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Management energy storage systems for flexible and efficient power systems

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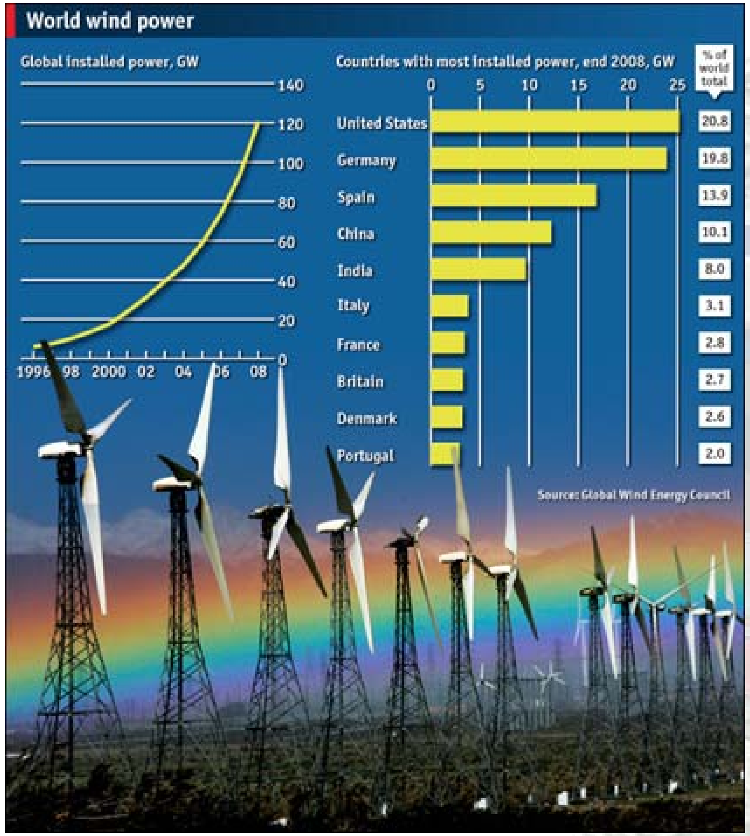
WINDINSPIRE

Template courtesy of Rajat Mittal

Integrating renewables into a changing power system

Wind and other renewable energy is making up a larger proportional of the power system world wide and this proportion is growing at an increasing rate

- Renewable integration challenges
  - Variability
  - Intermittency
  - Topological challenges
- Displacing of conventional generation
  - Maintaining adequate grid services, e.g. frequency regulation and reactive power support

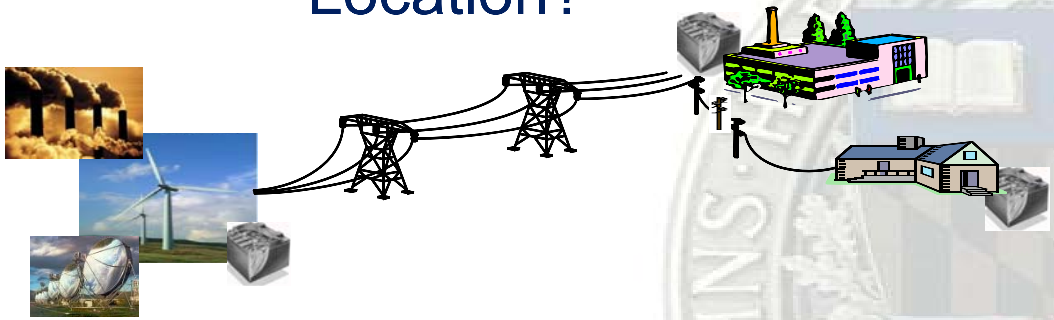


Grid-integrated storage: The Panacea

- Commodity arbitrage (peak shaving)
  - Efficiency improvements
- Asset investment deferral
- Renewable energy integration
  - Reliability (load following)
  - Providing reserve power
  - Stability and frequency support
  - Improving power quality (e.g. VAr support)



Size?
Type?
Location?



Grid-scale storage integration

Understand and characterize the important criteria in optimal storage dispatch and allocation

Economic analysis (no network model)

- E.g. Sioshansi et al. (2008), Denholm et al. (2010), Drury et al. (2011), Kraning et al. (2010), Su & Gamal (2013),

Storage operation and allocation in grids

- **Linearized Network Model (approximate Kirchoff's laws)**

  Chandy et al. (2010), Dvijotham et al. (2011), Thrampoulidis (2013), Ghofrani et al. (2013),
- **Full AC Network Model**

  Atwa & El-Saadany (2010), Lamadrid et al. (2012), Hu & Jewell (2011), Gabash and Li (2012), Gayme & Topcu (2012, 2013), Bose et al. (2012), Gopalakrishnan et al. (2013), Castillo & Gayme (2013)

Our approach to storage integration

Understand and characterize the important criteria in optimal storage dispatch and allocation

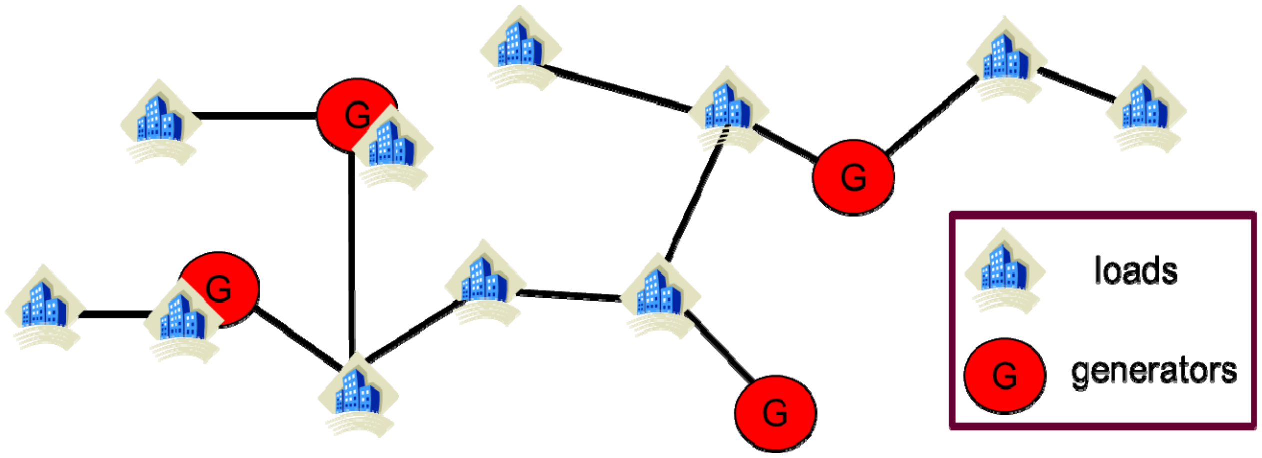
Optimal power flow (OPF) based framework

I. Start with full AC network model for storage siting and dispatch

II. Identify key drivers of OPF based storage integration

III. Develop a reduced model that retains the key features but is more computationally tractable

Optimal power flow (OPF) framework: nominal problem



$$l \in \mathcal{G} := \text{ set of generators}$$
$$k \in \mathcal{N} := \text{ set of all nodes}$$

Cost Function $\min \sum_{l \in \mathcal{G}} c_{l_1} \left(P_l^g\right)^2 + c_{l_1} P_l^g$

Real/Reactive Generation Limits:

$$P_l^{\min} \le P_l^g \le P_l^{\max}$$
$$Q_l^{\min} \le Q_l^g \le Q_l^{\max}$$

Voltage Limits $V_k^{\min} \le |V_k| \le V_k^{\max}$

Real power balance $\mathrm{Re}\left\{V_k I_k^*\right\} = P_k^g - P_k^d$

Reactive power balance $\mathrm{Im}\left\{V_k I_k^*\right\} = Q_k^g - Q_k^d$

ACOPF with storage (ACOPF+S) problem

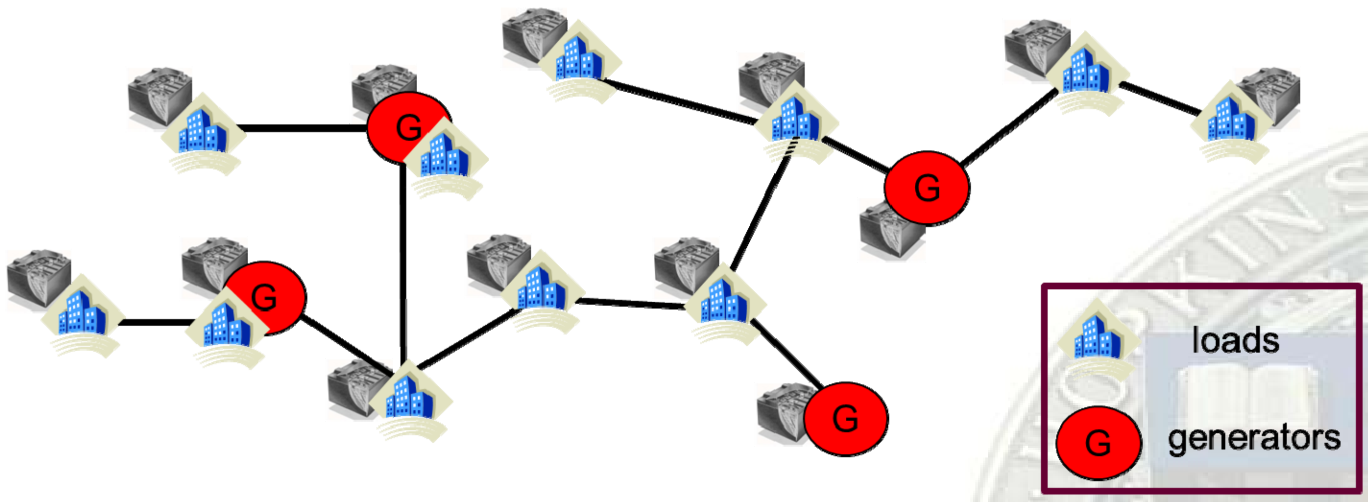
Cost Function $\min_{\mathcal{S}} \sum_{t=1}^{T} \sum_{l \in \mathcal{G}} f\left(P_l^g(t), t\right) + g(r_k^d, t)$ $k \in \mathcal{N} :=$ set of all nodes $l \in \mathcal{G} :=$ set of generators

Power Balance (KCL based constraint)

$$\mathrm{Re}\left\{V_k(t) I_k^*(t)\right\} = P_k^g(t) - P_k^d(t) - \left[r_k^c(t) - r_k^d(t)\right]$$

$$\mathrm{Im}\left\{V_k(t) I_k^*(t)\right\} = Q_k^g(t) - Q_k^d(t)$$

Real/Reactive Power Bounds
Voltage limits
Transmission line limits



ACOPF with storage (ACOPF+S) problem

Cost Function

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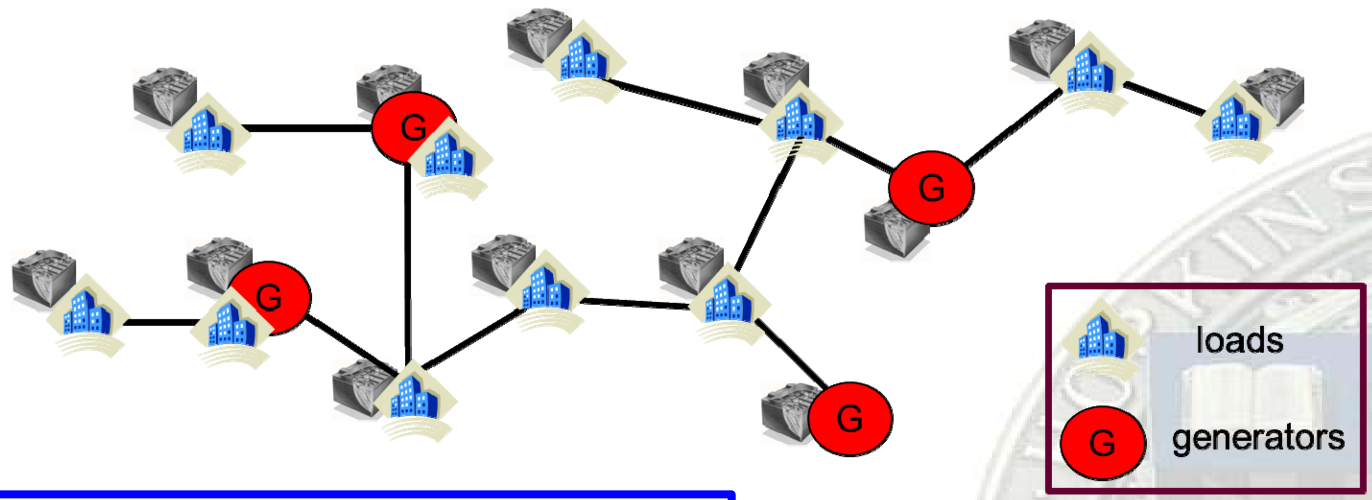
Real/Reactive Power Bounds

Voltage limits

Transmission line limits



Generator ramp rate limits

$$RR_l^{\min}(t) \le P_l^g(t) - P_l^g(t+1) \le RR_l^{\max}(t)$$

Total storage capacity limits

$$\sum_{k\in\mathcal{N}} B_k^{\max} \le h$$

Charge/Discharge Rate Limits

$$0 \le r_k^c(t) \le R_k^{c,\max}$$

$$0 \le r_k^d(t) \le R_k^{d,\max}$$

Storage Dynamics and Capacity Limits

$$b_k(t+1) = b_k(t) + \eta_c r_k^c(t) - \left(\eta_d\right)^{-1} r_k^d(t)$$

$$0 \le b_k(t) \le B_k^{\max}, \quad b(1) = g_k$$

ACOPF with storage (ACOPF+S) problem

Cost Function $\min_{\mathcal{S}} \sum_{t=1}^{T} \sum_{l \in \mathcal{G}} f\left(P_l^g(t), t\right) + g(r_k^d, t)$ $k \in \mathcal{N} :=$ set of all nodes $l \in \mathcal{G} :=$ set of generators

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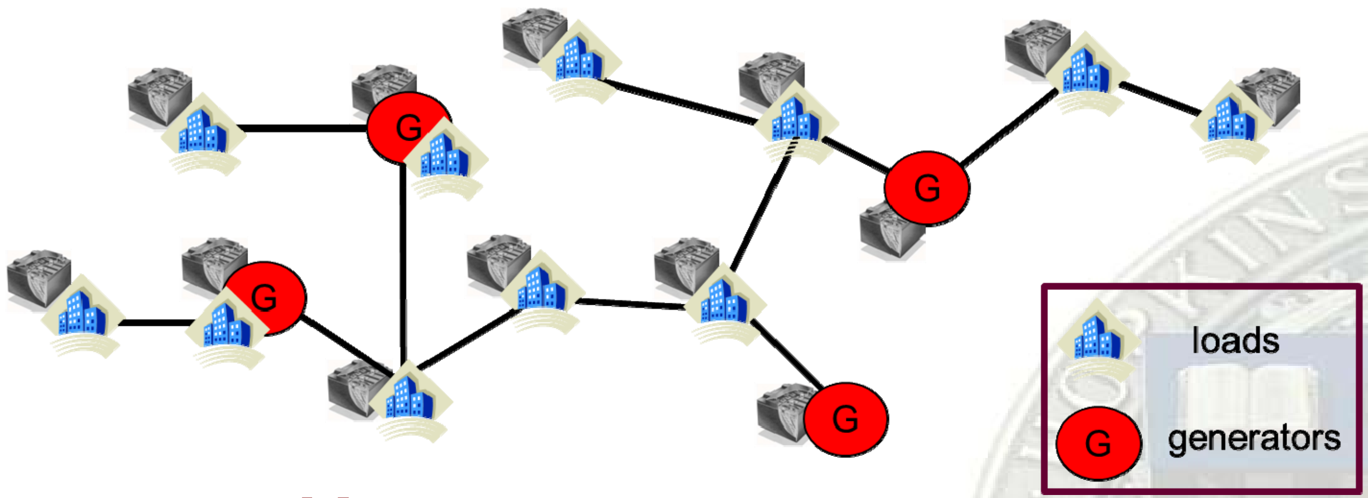
$$\mathrm{Im}\left\{V_k(t) I_k^*(t)\right\} = Q_k^g(t) - Q_k^d(t)$$



Real/Reactive Power Bounds
Voltage limits
Transmission line limits
Generator ramp limits
Charge/Discharge Rate Limits
Storage Dynamics and Capacity Limits

Decision Variables

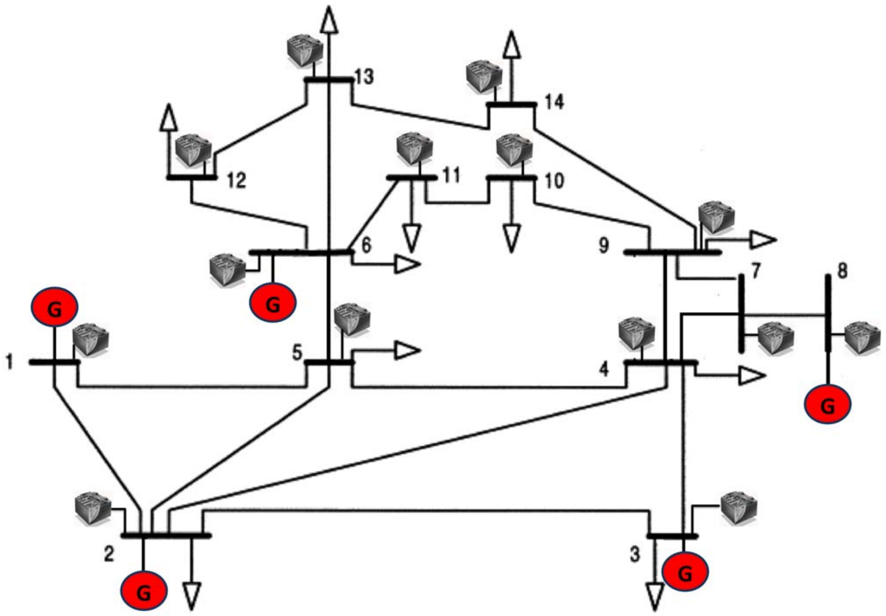
$$\mathcal{S} = \left\{P_l^G(t), Q_l^G(t), r_k^c(t), \mathrm{r}_k^d(t), B_k^{max}\right\}$$

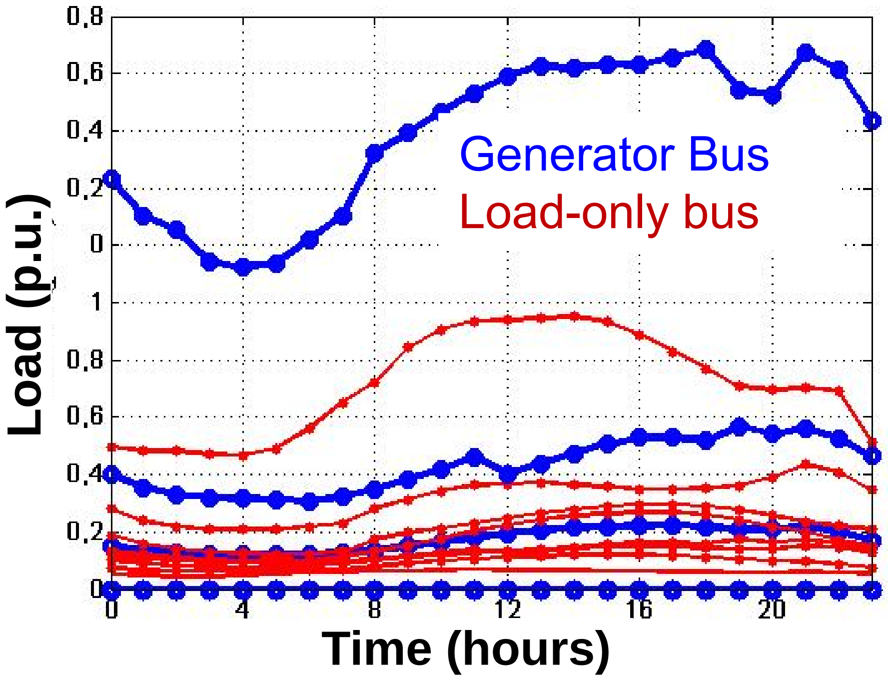
Real/reactive power dispatch
Storage charge/discharge scheduling
Storage sizing and siting

[Bose et al. 2012, Castillo & Gayme 2013]

ACOPF+S Case studies

IEEE 14 Bus Test System



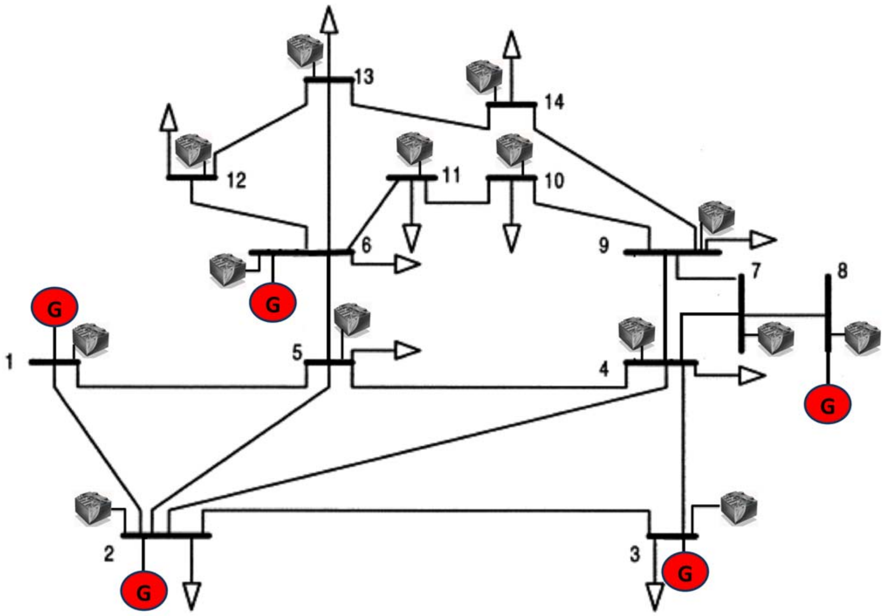


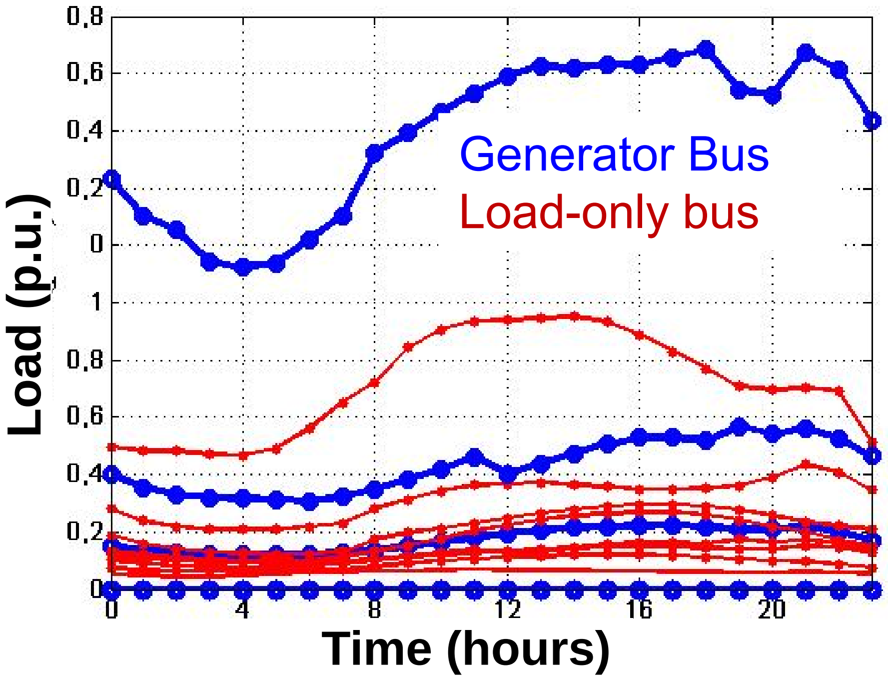
- 14 nodes with 5 generators
- Fixed topology and generation limits

- Demand curves based on 14 SCE feeders averaged over July 2009
- Peak-normalized based on IEEE test system

ACOPF+S Case studies

IEEE 14 Bus Test System





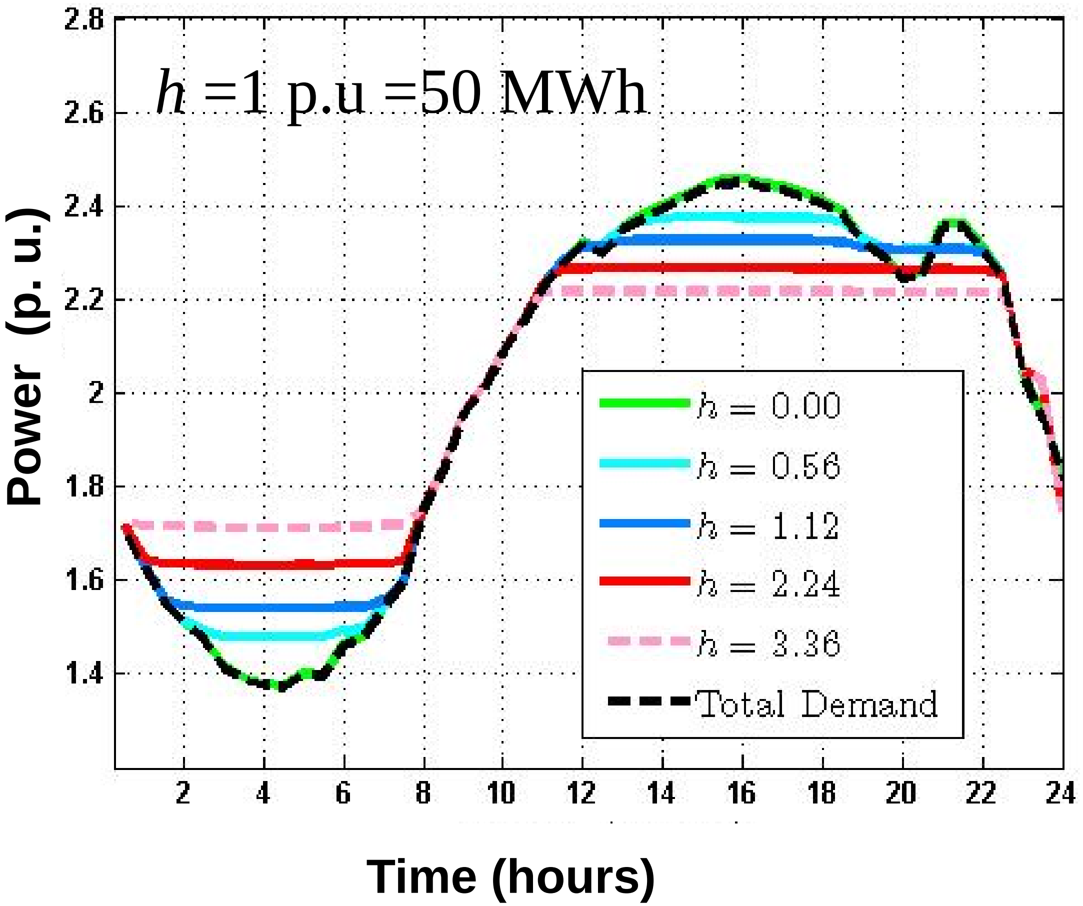
- 14 nodes with 5 generators
- Fixed topology and generation limits

- Demand curves based on 14 SCE feeders averaged over July 2009
- Peak-normalized based on IEEE test system

Solve this problem using a semi-definite relaxation that allows us to verifiably obtain a globally optimal solution

Energy arbitrage

Total storage budget $\sum_{k\in\mathcal{N}} B_k^{\max} \leq h$



- The quadratic cost functions lead to efficient peak shaving
- Results can be further improved with demand based cost functions
- All cases solved to optimality (zero duality gap)

The storage placement problem

Storage at different locations & scales serves different functions

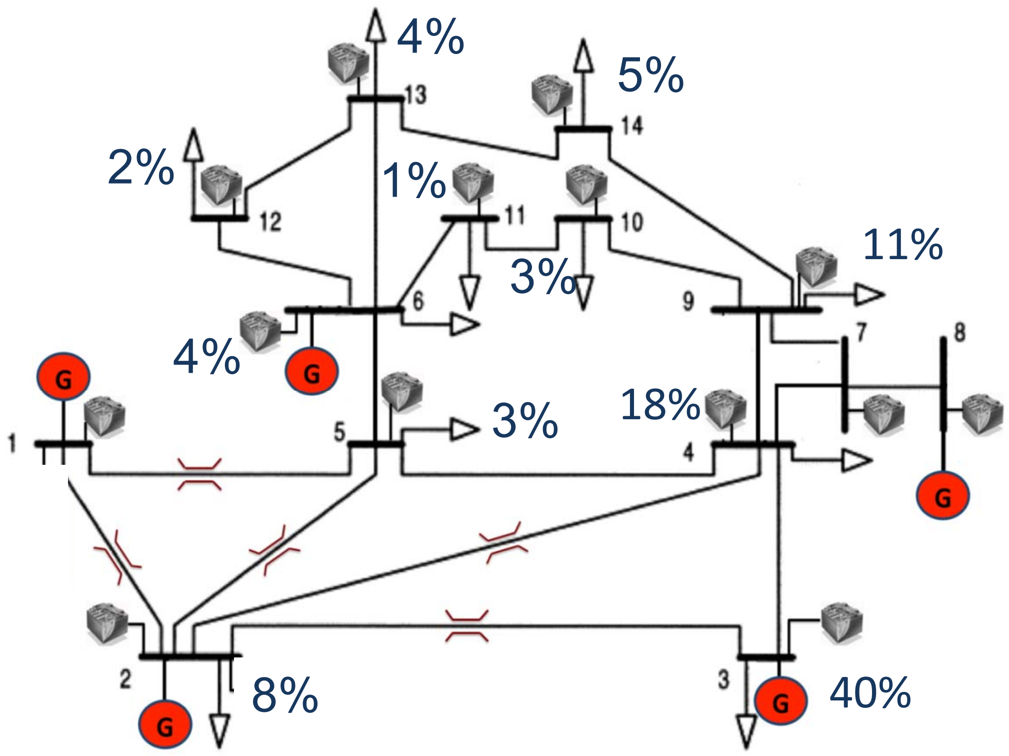
- At generators: smooths transients
- At loads: alleviates transmission

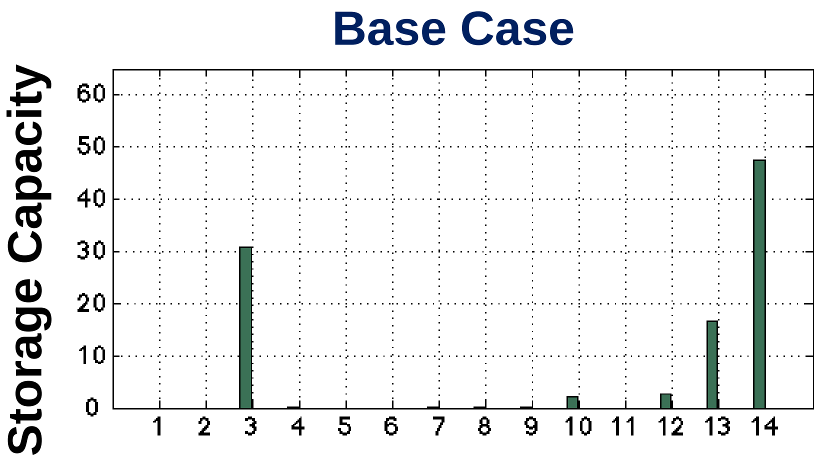
Use ACOPF based storage allocation to identify critical features of the problem to inform modeling efforts

- Most studies ignore the network or linearize to obtain the DCOPF+S problem, which is lossless
- Our relaxation allows us to solve the full ACOPF+S problem




Storage placement does not follow simple rules

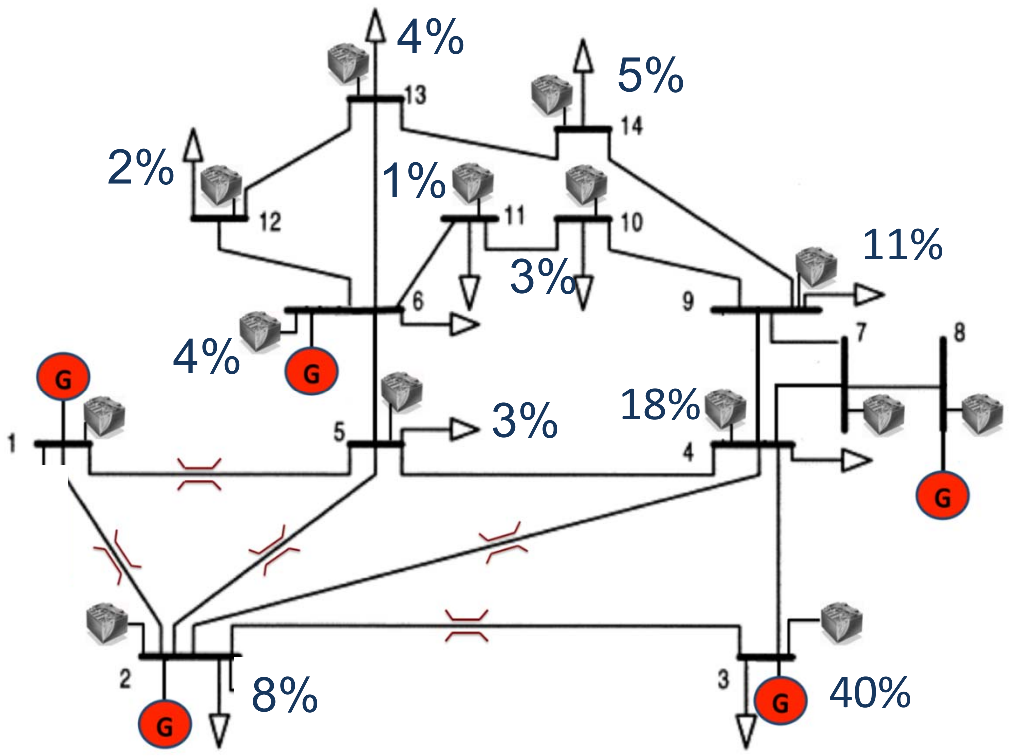




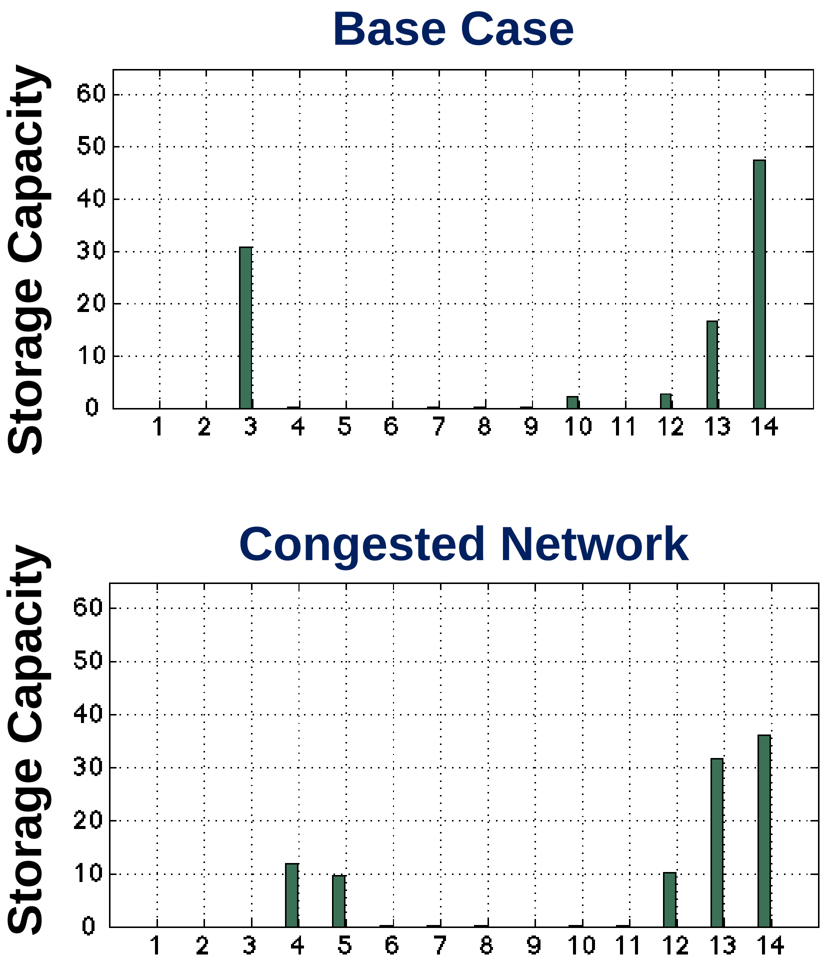
- Already see a difference from DCOPF in base case (no congestion, 100% efficient)
- Key observation is that neither loads nor generation alone drive storage allocation in the test system

Storage placement does not follow simple rules

Enforce line limits $\left(P_l^g(t)\right)^2 + \left(Q_l^g(t)\right)^2 \leq Q_l^{\max}(t)$ near low cost generators



- Congestion drives storage to the nodes immediately outside of the bottlenecks



Analyzing storage placement drivers

Theorem (sketch): Profit Maximizing Storage (no VAr support):

For an arbitrary operating cycle $1 \ldots T$, the energy storage capacity receives the most incremental value the node n that satisfies

$$\max_{n}\left(\max_{\lambda} \pi_n^{s,\mathrm{opt}}\right)$$

$$\pi_n^{s,\mathrm{opt}} = \sum_{t=1}^{T}\left(\lambda_n(t)^{\mathrm{opt}}\left[r_n^d(t)^{\mathrm{opt}} - r_n^c(t)^{\mathrm{opt}}\right]\right)$$ Storage Profits

$\lambda_n(t)^{\mathrm{opt}}$ Optimal locational marginal price (LMP) at node n in time t (dual variable)

$r_n^d(t)^{\mathrm{opt}}$ Optimal discharge rate for storage at node n in time t (primal variable)

$r_n^c(t)^{\mathrm{opt}}$ Optimal charge rate for storage at node n in time t (primal variable)

[Castillo & Gayme 2013, preprint 2017]

Analyzing storage placement drivers

$$\max_{n}\left(\max_{\lambda,\varphi}\pi_n^{s,\mathrm{opt}}\right)$$

$$\pi_n^{s,\mathrm{opt}}=\sum_{t=1}^{T}\left(\lambda_n(t)^{\mathrm{opt}}\left[r_n^d(t)^{\mathrm{opt}}-r_n^c(t)^{\mathrm{opt}}\right]\right)$$

Storage Profits

Storage is thus allocated as a function of LMPs (nodal prices)
Driven by

- available generation
- network properties (i.e. congestion and losses)

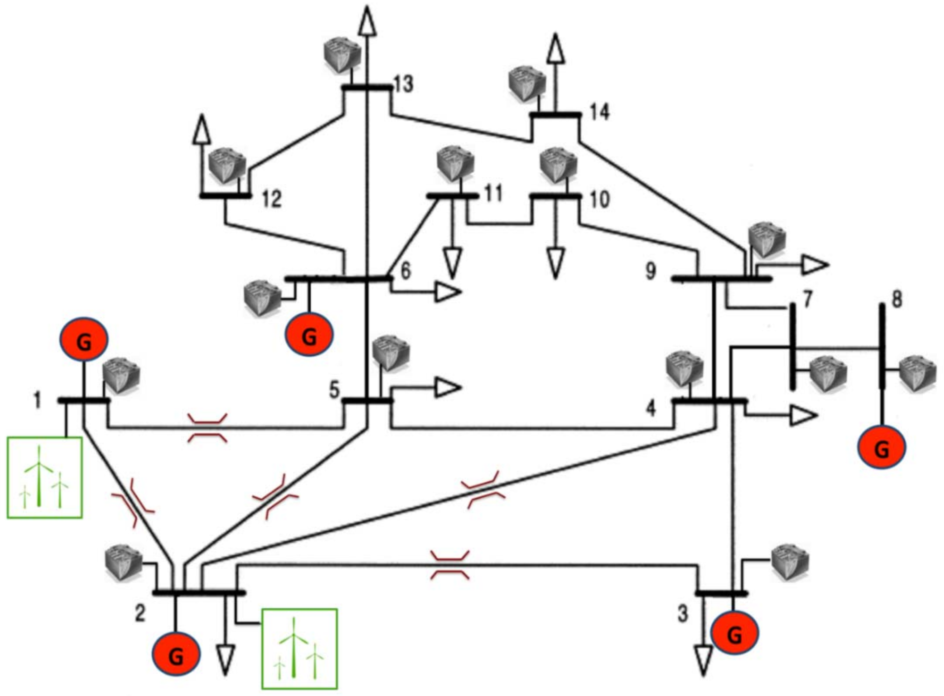
Network effects are critical aspects of the storage allocation and dispatch optimization

[Castillo & Gayme 2013, preprint 2017]

Storage placement and profits

$$\pi_n^{s,\text{opt}} = \sum_{t=1}^{T} \left(\lambda_n(t)^{\text{opt}} \left[r_n^d(t)^{\text{opt}} - r_n^c(t)^{\text{opt}} \right] \right)$$

- 15% wind penetration
- Congestion
- 81% round trip efficiency



Bus	ESS Storage Capacity (MWΔt)	Profits ($)
1	1.7	20.79
2	11.4	145.85
3	0	0
4	75.8	553.84
5	0	0
6-11	0	0
12	1.0	6.74
13	3.4	24.09
14	6.7	46.91
Total	100	798.37

[Castillo & Gayme 2013, preprint 2017]

Storage siting for multiple services

- Growing body of literature suggesting the economic benefits of using storage for multiple services

  e.g. Castillo & Gayme (2014), Hu et al. (2016), Teng & Strbac (2016), Xi & Sioshansi (2016), Strbac et al. (2017)
- ACOPF + S can be used to study the use of storage for reactive power support (e.g. via power electronics)
- Exploit ACOPF+S framework to examine the effects of using storage for simultaneous provision of energy services and reactive power (VAr) support
  - VAr is critical to proper grid function, e.g. transformers, voltage support
  - Typically provided by conventional generators who supply it by reducing their power factor
    - Opportunity cost due to less real power supply
  - Concern about reduced VAr availability as the composition of the grid changes
  - Key issue in VAr supply is that it is "local"

Storage and reactive power support

Simplest form (changes to base OPF+S)

Reactive power balance $\operatorname{Im}\left\{V_k(t)I_k^*(t)\right\} = Q_k^g(t) - Q_k^d(t) - z_k(t)$

Charge/Discharge Rate Limits $Z_k^{\min} \leq z_k(t) \leq Z_k^{\max}$

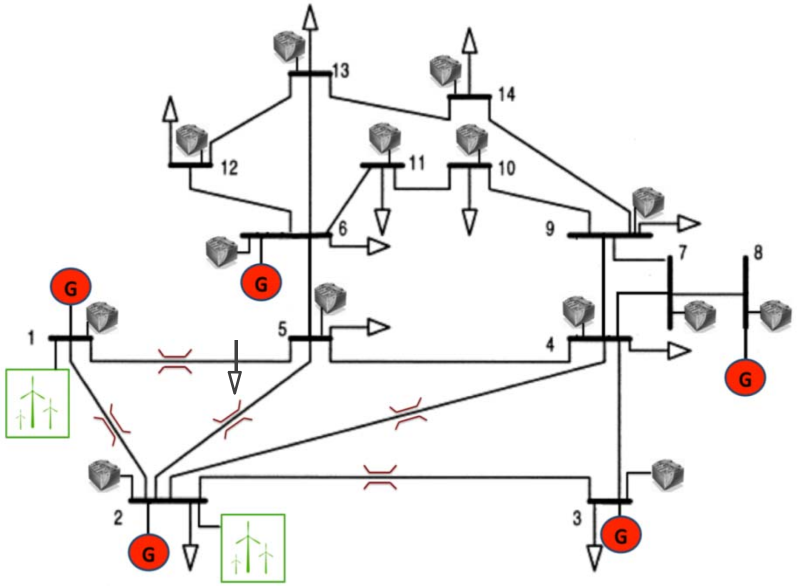
Decision Variables $\mathcal{S} := \left\{P_l^G(t), Q_l^G(t), r_k^{\,c}(t), r_k^{\,d}(t), z_k(t), B_k^{\max}\right\}$

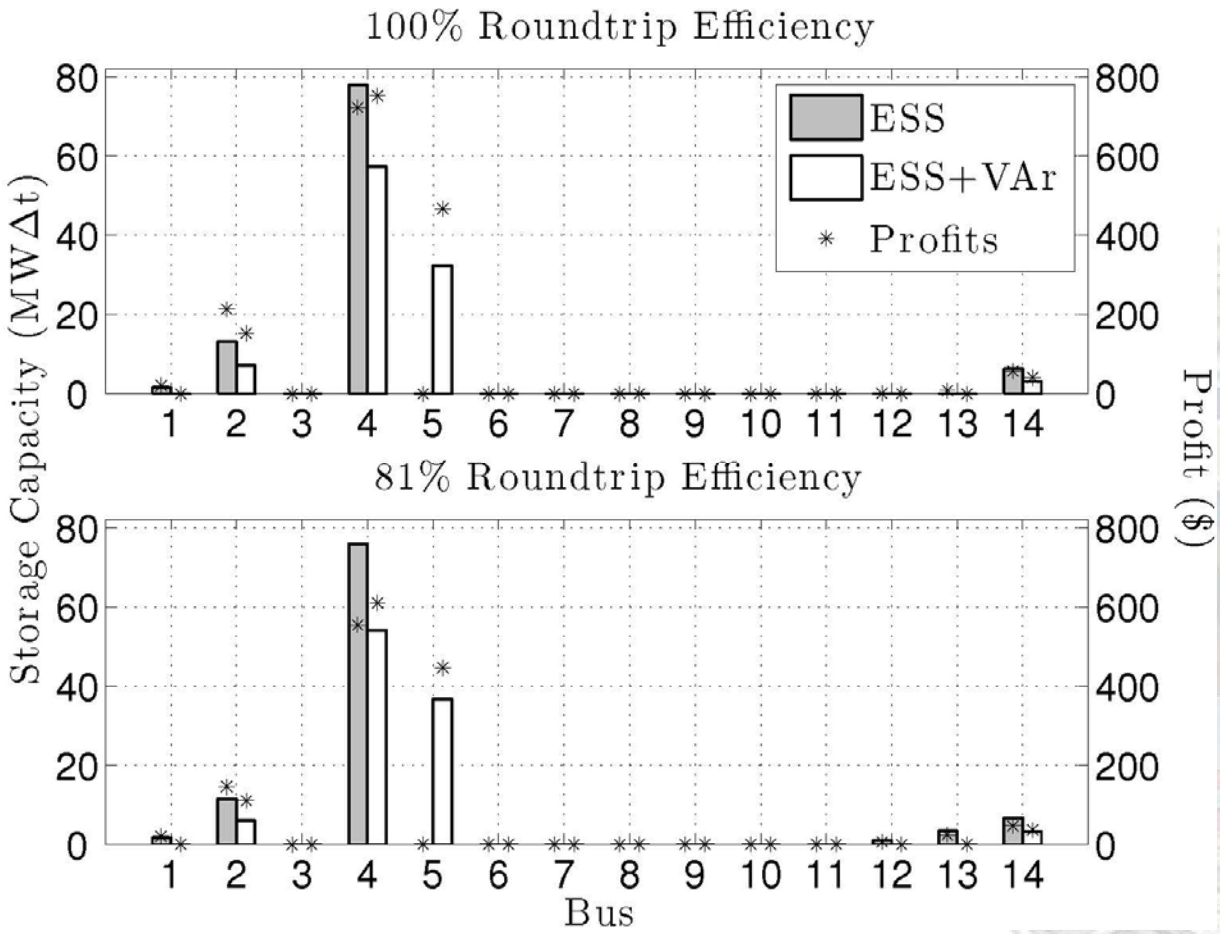
Real/Reactive power dispatch
Storage charge/discharge scheduling
Storage allocation at each bus
Reactive power dispatch from storage inverter

[Castillo & Gayme preprint 2017]

Example: Dual use storage placement results

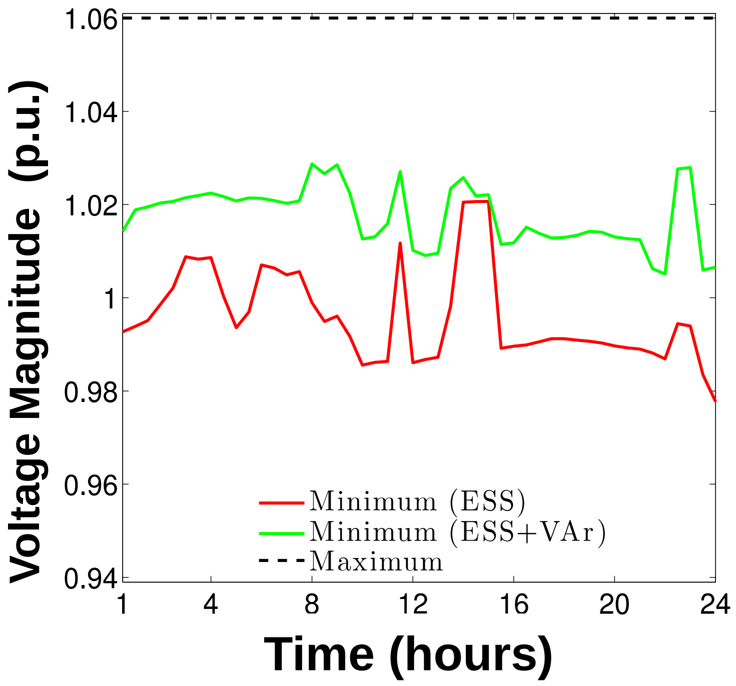
- 15% wind penetration, congestion, 81% round trip efficiency

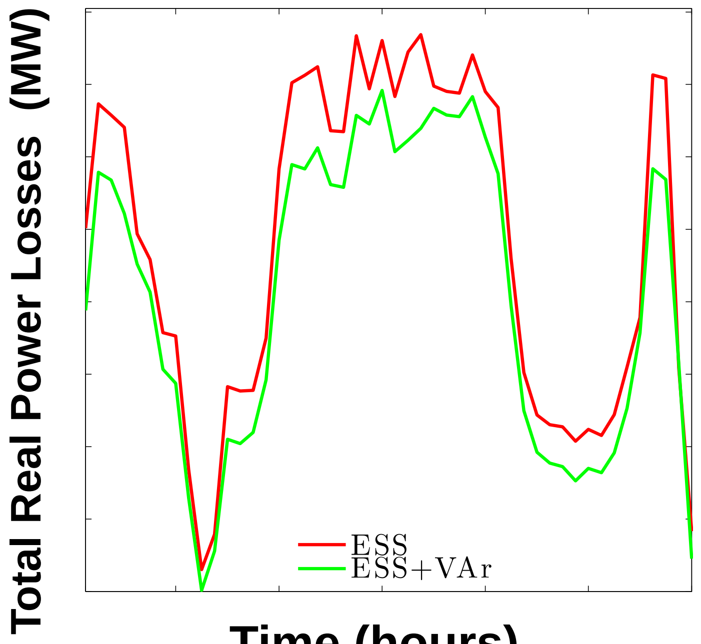




- Changes allocation substantially

VAr Support and operational efficiency





- Improves the overall system (Less losses, lower overall system costs

	ESS	ESS + VAr Support
Total System Cost, p^* ($)	206,164.00	204,697.28
Real Power Losses (MW)	151.7	145.1

[Castillo & Gayme 2017 preprint]

Profits: including reactive power support

$$\pi_n^{s,\mathrm{opt}} = \sum_{t=1}^{T} \left(\lambda_n(t)^{\mathrm{opt}} \left[r_n^d(t)^{\mathrm{opt}} - r_n^c(t)^{\mathrm{opt}} \right] \right) - \varphi_n(t)^{\mathrm{opt}} \left[z_n(t)^{\mathrm{opt}} \right]$$

$\lambda_n(t)^{\mathrm{opt}}$ Optimal locational marginal price (LMP) at node n in time t (dual variable)

$\varphi(t)^{\mathrm{opt}}$ Optimal reactive power (LMP) at node n in time t (dual variable)

$z_n(t)^{\mathrm{opt}}$ Optimal charge/ discharge rate for reactive storage support at node n in time t (primal variable)

- The VAr support is actually a reduction in the profits when the storage is supplying reactive power

[Castillo & Gayme 2017 preprint]

Storage operator profits

- Profits are reduced unless storage gets paid for VAr

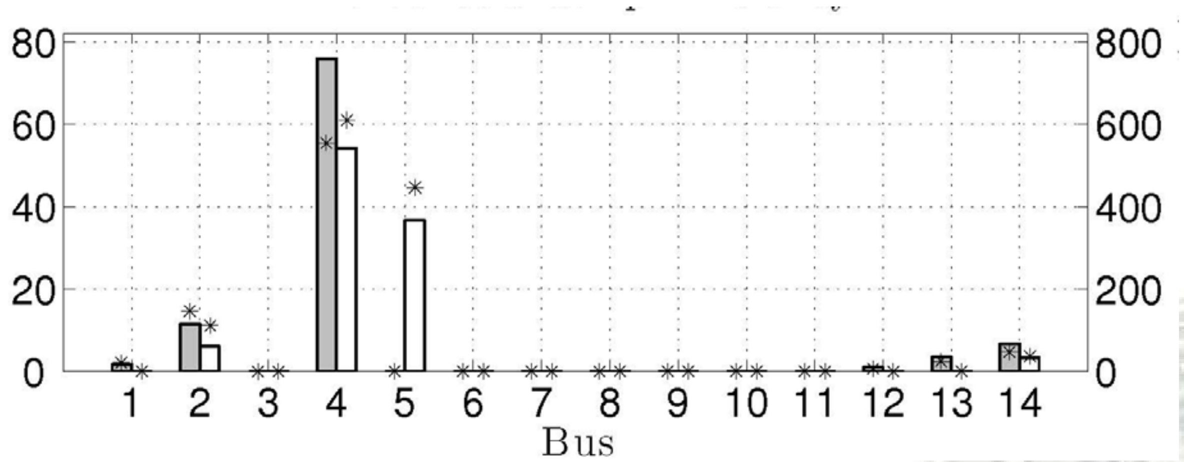
TABLE III: The total revenues, costs, and profits to ESS without and with VAr support where Q-LMP payments total to $459.93.

Energy Services	ESS	ESS + VAr Support
Revenues ($)	5,304.55	4,798.65
Costs ($)	4,506.17	4,056.19
Profits ($)	798.37	742.46
Reactive Power Compensation		
Revenues ($)	0	459.93
Costs ($)	0	0
Profits ($)	0	459.93
Total Profits ($)	798.37	1,202.39

[Castillo & Gayme 2017 preprint]

Comparison to other VAr payment mechanisms

Bus	Reactive Power Capability (MVAr)	max $\|z\|$ Reactive Dispatch (MVAr)	Total VAr Dispatch (MVAr)
1	0	0	0
2	3.0	0.08	1.69
3	0	0	0
4	27.05	27.05	1,298.79
5	18.3	18.3	879.56
6-13	0	0	0
14	1.65	1.63	74.70
Total	50	47.06	2,254.74

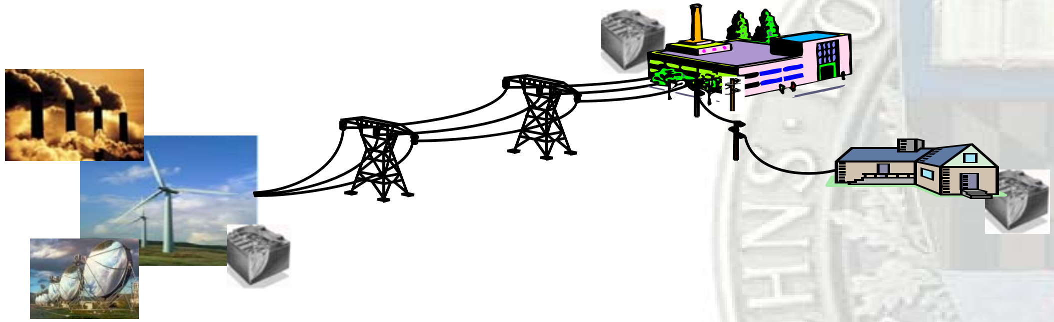


Bus	Q-LMP ($/Day)	NYISO Capability Rate ($/Day)	ISO-NE Capability Rate ($/Day)
1	0	0	0
2	0.04	32.21	18.00
3	0	0	0
4	213.61	290.43	162.30
5	233.06	196.49	109.80
6-13	0	0	0
14	13.22	17.72	9.90
Total	459.93	536.85	300.00

Recap

Storage allocation in the ACOPF framework allows us to study important questions about storage services that may improve the value proposition for storage

- Providing VAr support changes the allocation results substantially and suggest that VAr provision might be a good revenue source for storage
- Preliminary results show the use of a Q-LMP type mechanism tends to better match with the VAr requirements in the network

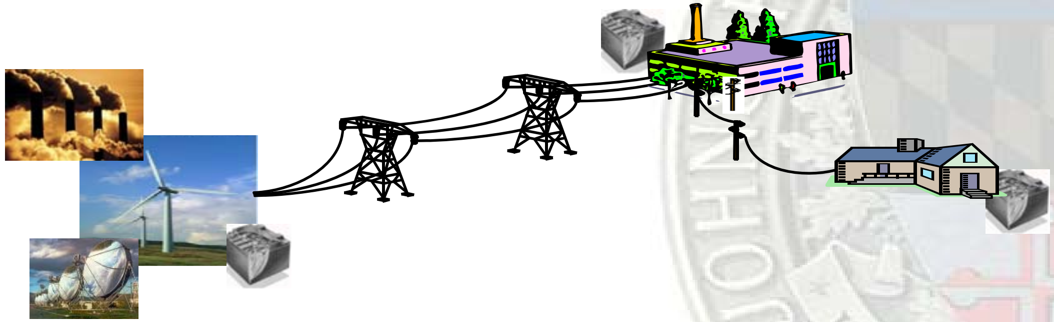


Recap

Storage allocation in the ACOPF framework allows us to study important questions about storage services that may improve the value proposition for storage

- Providing VAr support changes the allocation results substantially and suggest that VAr provision might be a good revenue source for storage
- Preliminary results show the use of a Q-LMP type mechanism tends to better match with the VAr requirements in the network

- Do not always care about providing VAr
  - Economics currently don't incentivize it Technical constraints that prevent greatly altering the power factor supplied
- AC OPF is still difficult to solve

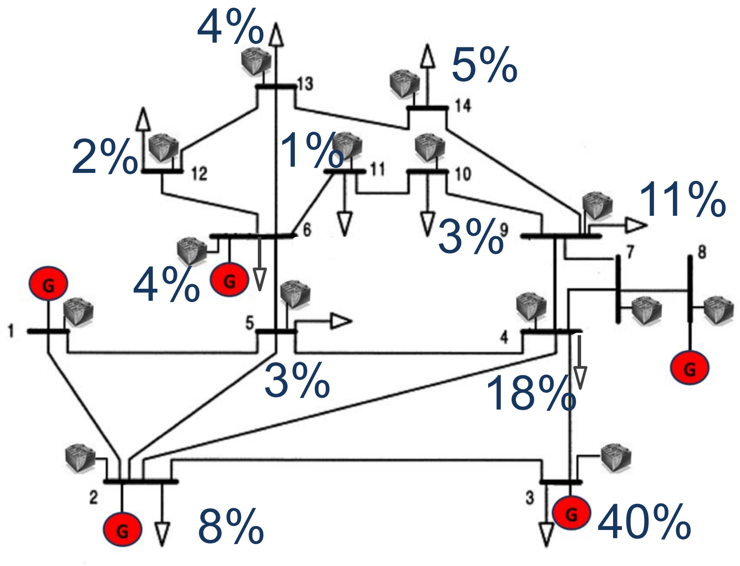


Simplifying the model: The role of losses

Without real power (i.e. I^2R network) losses

total generation (+ storage discharge) = total demand (+ storage charge)

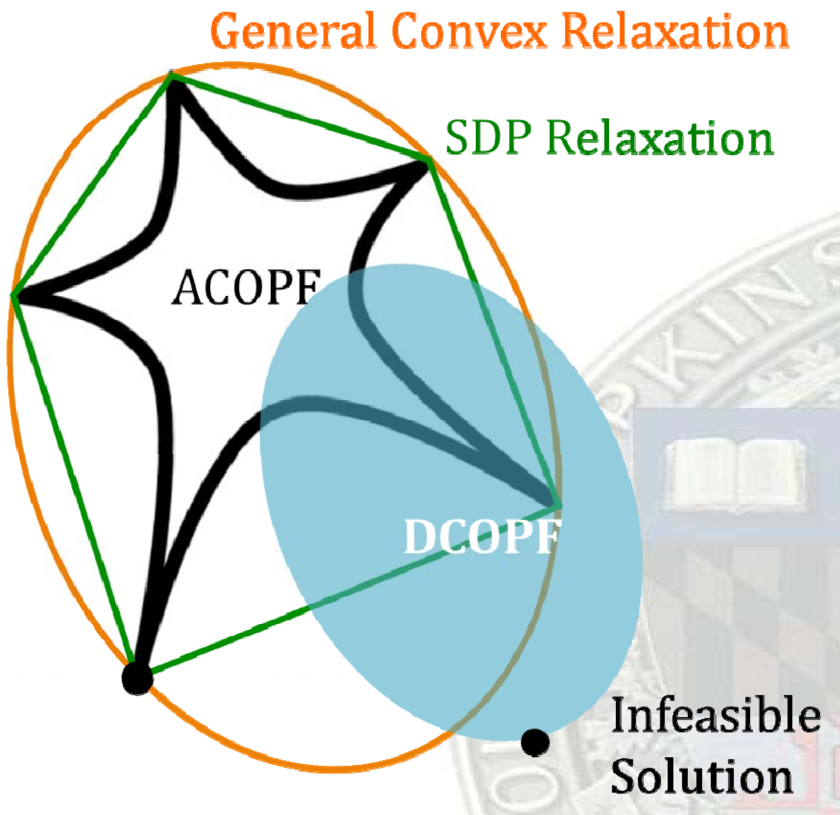
– energy storage capacity is allocated uniformly throughout the network with LMP $\pi_n^s = 40$ for all n



Bus	Baseline C_n	Baseline π_n^s	Doubled $\mathcal{R}$ C_n	Doubled $\mathcal{R}$ π_n^s	Tripled $\mathcal{R}$ C_n	Tripled $\mathcal{R}$ π_n^s
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0.36	200	0	0	0	0
4	0.02	10	0.19	70	0	0
5-9	0	0	0	0	0	0
10	0.05	30	0.08	30	0	0
11	0	0	0	0	0	0
12	0.03	20	0.08	30	0.2	20
13	0.16	90	0.27	100	0.4	100
14	0.38	210	0.38	150	0.4	310

Bridging the gap between AC & DC OPF

- DCOPF is a common linearization of ACOPF
  - Neglects reactive power
  - Assumes small angle differences between adjacent nodes $(\theta_n - \theta_i \approx 0)$
  - Constant (unit) voltage $|v_n| \approx 1$
  - Negligible resistance (low resistance-to-reactance ratios) $B_k \gg G_k \approx 0$



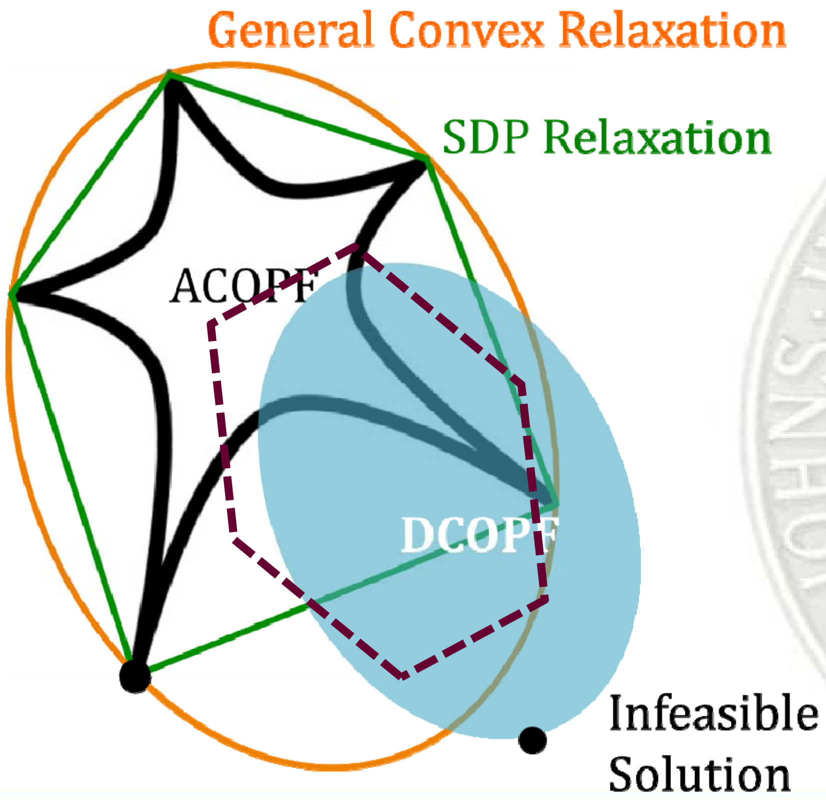
Bridging the gap between AC & DC OPF

- We want to augment DCOPF with real power losses
  - Small angle differences between adjacent lines $(\theta_{n,i} \approx 0)$
  - Constant (unit) voltage $|v_n| \approx 1$

Loss approximation

Taylor's series expansion $(\theta_{n,i} \approx 0)$

$$p^{\ell}_{k(n,i)} \approx G_k \left(\theta_{n,i}\right)^2$$



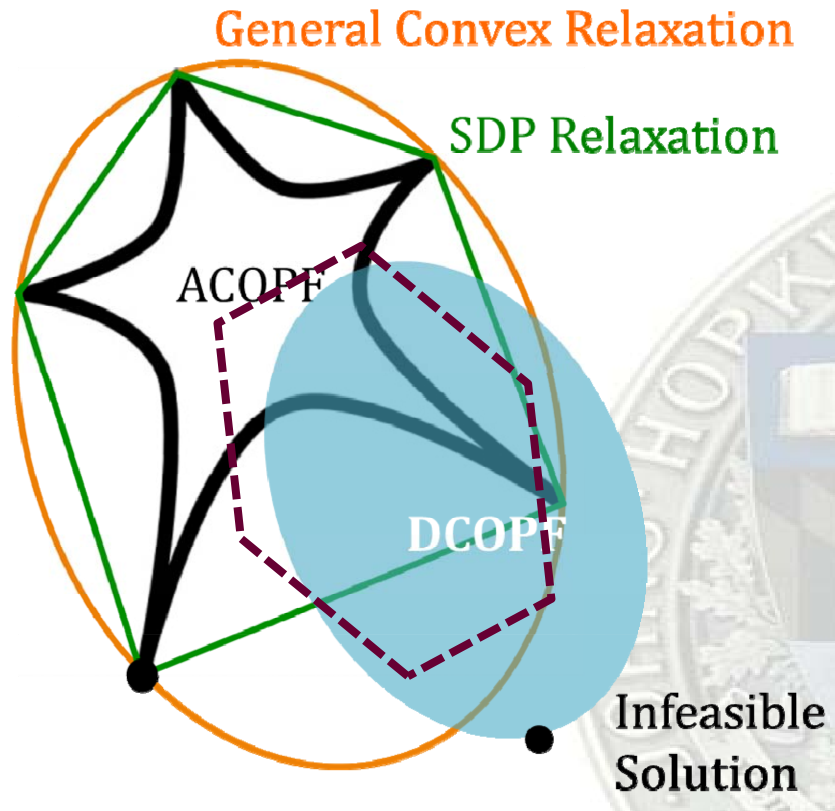
Bridging the gap between AC & DC OPF

Augment DCOPF with real power losses

- DCOPF $(\theta_n - \theta_i \approx 0), |v_n| \approx 1, B_k \gg G_k \approx 0$
  - Use the first two assumptions
  - Taylor's series expansion about

$$(\theta_{n,i} := \theta_n - \theta_i \approx 0)$$

Loss approximation: $p^{\ell}_{k(n,i)} \approx G_k \left(\theta_{n,i}\right)^2$



Lossy DCOPF (ℓ-DCOPF) with storage

Cost function $\min \sum_{n \in \mathcal{N}} f\left(p_n^g\right)$

Real power balance

$$p_n(t) = p_n^\ell(t) + p_n^d(t) + r_n^c(t) - p_n^g(t) - p_n^w(t) - r_n^d(t)$$

$$p_n(t) = \sum_{i \in \mathcal{A}} p_{k(n,i)}(t) = \sum_{i \in \mathcal{A}} B_k \theta_{n,i}(t)$$

$$p_n^\ell(t) = \sum_{i \in \mathcal{A}} p_{k(n,i)}^\ell(t) = \frac{1}{2} \sum_{i \in \mathcal{A}} \left(G_k \left(\theta_{n,i}(t)\right)^2 \right)$$

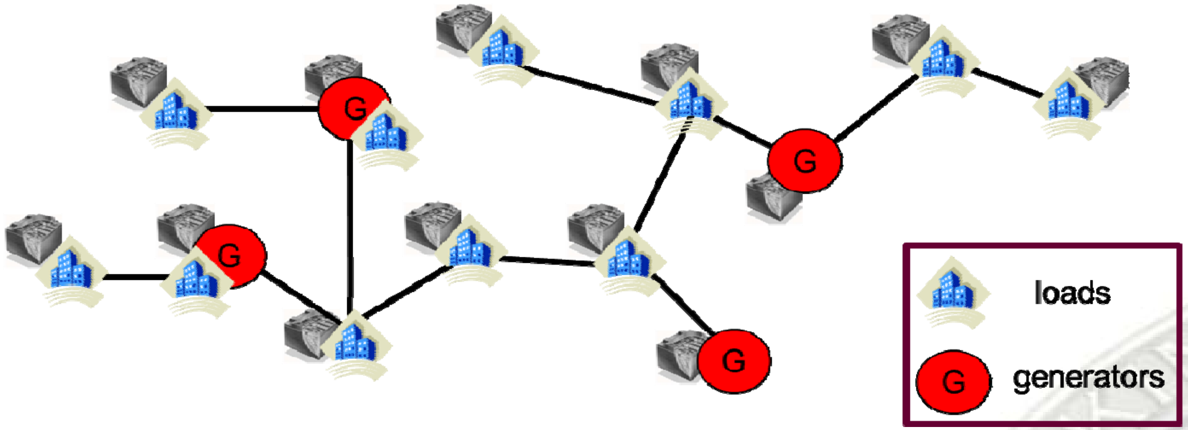
Wind availability

$$0 \le p_n^w(t) \le C_n^w(t)$$

Voltage angle limits

$$\left|\theta_{n,i}(t)\right| \le \Theta^{\max}(t)$$

Real power bounds and ramp rates
Transmission limits
Total storage in network
Charge and discharge rate limits
Storage level and initial condition



$n, i \in \mathcal{N}$:= set of nodes (buses)
$(n,i) \in \mathcal{A}$:= set of connected nodes
$k \in \mathcal{K}$:= set of lines
$k(n,i), k(i,n) \in \mathcal{F}$:= set of flows

[Castillo & Gayme 2014, 2017]

Exploiting convex relaxations

- The losses constraint makes this a QCQP

$$-p^{\ell}_{k(n,i)}(t) + \tfrac{1}{2} G_k \left(\theta_{n,i}(t)\right)^2 = 0$$

- We relax the equality constraint on the thermal losses

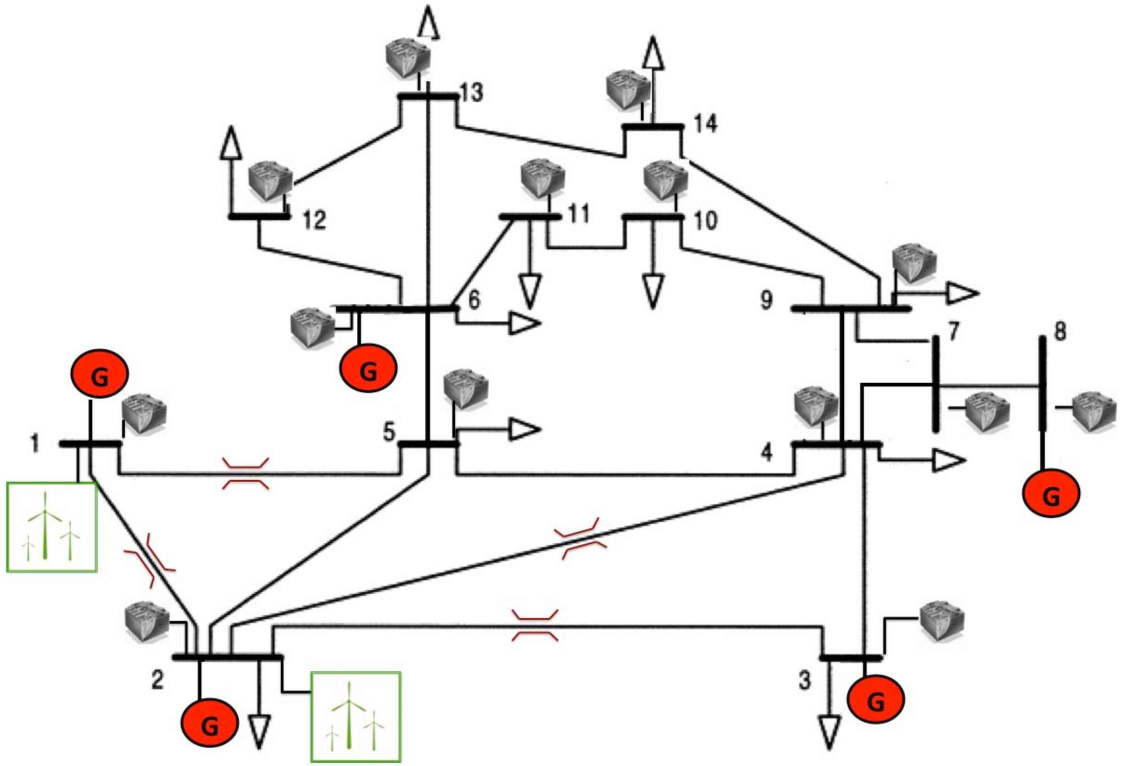
$$-p^{\ell}_{k(n,i)}(t) + \tfrac{1}{2} G_k \left(\theta_{n,i}(t)\right)^2 \leq 0$$

- Reformulate as either an SDP as before (or a SOCP)
  - Both of these are convex
- Main Computational Advantage (N bus system)
  - ACOPF problem is on the order of $O(N^2)$
  - ℓ-DCOPF introduces K-number of 2x2 solution matrices for a power network with K-lines (i.e. O(N))

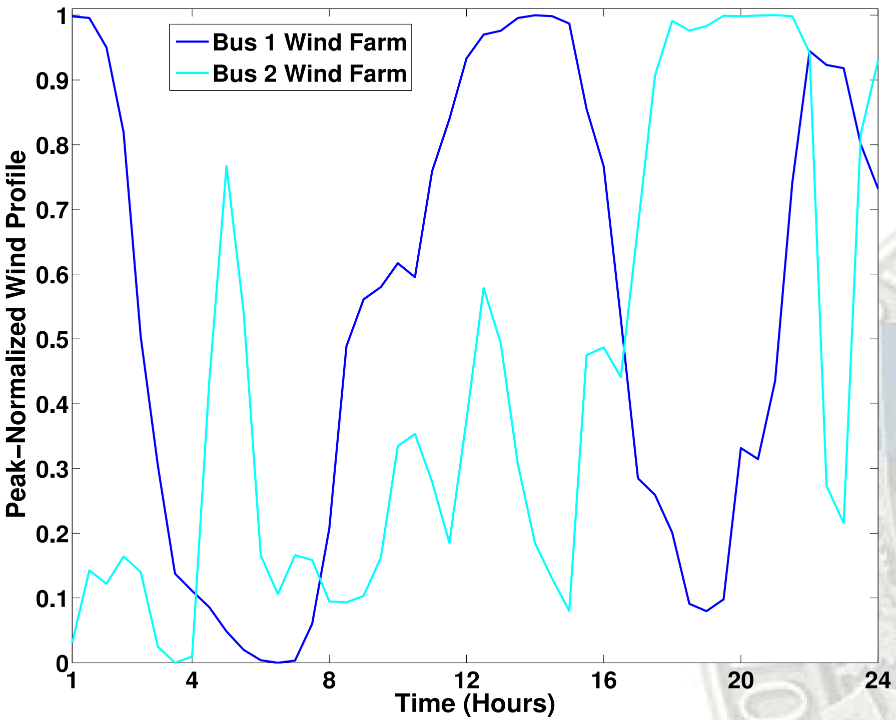
[Castillo & Gayme 2017]

Does this work?

Potential storage sites

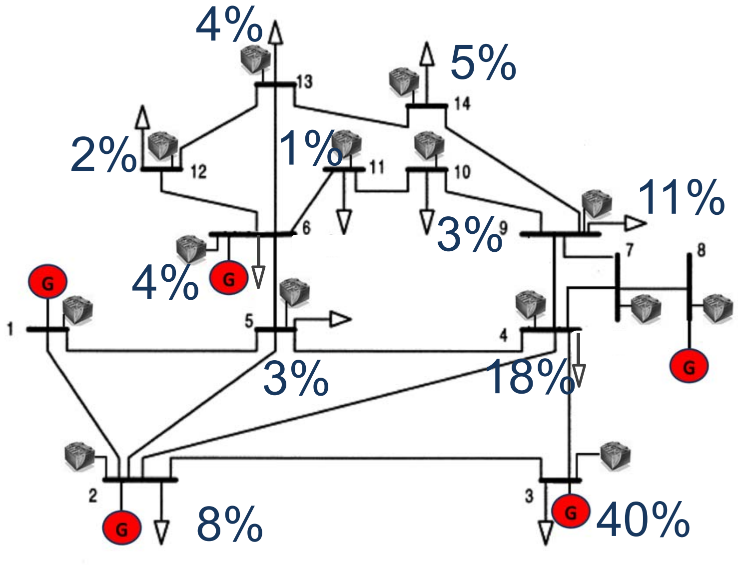


$$P_1^{\min} \leq P_1^g(t) \leq P_1^{\max}(t)$$



- Storage: 8MWΔt charge/discharge rate, 81% roundtrip efficiency
- 15% wind penetration distributed between buses 1 and 2

ℓ-DCOPF-based storage siting – no congestion



Bus	Approximations DCOPF+S C_n	π_n^s	ℓ-DCOPF+S C_n	π_n^s	Full ACOPF+S C_n	π_n^s
1	7.1	19.73	0.03	0.11	-	-
2	7.1	19.73	1.9	12.42	1	6.45
3	7.1	19.73	37	156.62	37.1	150.96
4	7.1	19.73	10.7	47.82	12.1	52.92
5	7.1	19.73	0.1	0.67	-	-
6	7.1	19.73	0.2	0.78	-	-
7	7.1	19.73	1.5	6.52	0.2	1.10
8	7.1	19.73	1.5	6.44	0.2	1.01
9	7.1	19.73	1.1	4.56	1.1	5.31
10	7.1	19.73	3.6	15.05	4.6	18.24
11	7.1	19.73	0.4	1.58	0.1	0.35
12	7.1	19.73	3.4	13.82	4.0	15.55
13	7.1	19.73	13.0	53.03	13.6	53.25
14	7.1	19.73	25.5	103.99	26.2	102.96
Total	100	276.22	100	423.40	100	408.10

- The ℓ-DCOPF is more accurate than the DCOPF at estimating storage placement and sizing

[Castillo & Gayme 2017]

ℓ-DCOPF-based storage siting- with congestion

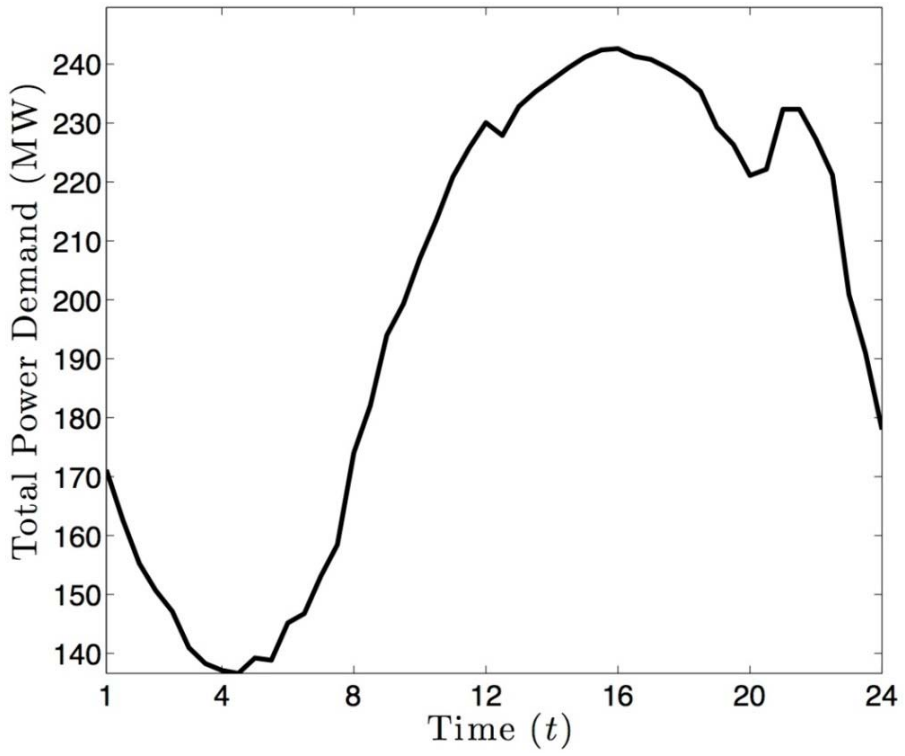
Bus	Approximations DCOPF+S C_n	π_n^s	ℓ-DCOPF+S C_n	π_n^s	Full ACOPF+S C_n	π_n^s
1	34.4	218.53	45.1	246.25	45.1	245.03
2	20.9	177.96	21.6	137.92	21.6	122.48
3	19.7	75.29	9	10.72	1.9	5.11
4	6.3	33.2	5.2	25.70	8.1	29.22
5	-	-	-	-	-	-
6	-	-	1.0	4.81	1.4	5.79
7	5.2	28.76	4.1	16.17	6	22.72
8	5.2	28.76	4.1	16.17	2.5	9.47
9	4.3	25.09	-	-	-	-
10	3	19.87	0.1	0.34	0.1	0.17
11	-	-	0.1	0.40	0.1	0.29
12	-	-	0.7	2.82	0.8	2.88
13	-	-	1.9	7.24	1.9	6.88
14	0.9	6.09	7	19.45	10.5	27.74
Total	100	613.55	100	487.99	100	477.78

- The greater accuracy is more acute in cases where there is network congestion
- Higher accuracy is also found for the IEEE 118 bus test case
- Computational times commensurate with DCOPF

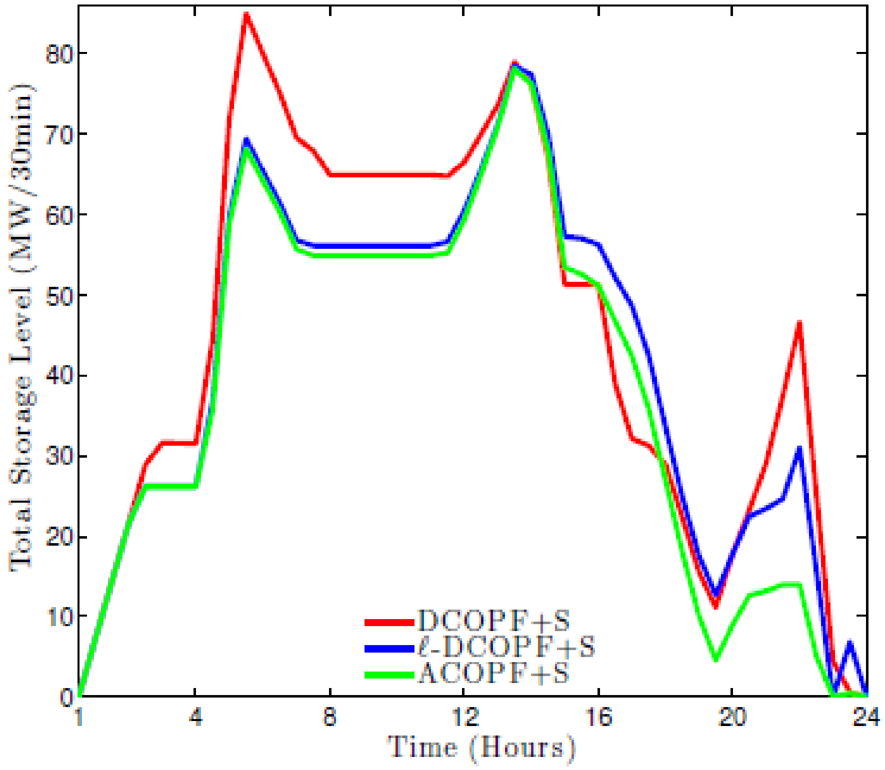
	Approximations DCOPF+S	ℓ-DCOPF+S	Full ACOPF+S
14-bus, Case I	1.1	1.4	14.7
14-bus, Case II	1.1	1.3	12.6
118-bus, Case I	4.6	6.2	n/a
118-bus, Case II	8.2	8.4	n/a

[Castillo & Gayme 2017]

ℓ-DCOPF-based storage dispatch



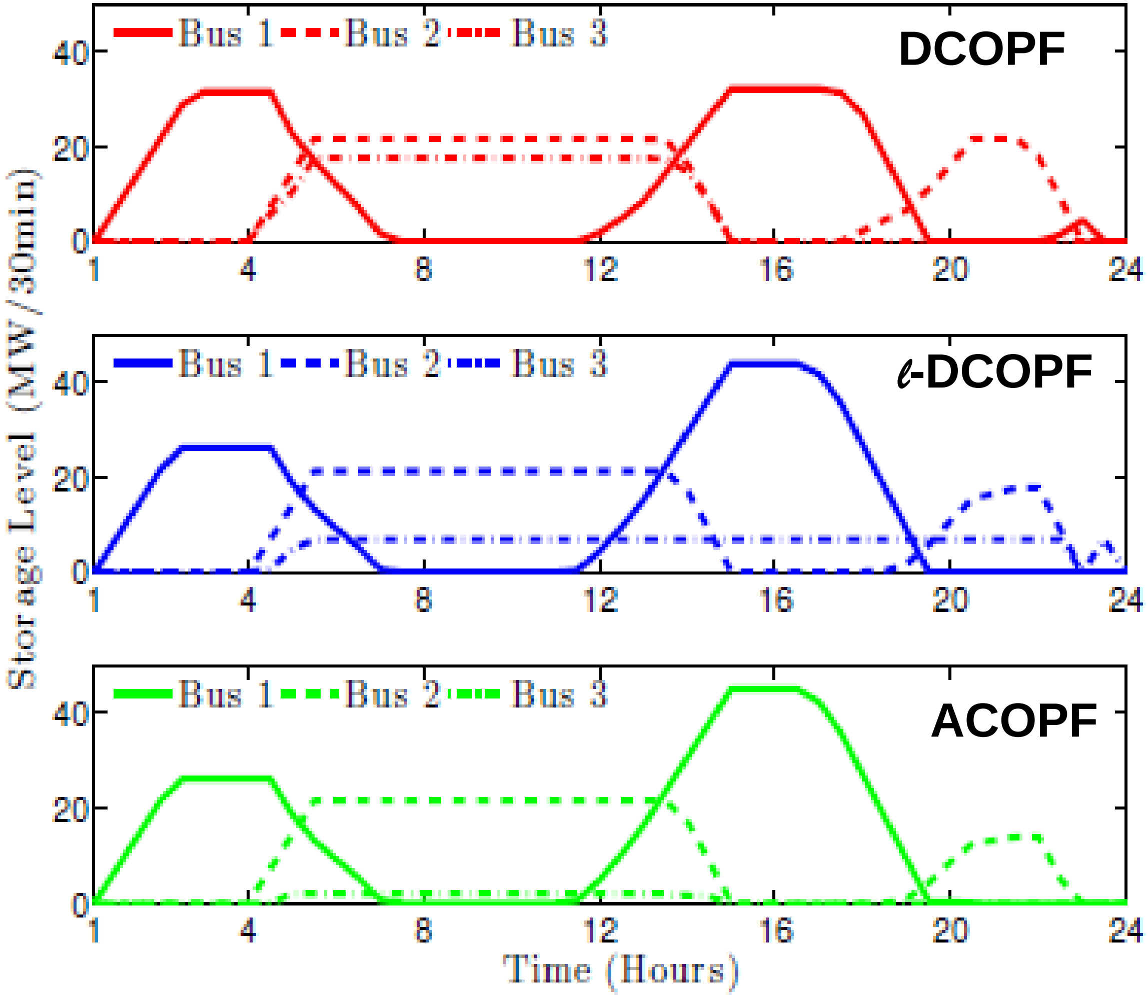
[Southern California Edison (July 2010)]



- Storage dynamics for the DCOPF approach deviate from the ACOPF considerably
- DCOPF over-estimates the energy arbitrage potential

[Castillo & Gayme 2017]

Per bus storage dispatch



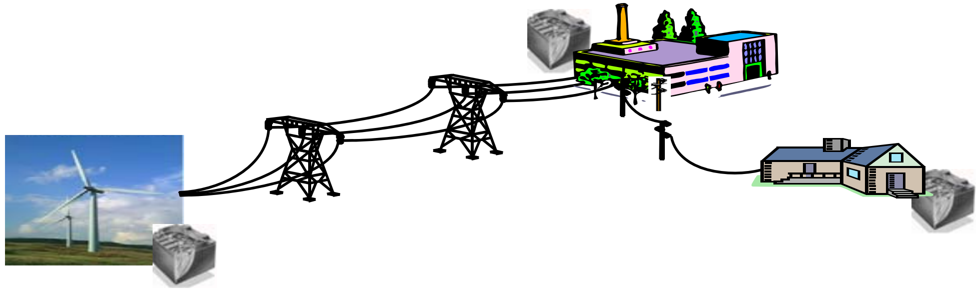
Summary

- Used ACOPF + S to understand drivers of optimal storage integration
  - Demonstrated a natural duality between system optimization and storage profit maximization in purely competitive market
  - Demonstrated trade-offs in using storage for traditional services plus VAr support
- Proposed a novel ℓ-DCOPF+S problem based on identified importance of network effects (LMPs)
  - Effective in determining the nodes where storage is most profitable (sizing of the storage can be over-estimated)
  - Improved computational tractability over ACOPF+S
  - More accurate than DCOPF+S
  - VAr support question cannot be studied directly

Case study results and implications

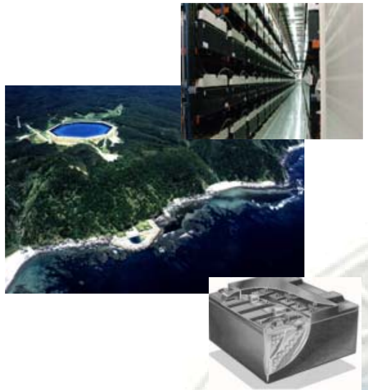
Network effects, in particular line losses are critical aspects of the storage allocation and dispatch optimization

- Storage placement results favor a few large facilities
- Results robust to charge and discharge efficiencies changes
- Storage placement does not change with constant versus time varying limits
  - Adding wind/solar later is unlikely to cause inefficiency
- Using storage for reactive power support changes the economics of energy storage and the placement strategies



Continuing work and related questions

- How does uncertainty affect the system [Sjödin et al. 2012]
- Different storage portfolios [Wogrin & Gayme 2015]
  - Dispatch problem
  - Investment problem
- Interactions with demand response [Wang et. al 2015]
- Economic trade-offs and connections to markets
  - Storage vs. fast-ramping back-ups or new transmission
- System reduction or other computational algorithms
  - Very preliminary idea [Shayesteh et. al 2018]



Thank you

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Now at Sandia National Labs!

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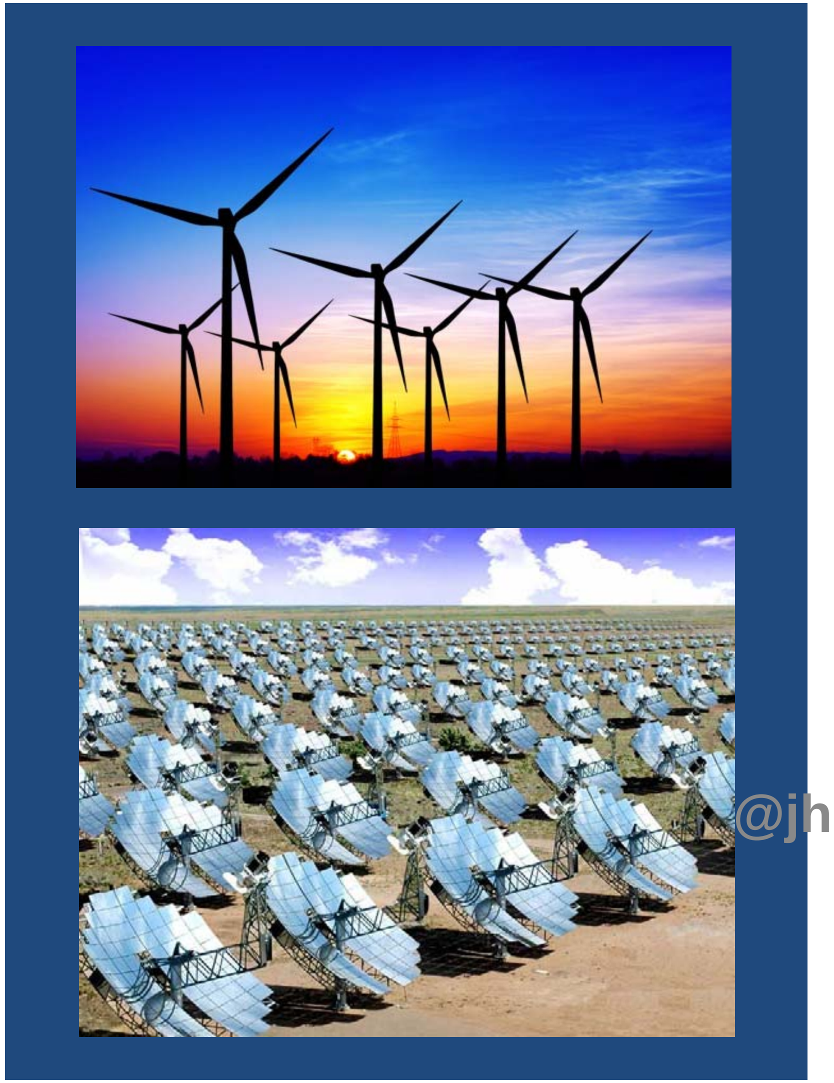

Thank You!

Questions?

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