the benefit of the society and the local community, including Vestforbænding and new consumers, compared to individual heat pumps.

Figure 5-34. Vestforbrænding incineration plant a natural part of the urban environment.

5.6.2. Methodology

The planning methodology is designed to be in accord with the Heat Supply Act; its aim is to select and implement the most cost-effective solutions for the society by considering such factors as Energy Agency price assumptions, criteria for environmental protection, cost of CO_2, levels of harmful emissions, and resiliency. Note that the planning methodology includes the basic principles from the Annex73 guidelines regarding sector integration, levels of assessment, and stakeholder analysis, and ensures that both project and base line have the same level of resiliency.

Sector integration considers the important interaction between district heating, gas infrastructure, electricity, waste, and (to some extend) district cooling. Previously, this was the optimal zoning between district heating and gas grids. Currently, optimal zoning between district heating and individual heat pumps strives to strike a balance between protecting the environment and maintaining district heating's ability to supplement fluctuating wind energy with the gas infrastructure as a wind energy backup. This integration uses waste diverted from landfills to generate energy and surplus heat from power generation (as long as power plants still operate in the market), and sets the stage for the dramatic switch from CHP to electric boilers when there is surplus wind energy in the market and electricity prices fall.

The coordination with the building sector is not perfect, as the building code is in conflict with the Heat Supply Act and EU directives, but fortunately the benefits of district heating encourage most developers to prefer district heating.

The **levels of assessment**: federation of states, states, regions, cities, campuses and buildings, and the rule that assessment at one level must always consider the impact on the level above, is fully included in the methodology. The Danish Heat Supply Act implements the EU directives, or rather has been a model for the directives. Because the municipalities are planning authorities with an obligation to plan for solutions that are cost effective at the national level, there is a strong coordination between the state and the municipal levels.

When it comes to regional planning that crosses municipal borders, Vestforbrænding supplies heat to six municipalities and has participated in comprehensive feasibility studies in the region in cooperation with the other regional utilities (VEKS, CTR and HOFOR) in integrating the district heating systems in Greater Copenhagen south and east of Vestforbrænding and the other district heating companies north of Vestforbrænding.

Vestforbrænding also cooperates with the Danish Technical University, Herlev Hospital, and several industrial campuses to determine the most cost-effective solutions, in particular those with combined district heating and cooling. Vestforbrænding has a long tradition of good cooperation with large social housing companies.

On the building level, the district heating price is competitive and stabile, something most building owners appreciate. For many commercial building owners, connecting to district heating is the most sustainable choice in terms of economic, environmental, and social sustainability.

The **stakeholder analysis** is a fundamental methodology in the planning of energy in areas where there are many stakeholders, which is normally the case. It will only be a success when there is an open approach and all stakeholders share real information of common interest. Thereby it is possible in the first step to identify the solution that is best for all parties in general, expressed as the total Net Present Value (NPV) benefit compared to the base line. The next step is to divide responsibilities, the point of sale, and proposed internal prices between the parties. The assessment will therefore automatically split the total NPV benefit among the parties. It is important to do this in an open process that provides all information on all data and that negotiates tariffs and responsibilities to create a win-win situation. In particular the party who invests most, e.g., the district heating company, should receive the largest benefit and those investments should be paid back before stakeholders with little engagement receive a benefit.

Engaging the main local stakeholders in such publicly owned utilities as energy, waste management, and wastewater utilities is important to successful implement the stakeholder analysis, although the same principle also applies to private utilities since it is mutually beneficial to cooperate to find the best plan for all.

In this pilot project, an alternative approach was used to find the best solution; the ERIN tool was not used. The alternative approach consisted of setting up different variants that achieve the same level of resilience, and then choosing the most cost-efficient one. To make sure that all solutions result in the same level of resilience, a BAU solution was set up and then components were varied to keep resilience high, for example by choosing another source of heat, or another form of storage that provides the same level of redundance and security of supply.

5.6.3. Heat Supply Zones

Figure 5-35 shows how the urban area in the northern part of Copenhagen is supplied with heat. Green areas indicate existing district heating areas supplied by Vestforbrænding and several other district heating companies. Blue areas are those currently supplied by gas boilers, and the blue numbered areas marked with a red dotted line are those areas included in Heat Plan 2030.

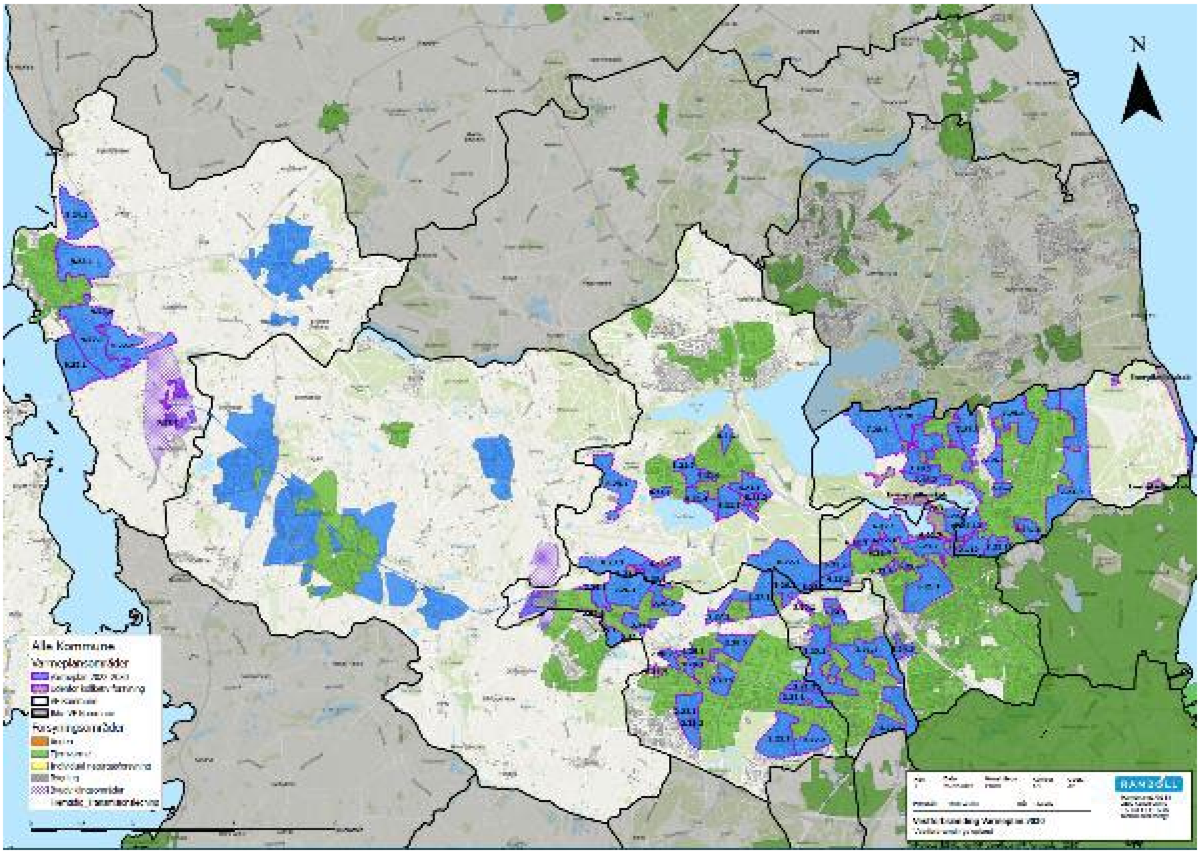

Figure 5-35. Heat Plan 2030, heat supply areas.

The selection of the areas and the internal ranking was based on the methodology presented in the Annex73 study:

- The heat demand was mapped based on the national building register and aggregated information from the gas company.
- The investment in networks and branch lines was based on geographic information and on a hydraulic simulation of extending the existing network to the new areas in combination with new production plants in some of the new areas.
- The investment key figures (investment in network)/heat demand) as well as (investment in network minus investment in individual heat pumps)/heat demand) was used to select the areas and rank them as first and second priority.
- The economic assessment both with and without the new districts was used to identify the selection criteria.
- The optimal heat production from existing and new capacities was then simulated for the total heat market (both existing and new markets).

It appeared that district heating was more profitable than small heat pumps in almost all the remaining one-family areas. Besides it would be difficult to establish individual heat pumps in many of the areas due to noise problems, particularly in townhouses.

The supply of district heating from Vestforbrænding to consumers in the six municipalities is expected to increase from 900,000 to 1,600,000 MWh according to the forecast shown in Figure 5-36.

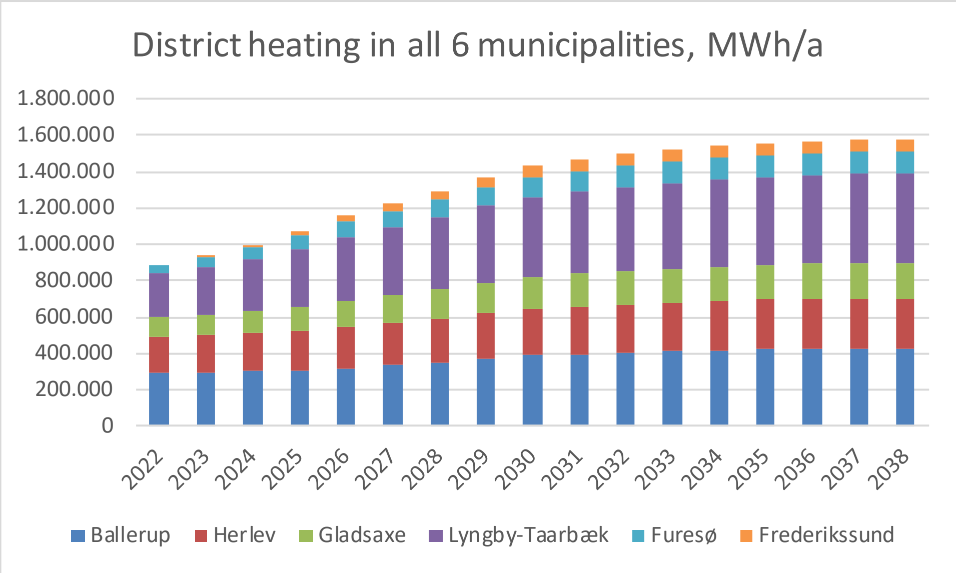

Figure 5-36. Heat supply to own existing and new consumers in the six municipalities.

5.6.4. Heat Production and Storage

To implement the plan, the total installed heat production capacity is expected to increase from 470 to 730 MW in 10 years. The thermal storage capacity is expected to increase from 8,000 to 50,000 m^3 volume.

The increase of waste heat from 2025 to 2026 (Figures 5-37 and 5-38) is due to the additional low temperature heat from the carbon capture.

Allocation of new production capacity year by year to meet the additional increase in heat demand was planned based on the following criteria:

- Total capacity demand corresponding to 3,200 max load hours (coldest day)
- Total based load capacity, waste heat, heat pumps, 25% of the electric boilers, 25% of the gas CHP corresponding to 5,000 max load hours (typical winter day)
- Total installed capacity to meet the capacity demand and sufficient spare capacity to compensate for an outage of the largest production plant, plus 50% of the electric capacity.

Moreover, the heat storage tanks are designed to level the daily production and thereby deliver both base load capacity and peak capacity.

This criteria for spare capacity was used for the whole system and for those parts of the system that is supplied through critical pipes, i.e., pipes located in such a way that they cannot be repaired within 24 hours (e.g., crossings under rails).

New base load plants have been proposed based on the following criteria:

- New base load plants are large heat pumps, which have been proved to be the most cost effective and important for integration of wind energy since they can be disrupted any time as long as needed when there is a shortage of wind and when electricity prices are high.
- Large heat pumps use local resources of industrial surplus heat, surplus heat from cooling, and heat from wastewater treatment plants.
- There shall be sufficient base load in each area from existing network and new local plants

New peak boiler plants have been proposed based on the following criteria:

- There will be new peak and spare capacity, and new large gas boilers will be able to shift to oil in case of disruption of gas.
- Electric boilers will be able to accommodate up to 50% of the capacity even though, under certain conditions, there may still be a shortage of electricity.

A gas infrastructure with line-pack storage capacity and underground storages is used as backup for the wind energy. In case of a shortage of electricity due to lack of wind or hydropower, the large heat pumps will stop and be replaced by heat from thermal storage and gas boilers, and from a gas-fueled CHP, which will come on line.

Similarly, electric boilers can use all surplus electricity at zero prices, which would otherwise be wasted by curtailing wind turbines or bypassing hydro turbines.

This “smart grid” operation is already in operation as all plants are equipped with control and monitoring systems and areoptimized in the markets for power services.

The selection of oil and gas for peak and spare capacity does not violate the national energy policy. Due to conversion from fossil gas to district heating and the increase in the use of upgraded biogas, we expect that all gas from the grid will be biogas by 2035. We also expect fossil oil to be replaced with electro oil by 2035.

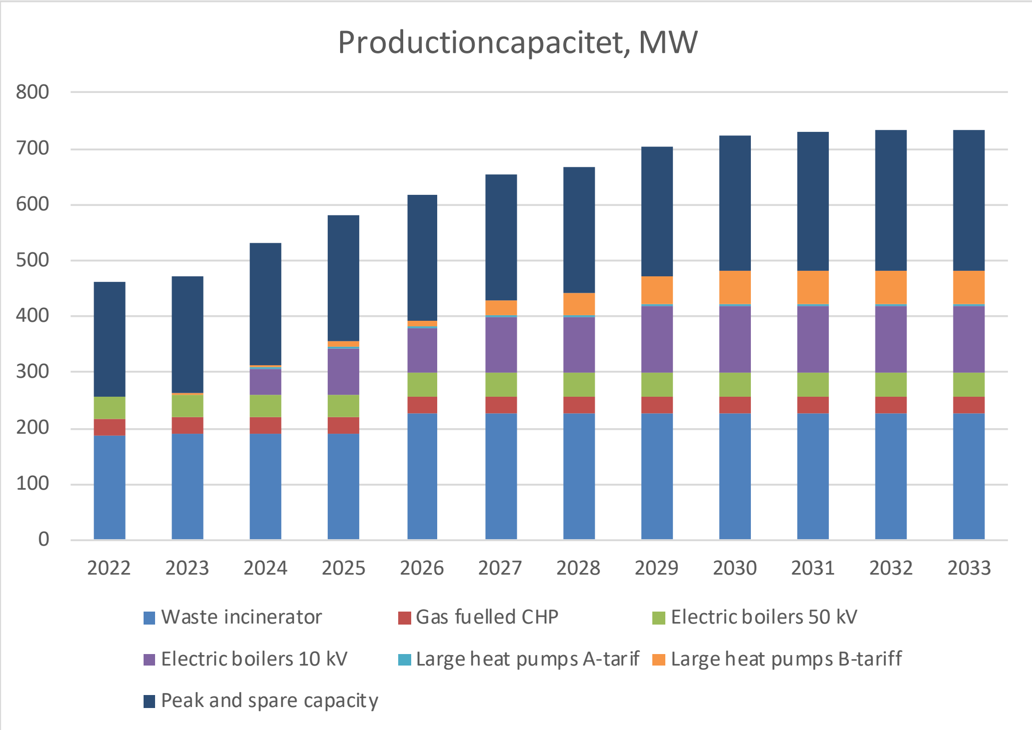

Figure 5-37. Heat production capacity.

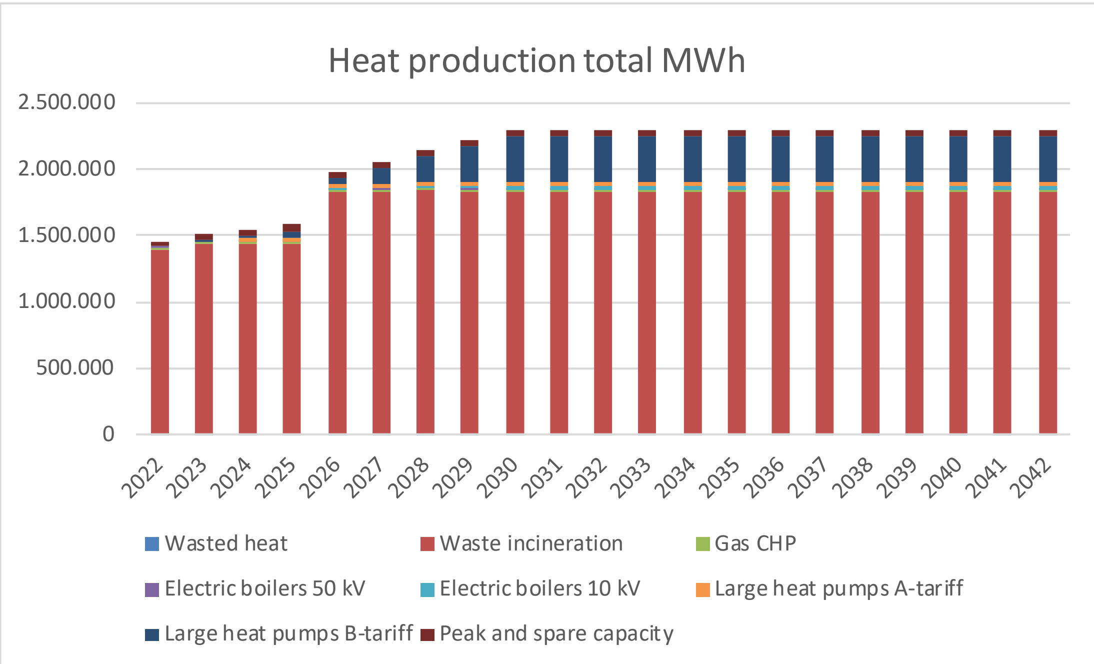

Figure 5-38. Total heat production to the existing and new consumers as well as transmission to CTR and VEKS.

The difference between Figure 5-38 (total production) and Figure 5-39 (production to own consumers) is equal to the heat transmission to the rest of the Greater Copenhagen district heating system (CTR an VEKS). A comparison of Figures 5-37 and 5-38 shows that the large heat pumps are the base load with max load hours above 5,000 max load hours in the new district heating areas, whereas the electric boilers have less than 1,000 max load hours.

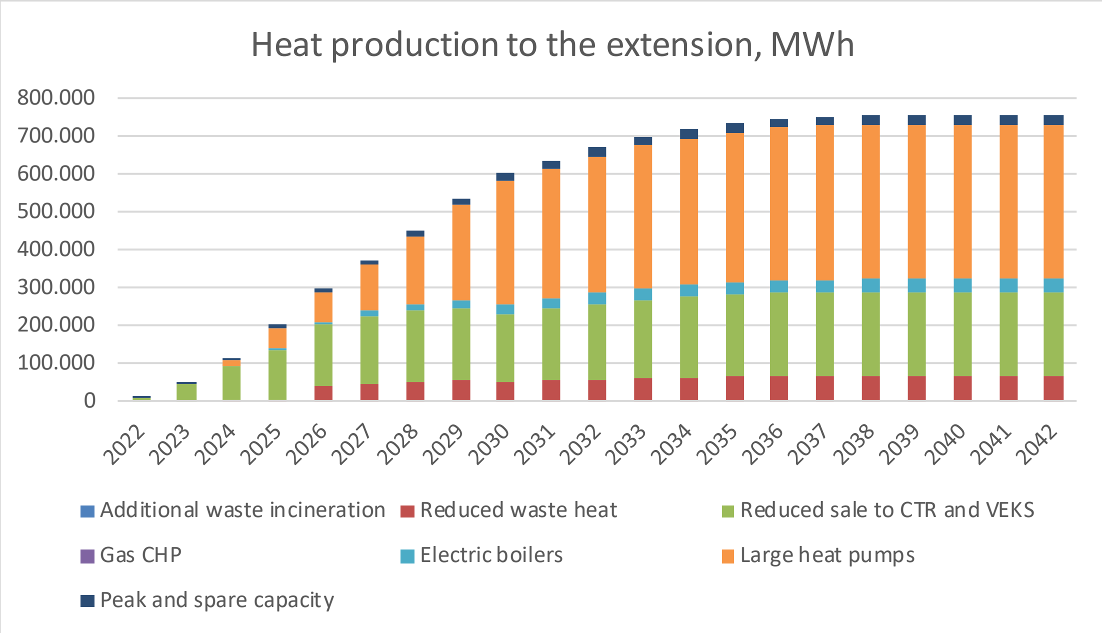

Figure 5-39. Heat net heat production to the new consumers.

Investments

Figure 5-40 and Table 5-41 detail a prognosis for the investments in network and production plants. The investment plan has been set up as a compromise between two conflicting criteria:

- The municipalities and the consumers would prefer to establish district heating to all the 30,000 buildings in 2022 due to the energy crisis, as the price of district heating from Vestforbrænding is stable, whereas the price of gas and electricity are unstable.
- Vestforbrænding prefers to distribute the investments over a longer period to avoid a dramatic price increase or a shortage of resources.

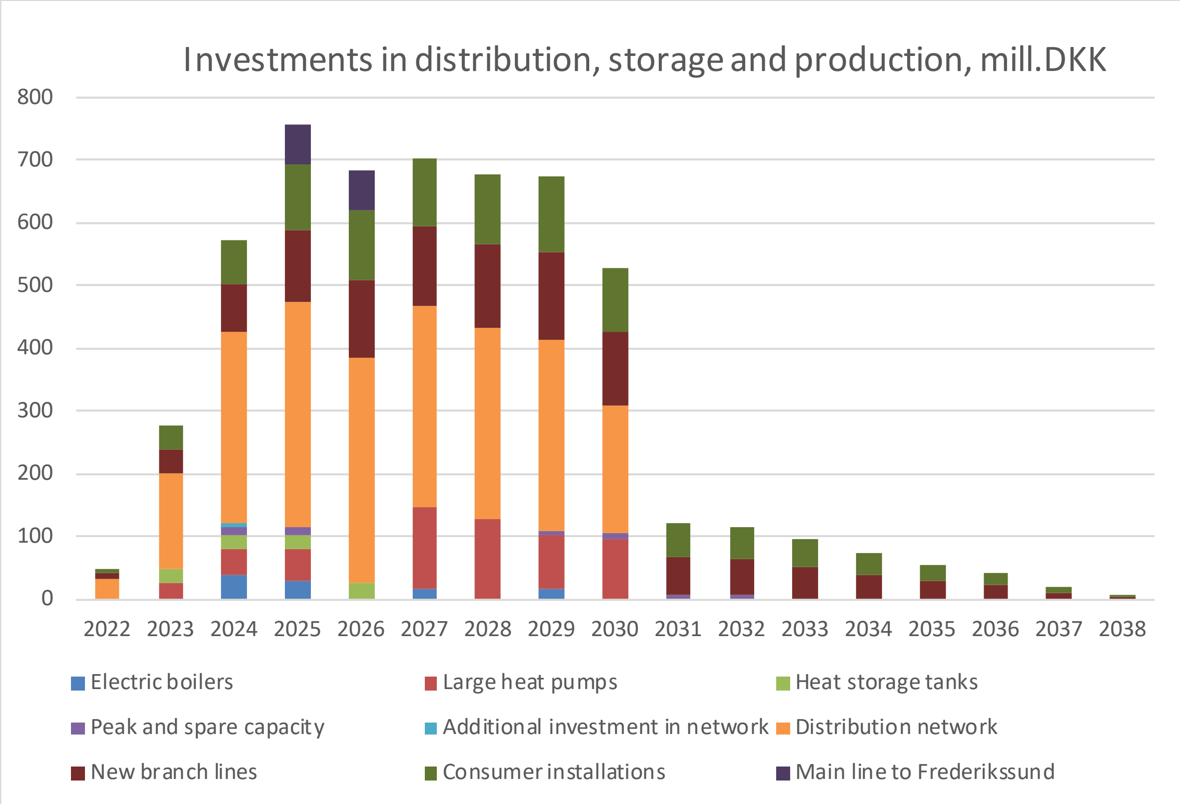

Figure 5-40. Investments.

Table 5-41. Investments in heat plan and baseline in 20 and 40 years.

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Investment summary, mill.DKK	**Heat Plan 2030 20 years**	**Base case 20 years**	**Heat Plan 2030 40 years**	**Base case 40 years**
District heating branch lines ,maximal	1.308		1.308	
District heating distribution lines	2.348		2.348	
Production and heat storage	810		1.128	
Consumer installations, maximal	1.321		2.643	
Individual heat pumps, maximal		4.026		8.051
Total with maximal connection	**5.788**	**4.026**	**7.427**	**8.051**
Total with expected connection	***5.320***	***3.565***	***6.174***	***7.380***
Main line to Frederikssund via Egedal municipality	126		126	
Closing gas pipes, maximal	182	182	182	182
Total with maximal connection	**6.095**	**4.207**	**7.734**	**8.233**
Total with expected connection	***5.606***	***3.725***	***6.460***	***7.540***

The total investments of 6.1 billion DKK in district heating are larger than the alternative investments in individual heat pumps, however seen in a 40-year perspective, the investments in the baseline are larger.

Operation Costs

Operation costs were estimated by simulating the operation of the district heating system and its optimal operation with help of the EnergyPro software program (described in the Guide and shown in Figure 5-41). The system considers heat storage capacity, and optimal operation of the CHP plants, large heat pumps, and electric boilers.

- The gas-fueled CHP plant operates only when electricity prices are high.
- The electric boilers operate only when electricity prices are low.
- The large heat pumps are interrupted when electricity prices are high.
- Both the CHP and the electric boilers generate heat when they operate under these conditions.

Note that the diagram in Figure 5-41 does not show all the production plants (large biomass CHP plants, other waste incinerators, heat pumps, electric boilers and peak boilers) and heat storage facilities in the heat transmission system (CTR and VEKS).

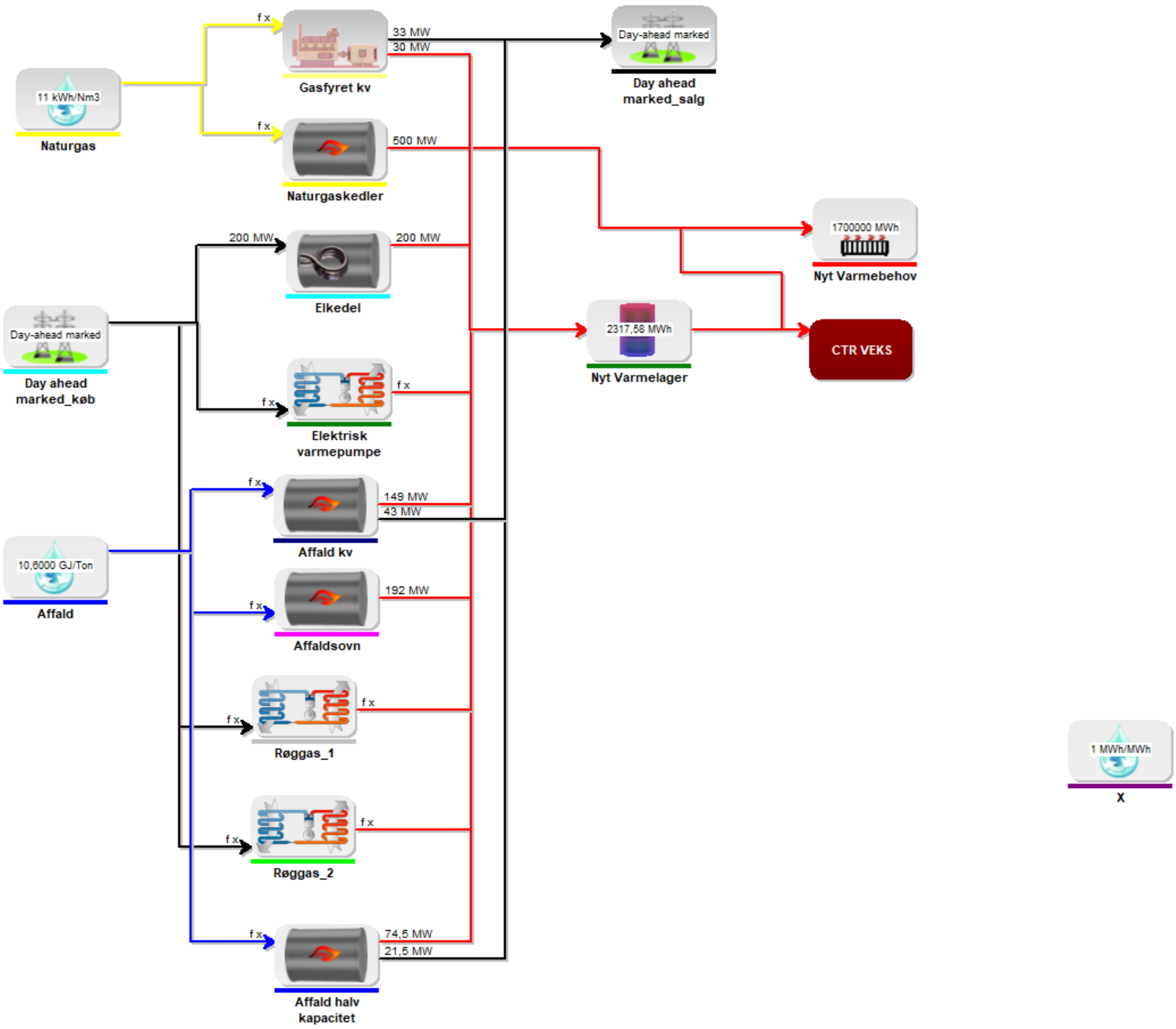

Figure 5-41. A simplified EnergyPro model.

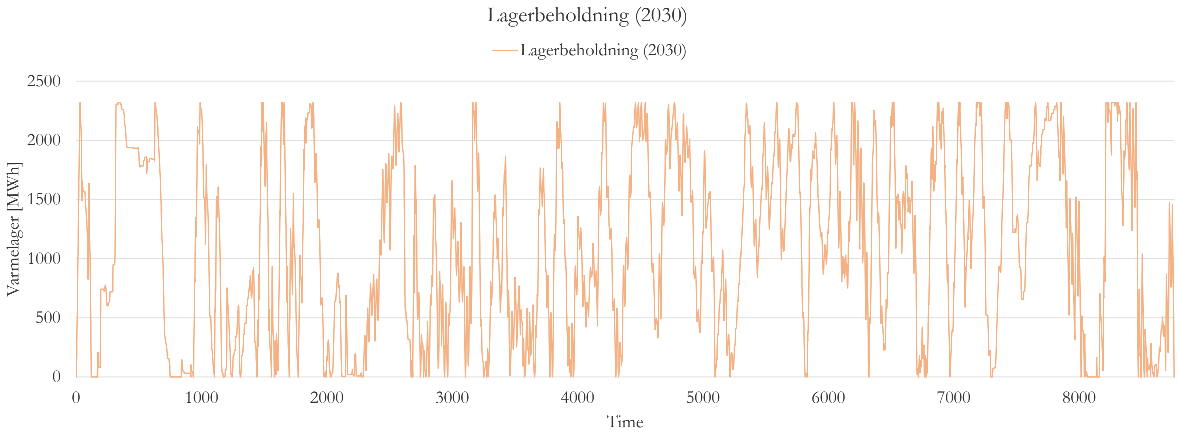

Figure 5-42. Heat storage operation.

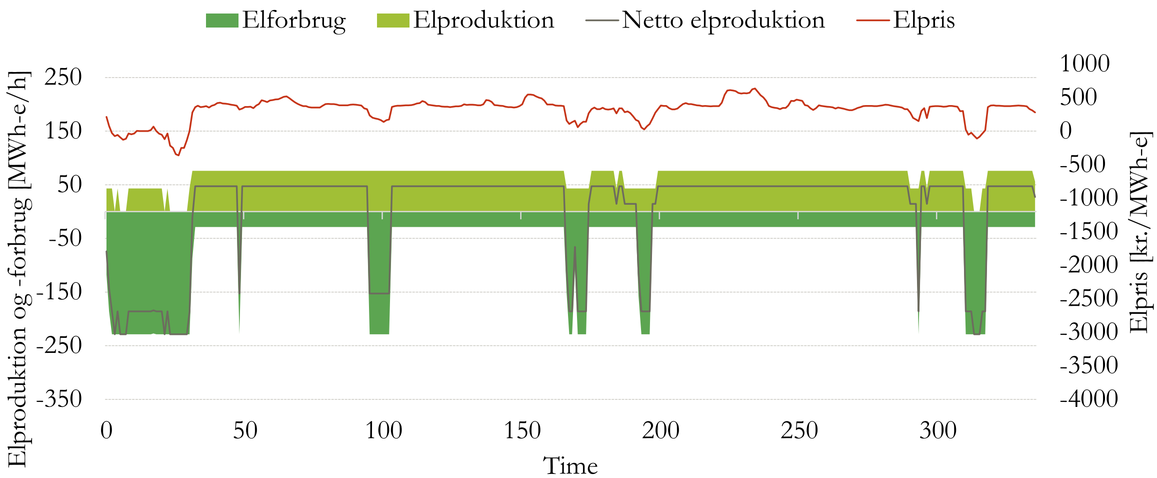

Figure 5-43. Responding to power prices (virtual battery).

The response of the system to electricity price fluctuations demonstrates its flexibility:

- Electric boilers use surplus electricity that else would be wasted.
- Once electricity prices are high
  - Heat pumps stop
  - gas- and biomass-fueled CHP plants replace condensing plants in the market and produce power (this is only the case in other countries; Denmark no longer has condensing plants),
- When electricity prices fall, gas- and biomass-fuelled CHP close or shift to bypass mode.

Overall, the system functions as if there were a huge electric battery installed (Figure 5-43). In short, we can say that the district heating system acts like a virtual battery that integrates wind energy in a smart and cost-effective way.

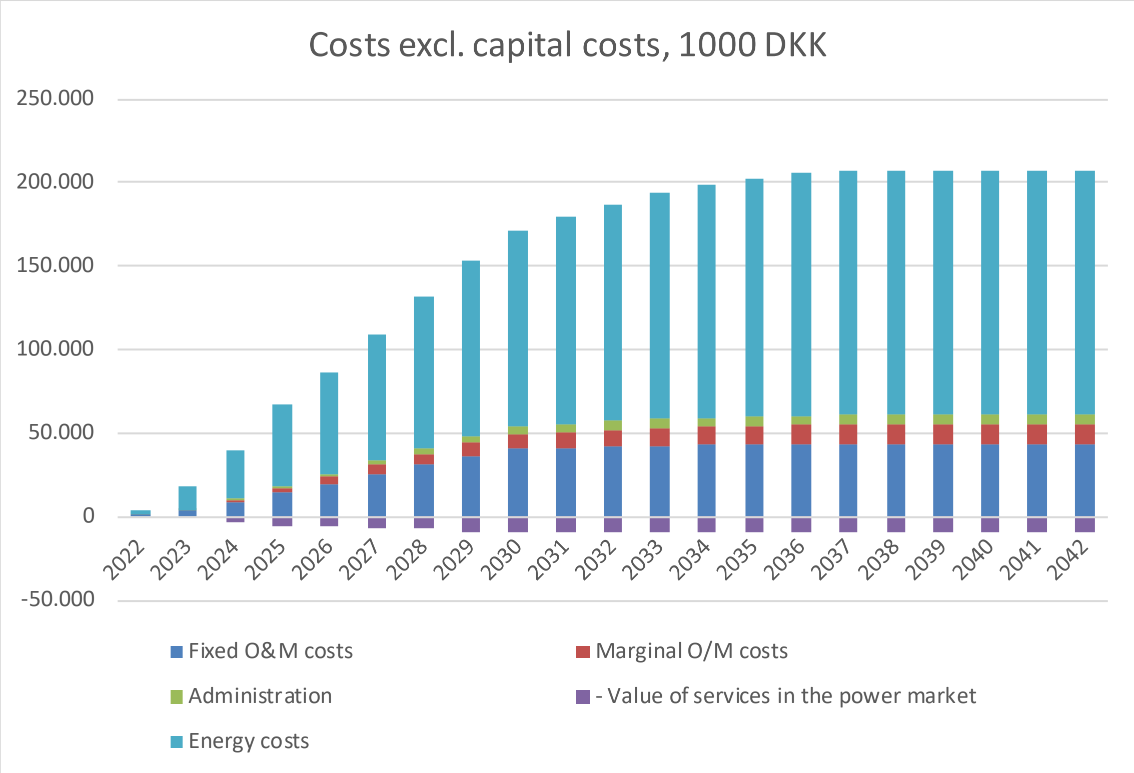

Figure 5-44. Total energy and operations and maintenance costs.

Profitability

The profitability of the heat plan was analyzed using the NPV Method for a 20-year period considering residual value of the investments, which have long lifetime. The district heating network is a natural part of the urban energy infrastructure and has a lifetime similar to that of the buildings it serves. The technical lifetime is not known, but is projected to be at least 60 years as maintenance costs are allocated to replace components that have a shorter lifetime.

The NPV benefit for the society is 0.6 billion DKK and the Internal Rate of Return (IRR) is 5.5%. These calculations are based on a discount rate of 3.5% issued by the Ministry of Finance and energy prices and environmental costs (CO_2 and harmful emissions) issued by the Energy Agency and costs.

The NPV benefit to the local community is 1.8 billion DKK and the IRR is 6.7%, based on a discount rate of 1%. Given the current district heating tariffs, which are offered to all consumers, this benefit is divided between Vestforbrænding, which represents all consumers, and the new consumers, i.e., 0.8 billion DKK for Vestforbrænding and 1.0 billion DKK for all new consumers.

A financial analysis of the profitability of the Vestforbrænding system considered current-year prices, inflation, efficient financing, and a 30-year depreciation of investments. Figure 5-45 shows the non-depreciated assets or long-term debt and the total debt (red curve) as would be in case if the annual profit were be paid back to the consumers. According to the Heat Supply

Act, the annual profit must be paid back to the consumers, and Vestforbrænding must improve efficiency and cost effectiveness to the benefit of the consumers in the owner municipalities.

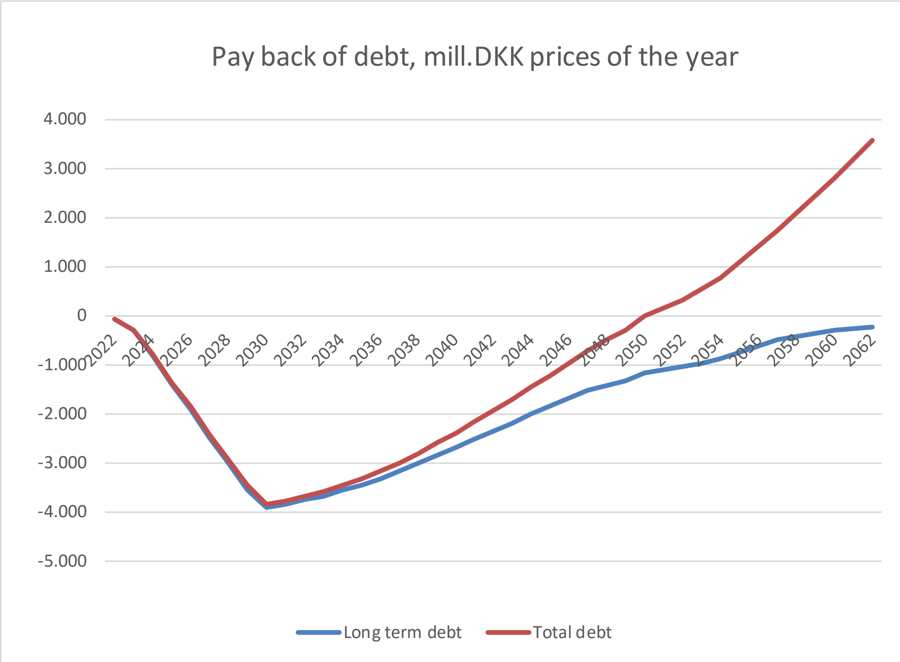

Figure 5-45. Financial projection.

Sensitivity Analysis

The sensitivity analysis shows that the end-user prices are generally stable due to the capital intensive investments and use of waste and multiple heat sources.

The biggest risk is that there will be lack of resources to meet the increasing interest in district heating throughout the country. Therefore, although all municipalities and consumers have expressed a desire to speed up the plan and connect all buildings within 1 year, the investment has been distributed over a period of 8 years.

CHAPTER 6. FREQUENTLY ASKED QUESTIONS

This chapter presents the conclusions from the pilot studies in the form of Frequently Asked Questions. Those involved in developing this work have expressed an important caveat, that users will experience a learning curve so the best thing to do is to get started. The following questions and answers below should help you through the process.

6.1. Why Should I Use the Resilience Energy Master Planning (EMP) Process?

The Resilience Energy Master Planning method gives specific directions on how to consider resilience and how to incorporate it into the planning process. Compared to familiar past procedures, the method leads to a much cleaner process, one that observers find easier to follow, and one that allows a useful comparison of results.

A comparison of the results using the Resilience Energy Master Planning method with the (pre-Annex 73) case studies shows that

- Before the streamlined process
    - Different methods, tools, databases, and a variety of different approaches have been used.
    - The steps and methods depend very much on who conducted the process, in pilot studies there is more common elements.
- When applying the Resilience EMP process, the processes all show the structure proposed in Figure 6-1.

Note that the proposed process leaves a great degree of freedom to the planning team. A thorough look at the pilot studies shows that different strategies, methods, and quantification tools have been used, depending on the people involved and on the planning culture of the host country.

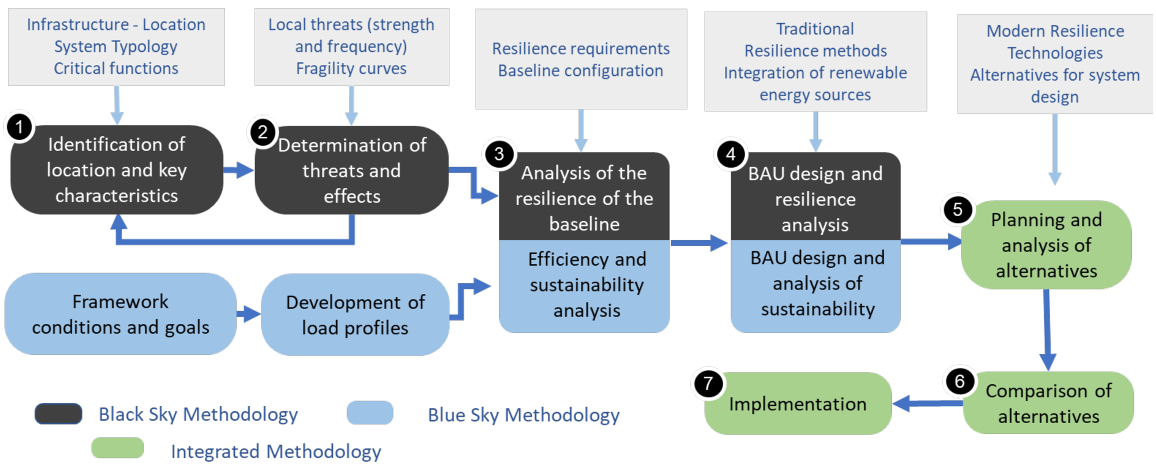

Figure 6-1. Process Chart of the Resilience Energy Master Planning.

6.2. Who Should Be Involved in the Process?

Different stakeholders should be included in the process, or at least considered. The stakeholder analysis is important, because to find good solutions, it is necessary to find common interests and share costs as well as benefits. Moreover, stakeholders have access to different pieces of information needed in the process like current energy consumption, critical functions, costs, age and repair strategies of components etc.

Persons to be involved in the resilience EMP process include:

- Someone who can clearly communicate the functions of the buildings: building user or representative, safety officer
- Someone with detailed knowledge about the buildings (envelope, building technology): building manager
- Someone with information on the backup systems (UPS)
- Someone with information on the energy supply system: Energy system officer
- The building owner.

Other people/organizations to be involved

- Decision-makers associated with the supply grid and district systems (possibility to adapt connections, increase redundancy)
- Public entities (regarding funding, local goals, energy communities)

The Danish pilot study shows that the the involvement of the main stakeholders in local publicly owned utilities, such as energy utilities, waste management utilities, and wastewater utilities can make the process easier, although this is also possible with privately owned utilities

6.3. How Can Goals and Constraints Be Fixed?

In the first stages of the process, goals and constraints must be established and clearly stated. Constraints consist of

- legal framework, e.g., there may be laws on energy efficiency to be achieved in buildings, or on specific processes to be followed.
- Environmental framework; like climate zone, this includes locally available renewable sources as well as existing ducts and grid supply.
- Economic constraints.

Goals can be set freely by the team, or after consideration of existing regional strategies. Goals can sometimes be difficult to be set as experience shows that different stakeholders have different goals. For example, a financial officer might want to save money, but a sustainability officer may be more interested in lowering GHG emissions. Moreover, while involved stakeholders are often the first to express goals, they are often shaped by regional and national policies and strategies. Goals for resilience also depend greatly on the cost of an outage or a disruption of critical processes.

Goals of the following kind can be defined:

- **Resilience Goals.** These can be quantitative goals for max time out or max load not served. It is also possible to define such goals as degree of redundancy, diversity of generation mechanisms, maximum capacity, or backup capacity.
- **Economic Goals.** These can be the cost of supply per m^2 or cost of kWh, but may also include a specific amortization time. Another economic goal can be the NPV (as was used in the Danish case study), or annual costs of supply.
- **Sustainability Goals.** These can be share of renewables, GHG emission, net zero balance, etc.

6.4. Which Scenarios Should Be Considered When Analyzing and Comparing Baseline, Base Case, and Alternative Concepts?

When comparing different options, calculation of specific terms is done under specific circumstances, namely the following scenarios:

- Black Sky scenarios feature the identified basic design threats.
- Blue sky scenarios are scenarios that do not present any disruption, but are based on assumptions regarding future price levels of energy supply and costs of emissions, which are provided by the Energy Agencies.

Analysis and experience from pilot studies shows that it makes sense to include some scenarios with large changes in price levels such as the unexpected price increases currently experienced in 2022. In all cases, it should be possible to adapt results with changed (economic) conditions.

For example, the goal of keeping energy price at a certain level certainly fails when prices rise fast. With this in mind, it may be useful to formulate goals in a way that is independent of current framework conditions, e.g., that energy costs should be equal or less than 10% of the budget.

While goals regarding costs may change and higher prices accepted, goals on resilience are likely to remain or to assume greater importance in more unsecure situations.

6.5. How Can Alternative Concepts Be Found?

Pilot studies show that alternative concepts depend strongly on what planners know and have seen in the neighborhood or in other demonstration projects.

Alternative concepts can be found by adding different components to the existing system or by starting from scratch. Elements to be considered are all elements of the system, namely:

- Storage of electricity, cold, heat and other fuels
- Generation plants
- Use of local (renewable) resources
- Converters — for sector-coupling
- Efficiency measures
- Additional ducts for increased redundancy
- Protection of critical infrastructure and its supply from direct damage due to threats

- Documentation, “know-how,” and qualified personnel on site, repairability of components, control system for fast detection of problems.

A full list including costs, lifetime, and repair characteristics can be found in the technology database (available through https://annex73.iea-ebc.org/publications). Another valuable output of the Annex 73 is the Catalog of energy system architectures: In the project, a common way of showing energy system architectures has been developed. (@Alex add link). This catalog includes a good method to analyze existing system architecture and to create alternative concepts.

There will often be a large number of possible alternative concepts so that some preselection will be necessary. Experience from the pilot study on JKU campus shows that this preselection is led very much by local culture and the current framework. A re-evaluation of the JKU campus study under changed circumstances due to the war in Ukraine shows that other sets of solutions would very likely be considered due to the large shift in economic conditions and available supply, which strongly differ from the previously investigated scenarios.

As mentioned in section 6.4, calculations can easily be adjusted and adapted to accommodate such new conditions as changed energy prices. If conditions depart further from the expected scenarios, calculations may need to be updated. This re-evaluation process may become more difficult if certain alternative concepts were excluded in an early phase. We strongly recommend that decision-makers include and document the many different options in the first step, and that they take care to not limit themselves to standard concepts.

6.6. Sector Integration

In general, the results/decisions taken in one pilot project (JKU Campus) show that in the long term, the district solutions employed in Denmark are more profitable than single building solutions. Note that this depends on the density of heat delivery etc.

In Denmark, the strategy to respond to demand for heat when there is enough electricity from wind generation plants is to follow this strategy:

- New base load plants are large heat pumps, which can be disrupted any time.
- Use industrial surplus heat, surplus heat from cooling, etc.
- In each area, endure that production plants can cover the base load.

6.7. Do I Have to Follow the Sequence of Steps Exactly?

Experience from the pilot study of the JKU campus also led to the conclusion that the steps outlined here need not be seen as strictly consecutive. For example, in later stages, input to the first steps may need to be updated. This is especially the case for the first four steps.

Thus, it might make sense to do the phases in consecutive order, but to also allow the flexibility to reevaluate earlier steps, or to project future anticipated steps. In our experience, it was good to maintain an Excel® file with sheets pertaining to the different phases. In such a way, it is always possible to correct data or update decisions of previous steps.

6.8. What Effort Is Required for the Process?

The process can be performed with different levels of effort. It is possible to do it in a few hours, a few weeks, or even to let it run for a whole year. The duration depends very much on information access, the level of detail of available information, and the expected output.

It makes sense to first run it conceptually as “thought experiment” to identify the necessary stakeholders and data.

6.9. Can the Process Be Applied on Every Level and in Each Location?

The framework is useful in that it allows the assessment of a number of locations across the globe. Although the sets of factors will vary by location, the EMP method will provide a consistent baseline. The process can be applied at every level, from single buildings to an entire region.

6.10. How Should I Quantify Resilience?

There are different methods to quantify resilience. A quantitative approach to resilience of system supplying energy to the building can include (but is not limited to) the following metrics:

- Energy System Robustness (ER)
- Energy System Recovery time
- Energy Availability (EA)
- Energy Quality (EQ).

The first three parameters are critical for the selection of the energy supply system architecture and the component technologies to satisfy requirements related to energy system resilience. As discussed in section 5.3.1 of the Guidebook, requirements for Energy Availability and Energy System Recovery Time depend on

4. Criticality of the mission being served by the system,
5. System repairability, which depends significantly on remoteness of the facility hosting the mission, and
6. Redundancy of facilities that can serve the same critical function.

The ERIN tool calculates specific values that are characterized by the system’s resilience, e.g., maximal downtime, and load not served or others (described in the Guidebook in Chapter 8). The values can be calculated using different **tools** like ERIN (Annex 73), or such others as IDA ICE, EnergyPro, and TRNSYS.

The method finally chosen will depend on the team structure, on the experience of the involved practitioners, and on the other tools that are available. In most pilot studies, the ERIN tool was used as developed in Annex 73.

An alternative method used in Pilot Study 6 (section 5.6, Denmark) is to first find different alternative concepts that ensure the same level of resilience, and then to do a cost benefit analysis.

6.11. How Can I Contribute? As a ...

Planner: Address resilience in your work by using the Resilience EMP methodology

Public Decision-Maker: Support Resilience in the planning process by giving more weight to local consumption and storage of renewable energies. To support resilient systems, consider design threats and consider Black Sky events in the calculations of cost benefit and revenue.

The example of Denmark shows that the legislation of the Heat Supply Act started to formulate concrete, long-term goals that could effectively support the transition of energy systems.

This long-term strategy is to satisfy heat and cooling demand by environmental and waste heat and cold or (second priority) heat pumps. The remaining high temperature demands can be met by biogas- and (in the short term) natural gas-fueled CHP(s).

Improve local energy balances by adapting generation to consumption, and by using storage.

Results from the pilot studies suggest that it is very helpful to devise a set of publicly agreed common goals for communities and regions that could be communicated via certification schemes or funding requirements. These should include

- High efficiency
- Low supply temperatures for heating and high supply temperatures for cooling.

Energy Supplier: Cooperate with local initiatives focused on energy resilience. Invest in diverse and decentralized energy solutions supporting regional balance

Financial Expert: Invest in resilient energy supplies to increase security. Diversification and regional supply are also expected to be profitable in blue sky scenarios, and protect investments in Black Sky scenarios. Avoid investing in systems that do not correspond to long-term goals and strategies

Home owner: Refer to national or regional guidelines for supportive action. Seek high efficiency and explore the possibility of load shifting and flexible energy use in your home. Plan to achieve low supply temperatures for heating and high supply temperatures for cooling

Building Manager: Formulate well developed strategies and implementation plans. Use equipment failures and required maintenance/repair downtime as opportunities to implement changes more quickly.

6.12. On Which Level Does the Resilience EMP Process Work Best?

The process can be carried out on different levels, ranging from the single building level to the national or even international levels. In many cases, the planning process is carried out on a municipal or other community level governed by a single common administration. The level should be chosen such that it allows for integration of waste heat and heat pumps of reasonable size and efficiency, and for space for storage and generation units.

Information from lower levels (e.g., plans to refurbish single buildings) should be considered in the assessment, as should strategies and goals originating from higher levels (like national goals and strategies, or the Heat Supply Act in Denmark).

6.13. What are Characteristics of a Resilient Energy Communities?

Resilient energy systems are characterized by

- **diverse generation** systems, use of various sources of (waste) heat, cold, and power
- **an integrated approach** for building, energy system, and building technology
- use of **renewable sources** and nature-based solutions
- **Redundancy**
- **Grid supportive** action e.g., load management
- **Adaptation** to frame conditions (cost of energy carriers, reliability of grid, etc.), e.g., vary heat source depending on availability of volatile sources and fuel costs
- **Storage** systems
- **Sector-coupling**, e.g., generate heat or fuels if surplus electricity is available
- A system that acts as **virtual battery.**

6.14. How Can I Compare and Visualize Results?

Step 8 compares the various alternative concepts to provide the basis for decision taking. Visualization helps decision making. But how can results be visualized to support the decision process? There are many different possibilities, some of which have been used in the pilot projects. It is possible to display results for alternative concepts

- in a table, e.g., see Table 5-39
- as set of energy system architecture maps
- by radar charts for each concept
- on a map which locates critical functions and energy system components, as in Figure 3-4
- as scatter plot
- as chart of the EMP process, see Figure 5-18.

A successful way to compare results is to perform the cost benefit analysis for local community and for the stakeholder – for each alternative concept- as described in the Danish Pilot Study (section 5.6) and the Danish Case Studies in the Case Studies Book of Annex 73.

6.15. What If I Want to Do Even More?

Once you have defined a strategy and implementation plan, you could consider additional measures like carbon capture, extraction of metals from the fly ash, creation of an information center, and circular economy action.

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ACRONYMS AND ABBREVIATIONS

Abbreviation	Term
AEWRS	Army Energy and Water Reporting System
CHP	Combined Heat and Power
CHPP	Central Heating and Power Plant
DHW	Domestic Hot Water
EA	Energy Availability
EBC	Energy in Buildings and Communities (Programme)
EMP	Energy Master Planning
ER	Energy Robustness
GHG	Greenhouse Gas
GSHP	Ground Source Heat Pumps
GUI	Graphical User Interface
HP	Hydroelectric Power
HVAC	Heating, Ventilating, and Air-Conditioning
IEA	International Energy Agency
IEWP	Installation Energy and Water Plan
IRR	Internal Rate of Return
IWU	Institut Wohnen und Umwelt
JKU	Johannes Kepler Universität
MC	Mission Critical
MTBF	Mean Time Between Failure
MTTR	Mean Time To Repair
NOAA	National Oceanic and Atmospheric Administration
NPV	Net Present Value
O&M	Operations and Maintenance
ODB	Outdoor Dry Bulb
OECD	Organization for Economic Cooperation and Development
OIB	Österreichisches Institut für Bautechnik [Austrian Institute for Structural Engineering]
OPEC	Organization of the Petroleum Exporting Countries
PV	PhotoVoltaic
R&D	Research and Development
ROI	Return on Investment
SMI	Smart Readiness Indicator
SMPL	System Master Planning Tool
TDT	Thermal Decay Test
TES	Thermal Energy Storage
TOML	Tom’s Obvious Minimal Language
UPS	Uninterruptible Power Supply