Applications of Energy Storage to Enhance Wind Generation

Supplement to the EPRI-DOE
Handbook of Energy Storage for Transmission and Distribution Applications

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DOE Energy Storage Program Peer Review Meeting
November 10-11, 2004

TECHNOLOGY
INSIGHTS

ESHB – Wind Supplement

- **Introduction**
- **Overview of grid connected wind power**
- **Applications (and functional requirements)**
  - Single applications
  - Combined applications
- **Benefits of respective applications**
- **Common financial parameters and cost elements**
- **Technology sections**
  - Update of major ESHB related content changes, etc
  - Summarize specific wind application experiences, major case studies and additional parameters needed
  - Assessments of worthy single and combined applications

Handbook Supplement available via PDF by end of year

Plans call for integrated, expanded ESHB in 2005

Wind Power with Energy Storage: Hardware Experience

- Hokkaido, Japan (2000 – 2001)*
  - Hokkaido EPC Host, CRIEPE Analyses
  - VRB/SEI: 170 kW, 6 hrs
  - Stabilizes single 275 kW turbine
- Aomori, Japan (2000 – 2001)*
  - Tohoku EPC Host
  - VRLA: 300 kW, 4hrs
  - Stabilizes single 300 kW turbine
- Hachijojima, Japan (2000 – 2001)*
  - TEPCO Host
  - NAS/NGK: 400 kW, 7.2 hours
  - Stabilizes single 500 kW turbine
- King Island, Tasmania (2003)
  - Hydro Tasmania Host + Australian Gov't - Greenhouse Office Cofund
  - VRB/Pinnacle VRB Ltd.: 400 kW, 10 sec or 200 kW, 4 hours + Diesel Genset
  - Stabilizes 2.5 MW wind farm
- Hokkaido, Japan (Early 2005)
  - J-Power Host + NEDO Cofund
  - VRB/SEI: 6 MW, 20 min / 4 MW, 1.5 hrs
  - Stabilizes 30 MW wind farm

* Funded by NEDO, Conducted by IEA

Wind Turbine with Vanadium Redox Flow Battery in Hokkaido, Japan (Courtesy NEDO)

Wind Generation with Energy Storage: Prominent Studies

- **West Texas (2002 - 2003)**
  - Lower Colorado River Authority, Ridge Energy Storage and Grid Services
  - Investigated construction of CAES systems to support over 900 MW of wind power generation in area of constrained transmission
  - Positive outlook for a CAES system, follow-up is planned
- **Iowa (2001 - 2004)**
  - Iowa Association of Municipal Utilities
  - Investigated construction of a 100-200 MW CAES plant with up to 200 MW wind generation (and other off-peak generation)
  - Currently under review
- **Hawaii (2002 - 2004)**
  - HELCO, State of Hawaii and Sentech
  - Investigating possible use of energy storage to stabilize grid on Big Island of Hawaii
  - Wind generation is a significant factor in instability and an important motivator for study
  - In progress
- **Foote Creek Rim, Wyoming (2004 - 2005)**
  - SAIC
  - Investigating use of VRB system with a 135 MW wind farm
  - In progress

Single Function Applications Summary Descriptions

- J: Transmission Curtailment (TC) – mitigation of power delivery constraint imposed by insufficient transmission capacity. Except for large CAES, reference duty cycle for analysis is derived from the reference 60 MW wind farm profile constrained to 50 MW by available transmission capacity, Valued at market electricity rates for the incremental wind generation delivered.
- K: Time-Shifting (TS) – firms and shapes wind generation by storing wind generation during the off-peak interval (6:00 pm to 6:00 am), supplemented by power purchased from the grid when wind generation is inadequate, and discharged during the on-peak interval (6:00 am to 6:00 pm). Valued at the market rates for the time-shifted, shaped energy.
- L: Forecast Hedge (FH) – mitigates errors (shortfalls) in wind energy bid three hours prior to the one-hour delivery interval. Valued at the incremental value of wind energy delivered at market rates .
- M: Grid Frequency Support (GFX) – supports grid frequency during sudden large decreases in wind generation over a 15-minute discharge interval. Valued at the cost of alternative solutions.
- N: Fluctuation Suppression (FS) – stabilizes wind farm generation frequency by suppressing fluctuations (absorbing and discharging energy during short duration variations in output). Valued at the cost of alternative solutions.

Combined Function Applications Summary Descriptions

- **C6: Combined Applications J, M, D (TC + GFX + RC)**
- **C7: Combined Applications K, M, D (TS + GFX + RC)**
- **C8: Combined Applications L, M, D (FH + GFX + RC)**
- **C9: Combined Applications M, L, D (GFX + FH + RC)**
- **C10: Combined Applications N, M, K (FS + GFX + TS)**

Single Function Applications and Duty Cycles

Parameters \ Applications	Grid Stabilization (GS)			Grid Operational Support (GOS)		Distribution Power Quality (PQ)		Load-Shifting (LS)		Wind Generation Support (WGS)				
										Firming & Shaping			Stabilization	
	Angular Stability (GAS)	Voltage Stability (GVS)	Frequency Excursion Suppression (GFS)	Regulation Control (RC)	Conventional Spinning Reserve (SR)	Short Duration PQ (SPQ)	Long Duration PQ (LPQ)	Short Duration LS (LS3)	Long Duration LS (LS10)	Transmission Curtailment (TC)	Time-Shifting (TS)	Forecast Hedge (FH)	Grid Frequency Support (GFX)	Fluctuation Suppression (FS)
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**
ES System Unit Power, MW	10 to 500 (10)	10 to 500 (10)	10 to 500 (10)	2 to 200 (10)	2 to 200 (10)	1 to 50 (10)	1 to 50 (10)	1 to 200 (10)	1 to 200 (10)	2 to 200 (10)	2 to 200 (10)	2 to 200 (10)	2 to 200 (10)	2 to 50 (2)
ES System AC Voltage, kV	4.2 to 750 (13.8)	4.2 to 750 (13.8)	4.2 to 750 (13.8)	4.2 to 115 (13.8)	4.2 to 115 (13.8)	4.2 to 34.5 (13.8)	4.2 to 34.5 (13.8)	4.2 to 115 (13.8)	4.2 to 115 (13.8)	4.2 to 34.5 (13.8)	4.2 to 34.5 (13.8)	4.2 to 34.5 (13.8)	4.2 to 34.5 (13.8)	4.2 to 34.5 (13.8)
Equivalent Full Power Discharge Duration	few seconds (1 sec)	few seconds (1 sec)	10 to 30 min (15 min)	3 to 30 min (7.5 min)	2 hr max (2 hr)	seconds (2 sec)	hours (4 hrs)	1 to 4 hrs (3)	5 to 12 hrs (10)	5 to 12 hrs (varies by ES Technology)			10 to 30 min (15 min)	few seconds (10 sec)
Energy Discharged Per Event	10 MJ to 1 GJ (10 MJ)	5 MJ to 30 GJ (10 MJ)	0.2 to 25 MWh (2.5 MWh)	0.1 to 25 MWh (2.5 MWh)	2 to 100 MWh (20 MWh)	2 MJ to 3 GJ (50 MJ)	1 to 400 MWh (40 MWh)	1 to 200 MWh (30 MWh)	5 to 600 MWh (100 MWh)	50 to 120 MWh (varies)			0.2 to 25 MWh (2.5 MWh)	10 to 200 MJ (20 MJ)
Energy Discharge Duty Cycle	10 events/yr 1 event/d 20 cyc/event	10 events/yr 1 event/d	10 events/yr 1 event/d	Continuous Market (Ref 2 cycles/hr)	10 events/yr 1 event/d	100 events/yr 5 events/d 1 event/hr	1 event/yr	60 events/yr 1 event/d	250 events/yr 1 event/d	Per reference wind profile, optimized for each technology			24 events/yr 1 event/d	Continuous triangular wave, Chrg & Disch, 90cy/hr
System Response Time	< 20 msec	< 20 msec	< 20 msec	<10 min	<10 min	< 20 msec	< 20 msec	<10 min	<10 min	< 1 min	< 1 min	< 20 msec	< 20 msec	< 20 msec
Basis for Economic Benefits	Capitalized Costs and Benefits of Alternative System			Market Rates		Capitalized Costs and Benefits of Alternative System		Reduced T Demand Charge, plus Δ Energy Savings plus Capitalized Costs and Benefits of Alternative System		Capitalized Costs and Benefits of Alternative System, Market Rates, Tax Credits, and Green Price Premiums				

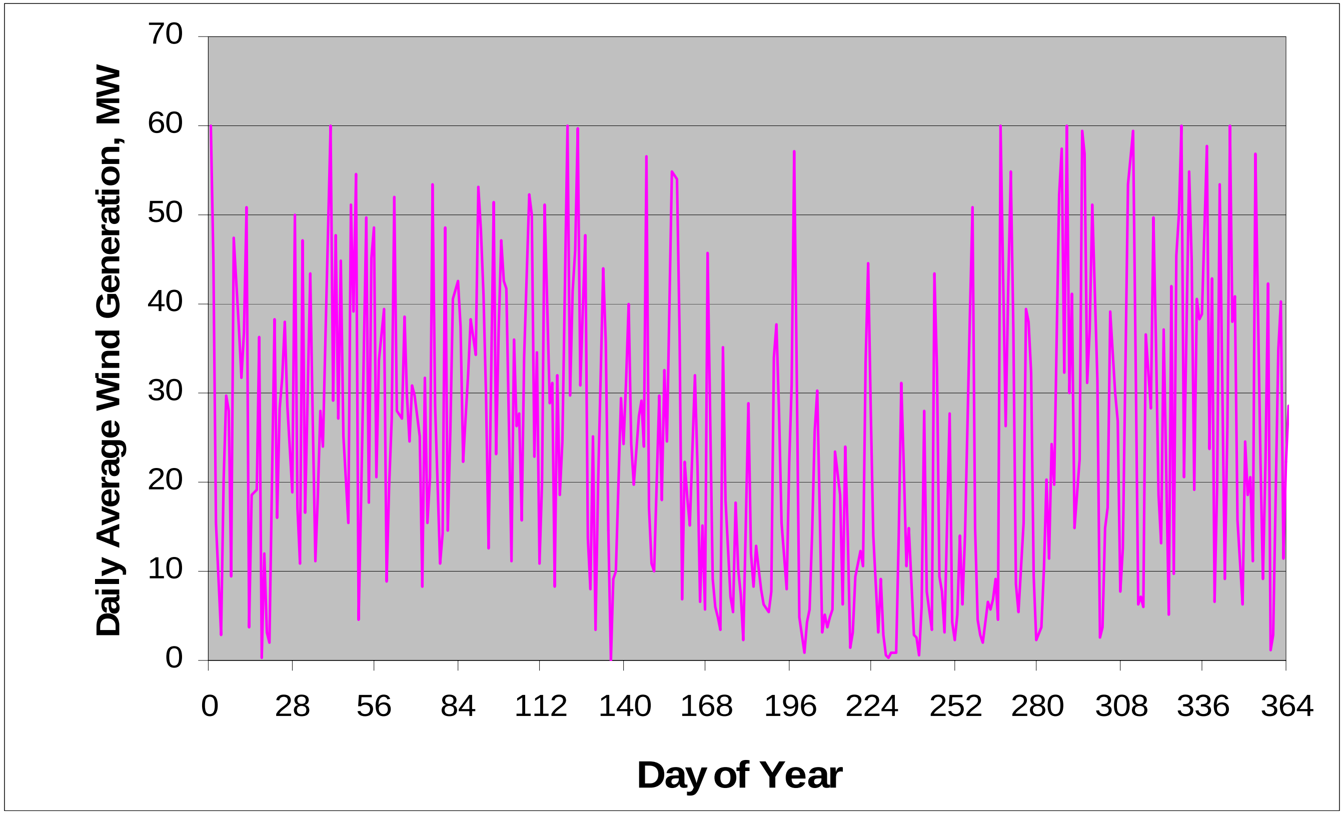
Electricity Rates & Financial Parameters

Electricity Market Rates	On-Peak (6:00 am to 6:00 pm) Firm Energy $/MWh	Non-Firm Energy $/MWh	Capacity Credit $/kW-mo	Off-Peak (6:00 pm to 6:00 am) Firm Energy $/MWh	Non-Firm Energy $/MWh	Capacity Credit $/kW-mo
Wind Generation Market						
Market Rates	120	60	6	60	30	6
Bid Shortfall Penalties	130			70		
Purchase Power Market						
Regulation Control, $/MW-Hour (power)	16					
Yearly Average Energy Charge, $/MWh	38					

Financial Parameters	
Dollar Value, year	2003
System Startup Date	June, 2006
Project Life, years	20
Real Discount Rate, %/yr	7.5%
Property Taxes & Insurance, %/yr	2
Fixed Charge Rate, %/yr (before income taxes)	9.8%

Wind Resource for App. J: Transmission Curtailment

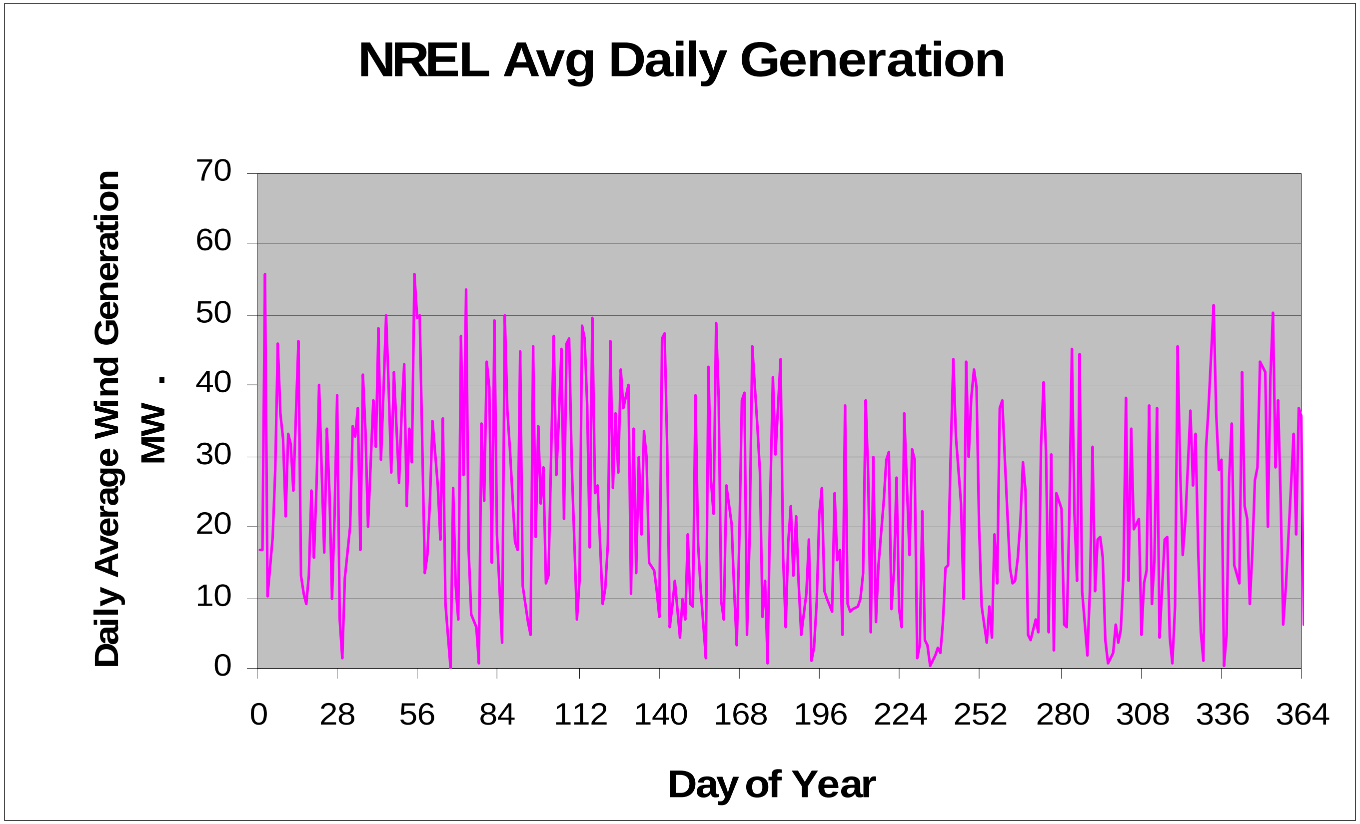
Hourly Wind Generation Data Representative of 60 MW West Texas Wind Farm*



**Study Of Electric Transmission In Conjunction With Energy Storage Technology, prepared by the Lower Colorado River Authority for the Texas State Energy Conservation Office, August 21, 2003

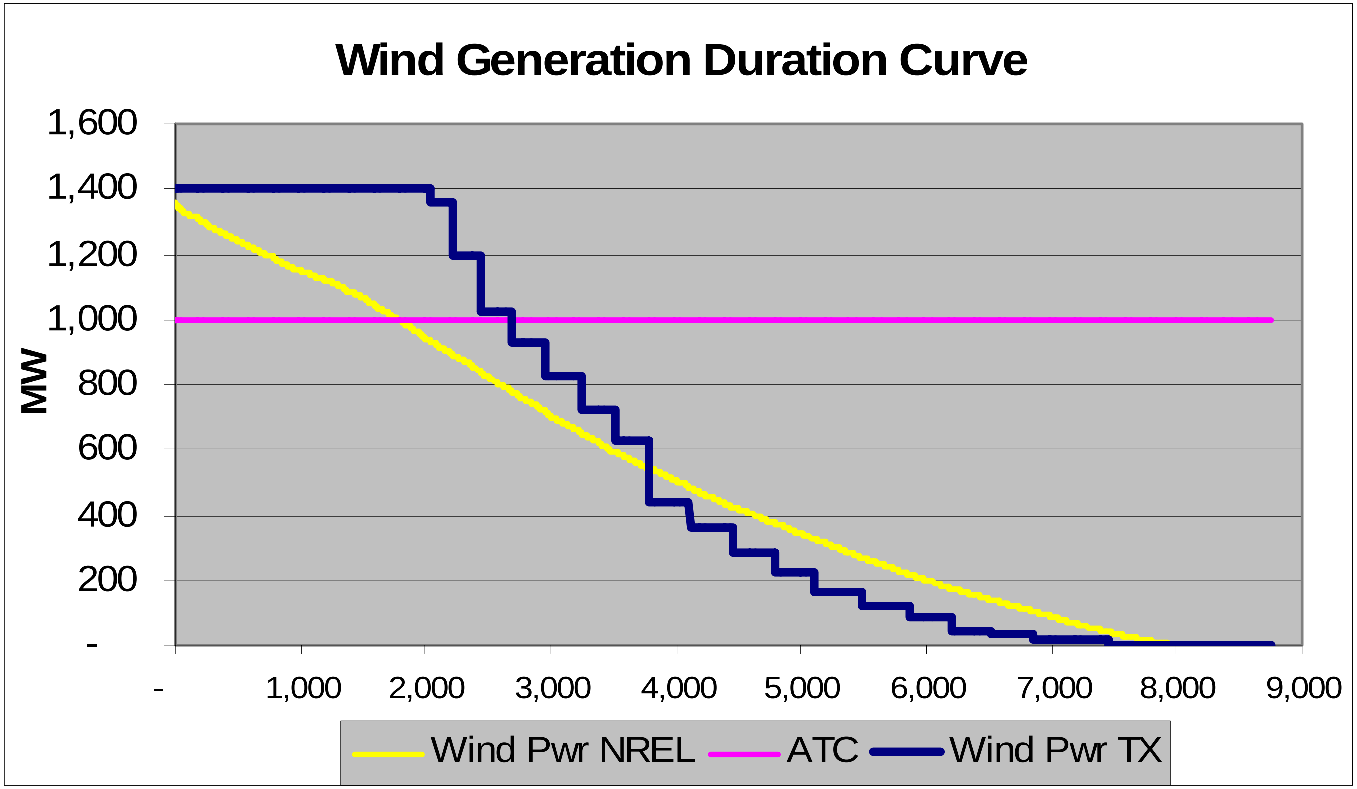
Wind Resource for App. K & L: Time-Shift and Forecast Hedge

Hourly Wind Generation Data Representative of Typical U.S. Wind Farm*

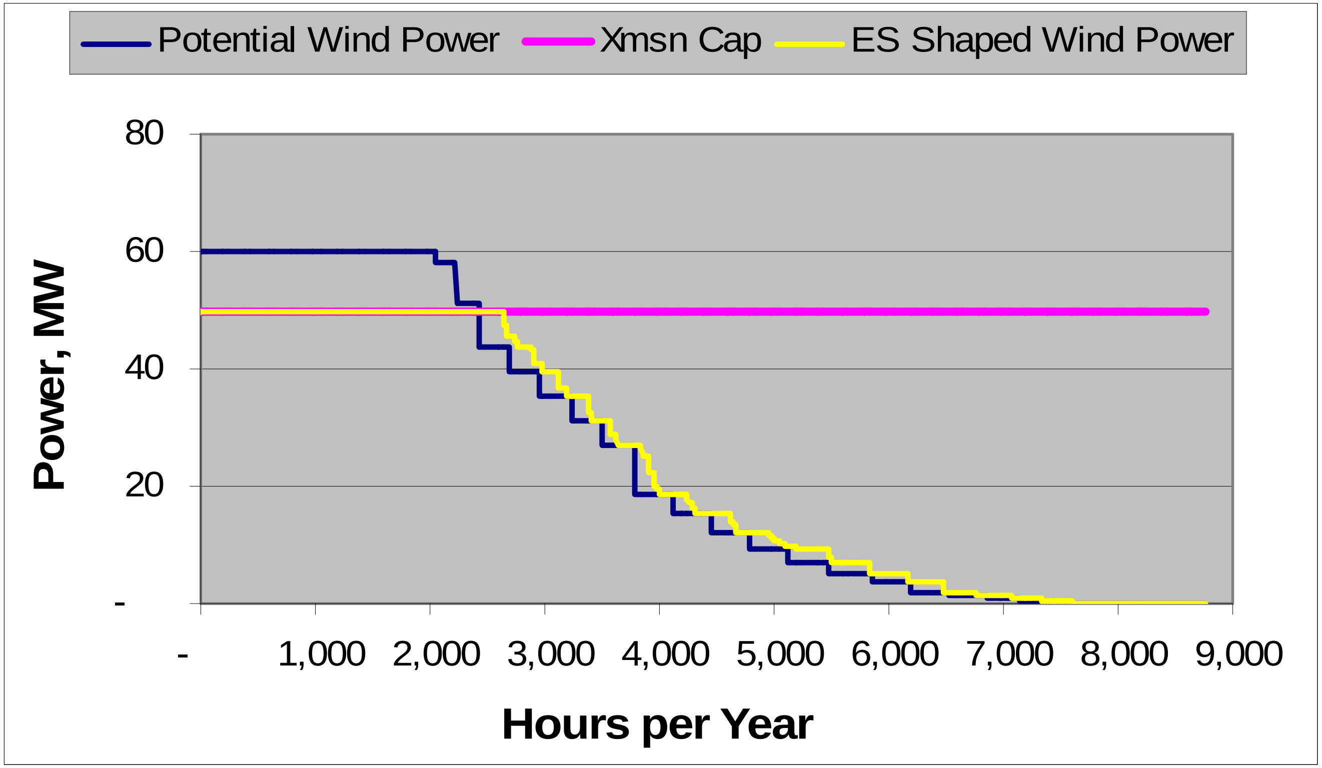


Comparison of NREL & TX Data for App. J: Curtailment

Hourly Wind Generation Data Representative of Typical U.S. Wind Farm*



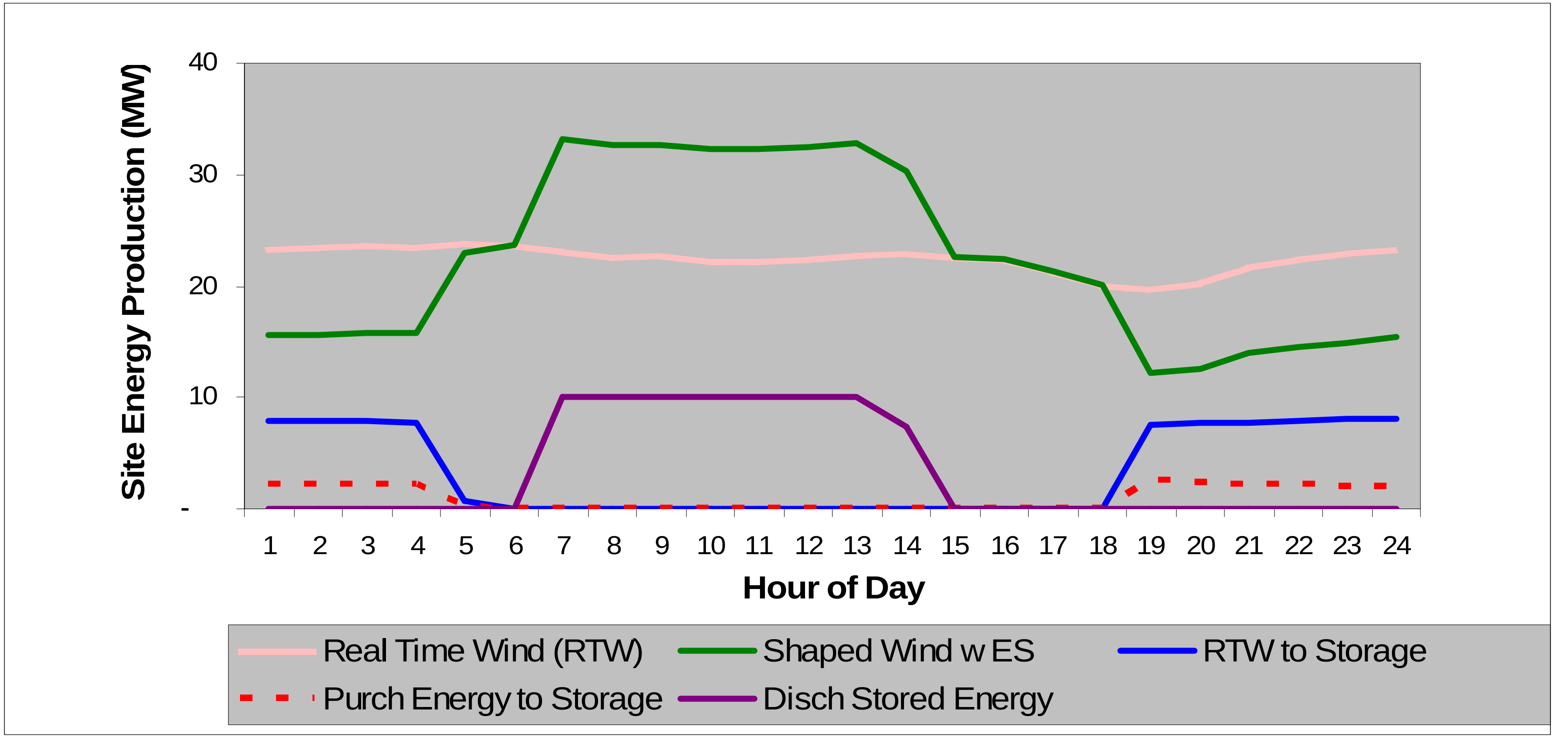
Change in Generation Capture with ES



Example for App K: Time-Shift Wind Generation

- **60 MW wind farm generation, NREL wind profile**
- **ES application:**
  - Store wind generation plus purchased power during off-peak (6:00 pm to 6:00 am) daily
  - Discharge stored energy during on-peak (6:00 am to 6:00 pm) daily
  - Direct wind valued at non-firm rates
  - Power from ES valued at firm rates
- **ES system parameters**
  - Power = 10MW, except underground CAES
  - Energy = TBD multi-hours per technology
  - TBD depth-of-discharge to match cycle life with demand
  - DC voltage range to match PCS per ESHB

Time-Shift Wind Generation
Annual Average Daily Profile



Time-Shift Wind Generation Value of Energy Storage

Electric Rates	On-Peak			Off-Peak		
	Firm $/MWh	Non-Firm $/MWh	Capacity $/kW-mo	Firm $/MWh	Non-Firm $/MWh	Capacity $/kW-mo
Rates	120	60	6	60	30	6
Penalties	130			70		
Value NO ES = 8,840 K$/yr						
Potential Wind Generation		5,864			2,976	
Value WITH ES = 10,495 K$/yr						
Direct Wind		5,864			2,113	
Stored Energy to Market	3,390		232			
(Value Wind to Storage)					(864)	
(Value Purch Enrg to Storage)					(240)	
Revenue NO ES, K$/yr	8,840					
Revenue WITH ES, K$/yr	10,495					
Net Value ES System, K$/yr	1,655					
Discount_Rate, %	7.5%					
Project Life, years	20					
CRF, %	9.8%					
NPV, K$	16,870					
Net ES System Value = 1,687 $/kW						

Combined Application C7: K, M, D (TS + GFX + RC)

Application Requirements	App C7: Time Shift 28290 MWh/yr +GFX + RC
Battery Selection	
Type of Modules	XYZ
Number of Modules	TBD
Pulse Factor	1.0
Max Charge Voltage	1,550
Min Discharge Voltage	930
Maximum DOD, %	90%
Cumulative Cycle Fraction	96%
Replacement Interval, yr	10
PCS Selection	
PCS Type (Chapter 5)	I
Duty Cycles	
Grid Support or Power Quality (GS or PQ)	
Power, MW	10
Event Duration, Hr	0.25
Load Shifting (LS)	
Power, MW	10.0
Load Shift Energy, MWh/yr	28,291
Load Shift Losses, MWh/yr	8,588
Cycle Life Fraction	74%
Regulation Control (RC)	
Power, MW	10.0
Hours per day, hr	20
Days per year, days	165
RC, MW-Hours/yr	33,000
RC Losses, MWh/yr	2,504
Cycle Life Fraction	22%
Summary System Data	
Standby Hours per Year	0
System Net Efficiency, % (See Note)	87.3%
Battery Standby Efficiency, %	100.0%
PCS Standby Efficiency, %	100.0%
System Footprint, MW/sqft (MW/m^2)	0.0014 (0.0152)
Battery Footprint, MW/sqft (MW/m^2)	0.0017 (0.0185)

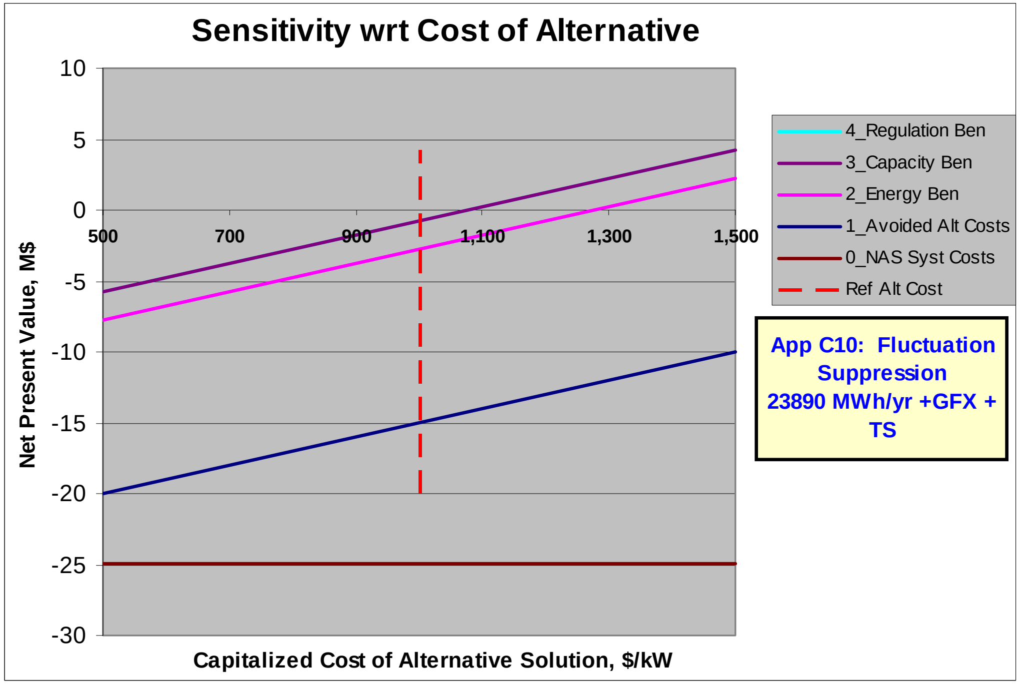
Note: System net efficiency includes losses for energy conversion and system standby expressed on an annual basis, i.e., one minus inefficiency, where inefficiency equals the ratio of annual energy losses to the product of system rated power times 8760 hours, expressed in percent.

Capital & Operating Costs	App C7: Time Shift 28290 MWh/yr +GFX + RC
Battery Capacity, MWhac	78
PCS Initial Cost, $/kW	239
BOP Initial Cost, $/kW	100
Battery Initial Cost, $/kW	1,523
Battery Initial Cost, $/kWh	196
Total Capital Cost, M$	18.6
O&M Cost – Fixed, $/kW-year	42.2
O&M Cost– Variable, $/kW-year	0.0
NPV Disposal Cost, $/kW	54.1

Note: The total initial cost may be calculated in two ways:
1. By mutiplying the sum of PCS, BOP and Battery initial costs expressed in $/kW by the reference power,
2. OR by mutiplying the sum of PCS and BOP expressed in $/kW by the reference power and then adding the product of Battery Initial cost expressed in $/kWh and the Battery Capacity

Combined Application C7: TS + GFX + RC - Results

Summary Economics	App C7: Time Shift 28290 MWh/yr +GFX + RC
Alt Solution Value, $/kW	1,000
Initial Installed Cost, M$	18.62
Total Costs, M$	(28.8)
Total Benefits, M$	31.3
Benefit to Cost Ratio	1.09
NPV, M$	2.5



ESHB Suitability Matrices With Preliminary Wind Results

Category			Application	PbA	NiCad	NAS	ZnBr	VRB	Regenesys	SMES	Flywheels	Ultracaps	CAES (10 MW above grade)	CAES (135 MW below grade)
				Energy Storage Technology										
Grid Stabilization (GS)			A: Angular Stability (GAS)	✓	M		M			✓	✓	✓		
			B: Voltage Stability (GVS)	✓						M		M		
			C::Frequency Excursion Suppression (GFS)	M	M									
Grid Operational Support (GOS)			D: Regulation Control (RC)											✓
			E: Cnvntnl Spinning Reserve (SR)											
Distribution Power Quality (PQ)			F: Short Duration PQ (SPQ)	✓	✓	✓	✓			✓	✓	✓		
			G: Long Duration PQ (LPQ)	M										
Load-Shifting (LS)			H: 3 hr (LS3)										✓	
			I: 10h (LS10)			✓		✓	✓				✓	✓
Combined Applications	"T" Utility	C1: GFS +	GAS+ GVS+ RC	M	M	M								
	"D" Utility	C2: SPQ +	LS10 + RC + SR			✓		✓	✓					
		C3: SPQ +	LS3 + RC + SR	✓	✓	✓	✓	✓	✓					
		C4: LPQ +	LS3 + RC + SR	✓		✓		M	✓					
	"T" or "D"	C5: LS10 +	RC + SR			✓	M	✓	✓				✓	✓

PRELIMINARY

Category		Application	PbA	NiCad	NAS	VRB	Flywheels	Ultracaps	CAES (10 MW above grade)	CAES (300 MW below grade)
			Energy Storage Technology							
Wind Generation Support (WGS)		J. Transmission Curtailment (TC)							✓	✓
		K. Time-Shifting (TS)							✓	✓
		L. Forecast Hedge (FH)			M				✓	✓
		M. Grid Frequency Support (GFX)	✓	✓						
		N. Fluctuation Suppression (FS)					✓	✓		
Combined Applications	C6: TC +	GFX, RC			✓	✓			✓	✓
	C7: TS +	GFX, RC			✓	✓			✓	✓
	C8: FH +	GFX, RC			✓	✓			✓	✓
	C9: GFX +	FH, RC			✓	✓				
	C10: FS+	GFX, TS			✓	✓				

Purpose is to screen leading ES systems against candidate applications. Optimization needed with respective vendors.