Simulating Energy Resilience in District Energy Systems

Energy Master Planning for Resilient Public Communities Virtual Training

Michael O'Keefe

Big Ladder Software

October 14, 2020

Agenda

- Energy Resilience Calculation
  - Concepts
  - Simulator
  - Load Profiles, Data as a Great Decoupling Mechanism
- MS Excel User Interface
- Using IEA Annex 73 Resources in Concert
- Summary

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Overview of

Energy Resilience Calculation

Concepts

- Resilience, Design Basis Threat, and Resilience Metrics
- Components and Networks
- Scenarios: Blue-Sky and Threats
  - Duration
  - Load Profiles
  - Probability of Occurrence
  - Damage Intensities and Fragility Curves
  - Reliability: Failure and Repair Distributions

Resilience and Design Basis Threats

- Resilience: ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions.
- Resilience is contextual — defined in relation to a threat
  - Example, system resilient to hurricanes may not be resilient to earthquakes
- Threats to plan against are called Design Basis Threats (DBTs)
  - Natural disasters, accidents, and man-made threats
  - Planners must select the threats that are most applicable
  - Important to include low frequency / potentially high consequence threats

Watson, J.P., R. Guttromson, C. Silva-Monroy, R. Jeffers, K. Jones, J. Ellison, C. Rath, J. Gearhart, D. Jones, T. Corbet, C. Hanley, and L. Walker. 2014. Conceptual Framework for Developing Resilience Metrics for the Electricity, Oil, and Gas Sectors in the United States. Sandia National Laboratories Report. SAND

Jeffers, B., Wachtel, A., Zhivov, A., Thompson, C., Srivastava, A., and Daniels, P. 2020. Integration of Resilience Goals into Energy Master Planning Framework for Communities. ASHRAE 2020 Winter Conference. Transactions 2020. Vol 126, pt1.

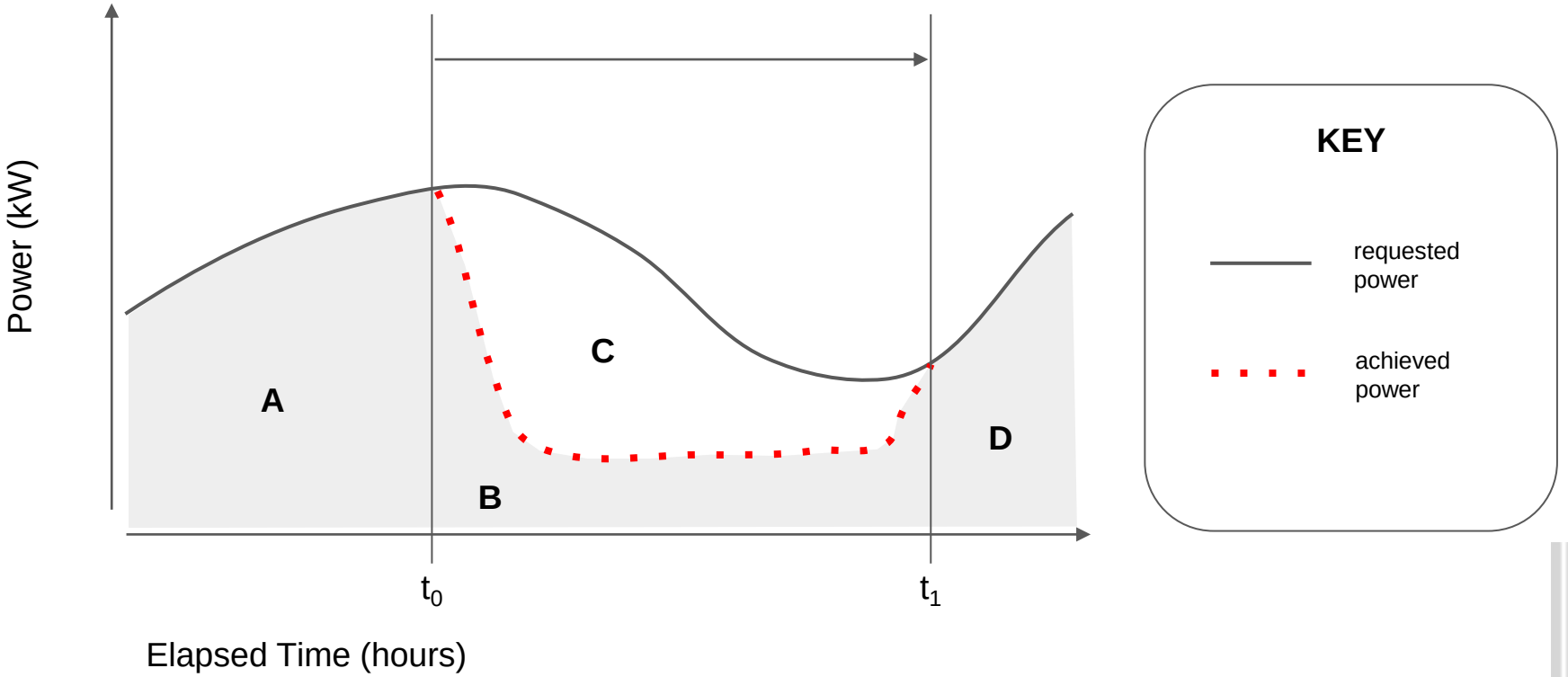
Resilience Metrics

(calculated ***by load***)

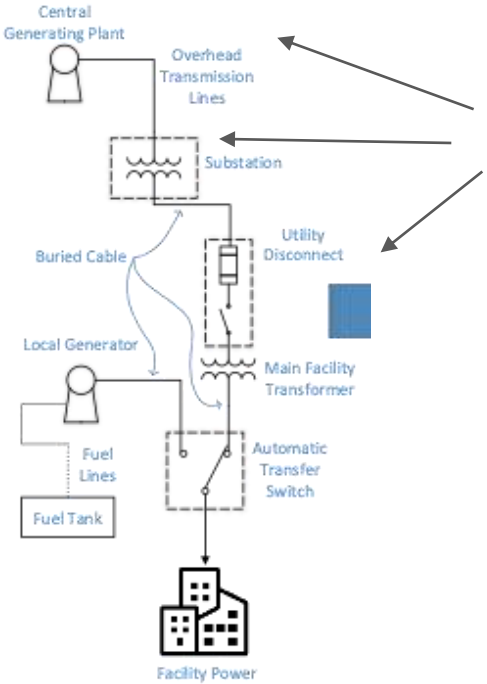
Energy Availability (%) = [(A+B+D) x 100%] / (A+B+C+D)

Max Downtime (hours) = $t_1 - t_0$

Load Not Served (kWh) = C



Components and Network



Components

How they're connected forms the network (topology)

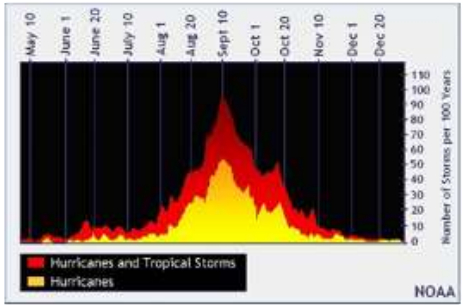
Example Scenario: Category 3 Hurricane

Intensities:

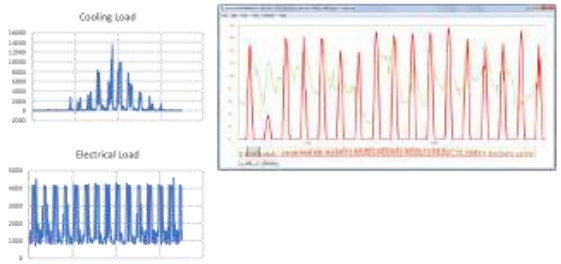
inundation (flooding):
X feet (from GIS flood plane analysis)

wind speed:
125 mph (from category 3 classification)

Probability of Occurrence:



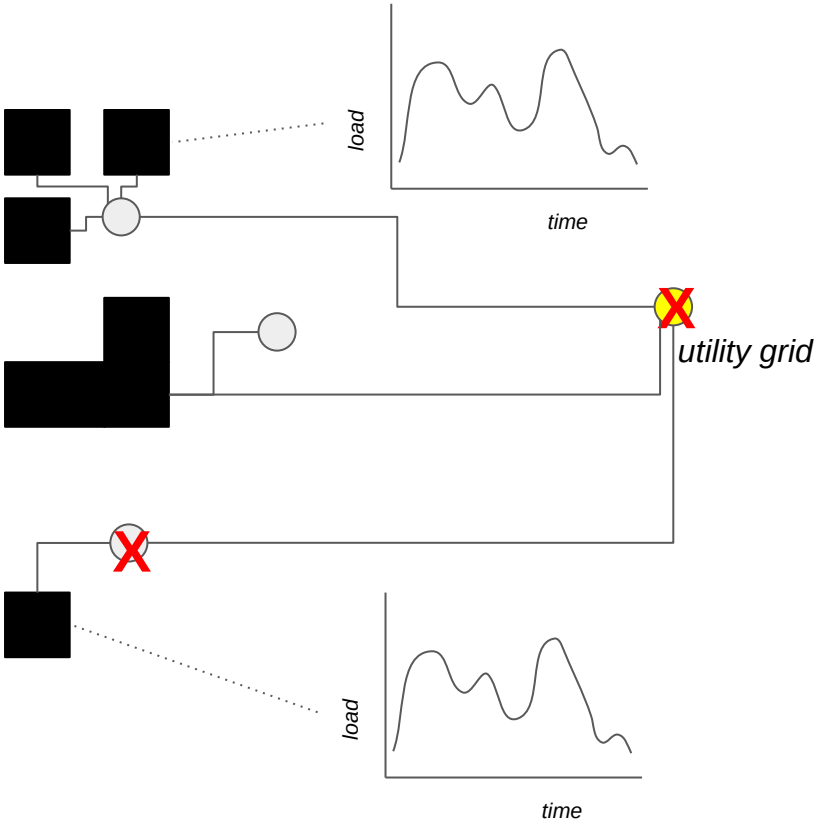
Weather and Loads:



A ***scenario*** has a:

- duration
- load profiles
- probability of occurrence
- maximum occurrences
- damage intensities
- a network to simulate
- whether to calculate reliability

Components and Networks are Simulated over Scenarios that May Involve Failure

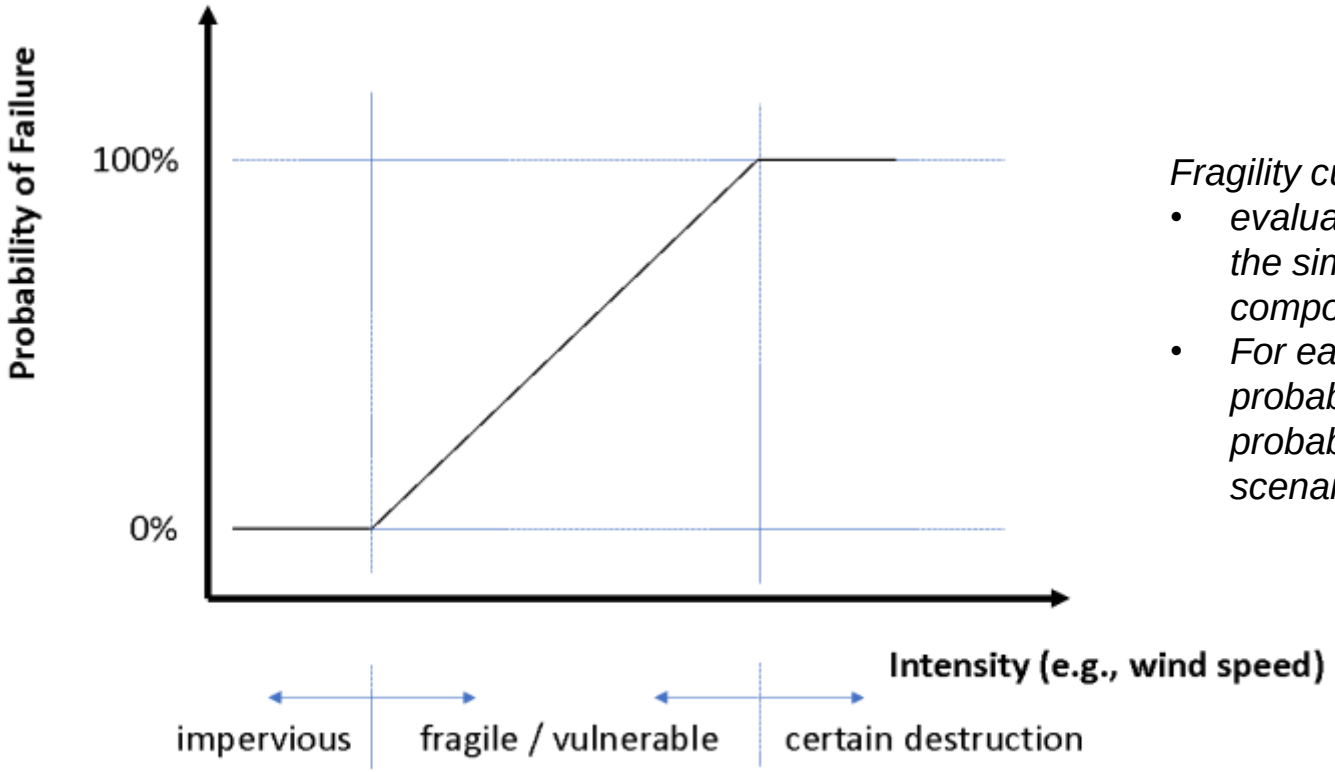


Two Types of Failures Considered

- Design Basis Threat based failures:
  - *failure due to extreme event*
  - “fragility” → “Fragility Curve”
  - Component is “failed” for the entire scenario
  - Assessment made at scenario start

- Reliability:
  - *failure due to routine wear and tear*
  - “reliability”→ “Failure Mode”
  - Component is “failed” until repaired
  - Assessment is made throughout simulated time
  - Reliability statistics are probably not accurate for extreme event stresses

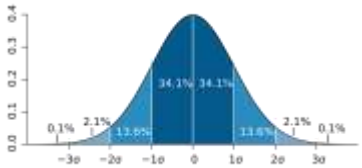
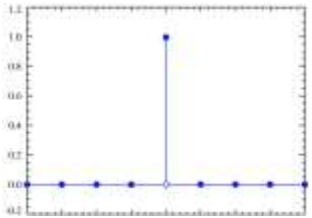
Fragility Curve in Concept: Maps Failure Probability to Various Damage Intensities From the Scenario…



Fragility curves:

- *evaluated at the beginning of the simulation for each component in a scenario*
- *For each component having a probability of failure, that probability is evaluated a scenario start.*

Reliability: Statistical Models of Failure Modes

Failure Mode	Failure Distribution	Repair Distribution
Starter battery dies	NormalDistribution(mean=1000 hours, stdev=100 hours) 	FixedDistribution(4hours) 

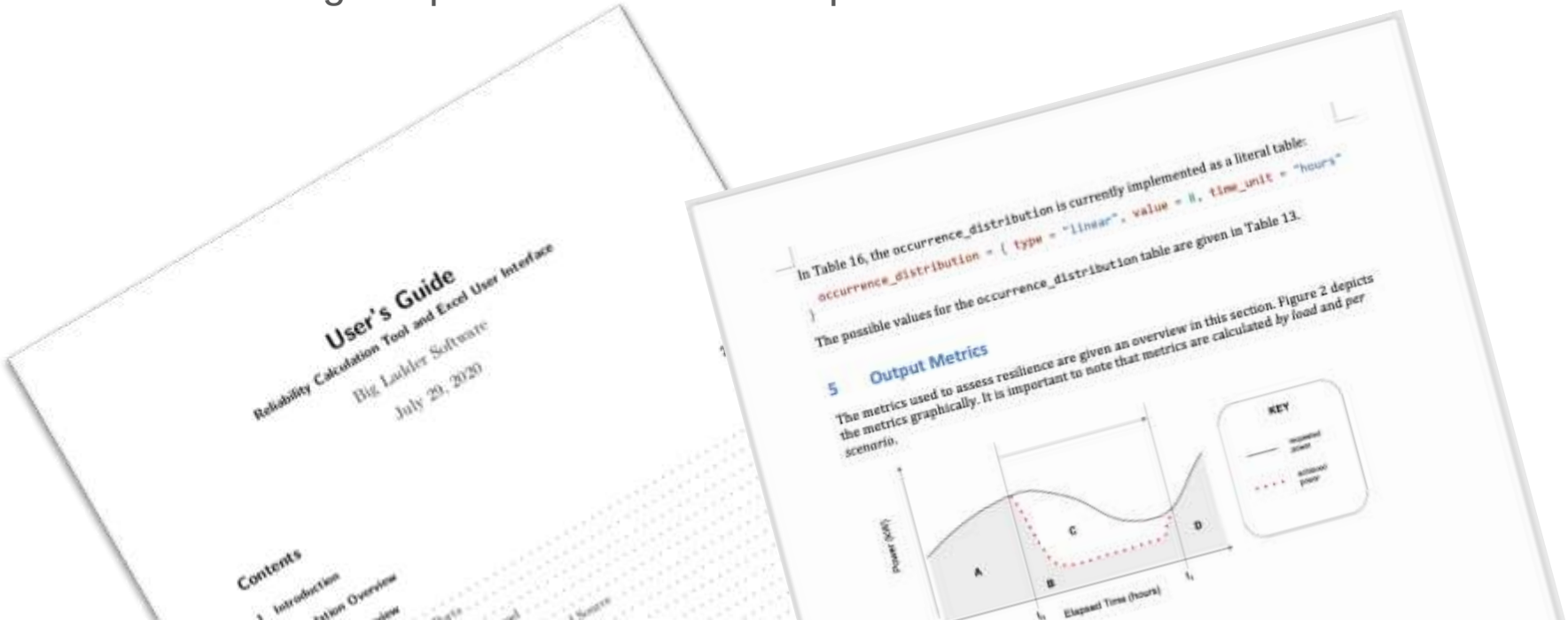
Reliability is only calculated if requested during a scenario and if at least one component has failure mode data.

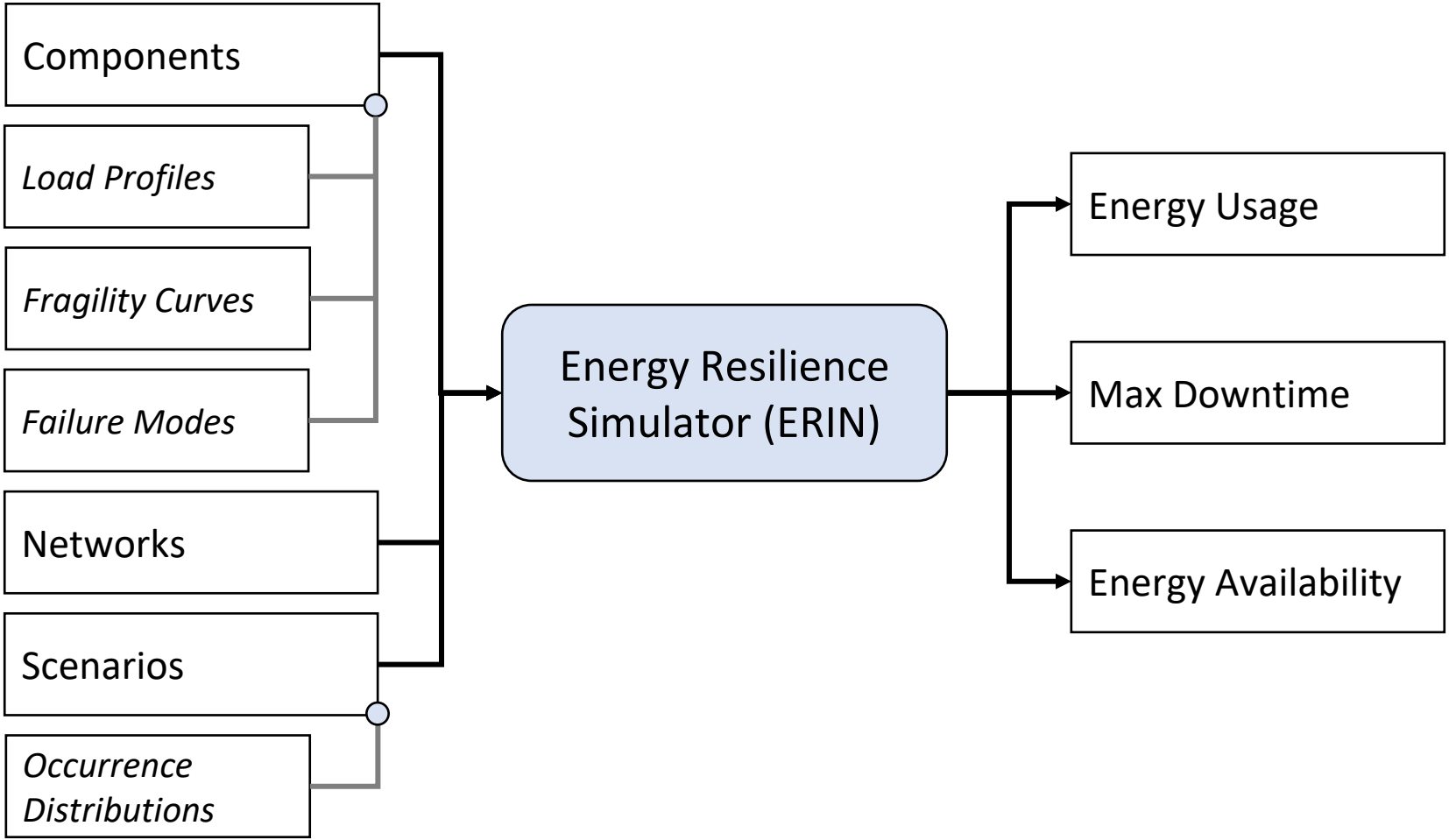
Simulation Engine Inputs and Outputs

- Introduction to the Simulation Engine
  - ERIN: Energy Resilience of Interacting Networks
  - Command Line program written in C++
  - To be free and open-source when released
  - Takes a text input file written in TOML format
  - Writes out two output files in CSV format (readable by MS Excel)
  - The simulation is a “discrete event simulator”
    - Change in the simulator happens at discrete events
      - e.g., the occurrence of a scenario
      - e.g., the change of a load’s requested power
      - e.g., failure of a component due to reliability
    - Energy usage and resilience statistics are calculated for output
- Powerflow Model that accounts for failures and keeps statistics
- Simulates unlikely threats repeatedly to get a statistical feel for resilience

User Guide For the Simulation Engine

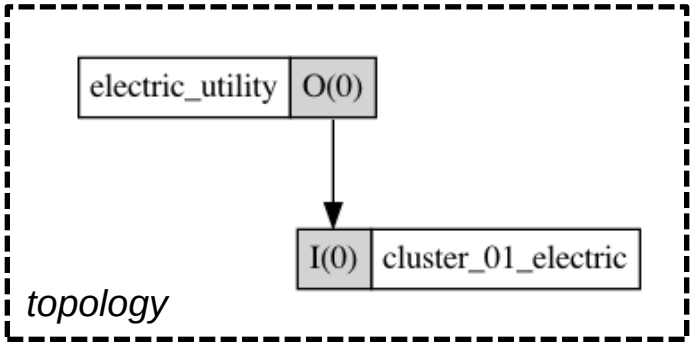
- A User's Guide comes with the simulation to assist in using the tool
- Continuing to update as needed as questions and comments arise

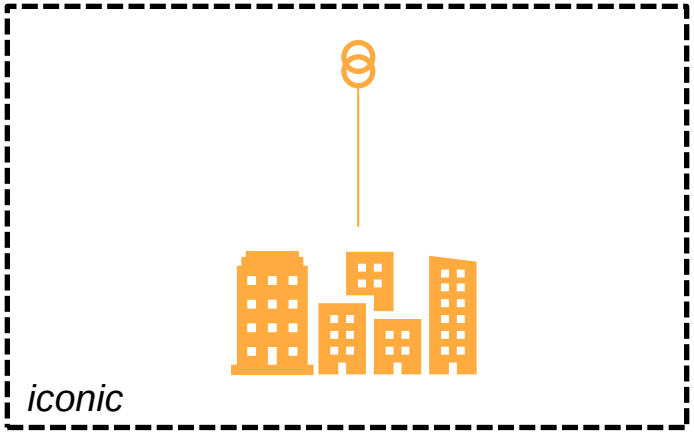



Components
Load Profiles
Fragility Curves
Failure Modes
Networks
Scenarios
Occurrence Distributions
Energy Resilience Simulator (ERIN)
Energy Usage
Max Downtime
Energy Availability

The Input File

A Picture is Worth a 1,000 Words… or 36 lines…

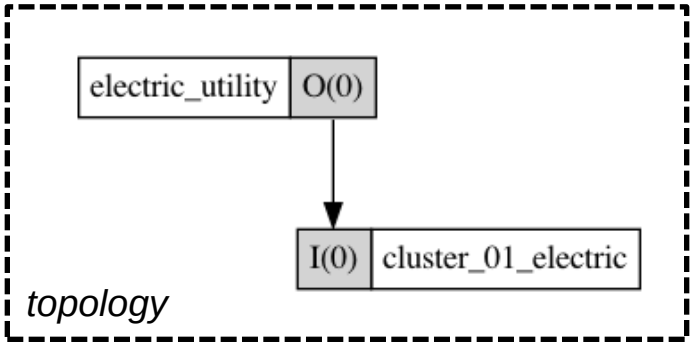


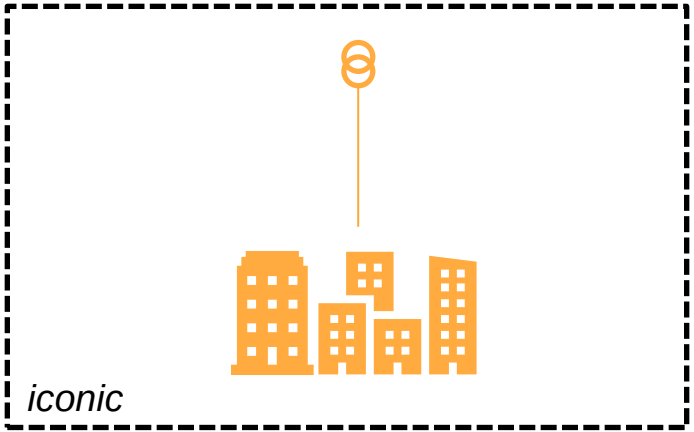



```toml
[simulation_info]
rate_unit = "kW"
quantity_unit = "kJ"
time_unit = "hours"
max_time = 4
############################################################
[loads.building_electrical]
time_unit = "hours"
rate_unit = "kW"
time_rate_pairs = [[0.0,1.0],[4.0]]
############################################################
[components.electric_utility]
type = "source"
# Point of Common Coupling for Electric Utility
output_stream = "electricity"
[components.cluster_01_electric]
type = "load"
input_stream = "electricity"
loads_by_scenario.blue_sky = "building_electrical"
############################################################
[networks.normal_operations]
# Specify network as an array of 3-tuples.
# The interpretation is as follows:
# 3-tuples: [COMPONENT_AND_PORT, COMPONENT_AND_PORT, STREAM_ID]
# COMPONENT_AND_PORT := COMPONENT_ID ":" ("IN" | "OUT") "(" \d+ ")" ;
# COMPONENT_ID := STRING_IDENTIFIER ;
# STREAM_ID := STRING_IDENTIFIER ;
# STRING_IDENTIFIER := [a-zA-Z_] [a-zA-Z_0-9]* ;
connections = [["electric_utility:OUT(0)", "cluster_01_electric:IN(0)", "electricity"]]
############################################################
[scenarios.blue_sky]
time_unit = "hours"
occurrence_distribution = {type = "fixed", value = 0}
duration = 4
max_occurrences = 1
network = "normal_operations"
```

The Input File

A Picture is Worth a 1,000 Words… or 36 lines…



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[simulation_info]
rate_unit = "kW"
quantity_unit = "kJ"
time_unit = "hours"
max_time = 4
############################################################
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time_unit = "hours"
rate_unit = "kW"
time_rate_pairs = [[0.0,1.0],[4.0]]
############################################################
[components.electric_utility]
type = "source"
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[components.cluster_01_electric]
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connections = [["electric_utility:OUT(0)", "cluster_01_electr
############################################################
[scenarios.blue_sky]
time_unit = "hours"
occurrence_distribution = {type = "fixed", value = 0}
duration = 4
max_occurrences = 1
network = "normal_operations"
```

simulation information

load profiles (loads)

components

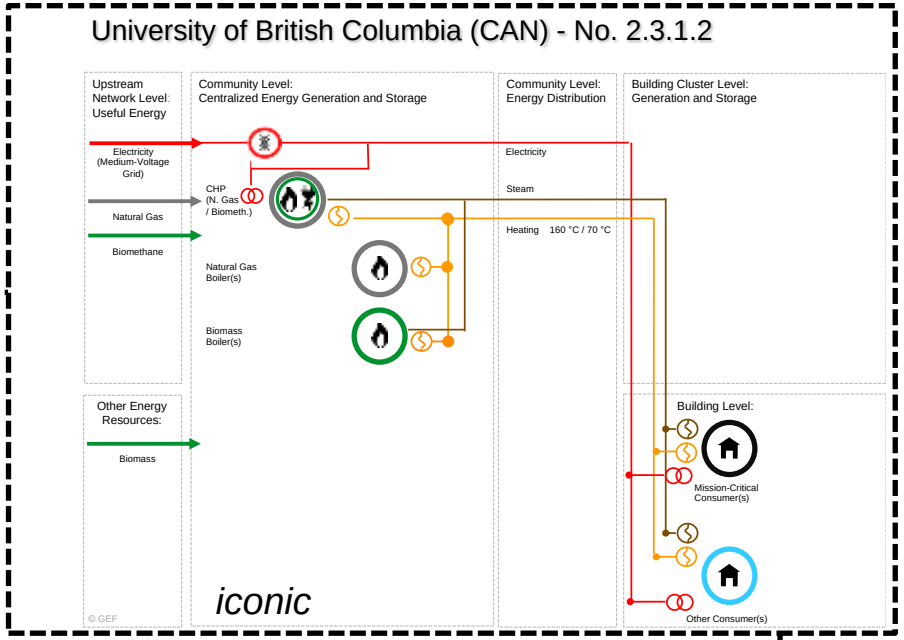
networks

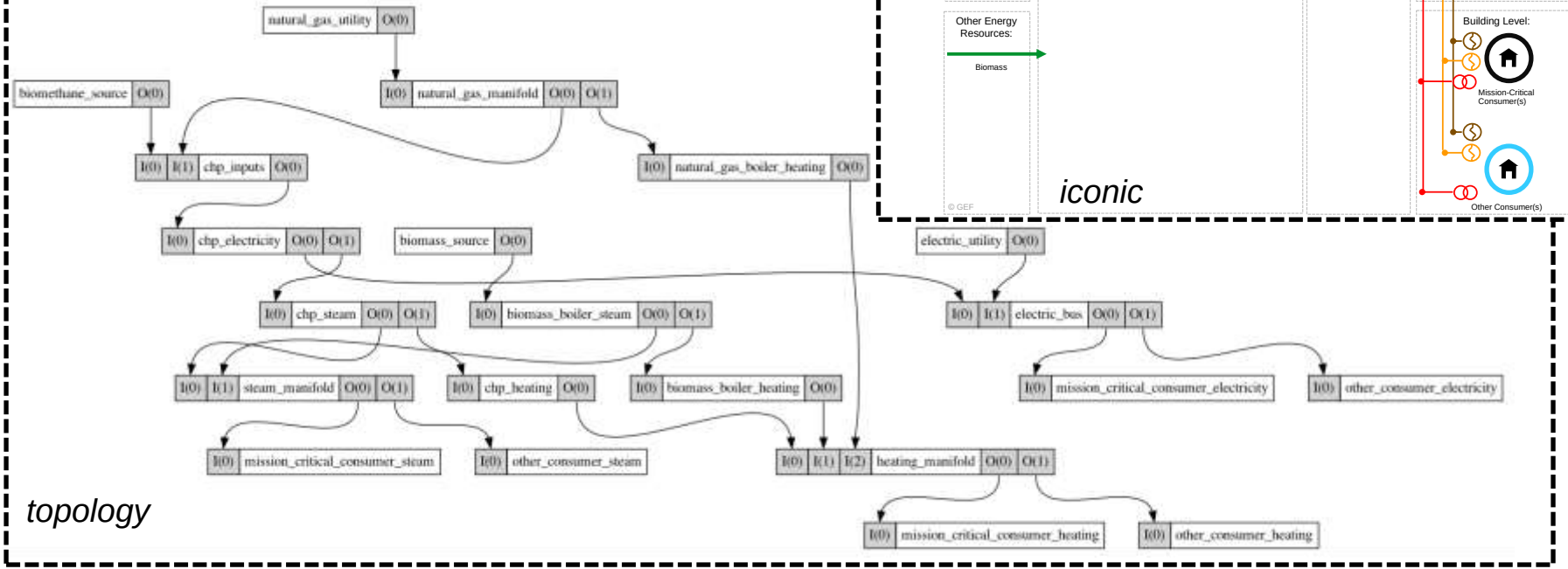
scenarios

The Input File

A Picture is Worth a 1,000 Words… or 205 lines…

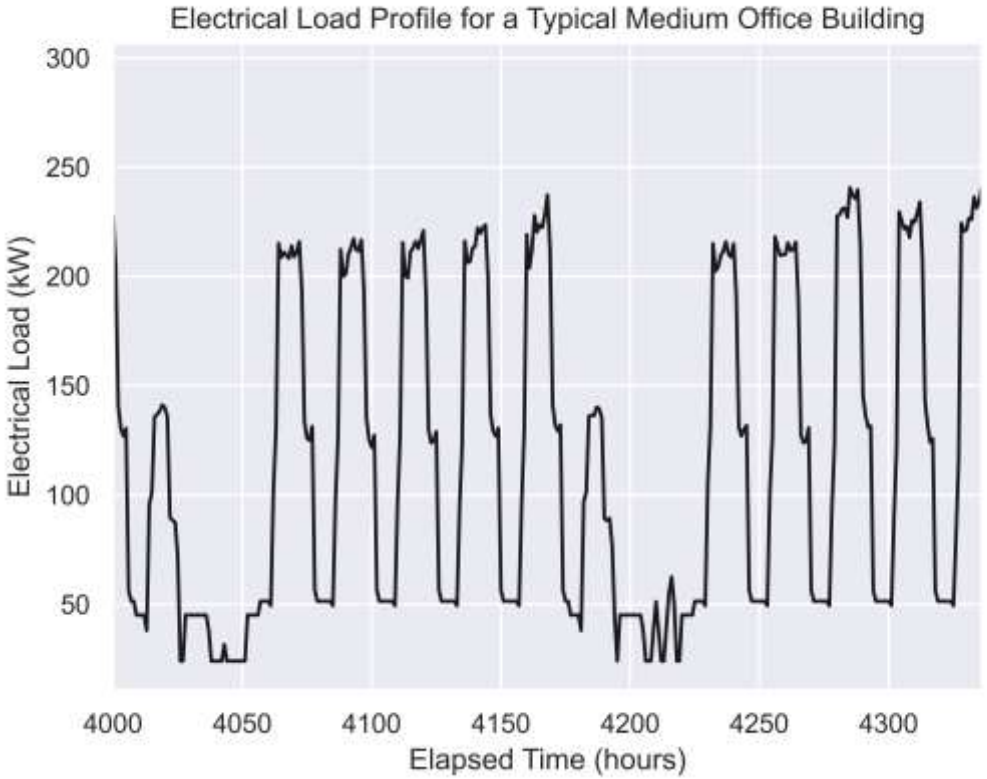
Note: multiple interacting networks (electrical, natural gas, biomethane, biomass, hot water loop, and steam)





Load Profiles

- Specify the load versus time for a given building (or other load asset)
  - Any flow of energy: electrical, district hot water, heating lines, cooling load, steam, etc.
- Data is a great decoupling mechanism!
  - Loads can be generated by any building energy simulation tool
  - Or provided as measured data (if available)
- Load profiles can represent a single building or cluster of building
  - the choice is up to the modeler / analyst



data source: https://reopt.nrel.gov/tool

Sources of Simulated Load Profiles:

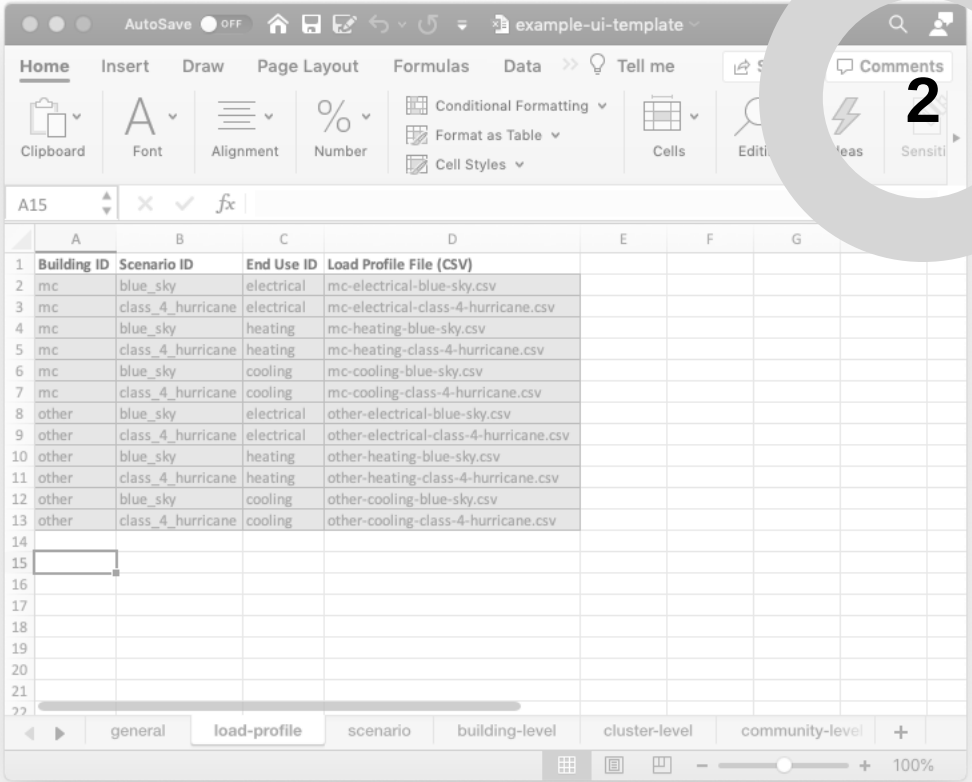
- U.S. DoE Commercial Reference Buildings
- University of Applied Sciences, Stuttgart (Germany), SimStadt
- U.S. Army Corps of Engineers, SMPL (EnergyPlus)
- EMD International A/S, energyPRO, https://www.emd.dk/energypro/
- CSIRO, (Australia) house energy rating tool – AccuRate
- REOpt Lite Website

	A	B
1	Hour	Load (kW)
2	1	50.404
3	2	54.492
4	3	58.735
5	4	62.474
6	5	70.75
7	6	72.332
8	7	72.463
9	8	42.304

User Interface

to the Calculation Engine in

MS Excel



Overview of Capabilities and Workflow

- Objective:
  - Allow access to the calculation engine without having to create an input file by hand
  - Constrain the problem to fixed levels of connectivity to reduce complexity

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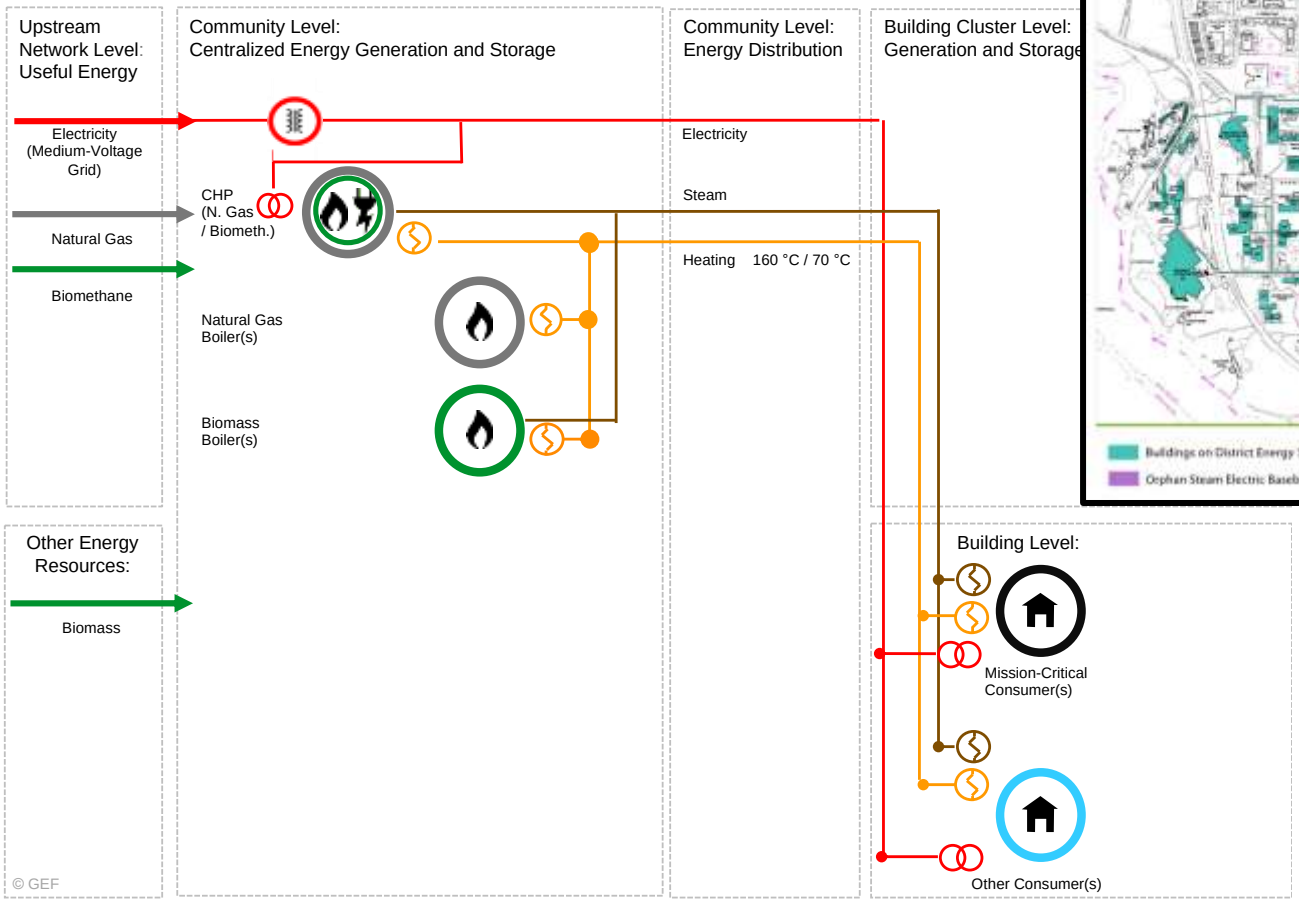
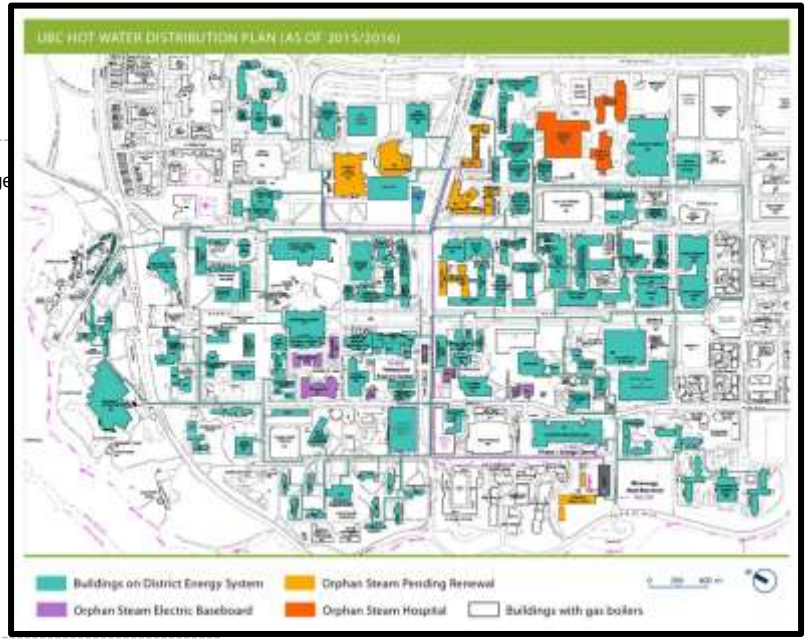
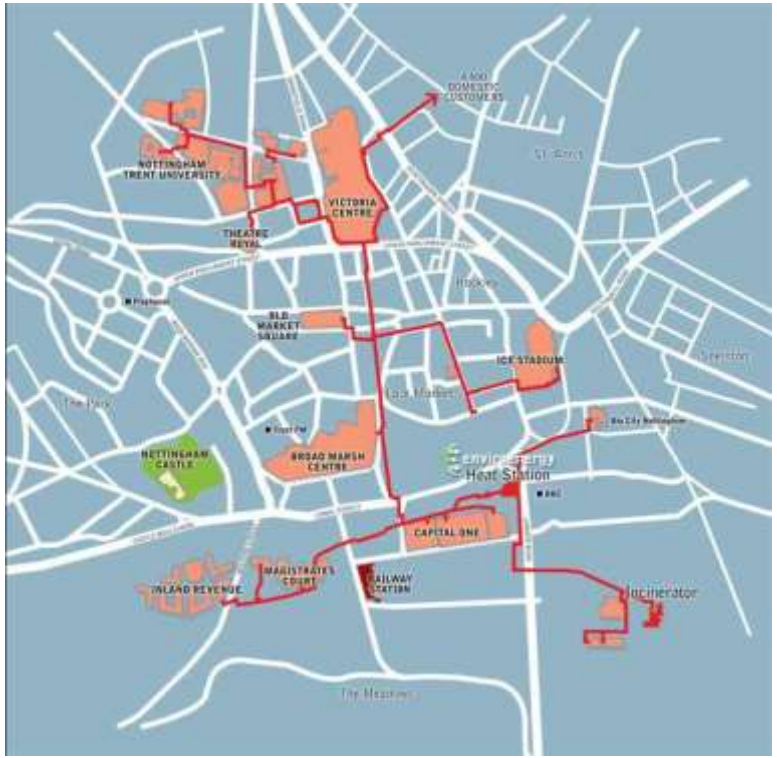




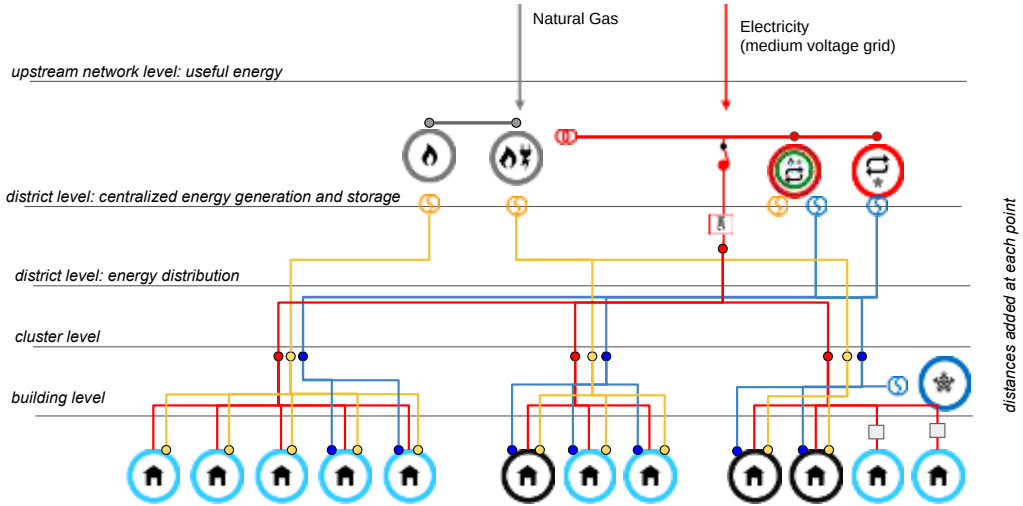
source: http://energy.ubc.ca/projects/district-energy/

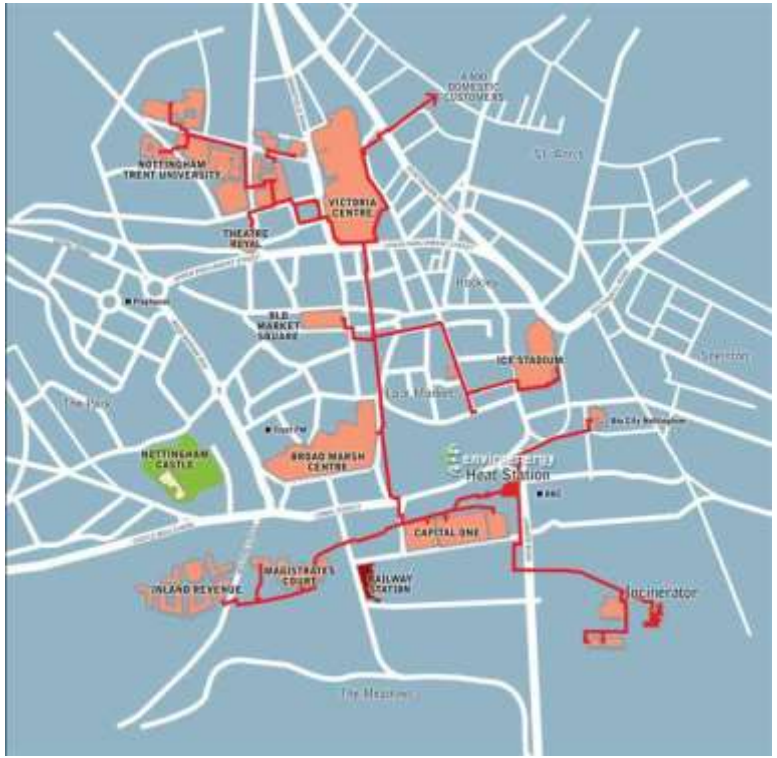
Schematic vs actual. Observe that both represent *Trees.*



source: https://informedinfrastructure.com/399/researchers-map-the-city-of-sheffieds-heat/

Conceptually...





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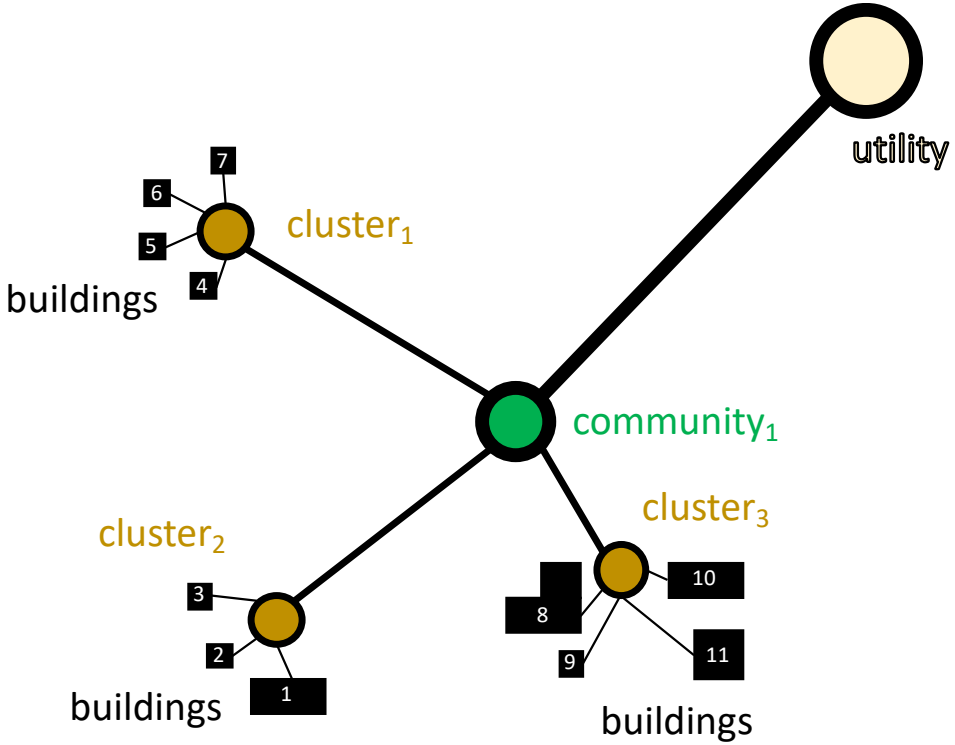
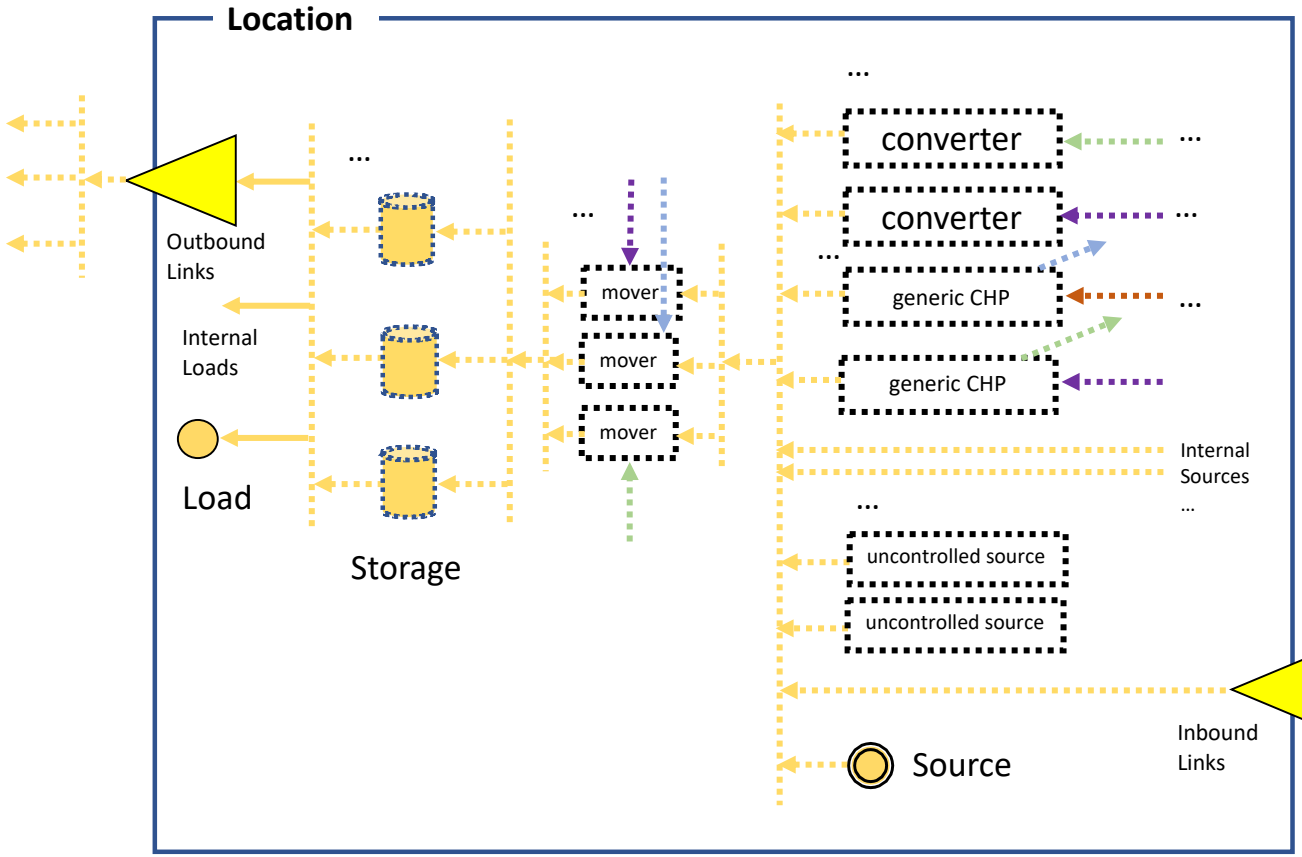
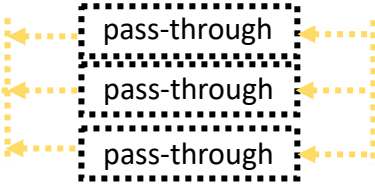
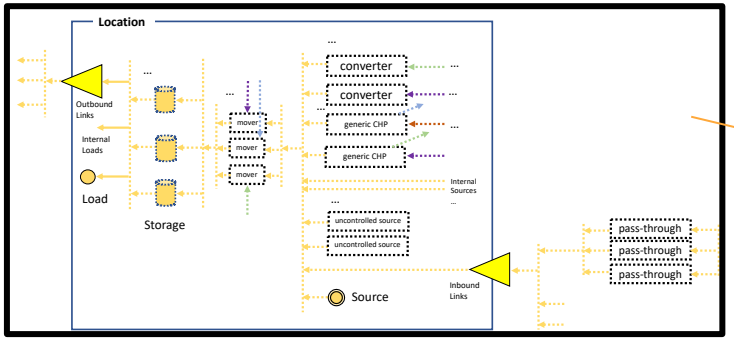


We use the concept of "*location*" to easily map between nodes in the above graph.



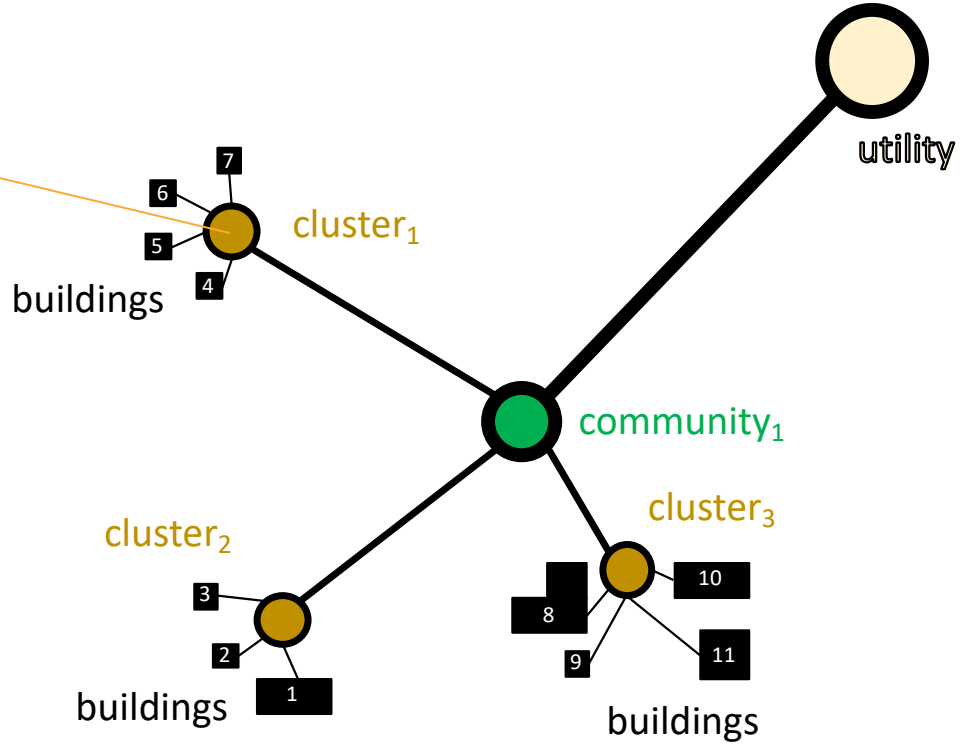
Each *location* contains a complex template to situate components and flows in a reasonable fashion.





The modeler's job is to:

- describe the **components** at each **location**
- describe how **locations connect** to each other
- describe the **scenarios** to simulate



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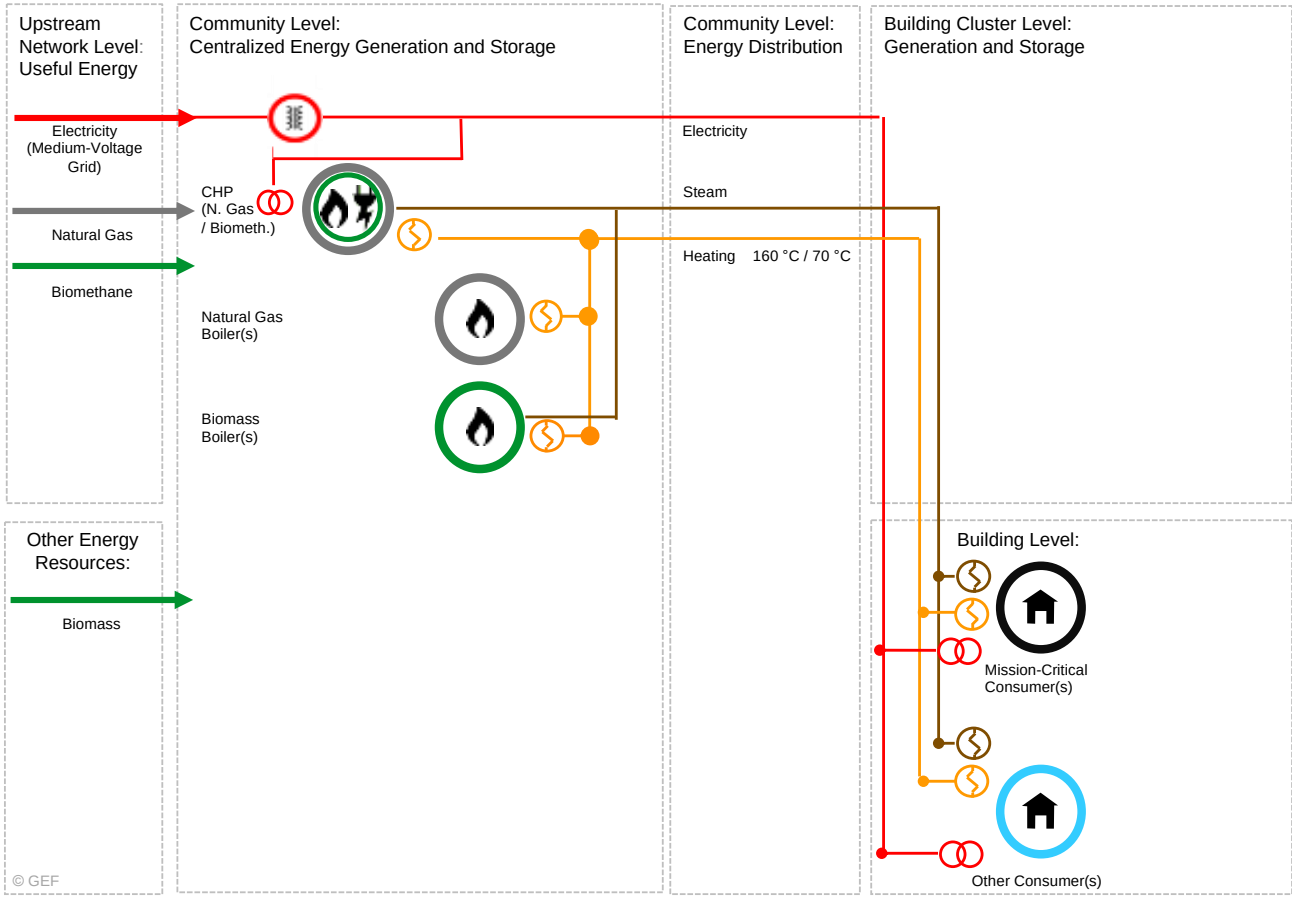
Let’s take an architecture and describe it in the tool!



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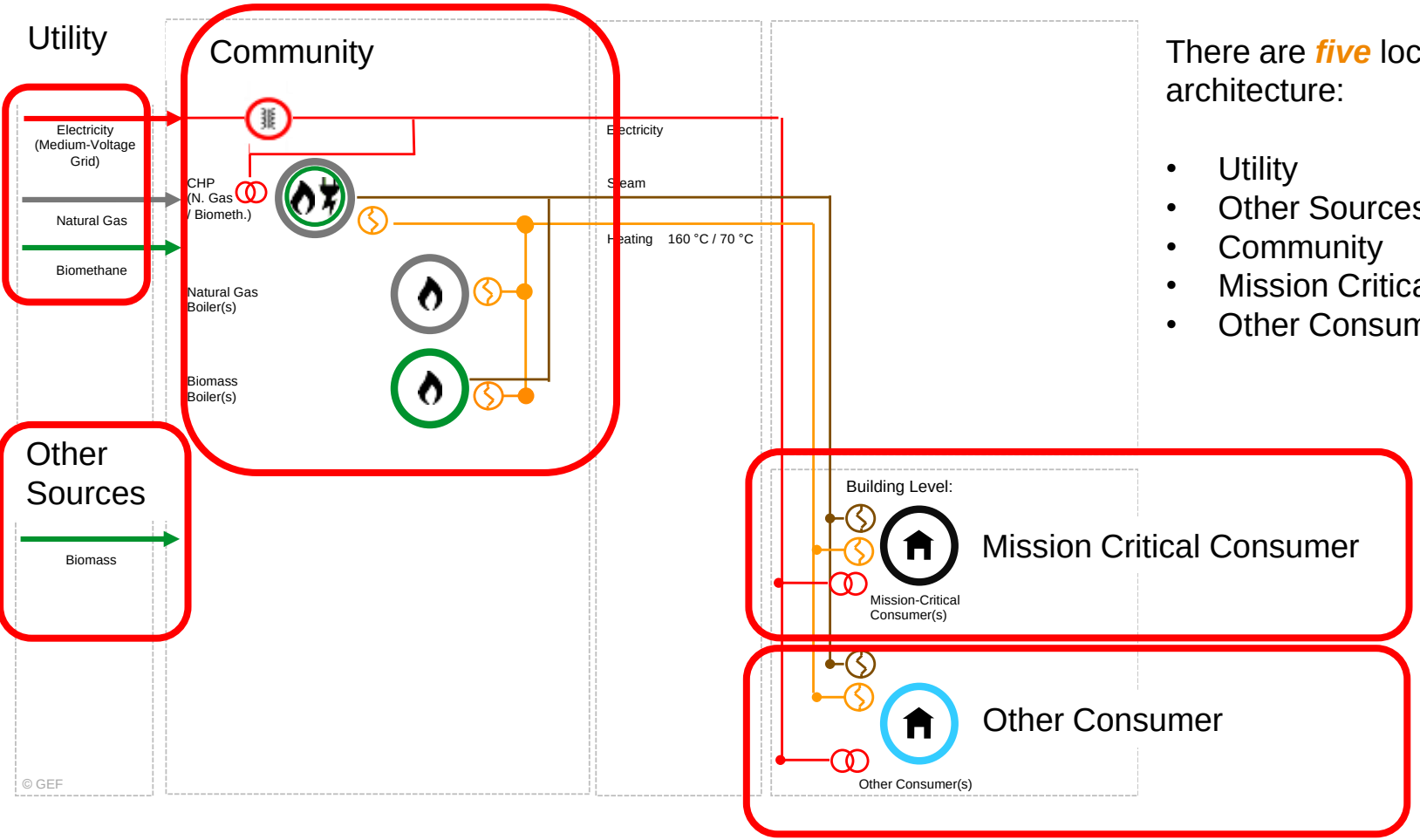
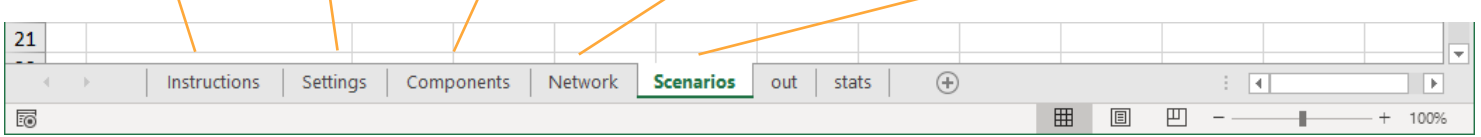


There are ***five*** locations in this architecture:

- Utility
- Other Sources
- Community
- Mission Critical Consumer
- Other Consumer

To use the Excel UI, walk along the tabs for each sheet from left to right.



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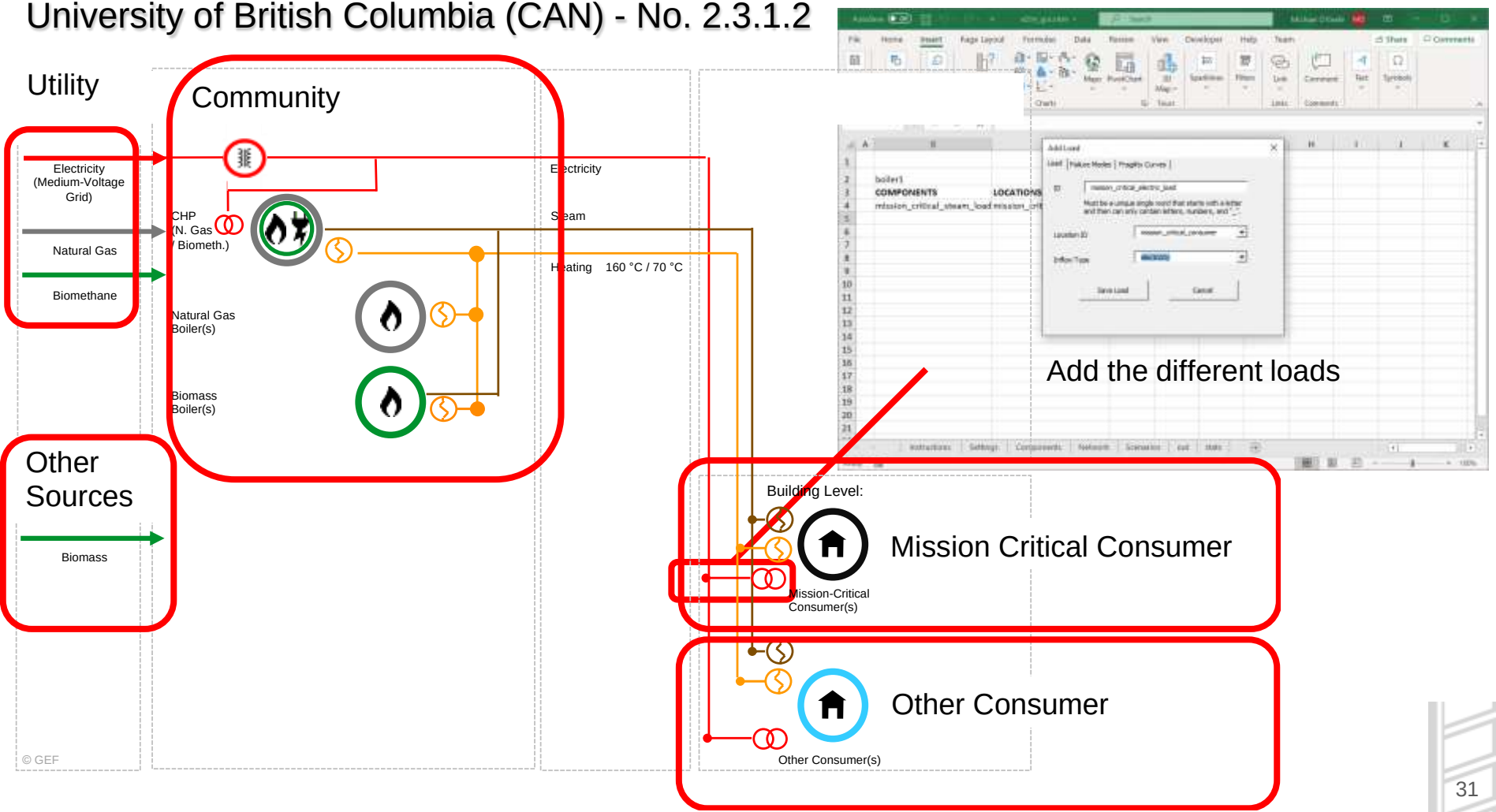

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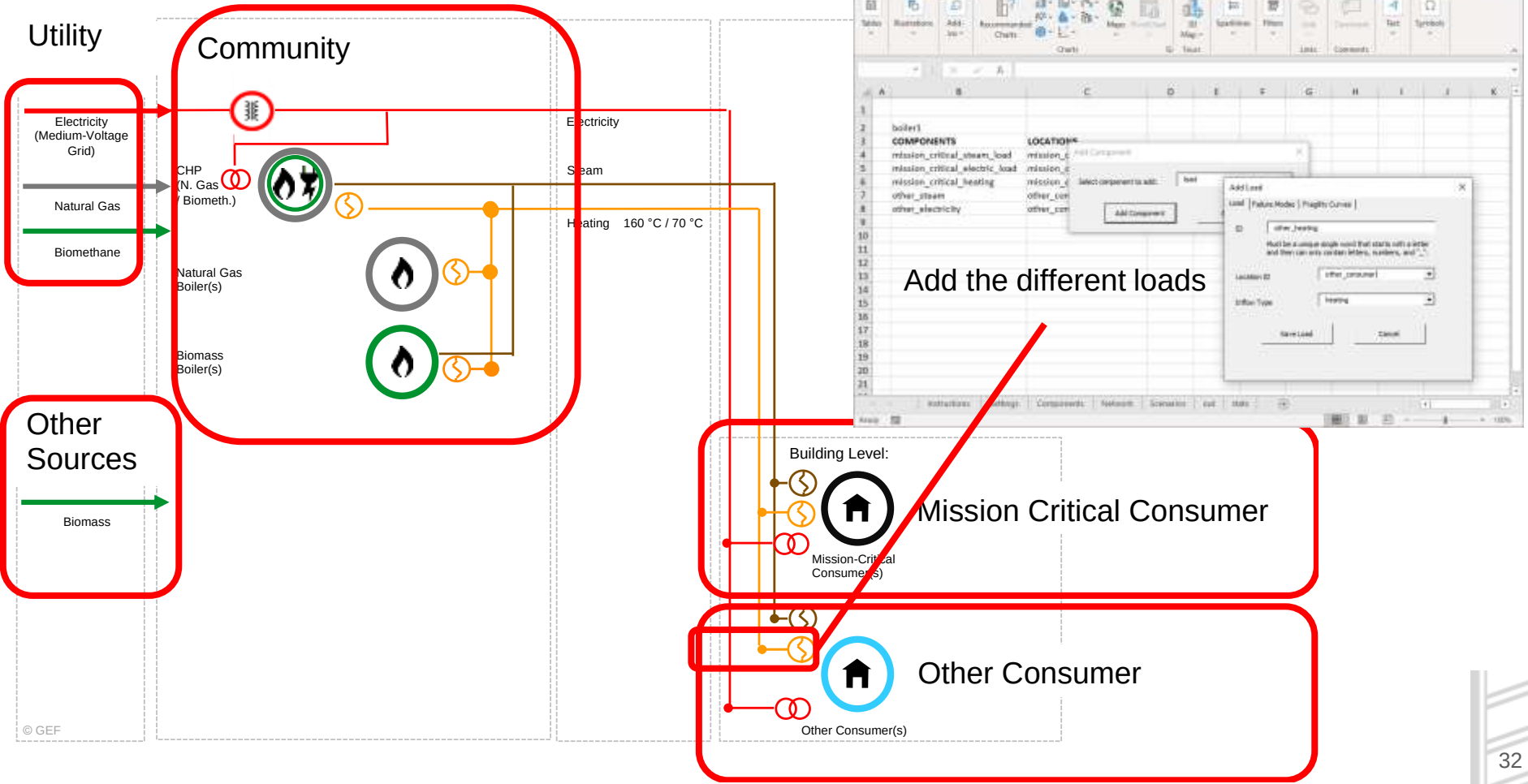

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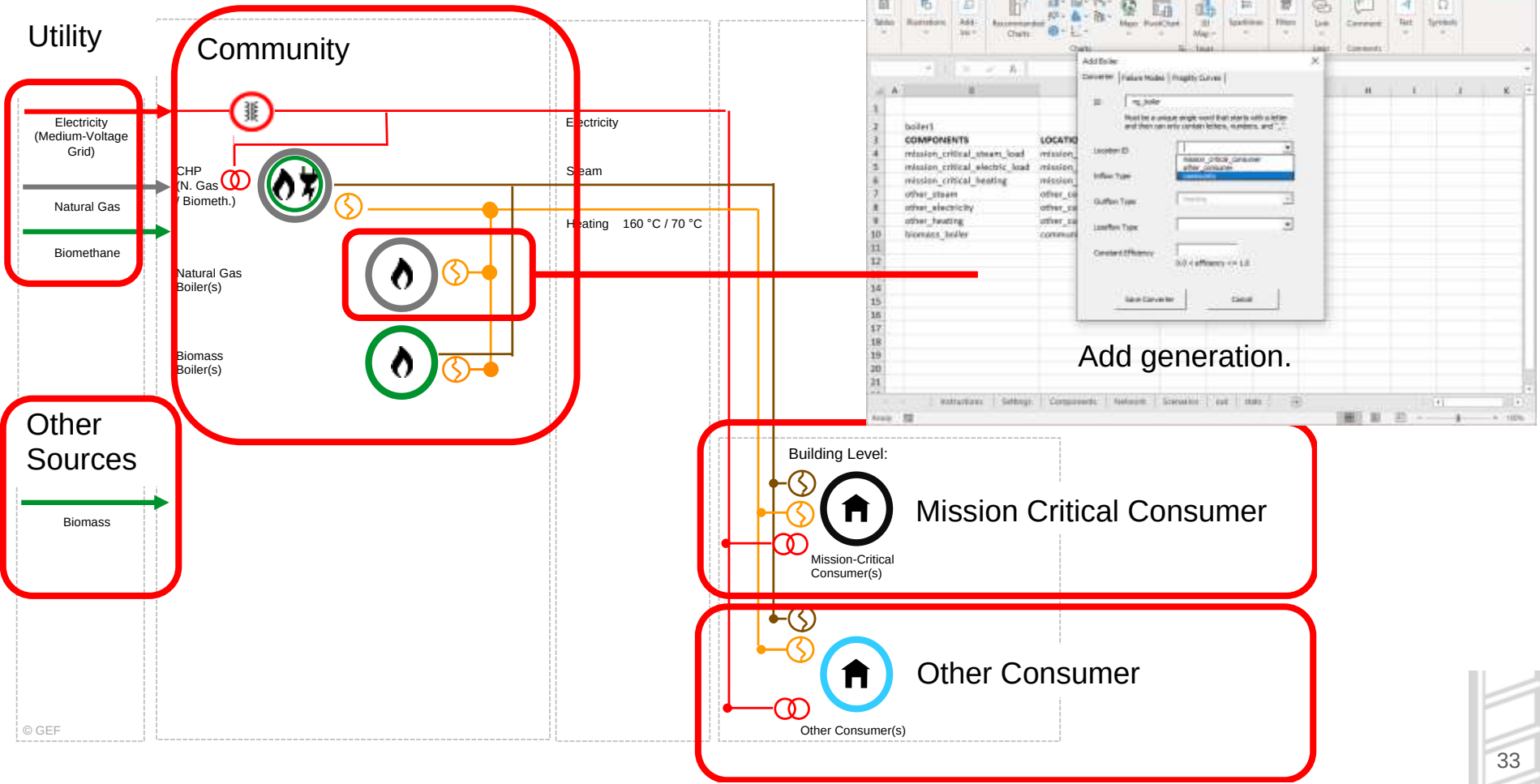
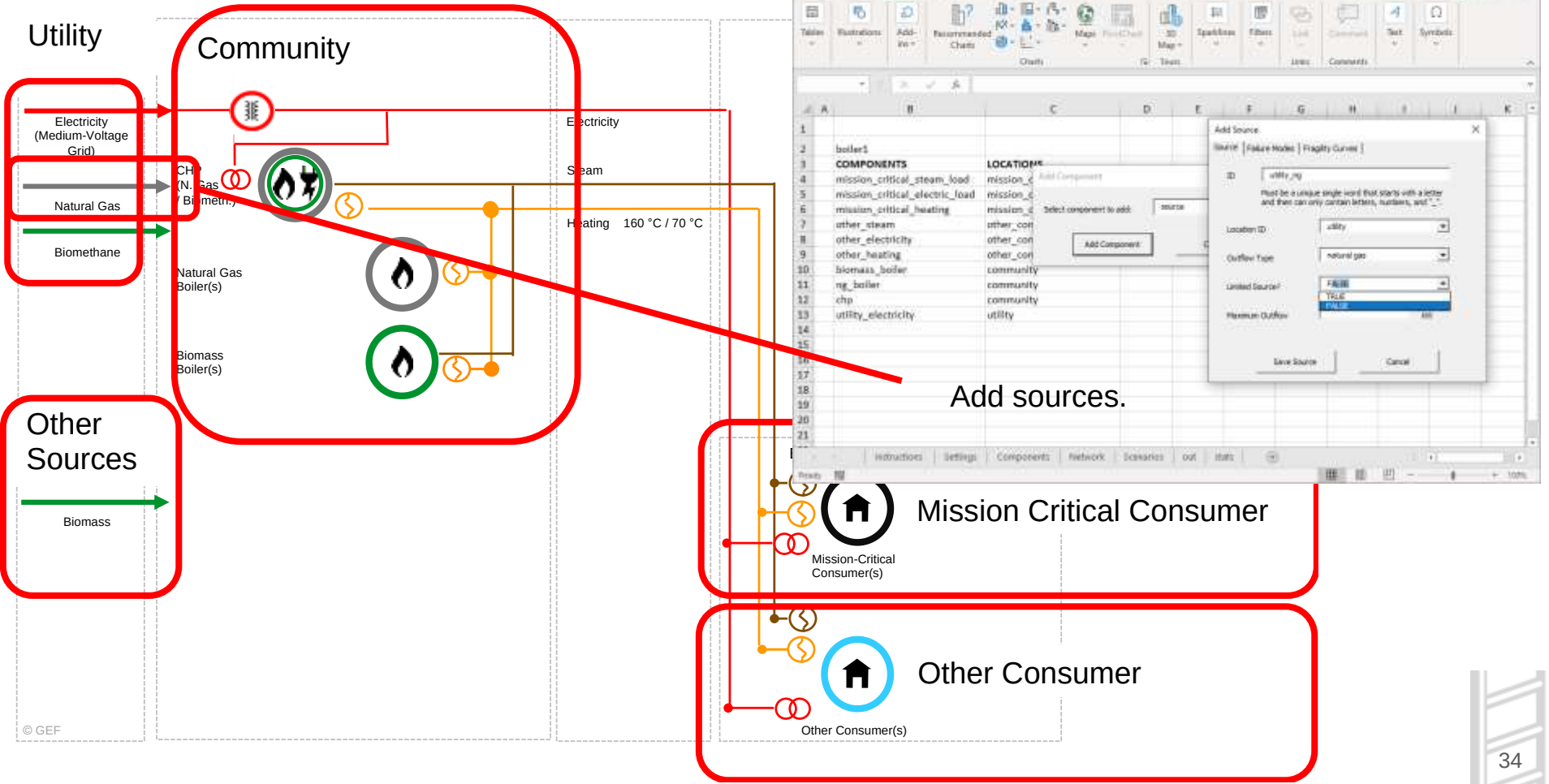
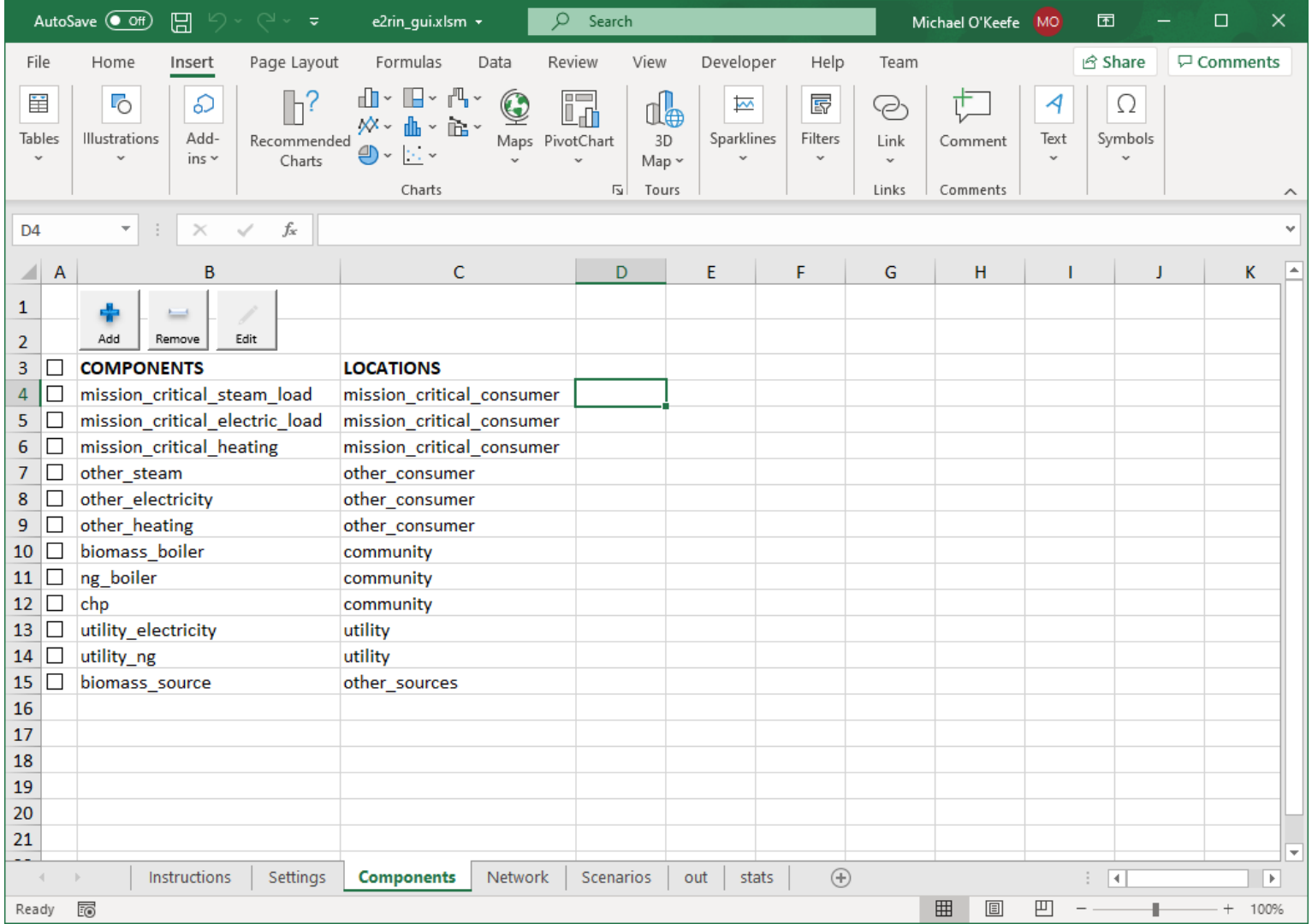


University of British Columbia (CAN) - No. 2.3.1

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e2rin_gui.xlsm
Search
Michael O'Keefe MO
File Home Insert Page Layout Formulas Data Review View Developer Help Team
Share Comments
Tables Illustrations Add-ins Recommended Charts Maps PivotChart 3D Map Sparklines Filters Link Comment Text Symbols
Charts Tours Links Comments
D4
Add Remove Edit
COMPONENTS LOCATIONS
mission_critical_steam_load mission_critical_consumer
mission_critical_electric_load mission_critical_consumer
mission_critical_heating mission_critical_consumer
other_steam other_consumer
other_electricity other_consumer
other_heating other_consumer
biomass_boiler community
ng_boiler community
chp community
utility_electricity utility
utility_ng utility
biomass_source other_sources
Instructions Settings Components Network Scenarios out stats
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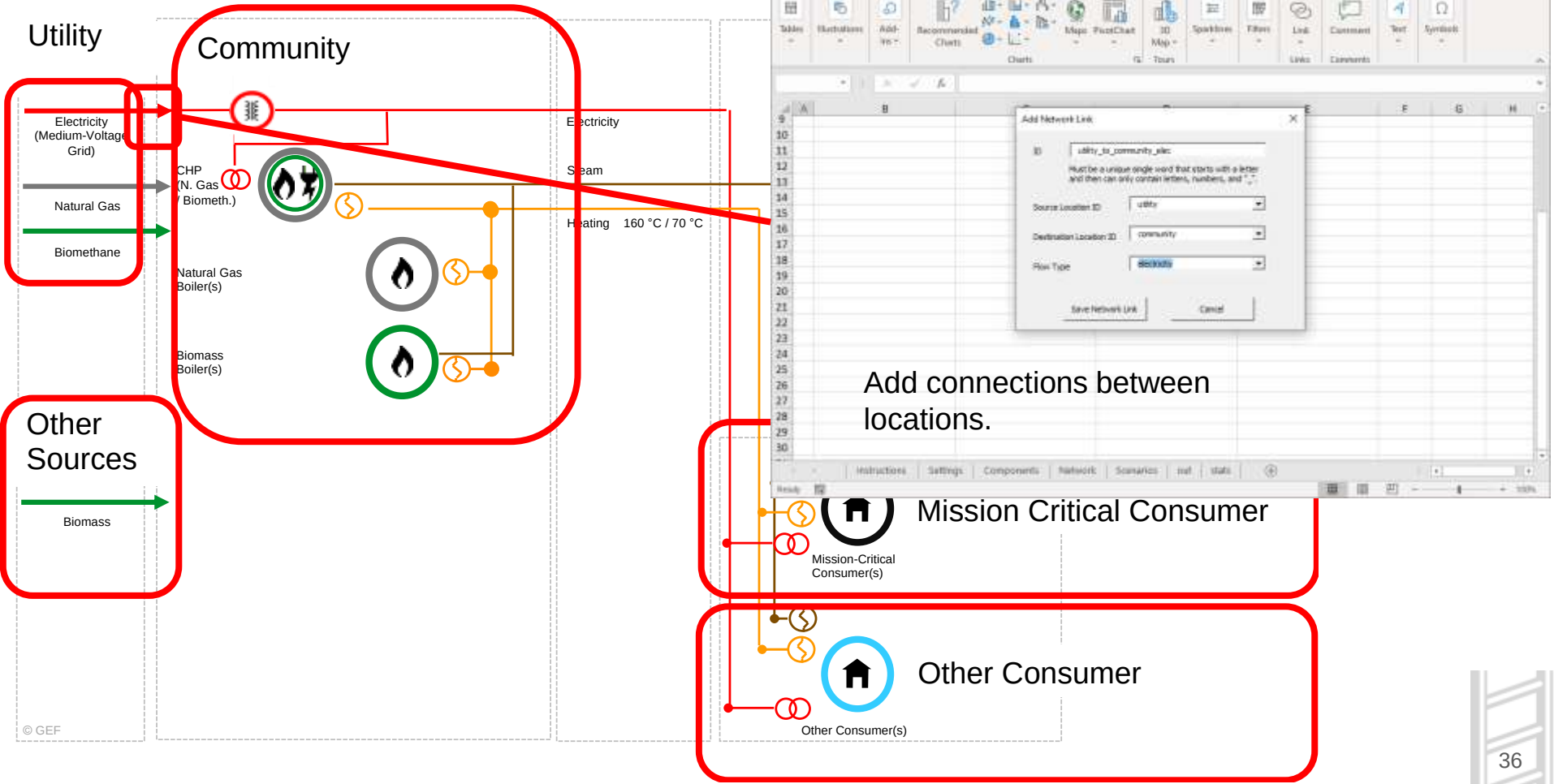
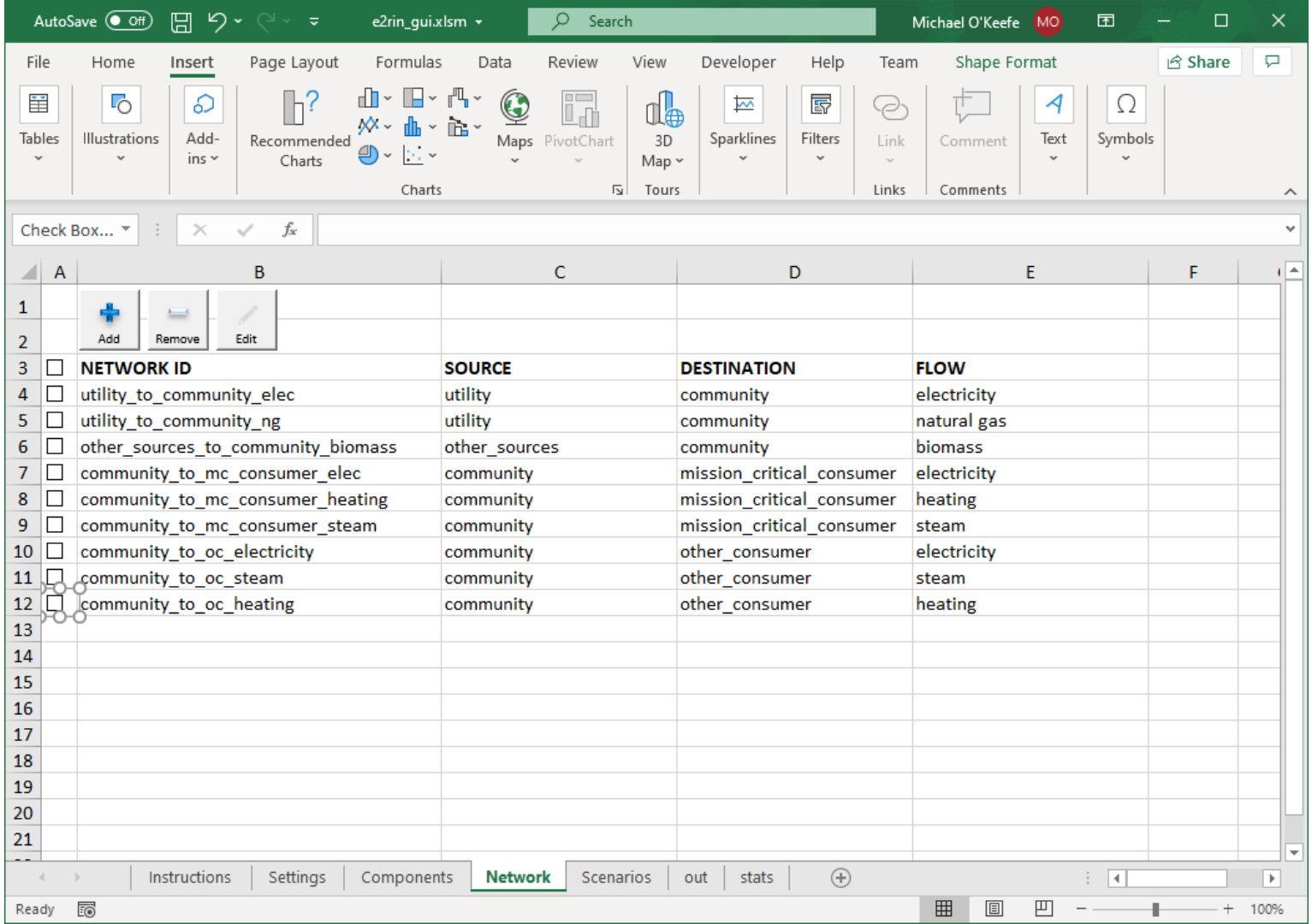
100%

University of British Columbia (CAN) - No. 2.3

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e2rin_gui.xlsm
Search
Michael O'Keefe MO
File Home Insert Page Layout Formulas Data Review View Developer Help Team Shape Format
Share
Tables Illustrations Add-ins Recommended Charts Maps PivotChart 3D Map Sparklines Filters Link Comment Text Symbols
Charts Tours Links Comments
Check Box...
Add Remove Edit
NETWORK ID SOURCE DESTINATION FLOW
utility_to_community_elec utility community electricity
utility_to_community_ng utility community natural gas
other_sources_to_community_biomass other_sources community biomass
community_to_mc_consumer_elec community mission_critical_consumer electricity
community_to_mc_consumer_heating community mission_critical_consumer heating
community_to_mc_consumer_steam community mission_critical_consumer steam
community_to_oc_electricity community other_consumer electricity
community_to_oc_steam community other_consumer steam
community_to_oc_heating community other_consumer heating
Instructions Settings Components Network Scenarios out stats
Ready
100%

AutoSave Off e2rin_gui.xlsm Search Michael O'Keefe MO

File Home Insert Page Layout Formulas Data Review View Developer

Tables Illustrations Add-ins Recommended Charts Maps PivotChart 3D Map Sparklines

Charts Tours

SCENARIOS

Add Scenario

Scenario | Load Profiles | Damage Metrics

ID: blue_sky

Must be a unique single word that starts with a letter and then can only contain letters, numbers, and "_".

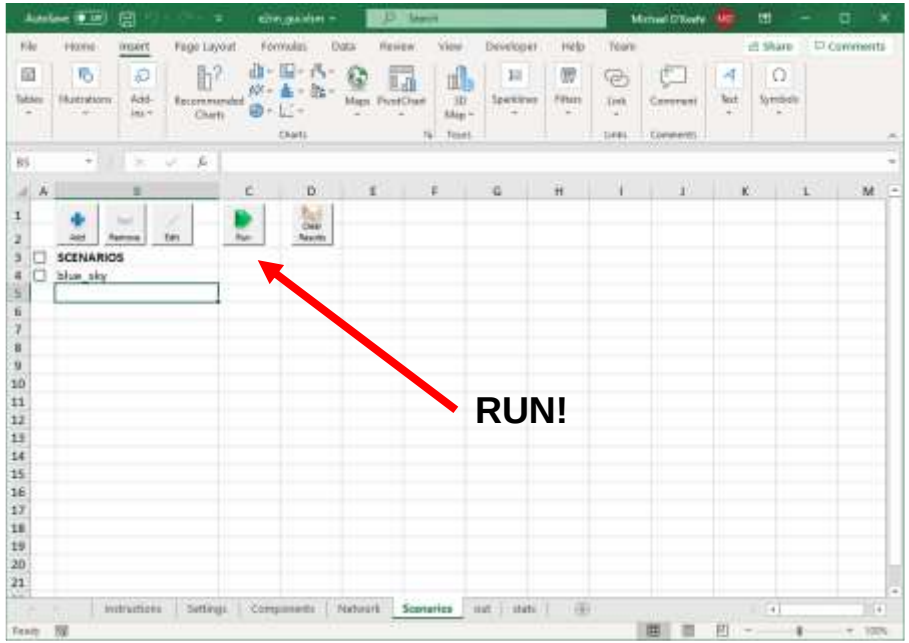
Duration: 8760 hours

Occurance Distribution: always

Calc Reliability: FALSE

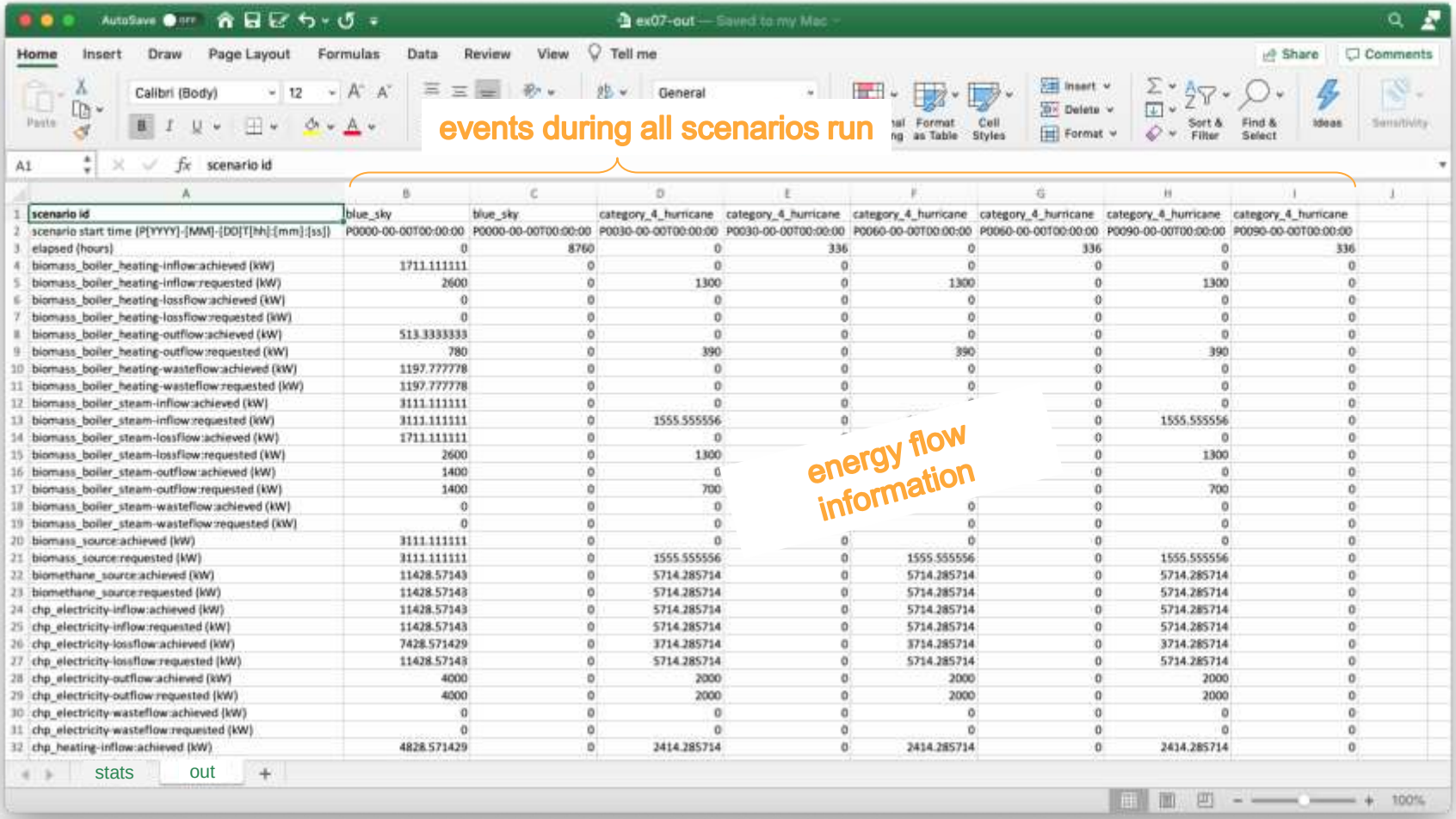
Max Occurances: 1

Save Scenario Cancel



Instructions Settings Components Network Scenarios out stats

Ready 100%



scenario id	blue_sky	blue_sky	category_4_hurricane	category_4_hurricane	category_4_hurricane	category_4_hurricane	category_4_hurricane	category_4_hurricane
scenario start time (P[YYYY]-[MM]-[DD]T[hh]:[mm]:[ss])	P0000-00-00T00:00:00	P0000-00-00T00:00:00	P0030-00-00T00:00:00	P0030-00-00T00:00:00	P0060-00-00T00:00:00	P0060-00-00T00:00:00	P0090-00-00T00:00:00	P0090-00-00T00:00:00
elapsed (hours)	0	8760	0	336	0	336	0	336
biomass_boiler_heating-inflow:achieved (kW)	1711.111111	0	0	0	0	0	0	0
biomass_boiler_heating-inflow:requested (kW)	2600	0	1300	0	1300	0	1300	0
biomass_boiler_heating-lossflow:achieved (kW)	0	0	0	0	0	0	0	0
biomass_boiler_heating-lossflow:requested (kW)	0	0	0	0	0	0	0	0
biomass_boiler_heating-outflow:achieved (kW)	513.3333333	0	0	0	0	0	0	0
biomass_boiler_heating-outflow:requested (kW)	780	0	390	0	390	0	390	0
biomass_boiler_heating-wasteflow:achieved (kW)	1197.777778	0	0	0	0	0	0	0
biomass_boiler_heating-wasteflow:requested (kW)	1197.777778	0	0	0	0	0	0	0
biomass_boiler_steam-inflow:achieved (kW)	3111.111111	0	0	0	0	0	0	0
biomass_boiler_steam-inflow:requested (kW)	3111.111111	0	1555.555556	0	1555.555556	0	1555.555556	0
biomass_boiler_steam-lossflow:achieved (kW)	1711.111111	0	0	0	0	0	0	0
biomass_boiler_steam-lossflow:requested (kW)	2600	0	1300	0	1300	0	1300	0
biomass_boiler_steam-outflow:achieved (kW)	1400	0	0	0	0	0	0	0
biomass_boiler_steam-outflow:requested (kW)	1400	0	700	0	700	0	700	0
biomass_boiler_steam-wasteflow:achieved (kW)	0	0	0	0	0	0	0	0
biomass_boiler_steam-wasteflow:requested (kW)	0	0	0	0	0	0	0	0
biomass_source:achieved (kW)	3111.111111	0	0	0	0	0	0	0
biomass_source:requested (kW)	3111.111111	0	1555.555556	0	1555.555556	0	1555.555556	0
biomethane_source:achieved (kW)	11428.57143	0	5714.285714	0	5714.285714	0	5714.285714	0
biomethane_source:requested (kW)	11428.57143	0	5714.285714	0	5714.285714	0	5714.285714	0
chp_electricity-inflow:achieved (kW)	11428.57143	0	5714.285714	0	5714.285714	0	5714.285714	0
chp_electricity-inflow:requested (kW)	11428.57143	0	5714.285714	0	5714.285714	0	5714.285714	0
chp_electricity-lossflow:achieved (kW)	7428.571429	0	3714.285714	0	3714.285714	0	3714.285714	0
chp_electricity-lossflow:requested (kW)	11428.57143	0	5714.285714	0	5714.285714	0	5714.285714	0
chp_electricity-outflow:achieved (kW)	4000	0	2000	0	2000	0	2000	0
chp_electricity-outflow:requested (kW)	4000	0	2000	0	2000	0	2000	0
chp_electricity-wasteflow:achieved (kW)	0	0	0	0	0	0	0	0
chp_electricity-wasteflow:requested (kW)	0	0	0	0	0	0	0	0
chp_heating-inflow:achieved (kW)	4828.571429	0	2414.285714	0	2414.285714	0	2414.285714	0

Outputs show all of the events over a scenario by component

Resilience Metrics and Energy Balance and Use Information Available

	G	H	I
	energy availability	max downtime (hours)	load not served (kJ)
mission_critical_consumer_electricity	1	0	0
mission_critical_consumer_heating	1	0	0
mission_critical_consumer_steam	1	0	0

mission_critical_consumer_electricity	load	electricity	1	0	0
mission_critical_consumer_heating	load	heating	1	0	0
mission_critical_consumer_steam	load	steam	1	0	0

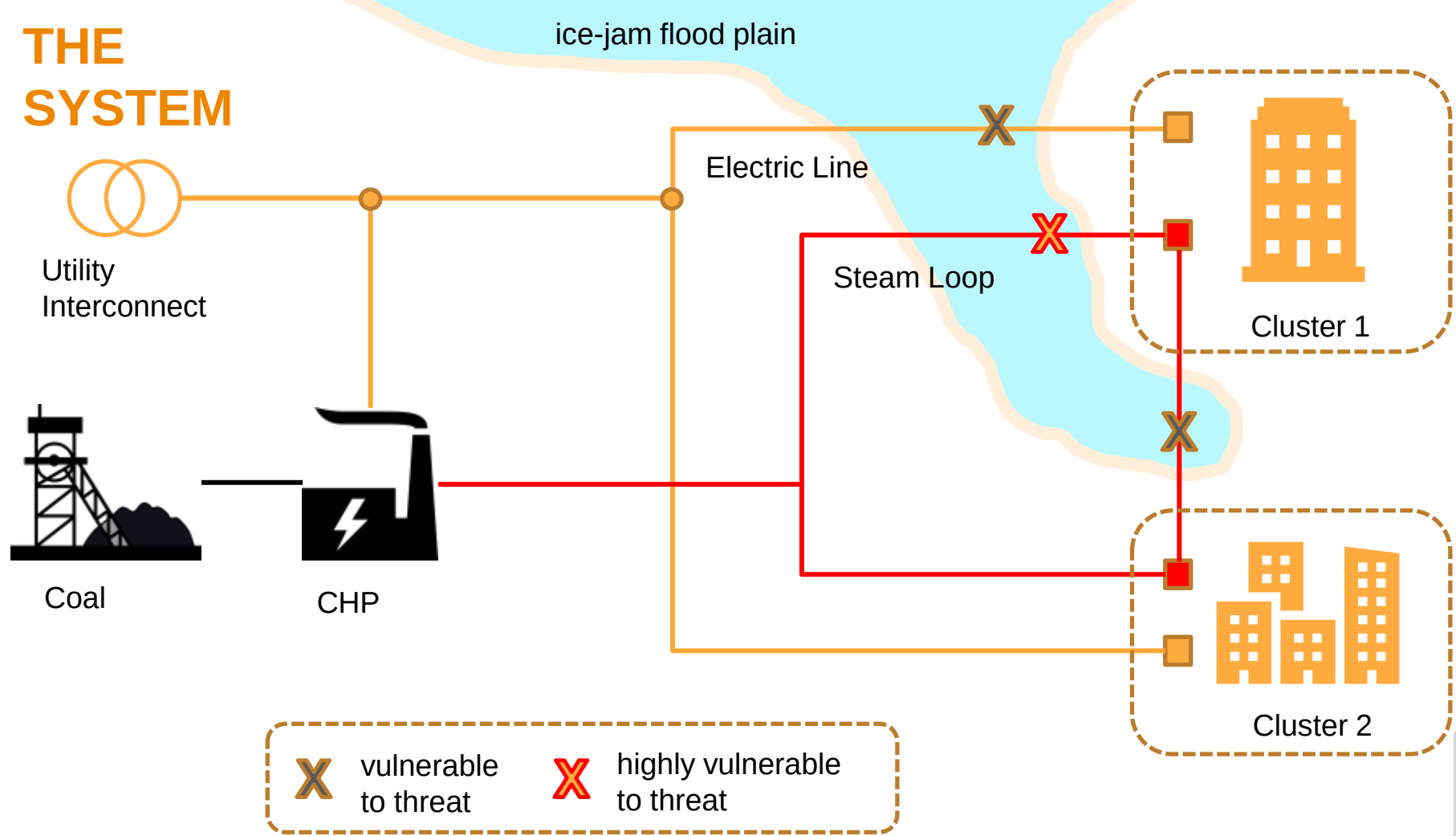
ENERGY BALANCE (source-(load+storage+waste))	0

3

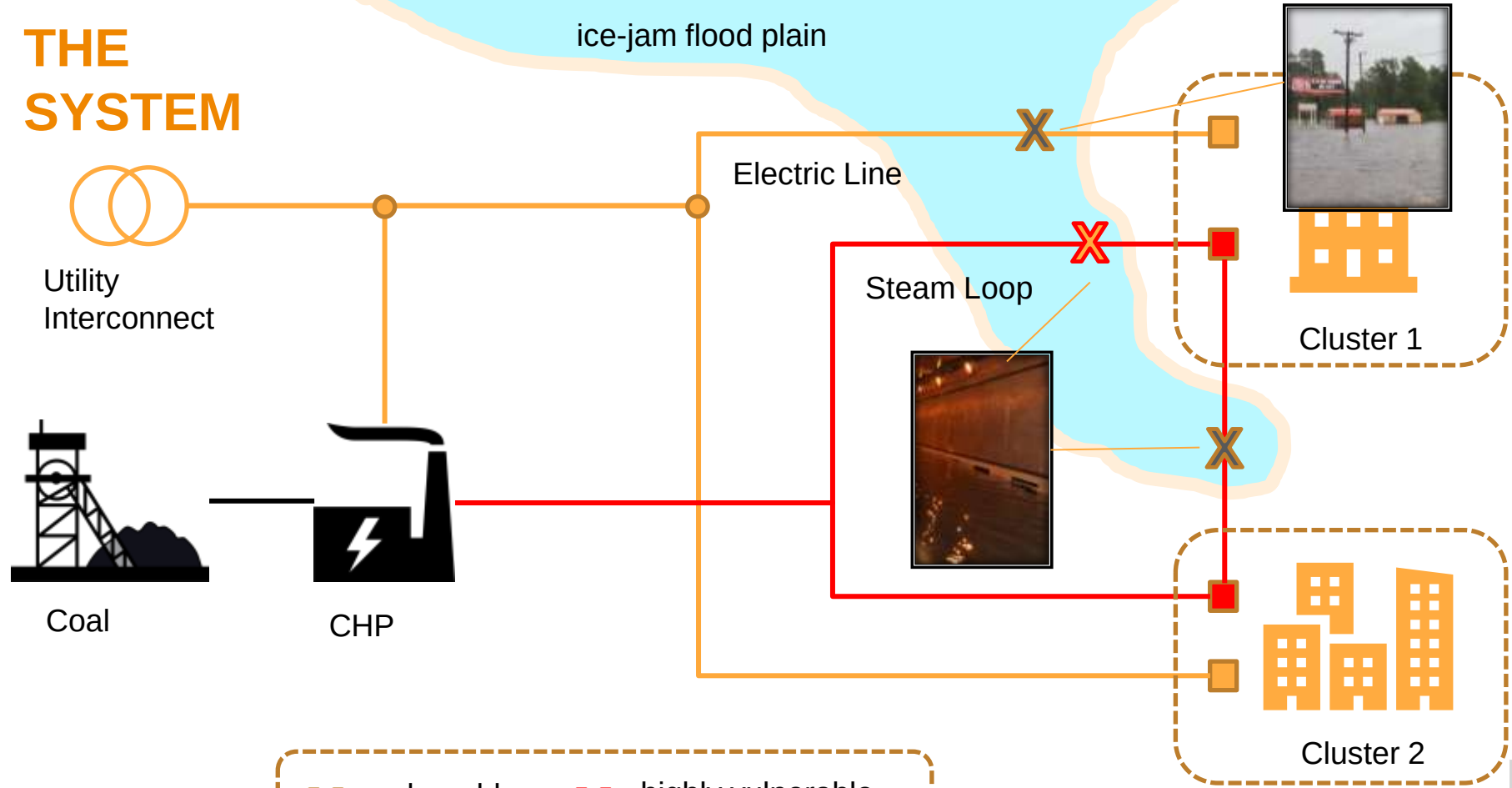
Using IEA Annex 73 Resources in Concert

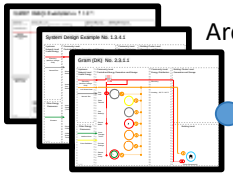
A Hypothetical Example Analysis

THE SYSTEM

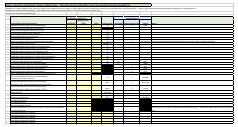

ice-jam flood plain
Electric Line
Utility Interconnect
Steam Loop
Cluster 1
Coal
CHP
Cluster 2
vulnerable to threat
highly vulnerable to threat

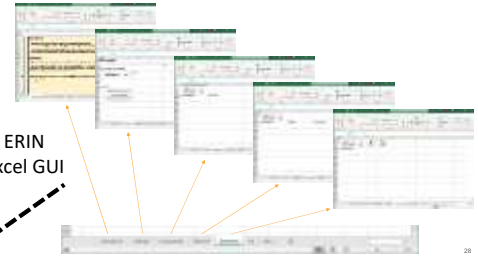
THE SYSTEM


ice-jam flood plain
Electric Line
Utility Interconnect
Steam Loop
Cluster 1
Cluster 2
Coal
CHP
vulnerable to threat
highly vulnerable to threat



Architectures





ERIN
Excel GUI

Site Criteria, Constraints, and Goals

Component Technology Database

Architecture Selection & Configuration

Describe Model

Input File(s)

- Components
- Network Connections
- Scenarios to Simulate
- Resilience and Reliability Information

ERIN
(energy resilience simulator)

Cost Calculation

Compare EA and Max down time for all buildings, evaluate gaps and select different architecture when necessary

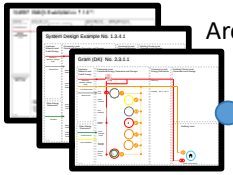
Outputs

- Blue sky (EA/reliability, energy use, cost)
- Energy availability and max downtime by scenario & buildings

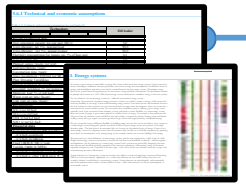
KEY

Modeler Activity

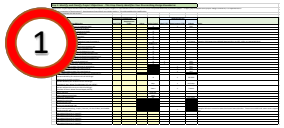
Data or Tool Calculation



Architectures

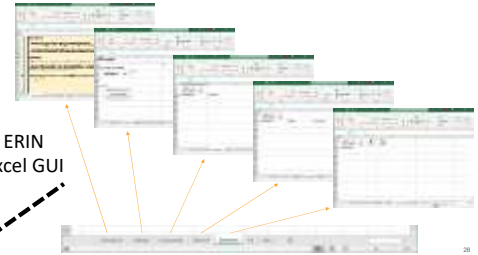


Component Technology Database



1

Site Criteria, Constraints, and Goals



ERIN Excel GUI

2 Architecture Selection & Configuration

3 Describe Model

Input File(s)

- Components
- Network Connections
- Scenarios to Simulate
- Resilience and Reliability Information

4 Cost Calculation

ERIN
(energy resilience simulator)

5 Compare EA and Max down time for all buildings, evaluate gaps and select different architecture when necessary

Outputs

- Blue sky (EA/reliability, energy use, cost)
- Energy availability and max downtime by scenario & buildings

Summary

Conclusions

- Free and open-source resilience calculation tool
  - Command line executable
  - MS Excel Minimal User Interface
- Part of a larger energy master planning process
  - Describing a model from an architecture template
  - Discussed how data products from IEA Annex 73 could be used in concert

Thank you!

Questions?