Energy Storage Siting and Sizing Methodology to Unlock Transmission Transfer Capacity – A Case Study in the UK National Grid

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Introductions

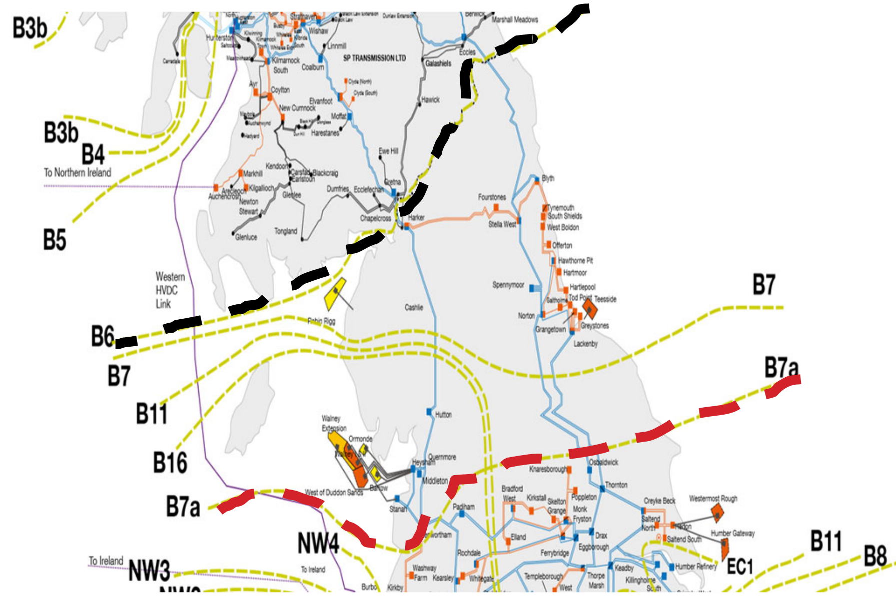
- **Dr. Hisham Othman**
  - *Vice President, Transmission & Regulatory*
  - Areas of expertise include power system dynamics and control, hybrid microgrids, grid integration of renewables and storage, economic analysis
  - PhD, Electrical Engineering, University of Illinois, Urbana
  - Over 30 years of technical and managerial experience in the electric power industry

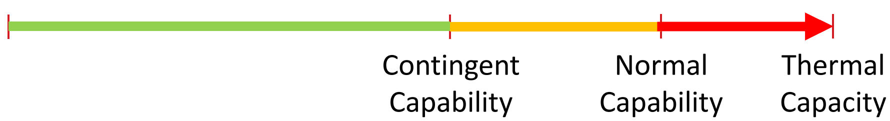
- **Abhishek Thurumalla** received an M.Sc. in Electrical Engineering from Arizona State University in 2016. He currently works as a principal engineer in the Transmission & Regulatory business area at Quanta Technology. He has 3 years of industry experience in transmission planning studies, EHV transmission line design, investigation of energy storage as a transmission asset, and system impact studies.

- **Dr. Xiaolin Ding** received a Ph.D. in Electrical Engineering from the Queen's University of Belfast, U.K., in 2006. She currently leads the innovation in power system and connection planning area at National Grid in the UK. She has over a decade of industry experience in network modeling, power system analysis, system planning, and power quality. Her research interests include the integration of renewables and energy storage, modeling, system stability, and WAMS-based protection and control.

UK National Grid

- **Challenge:**
  - UK has significant policy goals to de-carbonize via thermal generation retirements and large-scale deployment of renewables.
  - Scotland has substantial wind generation which is expected to grow.
  - Transmission capacity between Scotland and England is limited, causing wind curtailment in Scotland during periods of low load and high wind generation.
  - Boundary 400kV lines have sufficient thermal capacity, but not enough after accounting for contingencies.



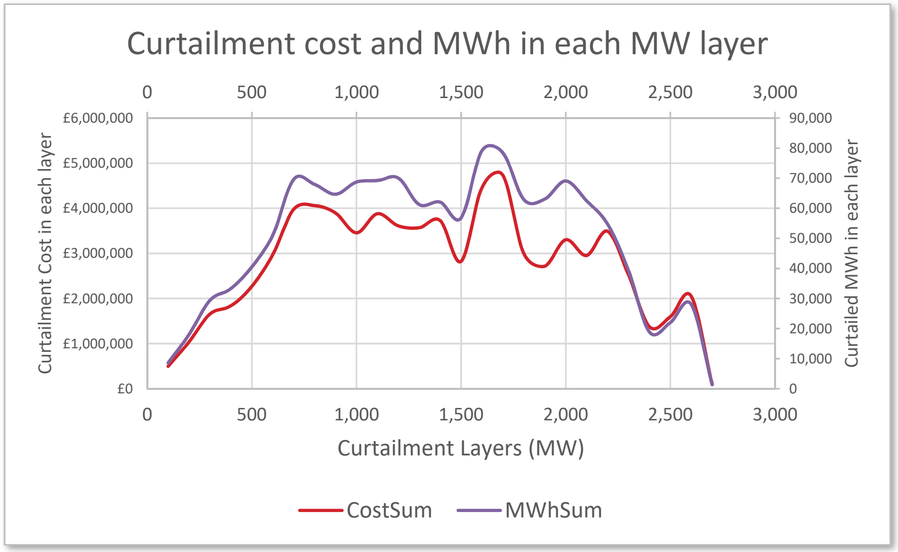


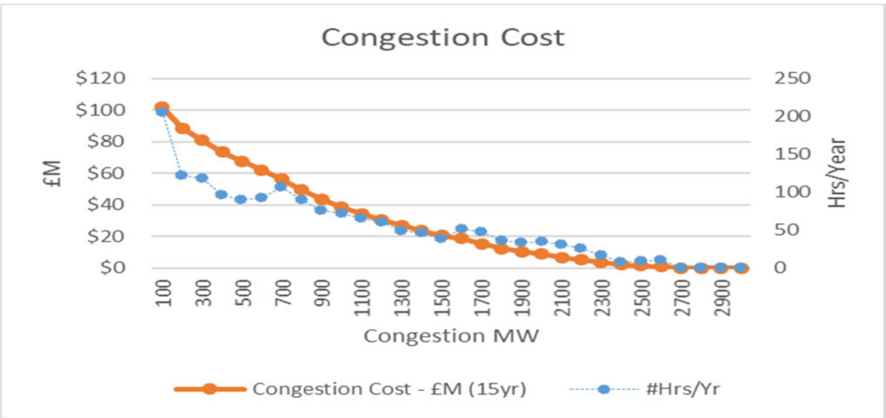
Boundary	Sum of Circuits Rating (MVA)	N-0 Limit (MW)	Contingent Limit (MW)	Desired Boundary Flow Limit (MW)
SP Transmission Ltd. to NGET (B6)	12,629	10,723	5,700	9,358
Upper North of England (B7a)	19,596	12,482	8,700	9,165

Economic Analysis of Wind Curtailment

(£M)	Curtailment Payments
2010	0.2
2011	34.1
2012	7.6
2013	49.7
2014	65.3
2015	96.8
2016	83.2
2017	108
2018	140.7

Other Congestion Direct and Indirect Costs:
- Out of Merit dispatch cost in England
- Carbon societal cost





- Up to 2800MW of wind is curtailed (paid not to produce). Increasing the B6 boundary limit to 8500 MW would mitigate curtailments.
- Curtailments initiated **3,278 half-hours** within 10 months in 2018/2019. Median curtailment is around 1600MW.
- Curtailed MWs most costly in the range of 700 – 2200 MW.
- Without congestion, additional 1350 GWh would have been transferred across the Boundary.
- Value of increasing the transfer limits has a diminishing return: first 100 MW increase avoids more curtailment cost than the second.

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Non-Wire Solution – Data and Analysis Requirements

- Reliability
- Market Efficiency
- Renewable Integration

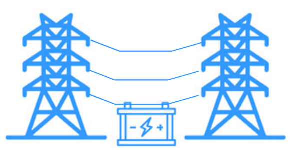
Thermal & Voltage Violations

Contingency List

Hourly Profiles (Load, VRE)

Uncertainty (load, Prices, Costs..)

Grid & NWA Analysis

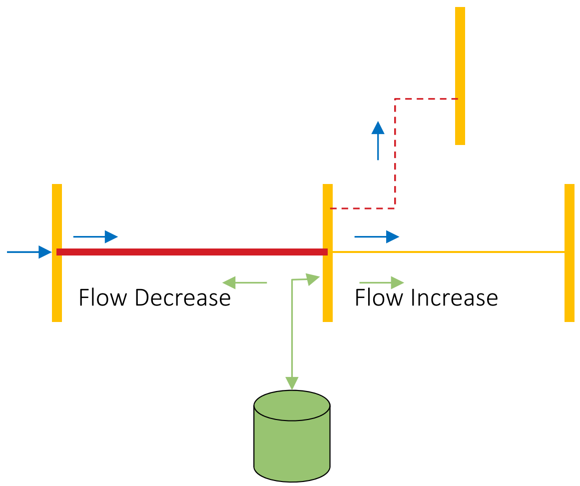


- Sites
- Sizes
- Costs
- Benefits
- Controls

Common analysis and design methodology of NWA solutions to Grid limitations stemming from multiple drivers

Non-Wire Solutions - Technical Approach

- Grid Congestion impedes transfers of renewable energy from resource-rich areas to load centers at a great cost to consumers.
- Grid is operated well below its thermal limits in order to assure its ability to handle a large list of potential contingencies.
- Energy storage has the ability to rapidly influence line flows and bus voltages in bulk transmission grids.
- Objective is to use energy storage to increase the transfer limits up to the normal system limits:
  - Operate the system at transfer flows above security limits.
  - When contingency occurs, storage will limit the flows to normal system limits, until system can be re-dispatched to alleviate the overloads.



Storage as Transmission Asset – Siting and Sizing Analysis

- **Siting Analysis**
  - **Rank each bus based on its ability to affect the flow in a group of congested interfaces post contingency.**
  - **Siting analysis** uses the power distribution factors (PDF) and line outage distribution factors (LODF) to identify optimal siting locations, given a list of monitored lines and a contingency list.

- **MW Sizing Analysis**
  - Size the energy storage systems to relieve overloads post contingency (N-1, N-1-1, ..) to allow the dispatcher to load the transmission grid, during normal operation, up to its N-0 limits, and then be ready to automatically offset any potential increase in power flows on overloaded lines that may result from contingency events.
  - Size optimization takes into consideration relative cost of storage at various sites using a linear program and allows a coordinated distributed storage deployment at multiple sites.
- **MWh Sizing Analysis**
  - Requires Time-Series security analysis

Storage Siting

- **Rank each bus based on its ability to affect the flow in a group of congested interfaces post contingency.**
- **Siting analysis** uses the distribution factors to identify optimal siting locations, given a list of monitored lines and a contingency list.

$$\text{Index} = \sum_k \mu_k \left(\sum_i \; h_{ki}.P_i\right) + \sum_k \mu_k.\; MAX_j \;\left(L_{kj}.F_j\right)$$

F_j is for the outaged line flow
L_{kj} is the line outage distribution factor
h_{kj} is the power transfer distribution factor
i is the injection generation and load nodes
k refers to the congested lines
j is the outage elements
μ_k is monitored line k shadow price

Bus	Sensitivity
COXSACK'	3.1728
'COXSACK'	3.1133
'GCE-tap'	3.2568
'GCE-tap'	3.2066
GCE'	3.1439
'WESTERLO'	2.6262
'N.BALT'	2.3649
'FREEHOLD'	1.8437

Developing a Heat Map of Effective Sites to Relieve a Set of Grid Congestions

Storage Sizing for Congestion Relief

- The objective of this **sizing analysis** is to size the energy storage systems for congestion relief to allow the dispatcher to load the transmission grid, during normal operation, up to its N-0 limits, and then be ready to offset any potential increase in power flows on congested lines that may result from N-1 contingency events.
- Assessment takes into consideration cost of storage using a linear program and allows distributed storage deployment at multiple sites:

$$\min\left(\max_j \sum_k \left(\mu_k \cdot \left(h_{ki}.\Delta P_i + L_{kj}. \sum_i h_{ji} \cdot P_i^{post}\right)\right) + \sum_i \propto_i \Delta P_i\right.$$

ΔP_i post-outage – pre-outage dispatch

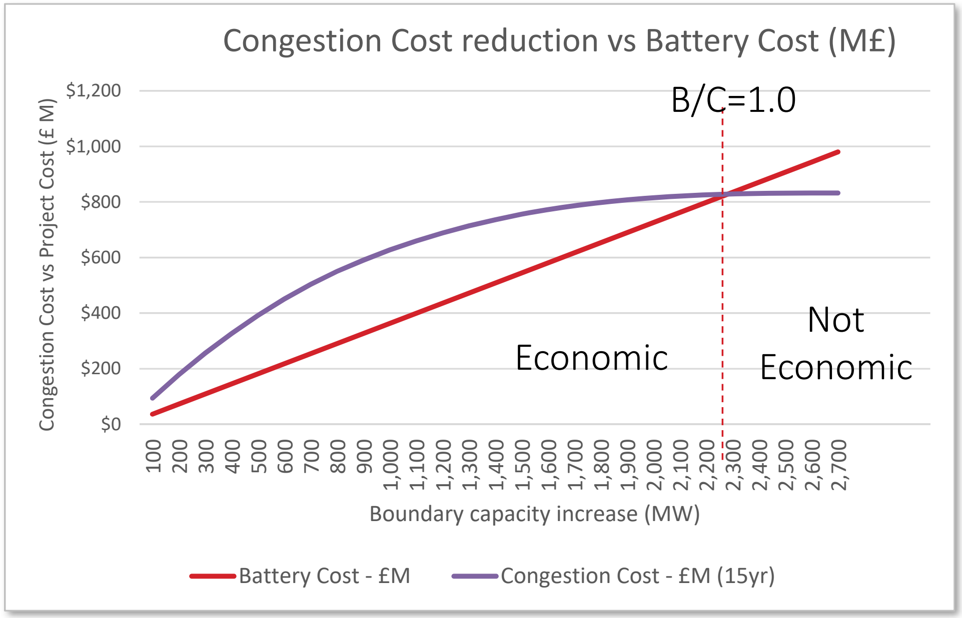
$\propto_i$ storage cost at node i

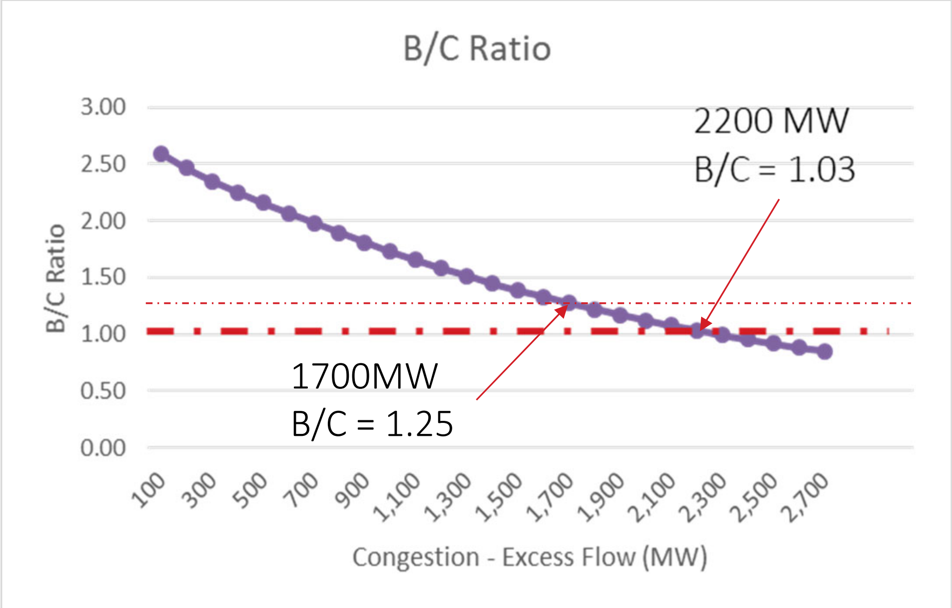
P_i^{post} post-storage injection at node at node i

Line Name	Line Flow Limit (MW)	(N-0) Loading %	(N-1) Loading %	Line Flow due to BESS MW	(N-1) After Storage%
Oasis - Termoflores I 1 110	115	13.5%	33.8%	5.06	29.4%
Oasis - Termoflores II 1 110	153	49.9%	54.9%	6.07	50.9%
Tebsa - Vte Julio 1 110	103	69.4%	110.2%	-10.46	100.0%
El Rio - Tebsa 1 110	105	89.5%	102.5%	2.66	100.0%
Oasis - Silencio 1 110	145	21.9%	25.5%	-3.44	23.1%
Tebsa 1 220/110	99	37.3%	49.5%	-5.13	44.4%
Flores 10 220/110	141	53.7%	75.5%	-5.32	71.8%

Right-Sizing Storage Systems to Cost Effectively Relieve Grid Congestion

Market Efficiency – Partial Mitigation





- Using a Benefit / Cost Ratio threshold of 1.03, the maximum increase in Boundary transfer limits that can be economically justifiable is 2200 MW.
- Increasing the B/C Ratio to 1.25, the maximum economically justifiable increase in Boundary transfer limit will be 1700 MW.

Conventional Solutions

Solution	Solution Components	Contingent Boundary Flow Limit (MW)	Total Cost £M
Conventional A	• A new 400kV line and substation. • Series Reactor. • Reactive support. • Re-conductor 400kV circuit.	9,276	337
Conventional B	• Two new 400kV lines. • Two new 275kV lines. • Two GSUs (400/275 kV) • Reactive Support. • Series Reactor.	9,276	1,022
Conventional C	• Two new 400kV lines. • Conversion of a 275kV line to 400kV. • Loop in a 400kV line.	9,276	943

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Hybrid Solutions

Hybrid Solution A:

I. Replace 2 GSUs (400/275kV)
II. Upgrade a limiting element on a 400kV line

Boundary Flow	9.3 GW	→	8.4 GW	→	7.4 GW	→	6.8 GW
Total Battery size	2480 MW		1550 MW		685 MW		125 MW
Total Cost (£M)	850		544		258		73

Hybrid Solution B.1:

I. Replace 2 GSUs (400/275kV)
II. Upgrade a limiting element on a 400kV line
III. Reconductor a 400kV line

Boundary Flow	9.3 GW	→	8.4 GW	→	7.4 GW
Total Battery size	2300 MW		1360 MW		505 MW
Total Cost (£M)	676		417		182

Hybrid Solution B.2:

I. Replace 2 GSUs (400/275kV)
II. Upgrade a limiting element on a 400kV line
III. Reconductor two 400kV lines

Boundary Flow	9.3 GW	→	8.4 GW	→	7.4 GW
Total Battery size	2050 MW		1250 MW		450 MW
Total Cost (£M)	632		412		191

Hybrid Solution C:

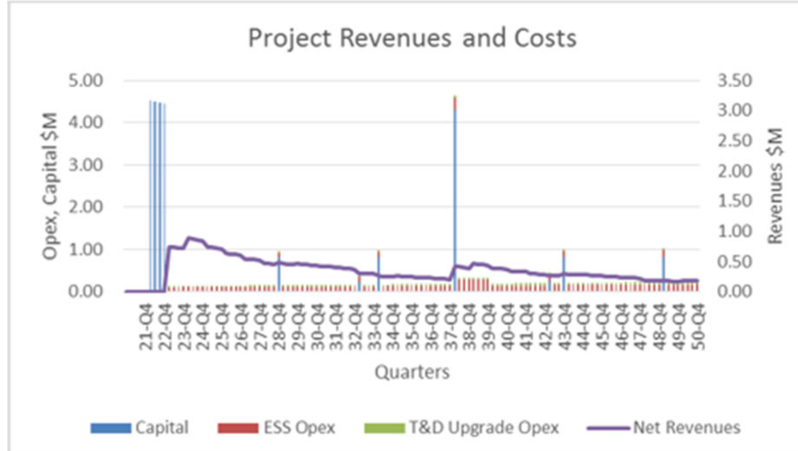
I. Replace 2 GSUs (400/275kV)
II. Two new 400kV lines.

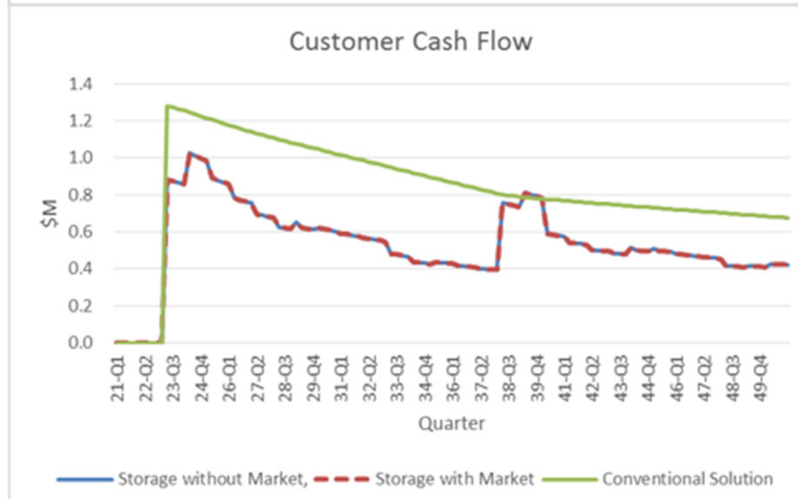
Boundary Flow	9.3 GW	→	8.4 GW	→	7.4 GW
Total Battery size	2550 MW		1620 MW		1050 MW
Total Cost (£M)	1,479		1,172		984

B6/B7a Transfer Limit	6.8 GW	7.4 GW	8.4 GW	9.3 GW
Incremental Boundary Increase (GW)	1.1	1.7	2.7	3.6
Battery Size (MW)	125	505	1250	2050
Hybrid Solution Cost (£M)	73	182	412	632
Ratio of Battery Size to Incremental Boundary Increase %	11%	30%	46%	57%

Comparative Financial Analysis - Methodology

- The economic evaluation of different hybrid solutions as compared to the conventional T&D solutions requires:
  - Lifetime modeling of the cost of each project from inception to retirement inclusive of project development activities and timeline, EPC, O&M, capacity management, replacement, and disassembly and recycling.
  - Modeling of relevant utility's capital structure including debt and equity ratios and costs, and tax rate.
  - Proper regulated asset base (RAB) accounting including treatment of depreciation.
  - Useful life estimates: The conventional T&D solutions have an assumed book life of 45 years, while the energy storage technology is assumed to have a useful life of 15 years for Li-Ion technology.





Financial Analysis - Conventional vs Hybrid Solutions

- Initial Capital Cost, Annual Operating Costs, Lifetime Project Costs, and Customer Cash Flows are shown for each of the considered solutions.
- Customer Cost Ratios for ESS to Conventional Solutions are cross-tabulated for all considered solutions.
- All currency in millions of pounds (£M)

	Conv. Solution A	Conv. Solution B	Conv. Solution C
Capital Cost (£M)	322	1,016	873
Annual OPEX (£M)	4.8	15.2	13.1
Lifetime Cost – PV (£M)	389.8	1,230	1,056.9
Customer Cash Flows -PV(£M)	426.3	1,345.1	1,155.8

Hybrid Solutions	**Total Initial Capital Cost (£M)**	**Annual OPEX (£M)**	**Lifetime Cost – PV (£M)**	**Customer Cash Flows – PV (£M)**	**Customer Cost Ratio (Storage Cost / Conv. Cost)**		
Hybrid A	1,048	32.5	1,836.6	2,136	501%	159%	185%
Hybrid B.1	988	30.4	1,723.1	2,003	470%	151%	173%
Hybrid B.2	913	27.6	1,575.1	1,828	429%	136%	158%
Hybrid C	1,681	42.4	2,617.7	2,994	702%	223%	259%
Partial Mitigation							
Boundary Capacity: 7.4 GW	273.6	7.16	435	499.5			48%
Boundary Capacity: 8.4 GW	605.6	17.72	1,025.6	1,187.7			103%

- Conventional Solution A is most economical, but difficult to realize.
- Hybrid solution can be very economical if the targeted increase in Boundary transfer capacity is limited to 1700MW. A break-even level is an increase of 2800MW.

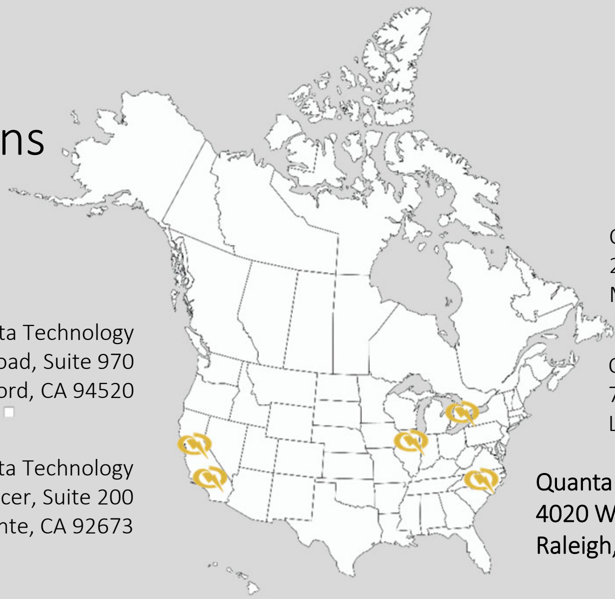
Summary and Conclusions

- Energy storage technology is technically feasible to increase the transfer limits of the transmission grid boundaries.
- Energy storage-based solutions are economically competitive at lower levels of capacity expansion and not as competitive at high levels of capacity expansion when compared to conventional solutions.
- Optimizing the level of transmission transfer capacity expansion is critical to the economic feasibility of energy storage solutions. This requires a careful analysis of historical and future projections of constraint costs and a proper benefit-cost analysis.
- The optimal siting and sizing of storage solutions is a fundamental requirement for this type of analysis.
- Energy storage solutions become competitive, even at high levels of boundary capacity expansion, if the conventional solutions take a long time to permit or if the energy storage cost reduction roadmap accelerates.

Questions and Answers

Thank you!

Office Locations



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