AC or DC Transmission for a Remote Wind Farm?
The Problem of Missing Money

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OBJECTIVE AND OUTLINE

- OBJECTIVE
  - Use an integrated economic/engineering framework (the SuperOPF) that determines reserves endogenously to evaluate the effects of:
    - 1) replacing existing coal capacity with wind capacity at a remote location
      - Must-take wind generation
      - Adding the ability to "spill" wind, if necessary
      - Spillable wind plus storage to reduce the variability of wind generation
      - Spillable wind plus an upgrade of the transmission tie line to the urban load center
      - Spillable wind plus storage and an upgrade of the tie line
    - 2) using a DC transfer of wind generation to the urban load center
      - Spillable wind
      - Spillable wind plus storage capabilities
      - Spillable wind plus storage and load shifting from peak to off-peak
- OUTLINE
  - PART 1: Description of the SuperOPF
  - PART 2: Specifications of the test network
  - PART 3: Results of the case study → Missing Money Matters

PART 1

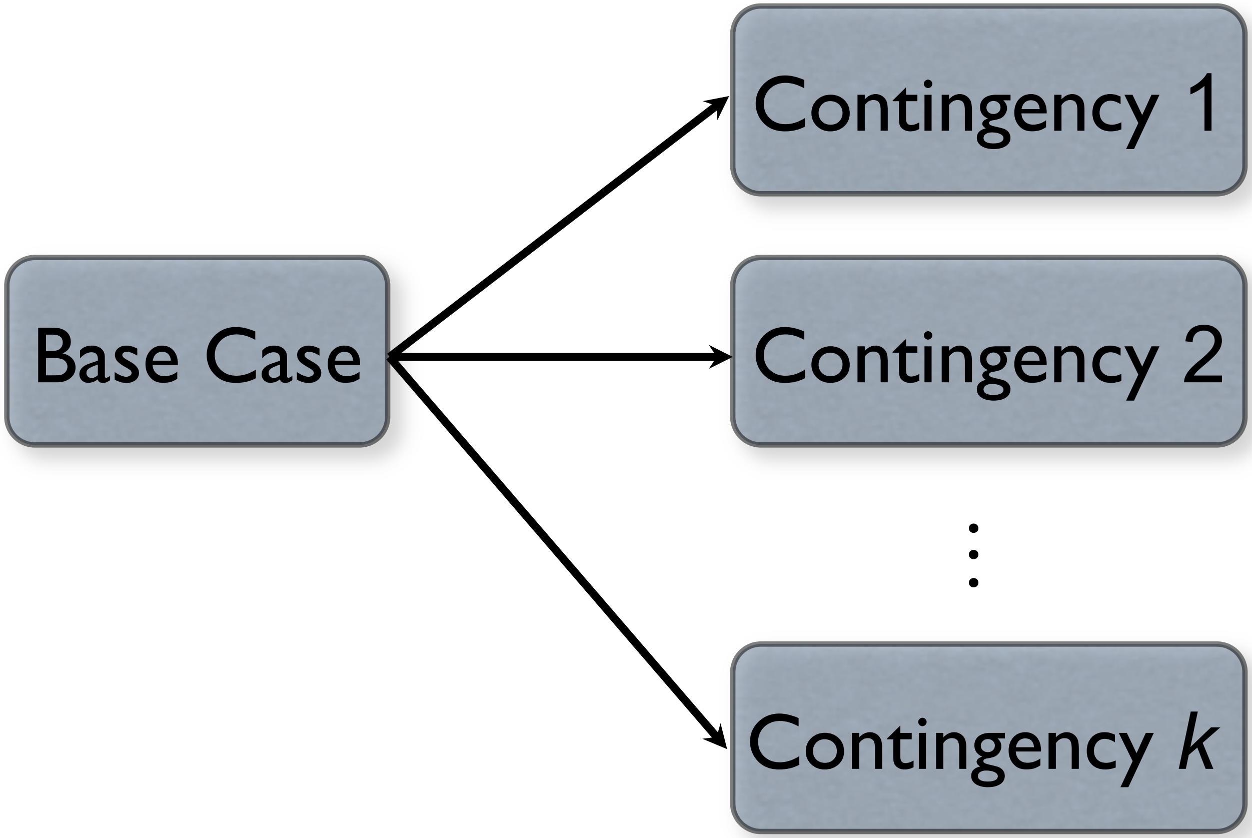
The Structure of the SuperOPF

What is the SuperOPF?

Determining the optimal power flows for operations and planning on an AC network are computationally complex due to many non-linear constraints (Kirkoff's Laws).

Traditional Approach	SuperOPF
Break into manageable sub-problems using DC approximations	Use a full AC network in a single mathematical programming framework.
sequential optimization using proxy constraints	co-optimization of the dispatch with explicit contingencies
incorrect prices	correct prices

Co-optimization over a Set of Credible Contingencies



Co-Optimization Objective Function

$$\min_{G,R} \sum_{k=0}^{K} p_k \left\{ \sum_{i=1}^{I} \left[C_{G_i}(G_{ik}) + C_{R_i}(R_i) \right] + \sum_{j=1}^{J} VOLL_j \times LNS(G_{ik}, R_{ik})_{jk} \right\}$$

Subject to meeting LOAD and all of the nonlinear AC CONSTRAINTS of the network

Where *k* is a CONTINGENCY

i is a GENERATOR

j is a LOAD

$C_G(G_i)$ is the COST of generating G MWh

$C_R(R_i)$ is the COST of providing R MW of RESERVES

$VOLL_j$ is the VALUE OF LOST LOAD

$LNS(G, R)_j$ is the LOAD NOT SERVED

Current objective includes:

Real and Reactive Power in “day-ahead” contracts

Up and Down Reserves for Real and Reactive Power

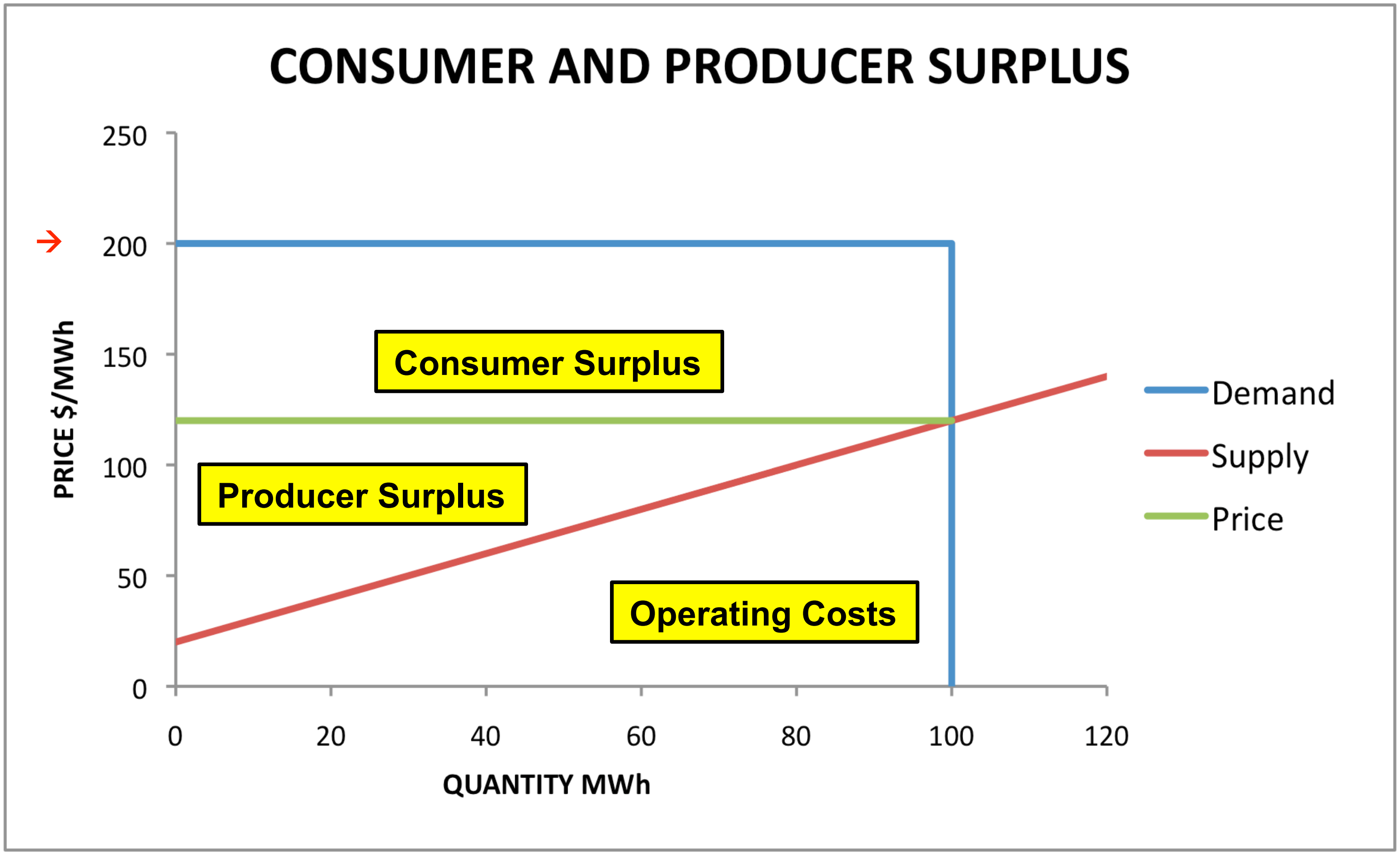
INCS and DECS for moving away from the day-ahead contract

Capabilities of the SuperOPF

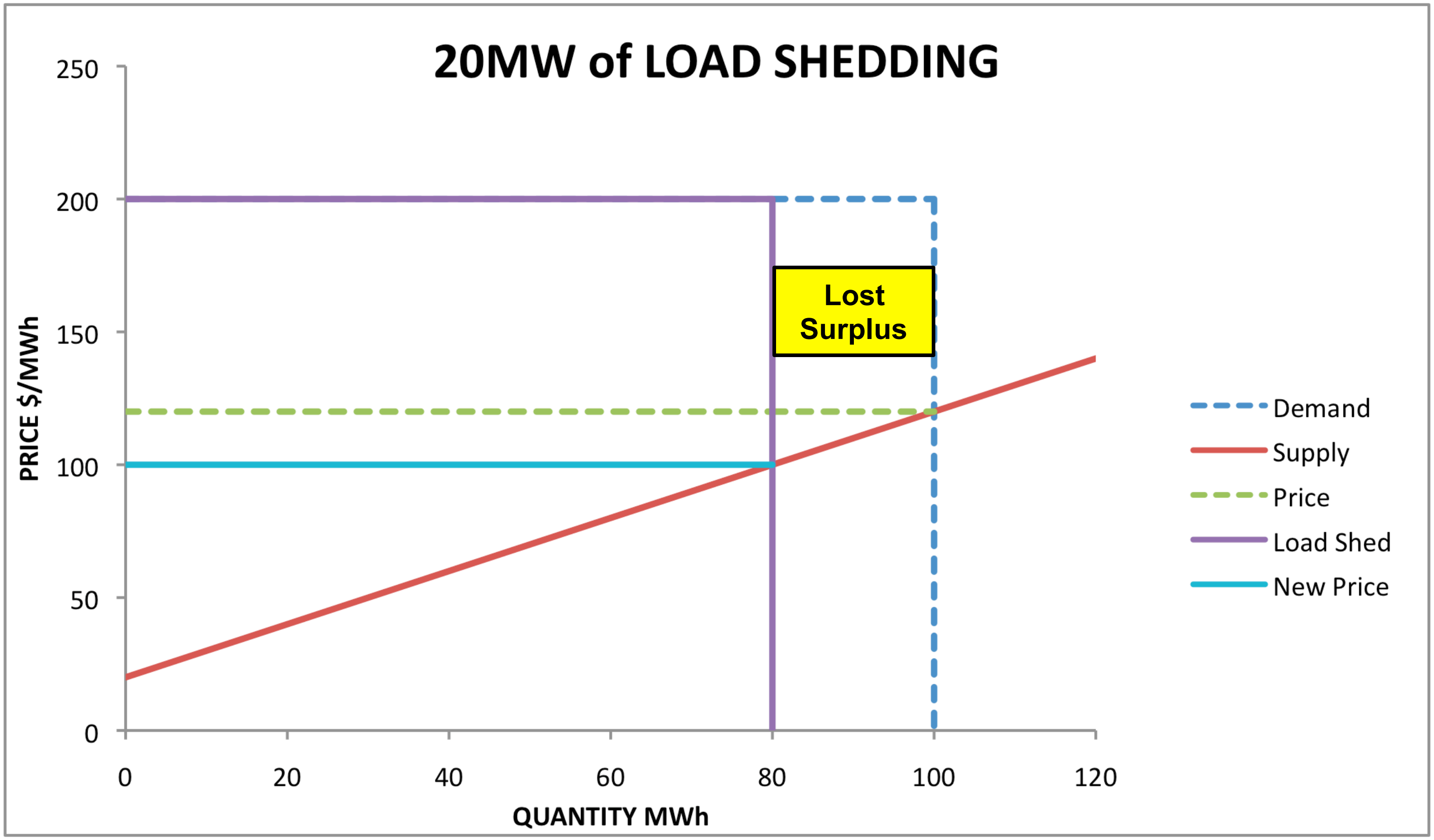
- Determines the commitment of active and reactive energy and geographically distributed up and down reserves for maintaining Operating Reliability ENDOGENOUSLY
- Puts an economic cost on failing to meet standards of Operating Reliability (i.e. shedding load at VOLL)
- Provides a consistent mechanism for subsequent re-dispatching and pricing when more information about uncertain quantities is available (Load, Wind Speed)
- The same analytical framework can be used for Planning to evaluate System Adequacy

Competitive Market Outcome
Maximize Total Surplus

VOLL →



The Effect of Load Shedding



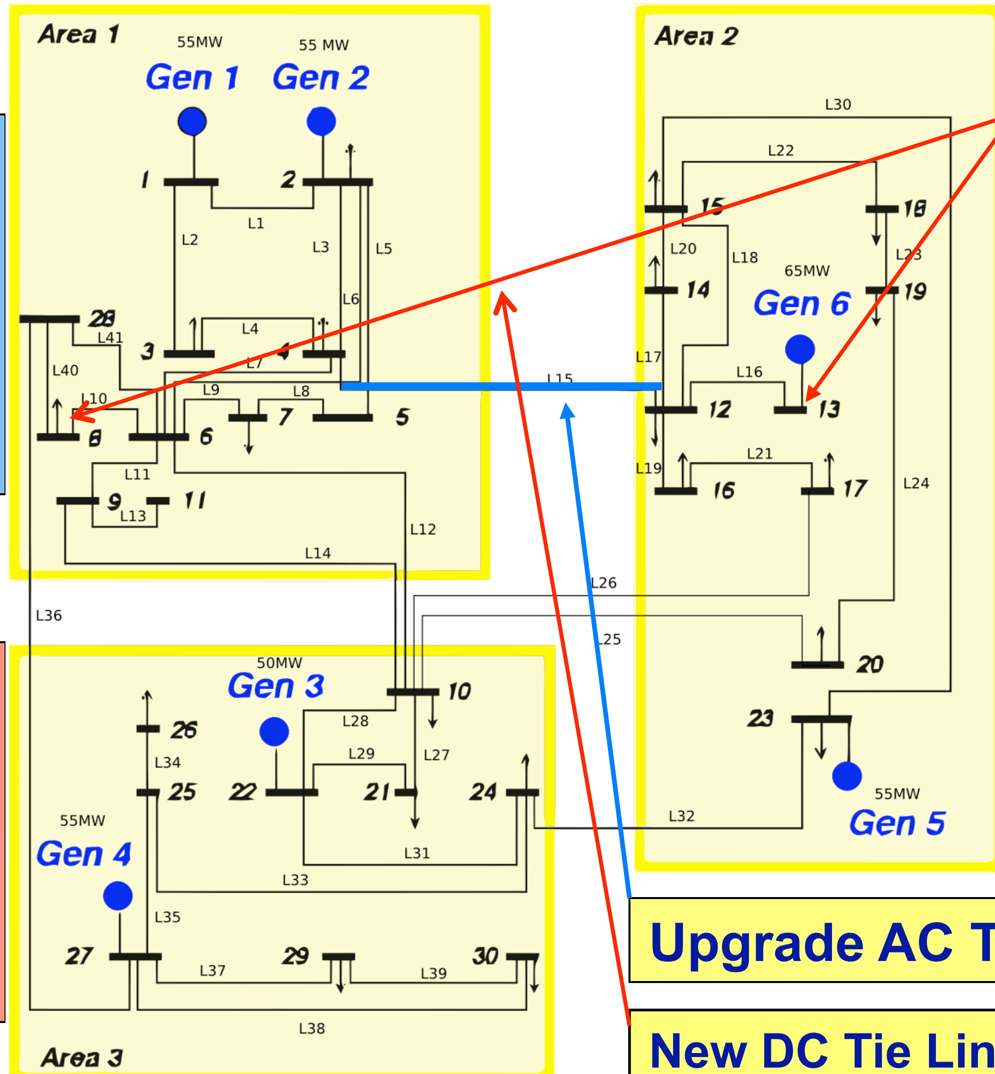
PART 2

Specifications of the 30-Bus Test Network

30-BUS TEST NETWORK

Area 1
- Urban
- High Load
- High Cost
- VOLL = $10,000/MWh

Area 3
- Rural
- Low Load
- Low Cost
- VOLL = $5,000/MWh



Wind Farm
+105MW Wind
-35MW Coal

Area 2
- Rural
- Low Load
- Low Cost
- VOLL = $5,000/MWh

Upgrade AC Tie Line

New DC Tie Line

“Normal” Wind Scenarios

Three Wind Forecasts with Four Possible Outcomes for each one

Forecasted Wind Speed	Probability of Forecast	Output (% of MW Installed)	Output Probability (Conditional on Forecast)
LOW (0-5 m/s)	11%	0%	66%
		7%	26%
		33%	5%
		73%	3%
MEDIUM (5-13 m/s)	46%	6%	24%
		38%	20%
		62%	18%
		93%	38%
HIGH (13+ m/s)	43%	0%	14%
		66%	4%
		94%	3%
		100%	79%

"Nice" Wind Scenarios with 35MW of Storage

Three Wind Forecasts with Four Possible Outcomes for each one

Forecasted Wind Speed	Probability of Forecast	Wind Output (% of 105MW)		Output Probability (Conditional on Forecast)
		Normal	Nice	
LOW (0-5 m/s)	11%	0%	35%	66%
		7%	35%	26%
		33%	35%	5%
		73%	38%	3%
MEDIUM (5-13 m/s)	46%	6%	41%	24%
		38%	55%	20%
		62%	55%	18%
		93%	58%	38%
HIGH (13+ m/s)	43%	0%	35%	14%
		66%	70%	4%
		94%	70%	3%
		100%	70%	79%

Contingencies Considered

(Generator Outages, Line Outages and Wind Speeds)

```
0  = wind 1 (root case)
1  = wind 2
2  = wind 3
3  = wind 4
4  = line 1  : 1-2   (between gens 1 and 2, within area 1)
5  = line 2  : 1-3   (from gen 1, within area 1)
6  = line 3  : 2-4   (from gen 2, within area 1)
7  = line 5  : 2-5   (from gen 2, within area 1)
8  = line 6  : 2-6   (from gen 2, within area 1)
9  = line 36 : 27-28 (main tie, areas 1-3)
10 = line 15 : 4-12  (main tie, areas 1-2)
11 = line 12 : 6-10  (other tie, areas 1-3)
12 = line 14 : 9-10  (other tie, areas 1-3)
13 = gen 1
14 = gen 2
15 = gen 3
16 = gen 4
17 = gen 5
18 = gen 6
```

97% (cases 0–3)

3% (cases 4–18)

All Equipment Failures are Specified
at the Lowest Realization of Wind (Case 0)

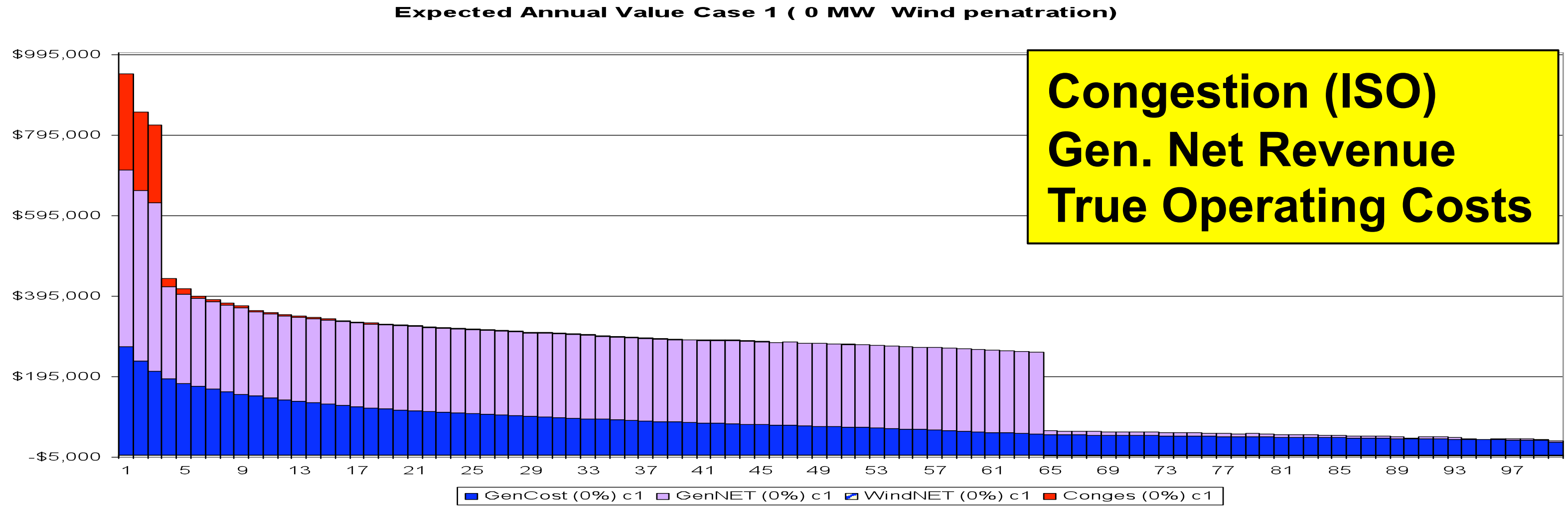
Scenarios Considered

- Case 1: NO Wind, Initial System Capacity
- Case 2: NORMAL Wind
  - 105MW of variable wind replaces 35MW of coal in Area 3
- Case 3: NICE Wind
  - Variable wind smoothed by storage in Area 3
- Case 3a: NASTY Wind
  - Variable wind with a "must-take" contract in Area 3
- Case 4: NORMAL Wind + Upgraded AC Tie Line
- Case 5: NICE Wind + Upgraded AC Tie Line
- Case 6: NORMAL Wind + Dedicated DC Tie Line
- Case 7: NICE Wind + Dedicated DC Tie Line

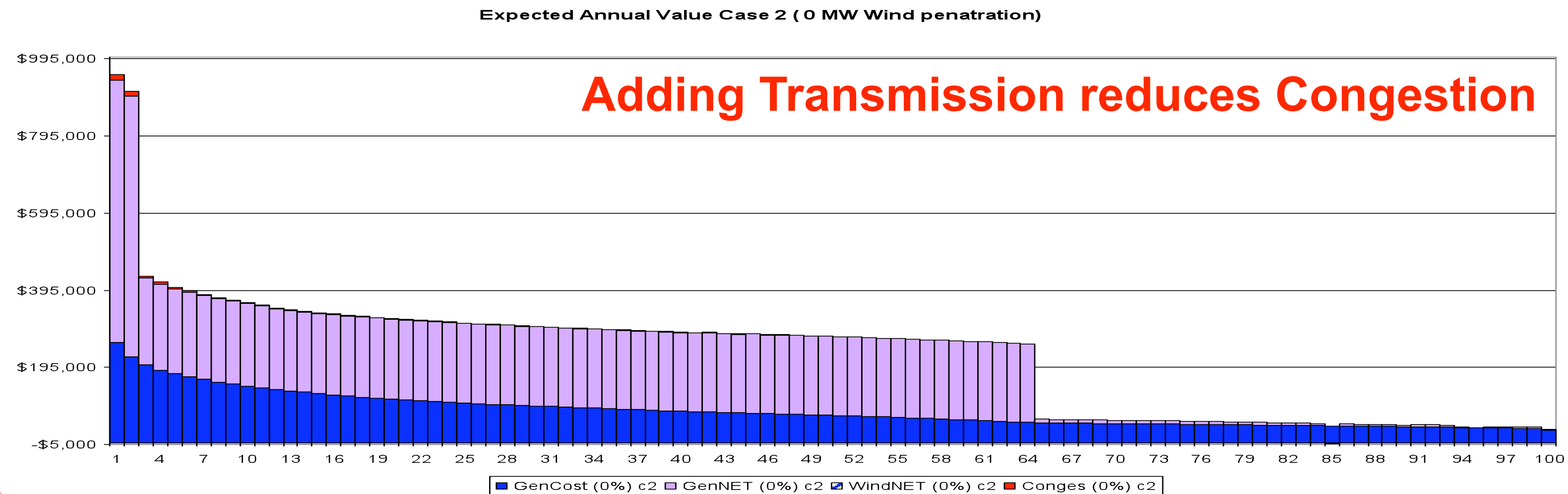
Expected Annual Revenues/Costs (NO Wind)

(High ← Ranked System Load → Low)

No Upgrade



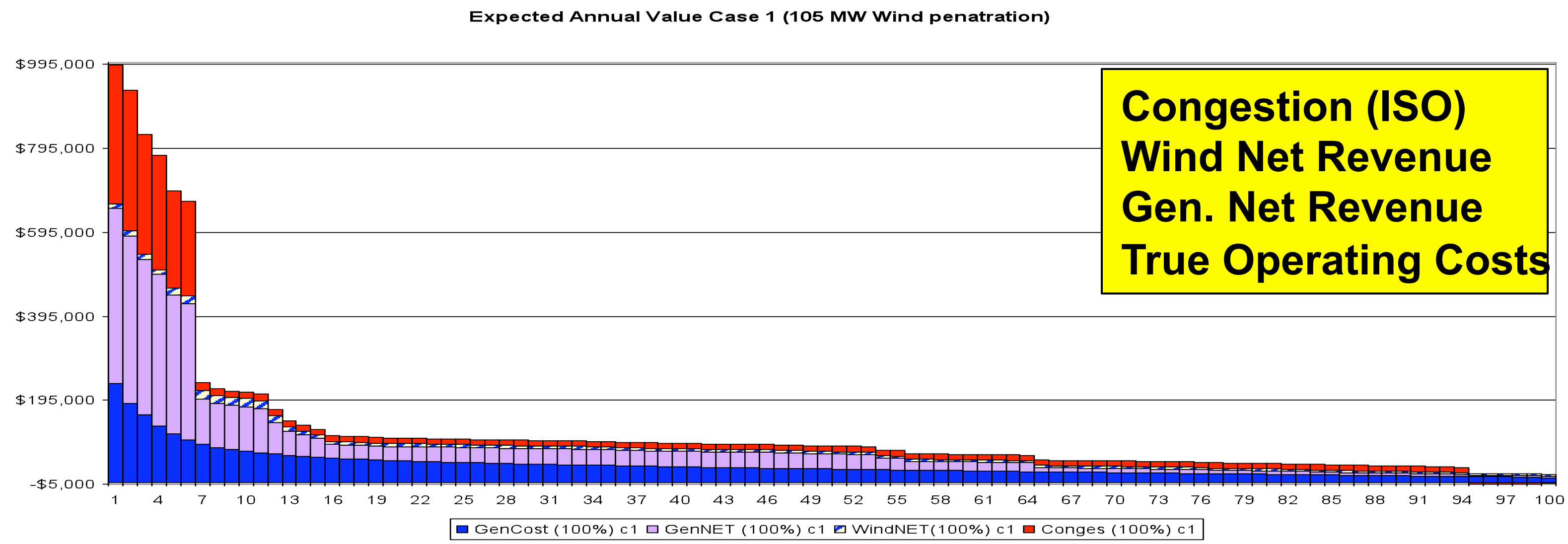
Tie Line Upgraded



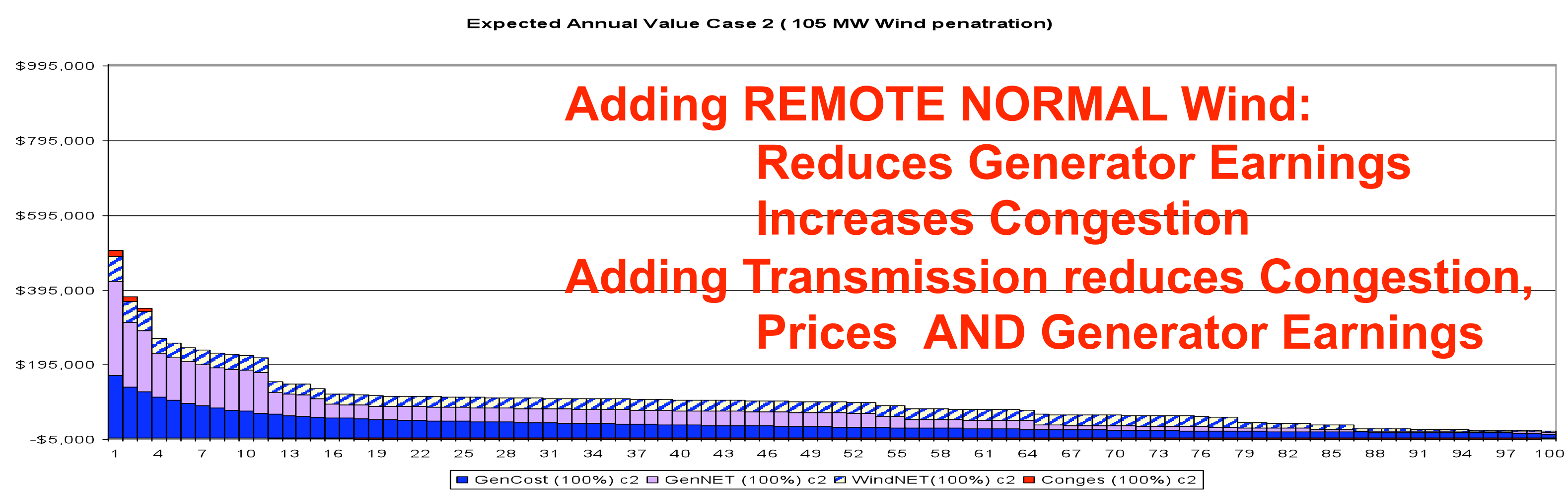
Expected Annual Revenues/Costs (NORMAL WIND)

(High ← Ranked System Load → Low)

No Upgrade



Tie Line Upgraded



PART 3

Results of the Case Study

Overview of the Results

	case1	case2	case3	case3a	case4	case5	case6	case7
Load Not Served (Hours/Year)	15.77	3.85	6.57	29.56	4.50	7.12	4.14	1.73
Gen Capacity Needed (MW)*	283	274	229	271	273	234	273	232
Max Wind Committed (MW)	0	32	41	96	59	61	60	61
Load Paid ($1000/Year)	$53,434	$22,373	$23,560	**	$14,705	$11,934	$14,363	$8,772

* 105MW of Wind capacity replaces 35MW of Coal capacity in Cases 2 - 7
** Offer Price for Wind = -$1500/MWh

Case 1: NO Wind with Initial System Capacity
Case 2: NORMAL Wind
Case 3: NICE Wind
Case 3a: NASTY Wind
Case 4: NORMAL Wind + Upgraded AC Tie Line
Case 5: NICE Wind + Upgraded AC Tie Line
Case 6: NORMAL Wind + Dedicated DC Tie Line
Case 7: NICE WIND + Dedicated DC Tie Line

- More Load Shed with NASTY Wind
- Less Conventional Capacity is needed with NICE Wind
- A lot of wind is spilt without a transmission upgrade (or must-take NASTY wind)
- The cost to customers is much lower with wind, and NICE wind with a Dedicated DC tie line has the lowest cost of all cases
- WHAT ARE THE IMPLICATIONS FOR CAPITAL COSTS?

Maximum Capacities Dispatched at the PEAK System Load (MW for Energy and Up Reserves)

Capacity Needed to Meet Peak Load (MW Energy + MW Up Reserves)								
	case1	case2	case3	case3a	case4	case5	case6	case7
Gen1	30	51	35	54	51	25	50	25
Gen2	55	52	39	55	52	46	52	44
Gen3	50	50	46	50	49	47	49	47
Gen4	35	42	35	47	40	36	41	37
Gen5	55	49	44	35	51	50	51	50
Gen6 Gas	23	30	30	30	30	30	30	30
Gen6 Coal	35	0	0	0	0	0	0	0
Wind	0	32	41	96	59	61	60	61
Total Non-Wind MW								
	260.33	273.95	228.67	270.64	272.99	233.79	272.69	232.43
Total "Unforced" Capacity MW								
	260.33	306.05	269.43	366.99	332.40	294.88	332.21	293.52

For most Non-Wind Generators, MORE CAPACITY (energy + up reserves) is needed to meet the SAME PEAK System Load when Wind Capacity is installed.

(RED is an INCREASE or the same as NO Wind, Case 1)

Case 1: NO Wind with Initial System Capacity
Case 2: NORMAL Wind
Case 3: NICE Wind
Case 3a: NASTY Wind
Case 4: NORMAL Wind + Upgraded AC Tie Line
Case 5: NICE Wind + Upgraded AC Tie Line
Case 6: NORMAL Wind + Dedicated DC Tie Line
Case 7: NICE WIND + Dedicated DC Tie Line

Expected Annual Capacity Factors

Annual Capacity Factor								
	case1	case2	case3	case3a	case4	case5	case6	case7
Gen1	0.22%	1.56%	1.06%	23.41%	1.75%	0.19%	1.75%	0.15%
Gen2	2.08%	7.20%	3.41%	27.26%	6.00%	1.75%	5.99%	1.37%
Gen3	72.67%	64.48%	60.67%	33.83%	62.29%	59.52%	62.28%	58.47%
Gen4	58.79%	52.54%	49.40%	39.65%	51.74%	47.70%	51.56%	46.66%
Gen5	65.37%	53.53%	42.64%	13.16%	53.46%	41.00%	53.56%	42.75%
Gen6	56.39%	99.16%	90.72%	22.59%	99.24%	91.75%	99.23%	95.55%
Wind	0.00%	16.64%	30.57%	59.80%	18.39%	33.45%	18.39%	32.87%

For Gen 3 - 5 in Areas 2 and 3, the Capacity Factors are LOWER when Wind Capacity is installed (The capacity factors for Gen 1- 2 in Area 1 are typically very low except for Must-Run Wind, Case 3a).

(RED shows a DECREASE from NO Wind, Case 1)

Case 1: NO Wind with Initial System Capacity
Case 2: NORMAL Wind
Case 3: NICE Wind
Case 3a: NASTY Wind
Case 4: NORMAL Wind + Upgraded AC Tie Line
Case 5: NICE Wind + Upgraded AC Tie Line
Case 6: NORMAL Wind + Dedicated DC Tie Line
Case 7: NICE WIND + Dedicated DC Tie Line

Expected Annual Operating Surplus

Expected Annual Net Costs/Benefits ($1000)								
	case1	case2	case3	case3a**	case4	case5	case6	case7
Operating Costs (Gen 1-6)	$13,967	$11,474	$7,582		$10,504	$6,099	$10,500	$6,173
Cost of Load Shed	$92	$24	$22		$29	$33	$27	$28
TOTAL REAL OPERATING COSTS	**$14,059**	**$11,498**	**$7,604**		**$10,532**	**$6,132**	**$10,528**	**$6,201**
Gen Net Rev	$38,787	$9,872	$8,947		$7,909	$4,732	$7,512	$2,271
Wind Net Rev	$0	$186	$1,097		$722	$2,446	$738	$2,187
TOTAL PRODUCER SURPLUS	**$38,787**	**$10,058**	**$10,044**		**$8,631**	**$7,178**	**$8,251**	**$4,458**
CONGESTION SURPLUS	**$680**	**$840**	**$5,934**		**-$4,430**	**-$1,343**	**-$4,388**	**-$1,860**
CONSUMER SURPLUS*	**$146,474**	**$177,603**	**$176,418**		**$185,266**	**$188,033**	**$185,610**	**$191,200**
TOTAL OPERATING SURPLUS	**$185,941**	**$188,502**	**$192,396**		**$189,468**	**$193,868**	**$189,472**	**$193,799**

*Consumer Surplus = 2x10^6 - RATES PAID BY CONSUMERS - VOLLxLOAD NOT SERVED

**Offers for Wind set at -$1500/MWh

- When Wind Capacity is installed
  - Operating Costs and Producer Surplus are LOWER
  - Congestion Surplus and Consumer Surplus are HIGHER
  - Consumer Surplus and Total Surplus are HIGHER
- When Transmission is upgraded
  - Operating Costs, Producer Surplus and Congestion Surplus are LOWER
  - Consumer Surplus and Total Surplus are slightly HIGHER

Case 1: NO Wind with Initial System Capacity
Case 2: NORMAL Wind
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Missing Money for Generators

Case 1: NO Wind							
Calculation of the Capacity Payments							
	Minimum Net Earnings $/Year	Actual Net Earnings $/Year	Difference $/Year	Missing Money $/Year	Maximum Capacity MW	Capacity Price $/MW/Year	Capacity Payments $/Year
Gen 1	$2,669,656	$1,229,420	-$1,440,236	-$1,440,236	30	$47,475	$1,440,236
Gen 2	$4,839,672	$2,862,343	-$1,977,329	-$1,977,329	55	$35,954	$2,610,924
Gen 3	$16,420,000	$9,738,230	-$6,681,770	-$6,681,770	50	$133,635	$11,415,950
Gen 4	$16,100,014	$11,335,694	-$4,764,320	-$4,764,320	35	$136,123	$7,991,189
Gen 5	$17,249,999	$4,692,455	-$12,557,544	-$12,557,544	55	$228,319	$12,557,544
Gen 6	$20,199,581	$8,928,583	-$11,270,998	-$11,270,998	58	$194,918	$13,202,378
TOTAL	**$77,478,922**	**$38,786,725**	**-$38,692,197**	**-$38,692,197**	**283**		**$49,218,220**

- **Minimum Net Earnings = Annualized Capital Cost x MW Committed**
  - **By type of generating unit**
- **Actual Net Earnings = Producer Surplus for Non-Wind Generators**
- **Missing Money = Min(Difference, 0)**
- **Maximum Capacity committed to meet the System Load**
- **Capacity Price = Missing Money/ Maximum Capacity**
- **Capacity Payments use the maximum Capacity Price by Area**
  - **Area 1 for Gen 1 and Gen 2**
  - **Area 2 and 3 for Gen 3 - 6**

Expected Annual Net Social Surplus

Total Surplus including Missing Money								
	case1	case2	case3	case3a**	case4	case5	case6	case7
Gen Capital Cost ($1000/Year)	$77,479	$72,215	$66,983		$72,252	$68,415	$72,220	$68,346
Gen Operating Surplus ($1000/Year)	$38,787	$9,872	$8,947		$7,909	$4,732	$7,512	$2,271
Gen Missing Money ($1000/Year)	$38,692	$62,343	$58,036		$64,343	$63,683	$64,707	$66,074
Gen Capacity Paqyments ($1000/Year)	**$49,218**	**$83,594**	**$78,233**		**$78,572**	**$77,441**	**$79,366**	**$80,105**
Trans Capital Costs ($1000/Year)	$30,000	$30,000	$30,000		$30,000	$30,000	$30,000	$30,000
Congestion Surplus	$680	$840	$5,934		-$4,430	-$1,343	-$4,388	-$1,860
Trans Payments ($1000/Year)	**$29,320**	**$29,160**	**$24,066**		**$34,430**	**$31,343**	**$34,388**	**$31,860**
Wind Surplus ($1000/Year)	$0	$186	$1,097		$722	$2,446	$738	$2,187
Consumer Surplus ($1000/Year)	$146,474	$177,603	$176,418		$185,266	$188,033	$185,610	$191,200
NET SOCIAL SURPLUS ($1000/Year)	**$67,936**	**$65,036**	**$75,216**		**$72,987**	**$81,695**	**$72,594**	**$81,422**
**Offers for Wind set at -$1500/MWh								

- Adding Wind Capacity:
  - LOWER Net Social Surplus with NORMAL Wind
  - HIGHER Net Social Surplus with NICE Wind
- Adding Transmission:
  - HIGHER Net Social Surplus with NORMAL and NICE Wind
  - Little difference between AC and DC upgrades

Case 1: NO Wind with Initial System Capacity
Case 2: NORMAL Wind
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Case 3a: NASTY Wind
Case 4: NORMAL Wind + Upgraded AC Tie Line
Case 5: NICE Wind + Upgraded AC Tie Line
Case 6: NORMAL Wind + Dedicated DC Tie Line
Case 7: NICE WIND + Dedicated DC Tie Line

Conclusions

- Adding wind capacity increases the amount of non-wind capacity needed to maintain Operating Reliability at the Peak System Load
- Adding wind capacity displaces a high proportion of the conventional generation when system loads are low and also reduces average market (wholesale) prices substantially.
- The net earnings of conventional generators fall substantially with wind capacity, particularly if transmission is upgraded, and this increases the amount of “missing money”.
- Upgrading transmission eliminates congestion payments to the System Operator, and additional sources of revenue would be needed to make transmission owners financially viable.
- There is little difference between the effects of the AC and DC Tie Lines BUT:
  - The full capabilities of adding Storage is not represented adequately in the analysis
  - Specifying a Dedicated DC Tie Line for Wind capacity only is too restrictive
  - A DC Tie Line with Storage could be used to flatten daily load cycles and cover contingencies
- The annual benefits for customers and wind generators increase with wind and a transmission upgrade but customers will have to pay other bills to maintain System Adequacy.

Implications for Future Research

- With higher penetrations of wind capacity:
  - The Financial Adequacy of conventional generators will be an increasingly important issue for maintaining System Adequacy
  - Lower Capacity Factors will make the "missing money" cost of meeting the system peak load more expensive per MW
  - The cost of adjusting dispatch patterns to offset the variability of wind generation should be included (INCS and DECS supported in the SuperOPF)
- Adding controllable load and storage:
  - Will compensate for wind variability
  - Will reduce System Peak Load
  - Will increase the minimum Capacity Factor of conventional generators
  - Will reduce the problem of Financial Adequacy for conventional generators
  - Will mitigate price spikes and undermine the viability of "energy only" markets
- Adding transmission capacity and wind capacity:
  - Customers will benefit from lower wholesale prices
  - Customers should pay for the transmission upgrade
  - Need smarter ways to provide the missing money for conventional generators and transmission owners (Performance Based Regulation?)