A Tool for Modeling Energy and Resilience for Community-Scale Networks of Buildings and District Systems

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ABSTRACT

Resilience is contextual. The concept of design basis threat can be used to capture a contextual scenario to measure the resilience of district energy systems against. Design basis threats are low-probability, high-impact events such as hurricanes, flooding, earthquakes, etc. We present a computer-based simulation program to assess the resilience of community-scale district energy systems to various design basis threats. This program simulates both building and district-level energy systems consisting of an interconnected network of components. Multiple flows of energy can be modeled: notably, both thermal (heating/cooling) and electrical flows and their interactions. This network of components is made subject to various scenarios which represent one or more ideal cases (i.e., "blue-sky") as well as design basis threats. Each scenario has a probability of occurrence and zero or more intensities associated with it such as wind speed, vibration, water inundation level, etc. Fragility curves are used to relate a scenario's damage intensities (e.g., wind speed) with a component's chance of failure. Performance of the network is assessed while taking into account the possibility of failure due to routine reliability as well as various threats. In so doing, various resilience metrics such as maximum contiguous downtime, energy availability, and load-not-served can be calculated.

INTRODUCTION

District energy systems play a major role in enabling energy efficient communities. However, energy efficiency is not the only concern. The effects that unplanned threats can have on a community can be devastating from the perspective of economics, security, and even loss of life. As such, the resilience of a community has started to come to the forefront of attention as a critical constraint on community master planning and design. Resilience stems from the Latin root, *risilio*, indicating the ability of an object to return to its original shape after being stressed (Shandiz et al. 2020). In its engineering context, resilience is defined by Watson (et. al. 2015) as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions."

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However, resilience is contextual. That is, one is resilient *to* something. For example, a design that is resilient against flooding may not be resilient against earthquakes. This paper uses the concept of a design basis threat (DBT), a term borrowed from the nuclear industry (see Stamp et. al. 2014), to contextualize resilience. Design basis threats are representative scenarios for low-probability, high-impact events such as hurricanes, flooding, earthquakes, terrorist attacks, tornados, ice storms, flu pandemics, etc. Taking into account relevant design basis threats is necessary for assessing the resilience of a community *to* those threats.

In this paper, we describe the need for a tool to assess resilience of community-scale energy designs to various threats during master planning. Next, we review similar tools from the literature. Then we describe the overall simulation and conceptual design of our computer-based simulation engine. Finally, we discuss future work including how the engine can be used during master planning for assessment of early stage designs for progress towards their energy and DBT-based resilience goals.

Energy master planning of communities involves balancing multiple criteria including cultural, organizational, technical, legal, financial, and, increasingly, safety and resilience. Although an energy master planning process and a resilience assessment framework exist (Zhivov et al. 2014, Jeffers et al. 2020, Shandiz et al. 2020), keeping track of all the necessary information and running the computations requires use of a computational tool to be practical for master planners to use when working on resilience-based energy master planning projects. The International Energy Agengcy (IEA) Energy in Buildings and Communities Programme (EBC) Annex 73 and the United States Department of Defense's Environmental Security Technology Certification Program (ESTCP) project EW 18-5281 "Technologies Integration to Achieve Resilient, Low-Energy Military Installations" are designed to enhance the previously developed energy master planning concept and the *NZP/SMPL Tool* (see Zhivov et al. 2014) to address resilience of energy supply solutions by integrating a capability for computation of thermal (heating and cooling) and electrical network characteristics with a capability to support resilience assessment without significant post processing. Based on research conducted under these projects, a "Guide for Energy Master Planning for Resilient Public Communities/Military Installations" has been developed that describes the methodology of Energy Master Planning and the process of integration of Energy Systems Resilience Analysis into the Energy Master Plan (Zhivov et al 2021). The guide also helps the user to establish energy goals and constraints and provides an understanding of the data required for energy master planning and resilience analysis. An important part of the Guide is devoted to defining, measuring and assigning resilience requirements to energy systems and offers a methodology for the selection of energy system architecture and technologies. Finally, the Guide offers a multi-criteria analysis methodology for selecting alternatives and describes economic and business models for implementation of energy master plans. This paper discusses the computer program that serves as the calculation "engine" for supporting the methodology described in the Guide. The engine is called *ERIN* (*Energy Resilience of Interacting Networks*) but we shall refer to it as "the engine" for the remainder of this paper.

The purpose of the engine is to assess the energy load/supply resilience against any number of user specified baseline (i.e., "blue sky") and/or design basis threat (i.e., "black sky") scenarios. The main contributions of the engine that we maintain are unique in aggregate are as follows: the tool accounts for both reliability and resilience over various scenarios (design basis threats) while also accounting for topology and interaction between an open-ended number of interacting energy networks while providing key energy usage, resilience, and reliability metrics for the master planning process.

The engine is written in the C++ programming language (Stroustrup 2013) as a command-line program that takes in an input file in TOML format (a plain text format; see Preston-Werner 2020) and writes output files in comma separated value format (Shafranovich 2005). The simulation uses the parallel discrete event simulation (PDEVS) paradigm and utilizes a PDEVS library called "adevs" (Nutaro 2010).

Several existing tools were investigated for potential use, ideas, and inspiration prior to conducting the existing work. The *Microgrid Design Tool* (*MDT*) is a tool developed by Sandia National Laboratory as a decision support tool for microgrid designers in the early stages of the design process (Eddy, Miner, and Stamp 2017; Stamp et al. 2016). The *MDT* incorporates a *Microgrid Performance and Reliability Module* (*PRM*) which is used to "statistically quantify the

performance and reliability of a microgrid operating in islanded mode." The *MDT* and *PRM* have been an inspiration to our solution. However, *MDT*, as the name implies, is focused on microgrid design and evaluation. As such, it requires inputs and knowledge of components that are not typically known by master planners and energy managers. For example, *MDT* contains control algorithms to simulate microgrid startup. This extra functionality, however, comes at the cost of added data requirements and complexity.

The *Energy Resilience Analysis* (*ERA*) *Tool* is a tool to "analyze energy resilience against the cost of possible energy architectures for military installations" (Millar 2019). The program uses a Monte Carlo simulation to test various basic architectures and builds a performance and cost model which represents the likelihood of correct operation in the face of the most common causes of power outages and service interruptions.

The *ERA Tool* is similar in objective and scope to what we are building. Our engine builds upon the thinking of the *ERA Tool* by adding topological information to the network used in the analysis and brings the analysis to a building-by-building level versus just at the installation level. We also felt it important to emphasize the notion of design basis threat events over what is available from the *ERA Tool*.

REopt is a "techno-economic decision support model used to optimize energy systems for buildings, campuses, communities, and microgrids." The tool is a mixed integer linear program simulation that optimizes the size, mix, dispatch and cost of various "behind-the-meter" components. (Anderson et al. 2017)

With regard to resilience, however, *REopt* does not include detailed topology, reliability statistics, or design basis threat.

The *NZI Opt* tool is described by Swanson (et al. 2014) as "a community-scale, mixed- integer linear programming (MILP) based model to assist in the selection of energy supply and distribution equipment and to determine optimal schedules of operation." As such, *NZI Opt* is similar to *REopt* and similar comments apply. Either *NZI Opt* or *REopt* could potentially be used as a sizing, dispatch, and technology mix optimization solution for the engine presented here.

SIMULATION OVERVIEW

The engine simulates energy flows over district energy system networks that supply both individual buildings, clusters of buildings, and other loads. These networks are comprised of components (loads, supply, conversion, routing, storage, and transmission) and connections. The connections between components form the topology of the network – what is connected to what. Multiple flows of energy can be modeled: notably, both thermal (heating/cooling) and electrical flows, as well as their interactions.

This network of components is subject to various scenarios, which represent one or more ideal cases (i.e., "blue sky") as well as design basis threats (also known as "black sky" events). Each scenario has a probability of occurrence and zero or more intensities associated with it, such as wind speed, vibration, water inundation level, etc. Fragility curves are used to relate the scenario's damage intensities with the percentage chance that a given component will fail to work under the duress of the scenario.

The engine simulates flows of energy throughout the network of components. These flows represent the behavior of the district energy system under study. The simulation is essentially a powerflow model, which accounts for potential failures. Components have zero or more inflow ports, and zero or more outflow ports provided there be at least one flow port per component. Flows exit outflow ports and are received by inflow ports. Source components have only one outflow port; load components have only one inflow port. Components are meant to represent real world equipment and devices for moving, converting, routing, storing, supplying, and consuming energy. Not all real-world components need to be added to the simulation but if the component significantly affects flow characteristics or if it plays a key topographical role in the network and may fail under one or more of the scenarios considered, then it should be added.

By looking at the performance of the network while taking into account the possibility of failure due to various threats or routine breakage, resilience metrics such as maximum downtime, energy availability, and load-not-served can be calculated. This can, in turn, help planners to see whether a proposed system or change to an existing system will meet their threat-based resilience goals.

The conceptual core or the fundamental design of the engine can be expressed as follows: *a tool that simulates, as a series of discrete events, the negotiated, conservative flows of energy and matter across and between components in a network under some dispatch strategy subject to unreliability over various scenarios*.

Let's unpack this dense, compact, statement with a focus on the key concepts mentioned:

- *simulates, as a series of discrete events*: Simulation is modeled as a series of discrete events. Specifically, model state (mainly, the state of flow) only changes during events. Discrete events allow us to accommodate the large gaps in time between infrequent occurrences such as component failures and threat scenario activations. During hour-by-hour simulation of load profiles, the simulation will typically jump from hour to hour. Other discrete events that are simulated include changes in non-controlled sources such as photovoltaic (PV) power generation, routine failure of a working component based on a statistical representation of reliability (e.g., a Weibull distribution), routine repair of a failed component, events due to physical limitations of devices (e.g., depleting the energy in a battery or diesel fuel tank), the initiation or ending of a scenario, and the application of fragility curves at a scenario start.
- *negotiated, conservative flows of energy and matter across and between components in a network*: Although the tool has been created with the idea of modeling district energy systems, actually, any flow could potentially be modeled as long as it is phrased in an energy basis. Although not yet implemented, the model could accommodate non-energy-based flows in the future (e.g., potable water). A flow also has a rate which is expressed in power. As a fundamental rule, the network never provides more flow than is requested but may provide less. Furthermore, any component in the network assumes it will get the flow it asks for unless it hears otherwise; this rule cuts down on unnecessary communication between models. Flows never change direction. Therefore, the minimum flow into any inflow port is zero. Flows are negotiated in the sense that loads send requests for flow upstream through the network and are subject to supply and other modeled limits (e.g., a request for power from a depleted energy storage unit would result in zero outflow achieved). Flows are conserved in the sense of energy conservation which is an inherent property of the models: energy is neither created nor destroyed. Components are built from elemental machines such as sources, sinks, converters, connectors, storage units, routers (splitters and mixers), and on/off switches (providing on/off behavior). A collection of multiple elemental machines together with their controls can be used to represent the behavior of a real-world component. A network includes the ideas of topology (i.e., "what is connected to what"). It also implies the notion of reachability and what is "on" (or "in") the network and what is not.
- *Dispatch strategy*: Dispatch is the notion of controlling how much, when, and from where in the network energy will flow. This current version of the engine uses a priority list strategy for dispatch. We hope to add more sophisticated algorithms at a later date as needed.
- *Subject to unreliability*: Unreliability is modeled as being either time-based or scenario-intensity based. Both forms of reliability involve toggling a component between operational and failed states. Under time-based reliability, when operational, an unreliable component will schedule itself to fail after a given amount of simulated time based on some failure distribution such as a Weibull distribution or Gaussian distribution. When failed, the time-based reliability component will schedule itself for repair which will take some amount of time as determined by the underlying repair distribution which is, again, some statistical distribution. In the case of scenario intensity-based unreliability, fragility curves are used to map scenario intensity to a chance of failure. If an intensity-based unreliable component fails, it is assumed to be unavailable for the duration of the scenario. If it survives, it is assumed to be available for the duration of the scenario. We anticipate future versions will provide enhanced capability to model repairs.
- *Over various scenarios*: A scenario is either active or inactive. Multiple scenarios can exist and are independent of each other; scenarios can even overlap in time since statistics are only aggregated per scenario (i.e., scenarios that overlap in time do not "see" each other; scenarios are simulated independent of each other). A scenario changes the intensity of various damage attributes (things like wind speed, inundation flood level, etc.). As

such, unreliable equipment susceptible to a scenario's intensity metric (e.g., above-ground power lines subject to high winds) may experience failure. Note that the engine simulates a scenario zero, one, or possibly many times depending on the scenario's probability of occurrence and occurrence limit. The engine typically simulates over large time horizons to allow scenarios to occur multiple times. When a time horizon of, say, 1000 years is chosen, we are not forecasting 1000 years into the future. Instead, we are simulating the case year 1000 times to get a sufficient number of samples of rare events to compute resilience metrics from.

Input/Output

The inputs and outputs of the engine are conceptually given in Figure 1. The figure depicts the various concepts which are described in the input TOML file. These are read into the engine, simulated, and the key outputs produced (by scenario) include the energy used by the network, energy availability, maximum contiguous downtime, and load not served. The key pieces of the input file include a description of the components to simulate along with their load profiles, fragility curves, and failure modes; networks which describe how component outflow ports connect to other component's inflow ports; and scenarios which describe normal operation and design basis threat events. Scenarios require occurrence distributions in order to determine when and how often they will occur.

Figure 2 shows an example load simulation as might be output from the tool. The black solid line shows the requested power to the given load, L, for the given scenario, S. The dotted line shows an interruption in power which might be the result of either a routine failure (i.e., reliability) or fragility-induced failure from a design basis threat. Three key resilience metrics are calculated by the engine: energy availability ($EA[L,S]$), maximum contiguous downtime ($t_{mcd}[L,S]$), and load not served ($LNS[L,S]$). The brackets used after the metrics in our notation are meant to remind the reader that these metrics are derived by load (L) and by scenario (S). Any given scenario can occur more than once and, therefore, the metrics are the summation over all instances of the scenario during the simulated time.

The equation for energy availability is given by Equation 1. Energy availability is reported as a percentage derived from the ratio of energy achieved (i.e., delivered), $E_A[L,S]$, to the energy requested, $E_R[L,S]$. A load that is perfectly satisfied during a scenario would have an energy availability score of 100%. Similarly, a load that is completely cut off from delivery of any energy during every instance of a sceanario simulated would have an energy availability of 0%. Referencing Figure 2, the energy availability for this case would be equal to $\frac{(A+B+D)\times 100\%}{A+B+C+D}$.

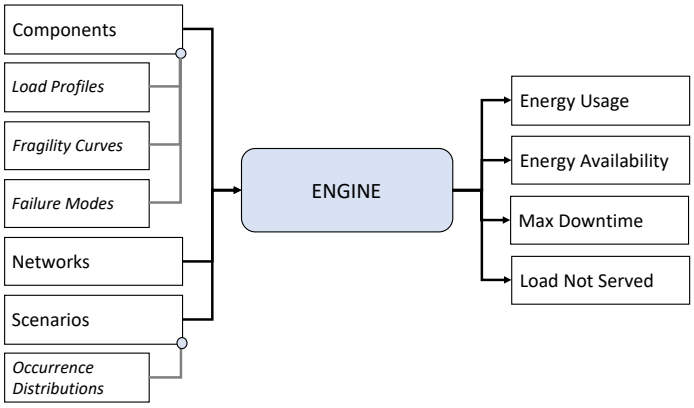

Figure 1 Input to and output from the resilience calculation tool engine. The major inputs are the components (equipment to simulate), networks (information for how component outflow ports connect to other component's inflow ports), and scenarios (the "blue-sky" or design basis threat events to simulate). Components can require load profiles, fragility curves, and failure mode information. Scenarios also require occurrence distributions to determine how often they occur. Key outputs include the energy usage, energy availability, max continguous downtime, and load not served. These outputs are given by load and by scenario.

The metric for maximum contiguous downtime, $t_{mcd}[L,S]$, is a measurement of the longest continuous stretch of time for which the load is not fully satisfied (i.e., disrupted or "down"). It is measured in a time unit such as minutes or hours. The maximum of all of the contiguous downtime durations is given as the maximum contiguous downtime. Referencing Figure 2, the maximum contiguous downtime is $t_1 - t_0$. The equation for $t_{mcd}[L,S]$ has been elided as it is easier to describe verbally and graphically than in equation form.

Finally, the metric, $LNS[L,S]$, yields the load not served. This metric is a measurement of the total energy not delivered to the given load for all occurrences of the given scenario. The equation for load not served is given by Equation 6; load not served is the integral over all scenario time for the difference between requested load, $P_R[L,S](t)$, and achieved load, $P_A[L,S](t)$. Referencing Figure 2, the load not served would be equal to C.

$$EA[L,S] = \frac{E_A[L,S]\times 100\%}{E_R[L,S]} \quad (1)$$

$$\text{LNS} = \int_{t=t_0}^{t_{end}} (P_R[L,S](t) - P_A[L,S](t))\, dt \quad (2)$$

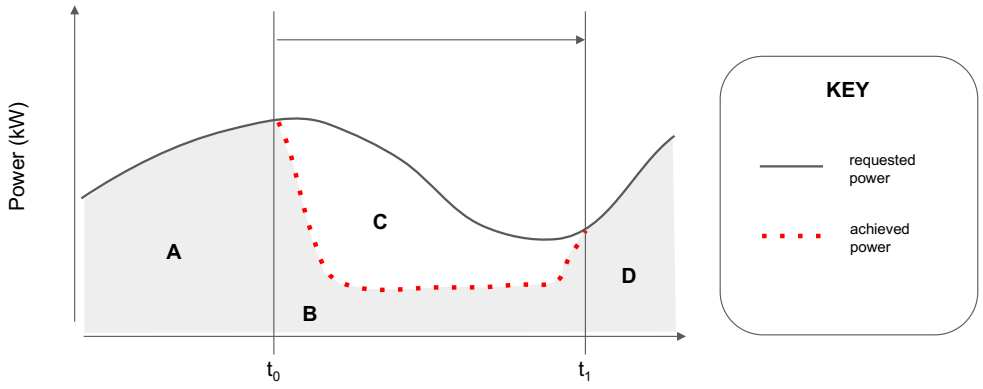

Figure 2 A load profile with power in the vertical and time in the horizontal depicting power disruption from time t_0 to t_1. The integrated energy under the curve is given by regions A (below the solid line up to t_0), B (below the dotted line), C (the blank area between the dotted and solid lines), and D (below the solid line from t_1 to end).

DISCUSSION

The engine presented in this paper is currently being applied to real district systems to assess resilience versus design basis threats. Real-world experience will be used to enhance our design. In addition to the calculation procedures presented here, additional processing capabilities will be required to handle the economic considerations (purchase, installation, maintenance, and operational costs plus time value of money). In addition, in order to handle the concept of mission readiness as presented by Jeffers and Wachtel (et. al. 2020), some post-processing capability will be required that would use outputs from our engine. For example, if mission readiness requires at least 80 beds for housing of personnel during a class 4 hurricane DBT and we have a campus with three dormatories – A, B, and C – with 40 beds each, our engine can predict how often loads are disrupted to any of the dormatories, but a post-processing step is required to determine if the *mission* succeeded. In this case, the mission of housing personnel succeeds any time two or

more of the three dormatories are operational.

The engine we have created is currently aimed at technical personnel. A Microsoft Excel User Interface is available to allow such personnel to use the engine without the need to directly write and edit the TOML input file or otherwise deal with running command line programs; outputs of the engine are pulled directly back into Excel, as well, which allows engineers to work from the comfort of a spreadsheet program to run the simulation engine discussed herein.

The data needs for the engine include component performance data, reliability data, and failure data. For the economics piece (not discussed here), cost data is required as well. Much of this data has been collected as part of the IEA Annex 73 efforts which included compiling a component technology database (IEA Annex 73 Website). Additional work is required to provide a user interface that is friendly to non-engineering personnel such as master planners.

Application to Resilience-based District System Architectue Selection

As part of the IEA Annex 73, a process was created to show how the engine discussed in this paper could be applied to assist a planner in selecting appropriate district energy system architectures, configuring them for their local situation, and assessing them for their costs, energy usage, and resilience benefits versus relevant design basis threats. The concept appears in Figure 3. Through this process, multiple architectures or different configurations of the same architecture (using different types or grades of equipment, for example) can be compared to each other for their cost, energy, and resilience to design basis threat. The process begins with the user's description of goals, site constraints and available resources as shown by the "happy face" in Figure 3. These criteria can be used to assist the user in selection (filtering out irrelevant choices and/or recommending especially relevant choices) and evaluation (tracking status of a design versus goals and/or constraints).

Next, the planner can proceed to architecture selection from a database of architectures. An architecture gives typical topological mappings to various network designs that are typically used in practice. Architecture selection can be guided by site criteria. For example, if the user specifies that they have electrical and heating loads only (i.e., no cooling load), only those architectures with heating and electrical supply will be made available to browse from. The architecture, once selected, must also be configured to match the user's unique situation. Configuration involves adjusting the selected architecture to better represent the desired situation by choosing specific equipment, specifying multiples, etc. Potential component technologies that fit with the architecture are looked up in a database of technologies. This results in the creation of an input file to be used by the engine.

Optionally, a user may desire to do a sizing study to evaluate the trade-offs between several combinations of potential component sizes as shown in the top right of Figure 3. External tools such as *NZI Opt* or *REopt* can be used to determine the most economical size of a component mix.

Once the architecture selection, configuration, and any sizing has been conducted, an input file can be written for the engine. When the entire simulation of all scenarios completes, energy availability, energy use, and energy cost as well as the energy availability and max downtime for different loads during different threats can be calculated. These metrics can be compared to goals to identify gaps or progress toward a goal. If sufficient progress has not been made, information from the last run can be used to enhance a subsequent architecture selection and configuration and the process can continue.

CONCLUSION

We have presented an engine that can be used to simulate district energy networks for their resilience against various design basis threats. This work showcases a novel approach that incorporates topology, building-by-building loads, multiple interacting energy flows, reliability-based failures, and fragility-based failures. We have further discussed a process for using the engine in a higher-level resilience-based energy master planning framework. Application of the engine to actual communities is currently under way.

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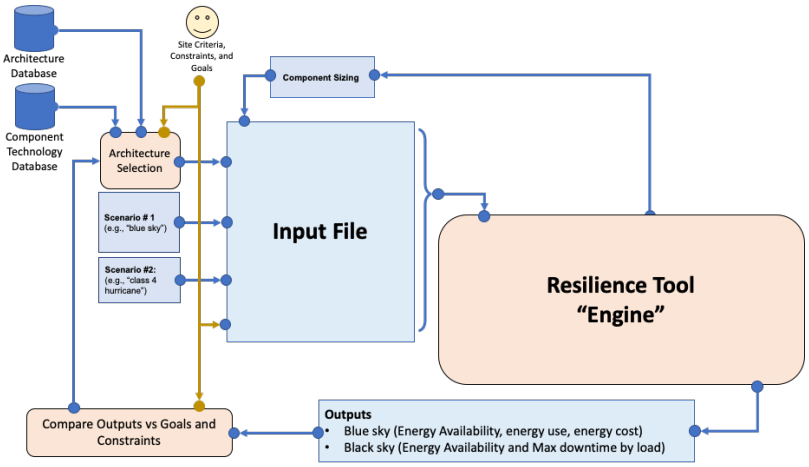

Figure 3 IEA Annex 73 Design Overview for a Resilience-based Assessment of District System Architectures.

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