DER-CAM+ DECISION SUPPORT TOOL FOR DECENTRALIZED ENERGY SYSTEMS

TOPOLOGY | ANALYTICS | PLANNING | OPERATIONS

Training Workshop: Applying DER-CAM

August 18th, 2016

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https://building-microgrid.lbl.gov/
https://gig.lbl.gov

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IEEE

Outline

- DER-CAM optimization formulation & characteristics
- Recent development work:
  - Ancillary services market (formulation & case study)
  - Multi-locational DER-CAM with electricity and heat transfer networks (formulation & case study)
- Using DER-CAM

DER-CAM Optimization

- I&P DER-CAM determines:
  - Optimal technology portfolio
  - Optimal technology sizes
  - Optimal technology placement
  - Optimal dispatch

  Such that:
  - Annual investment and operation cost (or CO_2) is minimized
- Formulated as a Mixed Integer Linear Program (MILP)

DER-CAM Optimization Main Blocks

To use DER-CAM, at least two runs are needed: 1) base case; 2) investment

Objective function (e.g., minimize annual energy cost for a typical year)

+ energy purchase costs
+ amortized DER technology capital costs
+ annual operation and maintenance costs
+ CO_2 costs
- energy sales

Financial constraints

- maximum allowed payback period

Energy balance (at each node)

+ energy purchase from utility at the node
+ energy generated at the node
+ energy imported from other nodes
= node demand
- demand response
- energy sales to the utility at the node
- Energy exported to other nodes

Storage and DR constraints

- electricity stored limited by battery size
- heat/cold storage limited by reservoir size

Regulatory constraints

- minimum efficiency requirement
- emission limits
- CO_2 tax
- zero-net-energy

Operational constraints

- generations, chillers, etc., operating within performance limits
- heat recovered limited by generated waste heat
- solar irradiation and wind speed
- footprint constraint

Base Case vs. Investment Runs

- Defining the base case run
  - 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)

- Defining the investment run
  - New technologies to consider?
  - New load management strategies to consider?

Run DER-CAM

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Ancillary Service Markets Modeling

- Four AS products considered:
  - Spinning reserves
  - Non-Spinning Reserves
  - Up-Regulation
  - Down-Regulation
- Key assumptions:
  - Building/microgrid is a price taker
  - Historic market clearing prices are used
  - All bids (at clearing prices) are won
  - Currently only generators and storage systems can provide AS
  - Effective utilization ratio is currently constant (does not depend on time of day)

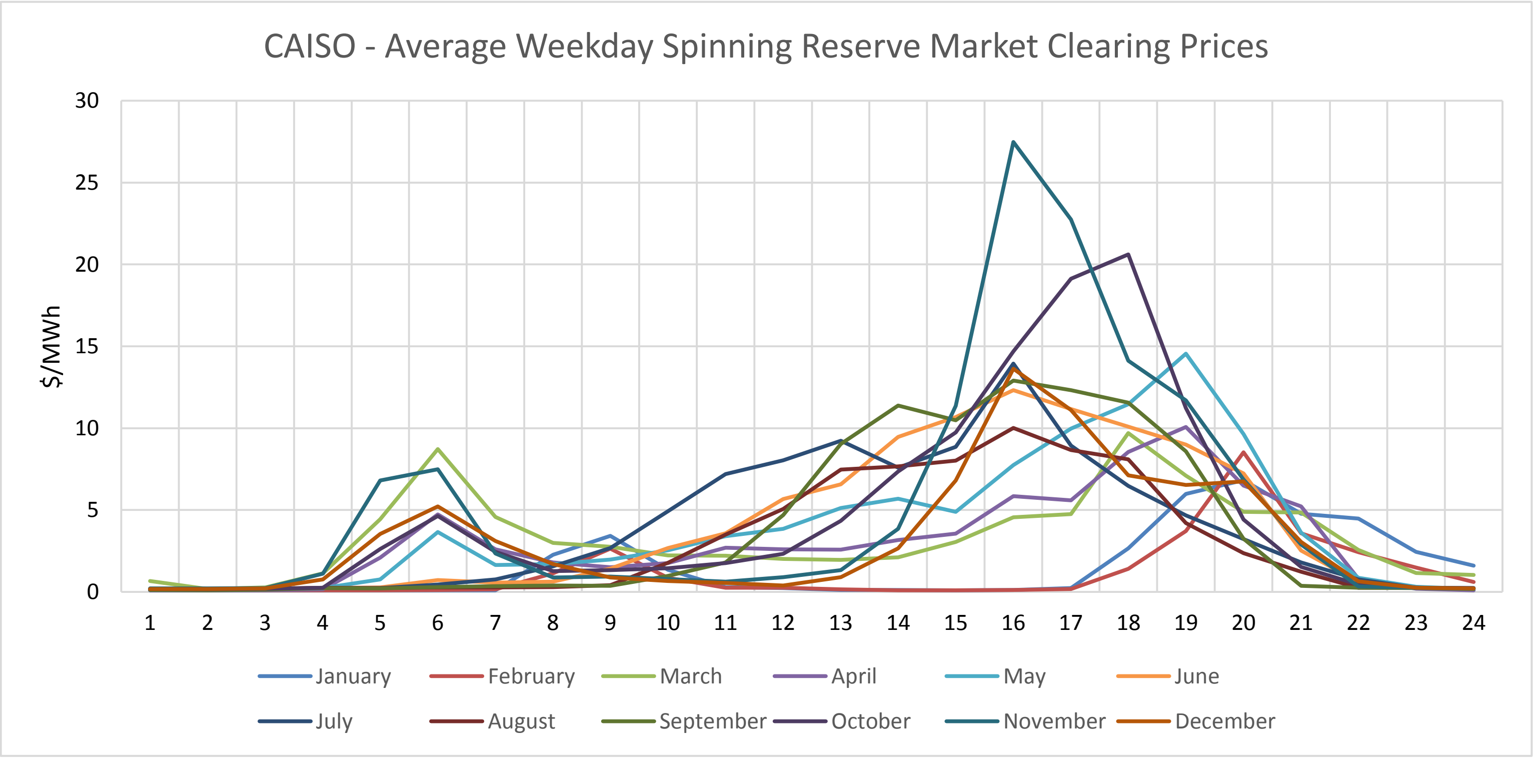
AS Markets Modeling – Key Inputs

- DER characteristics:
  - Time to start (black start)
  - Ability to ramp
  - Frequency regulation (Y/N?)
- Market information:
  - Clearing prices
  - Effective utilization ratio
- Market requirements:
  - Max. time to start
  - Max. time to ramp
  - Symmetric AS bids (Y/N?)
  - Min. bid
  - Min. bid duration
  - Min. asset size

AS Markets – Case Study

- Case-study: Analyze the impact of AS market participation in optimal DER investment decisions
- Building/Microgrid cases:
  - Residential
  - Office
  - Hospital
  - Aggregated (Residential + Office + Hospital)
- Service territories:
  - CAISO + PG&E
  - PJM + BG&E
- AS Products:
  - Spinning, non-spinning, up-regulation, and down-regulation

AS Markets – Case Study for CAISO



Example of AS spinning reserve market clearing prices used for CAISO runs

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AS Markets – Case Study – Key Results for CAISO

Costs in US$	Hospital			Aggregated system		
	Base case	Simple investment	With AS	Base case	Simple investment	With AS
Total Annual Costs	1,385,310	1,164,147	1,157,303	1,517,047	1,264,577	1,249,716
Electricity Costs	1,239,299	255,314	323,248	1,360,328	264,103	278,942
Fuel costs	146,011	379,486	363,445	156,719	391,958	410,706
Ann. Cap. cost	0	424,787	374,744	0	502,786	450,362
O&M cost	0	104,560	100,325	0	105,729	113,324
AS Revenue	-	-	3,618	-	-	4460
CO_2 (kg)	5,533,957	3,668,595	3,712,145	5,973,834	2,175,789	3,986,516
PV (kW)	-	1075	999	-	1343	1111
Total DG (kW)	-	900	750	-	1000	1000
CHP (kW)	-	750	750	-	750	750
Overall ¢/kWh	10.37	8.72	8.67	10.54	8.79	8.68

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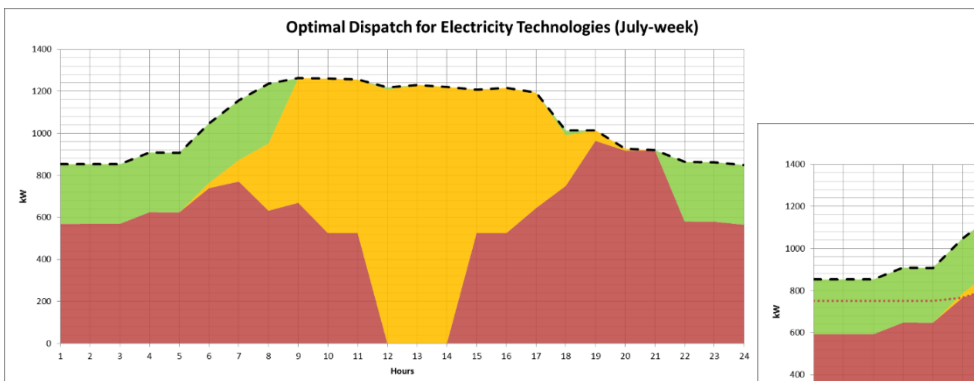
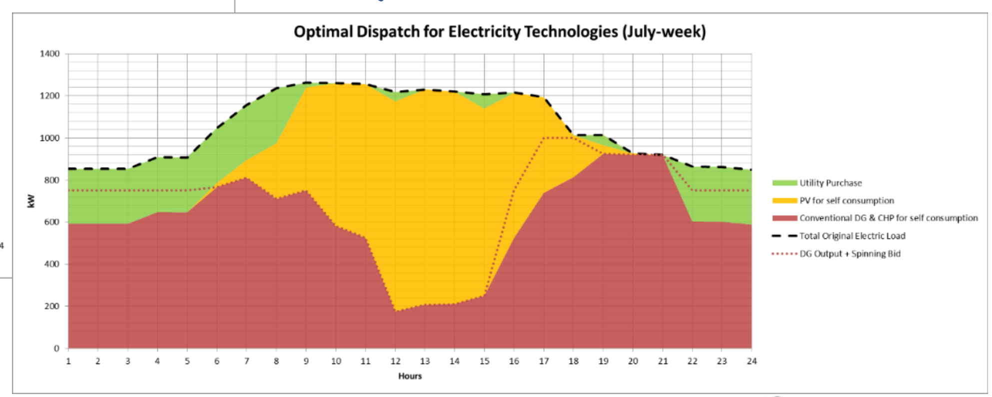
AS Markets – Case Study – Key Results for CAISO

- The impact of AS participation in overall annual costs was modest in all selected microgrid cases in CAISO.
- However, there was a noticeable impact in both investment portfolio and optimal dispatch:
  - Lower installed capacity overall
  - Higher capacity factor





AS Markets – Conclusions and Future Work

- Successful early development of AS market revenues in DER-CAM
- Four major products were included: spinning, non-spinning, up-regulation, and down-regulation
- Results show multiple behaviors depending on different market conditions
- Future work will expand range of AS-enabled DER
- Preliminary results suggest very high computational burden → potential solutions to be analyzed

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Multi-Node DER-CAM

- Multi-node vs. single-node aggregate modeling:
  - Energy balance at the node-level
  - Integration of power flow equations (2 models integrated)
  - Integration of heat transfer equations
- Benefits:
  - Ability to perform optimal DER allocation
  - Prevent under-estimation of DER sizes due to network constraints

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Multi-Node DER-CAM – Power Flow Model 1

- Applicable to both meshed and radial distribution networks (if the network meets a certain condition)
- Based on the model proposed in [Bolognani 2015]
- We enhanced the model by adding (active and reactive) losses
- Models active and reactive power flow in the network
- Imposes voltage magnitude and cable ampacity constraints

Bus voltage approximation

$$Vr_m(t) = V_0 + \frac{1}{V_0}\sum_{n\neq slack}\left(Zr_{m,n}\left(Pg_n(t) - Pl_n(t)\right) + Zi_{m,n}\left(Qg_n(t) - Ql_n(t)\right)\right)$$

$$Vi_m(t) = \frac{1}{V_0}\sum_{n\neq slack}\left(Zi_{m,n}\left(Pg_n(t) - Pl_n(t)\right) - Zr_{m,n}\left(Qg_n(t) - Ql_n(t)\right)\right)$$

Line current approximation

$$Ir_{m,n}(t) = Yr_{m,n}\left(Vr_n(t) - Vr_m(t)\right) - Yi_{m,n}\left(Vi_n(t) - Vi_m(t)\right)$$

$$Ii_{m,n}(t) = Yi_{m,n}\left(Vr_n(t) - Vr_m(t)\right) + Yr_{m,n}\left(Vi_n(t) - Vi_m(t)\right)$$

System loss approximation

$$\sum_m Pg_m(t) = \sum_m Pl_m(t) + \sum_m\sum_n zr_{m,n} \times I^{sq}_{m,n}(t)$$

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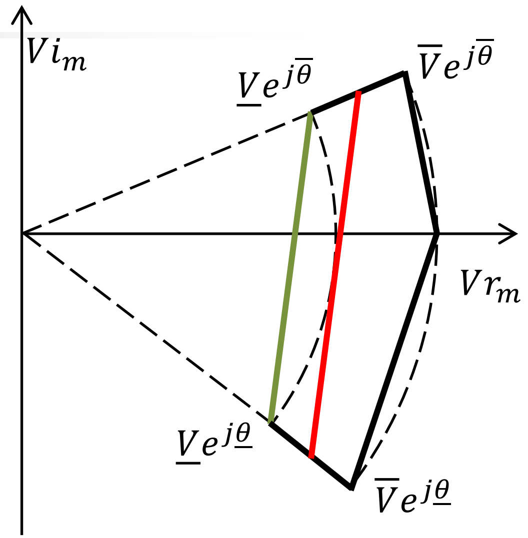
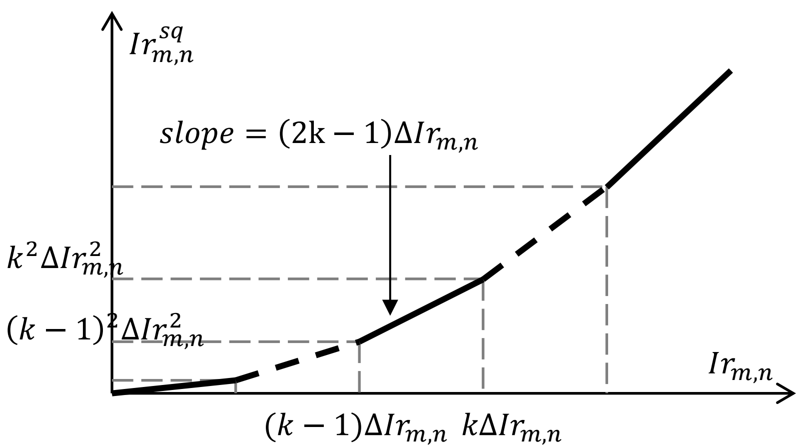
Multi-Node DER-CAM – Power Flow Model 1



Bus voltage constraints:

- Approximation based on [Franco 2013]
- Conservative on the upper bound
- Option for more or less binding constraint on the lower bound

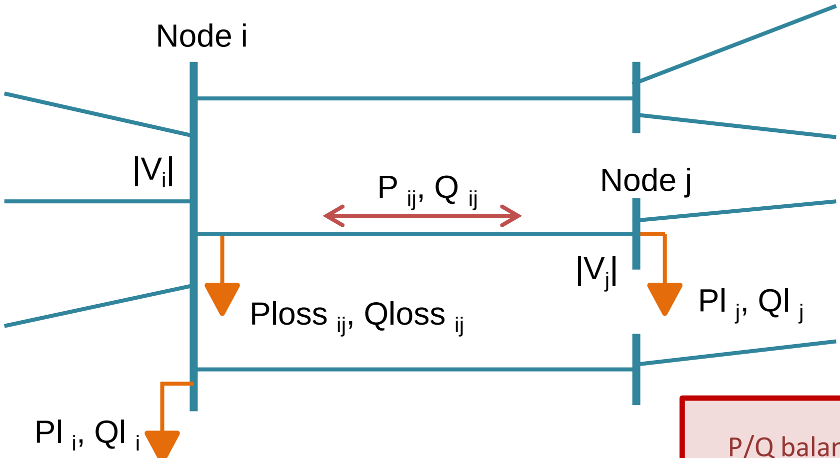


Current/power squared approximation:

- Using piece-wise linear approximation
- No binary variables needed due to the convex shape

Multi-Node DER-CAM – Power Flow Model 2

- Applicable to radial distribution networks
- Model based on LinDistFlow [Lingwen 2014]
- We enhanced the model by adding active/reactive losses
- Models active and reactive power flow in the network
- Imposes voltage magnitude and cable power 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

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

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

P/Q Loss approximation

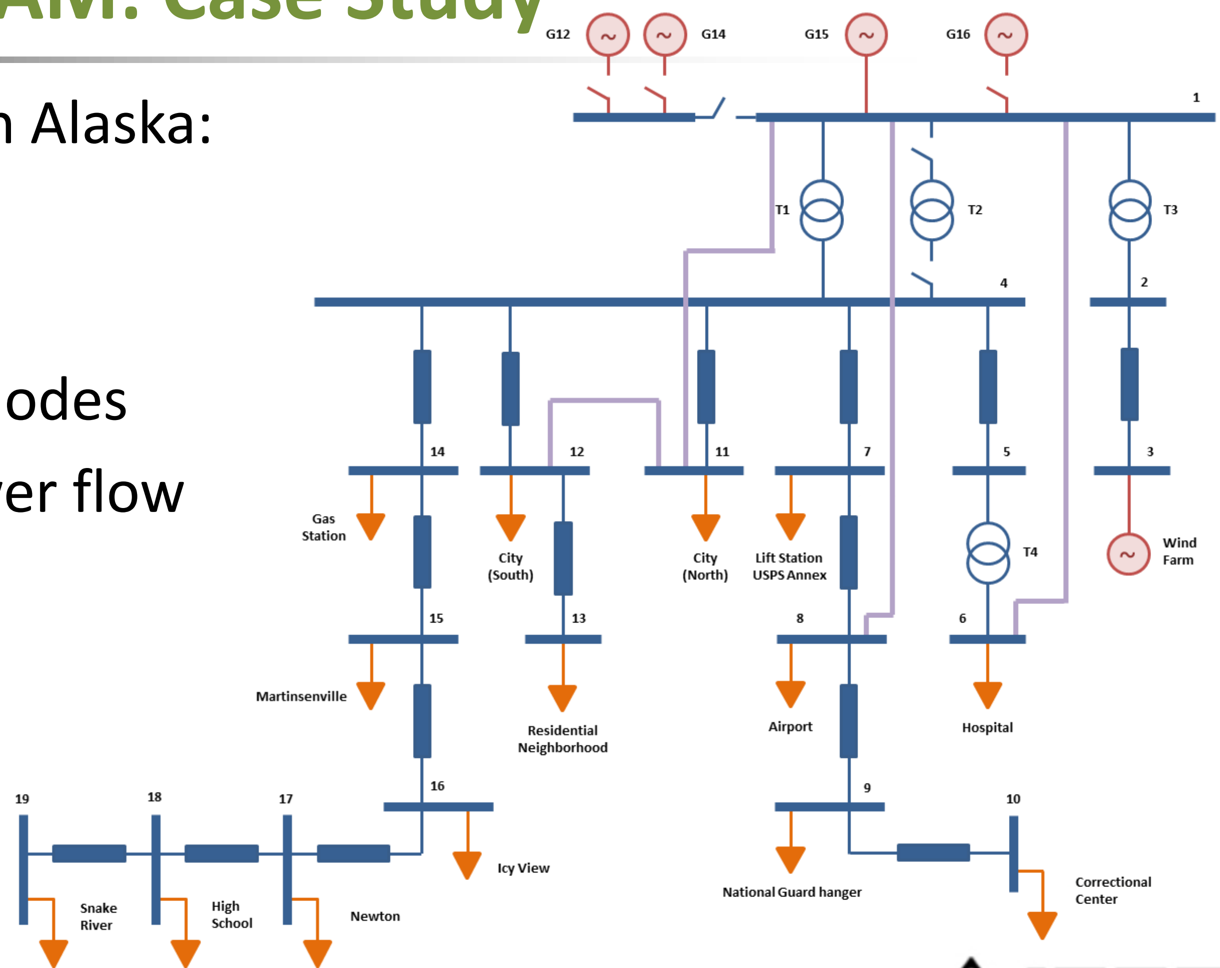
$$Ploss_{ij} = r_{ij} \times |I_{ij}|^2 = r_{ij} \times \frac{P_{ij}^2 + Q_{ij}^2}{|V_i|^2} \cong r_{ij} \times (P_{ij}^2 + Q_{ij}^2) \cong r_{ij} \times (PSq_{ij} + QSq_{ij})$$

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

Multi-Node DER-CAM: Case Study

A real-life microgrid in Alaska:

- Isolated microgrid
- <5MW peak load
- Modeled with 19 nodes
- Modeled with power flow model 2 (for radial networks)



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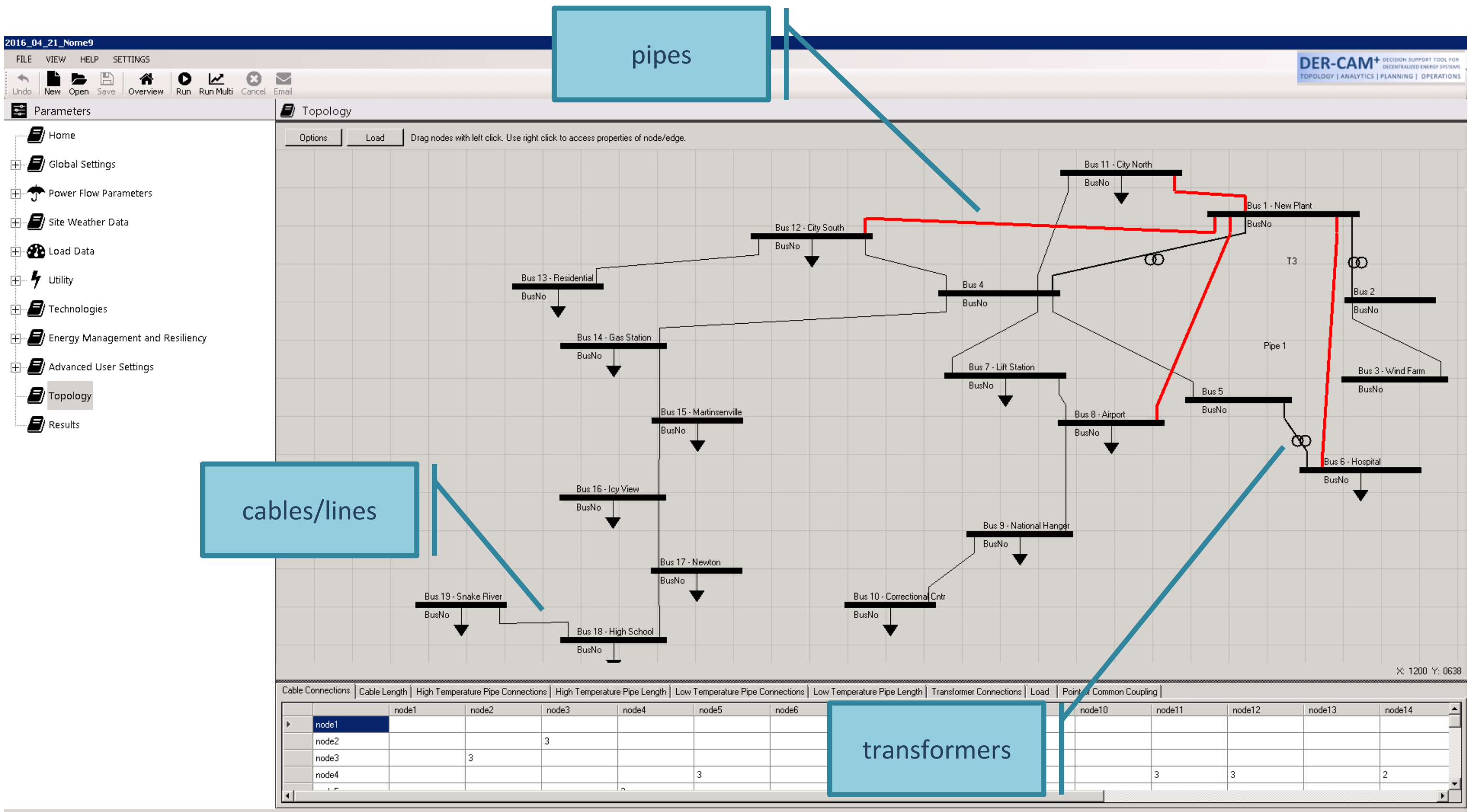
Multi-Node DER-CAM: Case Study



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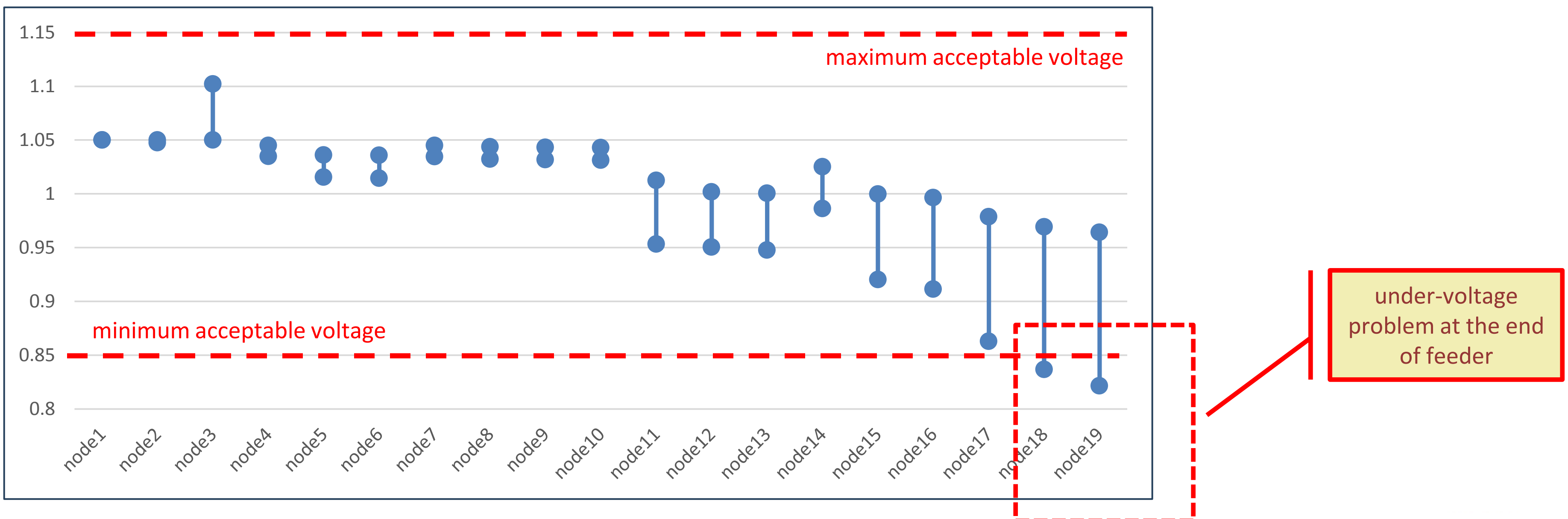
Multi-Node DER-CAM: Case Study – Base Case

- Running the base case shows under-voltage problem at the end of the long feeder (bus 18, 19)



Multi-Node DER-CAM: Case Study – Optimization Case

- DER-CAM optimization to re-design the system, to:
  - Reduce investment and operational costs
  - Alleviate the voltage problem
- For this example:
  - Allowed investment in PV, battery, and diesel in the network

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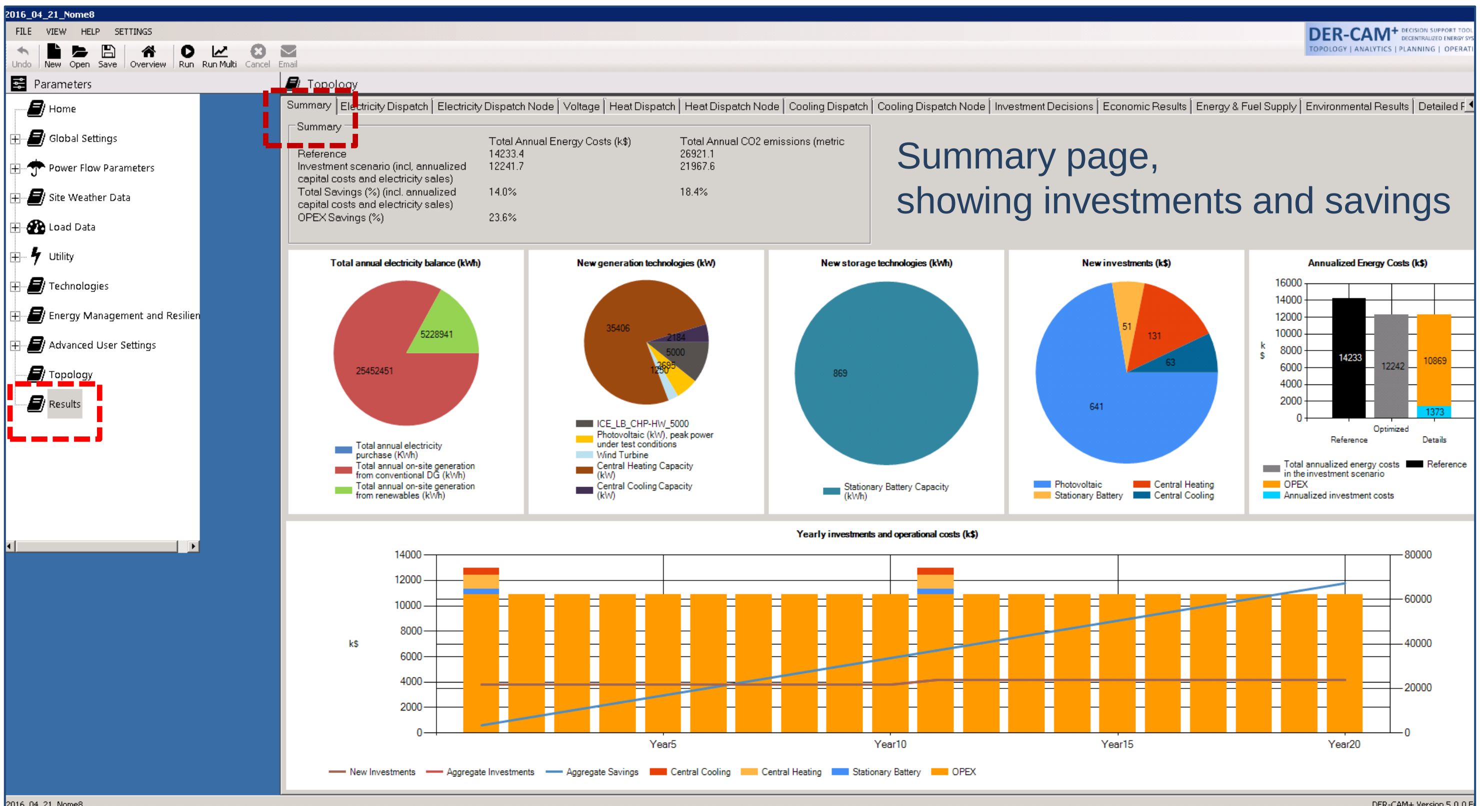
Multi-Node DER-CAM: Case Study – Optimization Case



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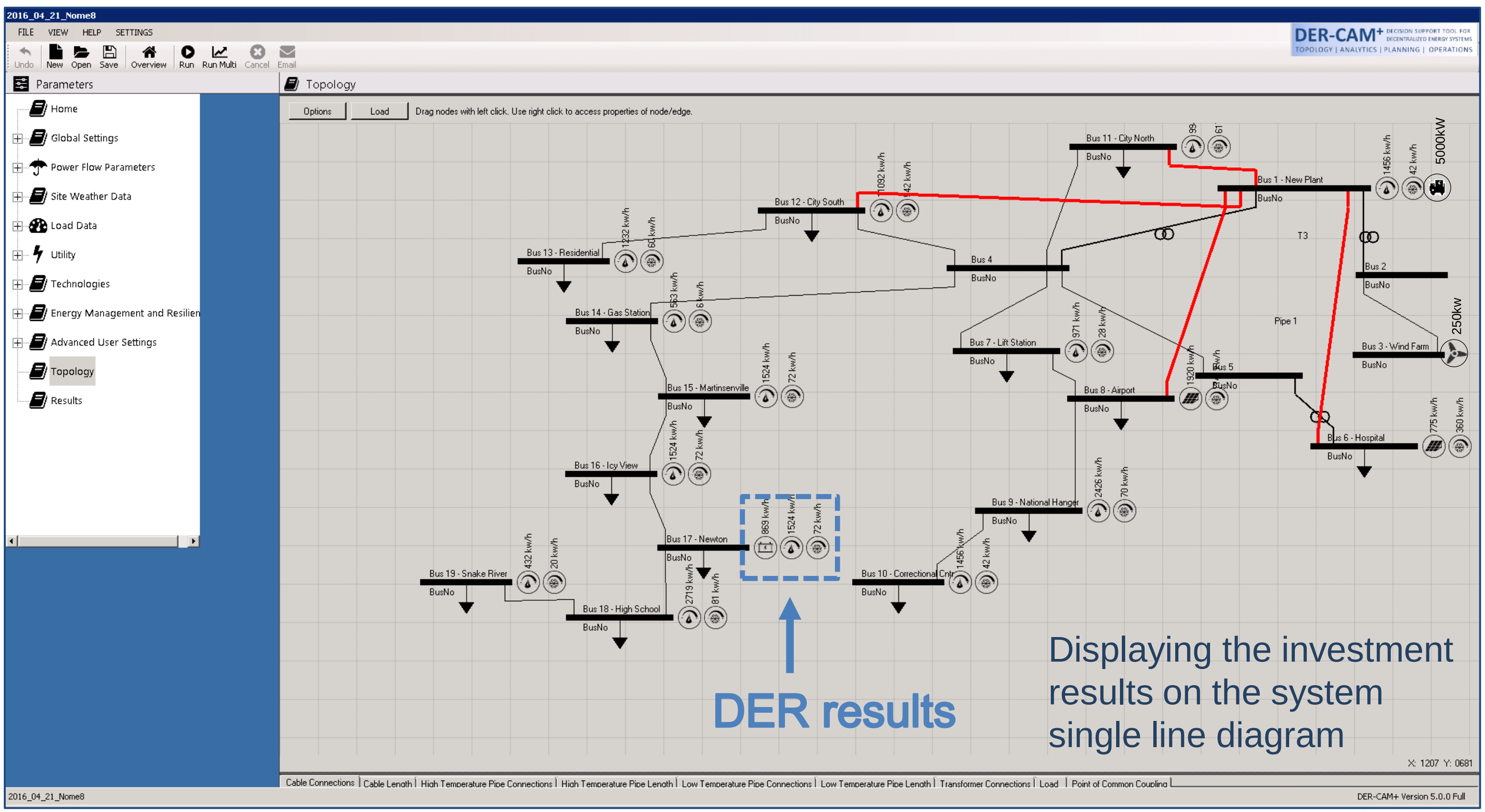
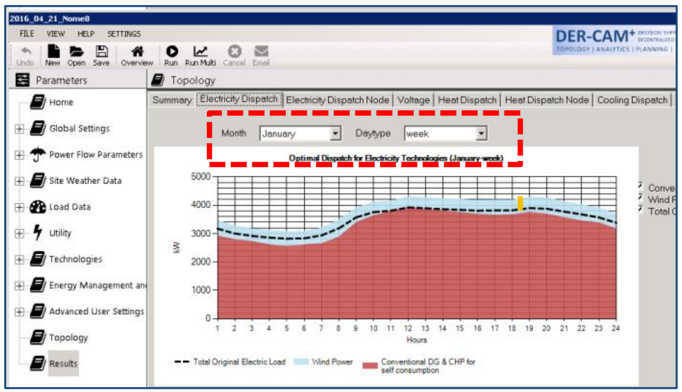
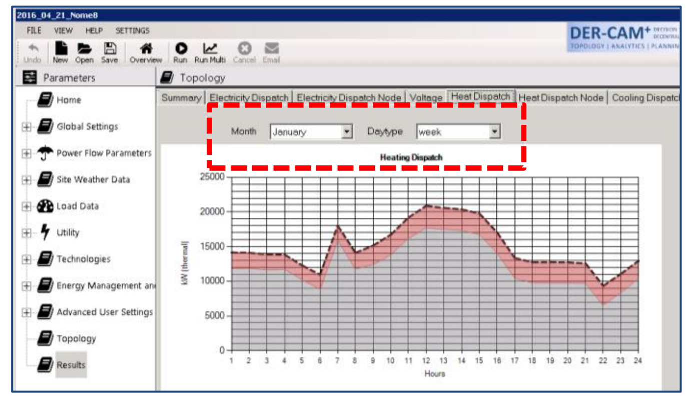
Multi-Node DER-CAM: Case Study – Optimization Case



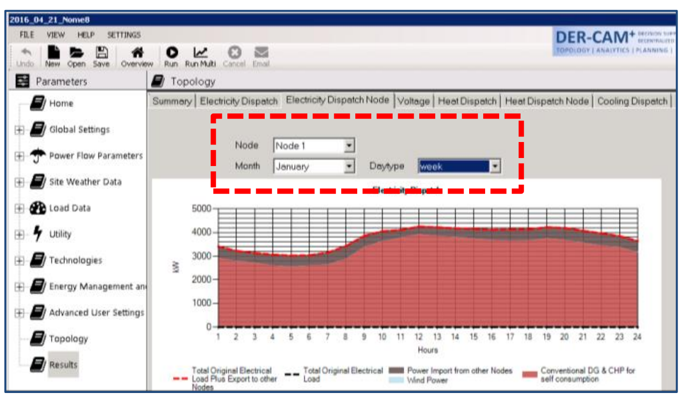
Multi-Node DER-CAM: Case Study – Optimization Case

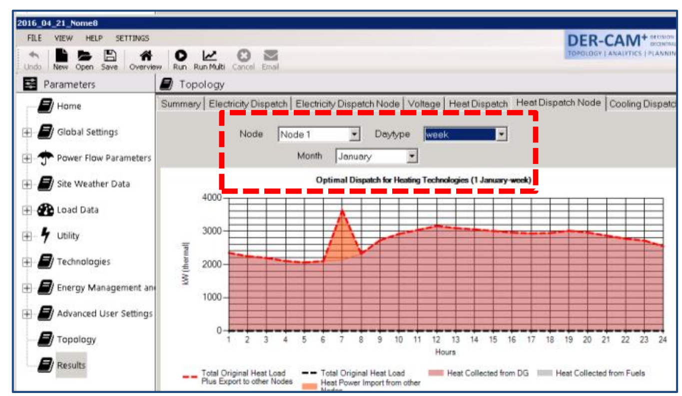
Aggregated dispatch results





Node-level dispatch results





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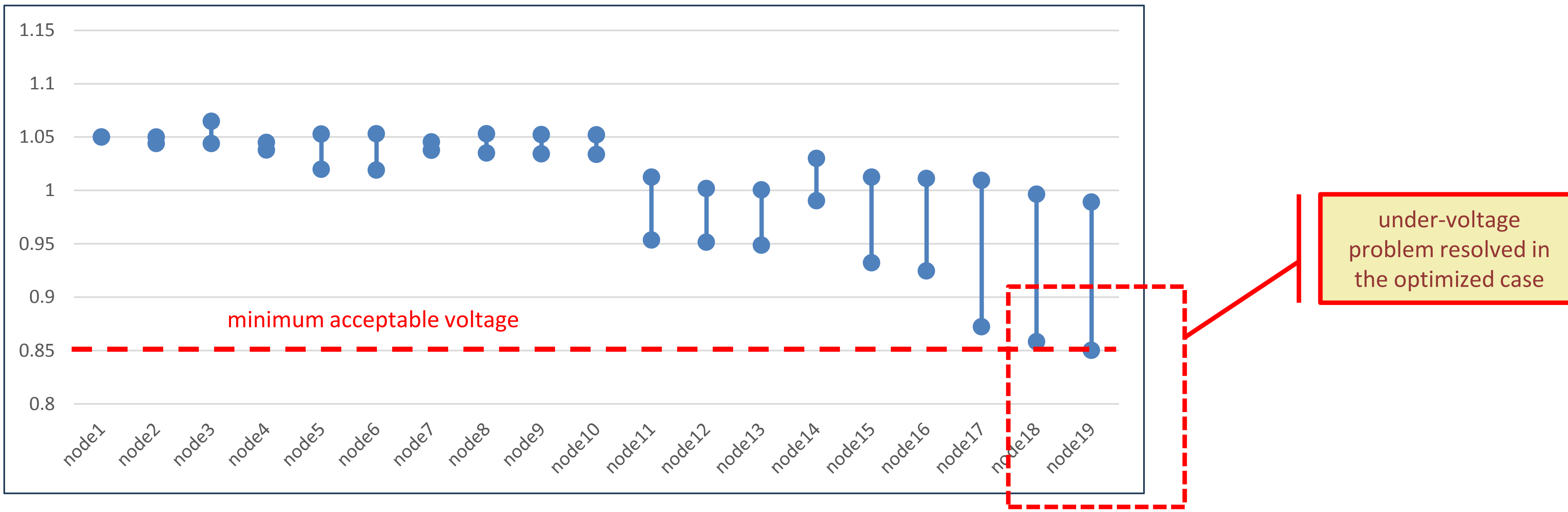
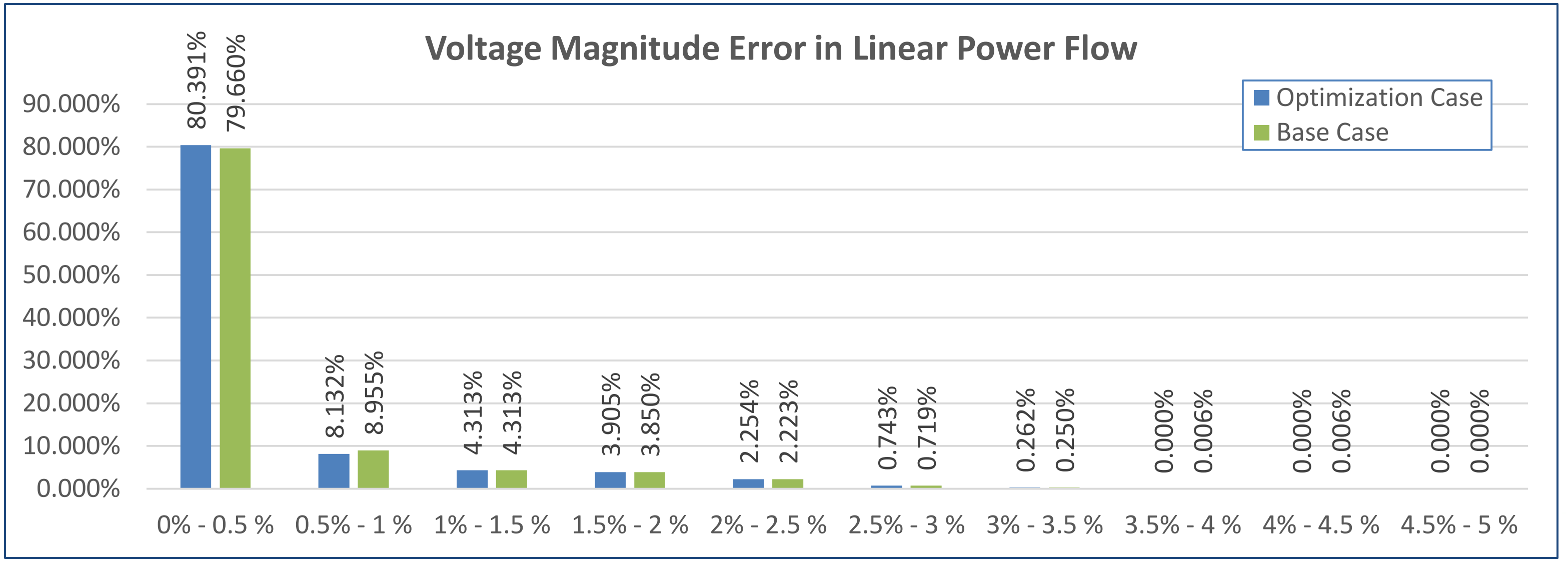
Multi-Node DER-CAM: Case Study – Optimization Case



Multi-Node DER-CAM: Case Study – Optimization Case

- The integrated power flow model 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)



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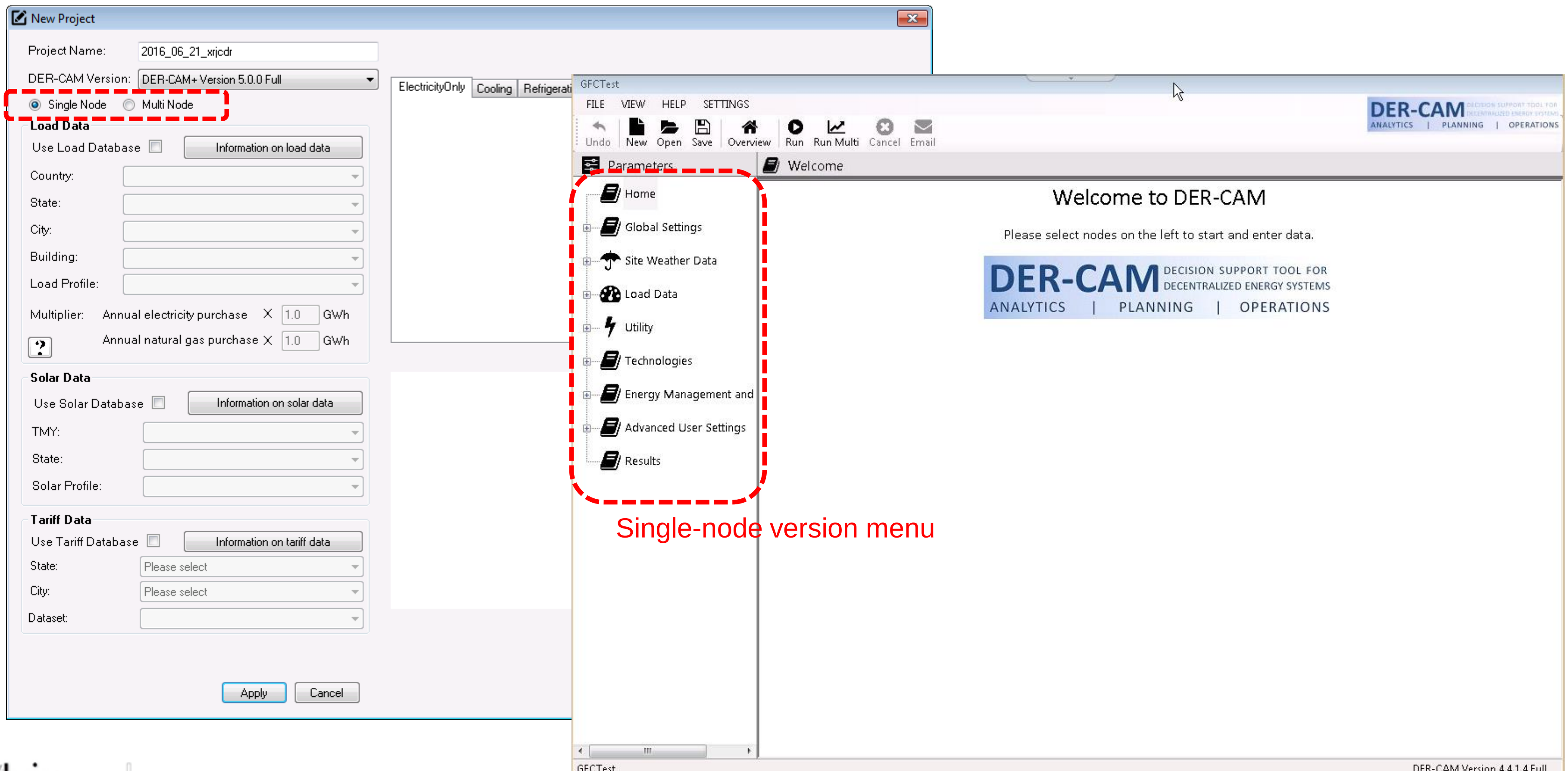
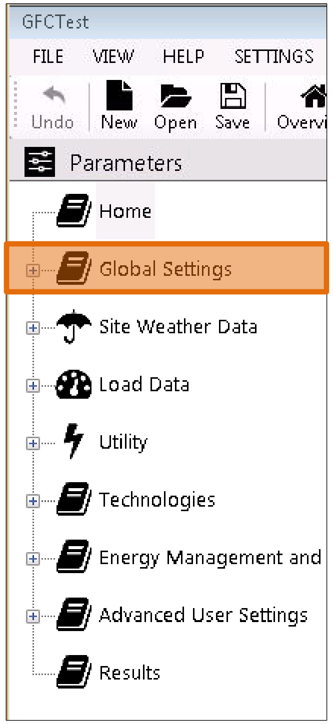
Graphical User Interface



Graphical User Interface

<u>General Options</u>

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



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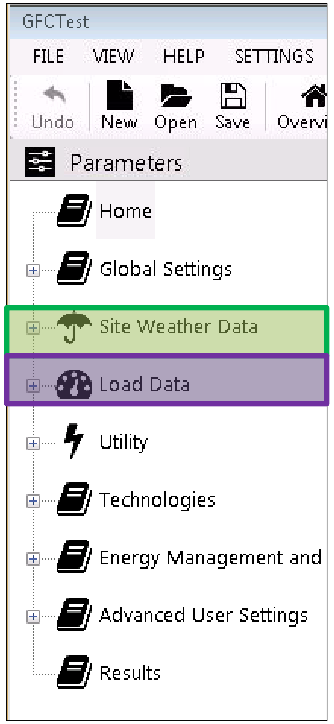
Graphical User Interface

<u>Data collection</u>

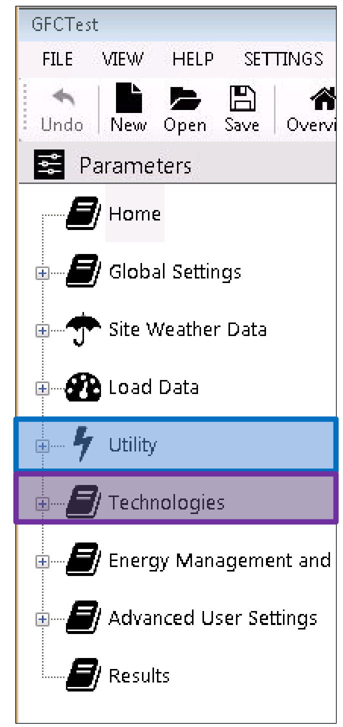
- Site / Weather information
  - Solar radiation
  - Ambient temperature
- End-use loads
  - Electricity
  - Cooling
  - Refrigeration
  - Space Heating
  - Water Heating
  - NG loads (cooking)



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



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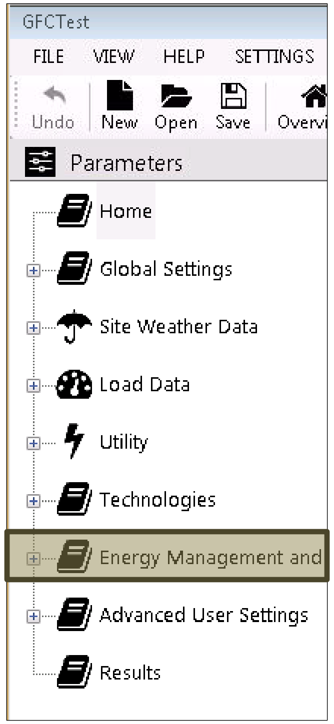
Graphical User Interface

Data collection

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



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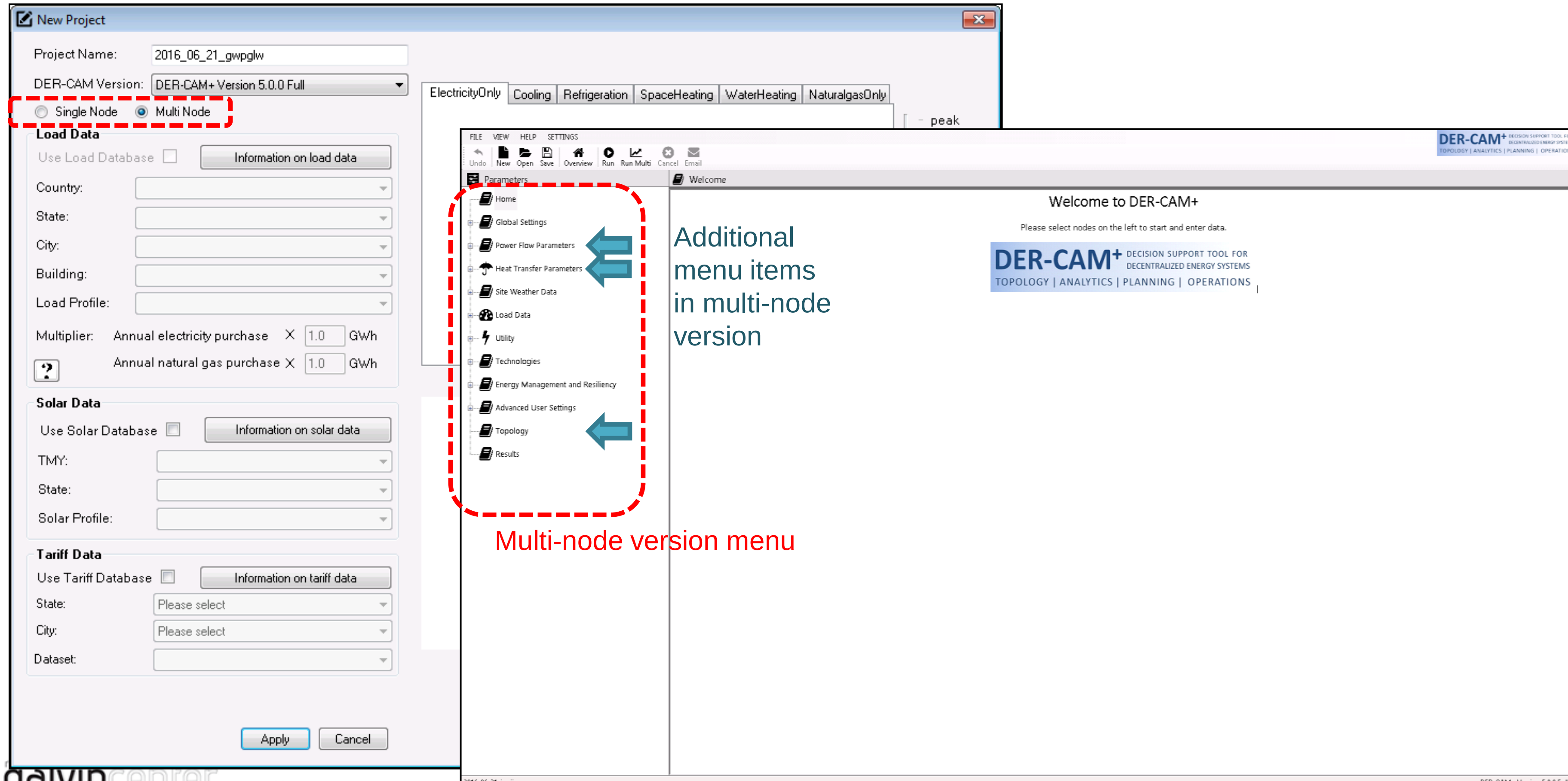
Graphical User Interface



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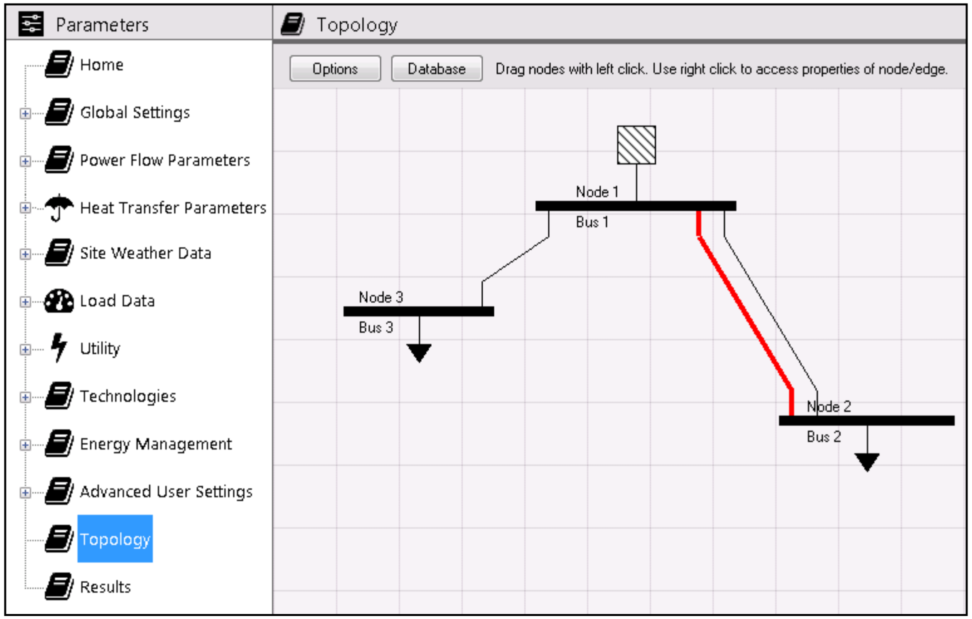
Graphical User Interface

<u>Electrical/thermal network topology</u>

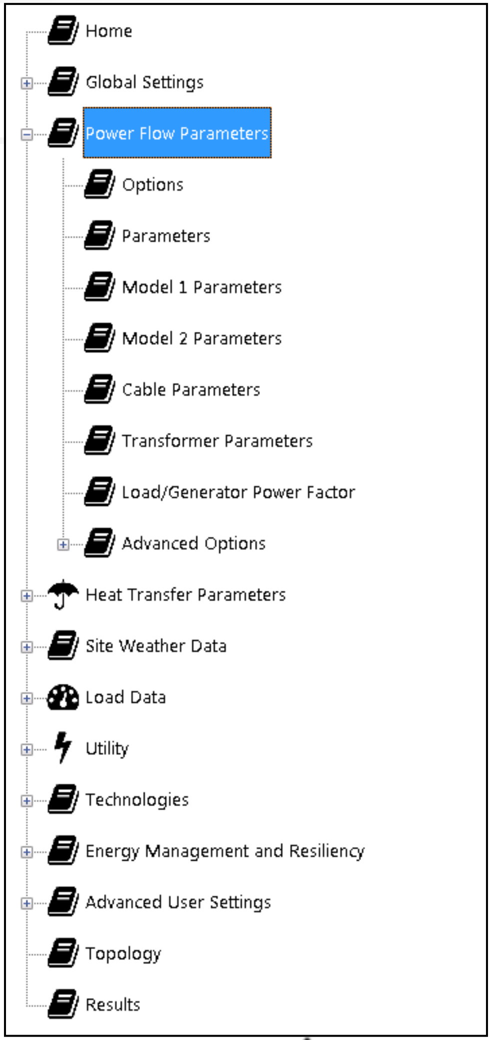
- Define electrical and thermal nodes
- Define cable connections
- Define transformer connections
- Define the point of common coupling
- Define high and low temperature pipe connections
- Define nodes with loads



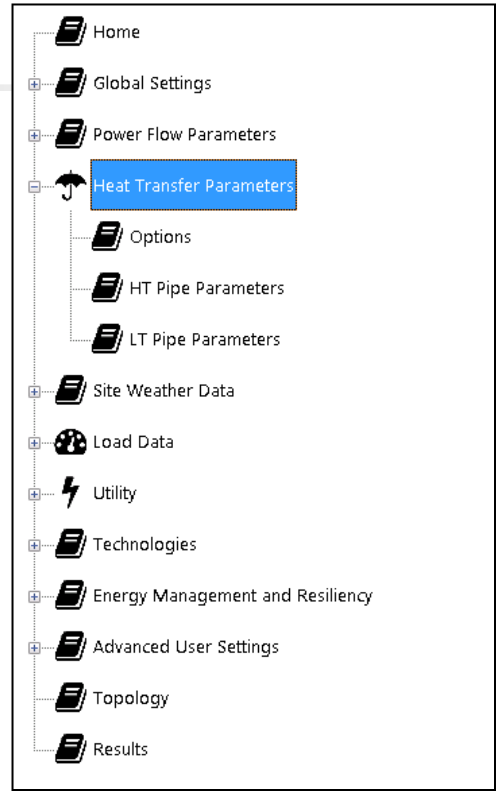
Graphical User Interface

<u>Power flow parameters</u>

- Enable/disable power flow
- Choose power flow model (1 or 2)
- Set power factor (cos phi) for loads and generators
- Enable/disable losses
- Enable/disable voltage constraints
- Enable/disable current/power constraints
- Define cable parameters
- Define transformer parameters



Graphical User Interface



<u>Heat transfer parameters</u>

- Enable/disable heat transfer
- Enable/disable heat transfer losses
- Define high-temperature pipe parameters
- Define low-temperature pipe parameters

Questions?
Feedback?

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High Level Mathematical Formulation

Objective Function

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

Key Constrains

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

DER-CAM+ DECISION SUPPORT TOOL FOR DECENTRALIZED ENERGY SYSTEMS

TOPOLOGY | ANALYTICS | PLANNING | OPERATIONS

Key Results: PJM

Costs in US$	Hospital			Aggregated system		
	Base case	Simple investment	With AS	Base case	Simple investment	With AS
Total Costs	1,001,780	837,859	782,605	1,343,417	919,607	856,020
Electricity Costs	9,45,984	73,175	130,433	1,281,700	23,308	34,380
Fuel costs	55,795	328,331	329,119	61,716	385,584	432,678
Ann. Cap. cost	0	275,645	301,883	0	331,310	370,779
O&M cost	0	159,433	129,760	0	170,051	120,892
AS Revenue	-	-	108,381	-	-	102,350
CO_2 (kg)	8,492,950	6,199,267	6,703,209	9,251,291	6,876,192	7,768,291
PV	-	-	-	-	9	-
Total DG	-	1250	1250	-	1325	1565
CHP	-	750	500	-	750	500
Overall ¢/kWh	7.02	5.87	5.48	8.61	5.90	5.49

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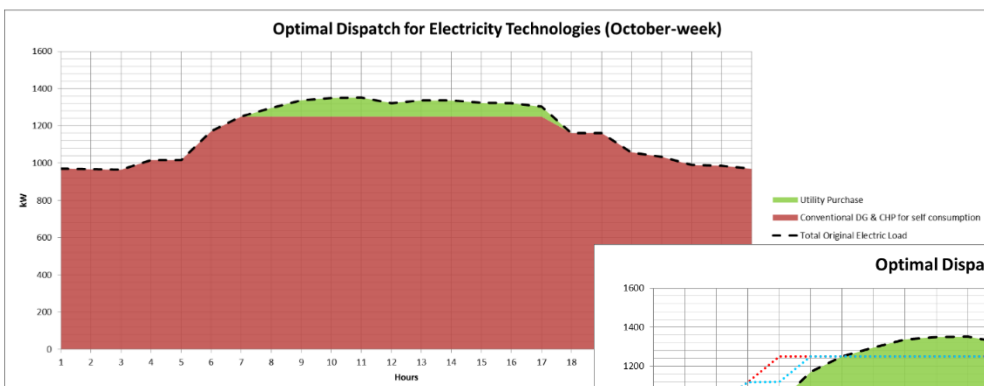
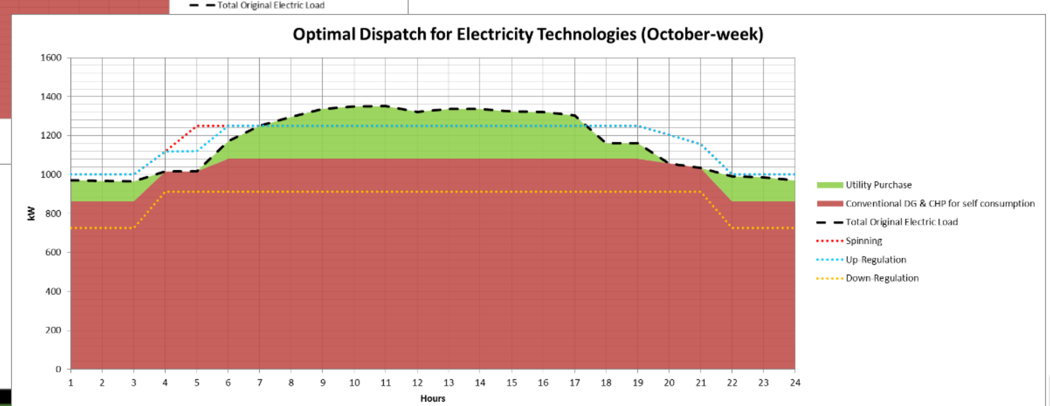
Key Results:

- The impact of AS participation in overall annual costs was significant in all selected microgrid cases in PJM.
- In terms of optimal investments, CHP were replaced by simple generators. Higher total installed capacity





Understanding DER-CAM Results

- Max Payback:
  - DER-CAM uses technologies with different lifetimes
  - “Max Payback” is a global payback and acts as a constraint
  - Min (total energy costs) such that:

    investment / annual savings <= 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