Sheffield-Highgate Export Interface

SHEI

vermont electric power company

VELCO

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

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

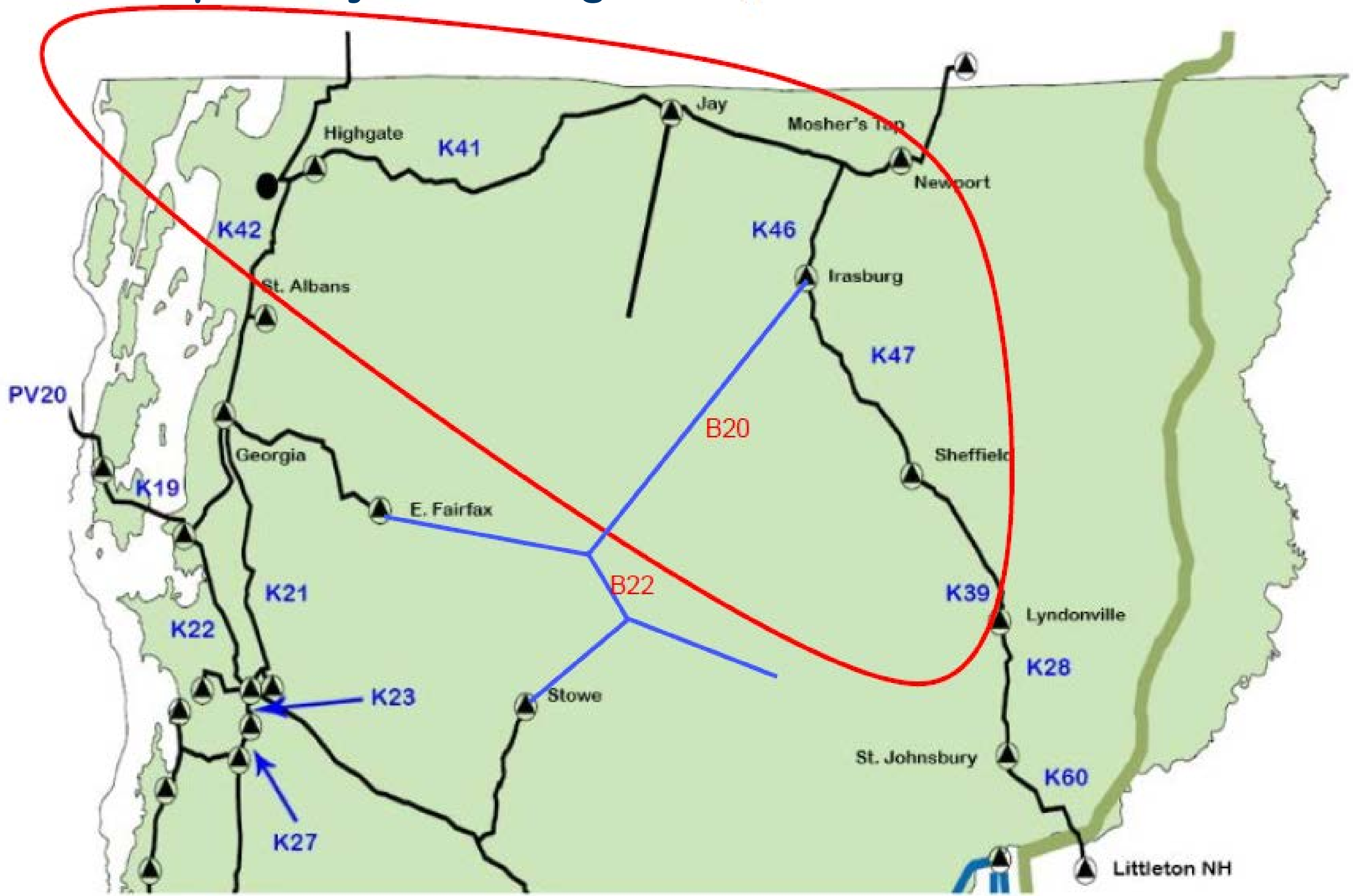
- Determine thermal export limit for all-lines-in case and Essex STATCOM-out case based on 100% summer emergency ratings
  - Ignore 115 kV line overloads south of Georgia and Sand Bar
    - Assuming that they can be addressed by reducing PV20 flows from New York

Notes

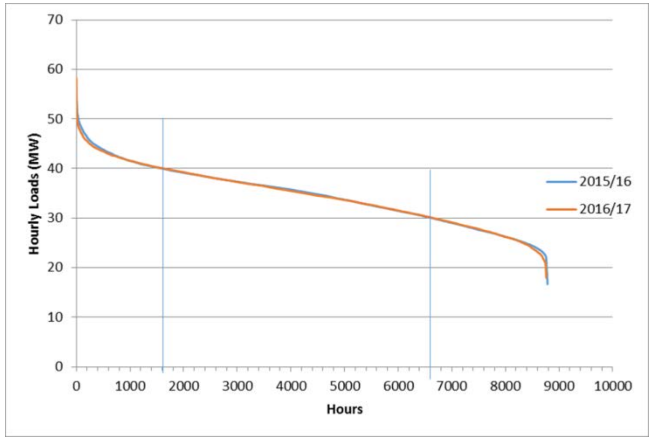
- MW export limit results should only be used to calculate incremental benefit (within +/- 5 MW) of each case/scenario
  - ISO-NE is responsible for determining system limits
  - ISO-NE cases may model different system assumptions
    - Essex STATCOM, capacitor bank dispatch, load distribution, tie flows
  - 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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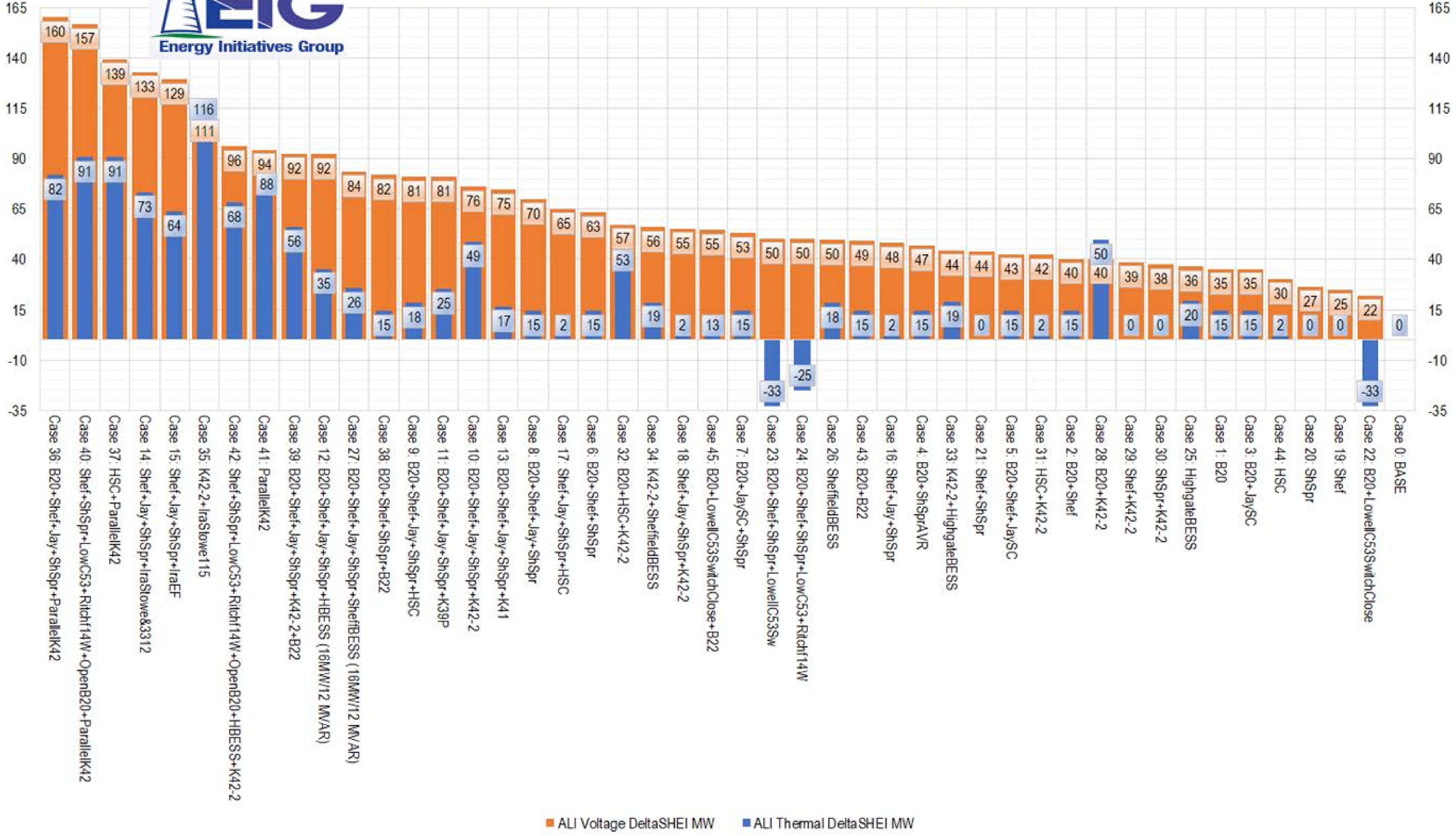
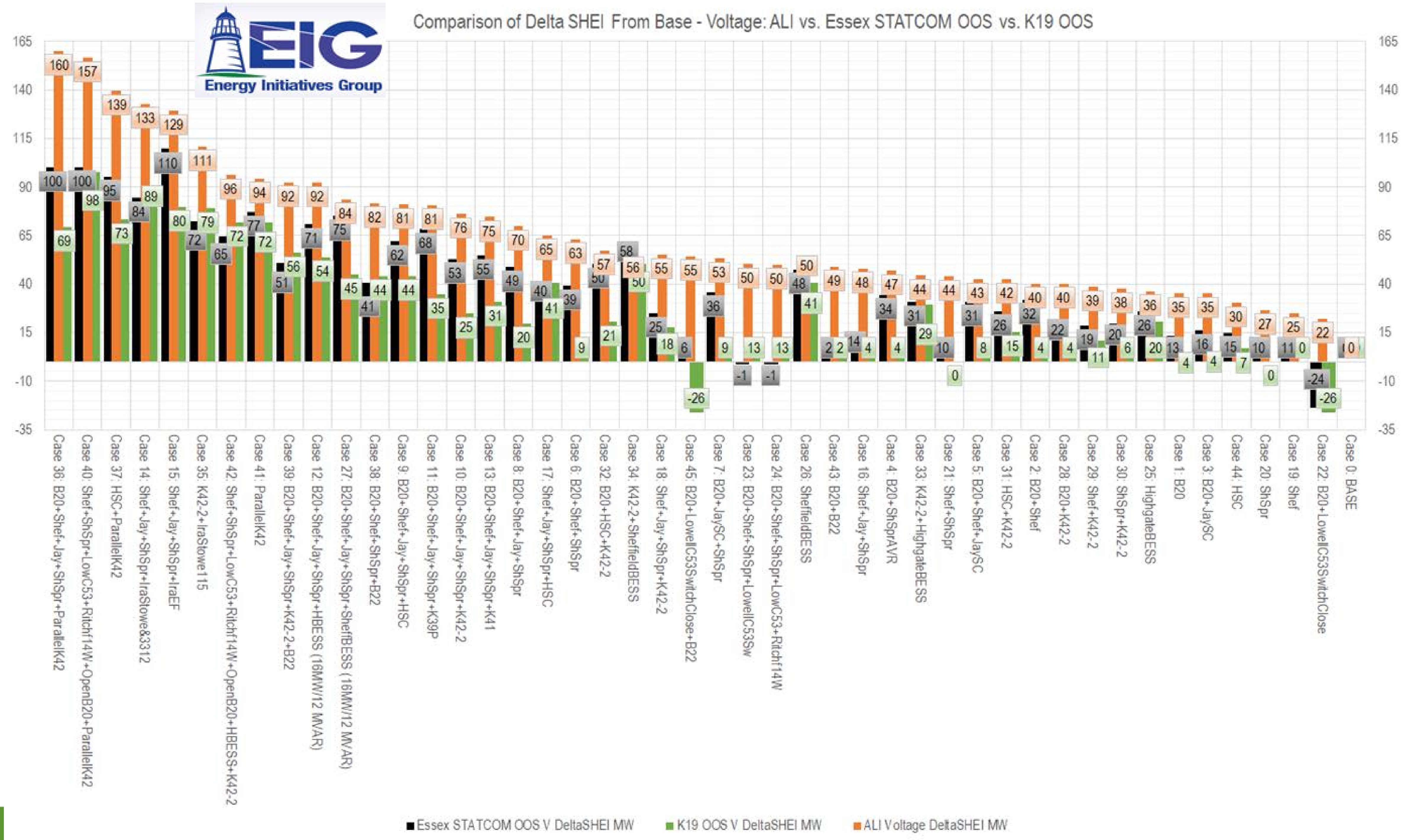
Comparison of Delta (Incremental) SHEI From Base - All Lines In: Voltage vs. Thermal




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

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Study Results – Thermal SHEI_TH in MW

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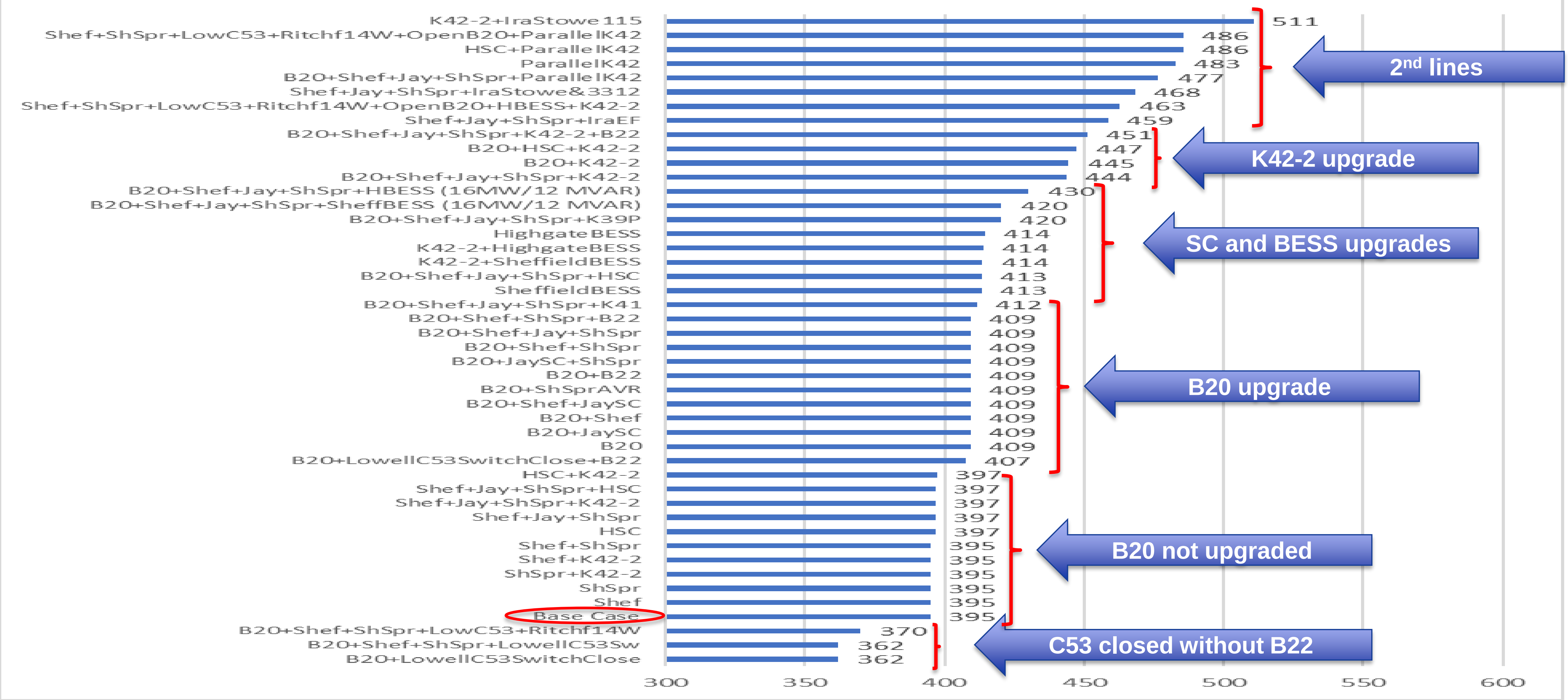
Navigating in a Changing Energy Industry



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Study Results – Voltage SHEI_V in MW

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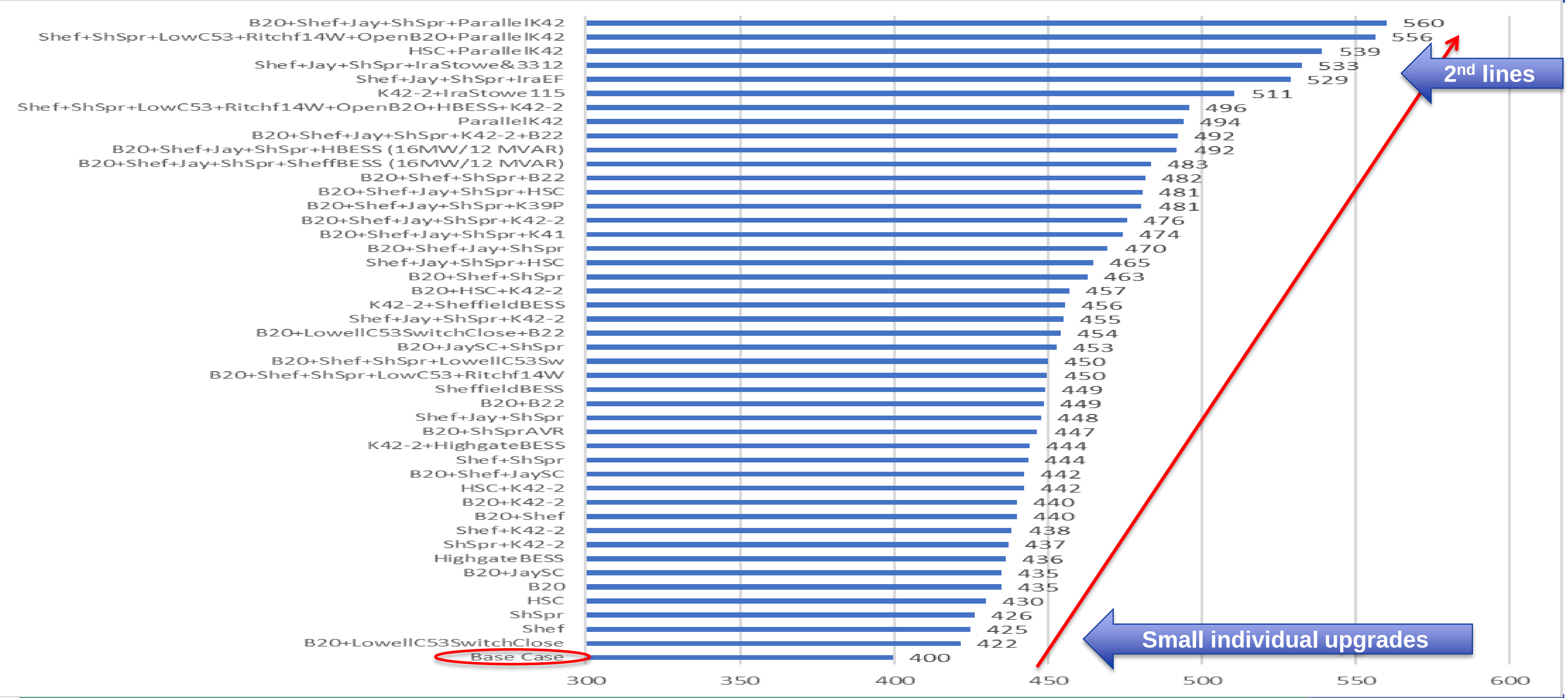
Navigating in a Changing Energy Industry



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

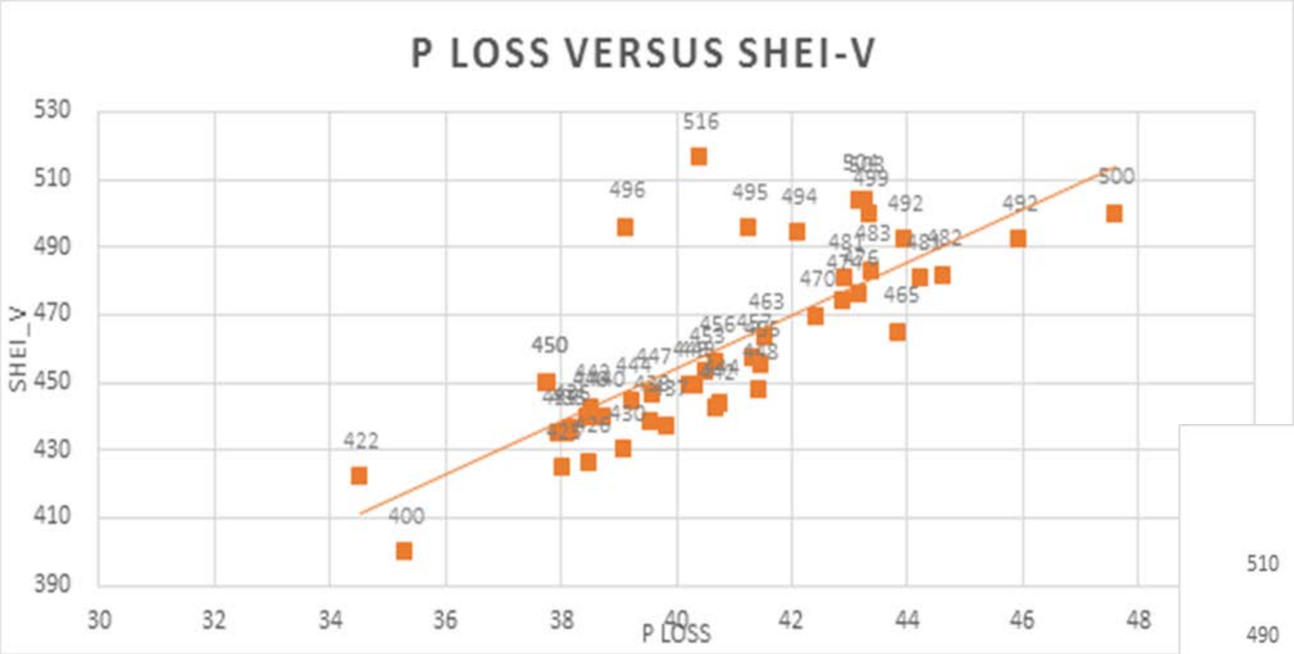
VELCO K42 asset condition evaluation

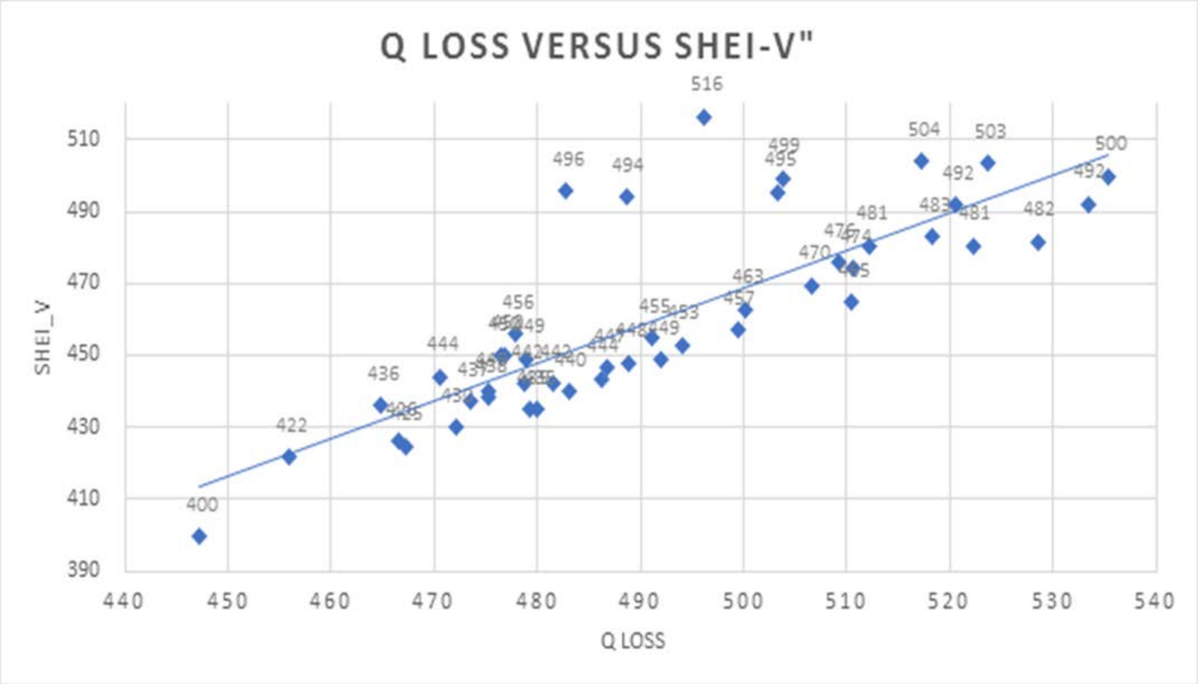
- K42 line was assessed in September
  - 16.75 miles from Highgate to Georgia, and 9.9 miles for limiting section
  - 50% of poles need to be replaced
  - Almost all poles will need to be replaced between 3 years and 15 years from now
- VELCO will determine whether it makes sense to rebuild entire line 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



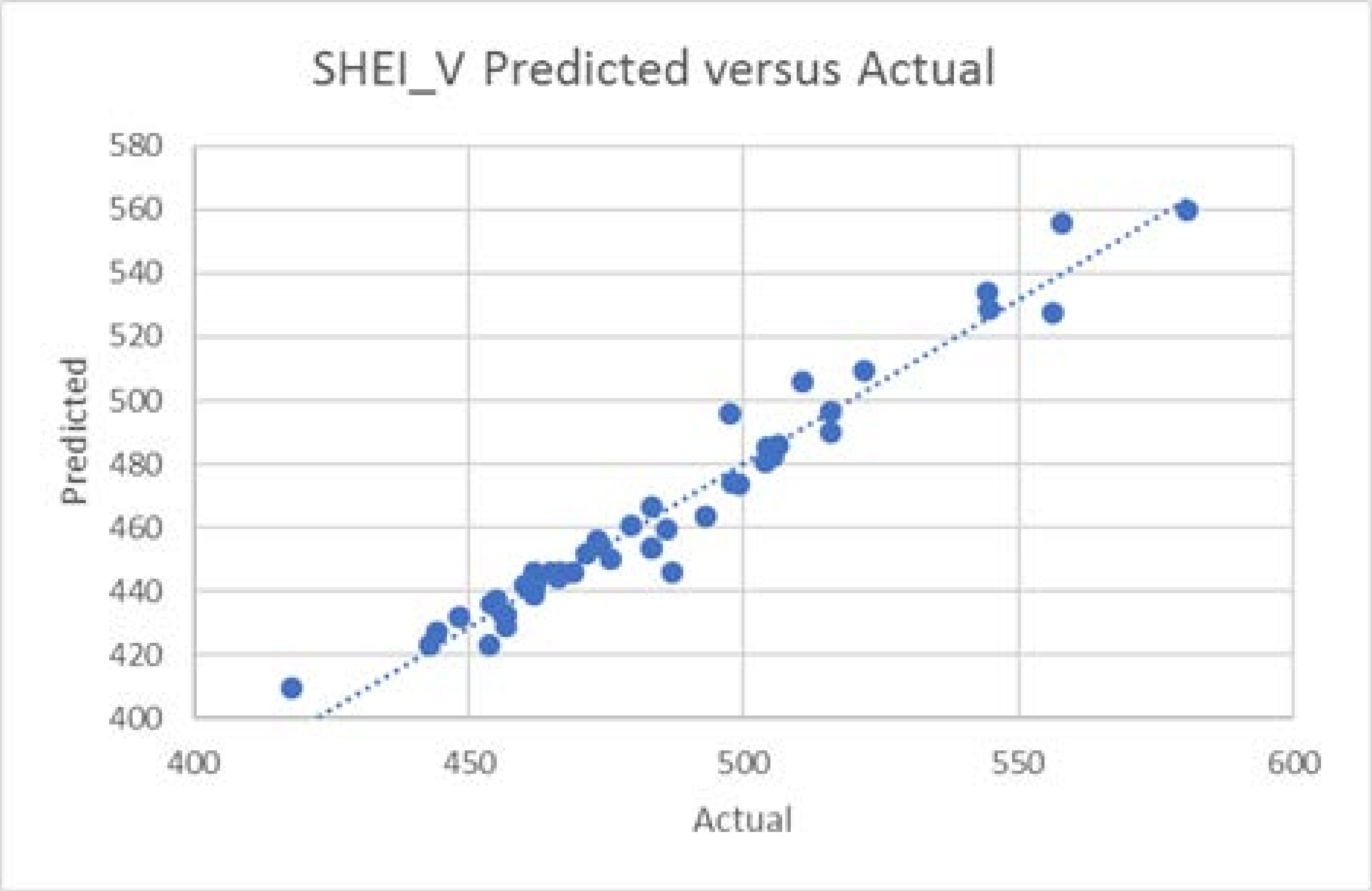


Regression Results SHEI_V

- 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
2nd 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

Regression Results
Predicted Versus Actual



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
<u>CASES</u>	**<u>Upgrades</u>**	**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

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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