vermont electric power company

VELCO

Sheffield-Highgate Export Interface

SHEI

VSPC Quarterly Meeting
October 18, 2017

Northern Vermont Export Study Update

- VELCO is providing information to enable evaluation of potential solutions
  - Incremental export limit increases from system upgrades involving reactive support, transmission, subtransmission, and battery storage
    - Analyzed individual solutions and combinations of solutions
  - Can also provide initial construction cost estimates of transmission, synchronous condenser and battery options
- Distribution utilities (DUs) purview
  - Estimate other options
  - Evaluate options with respect to their potential for increasing energy sales
  - Lead selection process for preferred options

Chronology

- July 12, 2017 — SHEI study kickoff and information sharing
  https://www.vermontspc.com/grid-planning/shei-info
  https://www.vermontspc.com/library/document/download/5810/20170712_SHEI_Preso_MtgVersion.pdf
- September 1, 2017 — study update
  https://www.vermontspc.com/library/document/download/5894/SHEI%20Study%20SeptemberUpdate.pdf
- September 11, 2017 — study update makeup session
  https://www.vermontspc.com/library/document/download/5894/SHEI%20Study%20SeptemberUpdate.pdf

System conditions tested

- Vermont load at 700 MW (about 55 MW inside SHEI)
- Summer long term emergency (LTE) ratings
- SHEI Wind plants at full output (105 MW)
- Newport block load served from Canada
- Highgate converter at 227 MW across the US/Canada border
- All-lines-in condition (N-1 testing)
- Five representative outages (N-1-1 testing)
  - Essex STATCOM
  - Sand Bar-Georgia K19 115 kV line
  - St Johnsbury-Lyndonville K28 115 kV line
  - Stowe 115/34.5 kV transformer
  - Marshfield-Plainfield 3317 34.5 kV line

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Power flow study approach (two types of export limits)

- Determine voltage export limit (at 95% of nominal voltage, or voltage collapse)
  - Adjust generation and Highgate imports until voltage limit is reached
    - Trip 34.5 kV lines when they are overloaded
    - Avoid tripping 34.5 kV lines when such tripping would cause a voltage collapse
      - Voltages can be above acceptable levels in these cases
  - Reduce SHEI load if voltage limit is not reached with maximum generation
    - This happens for the most robust options

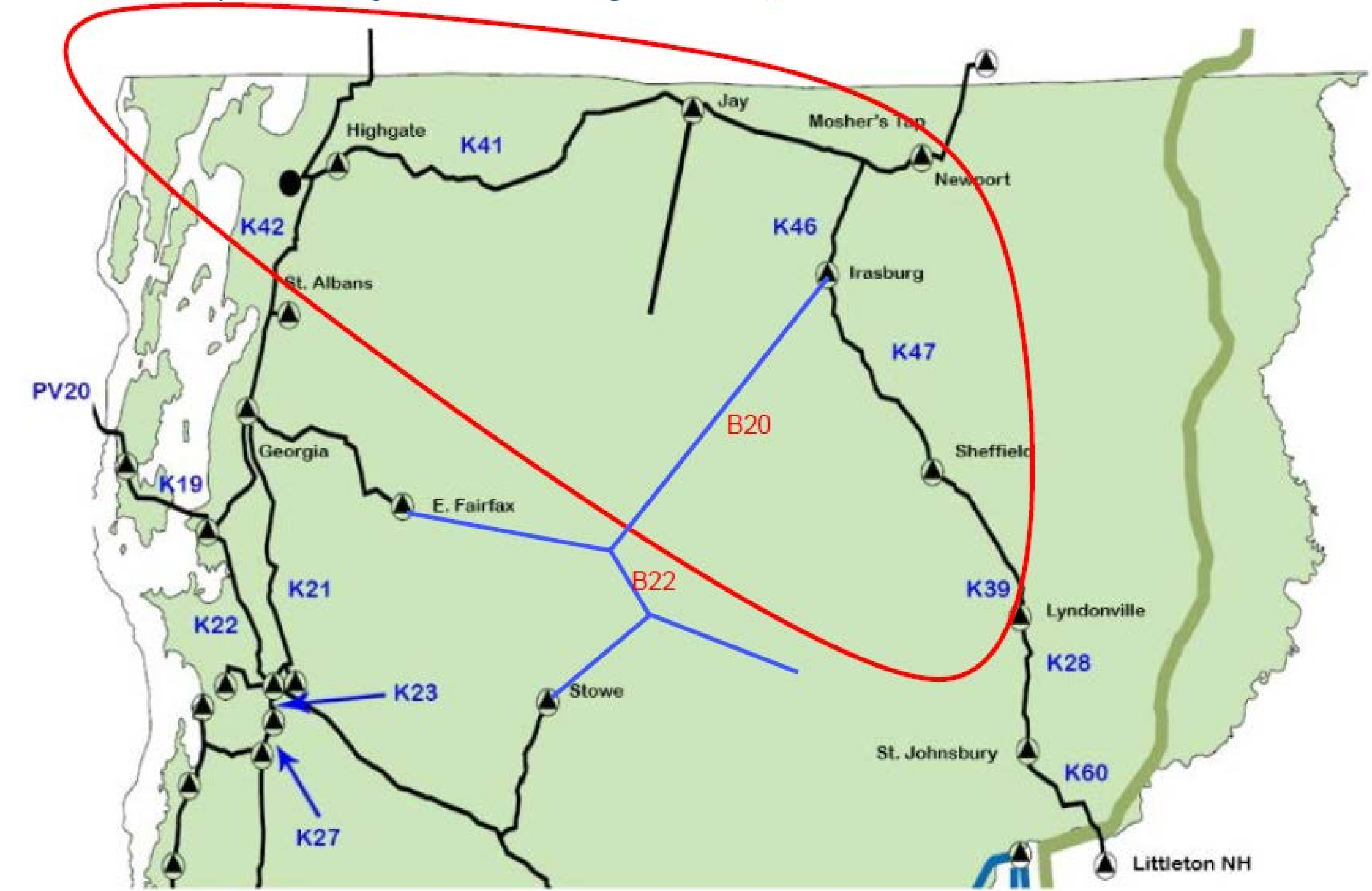
- Determine thermal export limit for all-lines-in case and Essex STATCOM-out case based on 100% summer emergency ratings
  - Ignore 115 kV line overloads south of Georgia and Sand Bar
    - Assuming that they can be addressed by reducing PV20 flows from New York

Notes

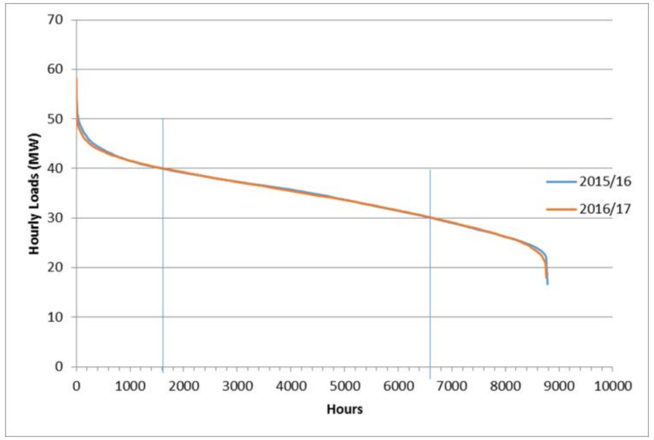
- MW export limit results should only be used to calculate incremental benefit (within +/- 5 MW) of each case/scenario
  - ISO-NE is responsible for determining system limits
  - ISO-NE cases may model different system assumptions
    - Essex STATCOM, capacitor bank dispatch, load distribution, tie flows
  - Case 0 results are the benchmarks within each column of results
- Utilized the same ISO-NE interface definition
  - Did not postulate how system operation (SHEI definition) or market implications would change following an upgrade
- Voltage limits are based on voltage collapse or low voltage at Highgate or St Albans 115 kV
- Thermal limits are based on overloads on K42, B20 or B22
  - B20 overloads when not upgraded
  - B22 overloads when the B20 line is upgraded

The Sheffield-Highgate Export Interface (SHEI)

ISO-NE determines the SHEI limits at or below which the system can withstand an anticipated system outage



- Average load is 35 MW
  - Between 20 MW and 60 MW



- Analysis of total generation production data is less useful
  - Affected by system limits, operating actions, internal plant constraints, and markets
- ISO curtailments more likely during spring and during transmission outages
  - Also less likely during summer

Initial study scope

		Cases																		
Options	**Description**	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	Reconductor the B20 34.5 kV line and upgrade the Lowell 46/34.5 kV transformer		X	X	X	X	X	X	X	X	X	X	X	X	X					
2	Enable voltage control at Sheffield			X			X	X		X	X	X	X	X	X	X	X	X	X	X
3	Recognize the Jay synchronous condenser 1.15 service factor				X		X		X	X	X	X	X	X	X	X	X	X	X	X
4	Enable voltage control at Sheldon Springs					X		X	X	X	X	X	X	X	X	X	X	X	X	X
5	Install a 15 MVAr synchronous condenser at Highgate 115 kV										X								X	
6	Reconductor K42 Highgate-St Albans 115 kV line											X								X
7	Install a 2nd 115 kV line alongside K39												X							
8	Install a 16 MW/12 MVAr battery energy storage system (BESS) at Highgate 115 kV													X						
9	Reconductor K41 Highgate-Jay 115 kV line														X					
10	Install a new Irasburg to Stowe 115 kV line															X				
11	Install a new Irasburg to East Fairfax 115 kV line																X			

Additional cases tested

		Cases																										
Opt #	**Upgrade elements**	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
1	B20 upgrade (line and Lowell transformer)				X	X	X			X	X				X				X		X	X				X		X
2	Enable the Sheffield AVR	X		X		X	X			X		X							X		X	X	X		X			
3	Recognize Jay synch cond 1.15 service factor									X									X			X						
4	Enable the Sheldon Springs AVR		X	X		X	X			X			X						X		X	X	X		X			
5	Install a 15MVAr synch cond at Hgate 115 kV													X	X					X							X	
6	Reconductor K42 Hgate-St Albans 115 kV line										X	X	X	X	X	X	X	X				X			X			
7	Install a 2nd K39 Sheffld-Lyndonvil 115 kV line																											
8	15 MVA Storage at Highgate 115 kV							X								X									X			
9	Reconductor K41 Highgate-Jay 115 kV line																											
10	Install a new Irasburg to Stowe 115 kV line																	X										
11	Install a new Irasburg to E Fairfax 115 kV line																											
12	Close the normally open Lowell C53 switch				X	X	X																X		X			X
13	Close Ritchford 14W & upgrade RF-HG46kV						X																X		X			
14	15 MVA battery storage at Sheffield 115 kV								X	X							X											
15	Install a 2nd 115 kV line alongside line K42																		X	X			X	X				
16	Upgrade 1.7 miles of B22 line to 39 MVA																				X	X				X		X
17	Open B20 line at Johnson																						X		X			

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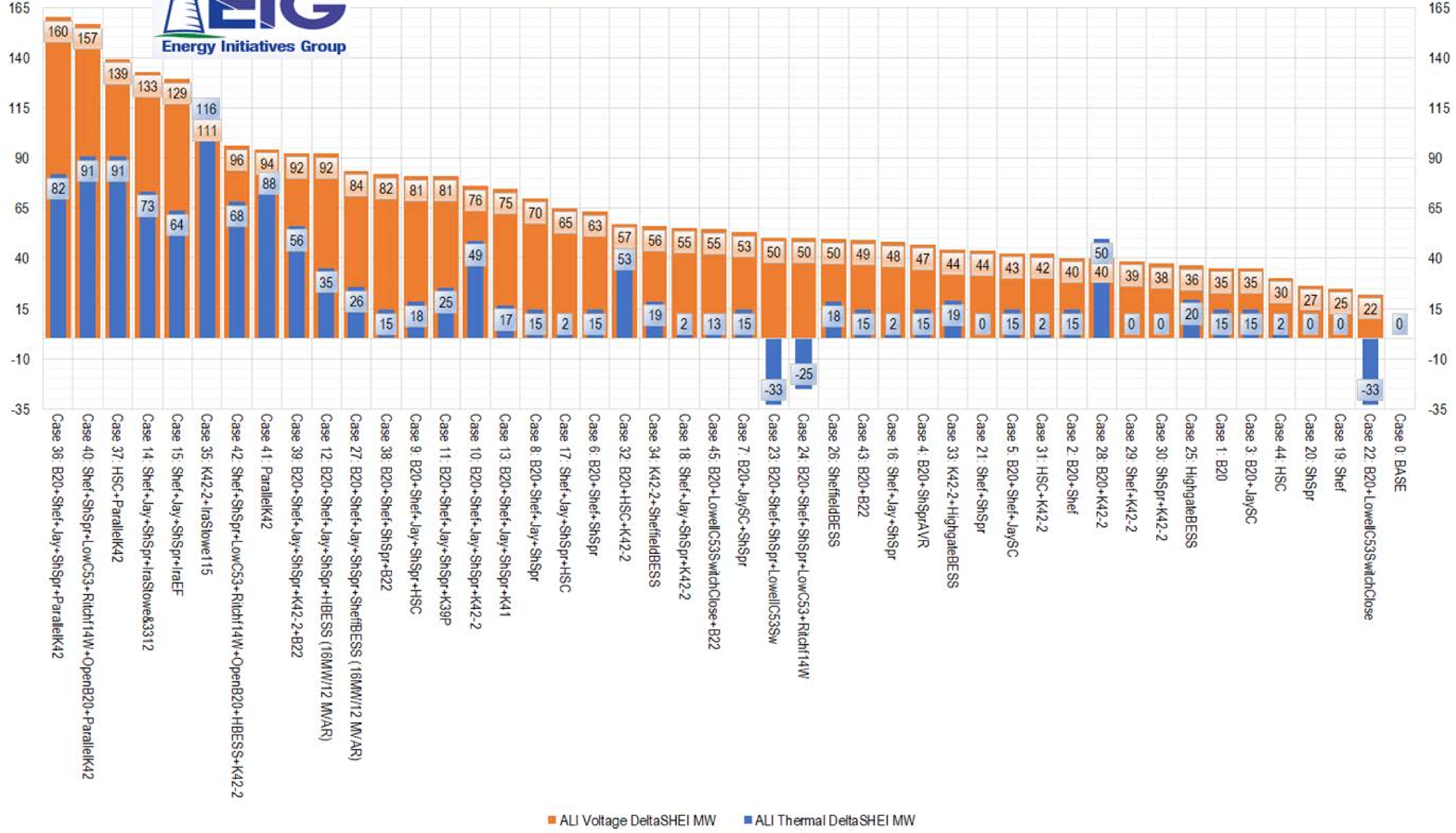
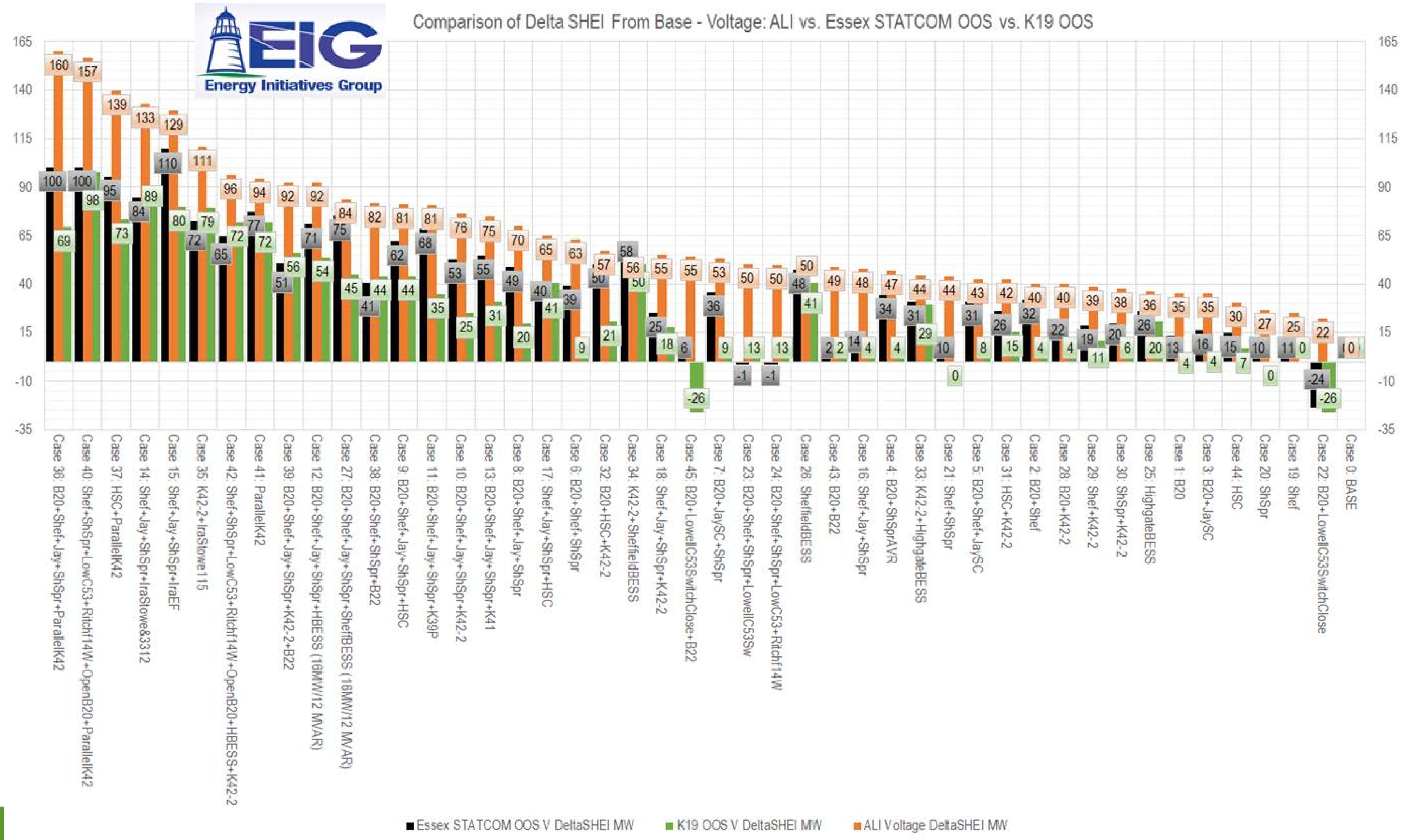
Comparison of Delta (Incremental) SHEI From Base - All Lines In: Voltage vs. Thermal




Comparison of Delta SHEI From Base - Voltage: ALI vs. Essex STATCOM OOS vs. K19 OOS
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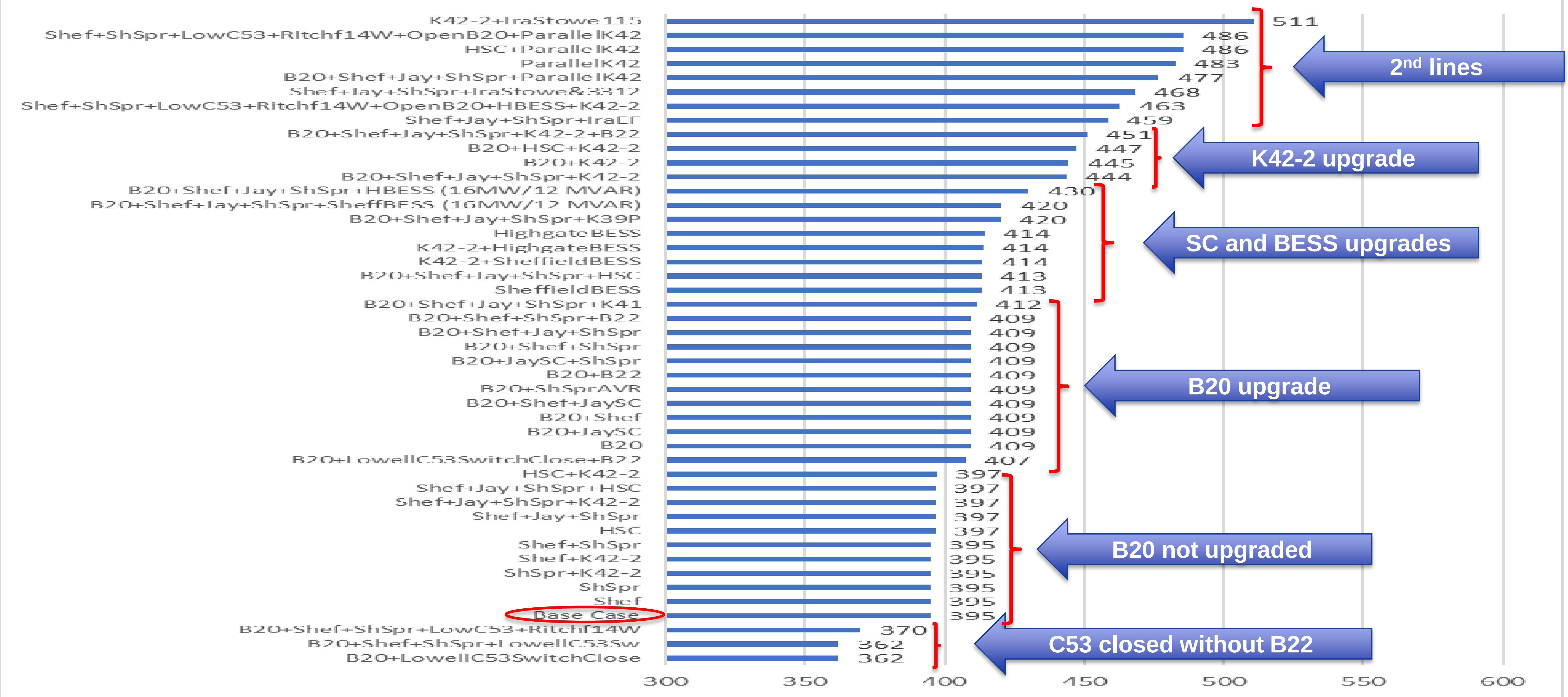
Case 36: B20+Shef+Jay+ShSpr+ParallelK42
Case 40: Shef+ShSpr+LowC53+Ritchf14W+OpenB20+ParallelK42
Case 37: HSC+ParallelK42
Case 14: Shef+Jay+ShSpr+IraStowe&3312
Case 15: Shef+Jay+ShSpr+IraEF
Case 35: K42-2+IraStowe115
Case 42: Shef+ShSpr+LowC53+Ritchf14W+OpenB20+HBESS+K42-2
Case 41: ParallelK42
Case 39: B20+Shef+Jay+ShSpr+K42-2+B22
Case 12: B20+Shef+Jay+ShSpr+HBESS (16MW/12 MVAR)
Case 27: B20+Shef+Jay+ShSpr+ShefBESS (16MW/12 MVAR)
Case 38: B20+Shef+ShSpr+B22
Case 9: B20+Shef+Jay+ShSpr+HSC
Case 11: B20+Shef+Jay+ShSpr+K39P
Case 10: B20+Shef+Jay+ShSpr+K42-2
Case 13: B20+Shef+Jay+ShSpr+K41
Case 8: B20+Shef+Jay+ShSpr
Case 17: Shef+Jay+ShSpr+HSC
Case 6: B20+Shef+ShSpr
Case 32: B20+HSC+K42-2
Case 34: K42-2+SheffieldBESS
Case 18: Shef+Jay+ShSpr+K42-2
Case 45: B20+LowellC53SwitchClose+B22
Case 7: B20+JaySC+ShSpr
Case 23: B20+Shef+ShSpr+LowellC53Sw
Case 24: B20+Shef+ShSpr+LowC53+Ritchf14W
Case 26: SheffieldBESS
Case 43: B20+B22
Case 16: Shef+Jay+ShSpr
Case 4: B20+ShSprAVR
Case 33: K42-2+HighgateBESS
Case 21: Shef+ShSpr
Case 5: B20+Shef+JaySC
Case 31: HSC+K42-2
Case 2: B20+Shef
Case 28: B20+K42-2
Case 29: Shef+K42-2
Case 30: ShSpr+K42-2
Case 25: HighgateBESS
Case 1: B20
Case 3: B20+JaySC
Case 44: HSC
Case 20: ShSpr
Case 19: Shef
Case 22: B20+LowellC53SwitchClose
Case 0: BASE
Essex STATCOM OOS V DeltaSHEI MW
K19 OOS V DeltaSHEI MW
ALI Voltage DeltaSHEI MW

Study Results – Thermal SHEI_TH in MW



Study Results – Voltage SHEI_V in MW

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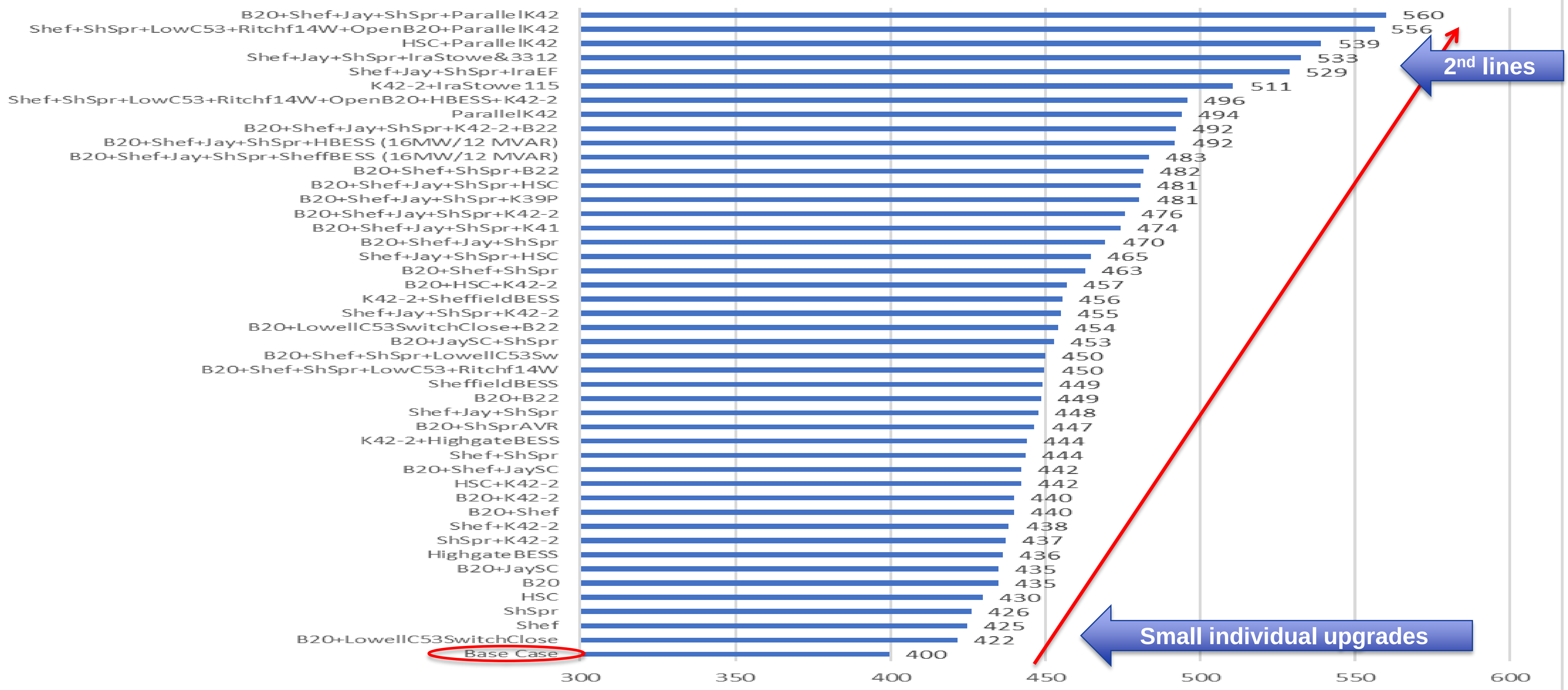
Navigating in a Changing Energy Industry



Highlights

- Multiple options can increase voltage limit
  - Utilizing capability of existing resources (Sheldon Springs AVR, Sheffield AVR) worth pursuing
- Highgate synchronous condenser (SC) provides 30 MW of incremental voltage benefit, but minimal thermal benefit
  - Combining Highgate SC with thermal upgrades can achieve reasonably high thermal and voltage improvements
  - Highgate battery performs better than SC because it acts like an SC with MW load increase
- Options that add a new 115 kV line are longer term options

More highlights

- B20 upgrade provides 35 MW of incremental voltage benefit and 15 MW of thermal benefit
  - B22 line will be limiting if B20 line is upgraded — B22 upgrade provides an additional 14 MW of voltage benefit, but no thermal benefit
  - Closing Lowell C53 switch has a negative impact if B22 line is not upgraded — in general, forcing more power through subtransmission system can be a concern in terms of overall system performance
- Thermal benefit of B20 and B22 is limited by K42-2 line section
  - Upgrading K42-2 with B20 and B22 raises thermal limit by over 50 MW
- K42-2 upgrade provides minimal voltage benefit unless redesigned to achieve lower reactance

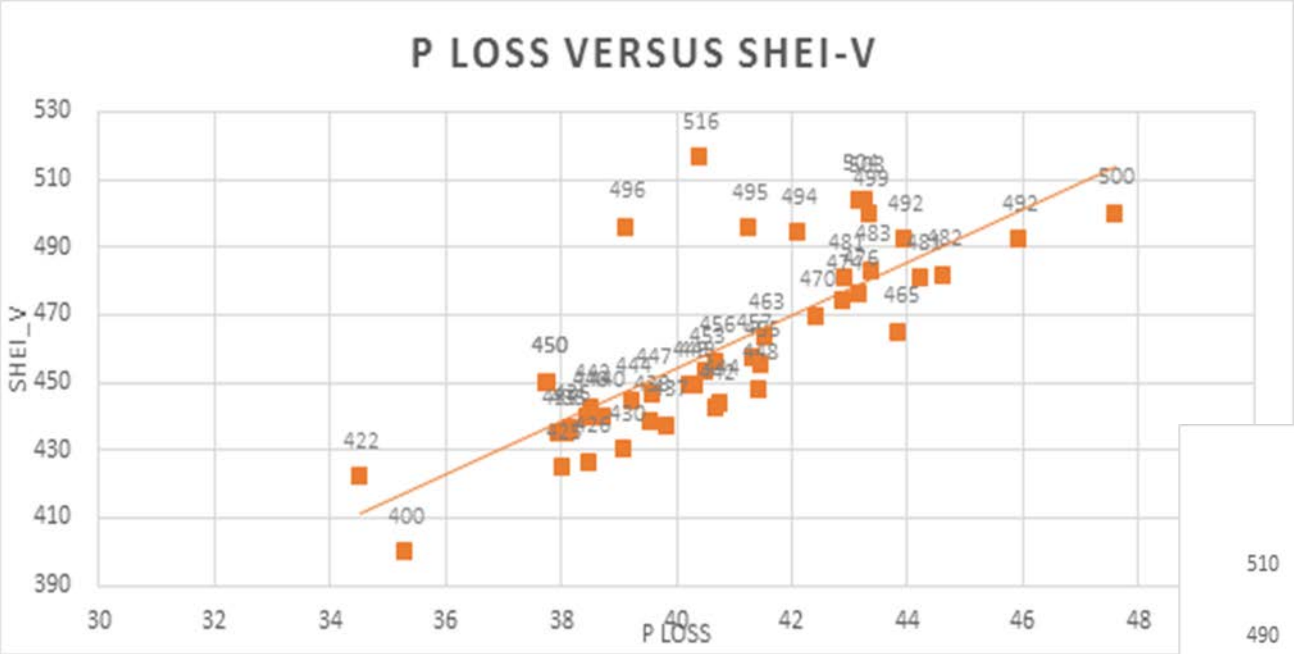
VELCO K42 asset condition evaluation

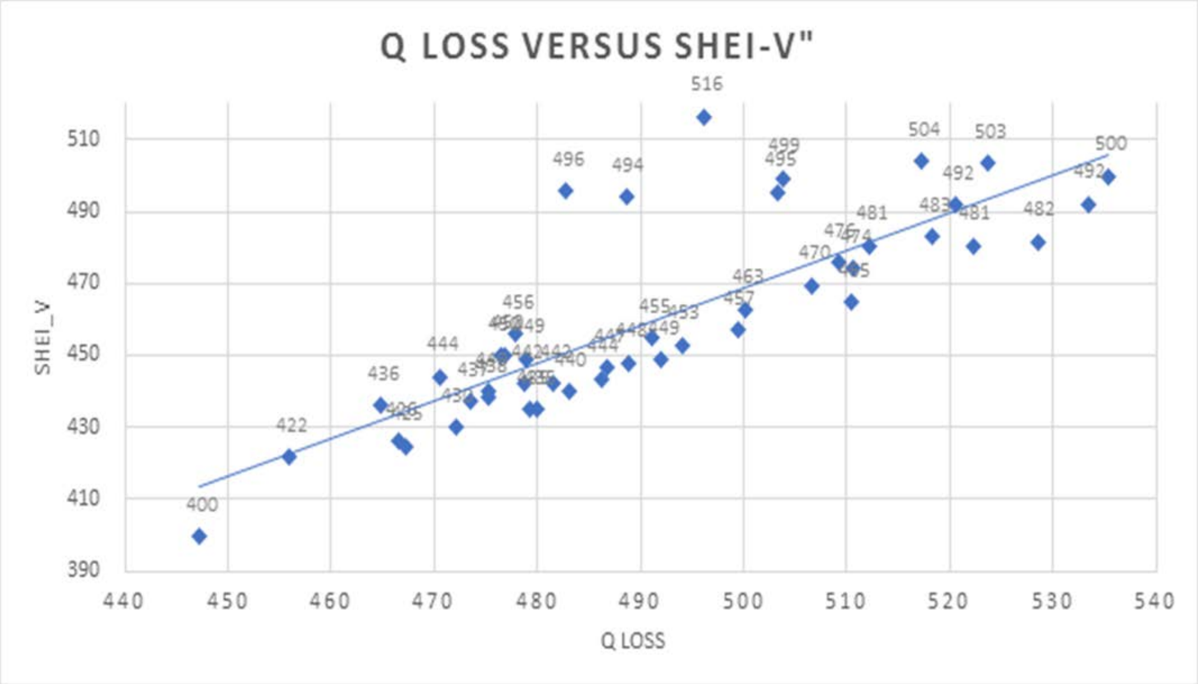
- K42 line was assessed in September
  - 16.75 miles from Highgate to Georgia, and 9.9 miles for limiting section
  - 50% of poles need to be replaced
  - Almost all poles will need to be replaced between 3 years and 15 years from now
- VELCO will determine whether it makes sense to rebuild entire line sooner rather than rebuilding it piecemeal
  - Construction efficiency leading to reduced cost for overall project
  - Line cannot be out of service for long periods of time
  - Opportunity to reduce losses (K42 is the most lossy line in Vermont)
  - Opportunity to further address SHEI concerns and facilitate reaching VT's long term renewable energy goals

What next after this technical analysis?

- Possible approaches to estimate benefit of options or combination of options that were not tested
  - Calculate incremental benefits of individual options as they are added to various combinations, and average these delta benefits
  - Perform regression analyses
    - To extract expected benefit of each option or combination of options
    - To highlight which options may be more significant than others
    - To construct a predictive model for estimating MW value of untested option combinations
- Considerations beyond incremental MW export
  - Other system benefits, real and reactive losses, robustness, operational flexibility, feasibility, asset condition, timing, aesthetic and environmental impacts, cost, market considerations, etc.

Loss comparison of cases





Regression Results SHEI_V

- Format of regression

  Y=b + a1*X1 + a2*X2 + a3*X3 + …….
  - Dependent variable "Y" represents SHEI_V
  - Independent variables "X" are modeled as a logical (1 or 0) for each upgrade option
  - Coefficients (a1, a2, a3, etc.) are in MW
- P-value is a measure of significance
  - Less than 0.05 is significant (highlighted green)
  - Greater than 0.05 is not significant (highlighted yellow or red)
- Intercept ("b") is 409.8 MW
- From the table we can calculate the predicted effect of building a line parallel to K42 from Highgate to St Albans tap (Coefficient is 96.1 MW)

  SHEI_V = 409.8+ (96.1* 1) = 505.9 MW
- For Case 41, actual load flow results calculated 494 MW (2.4% less)

	Coefficients	*P-value*
Intercept	409.801	0.000
B20	19.041	0.000
Sheffield	13.513	0.000
Jay SC	3.952	0.098
Sheldon	17.220	0.000
Highgate SC	21.853	0.000
K42-2	10.009	0.000
2^{nd} K39	16.973	0.003
Highgate	26.218	0.000
K41	10.673	0.055
Irasburg-	89.503	0.000
Irasburg-	84.415	0.000
Lowell C53	(5.996)	0.061
Sheffield	22.646	0.000
Parallel K42	96.109	0.000
B22	22.950	0.000
Open B20	25.345	0.000

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Regression Results
Predicted Versus Actual

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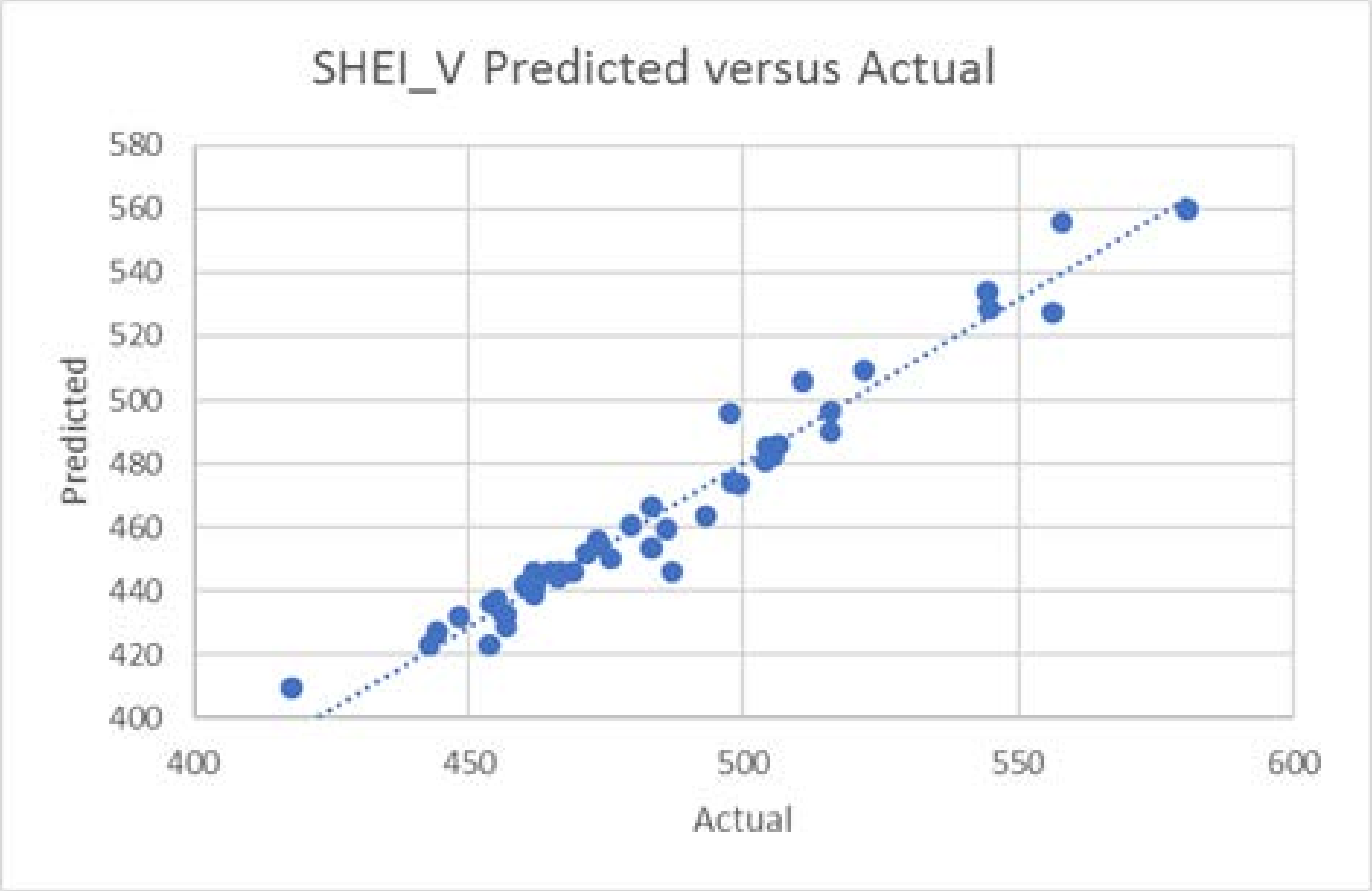
Navigating in a Changing Energy Industry



Characteristics of selected solution

- Coincident with timing and duration of curtailments
  - Every season, mostly spring and except perhaps in summer
  - Any time of day
- Able to respond to variability of wind power
- Dependable
- Implemented in a timely fashion
- Cost effective (expenditures lower than projected revenue gains)
  - Ranking based on payback, $/MW, cost-benefit, …
  - Analysis can include system loss benefits, asset condition improvements, other system benefits, and qualitative assessments

Proposed next steps

- VELCO participation
  - Transmission option cost estimates (lines, battery, SC)
  - Further assistance as requested by DUs
  - Evaluate T&D study cost options
- DUs conduct further analysis and develop process for solution selection
  - Estimate cost of subtransmission upgrades and other options
  - Non-wires alternatives
  - Economic evaluation of solutions
  - Solution selection
  - Regulatory process (with VELCO testimony on transmission system impacts as needed)
- Recommend estimating all options using common assumptions
  - VELCO tools are available

Results tables

APPENDIX

Thermal MW export limit results (based on overloads)

		All lines in	Essex STATCOM out
	Benchmark case 0 – No upgrades --→	395 MW	379 MW
CASES	**Upgrades**	**Incremental over benchmark**	
1	B20	15 MW	14 MW
2	B20+Sheffield AVR	15	23
3	B20+Jay Synchronous Condenser	15	16
4	B20+Sheldon Springs AVR	15	26
5	B20+Sheffield AVR+Jay Synchronous Condenser	15	23
6	B20+Sheffield AVR+Sheldon Springs AVR	15	26
7	B20+Jay Synchronous Condenser+Sheldon Springs AVR	15	26
8	B20+Sheffield AVR+Jay SC+Sheldon Springs AVR	15	28
9	B20+Sheffield+Jay SC+SheldonSprings+Highgate Sync Cond	18	31
10	B20+SheffieldAVR+Jay SC+Sheldon SpringsAVR+K42-2	49	51
11	B20+Sheffield AVR+JaySC +Sheldon Springs AVR+ 2nd K39	25	37
12	B20+Shef+Jay+ShSpr+HighgateBattery (16MW/12 MVAR)	35	45
13	B20+Sheffield AVR+Jay SC+SheldonSprings AVR+K41	17	28
14	Shef+Jay+Sheldon Springs+ New Irasburg Stowe&3312	73	89
15	Shef+Jay+Sheldon Springs+ New Irasburg E Fairfax	64	75
16	Sheffield AVR+Jay SC+Sheldon Springs AVR	2	15
17	Sheffld+Jay SC+Sheldon Springs+Highgate Sync Condenser	2	15
18	Sheffield AVR+Jay SC+Sheldon Springs AVR+K42-2	2	15

Voltage MW export limit results (based on low voltage)

		All lines in	Essex STAT out	K19 out	K28 out	Stowe transfrm out	3317 (MP) out
	Benchmark case 0 – No upgrades -→	400 MW	379 MW	367 MW	253 MW	399 MW	410 MW
CASES	**Upgrades**	**Incremental over benchmark**					
1	B20	35 MW	13 MW	4 MW	7 MW	41 MW	40 MW
2	B20+Sheffield AVR	40	32	4	33	49	48
3	B20+JaySC	35	16	4	22	41	43
4	B20+Sheldon Springs AVR	47	34	4	29	49	46
5	B20+Sheffield+JaySC	43	31	8	33	49	48
6	B20+Sheffield+Sheldon Springs	63	39	9	33	51	48
7	B20+JaySC+Sheldon Springs	53	36	9	29	47	48
8	B20+Sheffield+Jay+Sheldon Springs	70	49	20	33	53	50
9	B20+Sheffield+Jay+SheldonSprings+Highgate SC	81	62	44	33	73	70
10	B20+Sheffield+Jay+Sheldon Springs+K42-2	76	53	25	33	65	64
11	B20+Sheffield+Jay+SheldonS prings+K39P	81	68	35	33	68	64
12	B20+Shef+Jay+ShSpr+HgateBESS (16MW/12 MVAR)	92	71	54	63	77	75
13	B20+Sheffield+Jay+SheldonSprings+K41	75	55	31	33	58	62
14	Shef+Jay+Sheldon Springs+Irasburg Stowe&3312	133	84	89	206	102	94
15	Shef+Jay+Sheldon Springs+Irasburg E Fairfax	129	110	80	206	100	90
16	Sheffield+Jay+Sheldon Springs	48	14	4	23	39	32
17	Sheffield+Jay+Sheldon Springs+Highgate SC	65	40	41	23	57	56
18	Sheffield+Jay+Sheldon Springs+K42-2	55	25	18	23	49	44

MW export limit results for the additional cases

		All lines in Thermal	All lines in Voltage	Essex STATCOM out Voltage	K19 out Voltage
	Benchmark case 0 – No upgrades --→	400 MW	395 MW	379 MW	367 MW
CASES	**Upgrades**	**Incremental over benchmark**			
19	Sheffield AVR	0 MW	25 MW	11 MW	0 MW
20	Sheldon Springs AVR	0	27	10	0
21	Sheffield AVR + Sheldon Springs AVR	0	44	10	0
22	B20+LowellC53SwitchClose	-33	22	-24	-26
23	B20+Sheffield+Sheldon Springs+LowellC53Switch	-33	50	-1	13
24	B20+Sheffield+Shelson Springs+LowellC53+Ritchford14W	-25	50	-1	13
25	Highgate BESS (16MW/12 MVAR)	20	36	26	20
26	Sheffield BESS (16MW/12 MVAR)	18	50	48	41
27	B20+Shef+Jay+ShSpr+Sheffield BESS (16MW/12 MVAR)	26	84	75	45
28	B20+K42-2	50	40	22	4
29	Sheffield AVR+K42-2	0	39	19	11
30	Sheldon Springs AVR+K42-2	0	38	20	6
31	Highgate Synchronous Condenser+K42-2	2	42	26	15
32	B20+Highgate Synchronous Condenser+K42-2	53	57	50	21
33	K42-2+Highgate BESS (16MW/12 MVAR)	19	44	31	29
34	K42-2+Sheffield BESS (16MW/12 MVAR)	19	56	58	50
35	K42-2+Irasburg to Stowe 115 line	116	111	72	79

MW export limit results for the additional cases

		All lines in Thermal	All lines in Voltage	Essex STATCOM out Voltage	K19 out Voltage
	Benchmark case 0 – No upgrades -->	400 MW	395 MW	379 MW	367 MW
CASES	**Upgrades**	**Incremental over benchmark**			
36	B20+Sheffield AVR+Jay SC+Sheldon Spr AVR+ParallelK42	82 MW	160 MW	100 MW	69 MW
37	Highgate Synchronous Condenser+Parallel K42 line	91	139	95	73
38	B20+Sheffield AVR+Sheldon Springs AVR+B22	15	82	41	44
39	B20+Sheffield AVR+Jay SC+Sheldon Spr AVR+K42-2+B22	56	92	51	56
40	Shef+ShSpr+LowC53+Ritchf14W+OpenB20+ParallelK42 line	91	157	100	98
41	Parallel K42 line	88	94	77	72
42	Shef+ShSpr+LowC53+Ritchf14W+OpenB20+HBESS+K42-2	68	96	65	72
43	B20+B22	15	49	2	2
44	Highgate Synchronous Condenser	2	30	15	7
45	B20+LowellC53SwitchClose+B22	13	55	6	-26