# Electricity under Stress: Robustness and Economics of Distributed Generation

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# Introduction

- Electric power systems can be stressed by a variety of adverse conditions.  e.g. Targeting of electric power systems in conflict.  T&D system is particularly vulnerable
- Historical cases indicate that it is possible to disrupt an electric power system's ability to provide power for a relatively low price.
  - Bosnia: 56% of generating capacity incapacitated. $/kW cost low
- At same rate, overall cost can be a significant portion of reconstruction costs
  - Lebanon: 25% of reconstruction and development cost
- Power system planners have to account for this.  One way is to design the system to mitigate against stress

# Conflict is not a Hurricane

Planning requirements may be similar to those for extreme weather events, but there are significant differences:

- Persistence of Adverse Conditions - non-random events
- Length of Outage - Inability to quickly implement reconstruction and restoration
- Scope of Damage - Generators, T&D all impacted
- Coordination of Attack/Impacts - not single point failures

# Research Questions

- Hypothesis:  Distributed generation will be more robust under adverse conditions than centralized systems
  - DG should result in less reliance on a small number of large generators and be impacted less by damage to the T&D system
- Can Distributed Generation provide electric power economically and with improved reliability in cases where the electric power system is likely to be stressed?
  - How do centralized and distributed systems perform when stressed?
  - Can the robustness of systems be quantified in a manner that allows an overall comparison to be made between systems?
  - Can robustness be incorporated into the economic comparison of centralized and distributed systems?

# Some Relevant Literature

- Energy and Security - focus on nuclear weapons, nuclear power, and oil security
- Critical Infrastructure Protection - focus on OECD (especially U.S.), cyber-security, limited terrorism, protecting existing infrastructure
- Reliability Assessment - large body of literature on how to assess reliability of electric power systems. Standard methodology will be used for this analysis
  - DG and Reliability - Recognition of potential benefits of DG for reliability (with some caveats). Little systematic analysis of large-scale DG. Little analysis of DG as solution for systems under stress (primarily qualitative)

# Monte Carlo Reliability Simulation

- Centralized System and demand profile given by IEEE Reliability Test System.
  - Peak Demand 2850 MW, Capacity 3405 MW
  - Generating units have an unavailability (Forced Outage Rate)
- Compare available generating capacity (based on unit unavailabilities) and load to determine whether generating capacity is adequate.
- Loss of Load Expectation (hours/year) and Loss of Energy Expectation (MWh/year) are calculated

# Model Verification

| Index | Billinton and Li | Our Model |
| --- | --- | --- |
| LOLE (hr/yr.) | 9.4 | 9.6 |
| LOEE (MWh/yr.) | 1200 | 1180 |

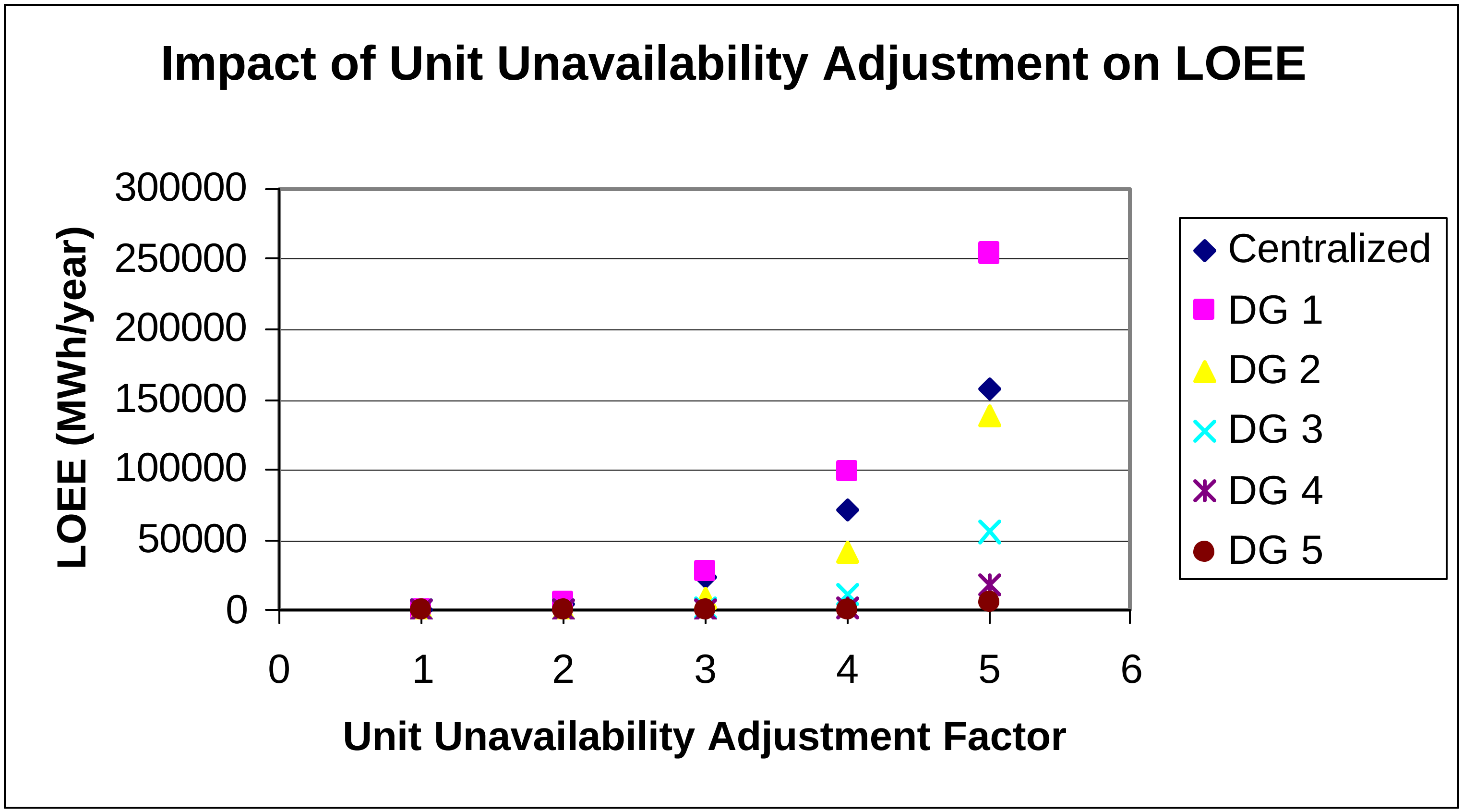
# Scenarios Analyzed

- Centralized System compared to 15 DG Scenarios:
  - DG Systems (even in absence of stress) are more reliable and result in capacity savings.
  - Five different levels of capacity:
    - Min: Number of units to have equal reliability with centralized system for given level of demand
    - Max: Same capacity as centralized system
  - Three different levels of co-generation (relevant for economic aspects of model)
- Five different levels of stress. Each stress level corresponds to an adjustment of the unit unavailability
- Model applicable to any situation in which stress is systematic and system-wide

# Simulation Results

- In absence of stress, significant capacity savings can be achieved with DG. Holding demand constant, the number of DG units required to match the reliability of the centralized system is nearly equal to peak demand.
- Of the two reliability indices, the Loss of Energy Expectation (LOEE) is more sensitive to changes in unit availability
- Distributed systems above the minimum number of units are less sensitive than the centralized system

# Simulation Results (cont)



# Some Future Work

- Inclusion of network effects (transmission system)
- Assessment of Infrastructure Interdependencies
  - e.g. Natural Gas
- Typology and Modeling of Stress
  - Different types of conflict
  - Stress conditions other than conflict
  - Model choices to reflect stress characteristics
- Political and institutional factors
  - Importance in both reducing the causes of stress and in aiding or hindering implementation of solutions

# Conclusions

- Historical record indicates the need to specifically consider deliberate attacks against energy systems in certain case
- Distributed generation holds the promise of improved reliability in comparison to centralized systems under these circumstances
- Results of Monte Carlo reliability simulation supports hypothesis.

# END

# Relevant Equations

$$DNS_k = \max\left\{0, D - \sum_{i=1}^{m} G_{ik}\right\}$$

$$EDNS = \frac{\sum_{k=1}^{N} DNS_k}{N}$$

$$LOEE = \frac{\sum_{k=1}^{N} DNS_k * 8760}{N}$$

$$LOLE = \frac{\sum_{k=1}^{N} I_k(DNS_k)}{N} * 8760, \text{ where } I_k = \begin{cases} 0 \text{ if } DNS_k = 0 \\ 1 \text{ if } DNS_k \neq 0 \end{cases}$$

$$P_i = \frac{NI_i}{8760}$$

$$EDNS_T = \sum_{i=1}^{NL} ENDS_i P_i$$

$$LOEE_T = \sum_{i=1}^{NL} LOEE_i P_i$$

$$LOLE_T = \sum_{i=1}^{NL} LOLE_i P_i$$

$$s_N^2 = \frac{1}{N-1}\left[(N-2)s_{N-1}^2 + (N-1)\overline{X}_{N-1}^2 - N\overline{X}_N^2 + X_N^2\right]$$

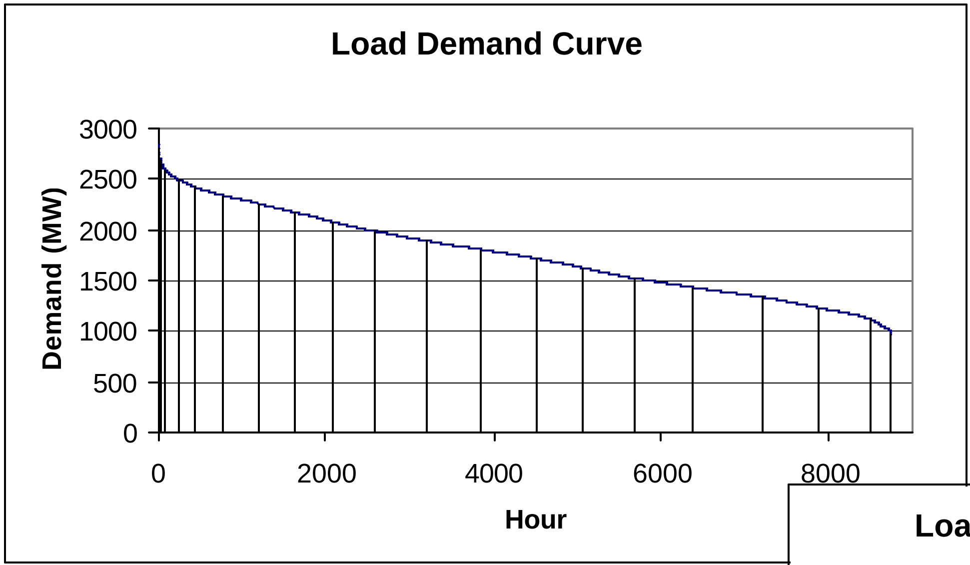
# Data Table of Results

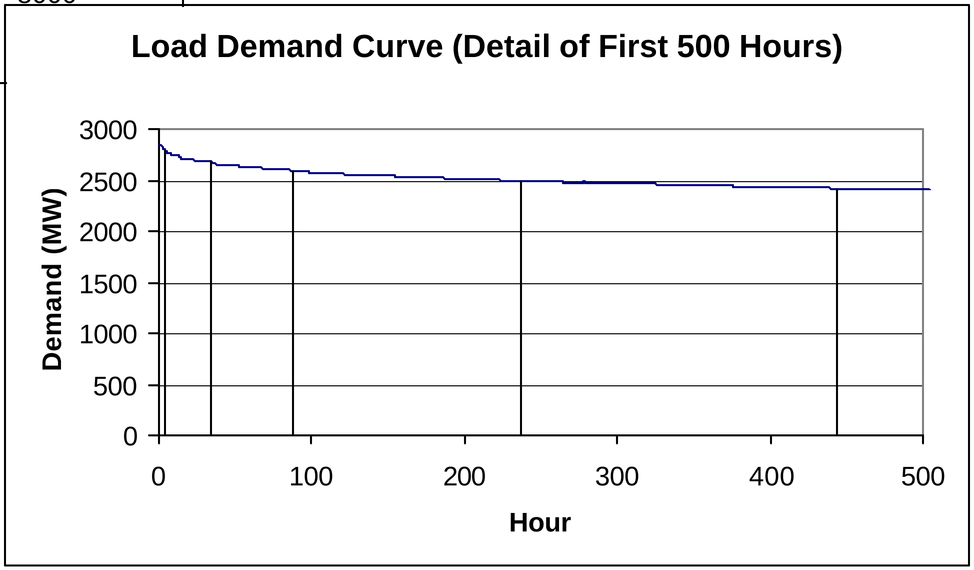
| | Centralized | | DG1 | | DG2 | | DG3 | | DG4 | | DG5 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Adjustment Factor | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. |
| 1 | 437 | 1.42E+01 | 435 | 4.11E-01 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 |
| 2 | 4770 | 5.62E+01 | 5380 | 6.62E+00 | 687 | 1.78E+00 | 1 | 6.39E-02 | 0 | 0 | 0 | 0.00 |
| 3 | 23963 | 2.07E+02 | 27368 | 2.30E+01 | 8368 | 8.56E+00 | 1191 | 3.79E+00 | 52 | 0.54 | 0 | 0.00 |
| 4 | 70907 | 5.65E+02 | 98721 | 6.33E+01 | 41649 | 3.87E+01 | 10898 | 1.22E+01 | 2267 | 4.67 | 300 | 0.84 |
| 5 | 157930 | 1.20E+03 | 253648 | 1.18E+02 | 138753 | 8.98E+01 | 55929 | 4.51E+01 | 18182 | 26.12 | 5375 | 9.98 |

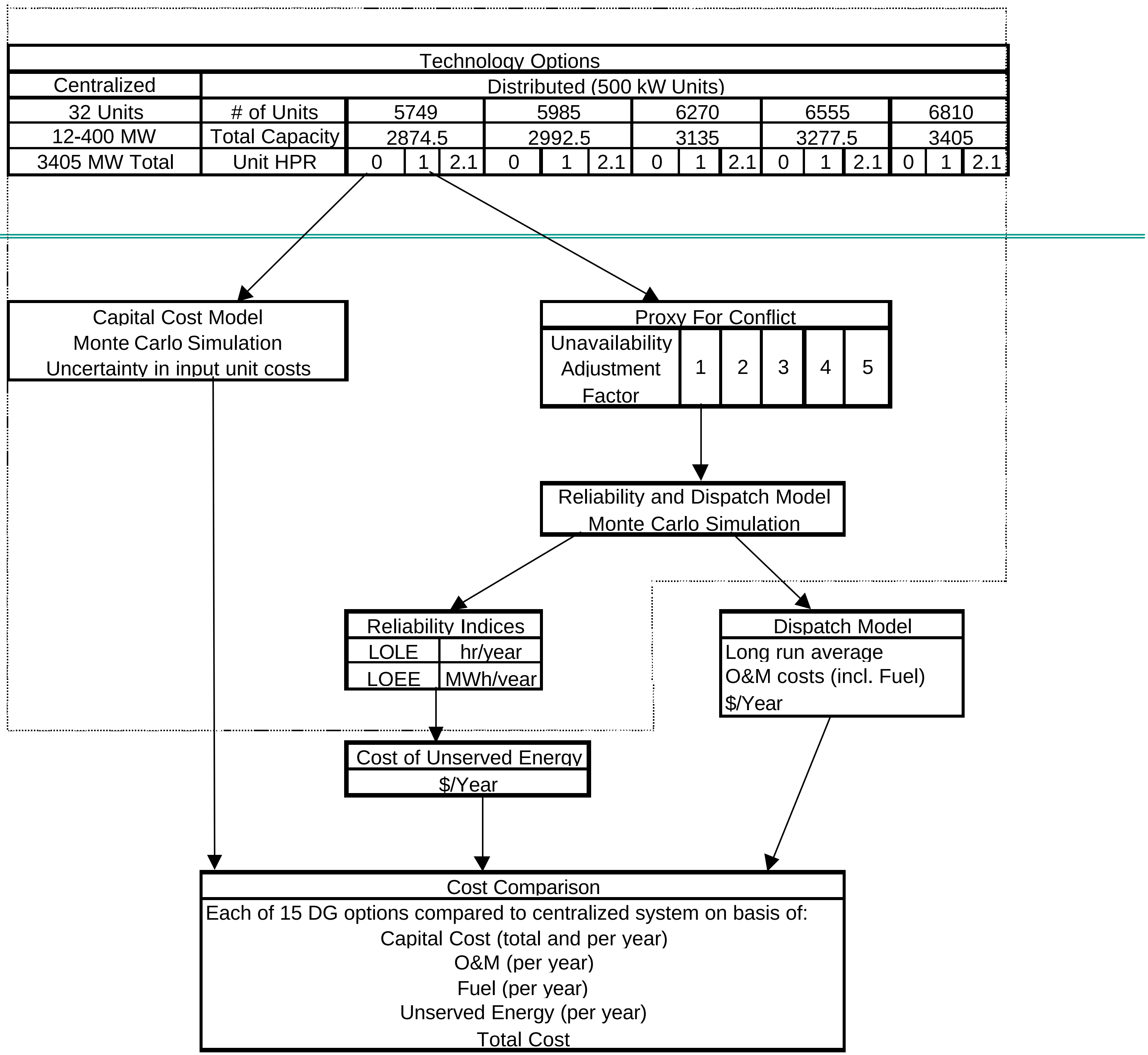
# Monte Carlo Reliability Simulation

- Analytical versus Simulation Techniques:
  - Analytical: Specify all system states and transitions between states and use to calculate reliability indices
  - Simulation: Use Monte Carlo or other simulation technique, drawing from distributions to determine availability of individual units in each run, compare to load, calculate reliability indices.
- Why Simulate?
  - Part of the path towards an integrated model that includes transmission systems
  - Analytical method difficult to implement with large N
  - Allows quantification of costs
  - Easily repeatable. Can change input parameters to simulate conflict and rerun model easily.

# Load Demand Curves





Technology Options
Centralized
Distributed (500 kW Units)
32 Units
# of Units
5749
5985
6270
6555
6810
12-400 MW
Total Capacity
2874.5
2992.5
3135
3277.5
3405
3405 MW Total
Unit HPR
0
1
2.1
Capital Cost Model
Monte Carlo Simulation
Uncertainty in input unit costs
Proxy For Conflict
Unavailability Adjustment Factor
1
2
3
4
5
Reliability and Dispatch Model
Monte Carlo Simulation
Reliability Indices
LOLE
hr/year
LOEE
MWh/year
Dispatch Model
Long run average
O&M costs (incl. Fuel)
$/Year
Cost of Unserved Energy
$/Year
Cost Comparison
Each of 15 DG options compared to centralized system on basis of:
Capital Cost (total and per year)
O&M (per year)
Fuel (per year)
Unserved Energy (per year)
Total Cost