ReNCAT: The Resilient Node Cluster Analysis Tool

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ABSTRACT

ReNCAT is a software application that suggests microgrid portfolios that reduce the impact of large-scale disruptions to power, as measured by the Social Burden Metric. ReNCAT examines a power distribution network to identify regions that can be isolated into microgrids that enable critical services to be provided even if the remainder of the study area is left without power. ReNCAT operates on a simplified representation of the power grid, one that aggregates and approximates loads and conductors. Microgrids are formed within the power network by setting switch states to split or join portions of the grid. ReNCAT identifies candidate microgrid portfolios with varying tradeoffs between cost and service availability.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
DBT	Design Basis Threat
FEMA	Federal Emergency Management Agency
GA	Genetic Algorithm
ReNCAT	Resilient Node Cluster Analysis Tool
DER	Distributed Energy Resource

1. RENCAT OVERVIEW

When power generation, transmission, or distribution infrastructure is damaged or disrupted, the electric grid becomes incapable of serving its usual customers. The duration and degree of the outage will be case-specific. Without decentralized generation options and control (switching), customers must wait until the entire service area is functional before power is restored. This can take considerable time and interrupt critical services. Additionally, because many infrastructure systems are interdependent and rely on power availability, a full grid outage will prolong the recovery process by inhibiting the ability of communications or transportation systems to be utilized in grid restoration. By contrast, if power can be provided to small, isolated regions within the service area, then it is possible to serve some critical loads, provide some critical services, and facilitate system-wide recovery, even before power has been restored to the entire service area. Doing so requires the islanded area to form a 'microgrid': a group of interconnected loads and distributed (localized) energy resources that act as a single controllable entity. Microgrids can mitigate extended-duration outage events by minimizing the impact of power and service loss to people [1].

Selecting the right portions of the electric grid to turn into self-sufficient microgrids is challenging. Powering all demands with microgrids and achieving total redundancy is cost prohibitive. Targeted upgrades must be economically viable and must provide measurable benefit to the community. These objectives can be met if critical service availability (e.g., availability of food, shelter, medical care, drinking water, and other critical needs) is used as the driving goal in siting and upgrade decisions. Powering locations that provide critical services that will be in high demand during an outage is key. These locations should ideally be close to people relying on the services, with service availability equitably distributed across the study area.

One way to assess critical service availability is with the S*ocial Burden Metric,* which was developed by Sandia National Laboratories and quantifies the burden a population experiences when attaining services needed from critical infrastructure [2-3]. This metric approximates the *effort* each person in the study area must expend to acquire needed services and is normalized by their *ability* to obtain those services. The Social Burden Metric considers the geospatial distribution of people within the study region, their ability to absorb additional cost and inconvenience, and their distance to service-providing facilities. Applied to microgrid planning, it is a measure of effectiveness and equity. The Social Burden Metric measures how well a microgrid portfolio (a set of one or more microgrids) serves the population in its service area.

The ReNCAT software application was developed by Sandia National Laboratories to assist communities in optimizing equitable energy resilience through islandable electrified clusters (e.g., microgrids). ReNCAT uses a genetic algorithm (GA) to analyze the distribution system and determine optimal placement of microgrids to ensure critical services remain available to the community most equitably during grid outages. ReNCAT identifies a suite of microgrid portfolios that minimize Social Burden at various price points. Decisionmakers examine the collection of portfolios suggested by ReNCAT to understand tradeoffs between financial cost and Social Burden, and to identify a balance that may be acceptable to the community. A key feature of ReNCAT is understanding how critical services map to critical infrastructure. ReNCAT can also be used as a stand-alone Social Burden calculator (in absence of detailed electrical system data) to assess the relative benefit of pre-selected sets of powered infrastructure, based on service levels and population data.

ReNCAT is a desktop application that runs on Windows operating systems. It is available to be used by government, educational, and commercial organizations.

2. THE RENCAT MODEL

ReNCAT identifies microgrid portfolios that can partially mitigate the loss of critical services during a large-scale power disruption. A ReNCAT model represents a community and its ability to access critical services directly after a disruptive event has impaired some or all the electric grid's normal operational capabilities. ReNCAT explores the power system topology to identify various microgrid portfolios that can improve access to services, each with its own tradeoff between cost and Social Burden. To support this analysis, ReNCAT requires data about the power distribution system, service-providing infrastructure, and the population in the study area.

2.1. The Distribution Network

ReNCAT works from a simplified representation of a power distribution system, one that focuses on how various parts of the distribution network are connected to each other, and how sections may be isolated from the rest of the distribution network to form microgrids.

The distribution network topology is represented as a set of power line sections connected by switches. A power line section is a portion of the distribution network that should be treated as a unit when deciding what regions should be powered by microgrids. A switch is a point in the distribution network that is a candidate for a microgrid boundary. These elements can be seen in the diagram below, where colored lines represent power line sections, and white squares represent switches.

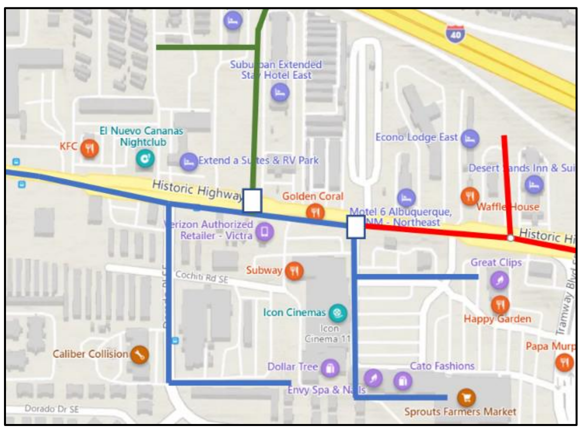

Figure 1. Sample Representation of Distribution Topology

2.1.1. Candidate Microgrid Boundary Points (Switches)

A switch represents a potential microgrid boundary in the distribution network topology. Each switch is an optional connection between two power line sections. If the switch is closed, the two sections are connected and power flows freely between the two sections; if the switch is open, the two sections are not connected at that point and the flow of power is halted. Switches can represent existing switch locations, or they can represent a candidate location for a new switch with an associated installation cost.

Microgrids are formed by opening and closing switches. Starting from any point in a microgrid, everything that can be reached by traversing a closed switch is part of the same microgrid. Open switches mark the microgrid's boundary.

Analysts provide the cost of opening or closing each switch. The cost and its meaning depend on what the switch represents. For example, a switch in the ReNCAT model that represents an existing real-world switch that is normally closed may have zero cost to close (because it is already closed), and a minimal non-zero cost to open (representing the cost of operators opening the switch). Another switch might represent a proposed new switch location. The cost to open this switch would be high because it represents the cost to acquire and install the new switch. The cost to close the switch would be zero because it represents the decision to NOT install a new switch at this location. Costs to upgrade manual switches to automated switches can also be captured in the model.

2.1.2. Power Line Sections

A segment of the distribution network between switches is called a power line section. Figure 1 above has three power line sections, colored red, green, and blue. One ReNCAT power line section typically represents many individual lines in a power flow model or one line diagram.

ReNCAT considers each power line section as a unit. If ReNCAT determines that a power line section is part of a microgrid then the entire section will be powered. If it is not part of a microgrid then the entire section will be left without power. The optimization will additionally determine whether or not to power the aggregated noncritical load on a microgrid power line and whether to selectively drop any critical loads. This determination is made by comparing the cost associated with dropping the loads to the cost of the generation needed to power them as part of the microgrid.

2.2. Infrastructure and Services

ReNCAT takes a services-forward view of power planning. Microgrid placement and investment decisions are guided by their impact on the provision of critical services. To assess how a microgrid portfolio impacts access to critical services, ReNCAT requires information about services and the infrastructure points that supply them.

2.2.1. Critical Services

A critical service is a category of need essential to human health and safety. These are services that are most important to sustain during an emergency event when the electric grid is partially or fully unavailable to power the critical infrastructure that provide those services.

While many core services will be widely applicable – such as food, water, shelter, and medical services – other services may vary with the context of the analysis. Community preferences, the details of the resilience event (e.g., likely duration of an outage), and the goals of the study may all influence the set of critical services included in a ReNCAT analysis. Communities are encouraged to thoroughly consider the working definition of critical services – those services which the community is least prepared to go without and draw up their lists of critical services accordingly.

Critical services which have been most commonly used in past and ongoing ReNCAT studies overlap in part with FEMA's lifeline services [4]. Critical services included in a ReNCAT analysis may include many FEMA lifeline services but can also include other services that the community and stakeholders determine to be critical to keep online during a grid outage. For example, a ReNCAT analysis may opt to consider electric vehicle (EV) charging a critical service for a study looking at the resilience of an area with widespread EV adoption and a high risk for coastal flooding and subsequent large-scale evacuation. Critical services in ReNCAT can be customized for each analysis based on localized needs.

2.2.2. Infrastructure Locations (Facilities)

Services are provided at infrastructure locations called facilities. Each facility is assigned a category, such as gas station or grocery store. The facility's category determines what services it provides, and at what level. A facility can represent a building (e.g., a hospital), an asset (e.g., a cell tower), or another infrastructure component (e.g., a traffic signal power supply) that provides one or more services and requires power to do so. The analyst and stakeholders determine which types of facilities should be included in the model for a given area.

Each facility is associated with a specific power line section. If the facility's line section is part of a powered microgrid, then the facility receives power and provides its services. A powered facility reduces Social Burden for the study area, especially for those who live close to the facility. Facilities whose line section is not part of a microgrid do not receive power, cannot provide services, and do not reduce Social Burden.

Each facility has a power load it imposes on its microgrid. Facility loads are among the factors considered when purchasing microgrid generators. The availability of critical services is directly determined by which facilities have power.

2.2.3. Service to Facility Mapping

Each facility is assigned a category. For each facility category, the analyst (based on stakeholder input) indicates which critical services that category supplies, and at what level. Remember that types of services can be customized for a given area based on local needs and priorities.

A single facility may provide several services at once (e.g., gas stations may provide fuel, water, and food at various levels). Likewise, the same service can be provided at multiple facility types (e.g., water and food may be available at both grocery stores and gas stations). Among different facility categories that supply the same type of service, the level of service can vary. Some of the considerations for determining the level of service include how many people the facility could serve, and if applicable, how much supply the facility has and how long it would last. Service levels are assessed from the viewpoint of how much service they provide to the community at large. A fire station may have ample shelter, food, and water for the firefighters who the facility is designed and stocked to house during normal operating conditions. However, that same supply of shelter, food, and water can fulfill only a fraction of the entire community's needs. Therefore, the service levels assigned to the fire station would be ranked low.

2.3. Threats

ReNCAT is a threat-informed analysis tool, meaning that it can take into account a user-defined Design Basis Threat (DBT) and recommend microgrid portfolios that are designed to address the anticipated outage duration, area of impact, and facility damage. Threats that should be considered for inclusion in a ReNCAT model are those that impact resilience and are considered to be low probability but high consequence. These might include natural hazards like flooding, wildfires, or hurricanes, or threats by malicious actors, like a cyberattack. A threat which is expected to damage facilities or make certain regions inaccessible can be modeled using an inclusion profile – an analyst-specified list of facilities that are eligible for potential inclusion in microgrid portfolios. Analysts may develop multiple inclusion profiles for the same region, although only one profile may be applied to each optimization run. If no inclusion profile is specified by the analyst, ReNCAT defaults to considering all facilities eligible for potential inclusion in microgrid portfolios.

2.4. Population Data

Attaining critical services may require certain members of the community to travel further than others in search of available facilities. Furthermore, some subsets of the population may be better able to absorb disruptions than others. ReNCAT requires information about the people in the study region so these factors can be incorporated into the analysis.

The study area is divided into population blocks. A population block represents the people living in a particular region within the study area. They often correspond to census block groups, though other levels of granularity may be used as well. The number of people living in each population block enables ReNCAT to consider how people are distributed within the study area. The distance between the centroid of each population block and facilities providing critical services is used as a proxy for the effort required to obtain critical services.

To account for differences in people's relative ability to absorb additional travel, cost, and disruption as they acquire services, analysts must assign a numeric *attainment factor* (the "ability" parameter of Social Burden) to each population block in the ReNCAT model. Population blocks with a lower attainment factor experience a greater increase in social burden when critical services become harder to obtain. Past ReNCAT studies have often used median household income as the attainment factor. However, other quantitative metrics can be used instead, provided they estimate the distribution of different people's abilities to absorb additional travel, cost, and disruption.

Social Burden scores are calculated for each population block, influenced by the block's proximity to service-providing facilities (the "effort" parameter of Social Burden), and the block's attainment factor. Block Social Burden scores are added together to find the total Social Burden for the study region. This approach allows ReNCAT to prefer portfolios whose microgrid locations reflect the population distribution, and those that better support vulnerable populations with less ability to attain critical services. Thus, the algorithm seeks out portfolios that are both spatially and equitably distributed according to the local population.

2.5. Loads and Power Generation

Each microgrid must have enough generation capacity to support all loads placed on it. Loads are tracked in two categories:

- *Facility loads*. Each facility imposes a critical load on its associated power line section.
- *Non-facility loads*. Each power line section has an aggregate non-facility (i.e., non-critical) load. This is a single value that represents the sum of all loads served by the line section, other than facility loads.

Each microgrid must have enough generation capacity to support all facility and non-facility loads for all its power line sections. Microgrids may use existing generators if present in the model and attached to the microgrid. If existing generators are insufficient, then new generators may be purchased. Analysts provide the cost and capacity of generator purchase options. ReNCAT can support both discrete and continuous generation options.

Another way to balance loads and generation is to disconnect one or more non-critical loads to reduce the total load on the microgrid. Analysts determine which non-critical loads may be disconnected, and what cost will be incurred for doing so. Critical facility loads may also be disconnect-eligible, though disconnecting a critical facility from a powered microgrid will increase

Social Burden. The analyst can choose, on an individual facility basis, whether to make that facility disconnect-eligible and the cost that will be incurred to disconnect it.

ReNCAT always chooses the least expensive combination of generator purchases and load disconnections that ensures the microgrid's generation capacity meets or exceeds its loads.

ReNCAT does not do any power flow (time-series analysis) modeling. Instead, it simply ensures that the sum of generation capacity is greater than the sum of loads for each microgrid that is powered.

3. MICROGRID PORTFOLIO OPTIMIZATION

The ReNCAT optimization is implemented as a genetic algorithm (GA). The GA works by generating a large set of candidate microgrid portfolios, where each candidate portfolio consists of an arbitrary number of microgrids placed at arbitrary locations. ReNCAT assesses the quality of each candidate portfolio, then uses what it learns to generate a new batch of portfolios. It repeats this process over many generations of candidate portfolios. Each generation is less random than the generation before, and eventually converges on a set of candidate portfolios that are best at reducing Social Burden at various cost points.

Each candidate portfolio goes through a three-step evaluation process:

1. *Generate the candidate portfolio.* The GA generates a microgrid portfolio, identifying switches to open or close to isolate portions of the distribution network. Some isolated regions become microgrids—areas within the study region that have power. Regions outside of microgrids are left without power.
2. *Balance generation and demand*. Each microgrid in the portfolio must have enough generation capacity to satisfy the microgrid's loads. Generation and demand are balanced by buying additional generators and/or disconnecting non-critical loads from power line sections. ReNCAT will always choose the least expensive combination of these actions that satisfy this constraint.
3. *Calculate cost and burden*. The total cost is the cost of the decisions made by the load balancing heuristic, and the cost of opening or closing switches as dictated by the microgrid portfolio. Burden is determined by which facilities have power relative to the location of the population and their demographic characteristics.

ReNCAT continues to generate and assess new portfolios until the algorithm can no longer find improvements.

3.1. Microgrid Formation

Microgrids are determined by choices made by the GA. The GA makes two sets of choices. First, it chooses whether each switch will be open or closed. Secondly, the GA chooses certain facilities to act as microgrid "seeds". The GA's choices are initially random. As the algorithm progresses, the GA makes these choices based on earlier choices that had good outcomes in previous generations.

Microgrids are formed based on the GA's choices. Starting with a "seed" facility, ReNCAT marks the facility's power line section as belonging to a microgrid. Any additional line sections that can be reached by traversing closed switches are also marked as belonging to the same microgrid. This process is repeated for each seed facility that is not already in a microgrid.

Figure 2. Example of Microgrid Formation

Figure 2 demonstrates how a microgrid (serving facilities in the blue shaded region) is derived from switch states and seed facilities. The Motel 6 on the red power line section has been selected by the GA to be a seed facility. The red line section is in the microgrid because it has a seed facility. The blue line section is also in the microgrid because it can reach the red line section by traversing a closed switch (the filled in blue square). The green line sections are NOT in the microgrid because there are no closed switches connecting them to the red or blue line sections (the open squares are open switches).

3.2. Objective Functions

ReNCAT performs a multi-objective optimization, where the two objective functions are cost and Social Burden. As the GA assesses a new candidate microgrid portfolio, it evaluates both objectives and then compares the results against the best (Pareto-optimal) candidates it has encountered so far. If the new candidate compares favorably, it is included in the set of best candidates and may cause previous candidates to drop out of the "best" list. If it compares unfavorably it is discarded. Here, favorable performance means that a given portfolio decreases Social Burden at a set cost point, or decreases cost for a set Social Burden point as compared to a previous solution with that same cost set point.

3.2.1. Cost

The first objective function is cost, which ReNCAT strives to minimize. Costs in ReNCAT represent one-time, new capital investment costs and do not capture O&M costs. The cost of each portfolio is the sum of the following components:

1. The cost of opening and closing switches
2. The cost of purchasing sufficient generation for each microgrid to satisfy its loads
3. The cost of disconnecting non-critical and/or critical loads

Each switch in a ReNCAT model has an associated dollar cost when closed and dollar cost when open. A conceptual discussion of switches and their costs is given in 2.1.1. At a high level, these two cost categories are based on the typical state of existing switches (open or closed), the cost of installing switches that don't currently exist, and upgrade costs to automate switches that are currently manual switches.

To power the microgrids within each portfolio, ReNCAT must purchase generation if existing generation is insufficient to meet demand. As described earlier, analysts can specify both discrete and continuous generation options in ReNCAT. The costs for discrete generation are tied to specific generator types and sizes, as specified by the analyst. ReNCAT will choose the least cost generator or combination of generators that meet the demand of a given microgrid. Continuous generation options in ReNCAT are specified as a dollar cost per kilowatt and the optimization will choose to purchase enough generation to power the microgrid, rounding to the nearest kilowatt that still covers the full demand.

Both non-critical and critical loads can be specified in the model to be disconnect eligible. If an analyst specifies that a non-critical load can be disconnected, they specify the associated cost for the entire aggregated non-critical load at the power line level. That disconnect cost should consider the number of loads contributing to that aggregate, the types of loads (i.e., residential versus commercial), and any anticipated costs to make disconnection possible (such as building-level switches). Critical loads are already associated with a single infrastructure asset, so disconnect eligible loads should account for the cost of additional equipment purchases needed to disconnect that load. ReNCAT will choose to drop loads if the cost is less than the cost of the additional generation needed to power the loads for a particular level of Social Burden.

3.2.2. Social Burden

The second objective function is Social Burden, which like cost, is also minimized by ReNCAT within the optimization. Social Burden represents the relative hardship people experience in the process of acquiring needed services [2]. Accessing services requires physical effort, time, expenditure of money, and other hardships and tradeoffs. Social Burden is comprised of several components. One component is the effort (typically Euclidean distance) associated with travel to a facility that provides a needed service, which can also include effort while at the facility such as waiting in line. Another component of Social Burden is the ability (typically median household income) of residents to acquire resources once at the service-providing facility, such as having to pay for the service. Social Burden is used in ReNCAT as a resilience metric, quantifying the human impact of loss of critical service availability following a major disruption to infrastructure resulting in electric grid outage. While Social Burden can be applied to dynamically changing situations, ReNCAT applies it statically, directly following a disruption to the electric grid.

Each person in the study area experiences burdens that depend on their location and their ability, both of which are treated as properties of the population block in which the person resides. Population blocks typically correspond to US census block groups [6]. Because per-person Social Burden values are the same for every person in a block, but vary between blocks, they are known as block-level Social Burden values. There are two types of block-level Social Burden values: block-level Per-Service Social Burden and block-level Overall Social Burden. A block-level Per-Service Social Burden is the per-person Social Burden for a specific service in a particular population block. Each block has a block-level Per-Service Social Burden value for each service. A block's Overall Social Burden is the sum of the block's Per-Service Social Burden values across all services. Both types of block-level Social Burden metrics are per-person.

Social Burden values for an entire study region are cumulative Social Burdens for all people in the study region. Like block-level Social Burden values, there are two types of Social Burden values for the study region: Per-Service Social Burdens (one per service type) and Overall Social Burden. Both types of regional Social Burden values are calculated by multiplying the corresponding per-person block-level Social Burden value for each block by the number of people in the block, then summing the per-block products. This effectively sums the Social Burden of every person in the study. It is this cumulative, overall Social Burden score that is used in the objective function.

4. OUTPUTS

A ReNCAT optimization run results in a set of candidate microgrid portfolios. Each portfolio consists of one or more microgrids, where each microgrid provides power to a region within the study area. Regions outside of a microgrid are left without power. The microgrids in a portfolio work together to reduce Social Burden across the study area.

Each microgrid consists of power line sections connected by closed switches, with open switches at the microgrid boundaries. Infrastructure facilities associated with the microgrid's power line sections receive power from the microgrid. Each microgrid has enough generation capacity to satisfy its facility loads and its non-critical line section loads that have not been disconnected.

Each candidate portfolio has a different balance between cost and burden. A portfolio with a higher cost has a lower burden. Plotting all portfolios results in a Pareto frontier of Pareto-optimal portfolios shows the tradeoff between cost and burden.

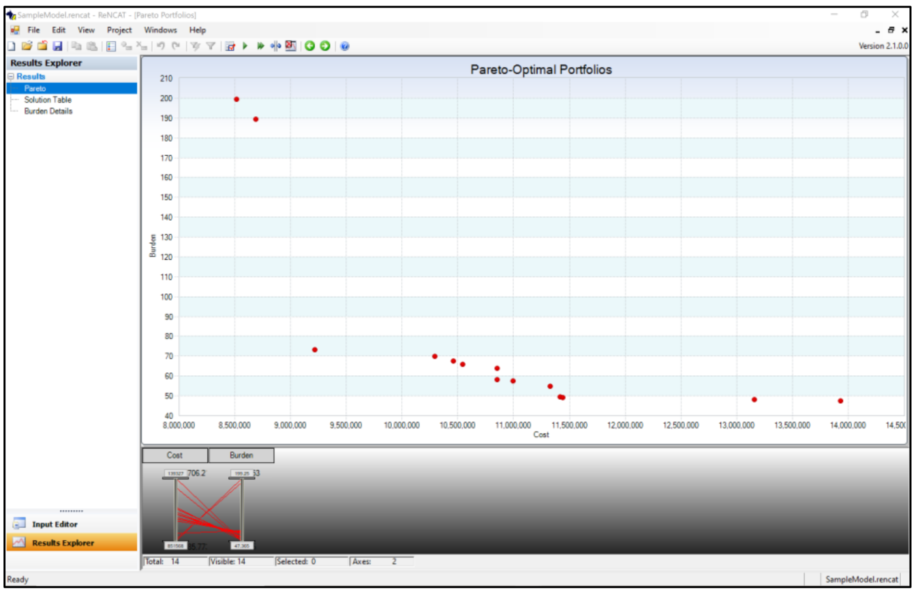

Figure 3. Example Pareto Frontier of Candidate Microgrid Portfolios

ReNCAT also provides detailed output for each portfolio including the number of microgrids in each portfolio, the cost, estimated Social Burden, the state of each switch in the model with any associated costs incurred, and which facilities are powered. Additionally, ReNCAT provides valuable detailed Social Burden data for each portfolio allowing the analyst to explore every component of Social Burden including the distance and effort for each powered facility; level of services for each facility category; attainment factor, population, and block-level Overall and Per-Service Social Burdens for each population block; aggregated region-wide Per-Service Social Burden for each service type across population blocks; and region-wide Overall Social Burden for the study area.

5. THE SOCIAL BURDEN CALCULATOR

In addition to its optimization capabilities, ReNCAT can also be run as a calculator. A sub-module of the ReNCAT application is the Social Burden Calculator. The Social Burden Calculator can be run from within the ReNCAT user interface, or as a command-line tool. When run from the ReNCAT user interface, analysts can select facilities with power in a particular scenario, and ReNCAT will display the overall Social Burden for that scenario. When run from the command line, the Social Burden Calculator generates full detailed output, including total-, by-group, and by-sector burden scores based on the availability of critical services input by the user. This functionality does not require extensive information about the electrical distribution system. The calculation is applicable to "blue-sky" conditions when all existing facilities are assumed to be powered and providing services at their baseline levels. It can also be used to calculate burden for "black-sky" conditions by selecting only the facilities that are expected to be powered by microgrids or other backup generation during a resilience event. This approach can be used to evaluate existing proposals or to determine which facilities in each service category contribute to the largest reduction in Social Burden when powered during a grid outage.

6. PRIOR APPLICATIONS

ReNCAT has been applied in a number of projects, both completed and ongoing. Projects have focused on understanding how to make investments to improve resilience in a geographically optimized and equitable way, while balancing the costs of those investments with inevitable budget constraints. A sampling of previous projects includes:

1. Puerto Rico: ReNCAT was used to identify potential microgrid locations in San Juan and across the entire island while incorporating threat profiles including flooding, high winds, landslides, and earthquakes [3]. Sandia has also partnered with the University of Puerto Rico Mayaguez, whose students and professors developed ReNCAT models for specific communities within Puerto Rico. The Social Burden of proposed scenarios for the Puerto Rican transition to 100% renewable generation is currently being evaluated.

2. New Orleans, Louisiana: ReNCAT was used to identify potential microgrids accounting for expected flooding throughout the city [6].

3. Pittsburg, Pennsylvania: ReNCAT-optimized microgrid locations were compared to planned investment projects within the city.

4. San Antonio, Texas: ReNCAT was used to assess a small area within the community to look at including EV charging stations as a critical service during grid outages that would need to be powered by microgrids.

5. Nags Head, North Carolina: ReNCAT was used as a calculator to identify clusters of service-providing facilities that present an efficient investment option with maximum benefit to residents (reduction in Social Burden). In this case, the demographics for census block groups were relatively homogenous, enabling validation of the service ranking process across a small area.

Communities face unique challenges in their pursuit of improved resilience due to geographic considerations, specialized infrastructure systems, and differences in population demographics. The use of ReNCAT in different study areas has underscored the importance of the tool's existing ability to customize scenarios, critical facilities, and critical services for each case study. Sandia researchers and partners continue to use ReNCAT to optimize microgrid placement and evaluate Social Burden in communities across the United States.

7. LIMITATIONS

While ReNCAT provides a unique method for identifying cost- and social burden-optimal microgrid investment alternatives, it also has certain limitations. Some of these limitations are the subject of ongoing research and may be integrated into subsequent ReNCAT releases in the future.

The way ReNCAT models the impact of distance on Social Burden may not match the real-world benefit of some facility types. The current implementation of ReNCAT does not limit the service area of any facility. Although the reduction in Social Burden decreases as one travels radially away from a facility, there is no fixed outer cut-off distance. In practice, certain services, such as municipal water and wastewater service, are provided within fixed service areas. It is not enough to simply travel to them to acquire the service, as may be the case with other services like food purchased from a grocery store. The difference in implementing services that are "delivered" such as water, cell phone service, etc. versus services that residents must travel to obtain, will be the subject of future research.

In addition, ReNCAT only provides critical services by powering existing facilities. Areas that are historically under-served even during blue-sky operations will remain under-served even if all facilities in the area are powered through microgrids. Rectifying these issues will require investing in new facilities, which is beyond the scope of what a ReNCAT analysis considers during optimization. However, by running several comparative models, it is possible to evaluate the effect of proposed facilities on Social Burden.

ReNCAT is limited in the types of investments it considers during optimization. Support is currently limited to investments that facilitate the formation of microgrids and hardening of express feeder lines. Supported microgrid investments include purchase of local generation, and switch investments that isolate subsections of the distribution network or permit load shedding. While other investments may be effective in improving a community's resilience, ReNCAT is not currently able to include them in its analysis. We intend to support other types of investments in future versions of ReNCAT.

Finally, ReNCAT does not directly seek to minimize variance of Social Burden scores across a study area, but instead seeks to minimize overall Social Burden regardless of how it varies across the study region. Variance in Social Burden at the census block group level may persist due to factors such as existing service locations or the configuration of the distribution system relative to where people are located.

8. CONCLUSION

ReNCAT is a tool that provides the capability to optimally site and size microgrids within a specified geographical area based on both cost and equity considerations. The inclusion of the Social Burden metric makes ReNCAT a first-of-its-kind tool to incorporate equity into the evaluation process by including Social Burden as one of the objectives in a multi-objective optimization. ReNCAT has already been used in multiple areas to help stakeholders and decision-makers understand the tradeoffs between cost and service accessibility within their communities while trying to maximize the benefit of resilience investments. Additionally, the team holds workshops and training courses focused on using ReNCAT and understanding Social Burden. Sandia continues to make usability and capability improvements to ReNCAT based on community needs and stakeholder feedback.

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APPENDIX A. DATA MODEL

A.1. Model Entities and Attributes

A.1.1. Power Line

Table 8-1. Power Line

Property	Description
Name	Unique identifying name or ID
Non-Facility Power Load (kW)	The sum of the electrical load of all buildings that are directly served by the power line, not including facilities
Is Disconnect Eligible	Whether the optimization is allowed to disconnect the line's non-facility load
Disconnect Cost ($)	The cost incurred if the non-critical load is disconnected from the line
R: Energized	Whether this power line is carrying electricity
R: Is Non-Facility Disconnected	Whether the line's non-facility load was disconnected
R: Effective Load	The load being served by this line, after any disconnections are considered

A.1.2. Switch

Table 8-2. Switch

Property	Description
Name	Unique identifying name or ID
Line A	One of the two lines connected by this switch (order doesn't matter)
Line B	The other of the two lines connected by this switch (order doesn't matter)
Cost If Open ($)	The cost incurred if the optimization chooses to open this switch
Cost If Closed ($)	The cost incurred if the optimization chooses to close this switch
R: State	Whether the switch is open or closed
R: Switch Cost	The cost incurred by this switch

A.1.3. Power Source (Generator)

Table 8-3. Power Source (Generator)

Property	Description
Name	Unique identifying name or ID
Generation Capacity (kW)	The maximum amount of power the generator can produce
Power Line	The power line the generator is attached to

A.1.4. Facility

Table 8-4. Facility

Property	Description
Name	Identifying Name
Category	The type of facility (grocery store, hospital, etc.)
Latitude/Longitude	The location of the facility
Line	The power line the facility gets its electricity from
Load (kW)	The peak power draw the facility requires
Is Disconnect Eligible	Whether the facility can be left unpowered
Disconnect Cost ($)	The cost incurred if the facility is left unpowered
Zero Distance Effort Parameter	Used in the burden calculation, the effort required to acquire this facility's services when no travel is required
Per-Foot Effort Parameter	Used in the burden calculation, the additional effort required to acquire this facility's services for each additional foot of distance
R: Powered	Whether this facility is receiving power

A.1.5. Population Block

Table 8-5. Population Block

Property	Description
Name	A unique identifying name or ID
Centroid (Latitude/Longitude)	The geometric center of the population block. The optimization algorithm will treat the block's entire population as if it lived at the centroid.
Weight	The relative importance of providing services to this block compared to other blocks (usually the block's population).
Attainment Factor	The relative ability of the block's population to retrieve services. Lower values represent a population that has a harder time traveling to reach facilities.
R: Burden	The burden for this population block. There is a per-service burden and total burden.

A.1.6. Service Mapping

For each facility category, the service mapping identifies the degree to which a facility of that category provides that types of service. An example is shown below:

Table 8-6. Service Mapping

Facility	Food	Shelter	Gas	Healthcare
Gas Station	Low	None	High	None
Grocery Store	High	None	None	Low
Warehouse Store	Very High	Low	None	None

Facility	Food	Shelter	Gas	Healthcare
Hotel	Low	High	None	None
Hospital	Low	Medium	None	Very High
Clinic	None	None	None	High

A.1.7. Candidate Topology

This is data about one complete candidate grid design. It obviously doesn't exist until results have been generated.

Table 8-7. Candidate Topology

Property	Description
R: Cost ($)	The total cost for the design, including the cost of opening and closing switches, disconnecting facilities, disconnecting non-facility power line loads, and purchasing new generation capacity
R: Burden	The value of the burden metric for the given topology. This is the sum of burden across all population blocks.
R: Disconnected Non-Facility Loads	Each power line with a disconnected non-facility load in this design
R: Unpowered Facilities	Each facility that disconnected from its subfeeder in this design
R: Powered Microgrids	The set of all powered microgrids, where each microgrid consists of a set of power lines that are connected to each other, with enough generation capacity to satisfy the microgrid's load
R: Unpowered Lines	The set of all power lines that are not part of a powered microgrid

A.1.8. Microgrid

This is data available for each powered microgrid in a candidate grid design. Microgrids only exist in results. They are only identified after switch states have been selected, so they pertain to a specific candidate grid design.

Table 8-8. Microgrid

Property	Description
R: Power Lines	The set of all power lines in the microgrid
R: Power Sources	All previously existing generators that supply power to the microgrid
R: Powered Facilities	Each facility receiving power through this microgrid
R: Disconnected Facilities	Each facility that was disconnected from a power line in this microgrid, and therefore left unpowered
R: Newly Added Generation Capacity (kW)	The amount of new generation capacity added to this microgrid

Property	Description
R: Newly Added Generation Cost ($)	The cost incurred to add new generation capacity to this microgrid
R: Generation Capacity (kW)	The total generation capacity for this microgrid, including both existing and new generators
R: Lines with Disconnected Non-Facility Loads	The set of all power lines in this microgrid whose non-facility load was disconnected
R: Total Cost ($)	The total cost of all aspects of establishing this microgrid, but not including switch costs. This includes facility disconnect costs, non-facility disconnect costs, and new generation capacity costs.
R: Facility Load (kW)	The load imposed by all facilities receiving power through this microgrid
R: Effective Load (kW)	The total load imposed on this microgrid, consisting of facility and non-facility loads that were not disconnected