DER-CAM DECISION SUPPORT TOOL FOR DECENTRALIZED ENERGY SYSTEMS

ANALYTICS | PLANNING | OPERATIONS

LBNL Contact Information
Michael Stadler
MStadler@lbl.gov
https://building-microgrid.lbl.gov/
https://gig.lbl.gov

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Core Berkeley Team: F. Ewald, G. Cardoso, M. Heleno, M. Stadler, N. DeForest, S. Mashayekh

Other Contributors: A. Mammoli, C. Milan, D. Baldassari, D. Steen, D. Weng, L. Le Gall, M. Groissböck, S. Narayanan, S. Wagner, T. Schittekatte, T. Forget, J. Reilly, J. Tjaeder, J. Wang

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What is DER-CAM?

Decision support tool for decentralized energy systems

- **Optimal energy supply solutions for buildings and microgrids**
- **Optimal dispatch of existing energy supply technologies in buildings and microgrids**

DER-CAM is…

- *A physically-based* ***(economic) optimization model***
  - Find most cost-effective mix of generation and storage + dispatch that minimizes costs / CO_2 emissions
  - Decisions consider load management options such as load shifting, load scheduling, load shedding
  - Constrains force energy balance and technology behavior

DER-CAM is not a…

- *transient power flow model*
- *simulation model*

What is DER-CAM?

Two main branches

- **Investment and Planning DER-CAM**
  - Considers hourly loads of representative day-types based in historic or simulated data
  - Finds optimal investment decisions for a representative year, or investment timeline up to 20 years in the future
  - Investment decisions are based in a bottom-up approach: optimized dispatch for representative day-types
  - Technologically neutral
- Operations DER-CAM (for Model Predictive Controllers)
  - Considers higher resolution time steps (1 min to 1 hour)
  - Finds optimal dispatch of local energy resources on a week-ahead basis
  - Uses existing load information and weather forecasts to forecast loads
  - Can be used to feed data to a building management system or SCADA

Optimization vs. Simulation

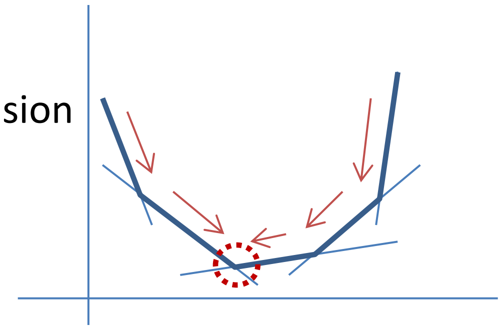
$$\min f = c^T x$$
$$s.t.$$
$$Ax \leq b$$
$$x \geq 0$$

DER-CAM is a ***pure*** optimization model:

- objective function
- constraints

Mixed integer linear formulation (MILP)

- decision variables can be integer or continuous
  - integer: number of engines to install; binary purchase decision
  - continuous: power output; PV Capacity
- objective function and constraints are linear
  - different linearization methods are used
- global minimum is guaranteed



Solution includes simultaneously the capacity portfolio and economic dispatch; Mathematical approach can lead to very large problem size (x10^6 var. and eq.)

High Level Mathematical Formulation

Objective Function

$$\min \mathrm{C} = \sum_m \mathrm{RTCharge}_m + \sum_m \sum_t \sum_h \sum_u URLoad_{m,t,h,u} \cdot \mathrm{RTEnergy}_{m,t,h} + \sum_s \sum_{m \in s} \sum_p \mathrm{RTPower}_{s,p} \cdot \max\left(\sum_{u \in eo,cl,rf} URLoad_{m,(t,h) \in p,u}\right) + \sum_j \sum_m \sum_t \sum_h \left(GenS_{j,m,t,h} + \sum_u GenU_{j,m,t,h,u}\right) \cdot \left(\mathrm{DERCostkWh}_{j,m} + \mathrm{DEROMvar}_j\right) + \sum_g InvGen_g \cdot \mathrm{DERmaxp}_g \cdot \left(\mathrm{DERcapcost}_g \cdot \mathrm{AnnuityF}_g + \mathrm{DEROMFix}_g\right) + \sum_{i \in c,k} (\mathrm{CFixcost}_i \cdot Pur_i + \mathrm{CVarcost}_i \cdot Cap_i + \mathrm{CDVarcost}_k \cdot SCRate_k) \cdot (\mathrm{AnnuityF}_i + \mathrm{DEROMFix}_i) + \sum_m \mathrm{NGBSF}_m + \sum_m \sum_t \sum_h \sum_u NGP_{m,t,h,u} \cdot \mathrm{NGPrice}_m - \sum_j \sum_m \sum_t \sum_h GenS_{j,m,t,h} \cdot \mathrm{RTEExport}_{m,t,h} \quad (1)$$

Key Constrains

$$\mathrm{Cload}_{m,t,h,u} + \frac{SInput_{k,m,t,h}}{\mathrm{SCEff}_k} = SOutput_{k,m,t,h,u} \cdot \mathrm{SDEff}_k + \sum_j GenU_{j,m,t,h,u} + URLoad_{m,t,h,u} \quad \forall m,t,h: k = \{ES\} \wedge u = \{eo\} \quad (2)$$

$$\mathrm{Cload}_{m,t,h,u} + \frac{SInput_{k,m,t,h}}{\mathrm{SCEff}_k} + Aload_{m,t,h} = SOutput_{k,m,t,h,u} \cdot \mathrm{SDEff}_k + \beta_u \cdot NGP_{m,t,h,u} + \sum_g RecHeat_{g,m,t,h,u} \quad \forall m,t,h: k = \{TH\} \wedge u \in \{sh, wh\} \quad (3)$$

$$\mathrm{Cload}_{m,t,h,u} = \sum_j GenU_{j,m,t,h,u} + URLoad_{m,t,h,u} \cdot \mathrm{COPu} \quad \forall m,t,h : u \in \{cl, rf\} \quad (4)$$

$$\mathrm{Cload}_{m,t,h,u} = NGP_{m,t,h,u} \quad \forall m,t,h : u = \{ng\} \quad (5)$$

$$\sum_u GenU_{g,m,t,h,u} + GenS_{g,m,t,h} \le InvGen_g \cdot \mathrm{DERmaxp}_g \quad \forall g,m,t,h \quad (6)$$

$$\sum_m \sum_t \sum_h \left(\sum_u GenU_{g,m,t,h,u} + GenS_{g,m,t,h}\right) \le InvGen_g \cdot \mathrm{DERmaxp}_g \cdot \mathrm{DERhours}_g \quad \forall g,m,t,h \quad (7)$$

$$\sum_u RecHeat_{g,m,t,h,u} \le \alpha_g \cdot \left(\sum_u GenU_{g,m,t,h,u} + GenS_{g,m,t,h}\right) \quad \forall g,m,t,h \quad (8)$$

$$Cap_i \le Pur_i \cdot \mathbf{M} \quad \forall i \in \{c,k\} \quad (9)$$

$$\sum_u GenU_{c,m,t,h,u} + GenS_{c,m,t,h} \le Cap_c \cdot \frac{\mathrm{ScEff}_{c,m,h}}{\mathrm{ScPeakEff}_c} \cdot \mathrm{Solar}_{m,t,h} \quad \forall m,t,h : c \in \{PV\} \quad (10)$$

$$\sum_c \frac{Cap_c}{\mathrm{ScPeakEff}_c} \le \mathrm{ScArea} : c \in \{PV\} \quad (11)$$

$$SOC_{k,m,t,h} = SInput_{k,m,t,h} - \sum_u SOutput_{k,m,t,h,u} + SOC_{k,m,t,h-1} \cdot (1 - \varphi_k) \quad \forall k,m,t,h \neq 1 \quad (12)$$

$$SOC_{k,m,t,1} = SOC_{k,m,t,24} \quad \forall k,m,t \quad (13)$$

$$SOC_{k,m,t,h} \ge Ecap_k \cdot \mathrm{MSC}_k \quad \forall k,m,t,h \quad (14)$$

$$SOC_{k,m,t,h} \le Ecap_k \quad \forall k,m,t,h \quad (15)$$

$$SInput_{k,m,t,h} \le Cap_k \quad \forall k,m,t,h \quad (16)$$

$$\sum_u SOutput_{k,m,t,h,u} \le Cap_k \quad \forall k,m,t,h \quad (17)$$

$$SInput_{k,m,t,h} \le ebiou_{k,m,t,h} \cdot \mathbf{M} \quad \forall k,m,t,h \quad (18)$$

$$\sum_u SOutput_{k,m,t,h,u} \le \left(1 - ebiou_{k,m,t,h}\right) \cdot \mathbf{M} \quad \forall k,m,t,h \quad (19)$$

$$GenU_{j,m,t,h,u} = Aload_{m,t,h} \cdot \mathrm{COPa} \quad \forall m,t,h : j = \{AC\} \wedge u = \{cl, rf\} \quad (20)$$

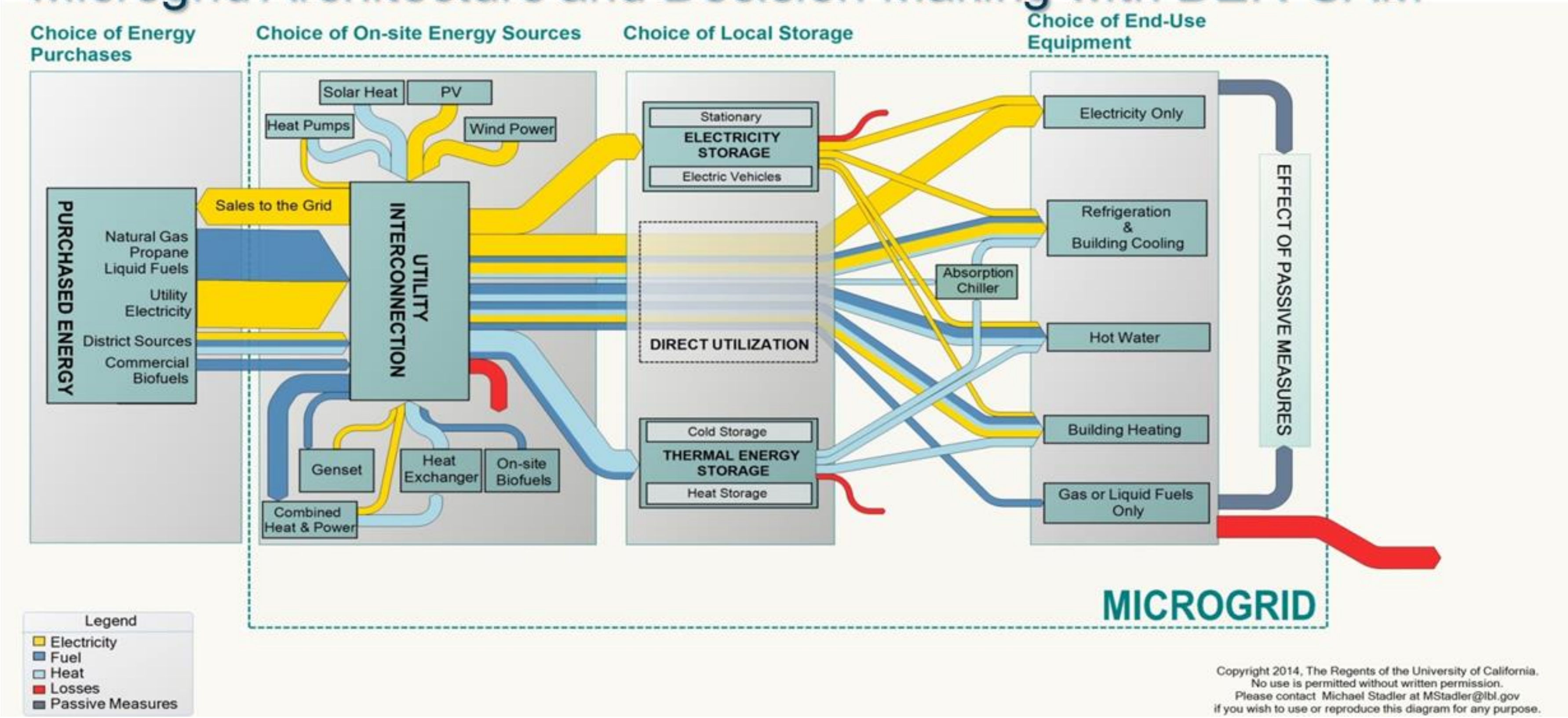
$$\sum_u URLoad_{m,t,h,u} \le psb_{m,t,h} \cdot \mathbf{M} \quad \forall m,t,h : u = \{eo, cl, rf\} \quad (21)$$

$$GenS_{j,m,t,h} \le \left(1 - psb_{m,t,h}\right) \cdot \mathbf{M} \quad \forall j,m,t,h \quad (22)$$

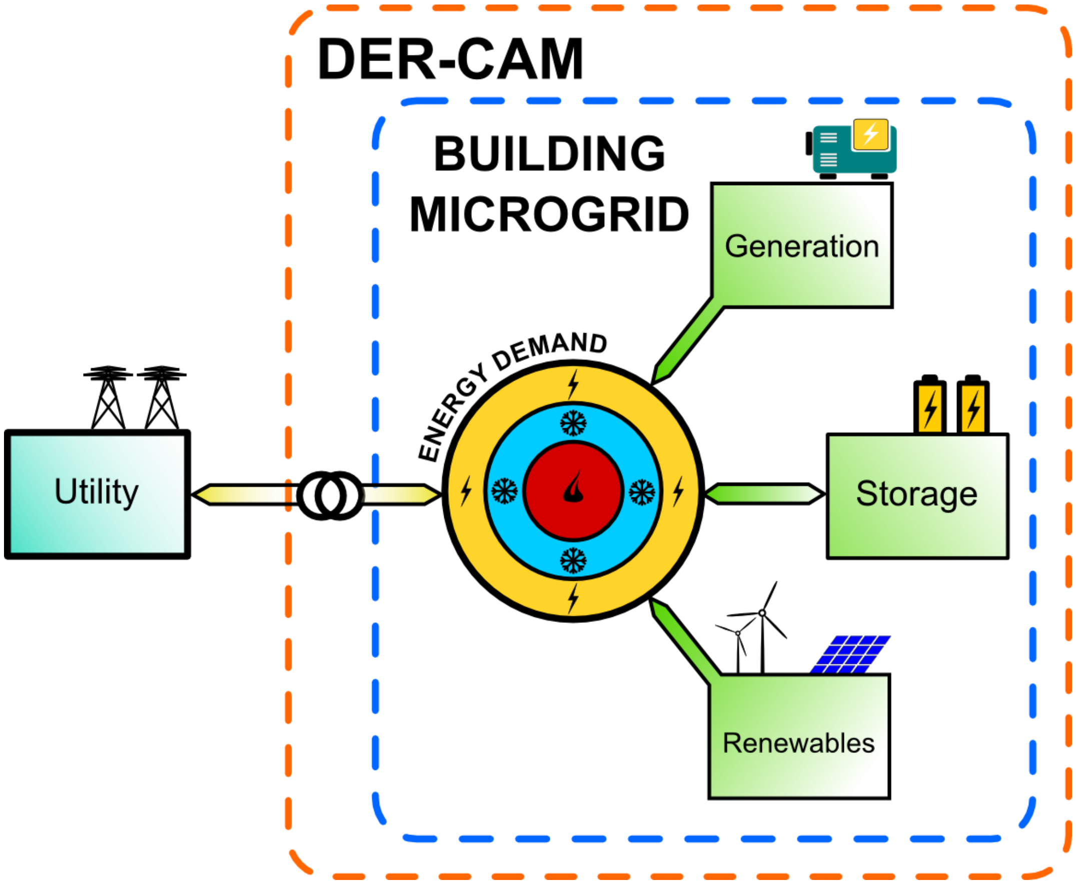
$$\mathrm{AnnuityF}_i = \frac{\mathrm{IntRate}}{\left(1 - \frac{1}{(1+\mathrm{IntRate})^{\mathrm{DERLifetime}_i}}\right)} \quad \forall i \quad (23)$$

$$\mathrm{C} \le \mathrm{BAUCost} + \sum_g InvGen_g \cdot \mathrm{DERmaxp}_g \cdot \mathrm{DERcapcost}_g \cdot \mathrm{AnnuityF}_g + \sum_{i \in c,k} (\mathrm{CFixcost}_i \cdot Pur_i + \mathrm{CVarcost}_i \cdot Cap_i) \cdot \mathrm{AnnuityF}_i - \quad (24)$$

Microgrid Architecture and Decision Making with DER-CAM



DER-CAM handles complex interactions between different technologies, tariffs, loads, technical constraints (e.g. max. charging rate of batteries), and economic constraints (e.g. max. payback periods)



Main Features / Technologies

Distributed Generation

Combustion engines, fuel cells, micro-turbines, CHP, photovoltaic, solar thermal panels, wind turbines

Energy Storage

Stationary storage, electric vehicles, heat storage, cooling storage

Energy Management

Demand response, load shifting, load shedding

Passive technologies

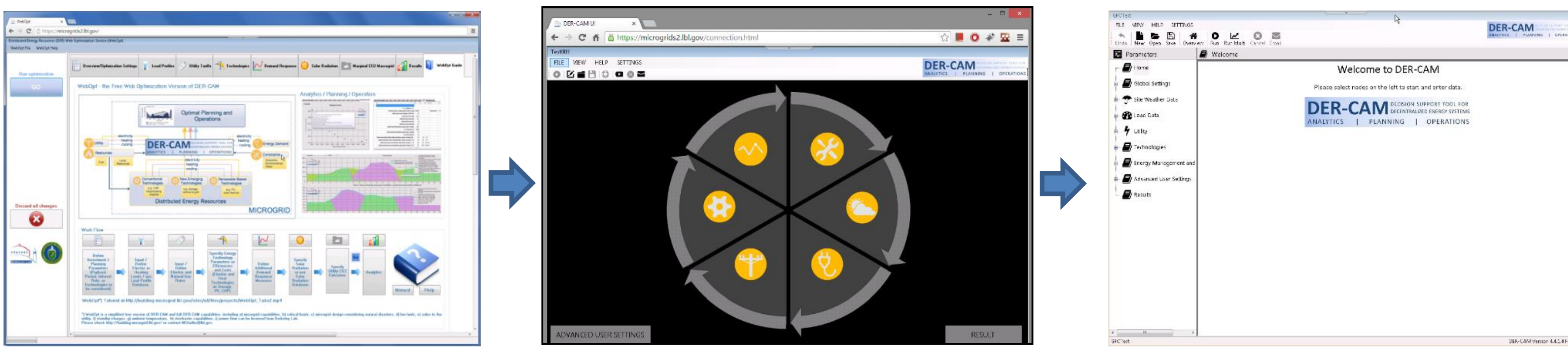
Building shell replacements (windows, doors, insulation)

Roadmap

Recent developments
- Multiple location support
- (Simplified) Power flow
- Fast cloud cover changes
- Tariff database

Work in progress
- Improved battery model
- Improved PV model
- …

DER-CAM's GUI Evolution



https://building-microgrid.lbl.gov/projects/how-access-der-cam

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APPLICATION 1

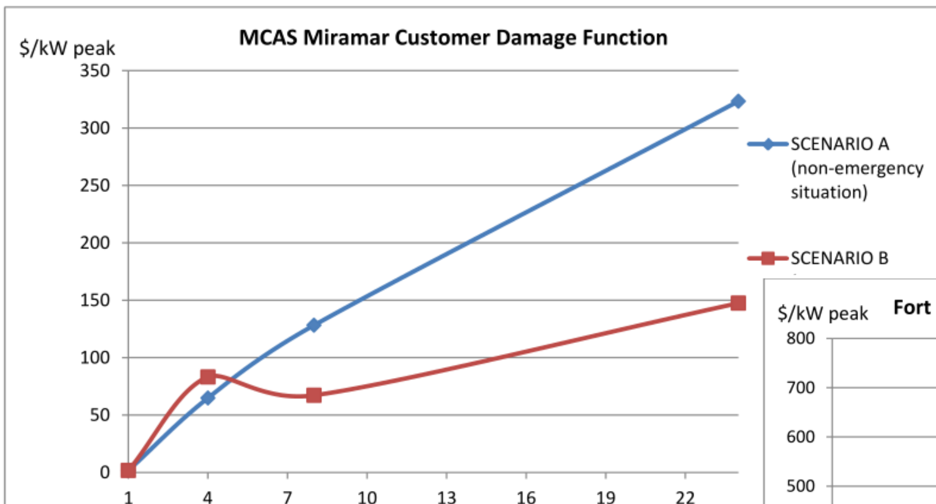
Using ***Investment & Planning*** ***DER-CAM*** to assess microgrid DER considering prolonged outages

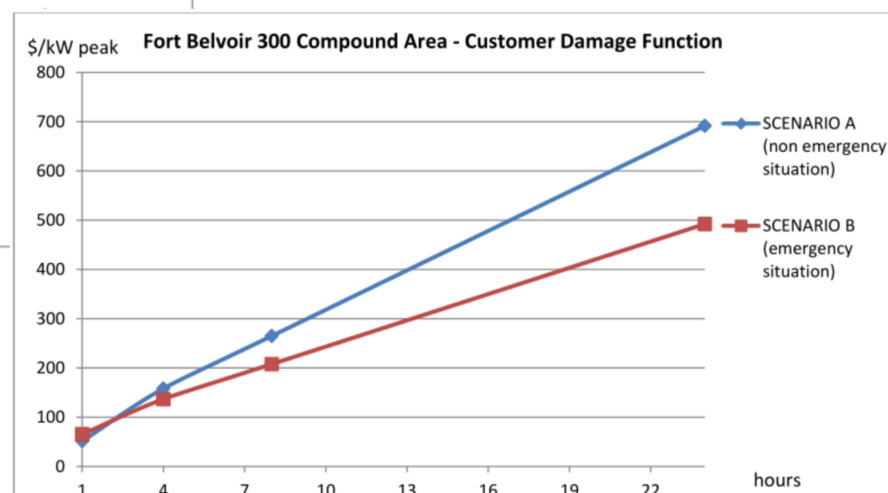
(DER-CAM v4.1.4; GUI v1.5.0)

Establishing Value of Lost Load (VoLL) / Customer Damage Function (CDF)

VoLL / CDF used to estimate outage costs as a function of the outage duration.

*Outage Cost ~ Outage Duration * $/kW peak * Demand*





Source:
Valuing Energy Security: Customer Damage Function Methodology and Case Studies at DoD Installations, NREL

Example: Large Office Building in Baltimore, Maryland

Procedure:

1) Simple Reference Case

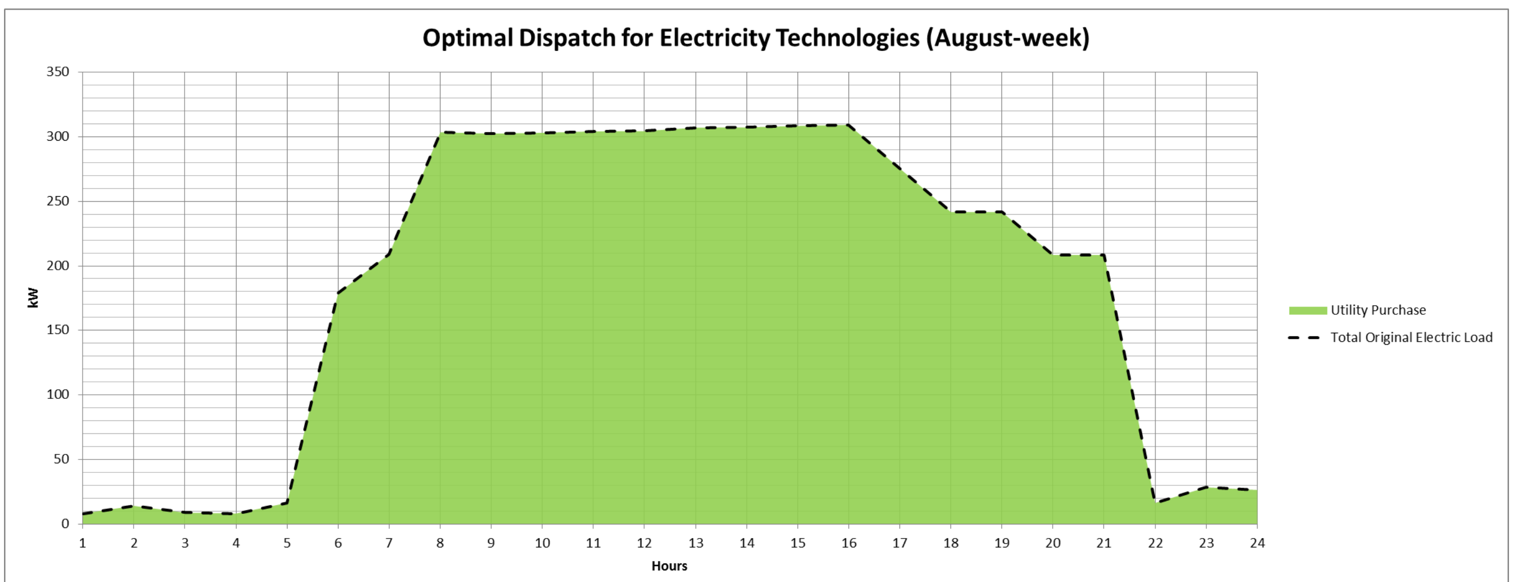
2) Outage Reference Case
- 2 day blackout in August
- 25% Critical Load (high priority); 50$/kW
- 75% Non-critical load:
  - 50% medium priority; 15$/kW
  - 25% low priority; 3$/kW

3) Resiliency Investment Case
- PV and Storage options

SCENARIO 1 : Simple Reference Case

Large Office Building in Baltimore, Maryland

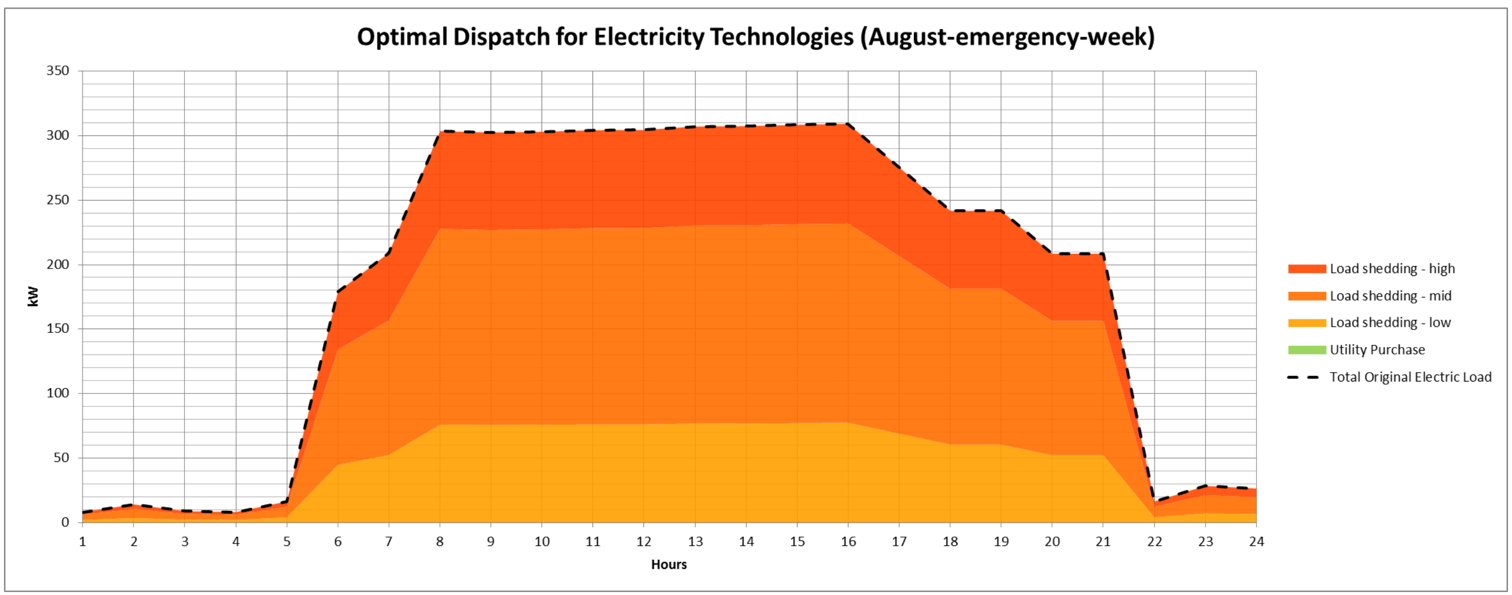
Annual energy costs ~ US$ 123k
All needs are met by utility purchase



SCENARIO 2: *Outage* Reference Case

Large Office Building in Baltimore, Maryland

Annual energy costs ~ US$ 307k
All load is curtailed

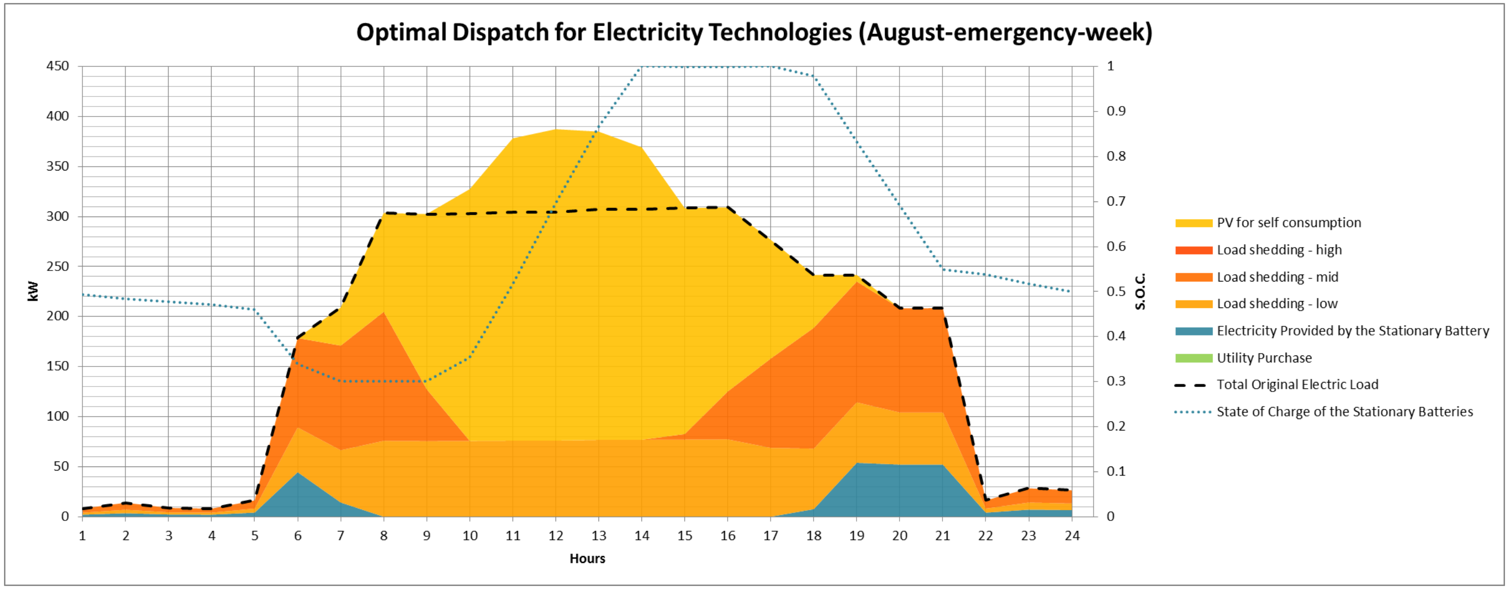


SCENARIO 3: Investment Case considering Outages

Large Office Building in Baltimore, Maryland

~400 kW PV
~400kWh Battery

Annual energy costs ~ US$ 196k
Some load is still curtailed in the event of a prolonged outage



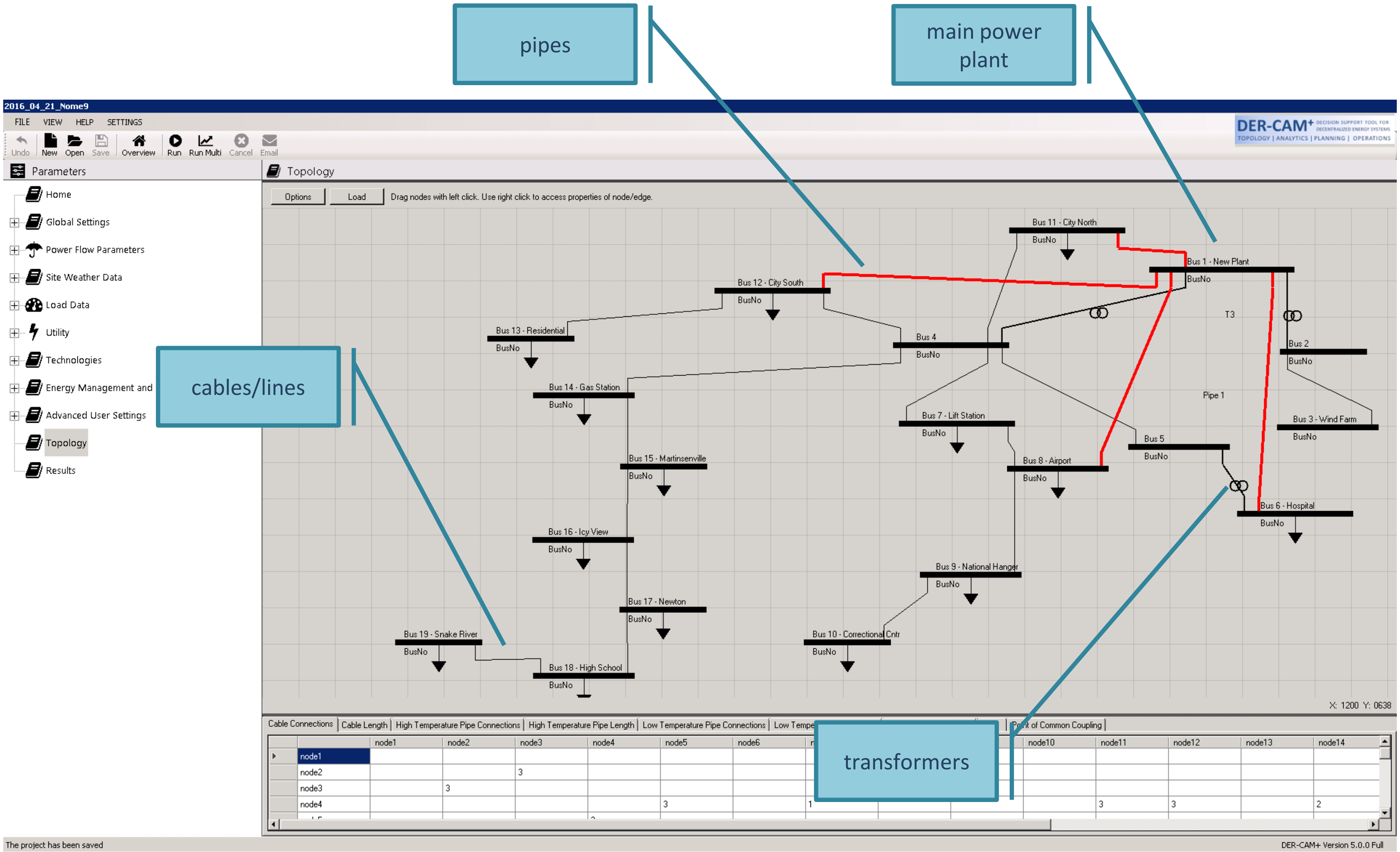
APPLICATION 3

Using ***Investment and Planning*** ***DER-CAM*** to design multi-node *microgrids* ***(DER-CAM+)***

(DER-CAM v5.0.0; GUI v2.0.0-alpha)

DER-CAM+ DECISION SUPPORT TOOL FOR DECENTRALIZED ENERGY SYSTEMS

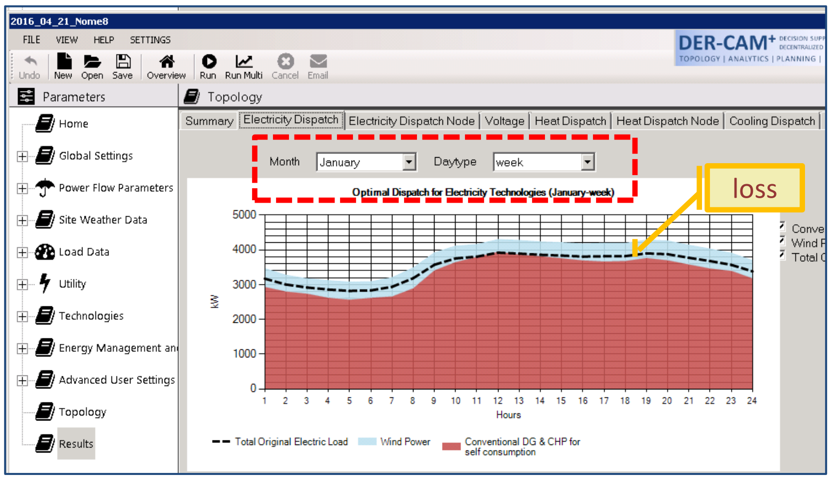
TOPOLOGY | ANALYTICS | PLANNING | OPERATIONS

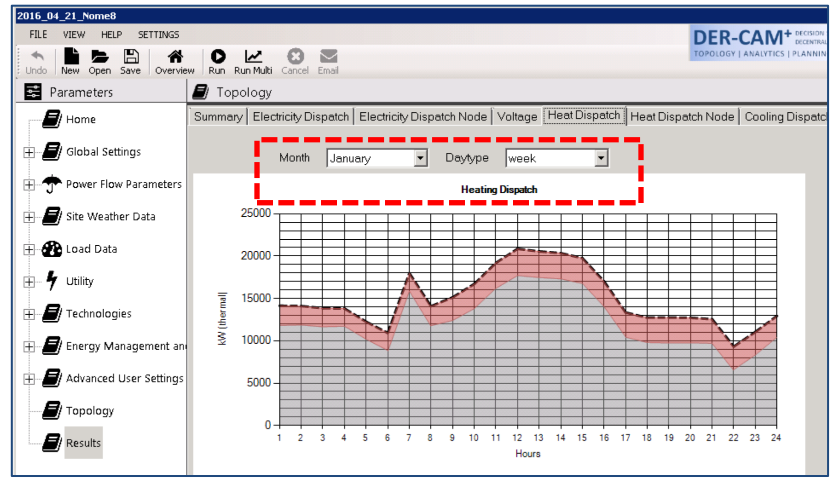


DER-CAM+ DECISION SUPPORT TOOL FOR DECENTRALIZED ENERGY SYSTEMS

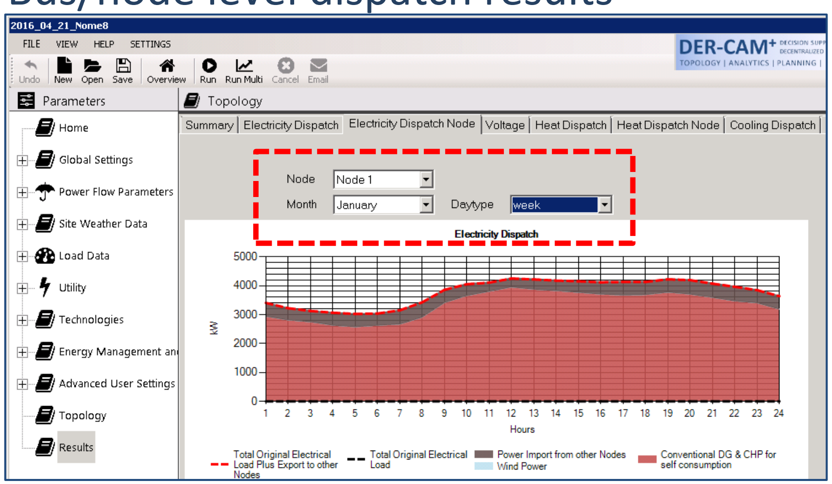
TOPOLOGY | ANALYTICS | PLANNING | OPERATIONS

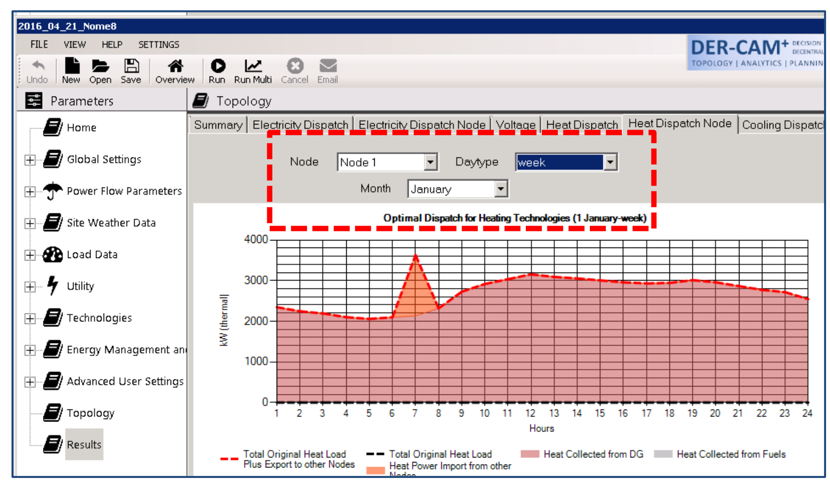
Aggregated dispatch results





Bus/node level dispatch results

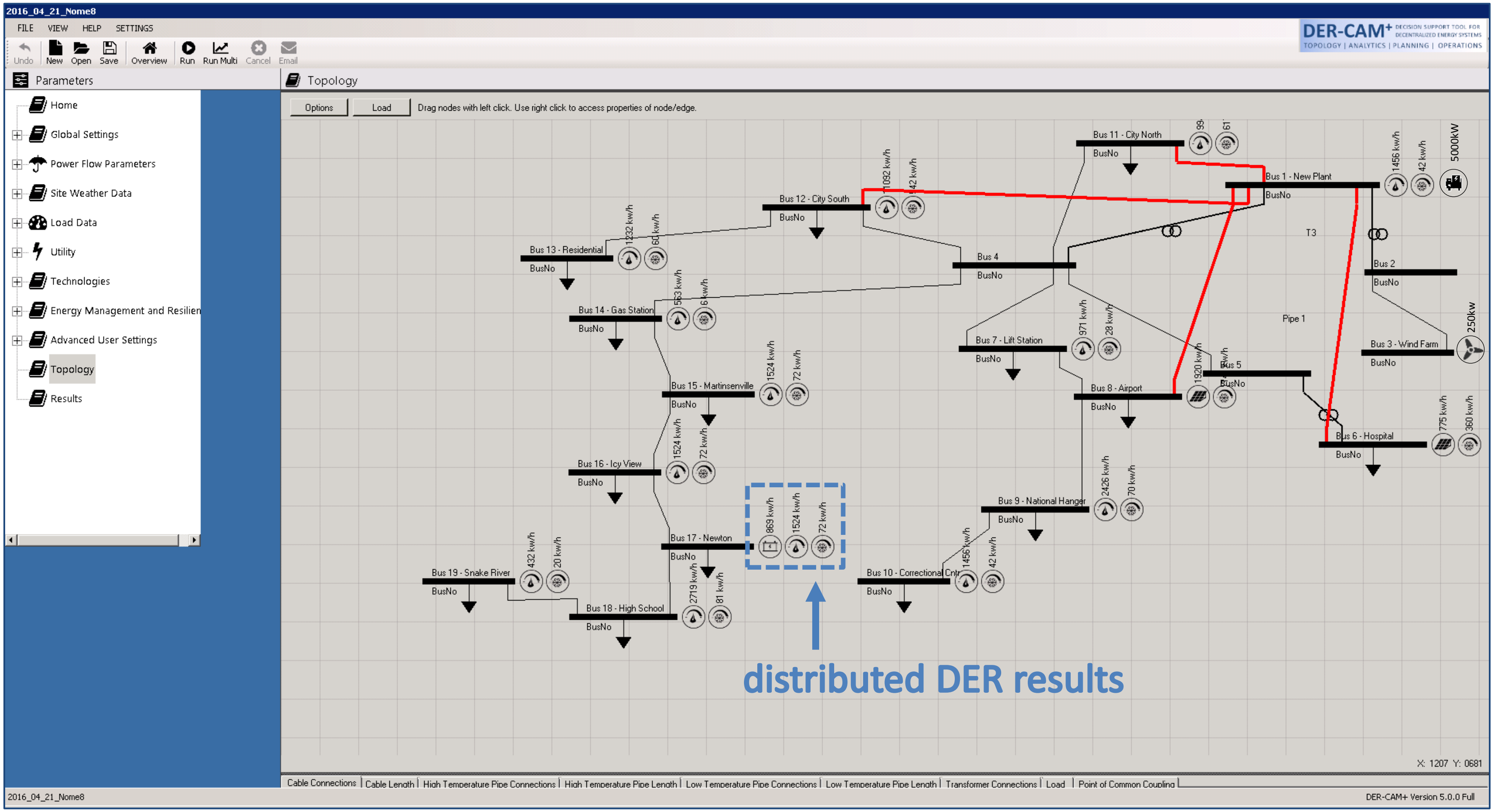




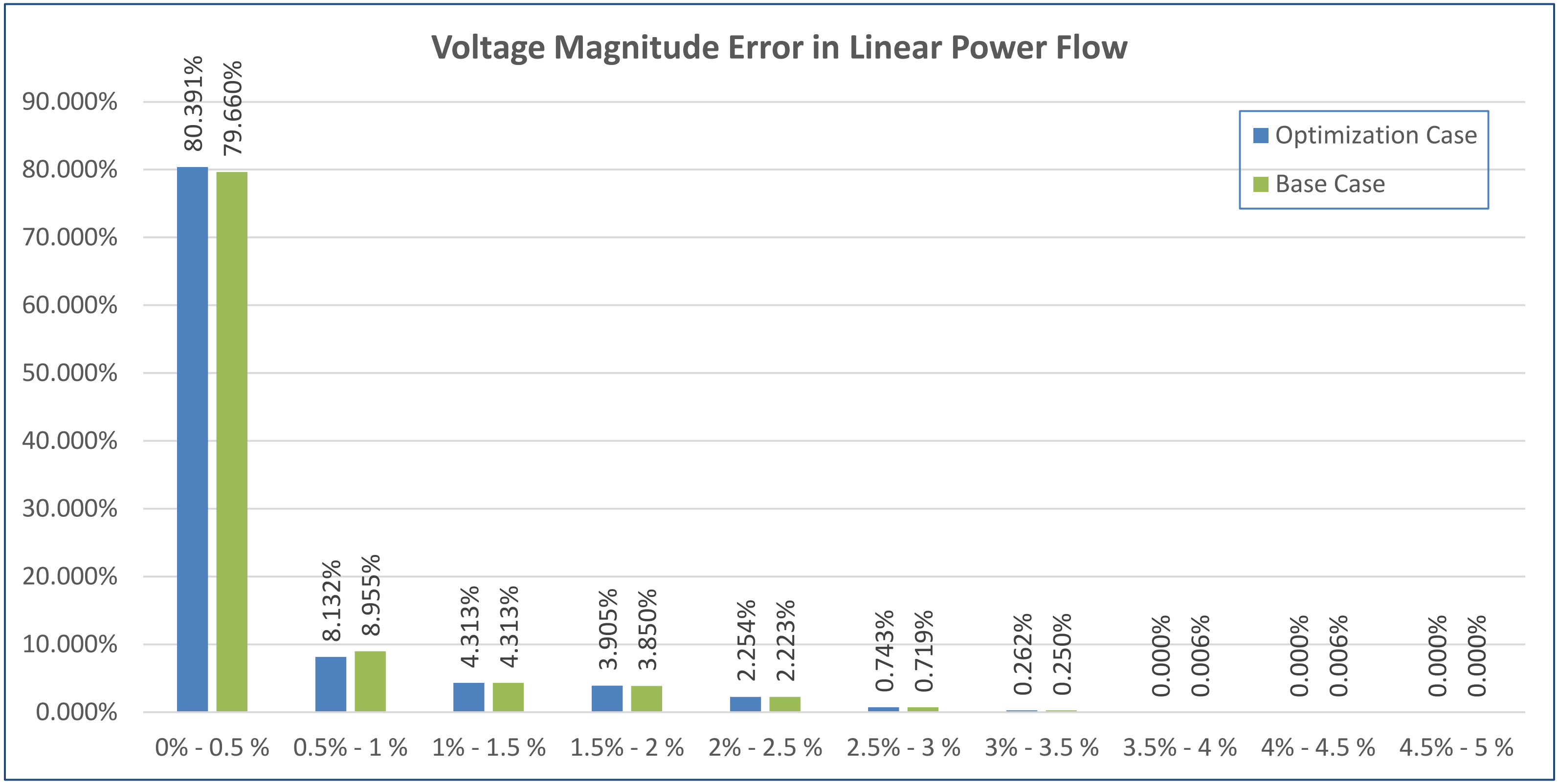
DER-CAM+ DECISION SUPPORT TOOL FOR DECENTRALIZED ENERGY SYSTEMS

TOPOLOGY | ANALYTICS | PLANNING | OPERATIONS

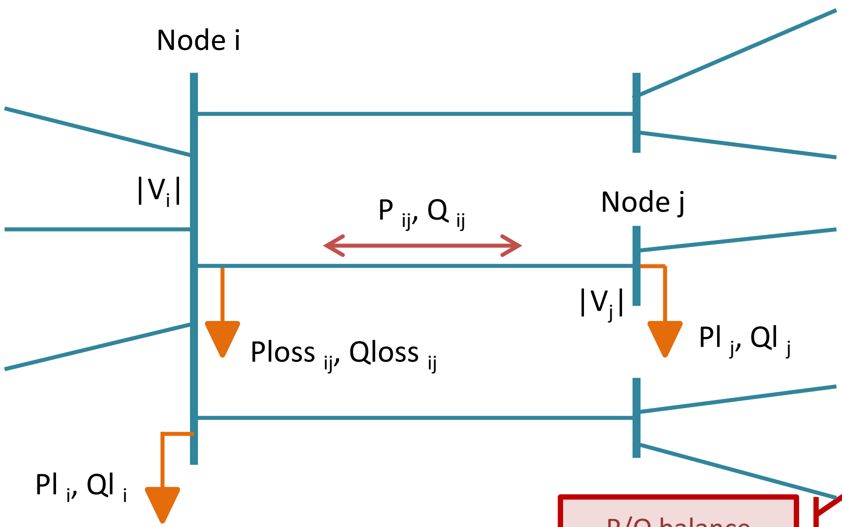
Displaying the investment results on the sys. diagram



- The integrated power flow (LinDistFlow with loss) performs well
- In the two cases, 80% of the voltage data points have an error less than 0.5% (compared to exact solution from GridLAB-D)



- Power flow equations are included:
  - model: enhanced (w/ loss) LinDistFlow applicable to radial distribution networks (separate model also included for meshed networks)
  - models active and reactive power flow in the network
  - models active and reactive power losses in the network
  - imposes voltage magnitude and cable power capacity constraints



Voltage approximation

$$|V_i|^2 - |V_j|^2 = VSq_i - VSq_j \cong 2 \times (r_{ij}P_{ij} + x_{ij}Q_{ij})$$

P/Q balance constraint

$$Pg_i - Pl_i - \sum_j Ploss_{ij} = \sum_j P_{ij}$$

$$Qg_i - Ql_i - \sum_j Qloss_{ij} = \sum_j Q_{ij}$$

P/Q Loss approximation

$$Ploss_{ij} = r_{ij} \times |I_{ij}|^2 = r_{ij} \times \frac{P_{ij}^2 + Q_{ij}^2}{|V_i|^2} \cong r_{ij} \times (P_{ij}^2 + Q_{ij}^2) \cong r_{ij} \times (PSq_{ij} + QSq_{ij})$$

$$Qloss_{ij} \cong r_{ij} \times (PSq_{ij} + QSq_{ij})$$

Piecewise linearization of P^2 and Q^2

APPLICATION 3

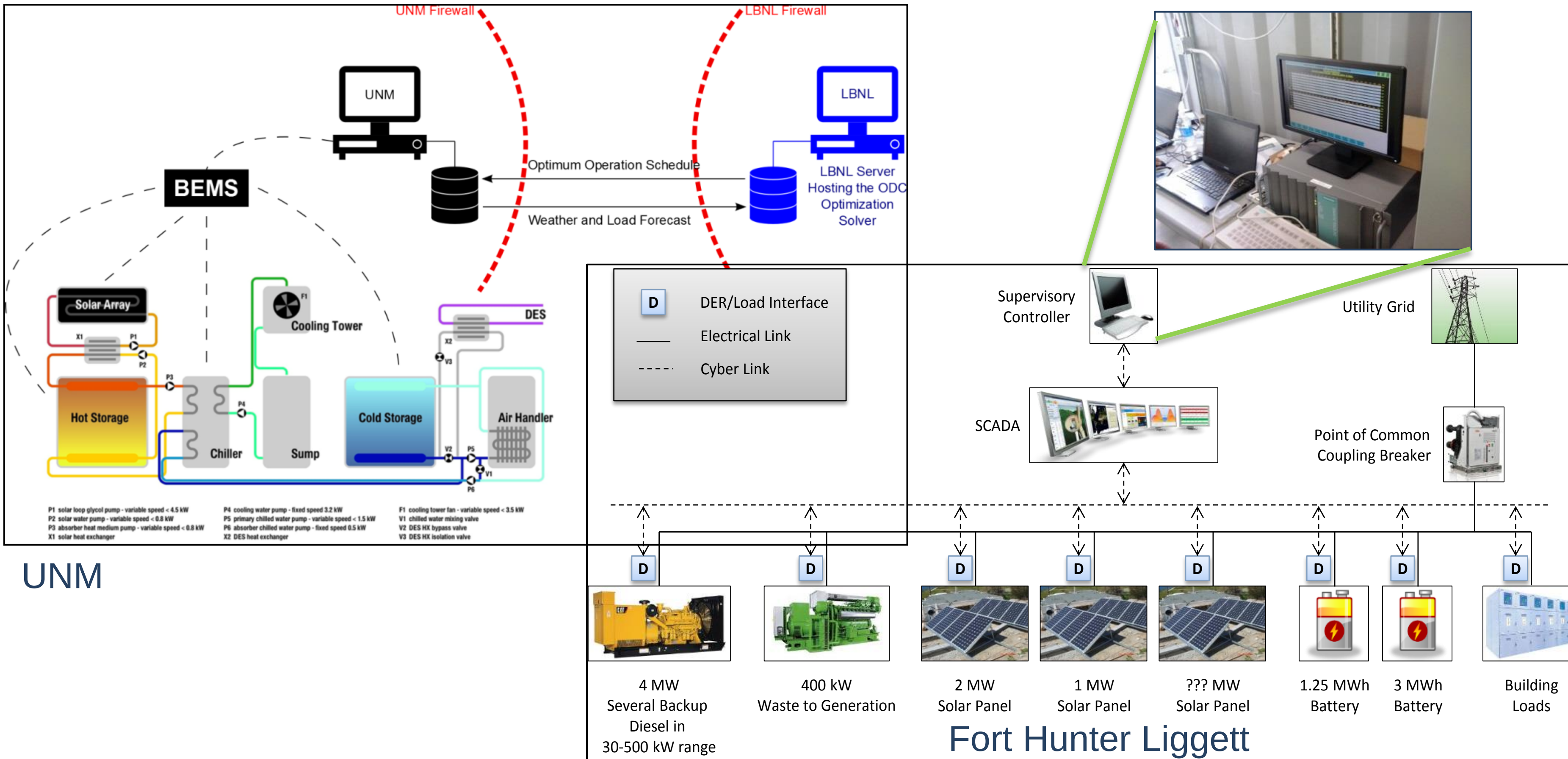
Using ***Operations*** ***DER-CAM*** to optimize local DER dispatch (MPC)

DER-CAM DECISION SUPPORT TOOL FOR DECENTRALIZED ENERGY SYSTEMS

ANALYTICS | PLANNING | OPERATIONS

DER-CAM for Optimal microgrid operation

(e.g. used at a Univ. of New Mexico UNM building and Fort Hunter Liggett)



UNM

Fort Hunter Liggett

USING DER-CAM

Workflow & the GUI v1.5.0

https://building-microgrid.lbl.gov/projects/der-cam

Understanding DER-CAM

Objective function:

Minimize total energy costs (or CO2) such that:

- energy balance is preserved
  - energy supply (t) = energy demand (t)
- technologies operate within physical boundaries
  - power output (t) <= max output
- ***financial constrains are verified***
  - **max payback**: savings obtained by the use of new DER must generate savings that repay investments within the max payback period

⇩

To use DER-CAM, ***at least*** two runs are needed: 1) Base Case; 2) Investment

1) Defining the Base Case

- Energy loads
  - 3 day-types: workday; weekend; peak
- Tariffs
  - time of use energy and power charges
- Existing technologies
  - CHP? PV?
- Load management strategies
  - Load shifting? Demand response?

Run DER-CAM
Save Total Energy Costs
(Total CO_2 emissions)

2) Defining the investment run

- New technologies to consider?
- New load management strategies to consider?

Run DER-CAM

Understanding Results

Max Payback

- DER-CAM uses technologies with different lifetimes
- "Max Payback" is a global payback
- Acts as a constrain

Min (total energy costs) such that annual savings / investment <= Max Payback

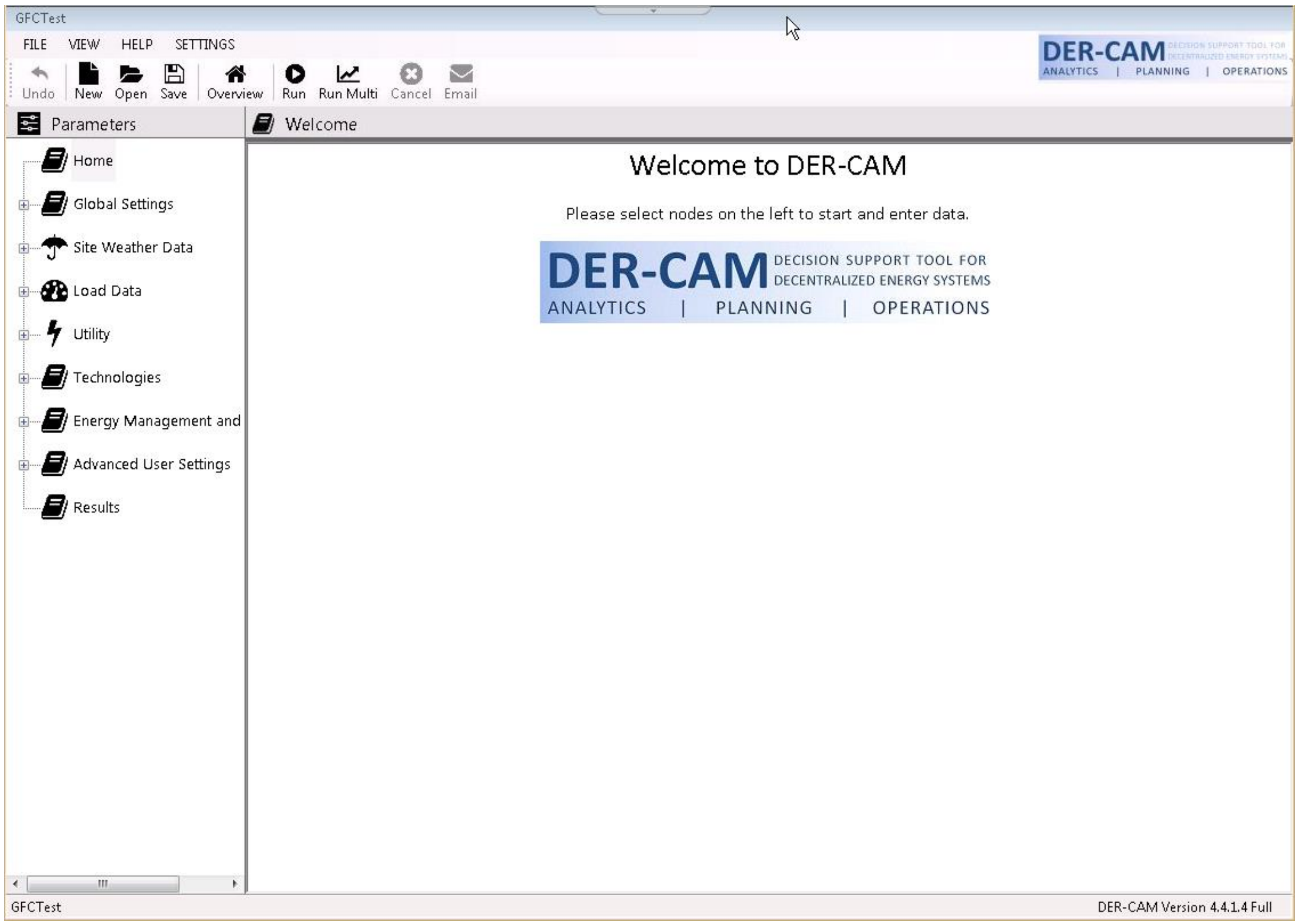
Annualized Capital Costs

- Different technology lifetimes require a method to compare them fairly
- Annualized Capital Cost is the cost per year of owning the equipment
- Total Energy Costs will include Annualized Capital Costs

Optimization algorithm

- "Greedy" approach
  - More of what is most efficient
- Solver precision & problem size
  - Flat solution space
- Indifferent preference
  - Cost vs. Benefit

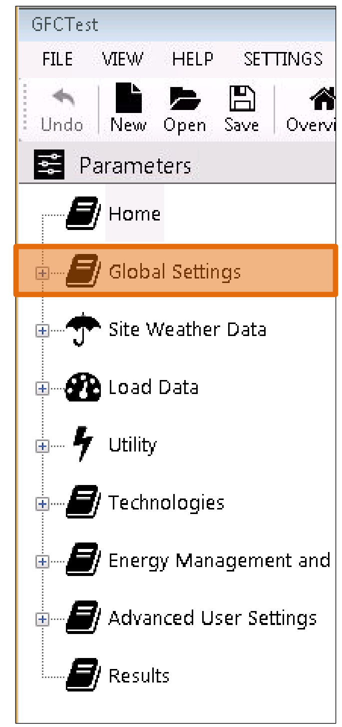
Graphical User Interface v1.5.0



Graphical User Interface

<u>General Options</u>

- Define the type of run
- Define objective function
- Select financial parameters
  - Discount rate
  - Max Payback
  - Reference costs
- Enable desired technology groups

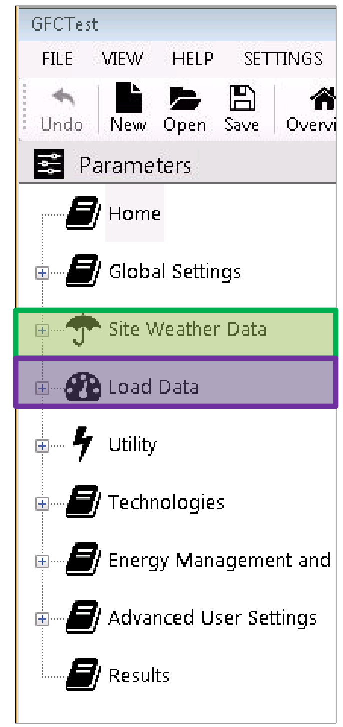


Graphical User Interface

<u>Data collection</u>

- Site / Weather information
    - Solar radiation
    - Ambient temperature

- End-use loads
    - Electricity
    - Cooling
    - Refrigeration
    - Space Heating
    - Water Heating
    - NG loads (cooking)

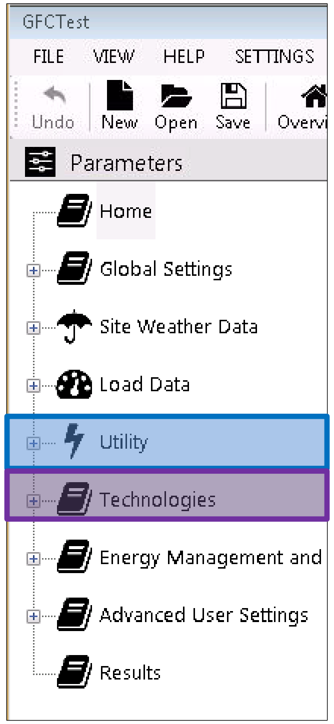


Graphical User Interface

<u>Data collection</u>

- Tariffs
  - Electric Costs
    - Fixed costs
    - Variable costs
      - TOU volumetric and power charges
  - Fuel costs

- Technologies
  - Capital costs
  - O&M Costs
  - Rated capacity
  - Efficiency
  - Charge / Discharge rate
  - Heat recovery



Graphical User Interface

<u>Data collection</u>

- Load management options
  - Demand response
  - Directly controllable loads
  - Load shifting
  - Resiliency
    - Outage costs
    - Utility outages
    - Load curtailments

THE END

Contact Information:
Michael Stadler
MStadler@lbl.gov
https://building-microgrid.lbl.gov/