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Title: Expansion Planning for the Smart Grid

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Intended for: SAMSI Smart Grid Workshop

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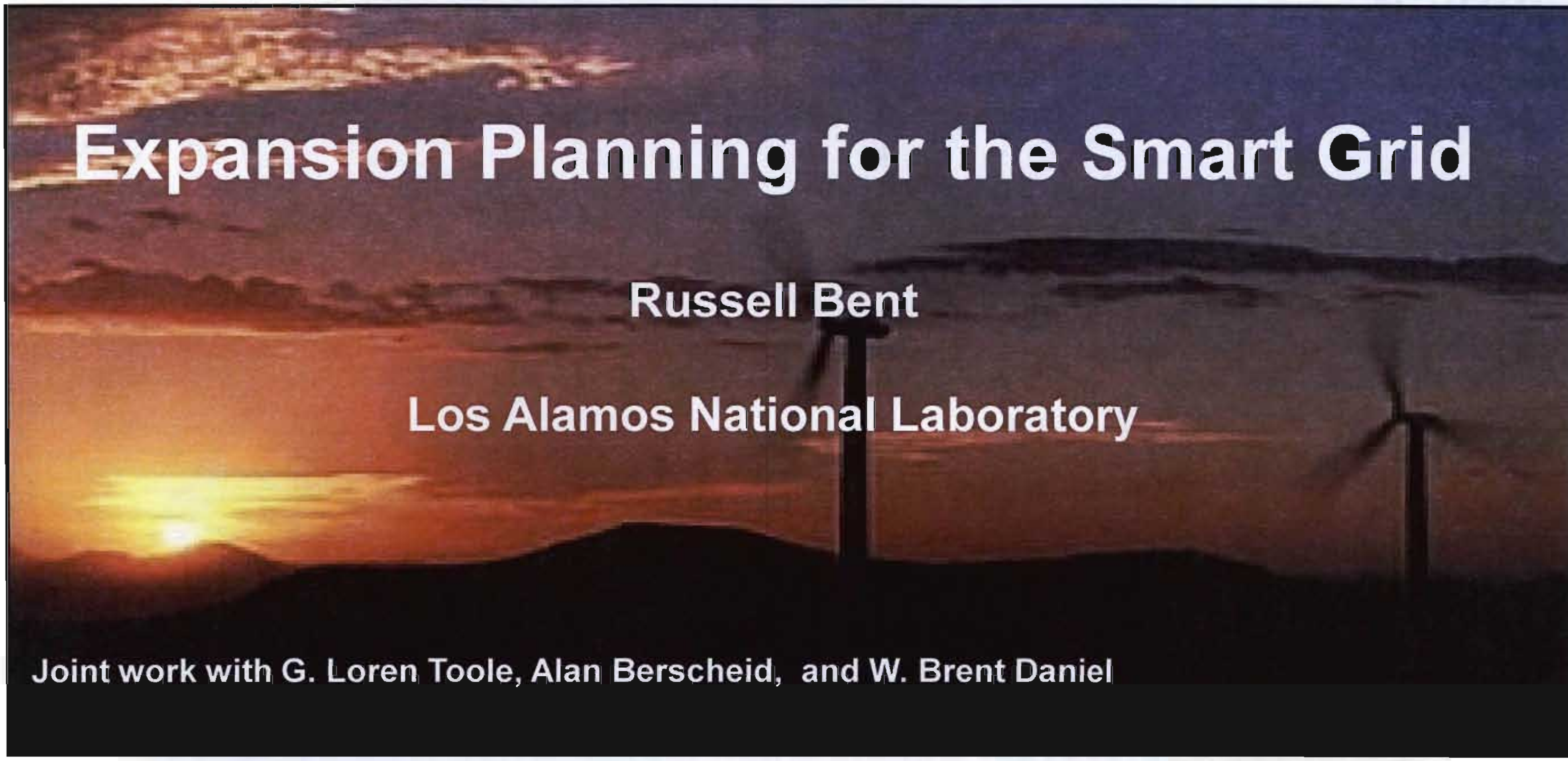
Expansion Planning for the Smart Grid

Russell Bent

The introduction of renewable and smart grid technologies into the electric power grid has created a number of challenges and opportunities for researchers. The challenges and opportunities spread across a number of areas including control, stability, and monitoring, to name a few. In this talk we discuss how smart grid and renewable technologies impact expansion planning for power systems. Broadly speaking these technologies have introduced an increased need to understand how the grid will be operated and controlled when making determinations of how and when to expand a power grid. We consider this problem by presenting algorithms for solving the grid expansion planning problem for arbitrarily complex models of powers systems to determine situations where traditional modeling approaches for expansion planning may not be sufficient. We propose extensions to the algorithm to address planning problems with operational components such as carbon emissions, variable load, and collector/export operational goals.



SAMSI Scientific Problems for the Smart Grid Workshop 2011

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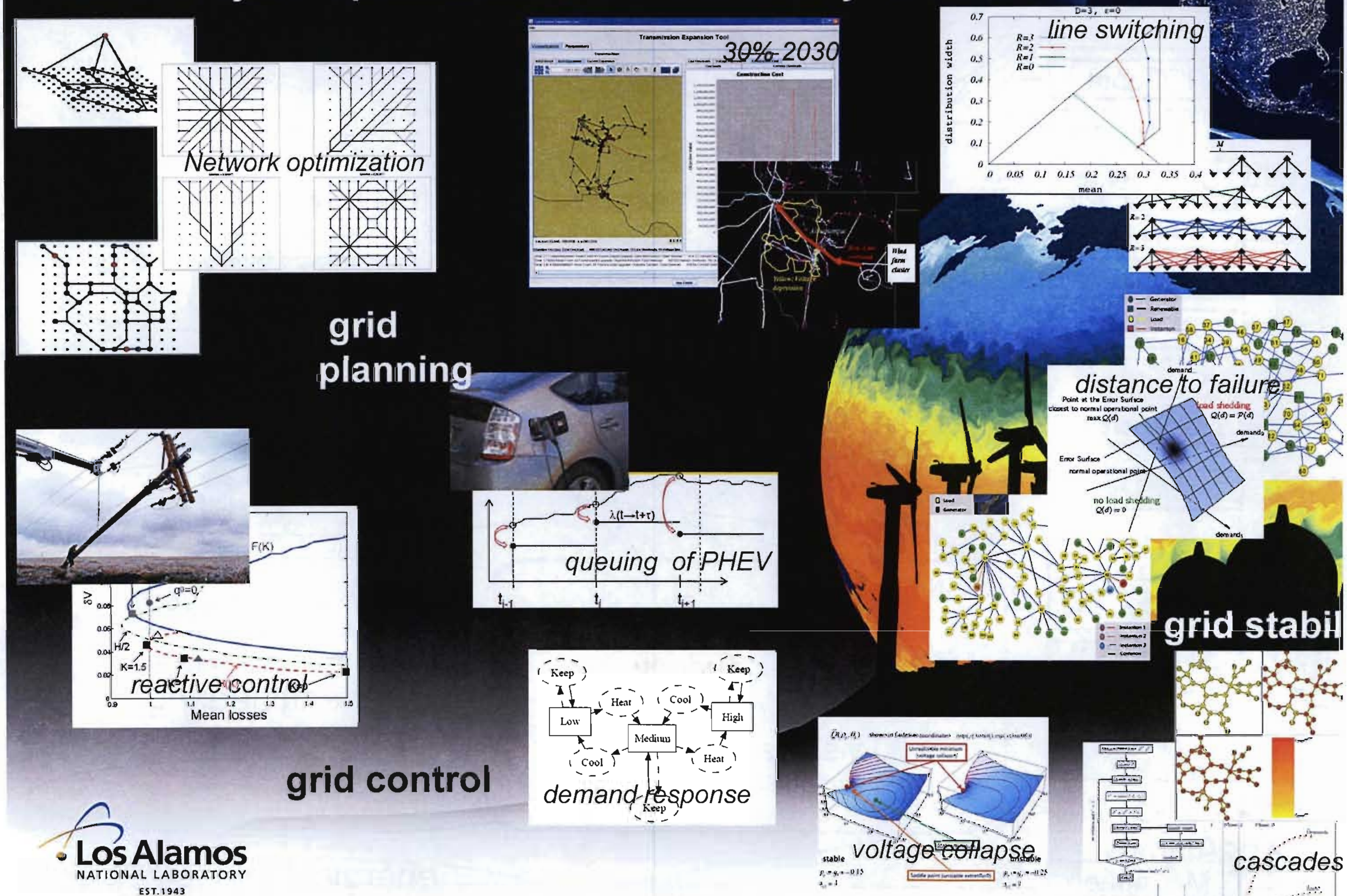
Outline

- Brief Overview of Smart Grid Research at Los Alamos
- Grid Expansion Planning Model
- Grid Expansion Planning Algorithm
- Experimental Results

LANL Project: Optimization & Control Theory for Smart Grids



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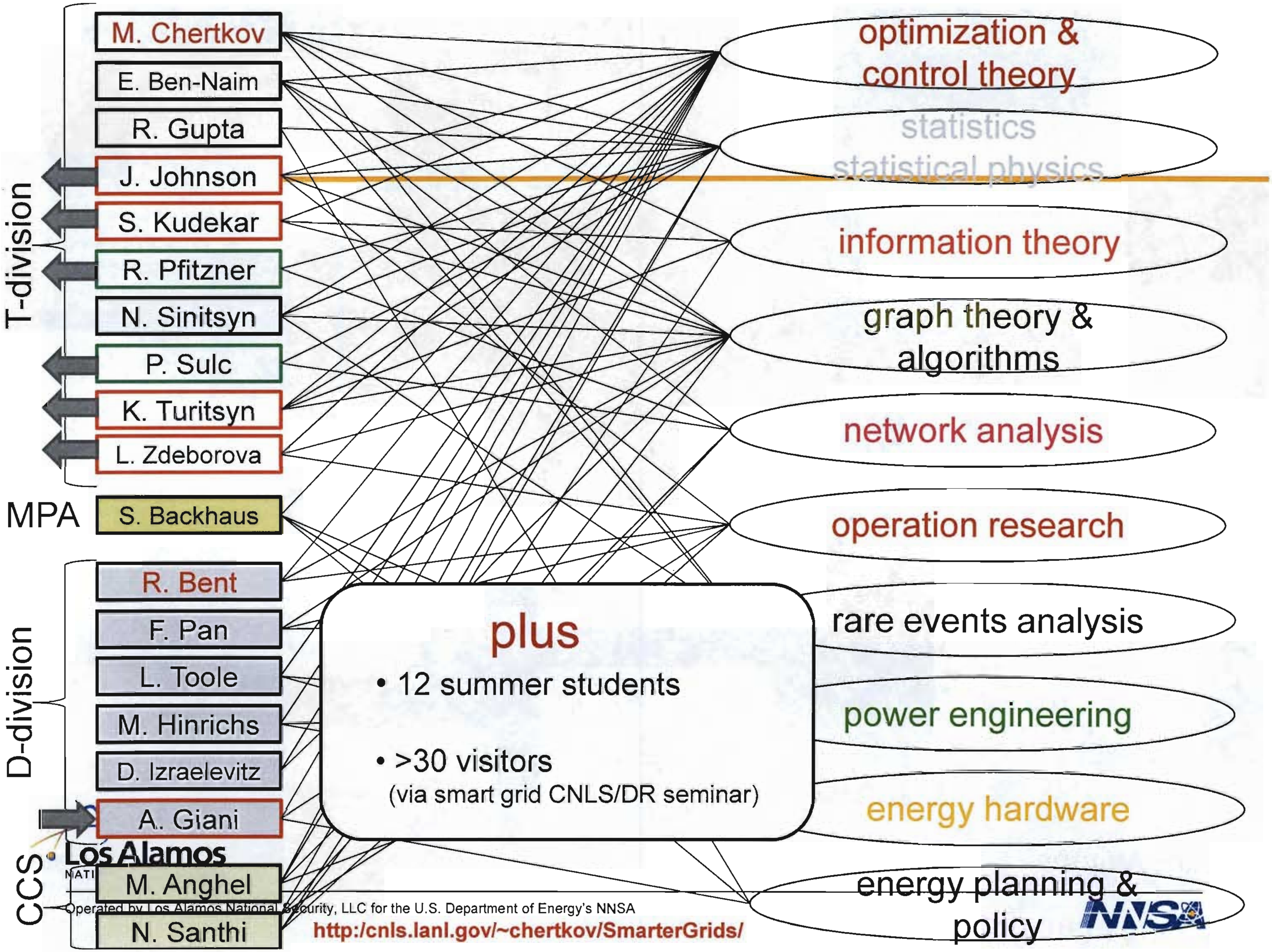
http://cnls.lanl.gov/~chertkov/SmarterGrids/



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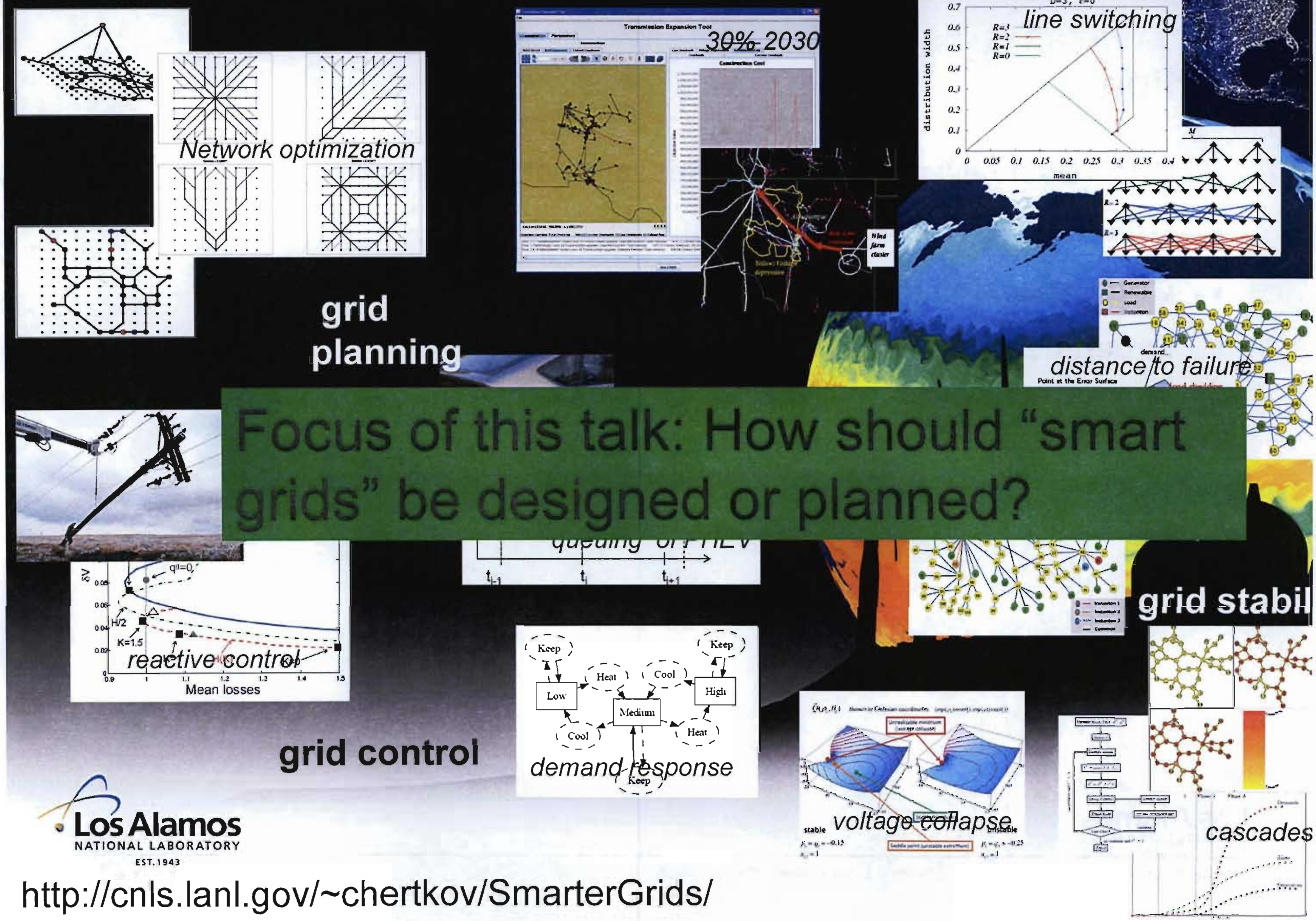
LANL Project: Optimization & Control Theory for Smart Grids



Focus of this talk: How should "smart grids" be designed or planned?

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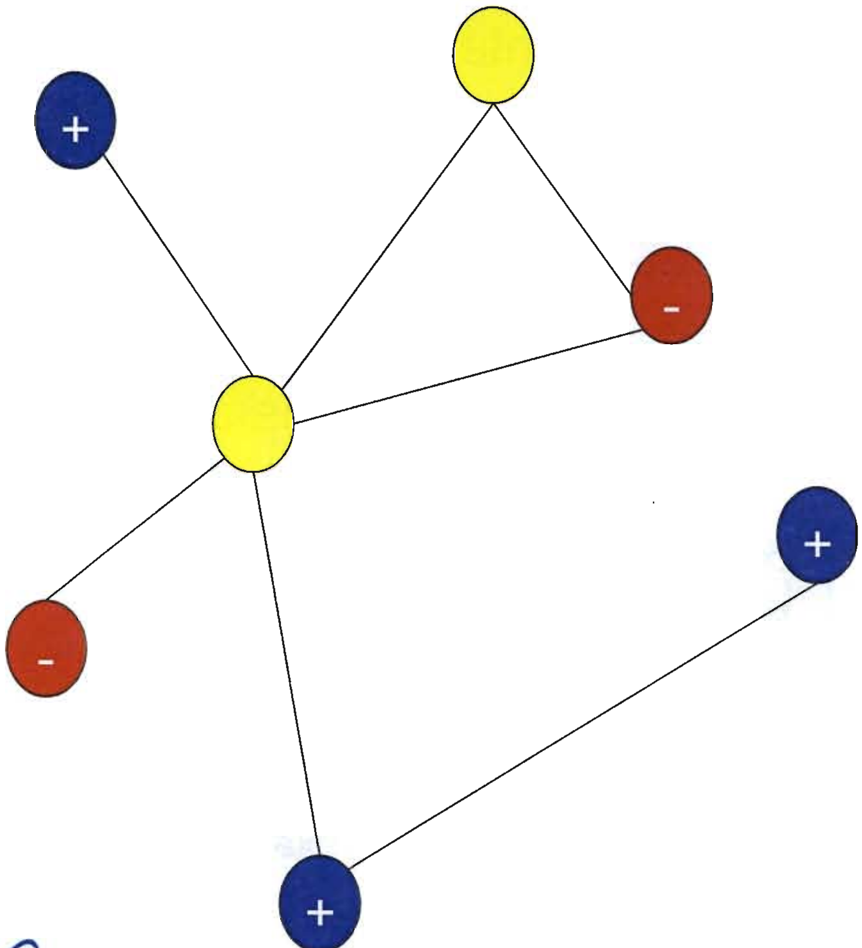
Traditional Expansion Planning

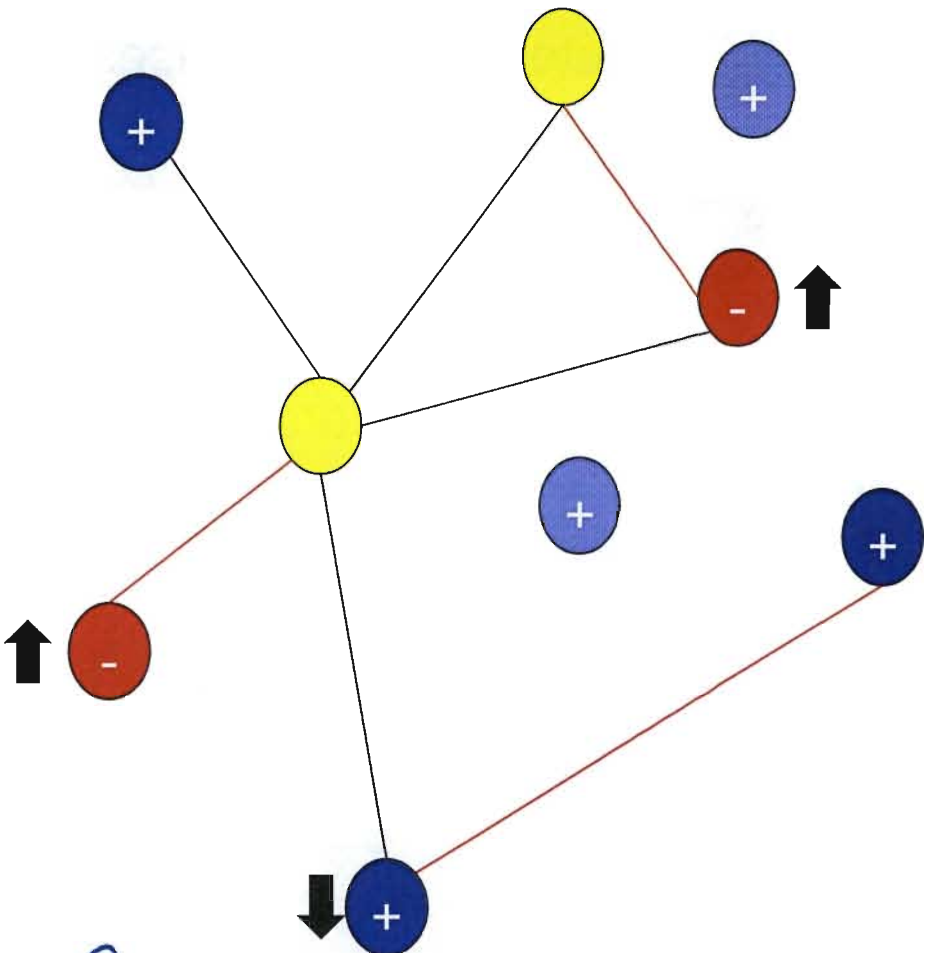


Internal Nodes (buses)

Power Consumers (loads)

Power Generators

Traditional Expansion Planning



Internal Nodes (buses)

Power Consumers (loads)

Power Generators

Upgrade (transmission lines, shunt compensation, renewable generators) an electric power system to accommodate changes in demand and meet renewable generation goals

- Eliminate constraint violations (line overloads and voltage violations)
- Minimize expansion cost
- Reliability constraints

Smart Grid Impacts to Planning

- **Reduce the need to expand**
  - Demand response modeled as "negative" generators
    - Antunes et al 2004 (and others)
  - Transmission switching
    - Khodaei et al 2010
  - Peak reduction analysis
    - Olympic Pennisula Project (PNNL)
- **Increase the need to expand**
  - Large penetration of renewables
    - Backup generation
    - Storage
    - Transmission capacity
  - Placement of monitors and controls
  - Microgrids

Operations can impact how systems are expanded.

Expansion Planning Optimization Model

$$P_i = \sum_{k=1..n} |V_i||V_k|(c_{ik}g_{ik}\cos(\Theta_i-\Theta_k) + c_{ik}b_{ik}\sin(\Theta_i-\Theta_k))$$

$$Q_i = \sum_{k=1..n} |V_i||V_k|(c_{ik}g_{ik}\sin(\Theta_i-\Theta_k) + c_{ik}b_{ik}\cos(\Theta_i-\Theta_k))$$

P_i = Real power of bus i

Q_i = Reactive power of bus i

V_i = Voltage of bus i

Θ_i = phase angle of bus

g_{ik} = conductance between i,k

b_{ik} = susceptance between i,k

c_{ik} = number of circuits between i,k

- Expansion may *introduce* physical violations (Braess's paradox)
- Extendable to incorporate other types of expansion options
- Highly non-linear, generally considered intractable

Reduced Expansion Planning Optimization Model

- Linearized DC approximation

$$P_i = \sum_{k=1..n} b_{ik} (\Theta_i - \Theta_k)$$

- Still a mixed integer non-linear program (can be converted to an integer program)

$$P_i = \sum_{k=1..n} b_{ik} c_{ik} (\Theta_i - \Theta_k)$$

- Modeling assumptions
  - Network normally stable
  - Minor changes in V and Θ
  - AC (Q) power a small contributor
  - Controllable generation
- Considered *straight-forward* by planners to modify a TNEP solution to more complex flow representations
- Not clear if these assumptions smart grid and renewables

Revisit the more complex models to better plan for smart grid, operations, renewables, etc.

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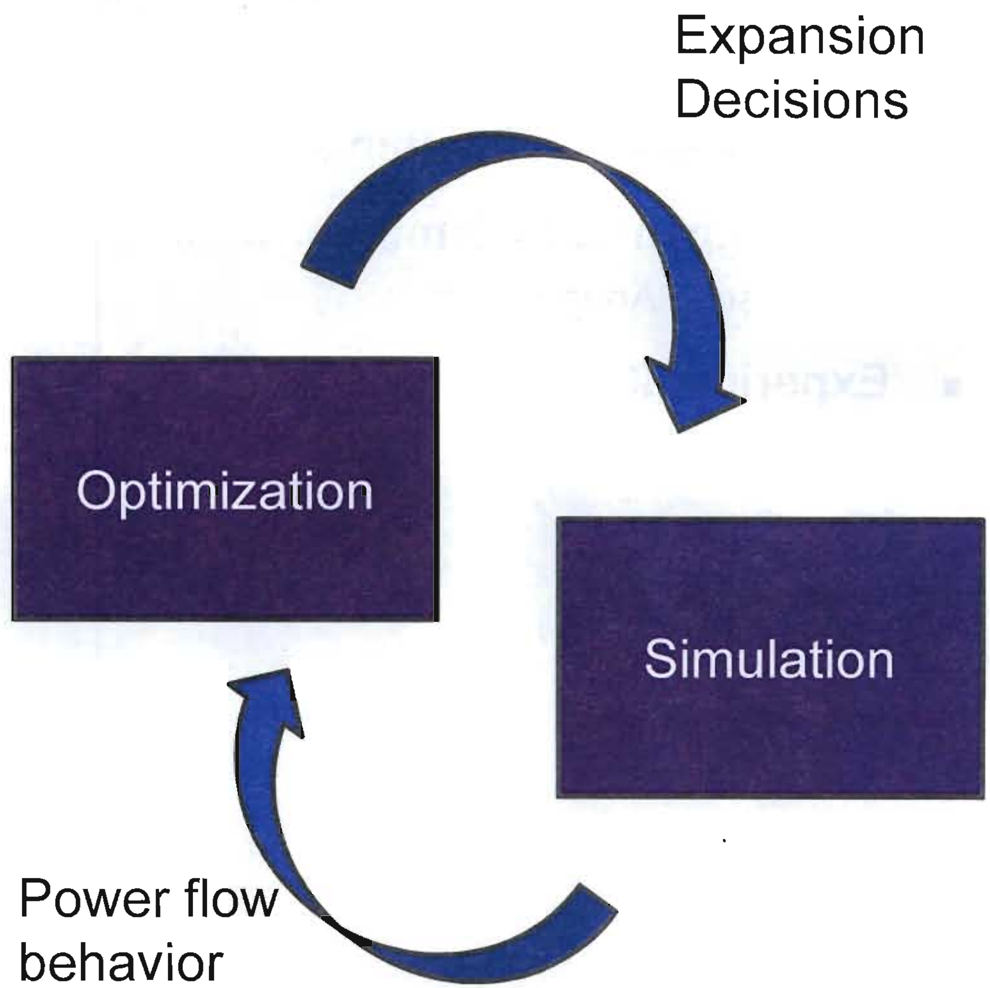
Algorithm Intuition: Simulation Optimization

- Encapsulate models difficult to represent in a *black box (simulation)*
- Typically used to evaluate objective function or feasibility
- Simulation results inform optimization choices
- Algorithm decoupled from the details of how power flows are modeled



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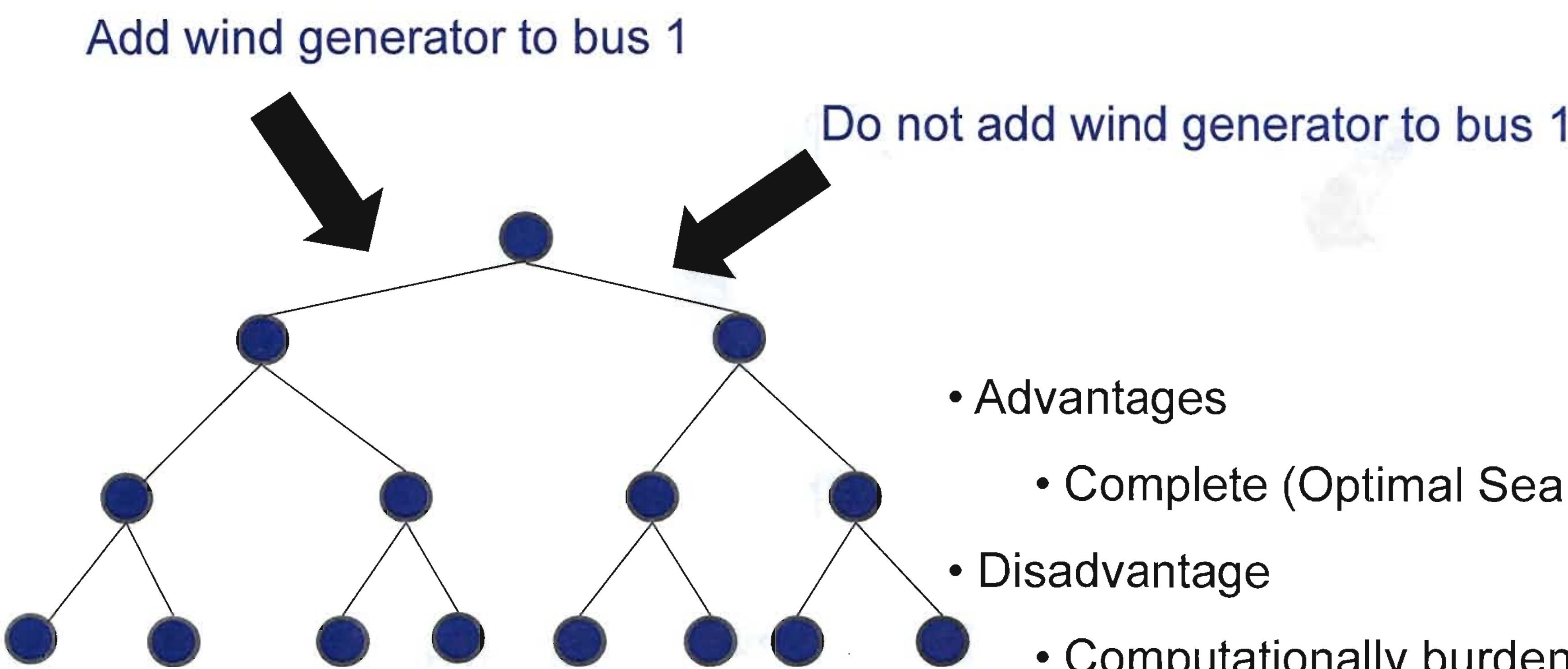
  - Existing Approaches
- **Experimental Results**

Branch and Bound

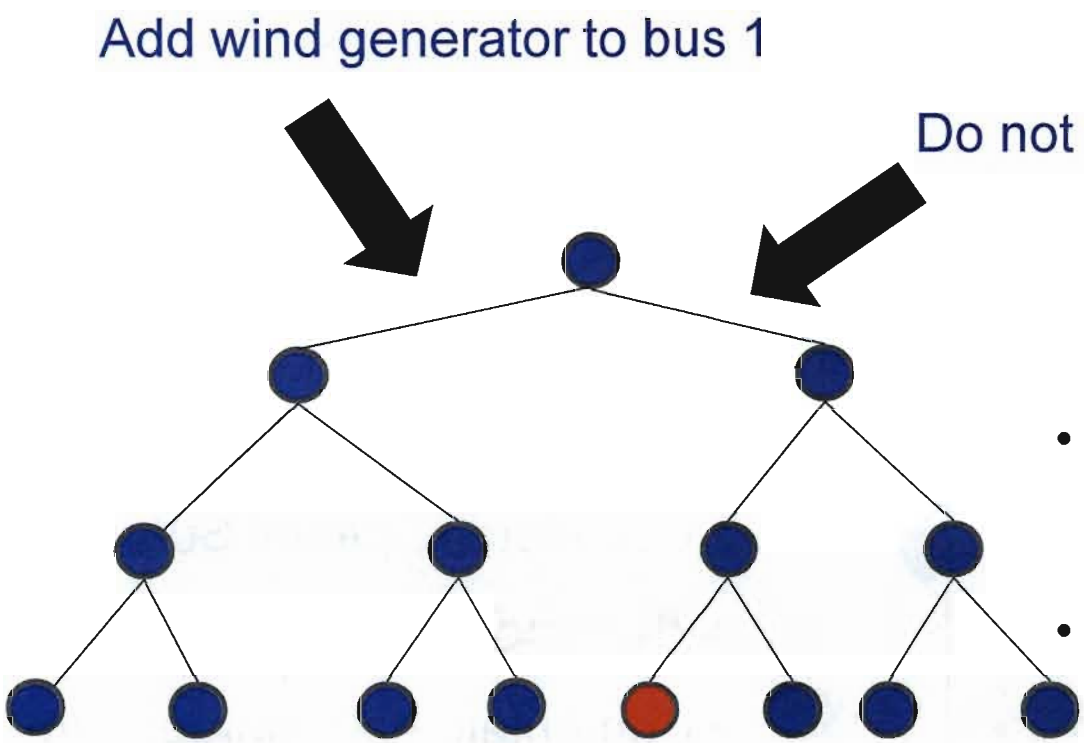
Example:



- Advantages
  - Complete (Optimal Search)
- Disadvantage
  - Computationally burdensome

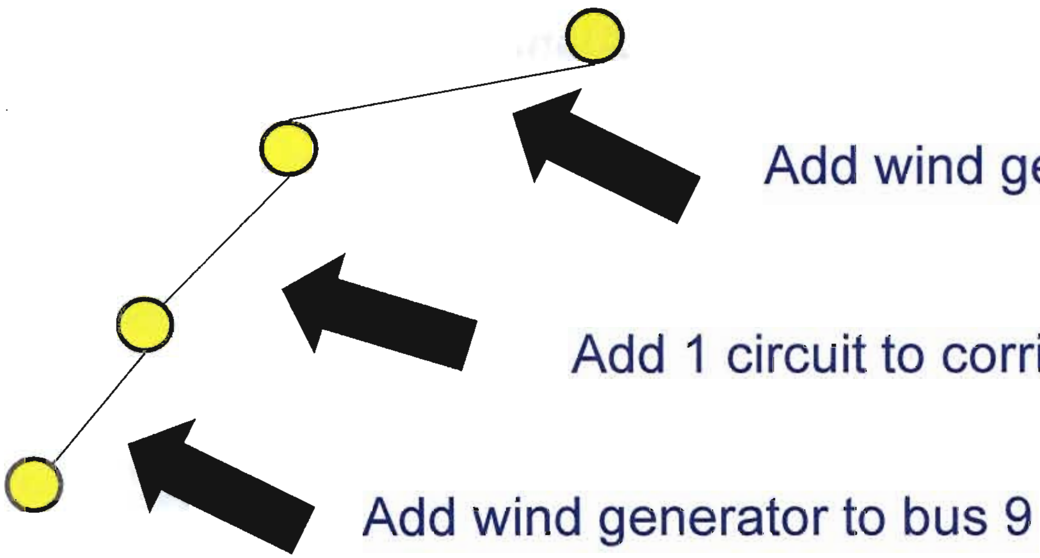
Branch and Bound

Example:



- Advantages
  - Complete (Optimal Search)
- Disadvantage
  - Computationally burdensome

Constructive Heuristic



- Advantages
  - Computationally efficient
- Disadvantage
  - Local optimality

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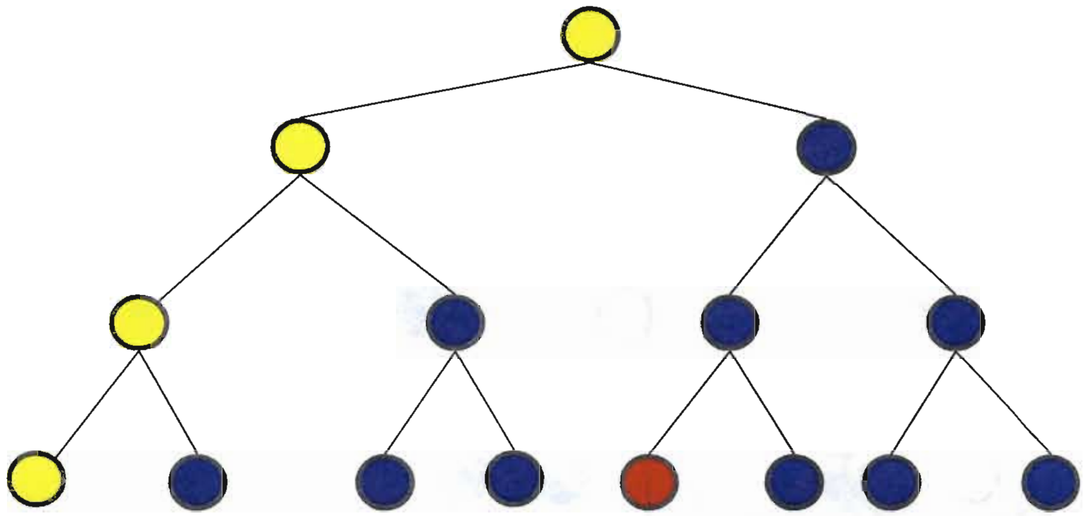
  - Existing Approaches
  - Our Approach (Hybridize)
- **Experimental Results**

Discrepancy Bounded Local Search – DBLS (Approach 1)

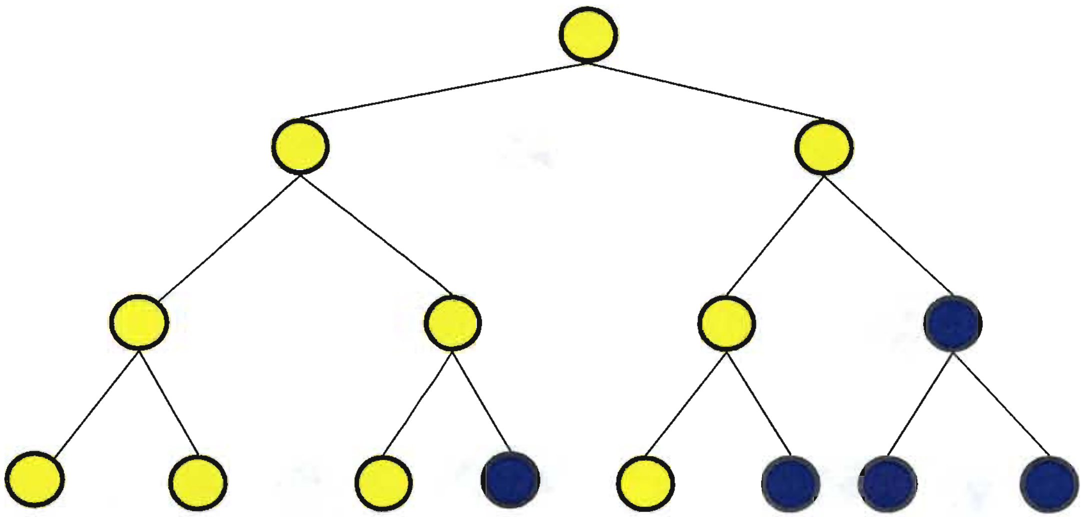


Hybridize the two approaches

Constructive heuristic is used as the branching heuristic

Still computationally expensive …

Discrepancy Bounded Local Search – DBLS (Approach 1)



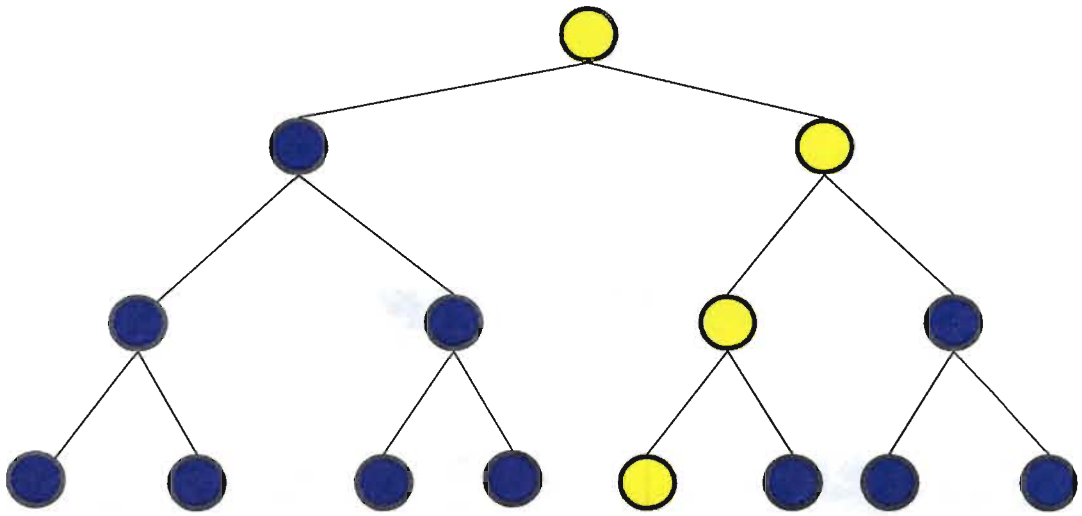
1 Discrepancy

Solution: Explore solutions near the heuristic

Up to δ distance (discrepancies) from the heuristic

Similar to Limited Discrepancy Search (Harvey & Ginsberg 95)

Randomized Constructive Heuristic – RCH (Approach 2)

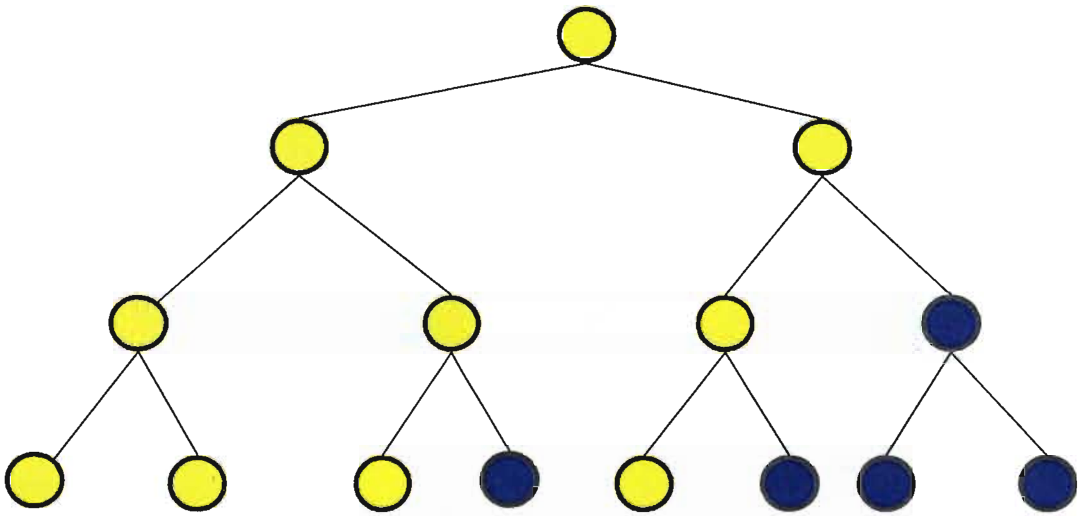


For any node in the search tree, order the expansion options by the constructive heuristic

Choose the i^{th} option, where i = (RANDOM([0,1])ß * # possible expansions)

Repeat the search multiple times to find alternate solutions

RCH and DBLS



Enhancements

- Execute simulation (power flow) for each partial solution
- Prune when partial solutions degrade solution quality too much

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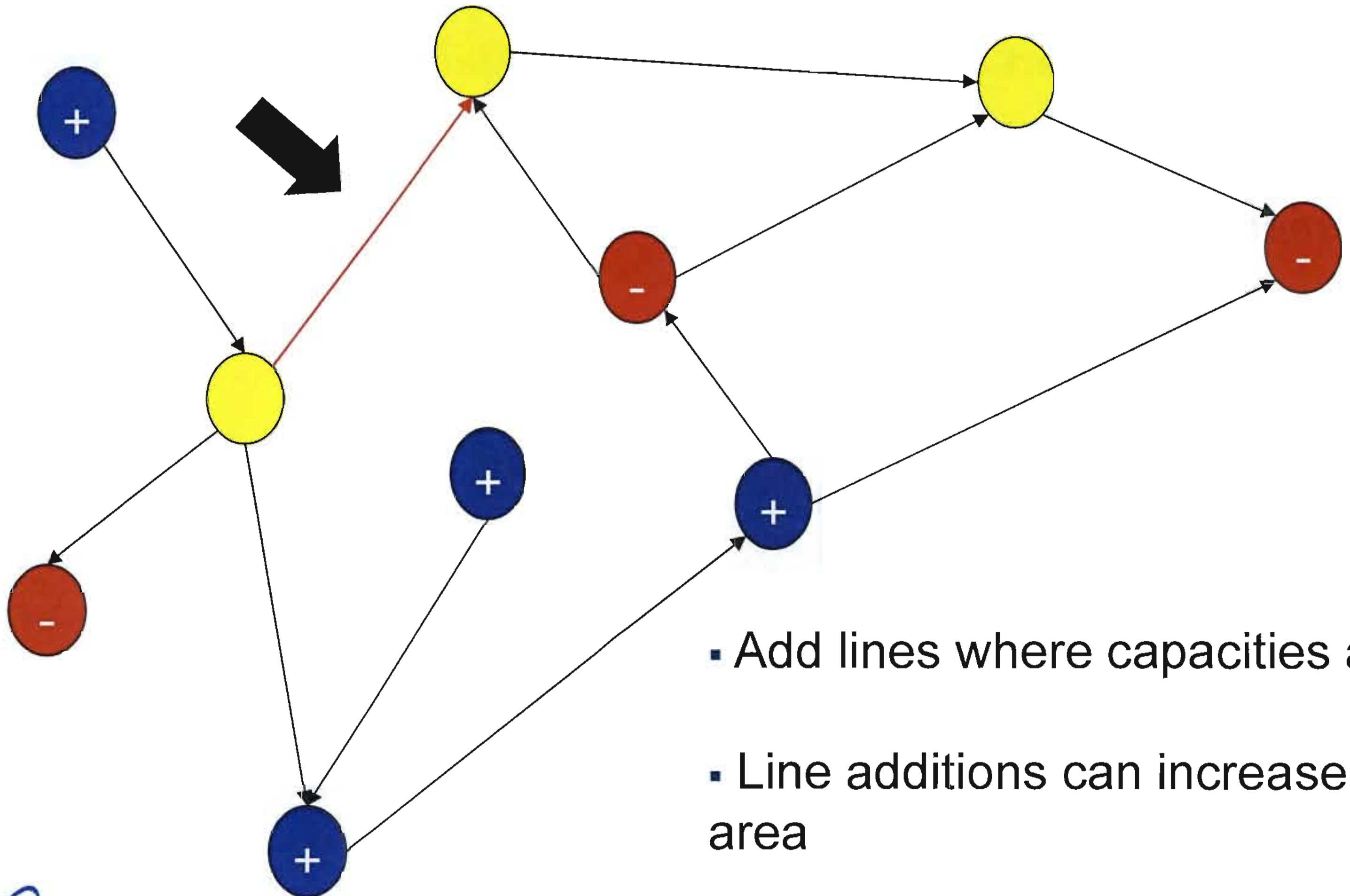
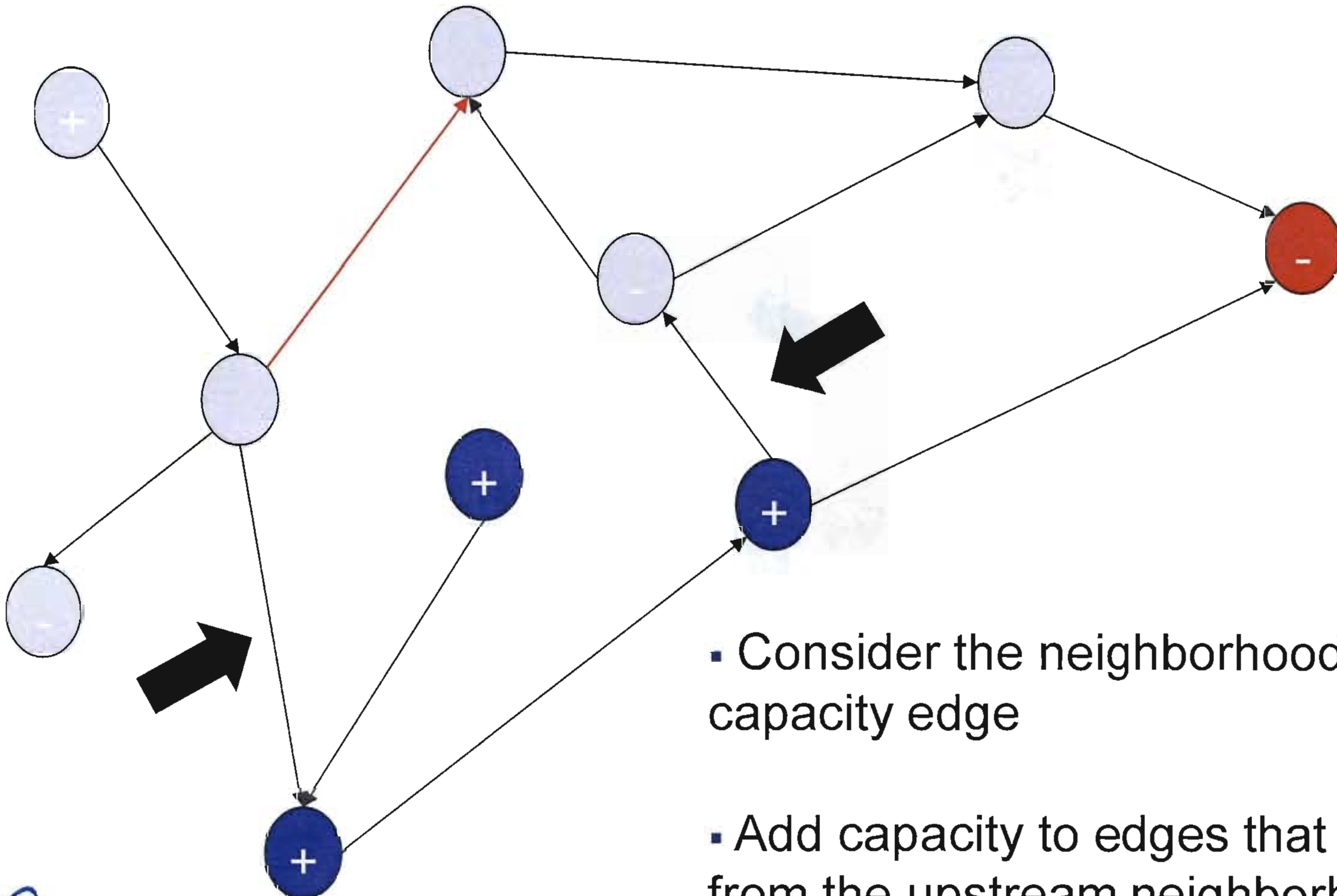
  - Branching Heuristics
- **Experimental Results**

Constructive Heuristic: Max Utilization (MU)



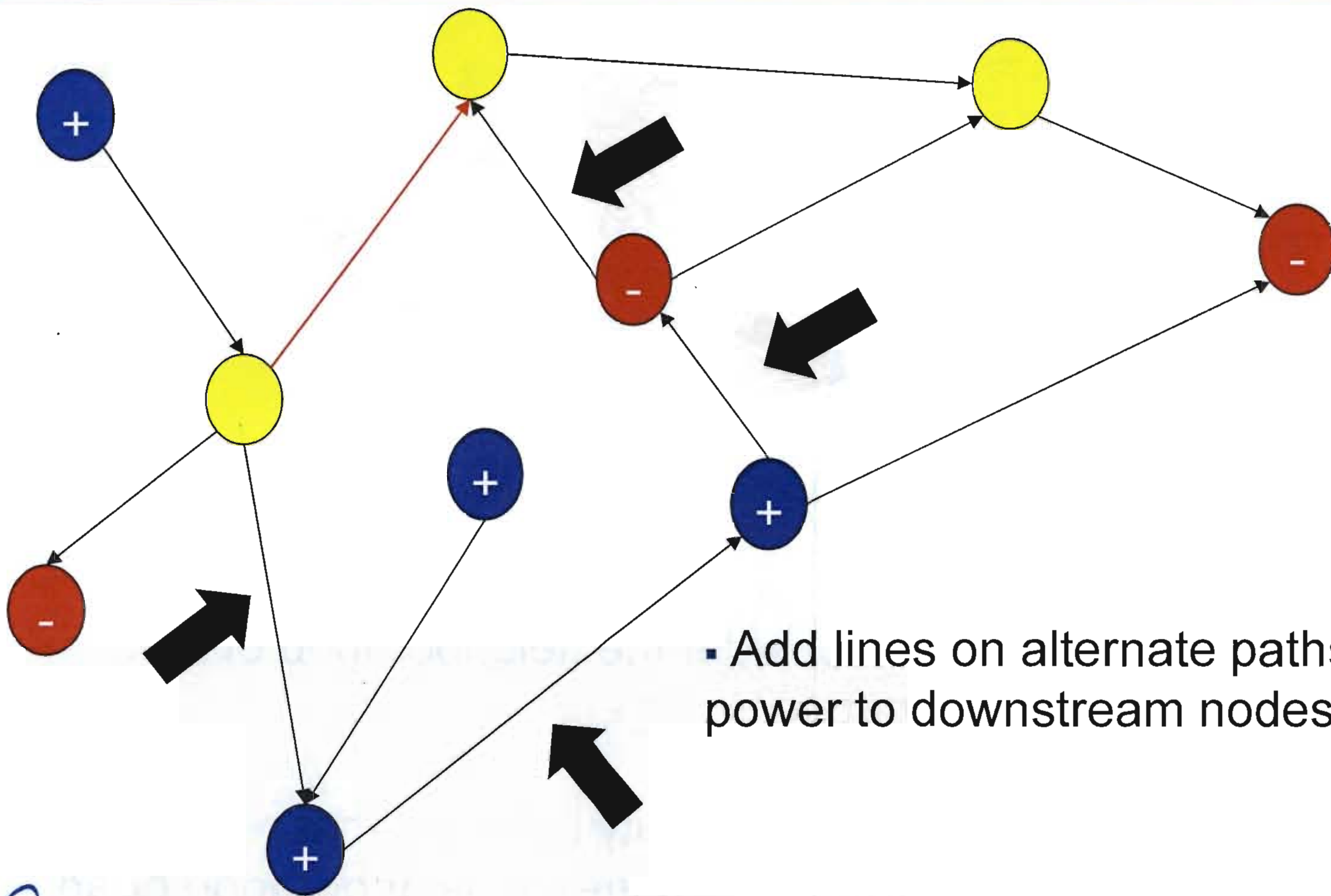
- Add lines where capacities are violated
- Line additions can increase flow in the area

Constructive Heuristic: Flow Diversion (FD)



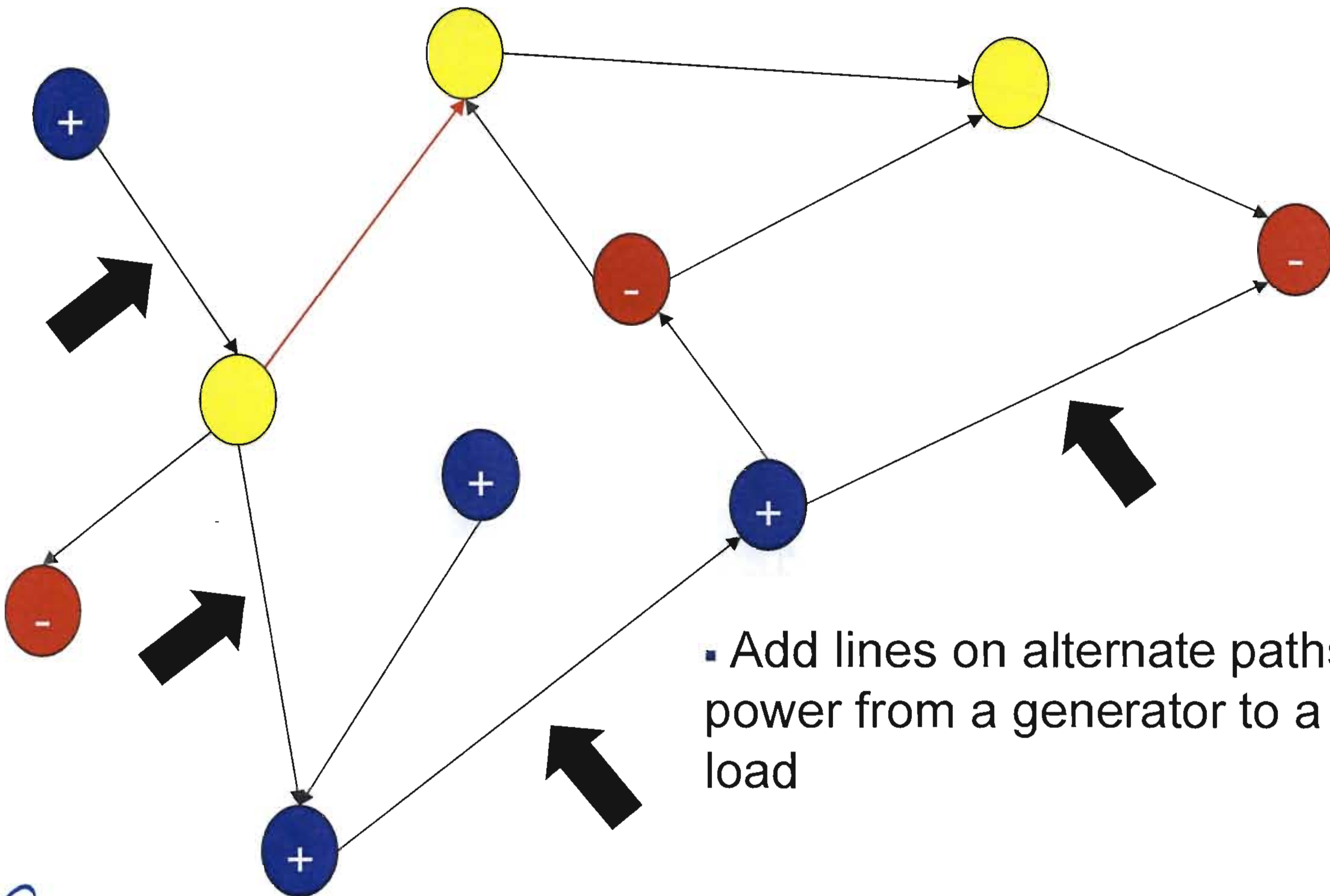
- Consider the neighborhood of an over-capacity edge
- Add capacity to edges that remove power from the upstream neighborhood or add power downstream

Constructive Heuristic: Alternate path (AP)



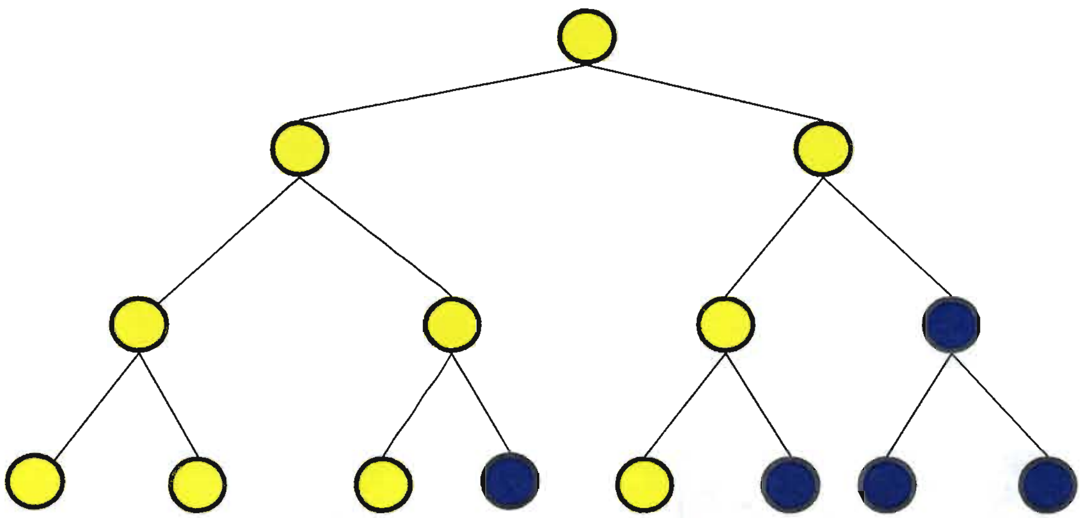
- Add lines on alternate paths that bring power to downstream nodes

Constructive Heuristic: Alternate path around (APA)



- Add lines on alternate paths that bring power from a generator to a downstream load

Constructive Heuristic: Most Improving (MI)



Choose the expansion that improves the partial solution the most

- *Bustamante-Cedeno and Arora 09, Romero et al 05, etc.*

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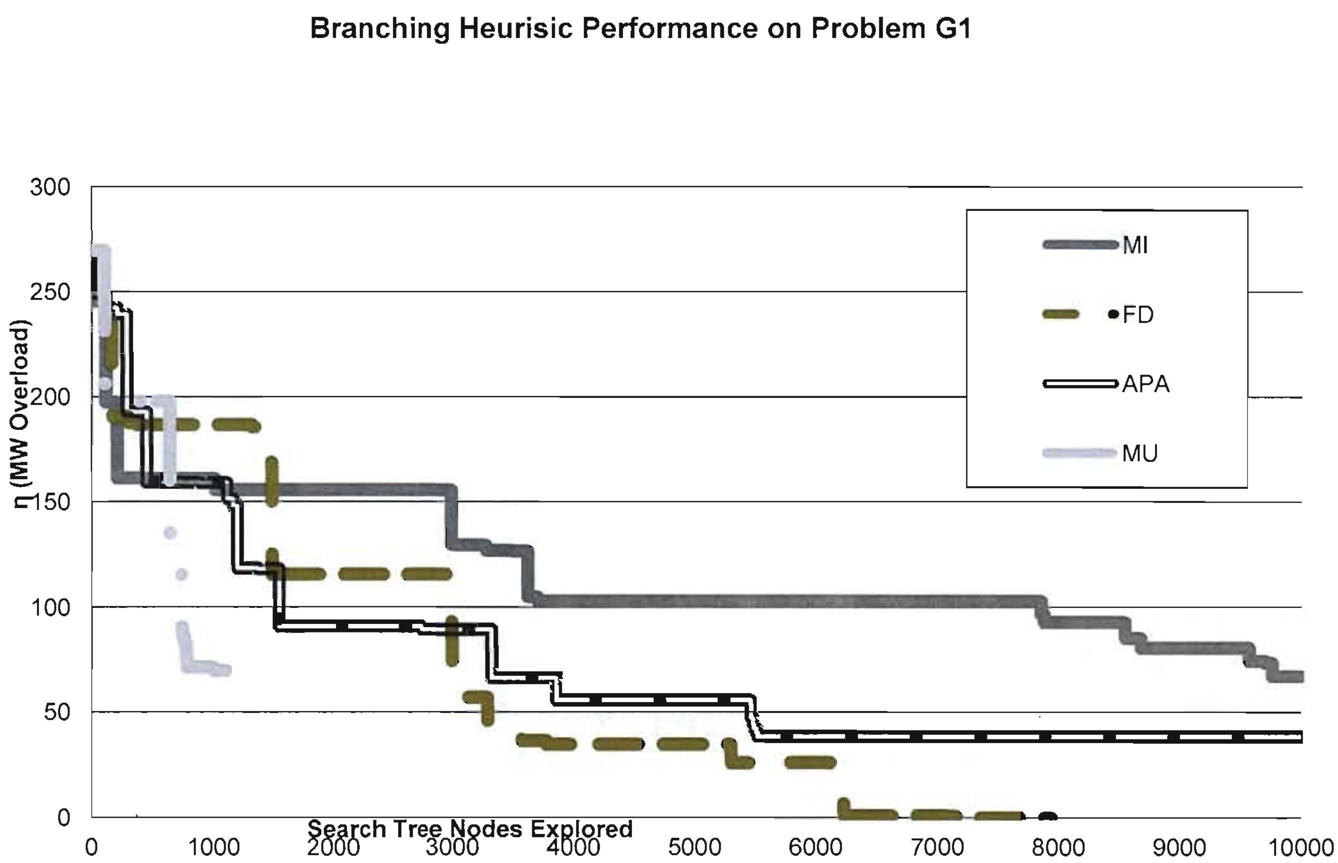
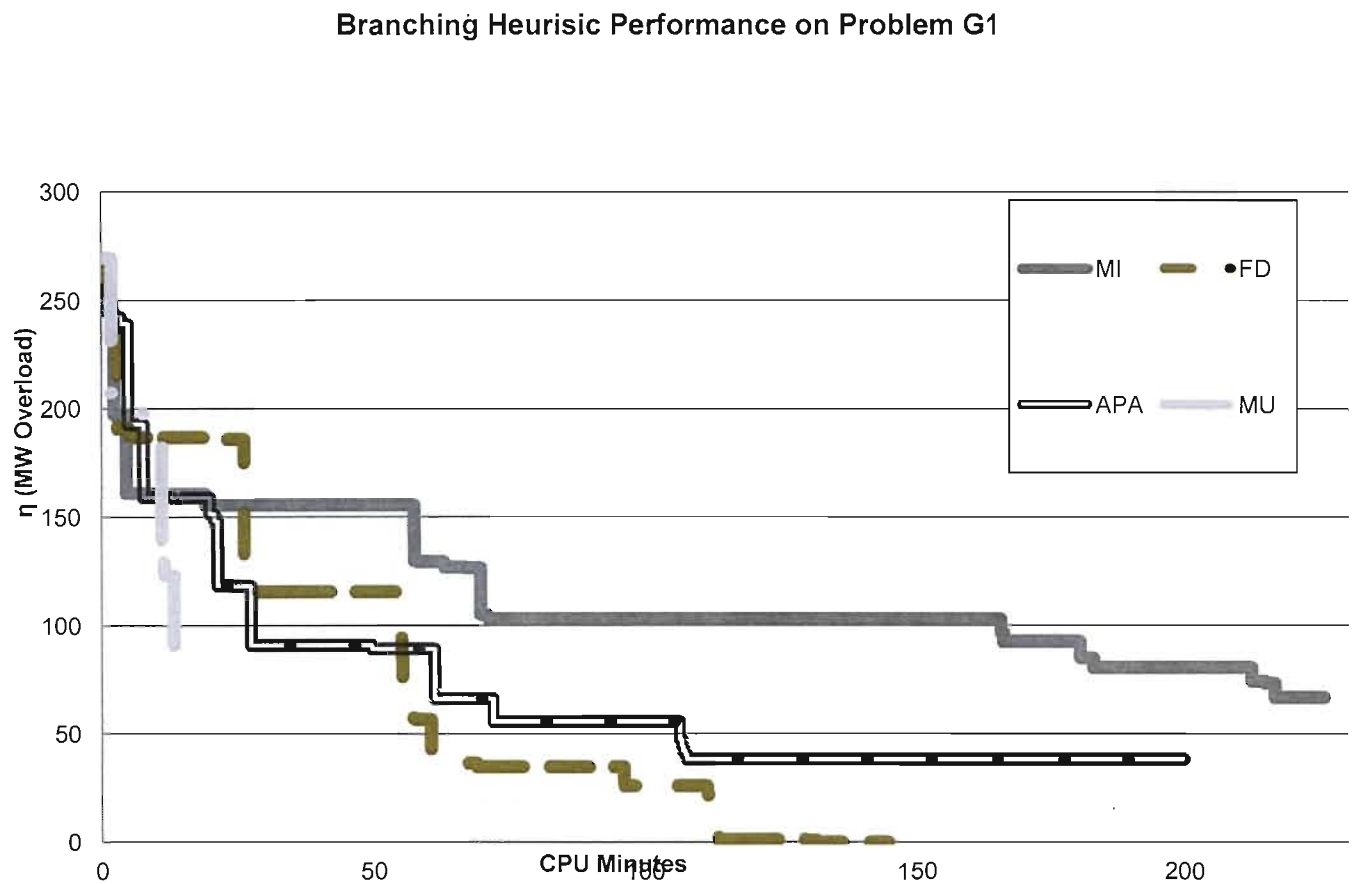
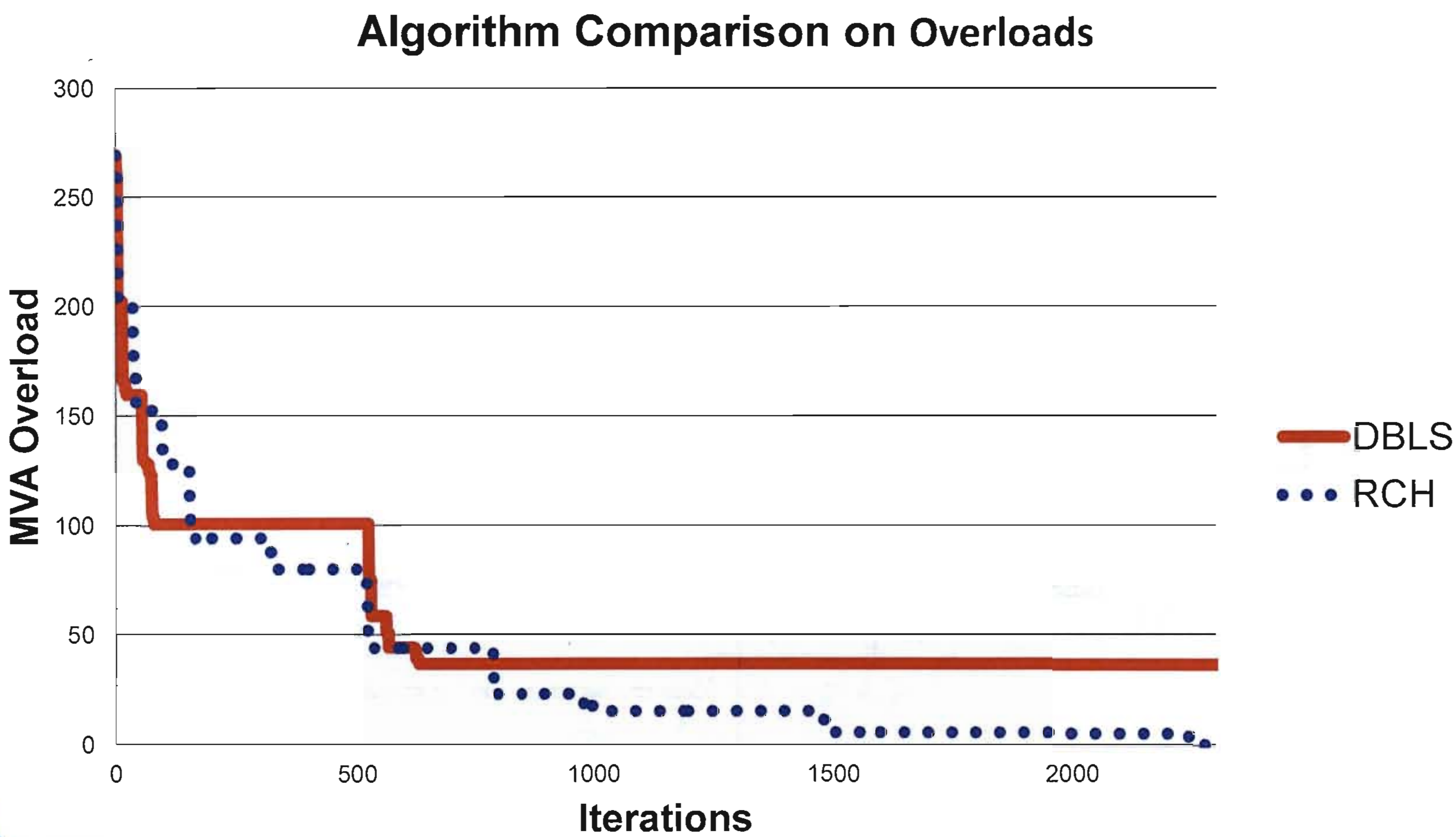
Comparison of results for different heuristics



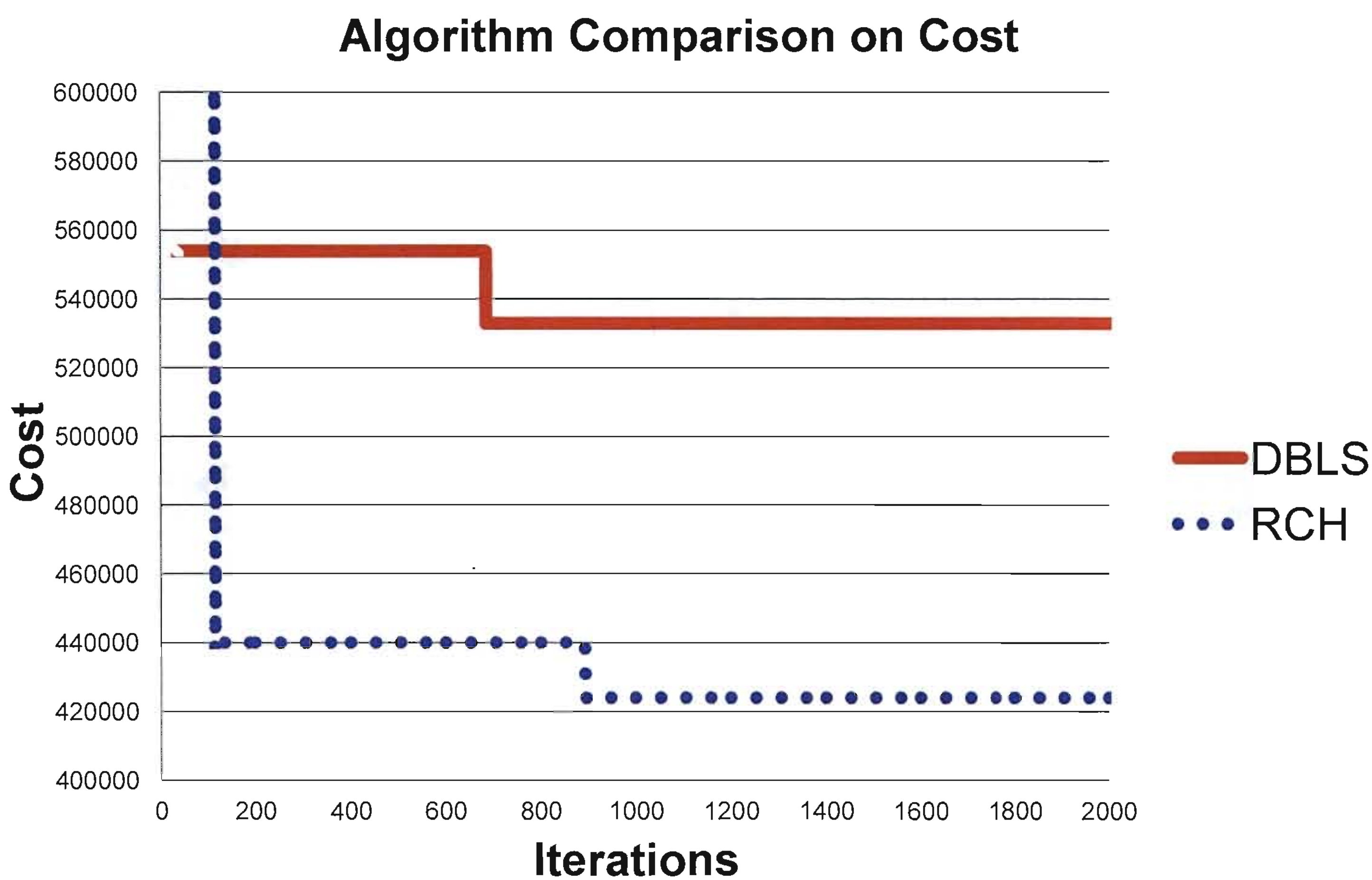
Comparison of results for different heuristics



Comparison of two algorithms



Comparison of two algorithms



Comparison with Existing Approaches

Solutions to the DC model

Problem	Best Known	Ref	Best Found
G1	438K	RRMS	390K
G2	451K	FH	392K
G3	218K	RRMS	272K
G4	376K	FH	341K

RRMS = Romero et al 05, FH = Feng and Hill 03

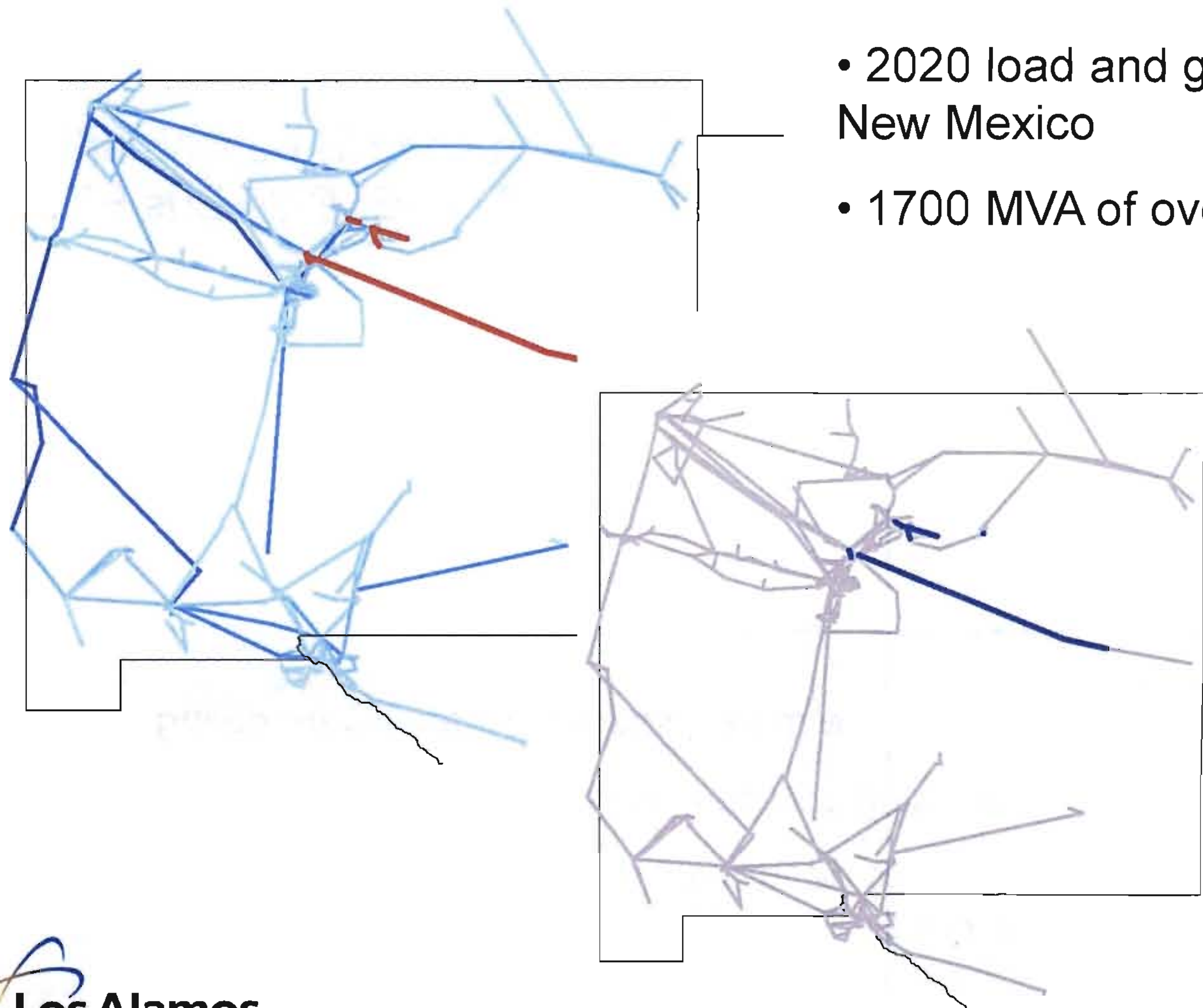
AC modeling vs. DC modeling

	DC	AC
G1	390K	1316K
G2	392K	1977K
G3	272K	1003K
G3	341K	1978K

- Feng and Hill benchmarks based on IEEE 24 Bus RTS problems

- Expansion based on AC modeling considerable more expensive than DC modeling
- Empirical evidence of the importance of using complex power flow models
- Problem is very constrained (no dispatchable generation, DC solution maxes some expansions, high percentage of reactive power, limited shunt compensation expansion options)

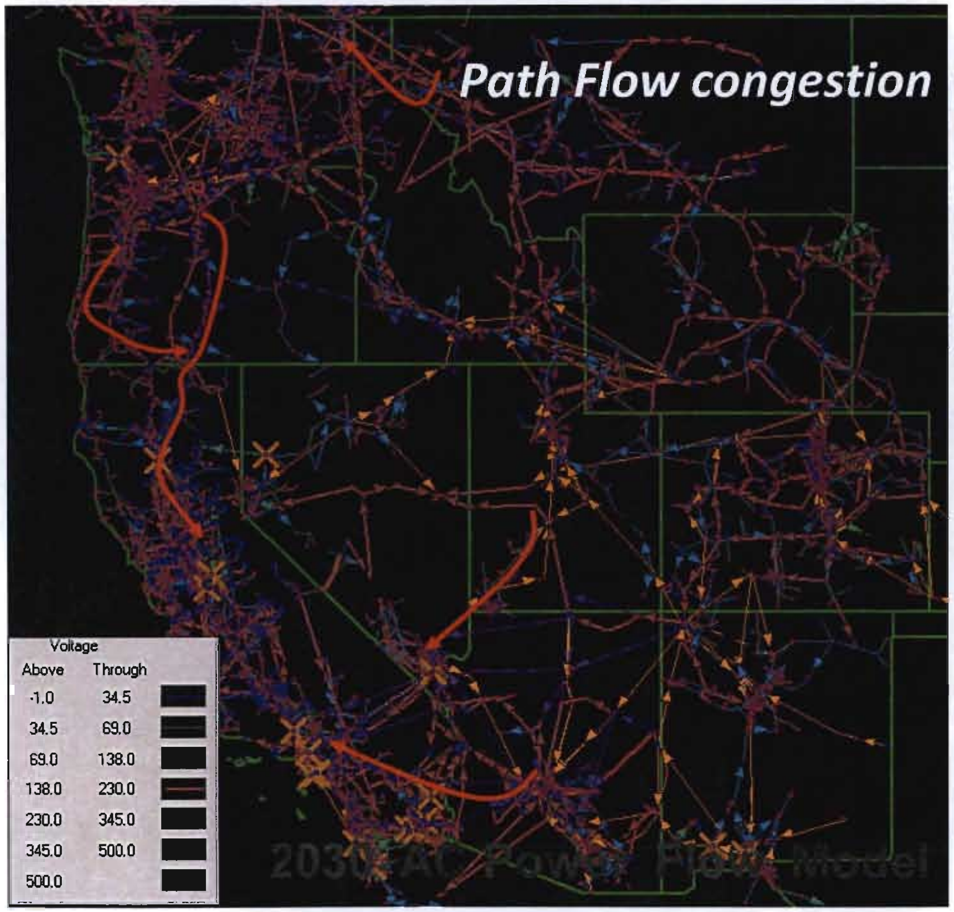
Expand the New Mexico Grid



- 2020 load and generation projections for New Mexico
- 1700 MVA of overloads in 31 corridors

- 30 circuits added to 28 corridors
- 300 Million in expansion costs

Expand for WECC



Scenario Factsheet: 2030 High Summer (NREL H3)		
Metric	**Value**	**Unit**
Added branch capacity	550 (incl. 125 pri. Transformer)	GVA
Added shunt capacity	69	GVAR
End-point L/R	Load 209; Resource 244	GW
Generation capacity	167 Conv.; 77 Nonconv (wind)	GW
Highest HV line loading	59 (NE California), 53 (SE Oregon)	%
Highest inflow	24 (Seattle), 17 (Phoenix)	GW
Highest outflow	13 (Seattle), 12 (San Francisco)	GW
Highest N-1 load shed	25 (Phoenix), 8 (SW New Mexico)	GW
New/Upgraded corridors	8,118	Miles
Primary voltage upgrades	100 to 230	kV
Transmission upgrade cost	10,544 M +/- 150	2009$

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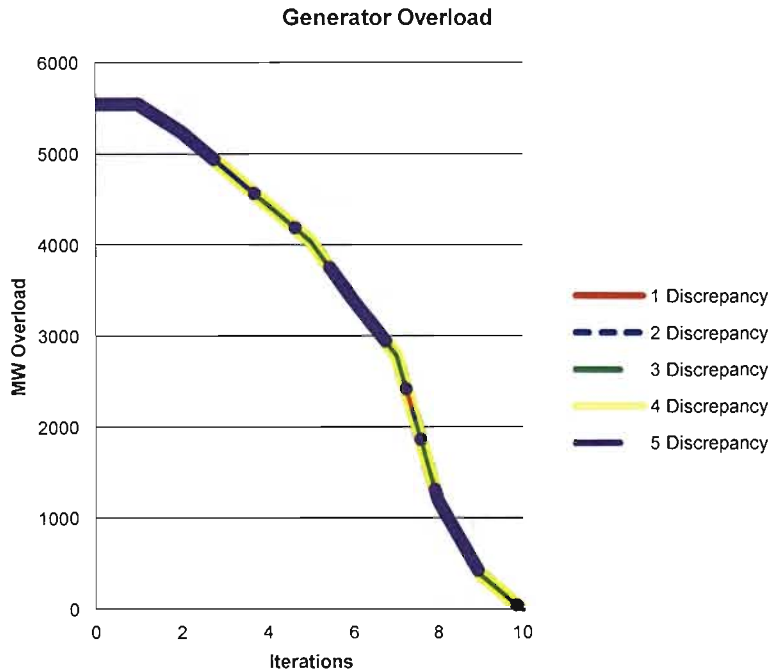
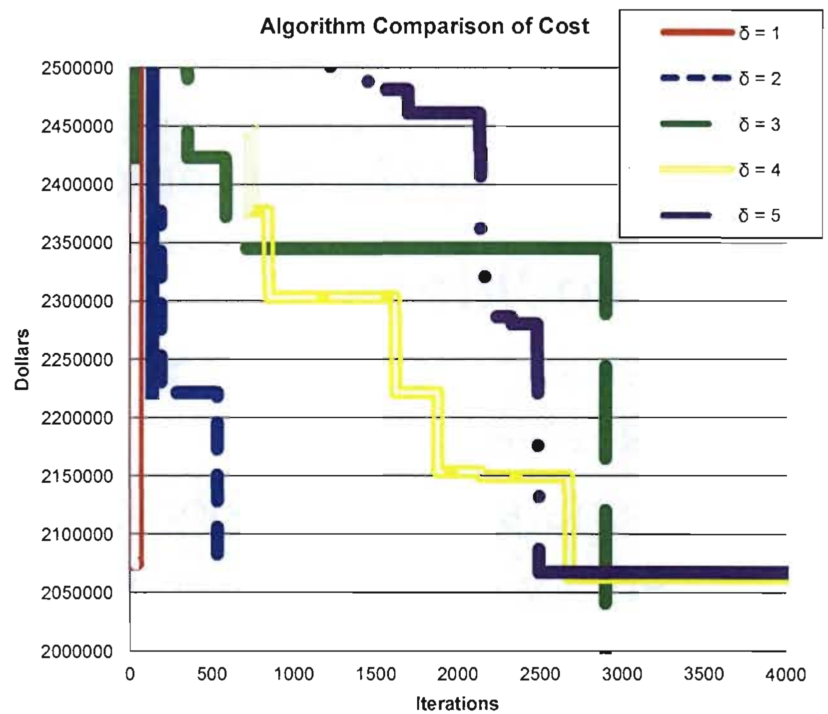
IEEE Benchmarks (Feng and Hill, 2003)

- **Existing benchmark**
  - Grew Loads and Generation of IEEE RTS-79 by 200-300%
  - 24 buses, 41 transmission corridors, 8550 MW of load
  - Expand with up to 3 additional circuits in each existing, and up to 3 circuits in 8 new corridors
- **Our additions**
  - Scale generation back to RTS-79 levels, make this a decision variable
  - Generation expansion costs roughly inline with transmission costs
  - See paper for the details

DC model results





DC model results

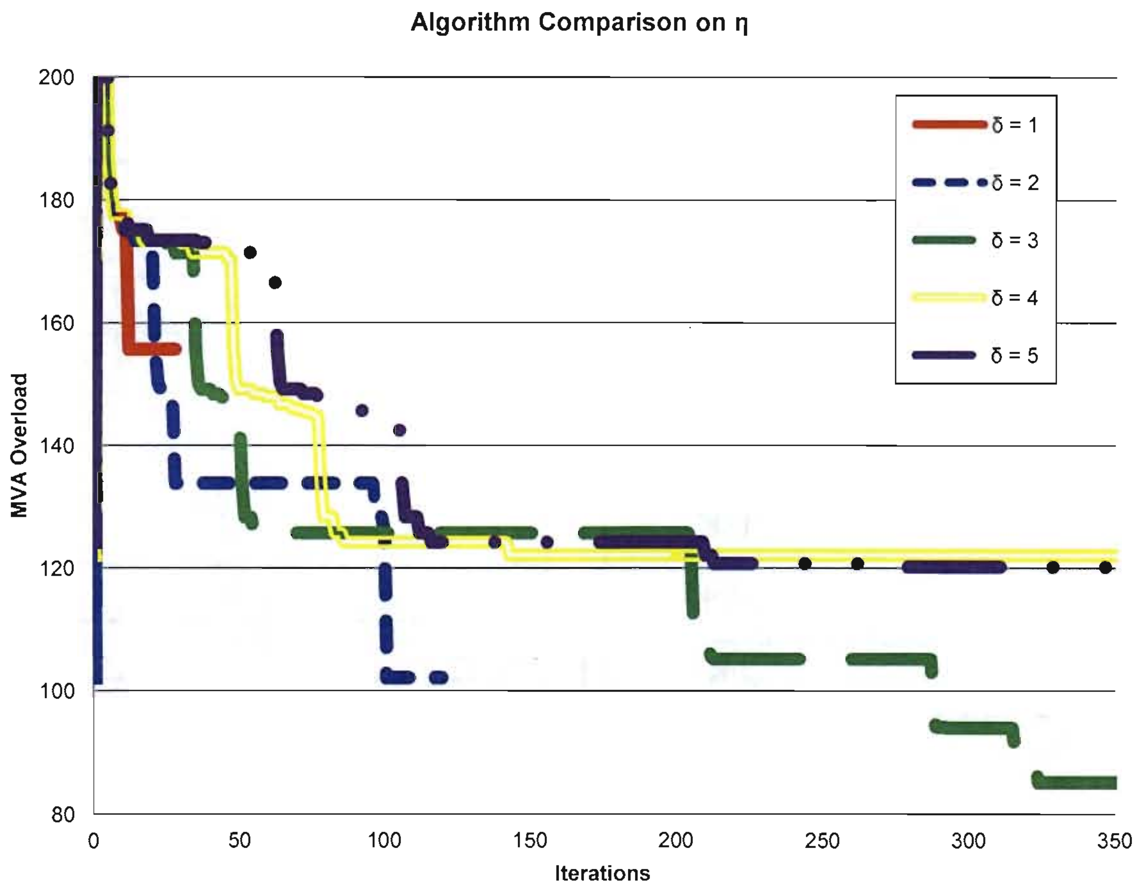
Bus	Generators	Cost
1	4	40K
2	4	80K
7	4	158K
13	8	600K
14	0	0K
15	4	36K
16	3	15K
18	2	200K
21	0	0K
22	3	148K
23	4	636K

1913K

Circuit	Lines	Cost
1,2	0	0K
1,5	0	0K
2,4	0	0K
2,6	0	0K
3,24	0	0K
5,10	0	0K
6,7	0	0K
6,10	1	16K
7,8	2	32K
8,10	0	0K
10,12	1	50K
10,11	0	0K
11,13	1	66K
14,16	0	0K
15,24	0	0K
16,17	0	0K

164K

AC Model Results



AC model results

Bus	Generators	Cost
1	4	40K
2	4	80K
7	4	158K
13	8	600K
14	0	0K
15	4	36K
16	3	15K
18	3	300K
21	0	0K
22	3	148K
23	3	477K

1854K

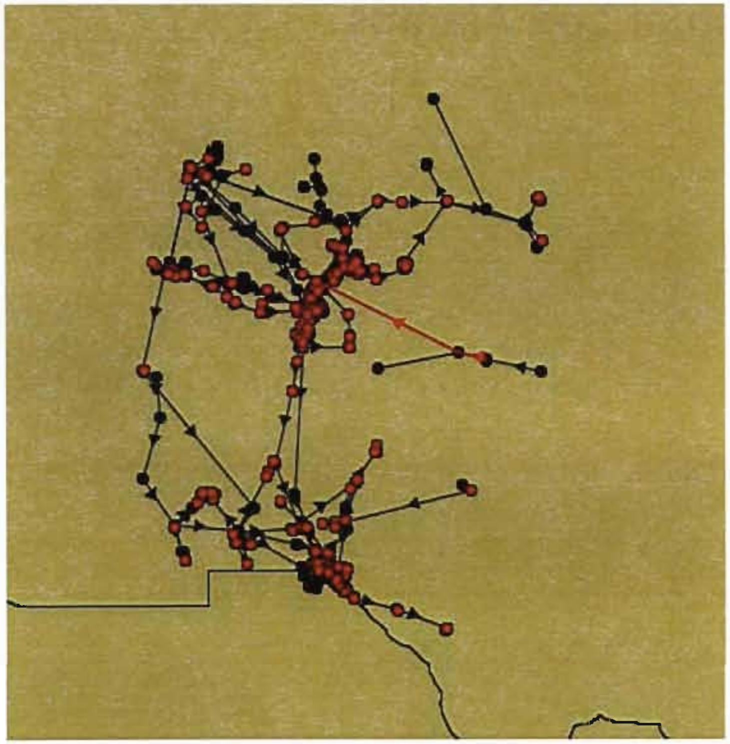
Circuit	Lines	Cost
1,2	1	3K
1,5	1	22K
2,4	1	33K
2,6	3	150K
3,24	1	50K
5,10	3	69K
6,7	3	150K
6,10	0	0K
7,8	3	48K
8,10	3	129K
10,12	0	0K
10,11	2	100K
11,13	1	66K
14,16	1	54K
15,24	1	72K
16,17	1	36K

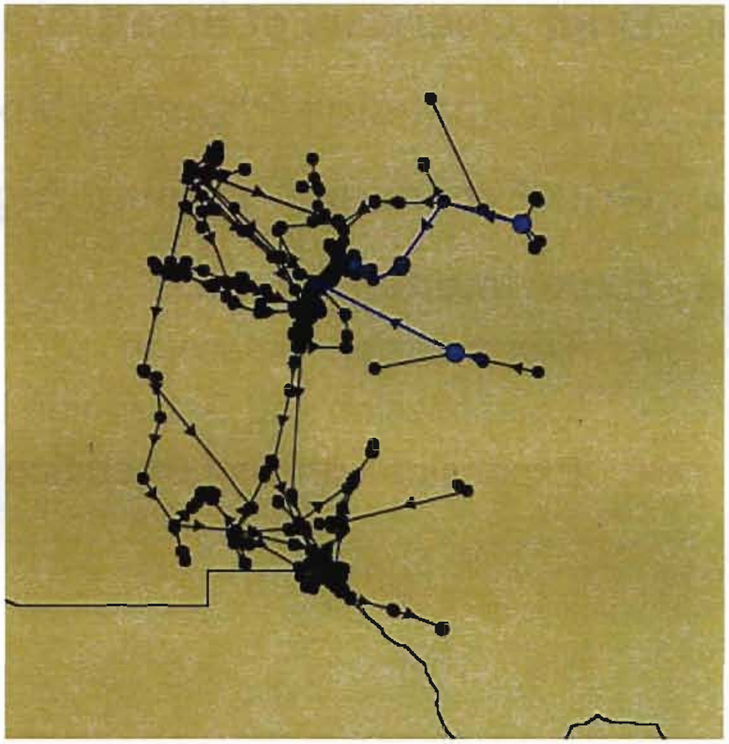
982K

New Mexico Case Study

- U.S. Department of Energy demand predictions for 2020.
- 7 buses selected for renewable expansion (2 solar, 5 wind) from *New Mexico renewable development study: 5, 10, and 20-year transmission collection, Technical Report LA-UR 10-6319*
- Solution builds bulk of new generation in Springer and Guadalupe areas
- 800 MVA in line overloads in 30 transmission corridors
- Solution adds 53 lines in 41 corridors
- ~$7,300 million in cost (~300 million for DC model)

New Mexico





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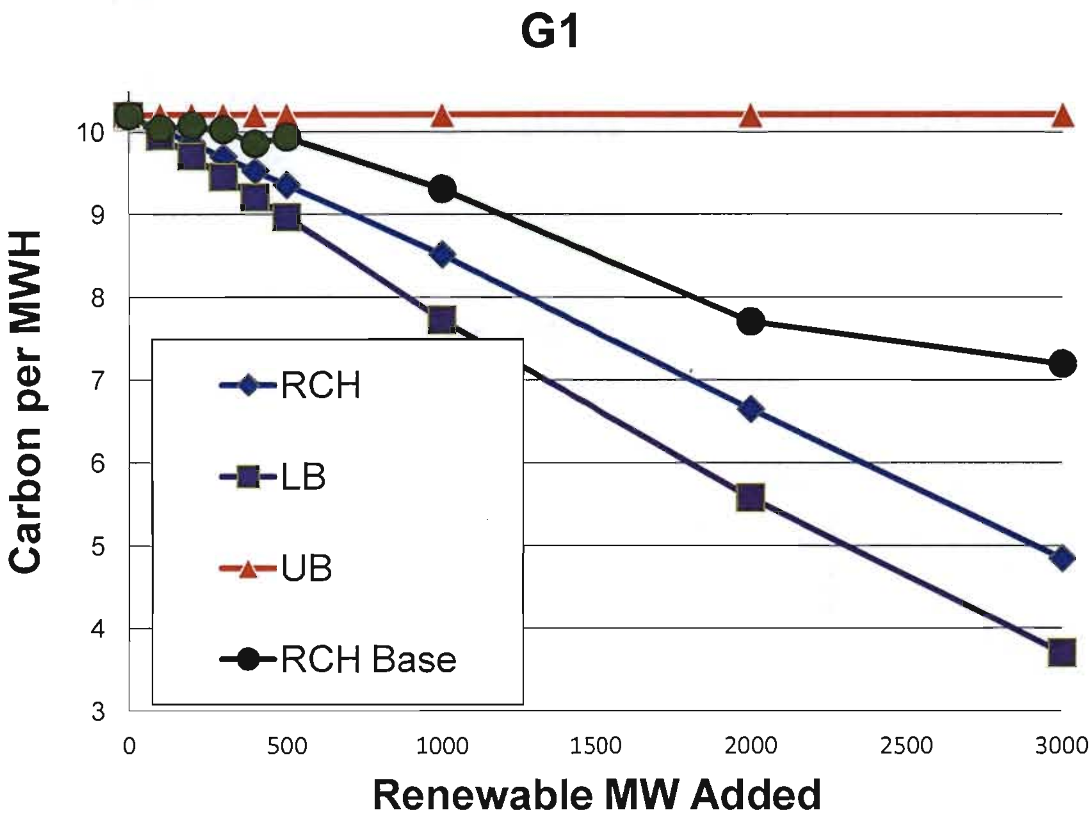
  - Transmission and Generation Expansion
  - Expansion with Grid Operations and Control

Example 1: Reduction of Carbon Emissions

- **Consider how adding renewable generation does/does not reduce carbon emissions**
- **Based on Feng and Hill 03 TNEP RTS-79 problems**
- **7 versions requiring the addition of 100, 200, 300, 400, 500, 1000, 2000, 3000 MW "must take" renewable energy**
  - Can be added to buses 1, 2, 7, 13, 15, 16, 18, 21, 22, and 23 (existing generation sites)
- **Model operations through the DC OPF**
  - Carbon emissions and operational costs taken from EIA Annual Energy Outlook

Example 1: Reduction of Carbon Emissions



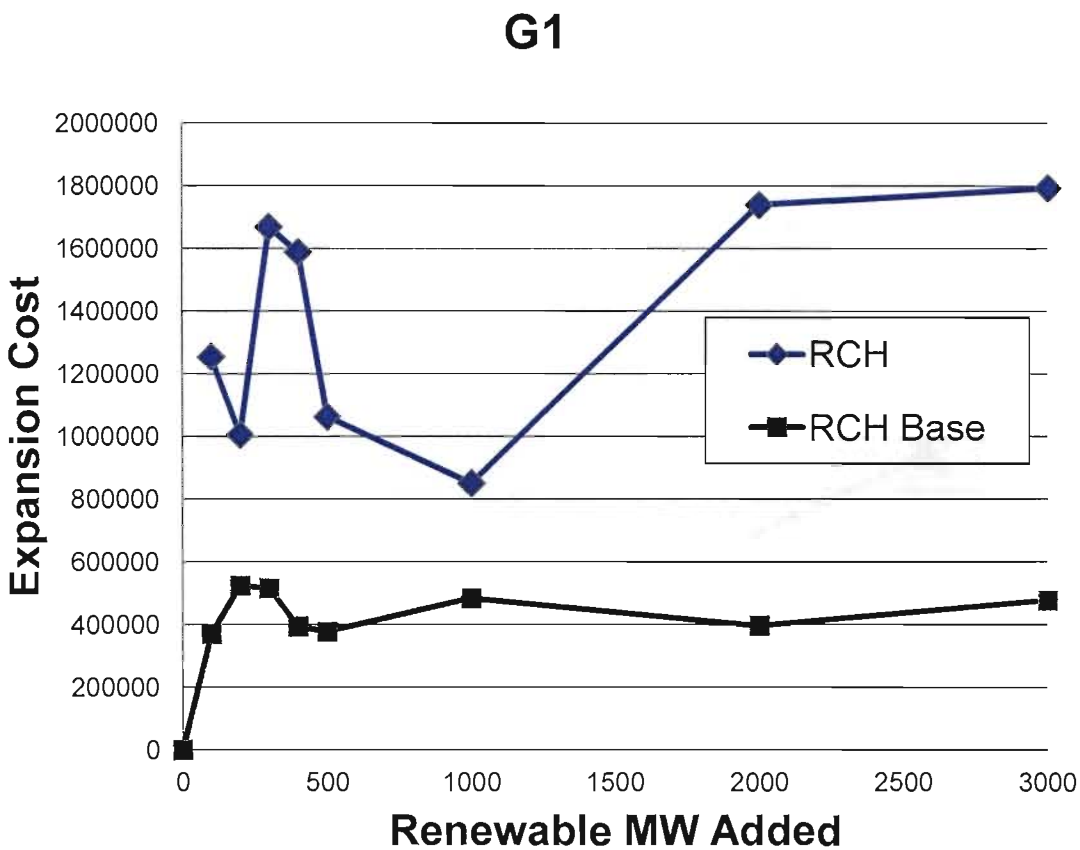
RCH – includes grid operations

LB – Lower bound on best possible carbon emissions

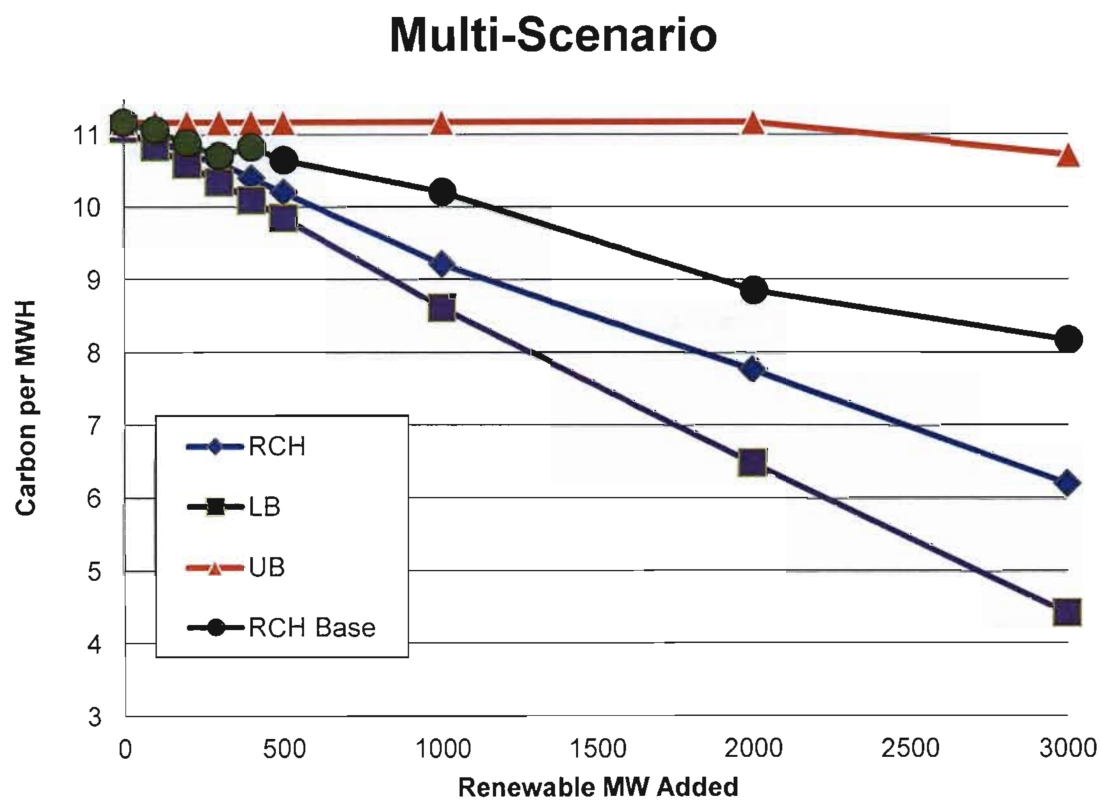
UB – Upper bound on worst possible carbon emissions

RCH Base – solution that does not include grid operations

Example 1: Reduction of Carbon Emissions

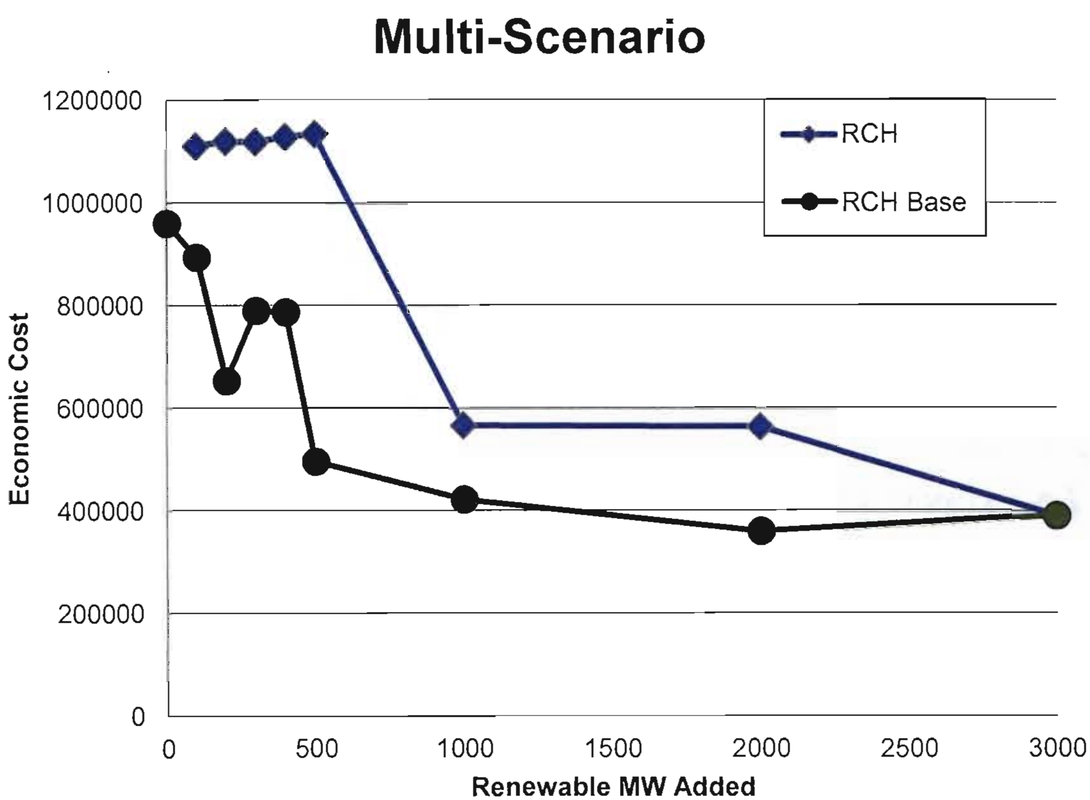


Example 1: Reduction of Carbon Emissions Multi-Scenario



Expansion for 4 load scenarios

Example 1: Reduction of Carbon Emissions Multi-Scenario



Expansion for 4 load scenarios

Example 2: State-Level Collector and Export

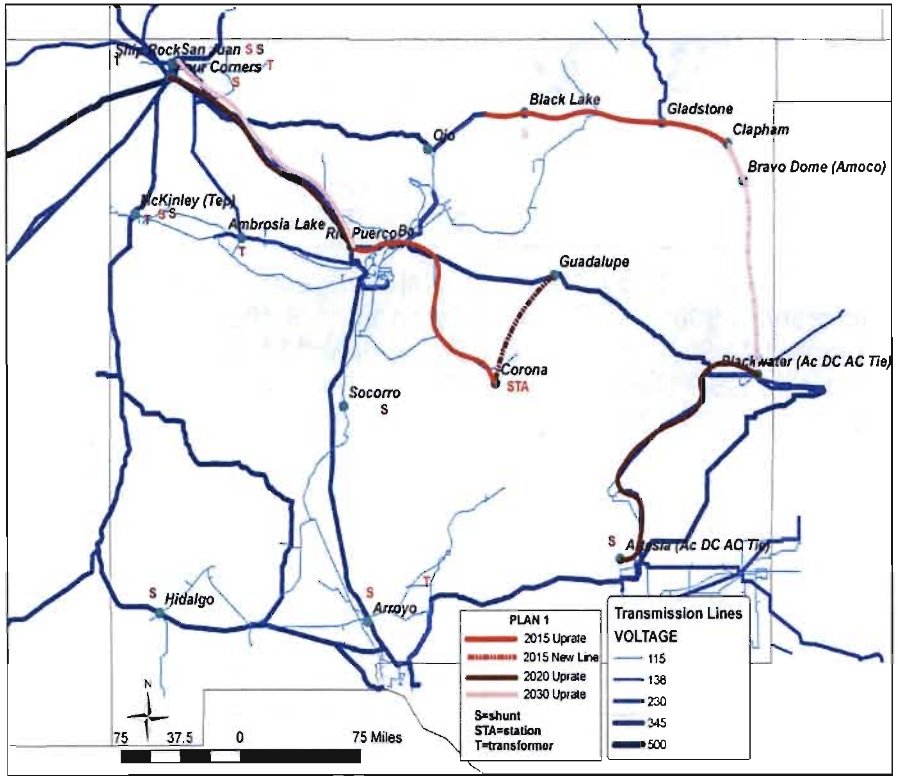
- New Mexico's transmission grid must be expanded to serve ***three purposes:*** [1] Meet projected load growth; [2] Increase utilization of renewables; [3] Maintain reliable delivery of power

- High Summer 2030 electric demand-supply based on WECC's planning assumptions[1]

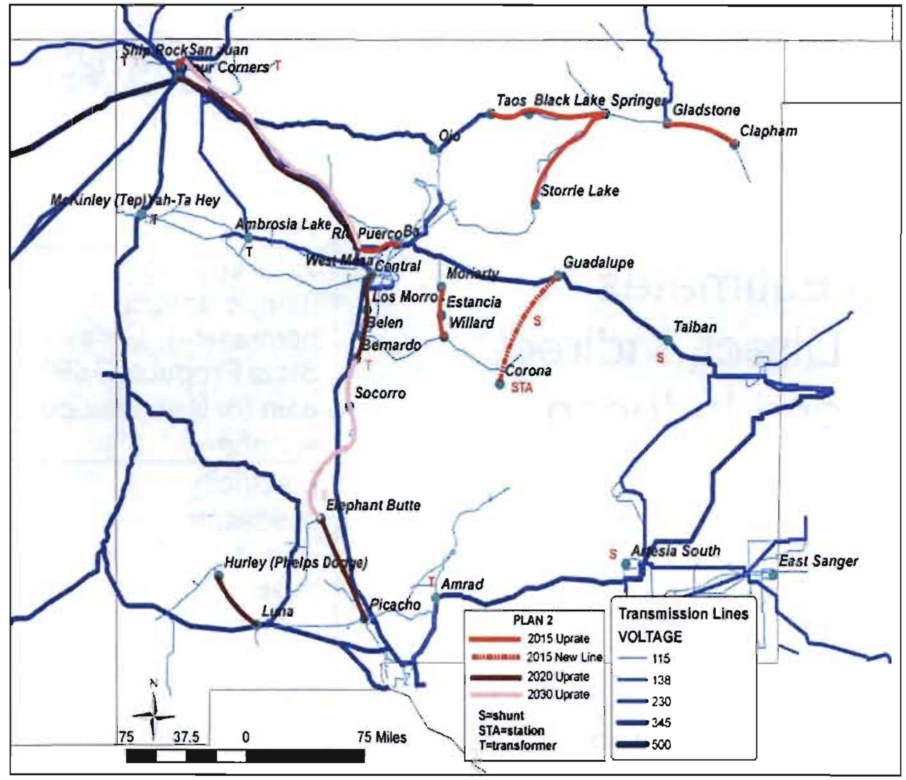
- Four Corners transmission hub will continue to serve as New Mexico's ***primary means for exporting*** power

***1* WECC:** Western Electricity Coordinating Council; primary planning organization for the 14-state western United States

Collection Plan 1, 2 Grid Design (2030)



Collector Plan 1: Uprate 530 miles of existing corridors, construct 311 miles of new corridors



Collector Plan 2: Uprate 849 miles existing corridors

Economic Impacts: Collector Plan 1 versus Plan 2

- State-level Input/output ***IMPLAN*** model
- Estimates Direct, Indirect and Induced effects
- Demonstrates the need to address complex economic operations

Feature	Collector Plan 1	Collector Plan 2
Total cost of installed transmission corridor upgrades over 20-year horizon.	$1,344,522,280; Annual bond cost is approximately $152,158,400	$1,032,679,080; Annual bond cost is approximately $116,867,300
Jobs created (temporary and permanent); Gross State Product [GSP] gain for New Mexico's economy	Total FTE-years: 24,800; Temporary: 9,900; Permanent: 14,900; Cumulative GSP Gain by 2030: $3,311,292,900	Total FTE-years: 21,000; Temporary: 8,400; Permanent: 12,600; Cumulative GSP Gain by 2030: $2,803,147,500
Electricity assessment incurred by each Collector system (dollars per month), 100% recovery at 20-year horizon	Residential: $3.76 per month Commercial: $32.68 per month Industrial: $595.51 per month	Residential: $2.89 per month Commercial: $25.14 per month Industrial: $458.17 per month
Tax revenue accrued from each Collector system	By 2015: $22,397,900 By 2020: $46,331,700 By 2030: $78,566,700	By 2015: $20,600,400 By 2020: $35,873,100 By 2030: $66,994,900

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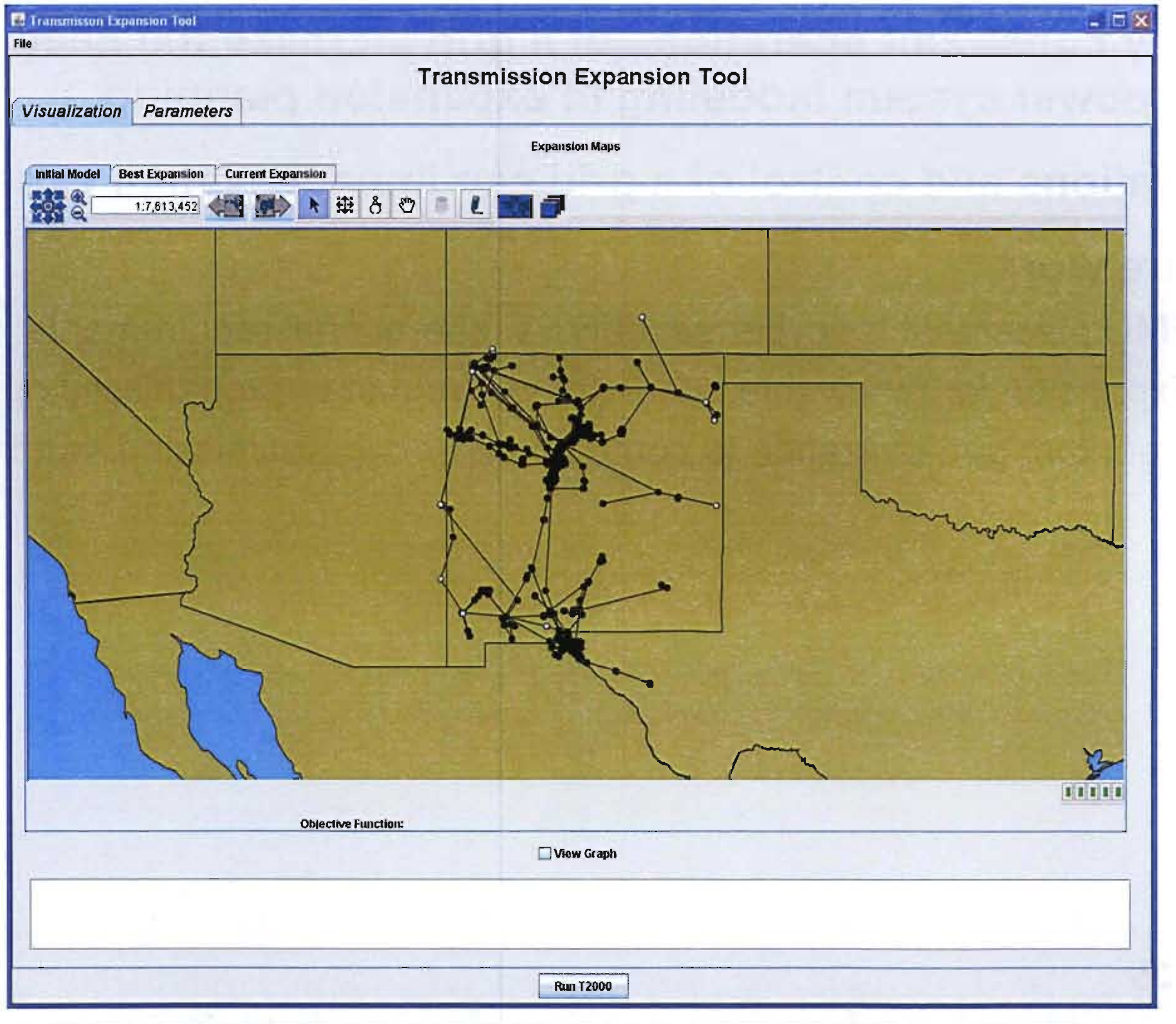
Demo



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Conclusions and Future Work

- **Highly constraint operations of a grid increase the need for complex (AC) power system modeling in expansion planning**
- **Operations and control of a grid can impact system expansions**
- **Future work**
  - PMU placement for cyber security vs. operational requirements
  - Expansion for renewable intermittency (robust or probabilistic operational goals)
  - Algorithm generalization to control problems (transmission switching)

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- The information science developed here ported to the RETA study: *New Mexico renewable development study: 5, 10, and 20-year transmission collection, Technical Report LA-UR 10-6319*