Northern Vermont Export Study

Prepared for:

Vermont Transco LLC

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Executive Summary

EIG was contracted by Vermont Transco LLC to perform power flow simulation studies on the northern Vermont transmission system to assess the ability to reduce curtailment of wind generation by increasing the ability to transfer power across the Sheffield Highgate Export Interface (SHEI) for all lines in conditions and facility-out conditions. Power flow simulation analysis was performed for the existing system and for 45 alternative combinations containing one or more of the following upgrade elements: reactive support, 115 kV transmission, 34.5 kV and 46 kV subtransmission, and battery storage. This report discusses the 45 alternative combinations in terms of their performance in comparison to the existing system. The results of this analysis are intended to provide system performance information that is only one of the factors that need to be evaluated to select the cost-effective solution. It is anticipated that stakeholders will determine the amount of additional export capability that will be necessary to meet individual needs or the good of the State of Vermont. Cost, robustness, operational flexibility, how quickly a solution can be implemented, and other factors will need to be considered to select the preferred solution.

Analysis was performed for the original benchmark case (Case 0) and 45 additional cases:

- 46 cases were tested:
    - All Lines In—SHEI Voltage limits analysis
    - All Lines In—SHEI Thermal limits analysis
    - Essex ±75 MVAR STATCOM out-of-service—SHEI Voltage limits analysis
    - Sandbar – Georgia (K19) 115 kV line out-of-service—SHEI Voltage limits analysis
- 19 cases were tested:
    - Essex ±75 MVAR STATCOM out-of-service—SHEI Thermal limits analysis

- Stowe 115/34.5 kV transformer out-of-service—SHEI Voltage limits analysis
- Marshfield – Montpelier (3317) 34.5 kV line out-of-service—SHEI Voltage limits analysis
- St. Johnsbury – Lyndonville (K28) 115 kV line out-of-service—SHEI Voltage limits analysis

SHEI interface flow is calculated by summing the flows from the following 115 kV lines, with due regard to the effects of area wind generation:

- K39 (Sheffield – Lyndonville)
- K42-2 (Highgate Tap – St Albans Tap)

The SHEI definition was revised for this study to the following, by adding the following facilities for some of the alternatives, to ensure that the alternatives are compared on the same basis:

- K39 (Sheffield – Lyndonville)
- K42-2 (Highgate Tap – St Albans Tap)
- New Irasburg – Stowe 115 kV Line
- New Irasburg – East Fairfax 115 kV Line
- New 115 kV Parallel Line to K42: Highgate – Georgia
- New 115 kV Parallel Line to K39: Sheffield – Lyndonville
- New Highgate Battery Energy Storage Device (BESS) [1]
- New Sheffield Battery Energy Storage Device (BESS) [4]

[1] Flow measured from high voltage side to low voltage side through BESS 115/34.5 kV transformer.

A further change was shown to be needed to adequately compare the effects of upgrades. A new metric, the SHEI+B20 flow captures the 34.5 kV line B20 flow out of Lowell. By including the B20 flow with SHEI, the SHEI+B20 export flow becomes a "closed interface", with all upgrades showing their direct impact on the export flow.

Overall, the upgrade options including construction of a new 115 kV line resulted in significantly higher voltage and thermal SHEI limits relative to the reactive or 34.5 kV upgrades alone. The new 115 kV line upgrades performed very well both for all lines in and facility out conditions. The top six cases (Cases 36, 40, 37, 14, 15, and 35) each included a new 115 kV line terminating in the western side of Vermont (Parallel line to K42, Irasburg – Stowe, and Irasburg – East Fairfax). These top six cases all showed large increases in All Lines In SHEI+B20 Voltage limits (+104 to +163 MW) relative to benchmark Case 0, plus also showed impressive increases in facility out Voltage and All Lines In Thermal limits, demonstrating significant overall benefit to SHEI limits, likely to be observed under many different system conditions.

Case 41, which had only a single upgrade, the Parallel 115 kV line to K42, also showed impressive overall SHEI+B20 limit increases, with a +93 MW All Lines In SHEI Voltage limit increase, +87 MW for All Lines In Thermal, +75 MW for Essex STATCOM out-of-service, and +70 MW for K19 out-of-service.

The remaining three of the top ten did not include new 115 kV lines. Cases 12 and 27 included reconductoring the B20 line, activating the Sheffield and Sheldon Springs AVRs, enhancing the Jay synchronous condenser reactive capability, plus adding a 20 MVA battery energy storage unit (at Highgate or Sheffield, respectively). Case 39 included the B20 and B22 34.5 kV line reconductoring, Sheffield/Jay/Sheldon Springs reactive upgrades, plus reconductoring 115 kV line K42-2 line from Highgate to St. Albans. These non-new 115 kV line options had fairly high All Lines In Voltage Delta SHEI+B20, however the facility out and thermal limits were less effective in comparison to the new 115 kV options.

Overall, with more upgrades combined per case, the higher the SHEI+B20 limits tended to be.

Power flow results demonstrate that the existing 34.5 kV B20 line is a major factor in permitting SHEI+B20 power transfers to be increased from northern to southern Vermont. This is because the B20 line is operated in parallel with the 115 kV system and causes thermal limitations for many of the study cases. For the All Lines In Voltage cases, B20 MW flow was calculated to be between 11 and 33 MW, while SHEI+B20 MW transfers were between 418 and 581 MW, for various upgrade configurations. After examining 17 upgrade options across 46 all lines in load flow cases, the percent of flow on the B20 line ranged between 2.1% and 7.1% of SHEI including B20 flow All Lines In Voltage limit ("SHEI_V+B20").

In order to predict the average influence of one upgrade option versus another, statistical techniques were performed. SHEI+B20 data points for 46 all lines in alternatives were evaluated for both voltage and thermal constraints. Each alternative consisted of multiple combinations of from one to six bundled upgrade options, out of a total of 17 upgrade options that were considered.

Regression analysis was performed to calculate the impact of each individual upgrade option. A prediction interval was produced for each of the options for comparison purposes. For example, it was determined that with 95 percent confidence, it can be concluded that installing a 2nd 115 kV line alongside the K42 line will increase the All Lines In Voltage SHEI+B20 Voltage interface by between 88.6 to 101.2 MW.

In summary, power flow results show low to high increase in SHEI through the use of multiple combinations of upgrade options. Regression analysis results provide a means to predict the average response of each of the upgrade options individually.

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1.0 Introduction

EIG was contracted by Vermont Transco LLC to perform power flow simulation studies on the northern Vermont transmission system to assess the ability to reduce curtailment of wind generation by increasing the ability to transfer power across the Sheffield Highgate Export Interface (SHEI) for all lines in conditions and facility-out conditions. Power flow simulation analysis was performed[2] for the existing system and for 45 alternative combinations containing one or more of the following upgrade elements: reactive support, 115 kV transmission, 34.5 kV and 46 kV subtransmission, and battery storage. This report discusses the 45 alternative combinations in terms of their performance in comparison to the existing system. The results of this analysis are intended to provide system performance information that is only one fo the factors that need to be evaluated to select the cost-effective solution. It is anticipated that stakeholders will determine the amount of additional export capability that will be necessary to meet individual needs or the good of the State of Vermont. Cost, robustness, operational flexibility, how quickly a solution can be implemented, and other factors will need to be considered to select the preferred solution.

[2] Steady-state power flow analysis was performed using Siemens/PTI's PSS®E power flow simulation software, version 33.7.

2.0 Methodology and Criteria

2.1 SHEI Definition

The Sheffield Highgate Export Interface (SHEI) is shown geographically in Figure 1 below. The SHEI boundaries are shown in Figure 2 below. SHEI interface flow is calculated by summing the flows from the following 115 kV lines, with due regard to the effects of area wind generation:

- K39 (Sheffield – Lyndonville)
- K42-2 (Highgate Tap – St Albans Tap)

Load adjustments do not affect system performance and SHEI flows in the same way as generation adjustments, for several reasons. First, the two monitored lines do not account for all flows from the SHEI area, which is therefore an open interface, since the B20 line (Lowell – Johnson 34.5 kV) is not monitored, even though it carries SHEI flows and can be a critical line with respect to system performance. In addition, because load adjustments are distributed in nature, load adjustments will have less of an effect on SHEI flows compared to similar generation adjustments that are concentrated at specific locations. Further, each generator can affect the interface in a different way, depending on its location and characteristics. The end result of these differences is that load additions can be half as positive as the wind plants are negative. For all of these reasons, load additions of the same size as the incremental capacity achieved by a system upgrade will be less effective than that upgrade. Table 1 illustrates how the interface flows change as generation and load are adjusted. A 30 MW load increase reduces SHEI flows by 20 MW.

Table 1: SHEI Flows Impacted by Load and Generation

	20 MW SHEI Load				50 MW SHEI Load			
Highgate HVDC North Bus	225	225	225	225	225	225	225	225
KCW	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5
Sheffield	40	40	40	40	40	40	40	40
Coventry	8	8	8	8	8	8	8	8
Highgate Falls	9.5	9.5	9.5	0	9.5	9.5	9.5	0
Sheldon Springs	23.5	23.5	0	0	23.5	23.5	0	0
Swanton GT	48	0	0	0	48	0	0	0
SHEI level	476	431	408	399	456	411	388	379

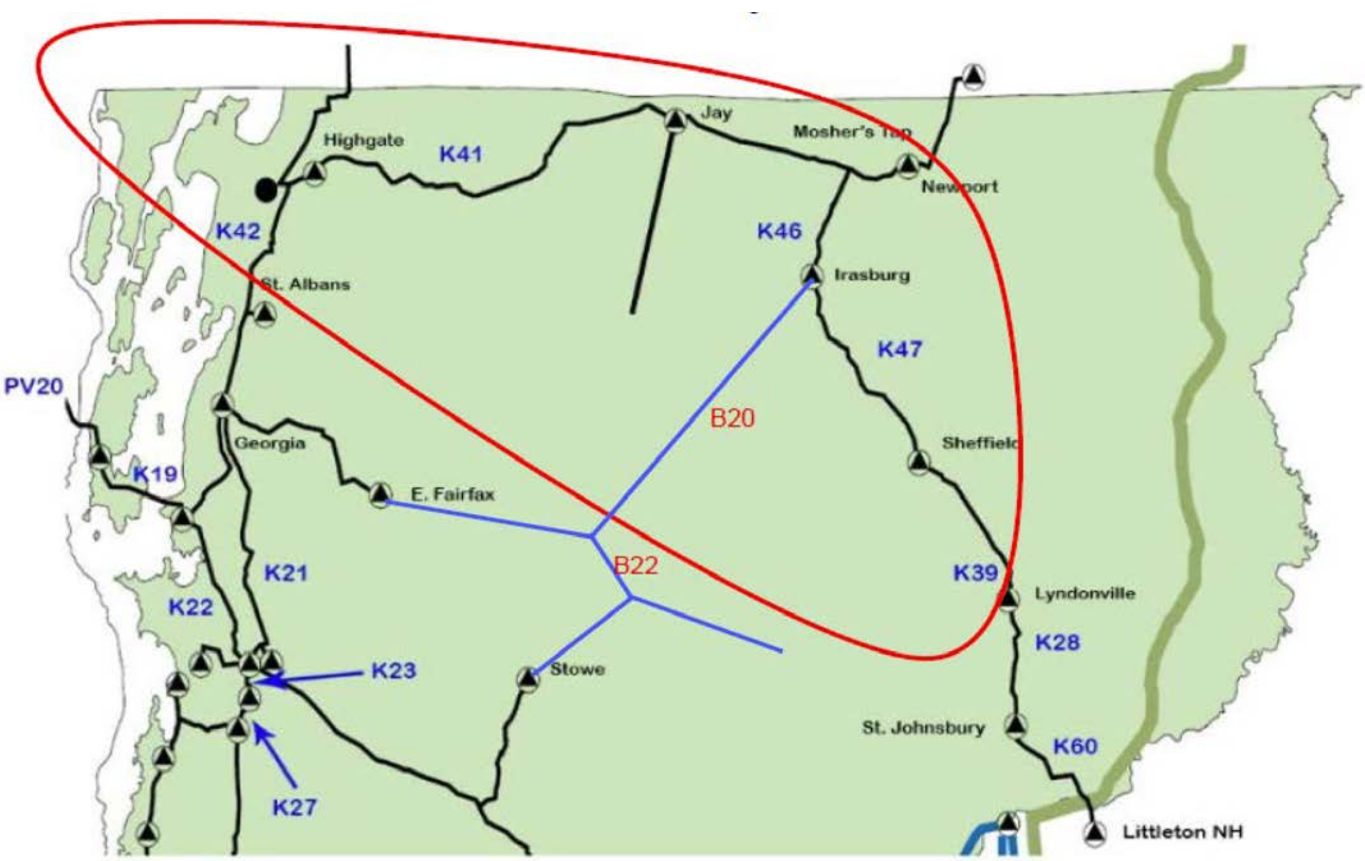

Figure 1: The Sheffield-Highgate Export Interface (SHEI)

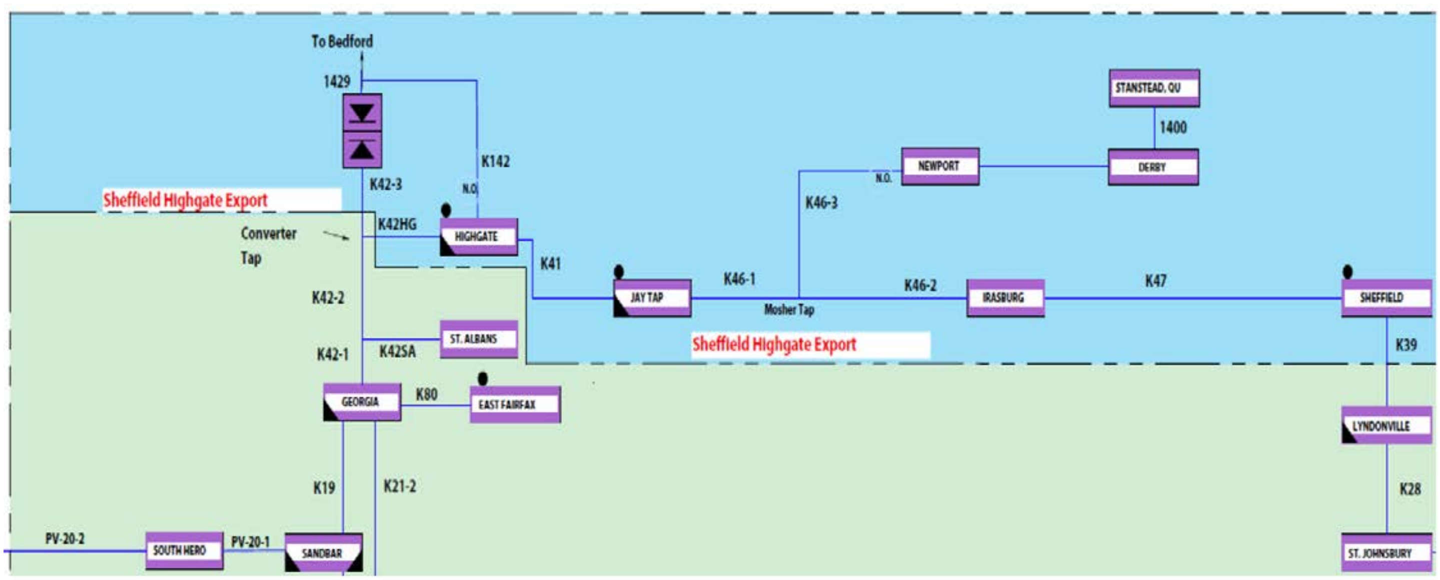

Figure 2: Sheffield-Highgate Export Interface (SHEI) Boundaries

2.2 Cases And Study Approach

EIG developed groupings of power flow cases for all lines in conditions, as well as for selected facility-out conditions:

- 46 cases were tested
  - All Lines In—SHEI Voltage limits analysis
  - All Lines In—SHEI Thermal limits analysis
  - Essex ±75 MVAR STATCOM out-of-service—SHEI Voltage limits analysis
  - Sandbar – Georgia (K19) 115 kV line out-of-service—SHEI Voltage limits analysis
- 19 cases were tested:
  - Essex ±75 MVAR STATCOM out-of-service—SHEI Thermal limits analysis
  - Stowe 115/34.5 kV transformer out-of-service—SHEI Voltage limits analysis
  - Marshfield – Montpelier (3317) 34.5 kV line out-of-service—SHEI Voltage limits analysis
  - St. Johnsbury – Lyndonville (K28) 115 kV line out-of-service—SHEI Voltage limits analysis

The seed base cases, upgrade modeling files, and contingency modeling files were provided by Vermont Transco LLC[3], and then used by EIG to develop and test study cases. The provided seed cases had prescribed Vermont generation and tie line dispatch conditions, which were left unchanged for the analysis. For all but the K28 out-of-service cases, only generation output in the northwestern corner of Vermont was modified. For each of the groups of cases, the following methodology was used:

[3] A select set of upgrades and contingencies were developed by EIG later in the study.

1. Using a seed case, appropriate upgrade modeling files were incorporated into the case to achieve the desired upgrade combinations.
2. Generation was adjusted higher or lower, utilizing northwestern Vermont generation:
   a. Sheldon Springs Hydro
   b. Highgate Falls Hydro
   c. Swanton Gas Turbines
3. If all of the generation above had been utilized to increase SHEI transfer, then load north of the SHEI interface could be reduced from 53 MW down to as low as 1 MW, however maintaining the initial reactive loads.
4. If all of the generation above had been turned off to lower SHEI transfer, then Highgate HVDC transfer could be reduced from its initial 224 MW, with associated reduction in filter capacitor banks online.
5. Following any of the aforementioned adjustments in generation, load, and/or HVDC transfer, adjustments were made to shunt capacitor bank output at prescribed discrete locations, in order to maintain dynamic reserve at two dynamic reactive devices:
   a. Jay Synchronous Condenser—capacitive reactive output between 0 and 2 MVAR
   b. Essex STATCOM—capacitive reactive output close to 10 MVAR (typically +/- 1 to 2 MVAR)
6. For cases incorporating new upgrades with dynamic reactive capability (Highgate Synchronous Condenser, Highgate BESS, or Sheffield BESS), the device was turned off briefly while setting the Jay and Essex outputs, then following an interim solution, the regulating voltage (at Highgate 115 kV or Sheffield 115 kV) would be set to the actual voltage, to allow the units

to maintain an initial zero MVAR output after turning back on and solved again. This would preserve a full dynamic reserve for the unit.

7. Following all of the case changes, the case would be named and saved, and then would be tested with what was expected to be the most limiting contingency, based on prior information. The results were monitored using a visual "slider" one-line diagram for a portion of the system. If the case solution diverged (or "blew up"), then the process would return to #2 above **to reduce generation** output and proceed through the steps back to #6. If the case solved with no violations (voltage for SHEI voltage limit testing, or thermal for SHEI thermal testing), then the process would return to #2 above **to increase generation** output and proceed through the steps to #6. When the respective voltage or thermal criterion was met, the case would be run against all contingencies using a batch contingency processor Python script, with results in spreadsheet format reviewed to confirm that the most-limiting contingency had determined the limit.

The 46 case combinations tested are shown in the matrix of Table 2 below. The approximate geographic locations of the upgrade options are shown in Figure 3, and are denoted with dashed lines. The contingencies tested are listed in Table 3.

Table 2: Studied Case Combinations Matrix

			Cases																						
Option	**Upgrade elements**	**Abbrev**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
1	Reconductor B20 Lowell-Johnson 34.5 kV line and upgrade the Lowell 46/34.5 kV transformer	B20		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X							X
2	Enable the Sheffield AVR	Shef			X			X	X		X	X	X	X	X	X	X	X	X	X	X	X		X	
3	Recognize Jay synch condenser 1.15 service factor	JaySC				X		X		X	X	X	X	X	X	X	X	X	X	X	X				
4	Enable the Sheldon Springs AVR	ShSpr					X		X	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	HSC										X								X					
6	Reconductor K42 Highgate-St Albans 115 kV line	K42-2											X								X				
7	Install a 2nd K39 Sheffield-Lyndonville 115 kV line	K39P												X											
8	20 MVA (16 MW / 12 MVAR) Battery Storage at Highgate 115 kV	HBESS													X										
9	Reconductor K41 Highgate-Jay 115 kV line	K41														X									
10	Install a new Irasburg to Stowe 115 kV line	IraStowe															X								
11	Install a new Irasburg to East Fairfax 115 kV line	IraEF																X							
12	Close the normally open Lowell C53 switch	LowC53																							X
13	Close the normally open Ritchford 14W switch and reconductor from Richford to Highgate 46 kV	Ritchf14W																							
14	20 MVA (16 MW / 12 MVAR) Battery Storage at Sheffield 115 kV	SheffBESS																							
15	Install a 2nd 115 kV line alongside the K42 line	ParallelK42																							
16	Upgrade 1.7 miles of B22 line for 39 MVA LTE rating	B22																							
17	Open B20 line at Johnson	OpenB20																							

			Cases																						
Option	**Upgrade elements**	**Abbrev**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**
1	Reconductor B20 Lowell-Johnson 34.5 kV line and upgrade the Lowell 46/34.5 kV transformer	B20	X	X			X	X				X				X		X	X				X		X
2	Enable the Sheffield AVR	Shef	X	X			X		X							X		X	X	X		X			
3	Recognize Jay synch condenser 1.15 service factor	JaySC					X									X			X						
4	Enable the Sheldon Springs AVR	ShSpr	X	X			X			X						X		X	X	X		X			
5	Install a 15 MVAr synchronous condenser at Highgate 115 kV	HSC									X	X					X							X	
6	Reconductor K42 Highgate-St Albans 115 kV line	K42-2						X	X	X	X	X	X	X	X				X			X			
7	Install a 2nd K39 Sheffield-Lyndonville 115 kV line	K39P																							
8	20 MVA (16 MW / 12 MVAR) Battery Storage at Highgate 115 kV	HBESS			X								X									X			
9	Reconductor K41 Highgate-Jay 115 kV line	K41																							
10	Install a new Irasburg to Stowe 115 kV line	IraStowe													X										
11	Install a new Irasburg to East Fairfax 115 kV line	IraEF																							
12	Close the normally open Lowell C53 switch	LowC53	X	X																X		X			X
13	Close the normally open Ritchford 14W switch and reconductor from Richford to Highgate 46 kV	Ritchf14W		X																X		X			
14	20 MVA (16 MW / 12 MVAR) Battery Storage at Sheffield 115 kV	SheffBESS				X	X							X											
15	Install a 2nd 115 kV line alongside the K42 line	ParallelK42														X	X			X	X				
16	Upgrade 1.7 miles of B22 line for 39 MVA LTE rating	B22																X	X				X		X
17	Open B20 line at Johnson	OpenB20																		X		X			

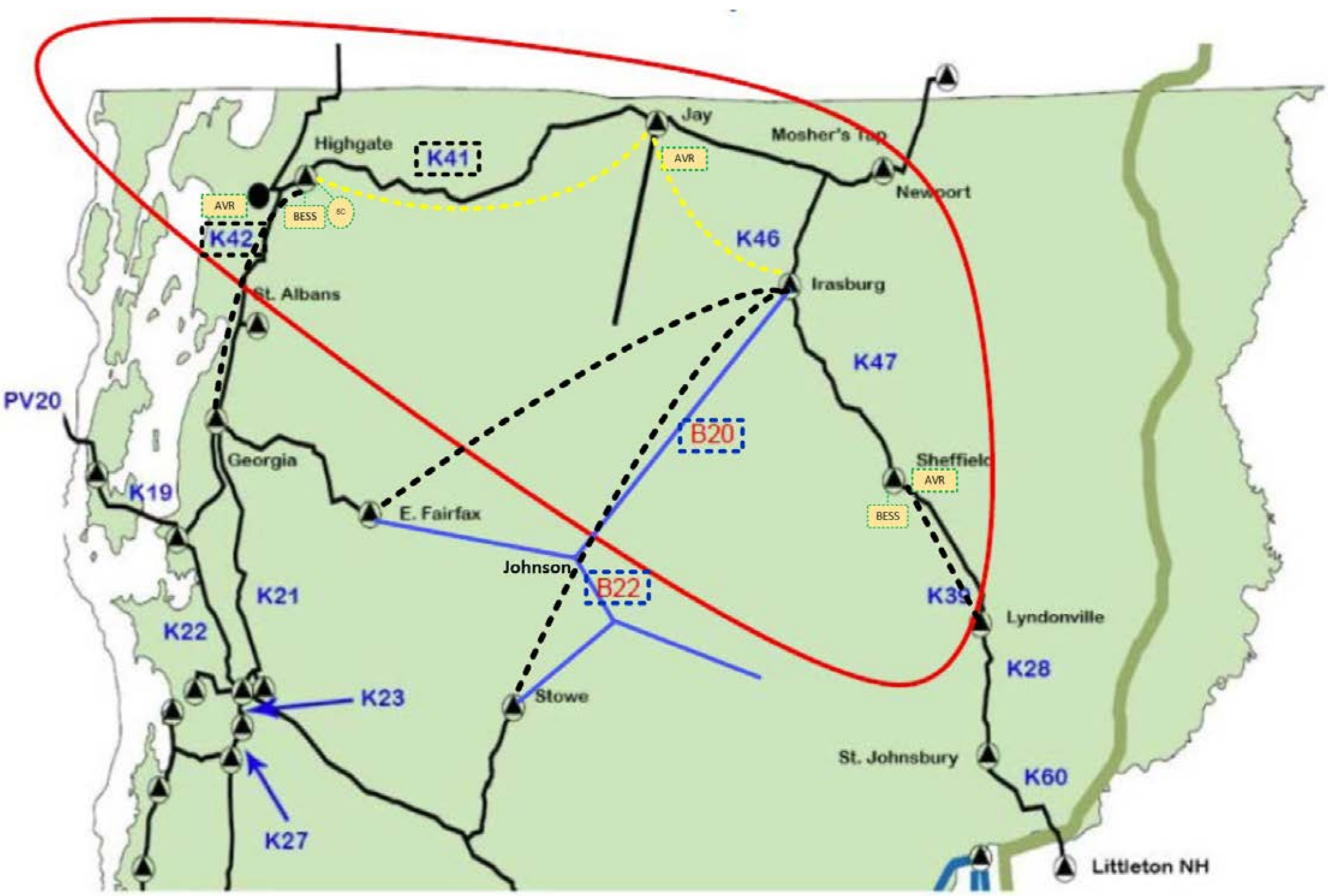

Figure 3: Approximate Geographic Locations of Upgrade Options

In Figure 3 above, dotted yellow lines represent closing normally-open 46 kV switches and 46 kV line upgrades, dotted black lines represent the addition of new 115 kV lines, line reconductoring is represented by a blue dotted box around the line number, "BESS" indicates the addition of a battery energy storage system, "AVR" indicates the enabling or enhancement of automatic voltage regulation of existing generation or synchronous condenser, and "SC" indicates the addition of a new synchronous condenser.

Table 3: List of Simulated Contingencies

Contingency	Contingency
115 kV Line 370	115 kV Line K43
115 kV Line F206	115 kV Line K46
Sheffield Wind Gen	115 kV Line K47
115 kV Line K18	115 kV Line K54
115 kV Line K19	115 kV Line K55
115 kV Line PV20	115 kV Line K56
115 kV Line K21	115 kV Line K60
115 kV Line K21 & 34.5 kV Line B22	115 kV Line K60 & 34.5 kV Line B22
115 kV Line K21 & Trip of Highgate HVDC Converter	East Fairfax 115/34.5 kV Transformer
115 kV Line K22	Stowe 115/34.5 kV Transformer
115 kV Line K23	Essex STATCOM
115 kV Line K24	Highgate HVDC Converter
115 kV Line K25	Kingdom Community Wind Gen
115 kV Line K27	Jay Synchronous Converter
115 kV Line K28	34.5 kV Line X29
115 kV Line K28 & 34.5 kV Line B20	34.5 kV Line B20
115 kV Line K28 & 34.5 kV Line B22	34.5 kV Line B22
115 kV Line K33	34.5 kV Line 3329
115 kV Line K39	34.5 kV Line 3319
115 kV Line K39 & 34.5 kV Line B20	34.5 kV Line 3317
115 kV Line K39 & 34.5 kV Line B22	New 115 kV Line Parallel to Line K39
115 kV Line K41	New 115 kV Line Irasburg - Stowe
115 kV Line K42	New 115 kV Line Irasburg - East Fairfax
115 kV Line K42 & 34.5 kV Line B20	New 115 kV Line Irasburg - East Fairfax & 34.5 kV Line B20
New 115 kV Parallel to Line K42	New 115 kV Line Irasburg - Stowe & 34.5 kV Line B20

2.3 Modification of SHEI Interface Definition For Comparative Analysis

The SHEI interface definition was modified for the purposes of this analysis to reflect the true benefits of the upgrades under review. Specifically, flow on any of the new 115 kV lines was summed into the SHEI, as well as any flow into a new battery energy storage device. Thus, the revised SHEI definition for this study was calculated by adding the components below:

- K39 (Sheffield – Lyndonville)
- K42-2 (Highgate Tap – St Albans Tap)
- New Irasburg – Stowe 115 kV Line
- New Irasburg – East Fairfax 115 kV Line
- New 115 kV Parallel Line to K42: Highgate – Georgia
- New 115 kV Parallel Line to K39: Sheffield – Lyndonville
- New Highgate Battery Energy Storage Device (BESS) [4]
- New Sheffield Battery Energy Storage Device (BESS) [4]

A further change was shown to be needed to adequately compare the effects of upgrades. A new metric, the SHEI+B20 flow captures the 34.5 kV line B20 flow out of Lowell. By including the B20 flow with SHEI, the SHEI+B20 export flow becomes a "closed interface", with all upgrades showing their direct impact on the export flow.

SHEI and SHEI+B20 flows shown throughout this report are pre-contingency flows only.

2.4 Criteria

To prevent voltage and thermal concerns in anticipation of a transmission outage, ISO New England maintains SHEI exports under predetermined export limits, by reducing generation under ISO New England's control. Currently, the all lines in voltage limit is slightly lower than the thermal limit when operational summer (April 1st to October 31st) ratings are in effect. The winter thermal export limit is significantly higher than the voltage limit, which does not change seasonally.

[4] Flow measured from high voltage side to low voltage side through BESS 115/34.5 kV transformer.

Therefore, any selected upgrade option needs to address voltage concerns, at a minimum, because increasing the thermal limit does not provide any benefit without increasing the voltage limit. Addressing the voltage limit without increasing the thermal limit provides some benefit, because of the seasonality of thermal limits and the amount of flexibility available to operators when responding to thermal constraints, which does not exist for voltage constraints. This analysis evaluates upgrade options that increase all lines in and facility-out voltage and thermal limits.

For the SHEI voltage limit analysis, the voltage at the Highgate 115 kV bus was not allowed to be below 0.95 per unit (95% of nominal) voltage, nor could any other 115 kV bus be below 0.95 per unit. 34.5 kV and 46 kV buses could not drop below 0.90 per unit voltage. Thermal violations (above 100% Normal rating for all lines in, or above 100% LTE rating for post-contingency) were ignored if observed on 115 kV facilities. However, if a thermal violation was observed on a 34.5 kV facility, it would be flagged to be tripped in the contingency definition file. The two 34.5 kV facilities shown to be overloaded (above 100% LTE rating post-contingency), and were tripped under certain circumstances were 34.5 kV lines B20 and B22. Some other 34.5 kV lines were shown to be overloaded under post-contingency conditions, however as their location was south of Georgia, it was assumed (based on guidance by Vermont Transco LLC) that the PV20 tie flow from New York could be used to reduce those loadings, thus those overloads were ignored for this analysis.

For the SHEI thermal limit analysis, the cases were stressed to a point that no facility north of Georgia was allowed to have a thermal violation.

For the K28 out-of-service cases, based on guidance from Vermont Transco LLC, the output of the Kingdom Community Wind and Sheffield Wind plants each was limited substantially, to address local concerns. If possible for some cases, after turning on all northwestern generation and reducing northern Vermont load, then the Kingdom and Sheffield generation output would be increased. This occurred for only three cases tested: two included a new 115 kV line from Irasburg, and a third with limited additional output from Kingdom and Sheffield, for a case that included the Highgate BESS device.

2.5 Modeling Notes

When load scaling was implemented to increase SHEI export, real components (MW) of bus loads were proportionally scaled in northern Vermont (Zones 725 and 735) from the original 53 MW total to other load levels (e.g., 45, 40, 35, 25…) as low as 1 MW total.

The new 115 kV Irasburg line additions were assumed to be 1272 ACSR single pole construction, with the Irasburg to Stowe line length assumed to be 45 miles, and the Irasburg to East Fairfax line length assumed as 42 miles. The second (parallel) K42 line from Highgate to Georgia was assumed to be 1351 ACSS single pole construction, of 17 miles. The reconductoring of 115 kV line K41 was assumed as 42 miles of 1272 ACSR single pole construction.

The 115 kV line K42-2 upgrade consisted of reconductoring the 9.9 mile section of the K42 line between the Highgate Tap and the St. Albans Tap, utilizing 1351 ACSS conductors and maintaining the existing H-frame tower configuration.

The 34.5 kV B20 line upgrade was assumed as 795 ACSR construction. The 34.5 kV B22 line upgrade was assumed to be for just over a 1.7 mile length, with a 39 MVA LTE line rating.

The Battery Energy Storage System (BESS) (either at Highgate or Sheffield) bus was modeled with two components. The active power absorption was modeled as a 16 MW equivalent load to represent charging of the BESS. The reactive power component was modeled as a 12 MVAR STATCOM to represent the capability of the BESS inverter to provide reactive power and voltage control. The STATCOM was set to regulate a voltage that would result in 0 MVAR output pre-contingency. The load was modeled at a 34.5 kV bus, and the STATCOM was modeled at a 480 V bus with a step-up transformer from 480 V to the 34.5 kV bus. A 34.5 kV to 115 kV step-up transformer connected the 34.5 kV bus to the 115 kV bus.

The Highgate Synchronous Condenser was modeled as a generator with 0 MW real capability, and a reactive capability range of 15 MVAR capacitive to 7.5 MVAR inductive, and connected to a 13.8 kV bus, with a 13.8 kV to 115 kV step-up transformer connection.

For several cases in which all available northwestern Vermont existing generation was turned on and northern Vermont load was reduced to a 1 MW minimum, a fictitious generator was added at Highgate, utilizing the same 13.8 kV bus used to model the Highgate Synchronous Condenser (the synchronous condenser was only modeled on for one of the cases). This fictitious generator was varied as needed until the appropriate voltage or thermal limit was reached.

3.0 SHEI Limits Analysis Results

Results are summarized in the following tables. Listed in each table is the:

- Pre-Contingency SHEI MW transfer limit for each case
- Delta SHEI MW—incremental SHEI MW from benchmark Case 0
- 34.5 kV line Pre-Contingency B20 flow in MW
- Pre-Contingency SHEI+B20 MW transfer limit
- Percentage of the SHEI+B20 export flowing on the B20 line Pre-Contingency
- Delta SHEI+B20 MW—incremental SHEI+B20 MW from benchmark Case 0
- Limiting Post-Contingency condition
- Resultant Post-Contingency voltage at the Highgate 115 kV bus (only shown in the voltage limit results tables, not thermal results tables)

For the voltage limits tables, if the SHEI limit is shown highlighted in purple, then the limit was determined by limiting a 34.5 kV line to not trip, as tripping the line would otherwise result in voltage violations or case divergence (indicative of a voltage stability/collapse condition). Contingencies causing the B20 line or the B22 line to overload and trip are noted as K39_B20 or K39_B22, respectively. A limiting condition noted as BC_Normal indicates that a normal rating was exceeded in the all lines in base case. SHEI limits highlighted in yellow indicate that the northwestern Vermont generation was maximized and northern Vermont load was minimized (to 1 MW total); for the All Lines In Voltage and Thermal testing, a fictitious generator was added at Highgate, and increased until a limit was achieved—these cases are denoted with an “X” (e.g., 35X).

There were many variables in each pre-contingency case setup and post-contingency determined threshold for limits:

- Discrete shunt capacitor bank dispatch of various sizes and locations

- Range of acceptable starting point for dynamic reactive devices
- Generation dispatch increments of up to 5 MW
- Voltage at or near 0.95 pu at St. Albans or Highgate—typical variance of +/- 0.005 pu
- Case divergence or case mismatch issues prior to 0.95 pu limits
- Thermal limitations on B20 or B22 line

Because of these variables, SHEI limits results between cases (within a grouping) that are within approximately 5 MW of each other should be considered essentially equivalent to one another.

Additionally, between groupings of cases, there were some overall differences in capacitor dispatch that would affect direct comparison of individual case results between the groupings. Therefore, raw limits should not necessarily be compared between groupings of cases. Instead, the incremental, or "Delta", SHEI limit from the Case 0 base case is a better comparator, removing influence from any relative capacitor bank dispatch differences between case groupings. In addition, these raw export limits should not be compared against those determined by previous ISO New England studies, because of several potential differences between the power flow cases utilized, including, but not limited to: load distribution, capacitor bank dispatch, and equipment modelling.

Results are shown in tables for all groupings of cases (defined in Section 2.2). Table 3 shows the raw SHEI Voltage limits for the All Lines In cases, listed in Case numerical order. Table 4 shows the raw SHEI Thermal limits for the All Lines In cases. Table 5 shows the raw SHEI Voltage limits for cases with the Essex STATCOM out-of-service. Table 6 shows the raw SHEI Thermal limits for cases with the Essex STATCOM out-of-service. Table 7 shows the raw SHEI Voltage limits for cases with 115 kV line K19 out-of-service. Table 8 shows the raw SHEI Voltage limits for cases with the Stowe 115/34.5 kV transformer out-of-service. Table 9 shows the raw SHEI Voltage limits for cases with

34.5 kV line 3317 out-of-service. Table 10 shows the raw SHEI Voltage limits for cases with 115 kV line K28 out-of-service.

Table 4: SHEI Voltage Limits – All Lines In Cases

CASE	UPGRADES	ALI SHEI-V	DELTA SHEI	B20	ALI SHEI+B20-V	% B20 / (SHEI+B20)	DELTA SHEI+B20	LIMITING CONT
0		400	0	18	418	4.3%	0	K39_B20
1	B20	435	35	22	457	4.8%	39	K39
2	B20+Shef	440	40	22	462	4.8%	45	K39_B22
3	B20+JaySC	435	35	22	457	4.8%	39	K39_B22
4	B20+ShSprAVR	447	47	22	469	4.8%	51	K39_B22
5	B20+Shef+JaySC	442	43	23	465	4.9%	47	K39_B22
6	B20+Shef+ShSpr	463	63	23	486	4.8%	68	K39_B22
7	B20+JaySC+ShSpr	453	53	23	476	4.8%	58	K39_B22
8	B20+Shef+Jay+ShSpr	470	70	23	493	4.7%	75	K39_B22
9	B20+Shef+Jay+ShSpr+HSC	481	81	24	504	4.7%	87	K28_B22
10	B20+Shef+Jay+ShSpr+K42-2	476	76	23	499	4.6%	81	K39_B22
11	B20+Shef+Jay+ShSpr+K39P	481	81	24	504	4.7%	86	K28_B22
12	B20+Shef+Jay+ShSpr+HBESS	492	92	24	516	4.7%	98	K39_B22
13	B20+Shef+Jay+ShSpr+K41	474	75	24	498	4.7%	80	K28_B22
14X	Shef+Jay+ShSpr+IraStowe&3312 (+HG Fict Gen)	533	133	12	544	2.1%	127	K41
15X	Shef+Jay+ShSpr+IraEF (+HG Fict Gen)	529	129	16	545	2.9%	127	K41
16	Shef+Jay+ShSpr	448	48	18	466	3.9%	48	K39_B20
17	Shef+Jay+ShSpr+HSC	465	65	19	483	3.8%	66	K39_B20
18	Shef+Jay+ShSpr+K42-2	455	55	19	474	4.0%	56	K39_B20
19	Shef	425	25	18	443	4.1%	25	K39_B20
20	ShSpr	426	27	18	444	4.1%	27	K39_B20
21	Shef+ShSpr	444	44	18	462	3.9%	44	K39_B20
22	B20+LowellC53SwitchClose	422	22	32	454	7.0%	36	K39_B22
23	B20+Shef+ShSpr+LowellC53Sw	450	50	33	483	6.9%	66	K39_B22
24	B20+Shef+ShSpr+LowC53+Ritchf14W	450	50	33	483	6.9%	66	K39_B22
25	HighgateBESS	436	36	18	454	4.0%	37	K39_B20
26	SheffieldBESS	449	50	17	467	3.7%	49	K39_B20
27	B20+Shef+Jay+ShSpr+SheffBESS	483	84	23	506	4.6%	89	K39_B20
28	B20+K42-2	440	40	22	462	4.7%	44	K39
29	Shef+K42-2	438	39	18	456	3.9%	38	K39_B20
30	ShSpr+K42-2	437	38	18	455	3.9%	37	K39_B20
31	HSC+K42-2	442	42	18	460	3.9%	42	K39_B20
32	B20+HSC+K42-2	457	57	22	479	4.7%	62	K39_B22
33	K42-2+HighgateBESS	444	44	18	462	3.9%	44	K39_B20
34	K42-2+SheffieldBESS	456	56	18	473	3.7%	56	K39_B20
35X	K42-2+IraStowe115 (+HG Fict Gen)	511	111	11	522	2.2%	104	K42
36X	B20+Shef+Jay+ShSpr+ParallelK42 (+HG Fict Gen)	560	160	21	581	3.6%	163	K39_B22
37X	HSC+ParallelK42 (+HG Fict Gen)	539	139	17	556	3.1%	138	K39_B20
38	B20+Shef+ShSpr+B22	482	82	24	505	4.7%	88	K39
39	B20+Shef+Jay+ShSpr+K42-2+B22	492	92	24	516	4.6%	98	K39
40X	Shef+ShSpr+LowC53+Ritchf14W+OpenB20+ParallelK42 (+HG Fict Gen)	556	157	2	558	0.3%	140	K39
41	ParallelK42	494	94	17	511	3.3%	93	K39
42	Shef+ShSpr+LowC53+Ritchf14W+OpenB20+HBESS+K42-2	496	96	2	498	0.3%	80	K39
43	B20+B22	449	49	22	471	4.8%	54	K39
44	HSC	430	30	18	448	4.0%	30	K39_B20
45	B20+LowellC53SwitchClose+B22	454	55	33	487	6.7%	69	K39
			Limit was determined by limiting a 34.5 kV line to not trip					

Table 5: SHEI Thermal Limits – All Lines In Cases

CASE	UPGRADES	ALI SHEI-TH	DELTA SHEI	B20	ALI SHEI+B20-TH	% B20 / (SHEI+B20)	DELTA SHEI+B20	LIMITING CONT
0		395	0	18	413	4.3%	0	K42
1	B20	409	15	22	431	5.1%	19	K39
2	B20+Shef	409	15	22	431	5.1%	19	K39
3	B20+JaySC	409	15	22	431	5.1%	19	K39
4	B20+ShSprAVR	409	15	22	431	5.1%	19	K39
5	B20+Shef+JaySC	409	15	22	431	5.1%	19	K39
6	B20+Shef+ShSpr	409	15	22	431	5.1%	19	K39
7	B20+JaySC+ShSpr	409	15	22	431	5.1%	19	K39
8	B20+Shef+Jay+ShSpr	409	15	22	431	5.1%	19	K39
9	B20+Shef+Jay+ShSpr+HSC	413	18	22	435	5.1%	22	K39
10	B20+Shef+Jay+ShSpr+K42-2	444	49	22	466	4.7%	53	K39
11	B20+Shef+Jay+ShSpr+K39P	420	25	22	442	4.9%	29	BC Normal
12	B20+Shef+Jay+ShSpr+HBESS	430	35	22	452	4.9%	39	BC Normal
13	B20+Shef+Jay+ShSpr+K41	412	17	22	433	5.0%	21	K39
14	Shef+Jay+ShSpr+IraStowe&3312	468	73	11	479	2.2%	66	K46
15	Shef+Jay+ShSpr+IraEF	459	64	14	473	3.0%	60	BC Normal
16	Shef+Jay+ShSpr	397	2	18	415	4.3%	2	K42
17	Shef+Jay+ShSpr+HSC	397	2	18	415	4.3%	2	K42
18	Shef+Jay+ShSpr+K42-2	397	2	18	415	4.3%	2	K42
19	Shef	395	0	18	413	4.3%	0	K42
20	ShSpr	395	0	18	413	4.3%	0	K42
21	Shef+ShSpr	395	0	18	413	4.3%	0	K42
22	B20+LowellC53SwitchClose	362	-33	31	393	7.9%	-20	K39
23	B20+Shef+ShSpr+LowellC53Sw	362	-33	31	393	7.9%	-20	K39
24	B20+Shef+ShSpr+LowC53+Ritchf14W	370	-25	31	401	7.7%	-12	K39
25	HighgateBESS	414	20	18	432	4.1%	20	K42
26	SheffieldBESS	413	18	17	430	4.0%	18	K42
27	B20+Shef+Jay+ShSpr+SheffBESS	420	26	21	442	4.8%	29	BC Normal
28	B20+K42-2	445	50	22	467	4.7%	54	K39
29	Shef+K42-2	395	0	18	413	4.2%	0	K42
30	ShSpr+K42-2	395	0	18	413	4.3%	0	K42
31	HSC+K42-2	397	2	18	415	4.2%	2	K42
32	B20+HSC+K42-2	447	53	22	469	4.7%	57	K39
33	K42-2+HighgateBESS	414	19	18	431	4.1%	19	K42
34	K42-2+SheffieldBESS	414	19	17	431	3.9%	18	K42
35X	K42-2+IraStowe115 (+HG Fict Gen)	511	116	11	522	2.2%	109	K42
36	B20+Shef+Jay+ShSpr+ParallelK42	477	82	21	497	4.2%	85	K39
37	HSC+ParallelK42	486	91	17	502	3.3%	89	K42Parallel
38	B20+Shef+ShSpr+B22	409	15	22	431	5.1%	19	K39
39	B20+Shef+Jay+ShSpr+K42-2+B22	451	56	22	473	4.7%	60	K39
40	Shef+ShSpr+LowC53+Ritchf14W+OpenB20+ParallelK42	486	91	2	487	0.3%	75	K42Parallel
41	ParallelK42	483	88	17	499	3.3%	87	K42Parallel
42	Shef+ShSpr+LowC53+Ritchf14W+OpenB20+HBESS+K42-2	463	68	2	465	0.4%	52	K39
43	B20+B22	409	15	22	431	5.1%	19	K39
44	HSC	397	2	18	415	4.3%	2	K42
45	B20+LowellC53SwitchClose+B22	407	13	32	439	7.2%	27	K39

Table 6: SHEI Voltage Limits – Essex STATCOM Out-Of-Service Cases

CASE	UPGRADES	Essex SHEI-V	DELTA SHEI	B20	ESSEX SHEI+B20-V	% B20 / (SHEI+B20)	DELTA SHEI+B20	LIMITING CONT
0		379	0	18	397	4.5%	0	K39
1	B20	393	13	22	415	5.3%	17	K39
2	B20+Shef	411	32	22	434	5.1%	36	K39
3	B20+JaySC	396	16	22	417	5.2%	20	K39
4	B20+ShSprAVR	414	34	22	436	5.1%	39	K39
5	B20+Shef+JaySC	410	31	22	433	5.2%	35	K39
6	B20+Shef+ShSpr	418	39	23	441	5.2%	44	K39
7	B20+JaySC+ShSpr	415	36	23	438	5.2%	41	K39
8	B20+Shef+Jay+ShSpr	428	49	22	450	4.9%	53	K39
9	B20+Shef+Jay+ShSpr+HSC	441	62	23	464	4.9%	67	K39_B22
10	B20+Shef+Jay+ShSpr+K42-2	432	53	22	454	4.8%	57	K39
11	B20+Shef+Jay+ShSpr+K39P	448	68	22	470	4.7%	72	K28
12	B20+Shef+Jay+ShSpr+HBESS	450	71	22	472	4.7%	75	K39_B22
13	B20+Shef+Jay+ShSpr+K41	434	55	22	456	4.8%	59	K39_B22
14	Shef+Jay+ShSpr+IraStowe&3312	464	84	11	474	2.2%	77	K41
15	Shef+Jay+ShSpr+IraEF	489	110	16	504	3.1%	107	K41
16	Shef+Jay+ShSpr	393	14	18	411	4.3%	14	K39_B20
17	Shef+Jay+ShSpr+HSC	419	40	18	438	4.2%	40	K39_B20
18	Shef+Jay+ShSpr+K42-2	404	25	18	422	4.2%	25	K39
19	Shef	391	11	18	409	4.4%	11	K39
20	ShSpr	390	10	18	408	4.4%	10	K39
21	Shef+ShSpr	390	10	18	407	4.4%	10	K39
22	B20+LowellC53SwitchClose	356	-24	31	387	8.0%	-10	K39
23	B20+Shef+ShSpr+LowellC53Sw	378	-1	32	410	7.7%	13	K39_B22
24	B20+Shef+ShSpr+LowC53+Ritchf14W	378	-1	31	409	7.6%	12	K39_B22
25	HighgateBESS	405	26	18	423	4.2%	26	K39
26	SheffieldBESS	427	48	17	444	3.9%	47	K39
27	B20+Shef+Jay+ShSpr+SheffBESS	454	75	22	476	4.5%	79	K39
28	B20+K42-2	401	22	22	423	5.1%	26	K39
29	Shef+K42-2	398	19	18	416	4.3%	18	K39
30	ShSpr+K42-2	399	20	18	417	4.2%	20	K39
31	HSC+K42-2	405	26	18	423	4.2%	26	K39
32	B20+HSC+K42-2	430	50	22	452	4.9%	54	K39
33	K42-2+HighgateBESS	410	31	18	428	4.2%	31	K39
34	K42-2+SheffieldBESS	437	58	17	454	3.8%	57	K39
35	K42-2+IraStowe115	452	72	10	462	2.3%	65	K41
36	B20+Shef+Jay+ShSpr+ParallelK42	479	100	20	499	4.0%	102	K39_B22
37	HSC+ParallelK42	475	95	17	492	3.5%	95	K39
38	B20+Shef+ShSpr+B22	420	41	22	442	5.0%	45	K39
39	B20+Shef+Jay+ShSpr+K42-2+B22	430	51	22	452	4.9%	55	K39
40	Shef+ShSpr+LowC53+Ritchf14W+OpenB20+ParallelK42	480	100	2	481	0.4%	84	K39
41	ParallelK42	456	77	16	472	3.4%	75	K39
42	Shef+ShSpr+LowC53+Ritchf14W+OpenB20+HBESS+K42-2	444	65	2	446	0.4%	48	K39
43	B20+B22	382	2	22	404	5.4%	6	K39
44	HSC	394	15	18	412	4.4%	15	K39
45	B20+LowellC53SwitchClose+B22	385	6	32	417	7.6%	19	K39
			Limit was determined by limiting a 34.5 kV line to not trip					

Table 7: SHEI Thermal Limits – Essex STATCOM Out-Of-Service Cases

CASE	UPGRADES	ESSEX SHEI-TH	DELTA SHEI	B20	ESSEX SHEI+B20-TH	% B20 / (SHEI+B20)	DELTA SHEI+B20	LIMITING CONT
0		379	0	18	397	4.5%	0	K39
1	B20	394	14	22	415	5.3%	18	K39
2	B20+Shef	402	23	22	424	5.2%	27	K39
3	B20+JaySC	396	16	22	417	5.2%	20	K39
4	B20+ShSprAVR	406	26	22	428	5.1%	30	K39
5	B20+Shef+JaySC	402	23	22	424	5.2%	27	K39
6	B20+Shef+ShSpr	406	26	22	428	5.2%	31	K39
7	B20+JaySC+ShSpr	406	26	22	428	5.2%	31	K39
8	B20+Shef+Jay+ShSpr	407	28	22	430	5.1%	32	K39
9	B20+Shef+Jay+ShSpr+HSC	411	31	22	433	5.1%	36	K39
10	B20+Shef+Jay+ShSpr+K42-2	430	51	22	452	4.9%	55	K39
11	B20+Shef+Jay+ShSpr+K39P	416	37	22	438	5.0%	40	NONE
12	B20+Shef+Jay+ShSpr+HBESS	425	45	22	447	4.9%	50	K39
13	B20+Shef+Jay+ShSpr+K41	408	28	22	430	5.1%	32	K39
14	Shef+Jay+ShSpr+IraStowe&3312	468	89	11	479	2.3%	82	K41
15	Shef+Jay+ShSpr+IraEF	454	75	14	468	3.1%	71	NONE
16	Shef+Jay+ShSpr	394	15	18	412	4.4%	15	K42
17	Shef+Jay+ShSpr+HSC	394	15	18	412	4.3%	15	K42
18	Shef+Jay+ShSpr+K42-2	394	15	18	412	4.3%	15	K42

Table 8: SHEI Voltage Limits – Line K19 Out-Of-Service Cases

CASE	UPGRADES	K19 SHEI-V	DELTA SHEI	B20	K19 SHEI+B20-V	% B20 / (SHEI+B20)	DELTA SHEI+B20	LIMITING CONT
0		367	0	18	385	4.6%	0	K39
1	B20	371	4	22	392	5.6%	8	K39
2	B20+Shef	371	4	22	393	5.6%	8	K39
3	B20+JaySC	371	4	22	393	5.6%	8	K39
4	B20+ShSprAVR	371	4	22	392	5.6%	8	K39
5	B20+Shef+JaySC	374	8	22	396	5.6%	12	K39
6	B20+Shef+ShSpr	375	9	22	397	5.5%	13	K39
7	B20+JaySC+ShSpr	375	9	22	397	5.5%	13	K39
8	B20+Shef+Jay+ShSpr	387	20	22	409	5.4%	24	K39_B22
9	B20+Shef+Jay+ShSpr+HSC	411	44	22	433	5.1%	49	K39_B22
10	B20+Shef+Jay+ShSpr+K42-2	392	25	22	414	5.3%	29	K39_B22
11	B20+Shef+Jay+ShSpr+K39P	401	35	22	423	5.2%	39	K28_B22
12	B20+Shef+Jay+ShSpr+HBESS	421	54	22	443	5.0%	59	K39_B22
13	B20+Shef+Jay+ShSpr+K41	398	31	22	420	5.3%	35	K39_B22
14	Shef+Jay+ShSpr+IraStowe&3312	455	89	10	466	2.2%	81	K41
15	Shef+Jay+ShSpr+IraEF	447	80	15	462	3.2%	77	K41
16	Shef+Jay+ShSpr	371	4	18	389	4.6%	4	K39
17	Shef+Jay+ShSpr+HSC	407	41	18	426	4.3%	41	K39_B20
18	Shef+Jay+ShSpr+K42-2	384	18	18	402	4.4%	18	K39_B20
19	Shef	367	0	18	385	4.6%	0	K39
20	ShSpr	367	0	18	385	4.7%	0	K39
21	Shef+ShSpr	367	0	18	385	4.7%	0	K39
22	B20+LowellC53SwitchClose	341	-26	31	372	8.4%	-13	K21_HGTrip
23	B20+Shef+ShSpr+LowellC53Sw	379	13	32	411	7.7%	27	K39_B22
24	B20+Shef+ShSpr+LowC53+Ritchf14W	380	13	32	411	7.7%	27	K39_B22
25	HighgateBESS	387	20	18	405	4.4%	20	K39
26	SheffieldBESS	407	41	18	425	4.1%	40	K39
27	B20+Shef+Jay+ShSpr+SheffBESS	412	45	22	433	5.0%	49	K39_B22
28	B20+K42-2	371	4	22	392	5.5%	8	K21_HGTrip
29	Shef+K42-2	378	11	18	396	4.5%	11	K39
30	ShSpr+K42-2	373	6	18	391	4.5%	6	K39
31	HSC+K42-2	382	15	18	400	4.5%	15	K39
32	B20+HSC+K42-2	387	21	22	409	5.3%	25	K39_B22
33	K42-2+HighgateBESS	396	29	18	414	4.3%	29	K39
34	K42-2+SheffieldBESS	417	50	17	435	4.0%	50	K39
35	K42-2+IraStowe115	446	79	10	456	2.2%	71	K41
36	B20+Shef+Jay+ShSpr+ParallelK42	436	69	20	456	4.3%	71	K39_B22
37	HSC+ParallelK42	440	73	16	456	3.5%	71	K39
38	B20+Shef+ShSpr+B22	411	44	22	433	5.2%	49	K39
39	B20+Shef+Jay+ShSpr+K42-2+B22	423	56	22	445	5.0%	61	K39
40	Shef+ShSpr+LowC53+Ritchf14W+OpenB20+ParallelK42	465	98	2	466	0.4%	82	K39
41	ParallelK42	439	72	16	455	3.5%	70	K39
42	Shef+ShSpr+LowC53+Ritchf14W+OpenB20+HBESS+K42-2	439	72	2	440	0.4%	56	K39
43	B20+B22	369	2	22	391	5.6%	6	K39
44	HSC	374	7	18	392	4.6%	7	K39
45	B20+LowellC53SwitchClose+B22	341	-26	31	372	8.4%	-13	K21_HGTrip
			Limit was determined by limiting a 34.5 kV line to not trip					

Table 9: SHEI Voltage Limits – Stowe 115/34.5 KV XFMR Out-Of-Service Cases

CASE	UPGRADES	STOWE SHEI-V	DELTA SHEI	B20	STOWE SHEI+B20-V	% B20 / (SHEI+B20)	DELTA SHEI+B20	LIMITING CONT
0		399	0	19	418	4.5%	0	K39
1	B20	440	41	23	463	4.9%	45	K39
2	B20+Shef	448	49	23	471	4.8%	53	K39
3	B20+JaySC	440	41	23	463	4.9%	45	K39
4	B20+ShSprAVR	448	49	23	471	4.8%	53	K39
5	B20+Shef+JaySC	448	49	23	471	4.8%	53	K39
6	B20+Shef+ShSpr	450	51	23	473	4.8%	55	K39_B22
7	B20+JaySC+ShSpr	446	47	23	469	4.8%	51	K39
8	B20+Shef+Jay+ShSpr	452	53	23	475	4.8%	57	K39_B22
9	B20+Shef+Jay+ShSpr+HSC	472	73	23	496	4.7%	78	K39_B22
10	B20+Shef+Jay+ShSpr+K42-2	464	65	23	487	4.7%	69	K39_B22
11	B20+Shef+Jay+ShSpr+K39P	467	68	23	489	4.6%	72	K28_B22
12	B20+Shef+Jay+ShSpr+HBESS	476	77	23	499	4.7%	82	K39_B22
13	B20+Shef+Jay+ShSpr+K41	457	58	23	480	4.7%	62	K39_B22
14	Shef+Jay+ShSpr+IraStowe&3312	501	102	14	515	2.7%	97	N/A
15	Shef+Jay+ShSpr+IraEF	500	100	16	516	3.1%	98	N/A
16	Shef+Jay+ShSpr	439	39	19	457	4.1%	39	K39_B20
17	Shef+Jay+ShSpr+HSC	456	57	19	475	4.0%	57	K39_B20
18	Shef+Jay+ShSpr+K42-2	448	49	19	467	4.0%	49	K39_B20
		(purple)	Limit was determined by limiting a 34.5 kV line to not trip					
		(yellow)	Northwestern VT gen maximized & No. VT load minimized					

Table 10: SHEI Voltage Limits – Line 3317 Out-Of-Service Cases

CASE	UPGRADES	3317 SHEI-V	DELTA SHEI	B20	3317 SHEI+B20-V	% B20 / (SHEI+B20)	DELTA SHEI+B20	LIMITING CONT
0		410	0	18	428	4.1%	0	K39
1	B20	450	40	22	472	4.6%	44	K39
2	B20+Shef	458	48	22	480	4.6%	52	K39
3	B20+JaySC	453	43	22	475	4.6%	47	K39
4	B20+ShSprAVR	456	46	22	478	4.6%	50	K39
5	B20+Shef+JaySC	458	48	22	480	4.6%	52	K39
6	B20+Shef+ShSpr	458	48	22	480	4.6%	52	K39
7	B20+JaySC+ShSpr	458	48	22	480	4.6%	52	K39
8	B20+Shef+Jay+ShSpr	460	50	22	482	4.6%	55	K39_B22
9	B20+Shef+Jay+ShSpr+HSC	480	70	23	503	4.6%	76	K39_B22
10	B20+Shef+Jay+ShSpr+K42-2	474	64	22	496	4.5%	68	K39_B22
11	B20+Shef+Jay+ShSpr+K39P	474	64	22	496	4.5%	68	K28_B22
12	B20+Shef+Jay+ShSpr+HBESS	484	75	24	508	4.6%	80	K39_B22
13	B20+Shef+Jay+ShSpr+K41	472	62	23	495	4.6%	67	K39_B22
14	Shef+Jay+ShSpr+IraStowe&3312	504	94	11	515	2.2%	88	N/A
15	Shef+Jay+ShSpr+IraEF	500	90	15	515	3.0%	88	N/A
16	Shef+Jay+ShSpr	441	32	18	459	3.9%	32	K39_B20
17	Shef+Jay+ShSpr+HSC	466	56	18	484	3.8%	57	K39_B20
18	Shef+Jay+ShSpr+K42-2	453	44	18	471	3.8%	44	K39_B20
		(purple)	Limit was determined by limiting a 34.5 kV line to not trip					
		(yellow)	Northwestern VT gen maximized & No. VT load minimized					

Table 11: SHEI Voltage Limits – Line K28 Out-Of-Service Cases

CASE	UPGRADES	K28 SHEI-V	DELTA SHEI	B20	K28 SHEI+B20-V	% B20 / (SHEI+B20)	DELTA SHEI+B20	LIMITING CONT
0		253	0	13	265	4.8%	0	K42
1	B20	260	7	16	276	5.8%	10	K42
2	B20+Shef	285	33	18	304	6.1%	38	K42
3	B20+JaySC	274	22	17	292	5.9%	26	K42
4	B20+ShSprAVR	282	29	18	300	6.0%	34	K42
5	B20+Shef+JaySC	285	33	18	304	6.1%	38	K42
6	B20+Shef+ShSpr	285	33	18	304	6.1%	38	K42
7	B20+JaySC+ShSpr	282	29	18	300	6.0%	34	K42
8	B20+Shef+Jay+ShSpr	285	33	18	304	6.1%	38	K42
9	B20+Shef+Jay+ShSpr+HSC	285	33	18	304	6.1%	38	K42
10	B20+Shef+Jay+ShSpr+K42-2	285	33	18	303	5.9%	38	K42
11	B20+Shef+Jay+ShSpr+K39P	285	33	18	304	6.1%	38	K42
12	B20+Shef+Jay+ShSpr+HBESS	315	63	20	335	6.0%	70	K42
13	B20+Shef+Jay+ShSpr+K41	285	33	19	304	6.2%	39	K42
14	Shef+Jay+ShSpr+IraStowe&3312	459	206	12	470	2.4%	205	IraStowe_B20
15	Shef+Jay+ShSpr+IraEF	458	206	17	475	3.6%	210	IraEF_B20
16	Shef+Jay+ShSpr	275	23	15	291	5.3%	25	K42
17	Shef+Jay+ShSpr+HSC	275	23	15	291	5.3%	25	K42
18	Shef+Jay+ShSpr+K42-2	276	23	15	291	5.1%	25	K42
			Limit was determined by limiting a 34.5 kV line to not trip					

3.1 Delta SHEI vs. Delta SHEI+B20

Figure 4 shows a comparison of the Delta SHEI and Delta SHEI+B20 All Lines In Voltage limits. When the B20 flow was included in the total Delta SHEI+B20 flow, the change from the original Delta SHEI flow was in the +/- 7 MW range, with the exceptions being for the closure of the 46 kV Lowell C53 switch, resulting in an increase of up to 17 MW with B20 line remaining closed, or up to a decrease of up to 16 MW with the opening of the B20 line. This demonstrates the importance of including the B20 flow in the closed SHEI+B20 interface.

Figure 5 shows a comparison of the Delta SHEI and Delta SHEI+B20 All Lines In Thermal limits. When the B20 flow was included in the total Delta SHEI+B20 flow, the change from the original Delta SHEI flow was in the - 7 to +4 MW range, with the exceptions being for the closure of the 46 kV Lowell C53 switch, resulting in an increase of up to 14 MW with B20 line remaining closed, or up to a decrease of up to 16 MW with the opening of the B20 line. Once again, this demonstrates the importance of including the B20 flow in the closed SHEI+B20 interface.

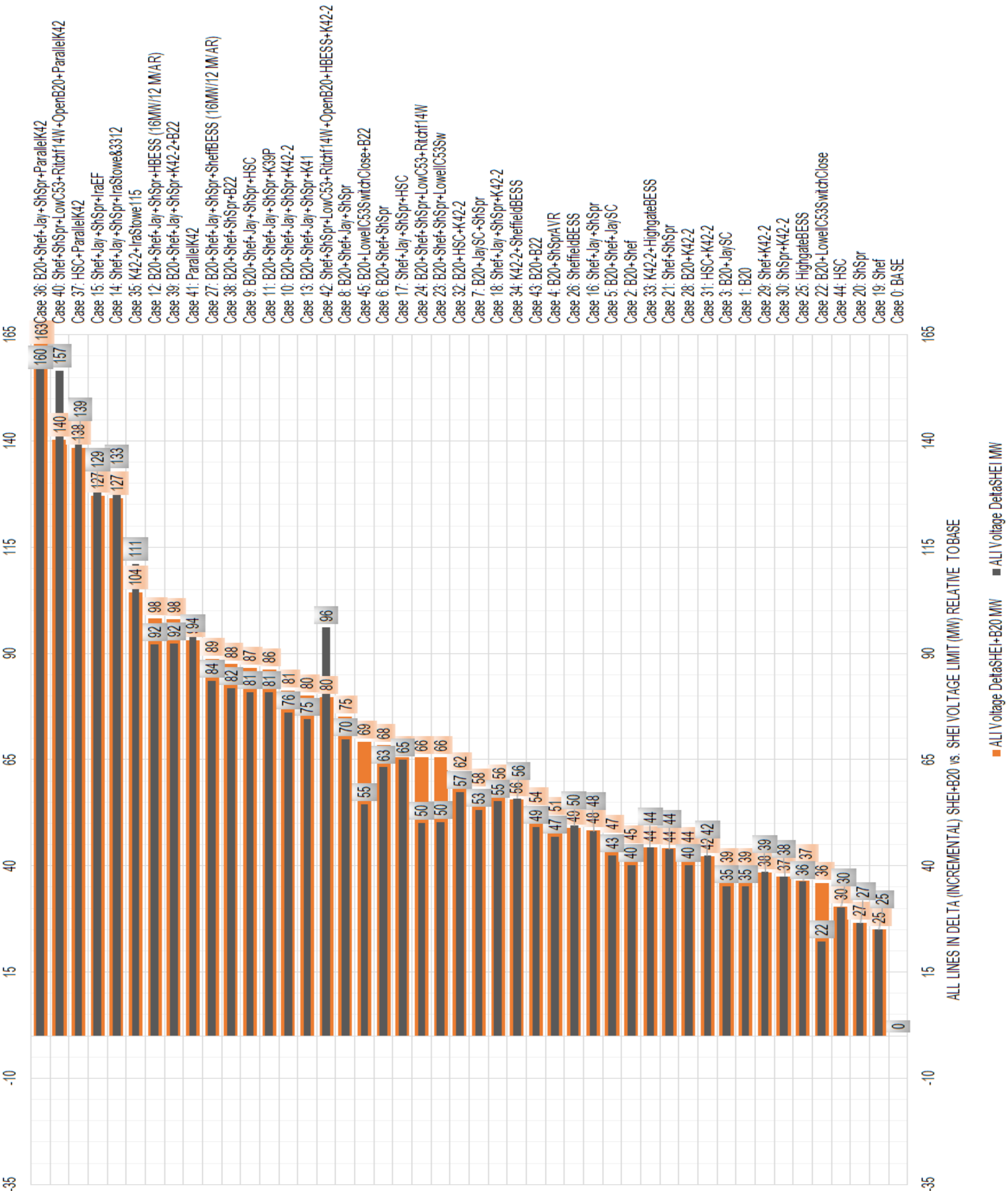

Figure 4: Comparison Delta SHEI vs. Delta SHEI+B20 Voltage Limits – ALI Cases

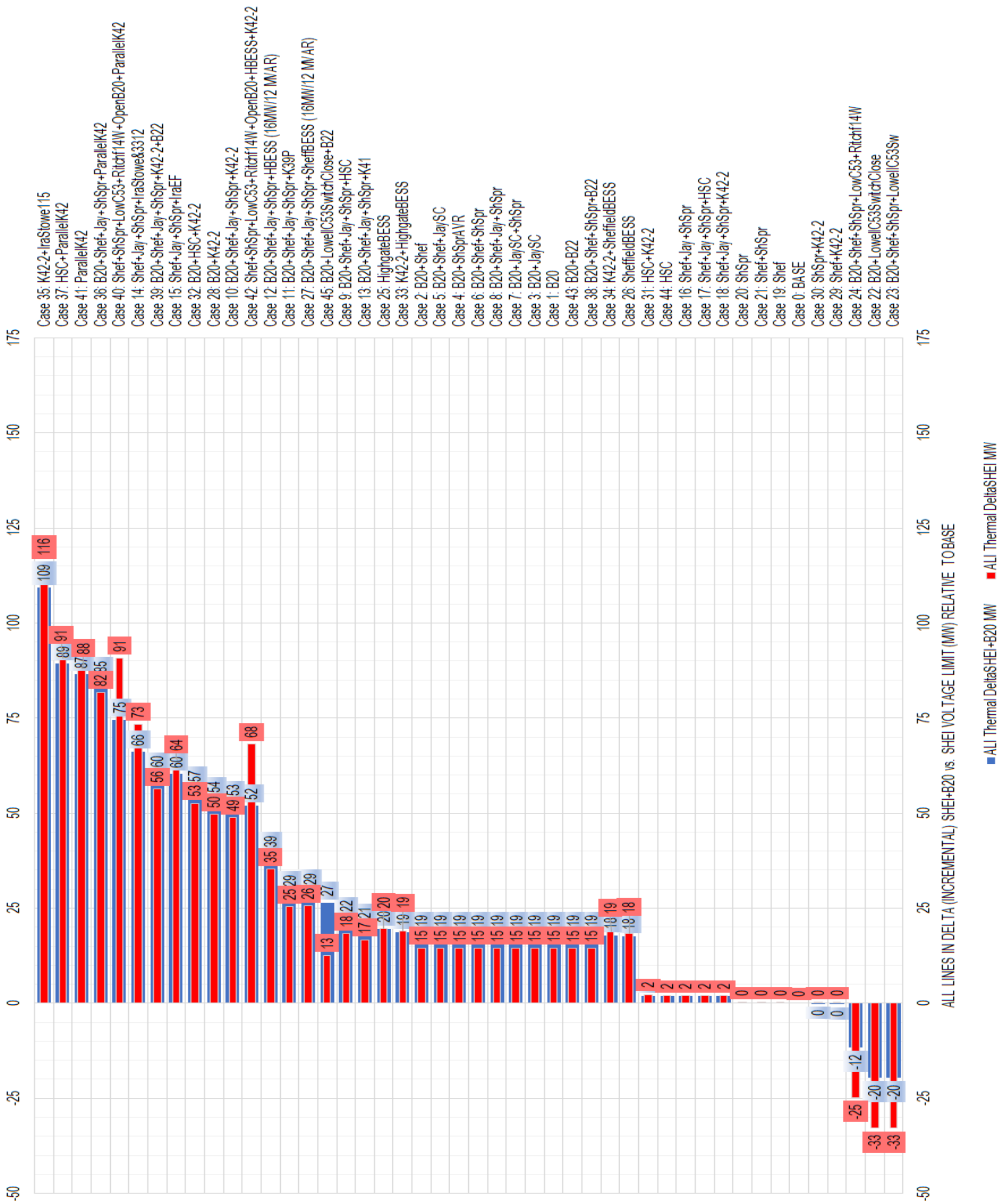

Figure 5: Comparison Delta SHEI vs. Delta SHEI+B20 Thermal Limits – ALI Cases

3.2 Delta SHEI+B20

From this point forward, only Delta SHEI+B20 plots will be shown, to be able to better capture the effects of the upgrade options.

Figure 6 and Figure 7 show All Lines In Voltage and Thermal Delta (incremental from base) SHEI+B20 limits, respectively, sorted from highest to lowest. Figure 8 shows a comparison of the Delta SHEI+B20 for All Lines In, comparing voltage and thermal limits. Figure 9 and Figure 10 show Essex STATCOM and K19 out-of-service Delta SHEI+B20 Voltage limits, respectively, sorted from highest to lowest. Figure 11 shows a comparison of the Delta SHEI+B20 Voltage, comparing All Lines In, Essex STATCOM out-of-service, and K19 out-of-service limits.

All of the Delta SHEI+B20 results that were negative included the Lowell C53 upgrade, which resulted in diverting additional flow down through the 34.5 kV network.

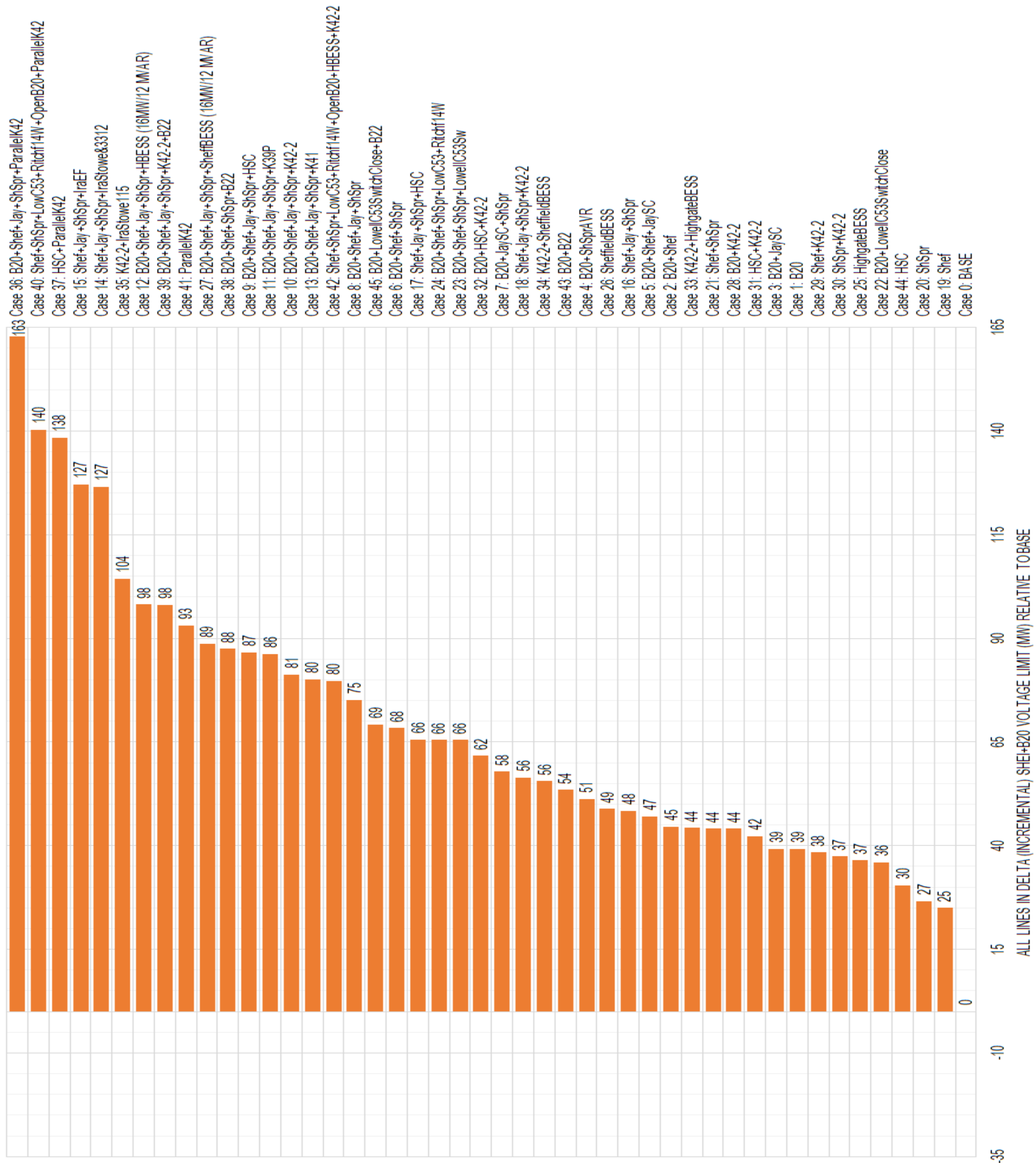

Figure 6: Delta SHEI+B20 Voltage Limits – ALI Cases – Sorted High To Low

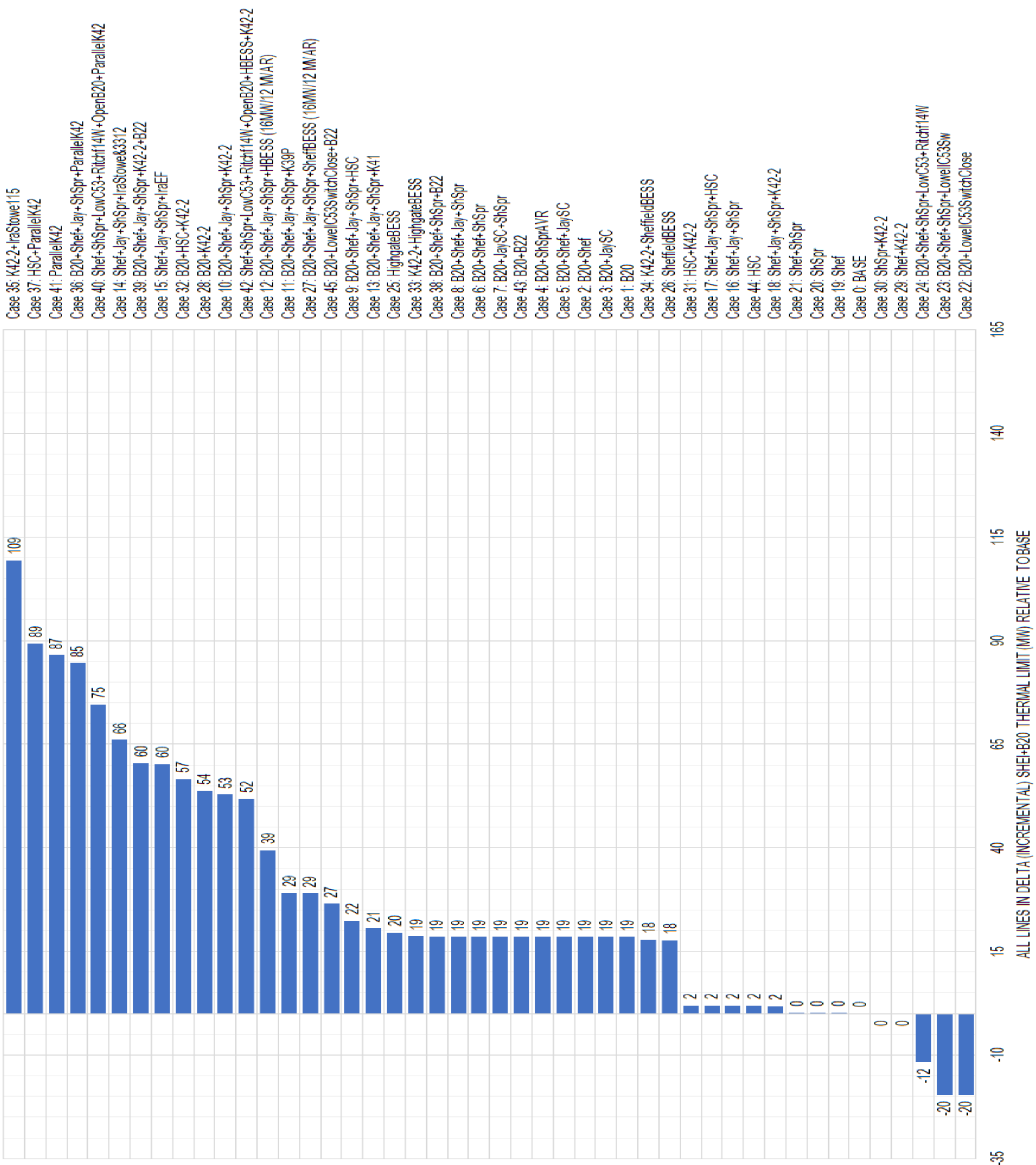

Figure 7: Delta SHEI+B20 Thermal Limits – ALI Cases – Sorted High To Low

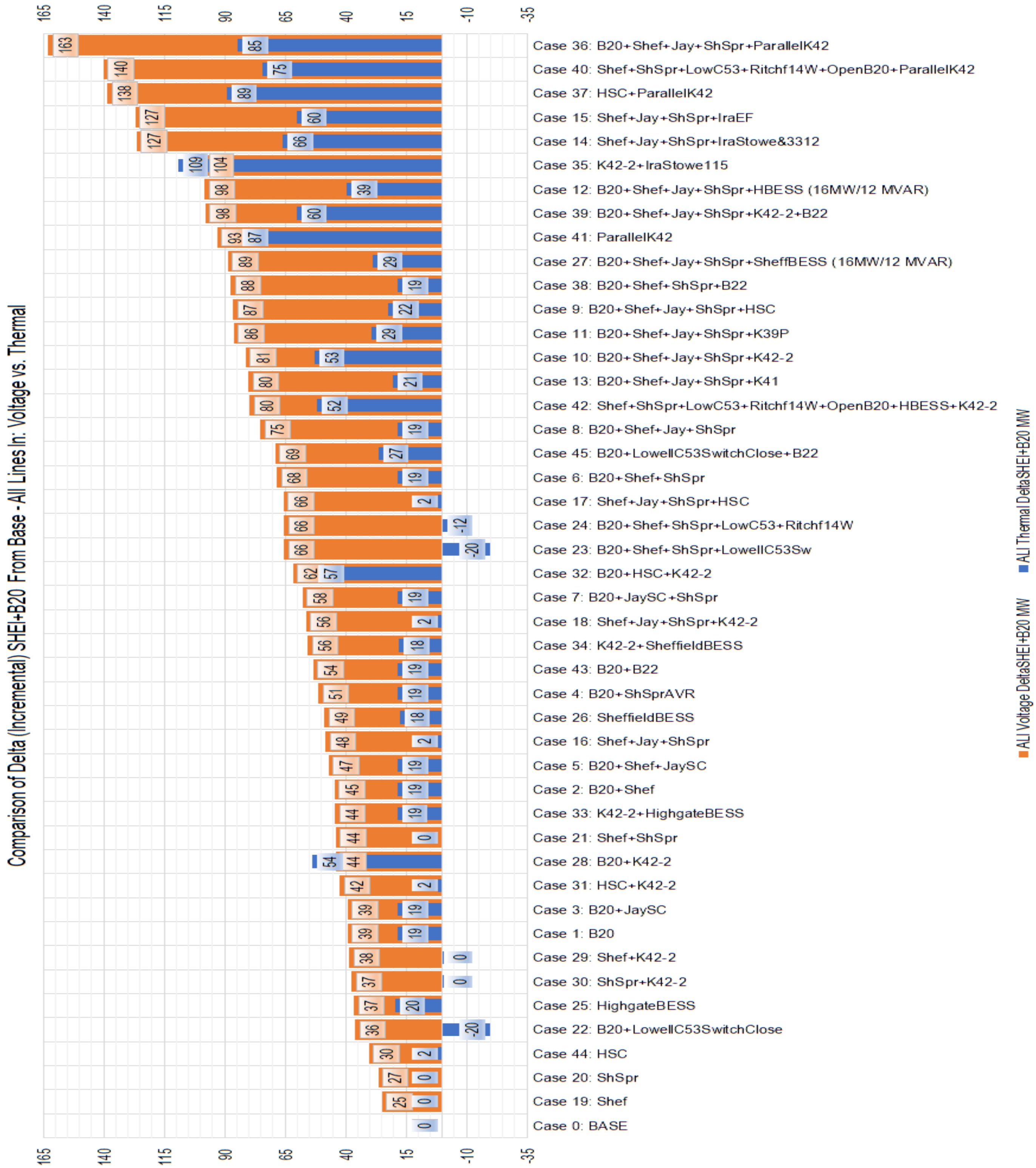

Figure 8: Comparison of Delta SHEI+B20 from Base – ALI: Voltage vs. Thermal

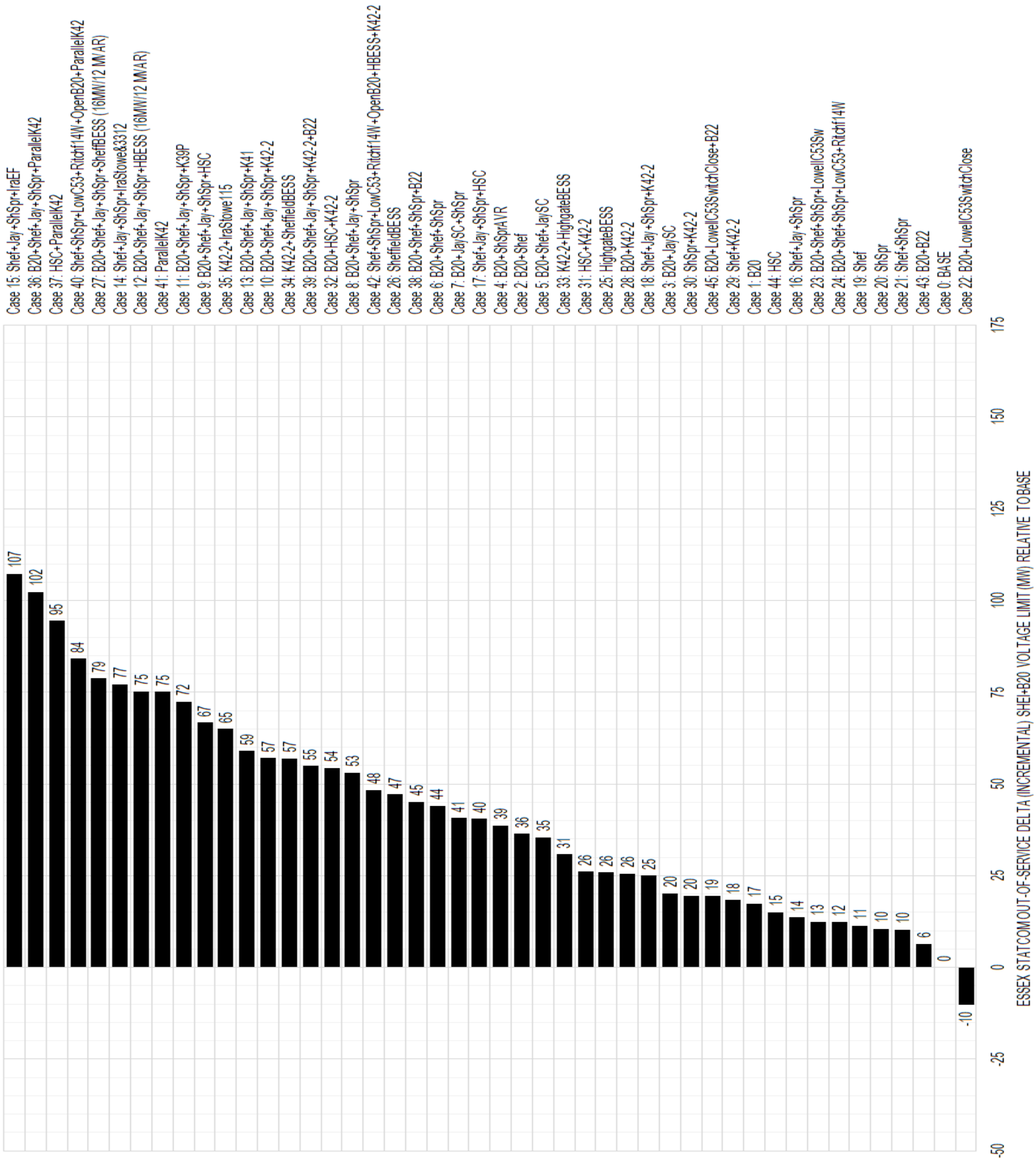

Figure 9: Delta SHEI+B20 Voltage Limits – Essex STATCOM OOS Cases

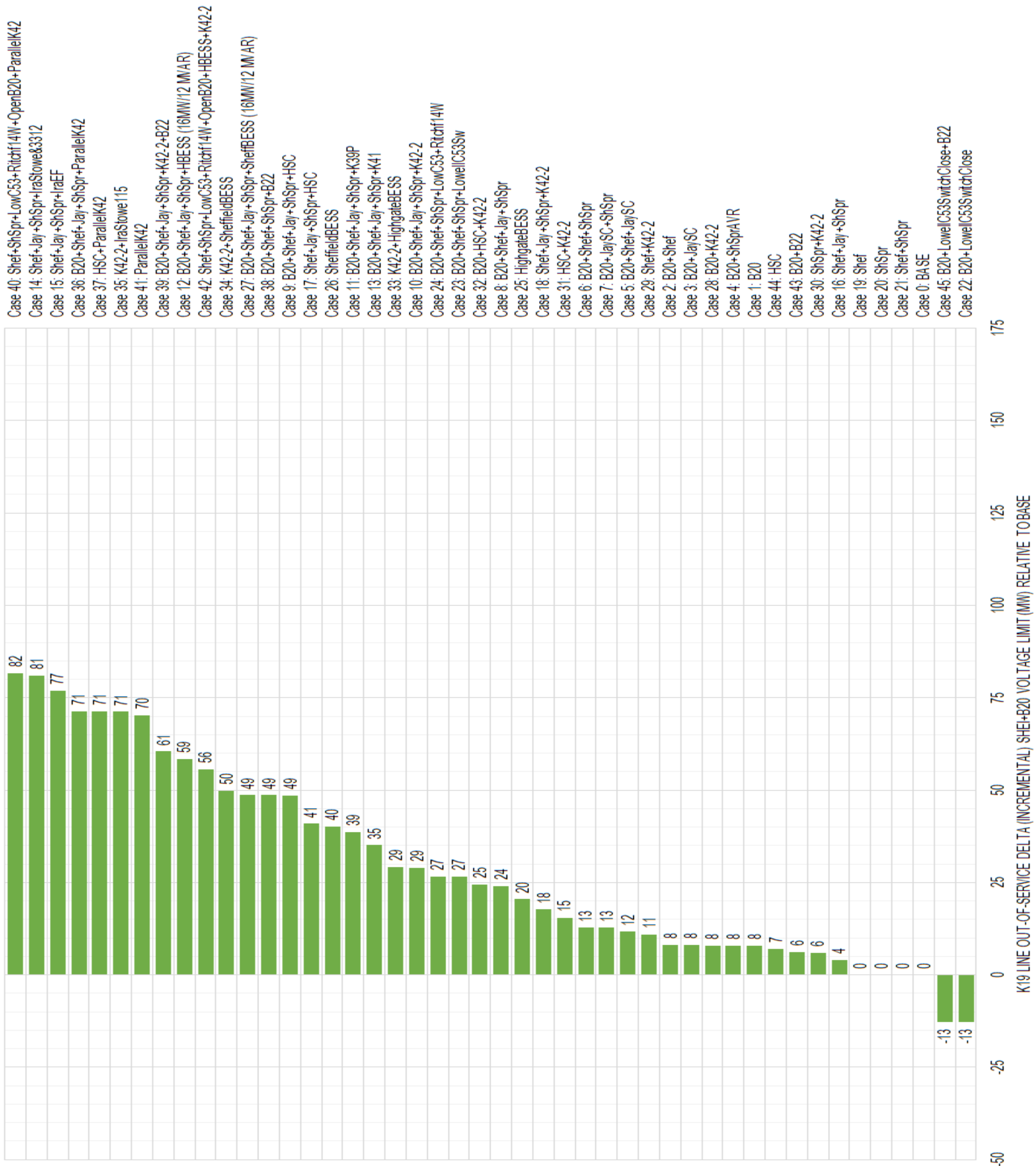

Figure 10: SHEI+B20 Voltage Limits – K19 OOS Cases – Sorted High To Low

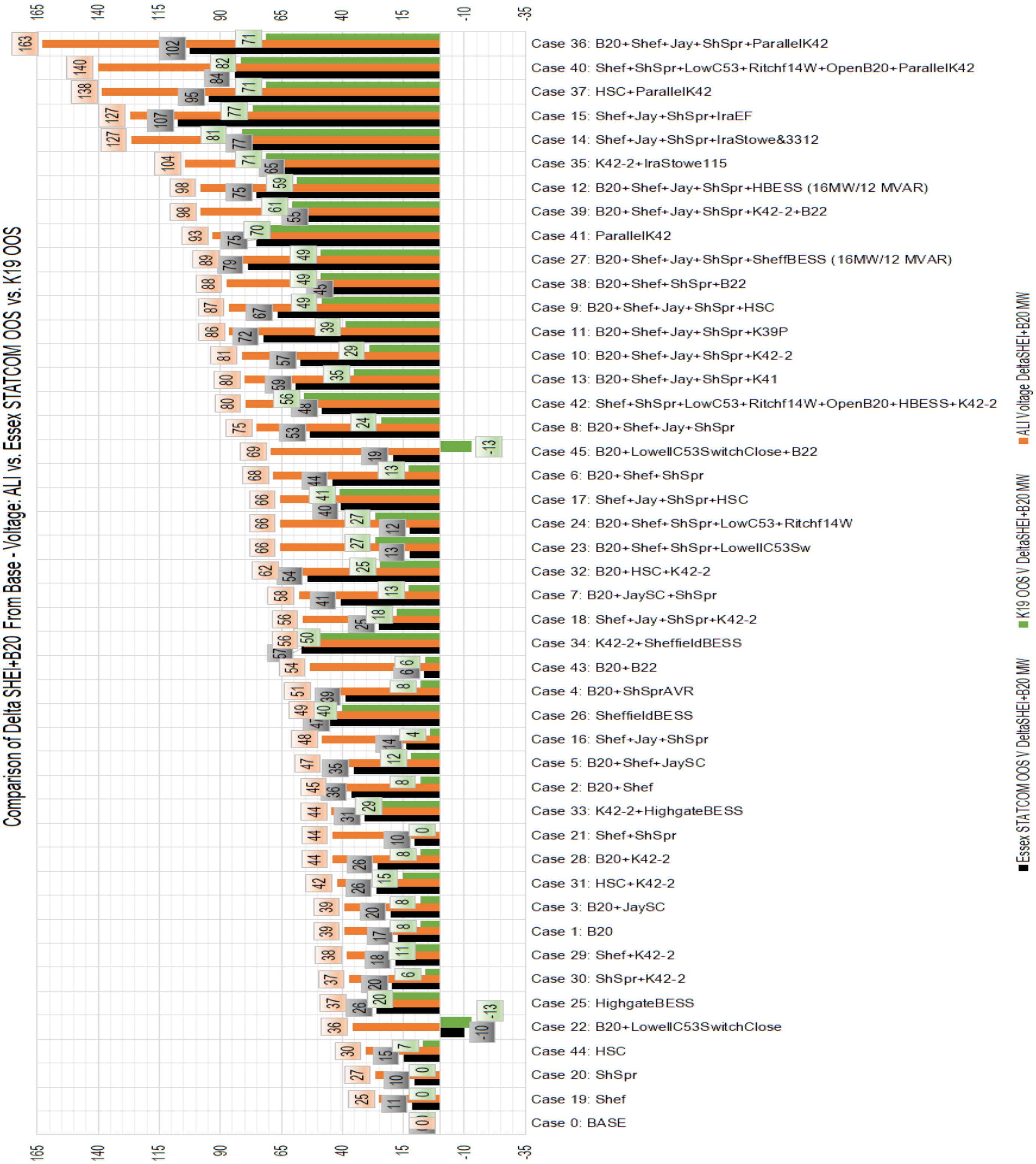

Figure 11: Comparison of Delta SHEI+B20 from Base –Volt: ALI vs. Essex vs. K19

4.0 Discussion of Results

Overall, the upgrade options including construction of a new 115 kV line resulted in significantly higher voltage and thermal SHEI limits relative to the reactive or 34.5 kV upgrades alone. The new 115 kV line upgrades performed very well both for all lines in and facility out conditions. Figure 12 shows the Delta (incremental) All Lines In SHEI+B20 Voltage limits, noting the trending of small individual upgrades from the low end (+25 MW) to the addition of new 115 kV transmission lines combined with other upgrade options at the top end (as high as +163 MW).

Figure 13 shows the All Lines In SHEI Thermal limits, noting cases that clustered together around these thermal upgrades:

- C53 closed without B22—the Lowell C53 switch closing diverted flow onto the underlying 34.5 kV network
- B20 not upgraded—essentially no SHEI+B20 Thermal benefit from any of these combinations of upgrades that did not include upgrading B20
- B20 upgrade—low benefit to SHEI+B20 Thermal when B20 was upgraded
- BESS upgrades—a low benefit to SHEI+B20 Thermal from combinations of upgrades that included either the Highgate or Sheffield battery storage upgrade
- K42-2 upgrades—a moderate benefit (when combined with other upgrades) to SHEI+B20 Thermal
- 2nd lines—a high benefit for combinations that included new 115 kV lines terminating in the western side of Vermont (the eastern-most parallel line to K39 only showed a low benefit)

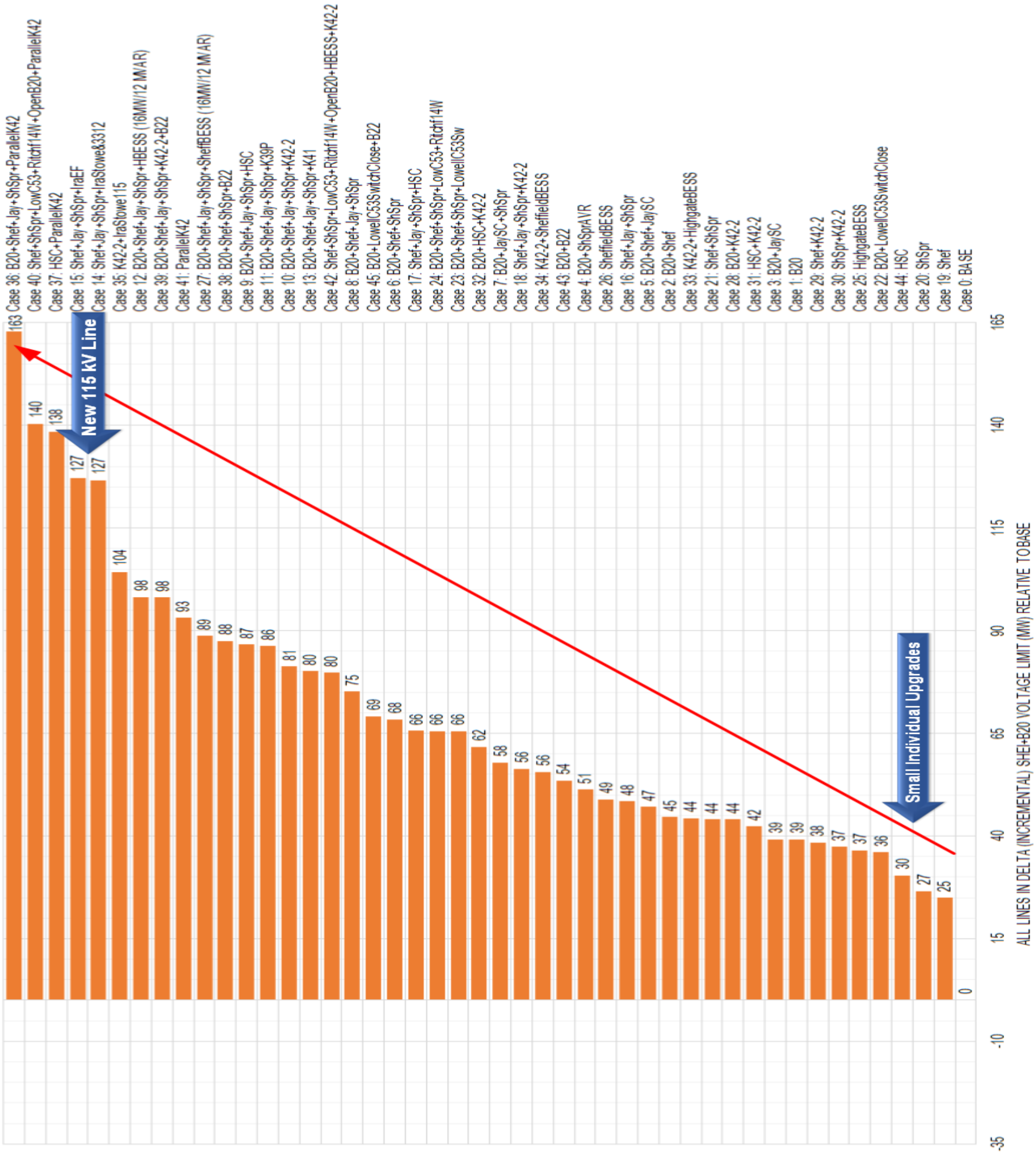

Figure 12: SHEI+B20 Voltage Limits – All Lines In Cases – Trending

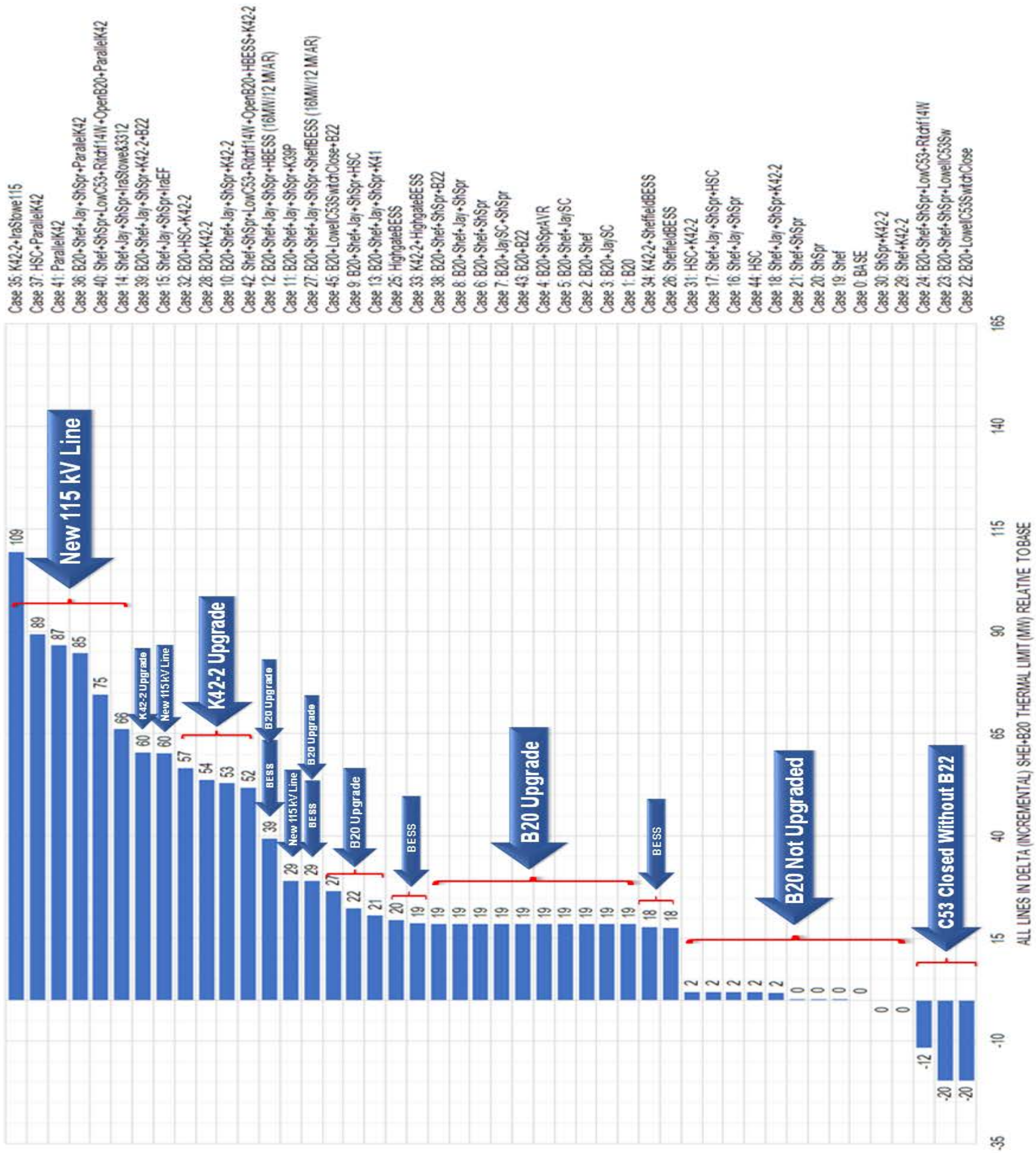

Figure 13: SHEI+B20 Thermal Limits – All Lines In Cases – Trending

4.1 Top Ten Cases With Highest SHEI-V+B20 Limits

Figure 14 shows the top 10 cases with the highest All Lines In SHEI+B20 Voltage limits with comparisons to the Essex STATCOM and K19 out-of-service SHEI+B20 Voltage limits as well as All Lines In SHEI+B20 Thermal limits. The top six (right-most in landscape view) cases (Cases 36, 40, 37, 14, 15, and 35) each included a new 115 kV line terminating in the western side of Vermont (Parallel line to K42, Irasburg – Stowe, and Irasburg – East Fairfax). These top six cases all showed large increases in All Lines In SHEI+B20 Voltage limits (+104 to +163 MW) relative to benchmark Case 0, plus also showed impressive increases in facility out Voltage and All Lines In Thermal limits, demonstrating significant overall benefit to SHEI+B20 limits, for the conditions tested.

Case 41, which had only a single upgrade, the Parallel 115 kV line to K42, also showed impressive overall SHEI+B20 limit increases, with a +93 MW All Lines In SHEI+B20 Voltage limit increase, +87 MW for All Lines In Thermal, +75 MW for Essex STATCOM out-of-service, and +70 MW for K19 out-of-service.

The remaining three of the top ten did not include new 115 kV lines. Cases 12 and 27 included reconductoring the B20 line, activating the Sheffield and Sheldon Springs AVRs, enhancing the Jay synchronous condenser reactive capability, plus adding a 20 MVA battery energy storage unit (at Highgate or Sheffield, respectively). Case 39 included the B20 and B22 34.5 kV line reconductoring, Sheffield/Jay/Sheldon Springs reactive upgrades, plus reconductoring 115 kV line K42-2 line from Highgate to St. Albans. These options that did not include a new 115 kV line had fairly high All Lines In Voltage Delta SHEI+B20, however the facility out and thermal limits were less effective in comparison to the new 115 kV line option combinations.

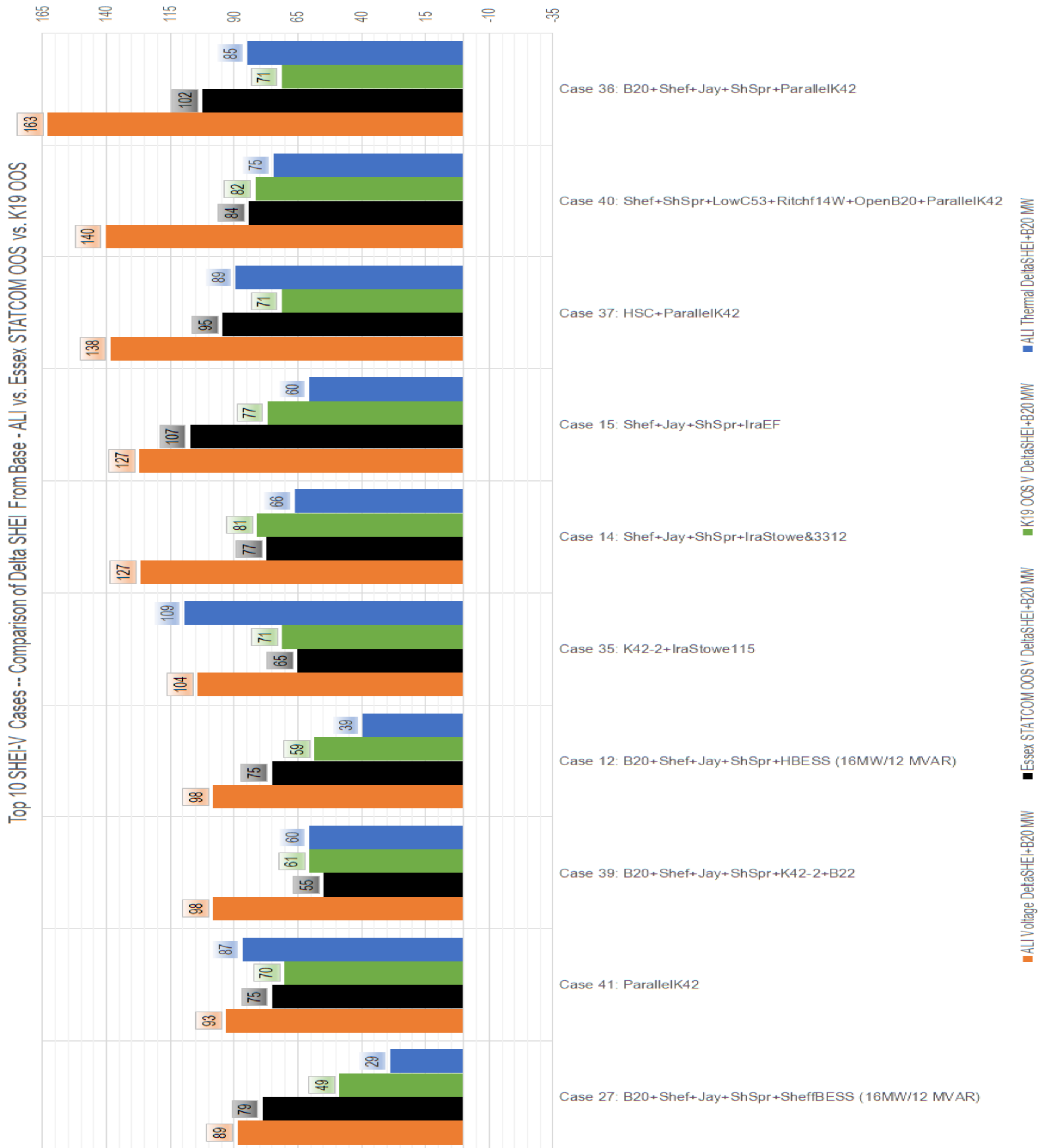

Figure 14: Top 10 SHEI-V+B20—Comparison– ALI vs. Essex OOS vs. K19 OOS

Overall, with more upgrades combined per case, the higher the SHEI+B20 limits tended to be. For example, for All Lines In SHEI Voltage limits testing, the upgrade of line B20 alone (Case 1) resulted in a 39 MW Delta SHEI+B20, whereas as other upgrades were bundled with the B20 upgrade, the voltage limit increased, as shown in Figure 15 below. As a comparison, Case 38, which includes the B20, Sheffield AVR, Sheldon Springs AVR, and B22 upgrades, showed an 88 MW Delta SHEI+B20 Voltage limit, an increase of 49 MW over the B20 upgrade alone. Also, any combination of upgrades that can be made to raise the voltage limit higher will help additionally under facility out conditions. This can be seen in the line B20 upgrade options shown in Figure 15. Also, the Essex STATCOM and line K19 out-of-service limits shown to be markedly higher with the additional bundled upgrades of Case 38.

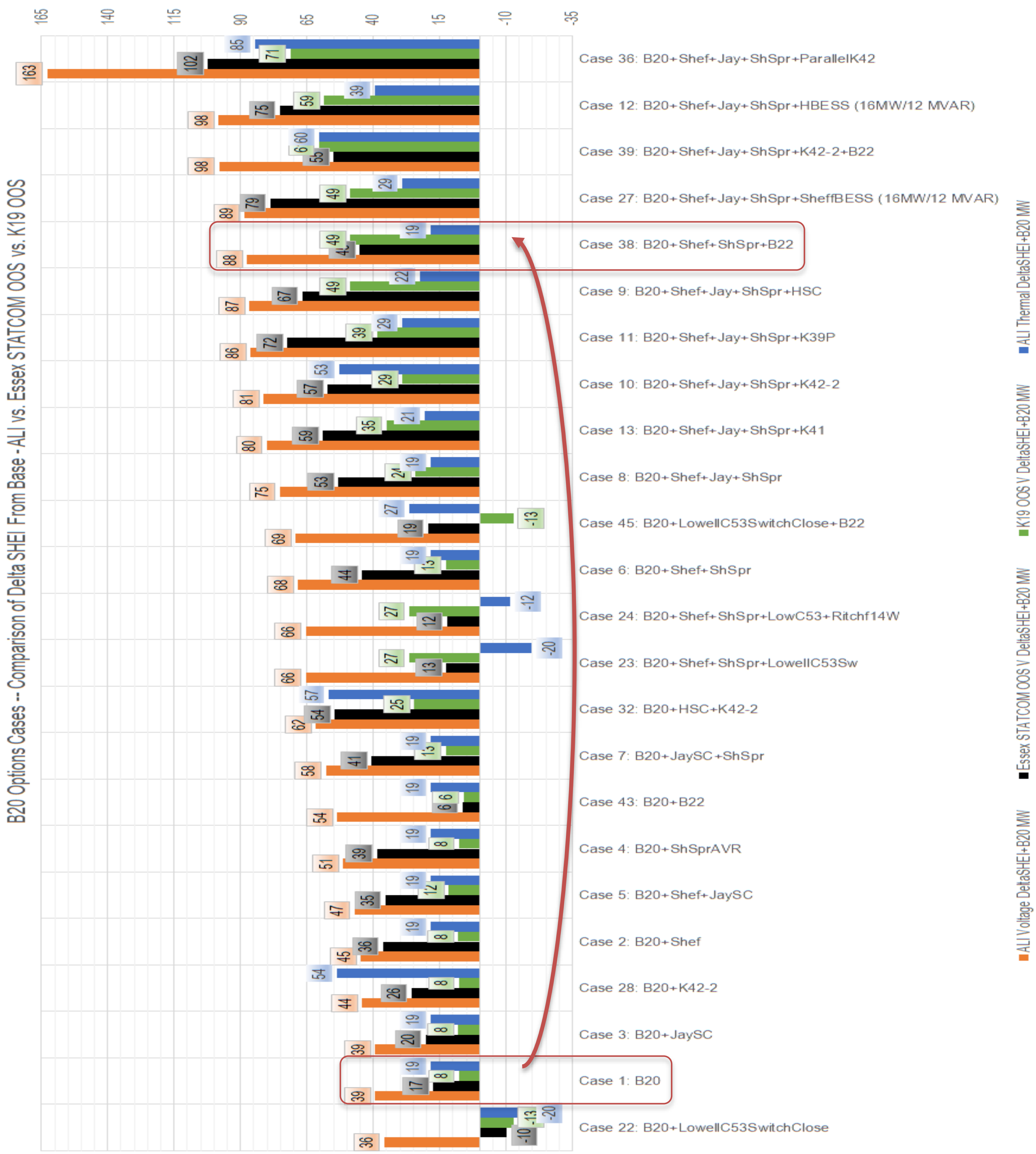

Figure 15: B20 Options - Comparison – Voltage: ALI vs. Essex OOS vs. K19 OOS

4.2 34.5 kV Line B20 Power Flow

Power flow results demonstrate that the existing 34.5 kV B20 line is a major factor in permitting SHEI+B20 power transfers to be increased from northern to southern Vermont. This is because the B20 line is operated in parallel with the 115 kV system and causes thermal limitations for many of the study cases. For the All Lines In Voltage cases, B20 MW flow was calculated to be between 11 and 33 MW, while SHEI+B20 MW transfers were between 418 and 581 MW, for various upgrade configurations (see Table 4).

To get a sense of the proportion of the interface that flows across this line, the B20 MW flow was divided by the SHEI+B20 MW flow for All lines in conditions.

$$\boldsymbol{B20\ as\ Percent\ of\ (SHEI_V + B20) = \frac{B20}{(SHEI_V + B20)}}$$

Figure 16 displays a plot of the “B20 Flow as a percent of SHEI_V+B20” versus “SHEI_V+B20” for All lines in cases. Groupings of data are circled on this graph to emphasize the nature of B20 contribution to SHEI_V+B20 and its relation to equipment upgrades.

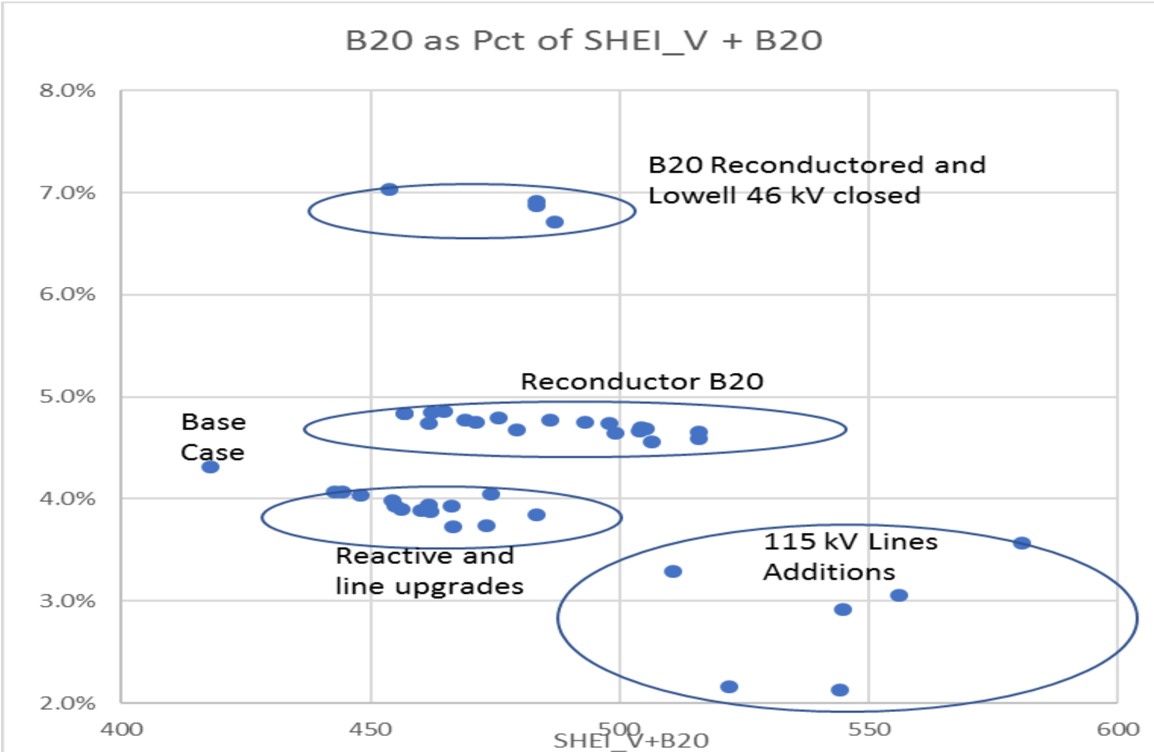

Figure 16: B20 MW Flow as Percent of SHEI_V+B20 Flow – All Lines In Cases

The benchmark Case 0, representing the existing electric system, shows that 4.3% of the SHEI_V flows on the B20 line (18 MW / 418 MW = 4.3%). Reactive and line reconductoring upgrades to the system decrease the flow on B20 line by one half percent (0.5%). Installing new 115 kV lines will decrease the B20 percent of SHEI_V by 1.0 to 2.3%. Reconductoring B20 increases the percent of flow by one half percent (0.5%). Reconductoring B20 and closing 46 kV lines near Kingdom Wind increases the B20 percent of flow by approximately 1% to 2.3%. In summary, after examining 17 upgrade options across 46 all-line-in load flow cases, the percent of flow on the B20 line ranged between 2.1% and 7.1% of SHEI_V+B20 (with 0.3% when B20 was opened).

4.3 Regression Analysis

The power flow analysis performed for this study included 46 All lines in alternatives, that consisted of multiple combinations of from one to six bundled upgrade options, out of 17 considered upgrade options (Table 2). In order to predict the average influence of one upgrade option versus another, statistical techniques would be required. SHEI data points were evaluated for both voltage and thermal constraints.

Microsoft Excel's Regression Analysis tool (via the Excel "Analysis Toolpak") was chosen to test a linear model with multiple variables as shown in the following equation:

$$\boldsymbol{Y = b + (a_1 * X_1) + (a_2 * X_2) + (a_3 * X_3) + \cdots + (a_n * X_n)}$$

The dependent variable ***Y*** represents ***SHEI_V+B20*** (predicted SHEI All Lines In Voltage limit including B20 line flow) or ***SHEI_TH+B20*** (predicted SHEI All Lines In Thermal limit including B20 line flow). In this model the Y axis intercept (which can be interpreted as the limit with no upgrades) is modeled as "b" with units of MW. Independent variables "X_i" are modeled as a logical (1 or 0) variables for each upgrade option. Coefficients (a_i, a_1, a_2, a_3, etc.) are calculated by the Regression tool and have units of MW.

To understand the importance of each individual Coefficient (a_i) of the X_i, the values for ***Standard Error*** and ***P-value*** calculated by the Regression tool also should be understood. ***Standard Error*** is used to calculate a Prediction Interval (high/low) about the Coefficient. The 95% Prediction Interval (***PI***) is approximately equal to the following:

$$\boldsymbol{PI = Coefficient\ Value \pm (2.05 * Standard\ Error)}$$

In linear regression, the ***P-value*** is a measure of significance:

- Less than 0.05 is significant
- Greater than 0.05 is <u>not</u> significant

When a coefficient is determined to be "Not Significant," it means that the X value is redundant to other values in the model and it can be removed without an impact on the ability to predict the outcome of "Y."

The regression analysis tool provides an indicator value called "R-squared" that measures the overall strength of the model—it is the percentage of the response variable that is explained by this linear model. While performing a regression of SHEI data from the power flow study, the R-squared values ranged between 0.904 and 0.987, meaning the linear model fits the data very well.

4.3.1 Regression Analysis for All Lines In Voltage

Table 12 below shows the regression results for model coefficients ($\boldsymbol{a_i}$), ***Standard Error*** ($\boldsymbol{SE_i}$), and ***P-value$_i$*** for the All Lines In Voltage SHEI_V+B20 model.

Table 12: All Lines In SHEI_V Regression

Voltage (SHEI_V+B20)			
R Square	0.986	Adjusted R Square	0.978
	Coefficients	*Standard Error*	*P-value*
Intercept	427.4	2.0	0.000
ParallelK42	94.9	3.1	0.000
IraStowe	82.9	4.0	0.000
IraEF	81.7	5.5	0.000
HBESS	26.5	3.0	0.000
B20	23.5	2.0	0.000
B22	23.5	2.9	0.000
SheffBESS	22.4	3.4	0.000
HSC	22.2	2.4	0.000
ShSpr	17.7	2.1	0.000
K39P	17.4	5.3	0.003
SHEF	13.9	2.1	0.000
K41	11.2	5.3	0.044
K42-2	10.0	1.9	0.000
LowC53	4.1	3.1	0.190
Jay	4.0	2.3	0.1
OpenB_20	(1.1)	5.5	0.839

In Table 12, for regression of All Lines In Voltage SHEI plus B20 flow (SHEI_V+B20), thirteen of the sixteen options that were modeled had coefficients that were positive values and were significant, with P-value<<0.05 (highlighted in green). Comparing the coefficients of each option helps to determine effectiveness of one upgrade option versus another. From this analysis, coefficients for the upgrade Options 3, 12 and 17 were not significant, and are highlighted in red.

The following discusses options that were shown not significant:

- Option 3—*Jay*: Recognize Jay synch condenser 1.15 service factor

   - Coefficient for Jay is relatively small and has a large Standard Error.
   - Other reactive improvements are more effective than this option
- Option 12—*LowC53*: Close the normally open Lowell C53 switch
   - This option has a relatively small Coefficient value and a large Standard Error
   - Closing the 46 kV will encourage more flow onto the B20 as shown in Figure 16 above, which can aggravate a thermally limited piece of equipment.
- Option 17—*Open_B20*: Open 34.5 kV line B20 at Johnson.
   - Coefficient is slightly negative and has a large Standard Error
   - Opening B20 does not have a significant impact on SHEI voltage limit

For the regression of SHEI_V+B20, the R-Squared was calculated as 0.986, which indicates a robust model for predicting the impact of each upgrade option. This means that the model will predict the outcome of SHEI_V+B20 98.6% of the time. The other 1.4% represents error in the model that can be attributed to other factors that were not included in the model.

For example, values from Table 12 are used to calculate the predicted effect of upgrade Option 15 (Install a 2nd 115 kV line alongside the K42 line) on the ALI SHEI_V+B20 transfer limit—this is then compared against the actual Case 41 SHEI_V+B20:

- Intercept coefficient "***b***" is estimated as 427.4 MW
- Coefficient a_{15} for X_{15} is estimated as 94.9 MW
- X_{15} = 1
- Thus, ***SHEI_V+B20 = 427.4+ (94.9 * 1) = 522.3 MW***
- For Case 41, which only includes Option 15, the actual calculated power flow result was 511 MW (2.2% less).

Figure 17 shows a graph comparing predicted versus actual All lines in SHEI_V+B20 Voltage limits. The predicted showed a close approximation to actual and follow a linear trend.

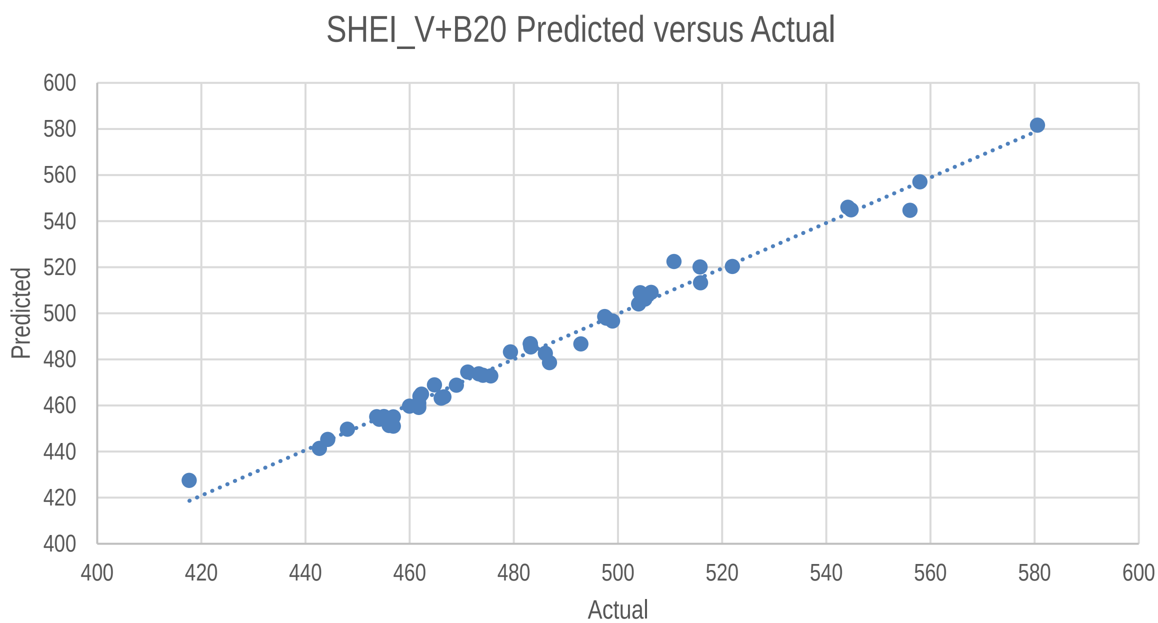

Figure 17: Predicted All Lines In SHEI_V+B20 vs. Actual

The Prediction Interval represents the range where a single new calculation of SHEI_V+B20 transfer is likely to fall, given specific settings in the power flow base case. Using the prior example for Option 15 (Install a 2nd 115 kV line alongside the K42 line), the coefficient can range between 89.8 and 102.5. Expressed another way, "with 95 percent confidence, it can be concluded that installing a 2nd 115 kV line alongside the K42 line will increase the All Lines In Voltage SHEI_V interface by between 89.8 to 102.5 MW."

Figure 18 displays the coefficients with their 95% Prediction Intervals (PI), calculated using the previously noted formula:

$$\boldsymbol{PI = Coefficient\ Value \pm (2.05 * Standard\ Error)}$$

It is observed for the plotted data for Coefficients LowC53, Jay and OpenB_20, the PI crosses zero, which is consistent with P-value being >0.05, indicating non-significant contribution to the model. It is also worth noting that Option 9, reconductoring 115 kV line K41, is marginally significant with a Lower 95%=0.3 (as shown in Figure 18) and P-value of 0.044 (Table 12).

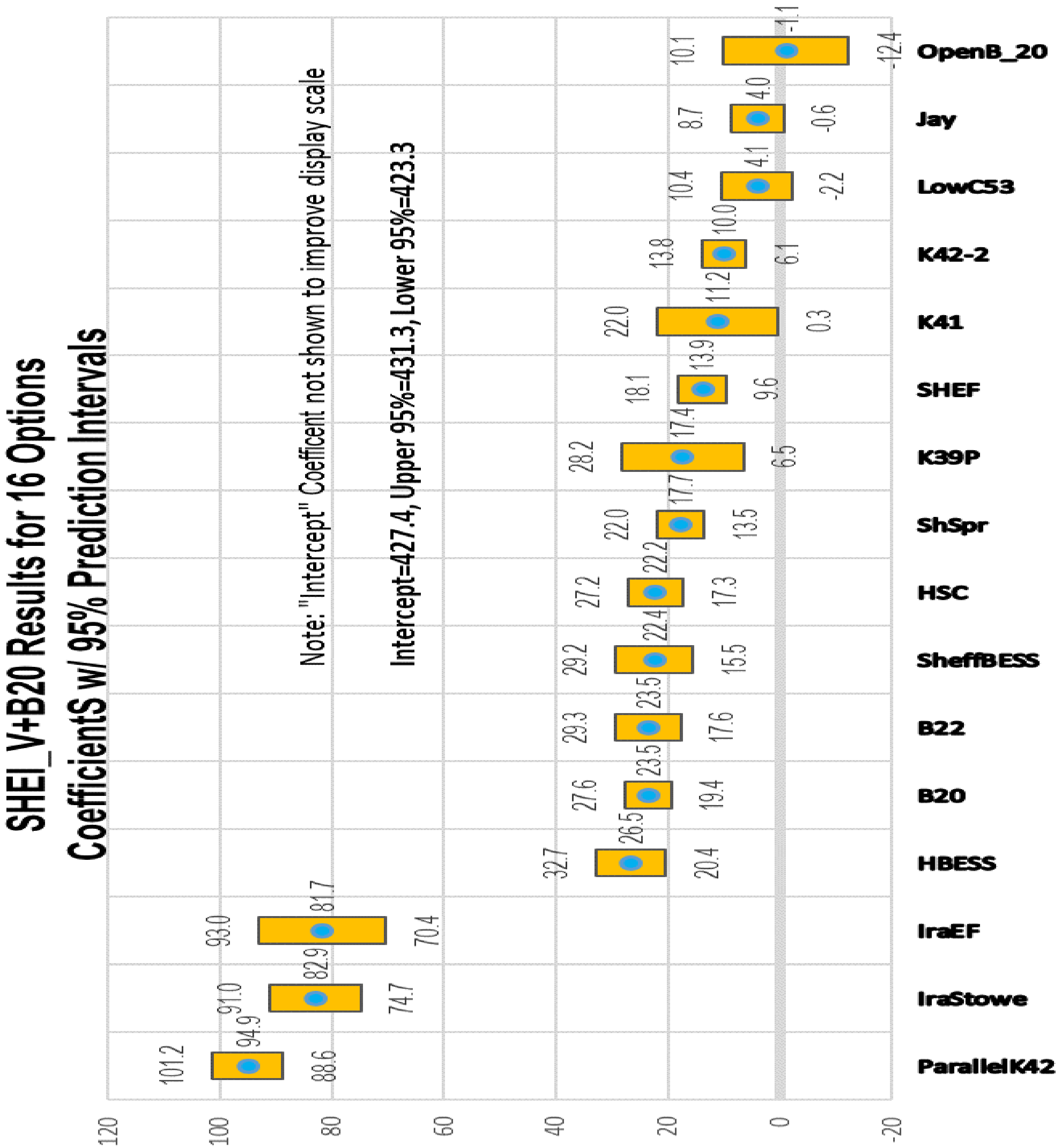

Figure 18: SHEI_V+B20 Results - Coefficients w/ 95% Prediction Intervals

4.3.2 Regression Analysis for All Lines In Thermal

Table 13 below shows the regression results for model Coefficients (***a***$_i$), **Standard Error**$_i$ (***SE***$_i$), and ***P-value***$_i$ for the All Lines In Thermal SHEI_TH+B20 model.

Table 13: All Lines In SHEI_TH+B20 Regression

Thermal (SHEI_TH+B20)			
R Square	0.904	Adjusted R Square	0.851
	Coefficients	*Standard Error*	*P-value*
Intercept	409.3	4.6	0.000
IraStowe	84.4	9.2	0.000
ParallelK42	78.0	7.1	0.000
IraEF	68.0	12.8	0.000
OpenB_20	43.9	12.7	0.002
B20	25.4	4.6	0.000
HBESS	19.4	7.0	0.009
K42-2	17.7	4.4	0.000
B22	14.4	6.6	0.037
SheffBESS	13.9	7.8	0.1
K39P	11.5	12.2	0.357
HSC	6.5	5.6	0.253
K41	3.0	12.2	0.810
Jay	2.0	5.3	0.702
SHEF	(2.9)	4.8	0.552
ShSpr	(3.5)	4.8	0.477
LowC53	(28.4)	7.1	0.0

In Table 13, for regression of the All Lines In Thermal SHEI plus B20 flow (SHEI_TH+B20), nine of the sixteen options that were modeled had coefficients that were significant with P-value < 0.05 (highlight in green).

For eight of these nine, the coefficients were positive. The coefficient for Option 12 (LowC53) was significant, and had a negative value. Comparing the coefficients of each option helps to determine effectiveness of one upgrade option versus another.

The following discusses options that were significant:

- Option 1—*B20*: Reconductor B20 Lowell-Johnson 34.5 kV line and upgrade the Lowell 46/34.5 kV transformer
  - Reconductoring lowers the impedance of the 34.5 kV B20 line, thereby increasing the flow on the line, which offloads the most thermally limiting 115 kV element, K42
  - Increases thermal rating on the B20 line which is an interface constraint
  - Increase in SHEI_TH+B20 flow until 34.5 kV B22 line is limiting
- Option 6—*K42-2*: Reconductor K42 Highgate-St Albans 115 kV line
  - Decreases the impedance and increase the thermal rating for the most thermally limiting element, K42
- Option 8—*HBESS*: 20 MVA (16 MW / 12 MVAR) Battery Storage at Highgate 115 kV
  - Charging of the battery increases load at Highgate, so that flow will decrease on the most thermally limited element, K42
- Option 10—*IraStowe*: Install a new Irasburg to Stowe 115 kV line

- Construct a 115 kV line in parallel with the most thermally limiting element, K42

- Option 11—*IraEF*: Install a new Irasburg to East Fairfax 115 kV line
  - Construct a 115 kV line in parallel with the most thermally limiting element, K42
- Option 12—*LowC53*: Close the normally open Lowell C53 switch (this option always was paired up with Option 1, reconductoring of line B20, however the regression analysis separated out its effect from B20)
  - Increase flow on the 34.5 kV line B20, which relieves flow on 115 kV line K42. This results in a thermal overload on 34.5 kV line B22, therefore SHEI_Th+B20 had to be reduced.
- Option 15—*ParallelK42*: Install a 2nd 115 kV line alongside the K42 line
  - Construct a 115 kV line in parallel with the most thermally limiting element, K42
- Option 16—*B22*: Upgrade 1.7 miles of B22 line for 39 MVA LTE rating
  - Decrease the impedance and increase the thermal rating
  - Small contribution to SHEI_TH+B20 transfer
  - Large Prediction Interval around coefficient, which indicates marginal performance of this option (P-Value=0.037)
- Option 17—*OpenB_20*: Open B20 line at Johnson

- Shifts power onto the 115 kV system and eliminates 34.5 kV thermal overloads
- Option was used in combination with K42 upgrades, thus allowing more power to flow on the 115 kV system

From this thermal analysis, coefficients for seven of the sixteen upgrade options were <u>not</u> significant and are highlighted in red in Table 13. These upgrade options fell into one of two categories:

a. reactive support with little thermal benefit, or
b. line addition or reconductoring that did not provide thermal support for the most limiting element, K42.

Typically, one would consider removing predictors from the model if the P-Value was greater than 0.05. For this regression analysis, the non-significant upgrade options were left in the model, for discussion purposes. The following options were not significant:

- Option 2—*SHEF*: Enable the Sheffield AVR (+/- 13 MVAR)
    - Reactive support with little thermal benefit
- Option 3—*Jay*: Recognize Jay synch condenser 1.15 service factor (+31.6 / -14 MVAR)
    - Reactive support with little thermal benefit
- Option 4—*ShSpr*: Enable the Sheldon Springs AVR (+/-8 MVAR)
    - Reactive support with little thermal benefit
- Option 5—*HSC*: Install a 15 MVAR synchronous condenser at Highgate (+15 / -7.5 MVAR)
    - Reactive support with little thermal benefit
- Option 7—*K39P*: Install a 2nd K39 Sheffield-Lyndonville 115 kV line

- K39 does not provide thermal support for the most limiting element, K42

- Option 9—*K41*: Reconductor K41 Highgate-Jay 115 kV line
  - K41 does not provide thermal support for the most limiting element, K42
- Option 13—*Ritch*: Close the normally open Richford 14W switch and reconductor from Richford to Highgate 46 kV
  - Preliminary runs found this upgrade Option to be non-significant.
  - Due to an Excel limitation to 16 X_i variables, this option was removed
- Option 14—*ShefBESS*: 20 MVA (16 MW / 12 MVAR) Battery Storage at Sheffield 115 kV
  - Option was marginally significant with P-value = 0.084,
  - Too remote from Highgate to help the K42 overload

For the regression of the All Lines In Thermal SHEI_TH+B20, the R-Squared was calculated as 0.904, which was less than the All Lines In Voltage SHEI_V+B20 (0.986, noted in Section 4.3.1), but still indicates a robust model for predicting the impact of each upgrade option. This means that the model will predict the outcome of SHEI_V+B20 90.4% of the time. The other 9.6% represents error in the model from parameters that were <u>not</u> included in the model.

Values from Table 13 are used to calculate the predicted effect of upgrade Option 8 (20 MVA (16 MW / 12 MVAR) Battery Storage at Highgate 115 kV) on the ALI SHEI_TH+B20 transfer limit—this is then compared against the actual Case 25 SHEI_TH+B20:

- Intercept coefficient "***b***" is estimated as 409.3 MW.
- Coefficient a_8 for X_8 is estimated as 19.4 MW.
- X_8 =1
- Thus, ***SHEI_TH+B20 = 409.3+ (19.4 * 1) = 428.7 MW***
- For Case 25, which only includes Option 8, the actual calculated power flow result was 432 MW (0.8% higher).

Figure 7 shows a graph comparing predicted versus actual All lines in SHEI Thermal limits. The predicted showed a close approximation to actual and follow a linear trend.

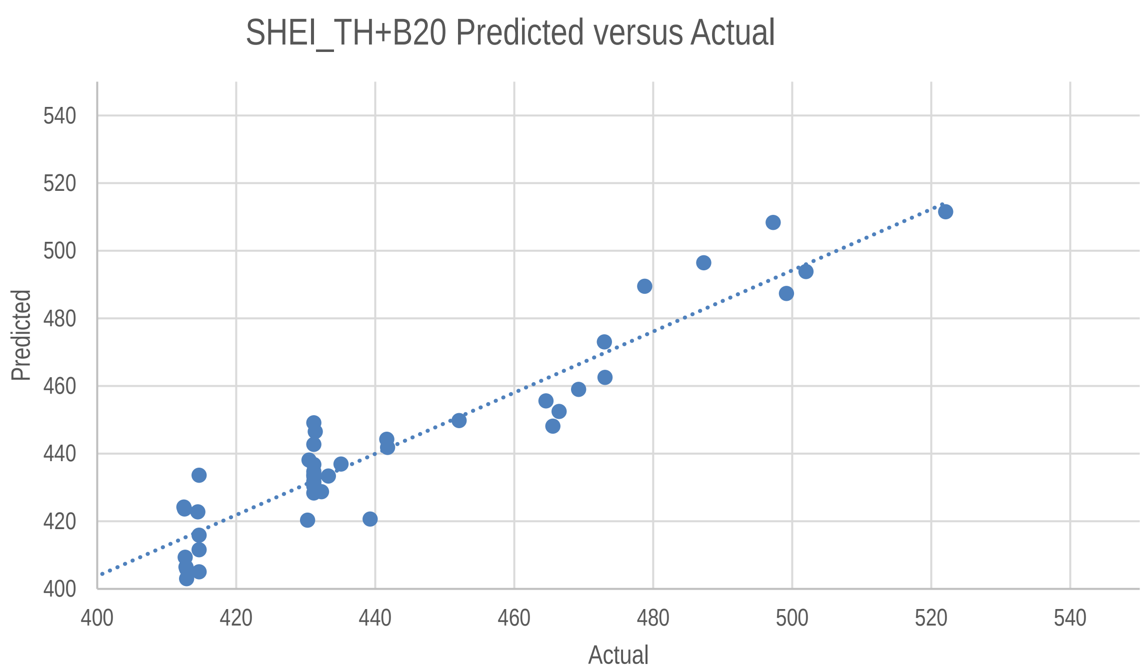

Figure 19: Predicted All Lines In SHEI_TH+B20 vs. Actual

The Prediction Interval represents the range where a single new calculation of SHEI_V+B20 transfer is likely to fall given specific settings in the power flow base case. Using the prior example for Option 8 (20 MVA (16 MW / 12 MVAR) Battery Storage at Highgate 115 kV), the coefficient can range between 5.1 and 33.7. Expressed another way, "with 95 percent confidence, it can be concluded that installing 20 MVA Battery Storage at Highgate 115 kV will increase the All Lines In Thermal SHEI_TH interface by between 5.1 to 33.7 MW."

Figure 20 displays the coefficients with their 95% Prediction Intervals (PI). It is observed for the plotted data for Coefficients SheffBESS, K39P, HSC, K41, Jay, Shef, and ShSpr, the PI crosses zero, which is consistent with P-value being >0.05 (as shown in Table 13) to indicate non-significant contribution to the model.

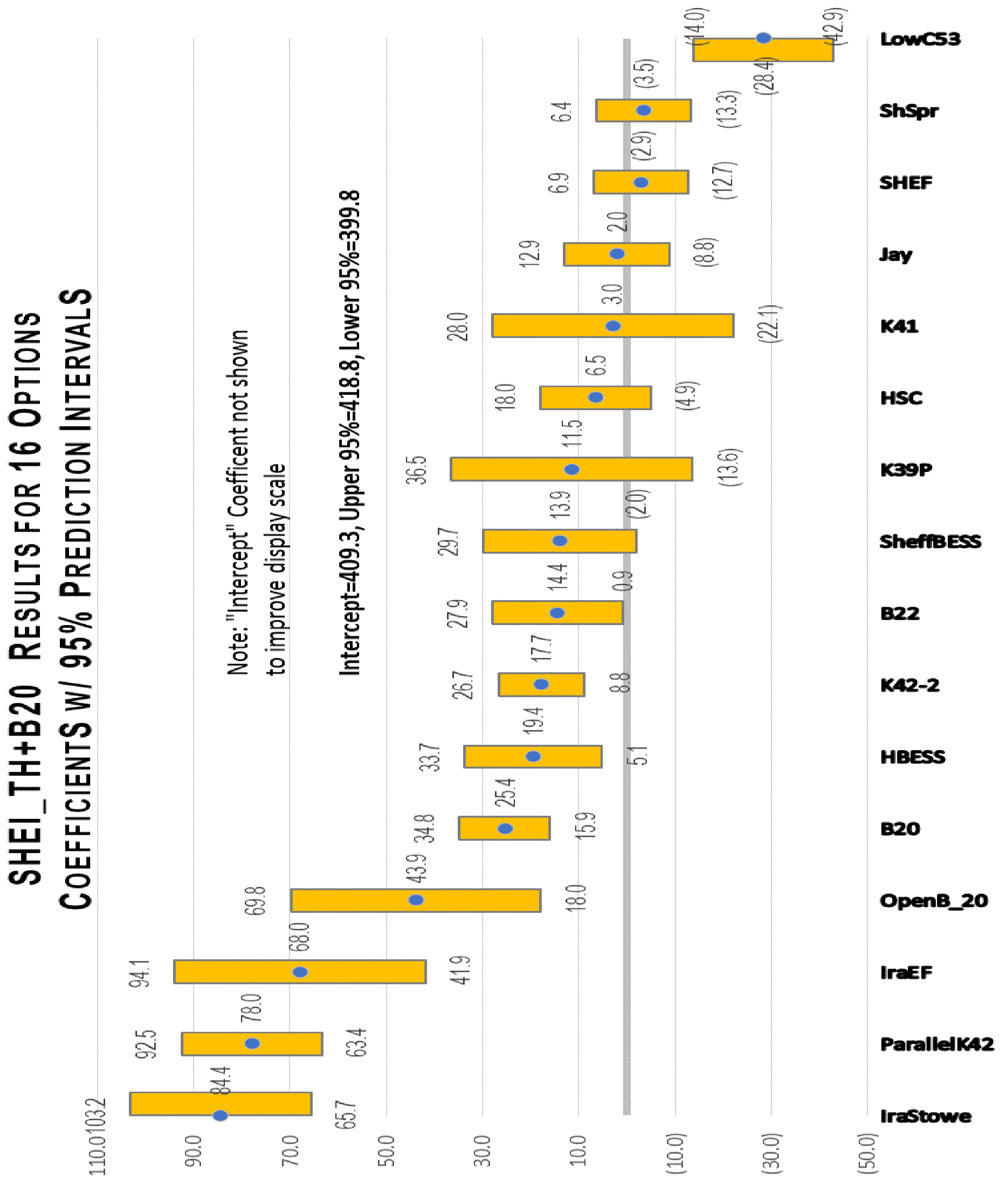

Figure 20: Predicted All Lines In SHEI_TH+B20 vs. Actual

4.4 Summary of Individual Options

4.4.1 Option 1: Reconductor B20 Lowell-Johnson 34.5 kV Line and Upgrade the Lowell 46/34.5 kV Transformer

Option 1, reconductoring the 34.5 kV B20 line and upgrading the Lowell 46/34.5 kV transformer, was included as a component of more than half (26 of 45) of the upgrade cases studied. Reconductoring the line lowers the impedance, thus increasing flow on it, and in the process, offloading the most-thermally limiting 115 kV element, the K42 line. Although B20 is not included in the ISO New England definition of SHEI, it is a critical parallel path to the 115 kV; by increasing its thermal rating, it also benefits the SHEI thermal limit. In the process of diverting more flow down the 34.5 kV, the B20 reconductoring does show an impact on the B22 line, which becomes a subsequent thermally-limiting element.

From a SHEI voltage limit perspective, the reconductoring of the B20 line helps avoid a possible line trip due to overloading, thus providing additional voltage support to the region. As shown in the voltage results, a trip of the B20 line, assumed due to thermal overloading, tended to degrade voltage stability in the Highgate / St. Albans area. Thus, the thermal limit increase of B20 due to reconductoring showed an improvement to SHEI voltage limits.

Table 14 summarizes Option 1 regression analysis 95% Prediction Interval ranges and Coefficients.

Table 14: Option 1 Regression Analysis Values

Limit	95% Prediction Interval Range (MW)	Coefficient (MW)	Significant
All Lines In SHEI Voltage + B20	19.4 to 27.6	23.5	Yes
All Lines In SHEI Thermal + B20	15.9 to 34.8	25.4	Yes

4.4.2 Option 2: Enable the Sheffield AVR

Option 2, enabling the Sheffield Wind AVR (automatic voltage regulation), was included as a component of more than half (25 of 45) of the upgrade cases studied. Utilizing the voltage-regulation reactive capability of this existing resource shows potential to increase the All Lines In SHEI+B20 Voltage limit by 10 to 18 MW, and could be a valuable element when bundled with additional upgrade options. Its contribution to the thermal limit was not significant.

Table 15 summarizes Option 2 regression analysis 95% Prediction Interval ranges and Coefficients.

Table 15: Option 2 Regression Analysis Values

Limit	95% Prediction Interval Range (MW)	Coefficient (MW)	Significant
All Lines In SHEI Voltage + B20	9.6 to 18.1	13.9	Yes
All Lines In SHEI Thermal + B20	-12.7 to 6.9	-2.9	No

4.4.3 Option 3: Recognize Jay Synch Condenser 1.15 Service Factor

Option 3, recognizing the Jay synchronous condenser 1.15 service factor, was included as a component of more than a third (17 of 45) of the upgrade cases studied. This is an extension of the existing synchronous condenser's reactive capability range. Results showed a negligible increase in voltage limits, likely due to the synchronous condenser's relative electrical location relative to system need. It showed no increase in thermal limits. Table 16 summarizes Option 3 regression analysis 95% Prediction Interval ranges and Coefficients.

Table 16: Option 3 Regression Analysis Values

Limit	95% Prediction Interval Range (MW)	Coefficient (MW)	Significant
All Lines In SHEI Voltage + B20	-0.6 to 8.7	4.0	No
All Lines In SHEI Thermal + B20	-8.8 to 12.9	2.0	No

4.4.4 Option 4: Enable the Sheldon Springs AVR

Option 4, enabling the Sheldon Springs Hydro AVR (automatic voltage regulation), was included as a component of more than half (25 of 45) of the upgrade cases studied. Utilizing the voltage-regulation reactive capability of this existing resource shows potential to increase the All Lines In SHEI+B20 Voltage limit by 14 to 22 MW, and could be a valuable element when bundled with additional upgrade options. Its contribution to the thermal limit was not significant. Table 17 summarizes Option 4 regression analysis 95% Prediction Interval ranges and Coefficients.

Table 17: Option 4 Regression Analysis Values

Limit	95% Prediction Interval Range (MW)	Coefficient (MW)	Significant
All Lines In SHEI Voltage + B20	13.5 to 22.0	17.7	Yes
All Lines In SHEI Thermal + B20	-13.3 to 6.4	-3.5	No

4.4.5 Option 5: Install a 15 MVAR Synchronous Condenser at Highgate 115 kV

Option 5, installing a 15 MVAR synchronous condenser at Highgate 115 kV, was included as a component of more than an eighth (6 of 45) of the upgrade cases studied. It showed a 17 to 27 MW benefit to the All Lines In SHEI Voltage limit, likely due to its location at one of the critical points needing voltage support. It also showed negligible support to thermal limits, likely due to its help in reducing reactive power flow on the limiting K42-2 115 kV line.

The addition of a synchronous condenser provides additional short circuit strength, which is especially important for inverter-based resources (e.g., HVDC, wind, PV). For new interconnections of inverter-based resources, ISO New England likely would require evaluation of their models under low short circuit strength conditions[5], thus an improvement to short circuit strength is a valuable consideration when evaluating alternatives, both for existing and possible future generation interconnections.

Table 18 summarizes Option 5 regression analysis 95% Prediction Interval ranges and Coefficients.

Table 18: Option 5 Regression Analysis Values

Limit	95% Prediction Interval Range (MW)	Coefficient (MW)	Significant
All Lines In SHEI Voltage + B20	17.3 to 27.2	22.2	Yes
All Lines In SHEI Thermal + B20	-4.9 to 18.0	6.5	No

[5] References: Section 6.6, ***PSCAD Testing,*** and Appendix C, ***Requirements of PSCAD Models***, of ISO New England Planning Procedure 5-6 https://www.iso-ne.com/static-assets/documents/rules_proceds/isone_plan/pp05_6/pp5_6.pdf

4.4.6 Option 6: Reconductor K42 Highgate-St Albans 115 kV Line

Option 6, reconductoring the K42-2 115 kV line between Highgate and St. Albans, was included as a component of more than a quarter (12 of 45) of the upgrade cases studied. Reconductoring the line decreases the impedance and increases the thermal rating of the line, which is the most thermally-limiting element of the SHEI interface. On its own, it does not show a large improvement to SHEI voltage or thermal, however when combined with the 34.5 kV line B20 upgrade and reactive upgrades (e.g., Sheffield AVR, Sheldon Springs AVR, Highgate synchronous condenser), the grouping shows a good improvement, both for all lines in and facility out conditions.

Table 19 summarizes Option 6 regression analysis 95% Prediction Interval ranges and Coefficients.

Table 19: Option 6 Regression Analysis Values

Limit	95% Prediction Interval Range (MW)	Coefficient (MW)	Significant
All Lines In SHEI Voltage + B20	6.1 to 13.8	10.0	Yes
All Lines In SHEI Thermal + B20	8.8 to 26.7	17.7	Yes

4.4.7 Option 7: Install a 2nd K39 Sheffield-Lyndonville 115 kV Line

Option 7, installing a parallel 115 kV line to 115 kV line K39 (Sheffield to Lyndonville), was included as a component of only one of the upgrade cases studied. It provided some benefit to the voltage limit, and not significant thermal benefit, however as a new 115 kV line, it did not provide as much benefit to SHEI limits as other new 115 kV lines did.

Table 20 summarizes Option 7 regression analysis 95% Prediction Interval ranges and Coefficients.

Table 20: Option 7 Regression Analysis Values

Limit	95% Prediction Interval Range (MW)	Coefficient (MW)	Significant
All Lines In SHEI Voltage + B20	6.5 to 28.2	17.4	Yes
All Lines In SHEI Thermal + B20	-13.6 to 36.5	11.5	No

4.4.8 Option 8: 20 MVA (16 MW / 12 MVAR) Battery Storage at Highgate 115 kV

Option 8, the addition of a 20 MVA (16 MW / 12 MVAR) battery energy storage device at Highgate 115 kV, was included as a component in four of the 45 upgrade cases studied. It provides voltage support, with its dynamic reactive capability, showing a 20 to 33 MW increase in the All Lines In SHEI+B20 Voltage limit. While in its charging mode, it acts as a load, providing thermal limit benefit, as it unloads the most-limiting SHEI element, 115 kV line K42-2. Additionally, the dynamic reactive capability of the battery would reduce the K42-2 line reactive power loading, similar to that of the Highgate synchronous condenser.

Table 21 summarizes Option 8 regression analysis 95% Prediction Interval ranges and Coefficients.

Table 21: Option 8 Regression Analysis Values

Limit	95% Prediction Interval Range (MW)	Coefficient (MW)	Significant
All Lines In SHEI Voltage + B20	20.4 to 32.7	26.5	Yes
All Lines In SHEI Thermal + B20	5.1 to 33.7	19.4	Yes

4.4.9 Option 9: Reconductor K41 Highgate-Jay 115 kV Line

Option 11, reconductoring 115 kV line K41 (Highgate to Jay), was included as a component of only one of the upgrade cases studied. As a 115 kV upgrade, it provided only a limited benefit to the voltage limit, and a no benefit to the thermal limit.

Table 22 summarizes Option 9 regression analysis 95% Prediction Interval ranges and Coefficients.

Table 22: Option 9 Regression Analysis Values

Limit	95% Prediction Interval Range (MW)	Coefficient (MW)	Significant
All Lines In SHEI Voltage + B20	0.3 to 22.0	11.2	Yes
All Lines In SHEI Thermal + B20	-22.1 to 28.0	3.0	No

4.4.10 Option 10: Install a New Irasburg to Stowe 115 kV Line

Option 10, installing a new 115 kV line from Irasburg to Stowe, was included as a component of two of the upgrade cases studied. It provided one of the highest benefits to both voltage and thermal limits, including under facility out conditions. It bypasses the thermal limitations of the 34.5 kV B20/B22 lines, as well as the 115 kV K42 line.

Table 23 summarizes Option 10 regression analysis 95% Prediction Interval ranges and Coefficients.

Table 23: Option 10 Regression Analysis Values

Limit	95% Prediction Interval Range (MW)	Coefficient (MW)	Significant
All Lines In SHEI Voltage + B20	74.7 to 91.0	82.9	Yes
All Lines In SHEI Thermal + B20	65.7 to 103.2	84.4	Yes

4.4.11 Option 11: Install a New Irasburg to East Fairfax 115 kV Line

Option 11, installing a new 115 kV line from Irasburg to East Fairfax, was included as a component of only one of the upgrade cases studied. It provided one of the highest benefits to both voltage and thermal limits, including under facility out conditions. It bypasses the thermal limitations of the 34.5 kV B20/B22 lines, as well as the 115 kV K42 line.

Table 24 summarizes Option 11 regression analysis 95% Prediction Interval ranges and Coefficients.

Table 24: Option 11 Regression Analysis Values

Limit	95% Prediction Interval Range (MW)	Coefficient (MW)	Significant
All Lines In SHEI Voltage + B20	70.4 to 93.0	81.7	Yes
All Lines In SHEI Thermal + B20	41.9 to 94.1	68.0	Yes

4.4.12 Option 12: Close the Normally Open Lowell C53 Switch

Option 12, closing the normally-open 46 kV C53 switch at Lowell, was included as a component of more than an eighth (6 of 45) of the upgrade cases studied. Closing of the C53 switch diverts flow from the 46 kV onto the underlying 34.5 kV subtransmission network, mainly the B20 and B22 lines. No significant voltage limit benefit, and a negative to the SHEI+B20 thermal limit were observed with Option 12.

Table 25 summarizes Option 12 regression analysis 95% Prediction Interval ranges and Coefficients.

Table 25: Option 12 Regression Analysis Values

Limit	95% Prediction Interval Range (MW)	Coefficient (MW)	Significant
All Lines In SHEI Voltage + B20	-2.2 to 10.4	4.1	No
All Lines In SHEI Thermal + B20	-42.9 to -14.0	-28.4	Yes

4.4.13 Option 13: Close the Normally Open Richford 14W Switch and Reconductor From Richford to Highgate 46 kV

Option 13, closing the normally-open 46 kV Richford 14W Switch and reconductoring the 46 kV from Richford to Highgate, was included as a component of three of the upgrade cases studied. It was only included with Option 12, the closure of the 46 kV Lowell C53 Switch, so no independent information is available. Regression analysis was not performed on this option, with an Excel software limitation of 16 regression elements.

4.4.14 Option 14: 20 MVA (16 MW / 12 MVAR) Battery Storage at Sheffield 115 kV

Option 14, the addition of a 20 MVA (16 MW / 12 MVAR) battery energy storage device at Sheffield 115 kV, was included as a component in three of the 45 upgrade cases studied. It provides voltage support, with its dynamic reactive capability, showing a 16 to 29 MW increase in the All Lines In SHEI+B20 Voltage limit. While in its charging mode, it acts as a load, providing thermal limit benefit (though not significant), as it helps unload the most-limiting SHEI element, 115 kV line K42-2. The Highgate location for the battery storage unit showed to be more beneficial to voltage and thermal limits than the Sheffield location.

Table 26 summarizes Option 14 regression analysis 95% Prediction Interval ranges and Coefficients.

Table 26: Option 14 Regression Analysis Values

Limit	95% Prediction Interval Range (MW)	Coefficient (MW)	Significant
All Lines In SHEI Voltage + B20	15.5 to 29.2	22.4	Yes
All Lines In SHEI Thermal + B20	-2.0 to 29.7	13.9	No

4.4.15 Option 15: Install a 2nd 115 kV Line Alongside the K42 Line

Option 15, installing a new 115 kV line from Highgate to Georgia parallel to the K42 line, was included as a component of four of the upgrade cases studied. Even by itself, without other bundled upgrades, it provided one of the highest benefits to both voltage and thermal limits, including under facility out conditions. Like other new 115 kV lines, it bypasses the thermal limitations of the 34.5 kV B20/B22 lines, as well as the 115 kV K42 line.

Table 27 summarizes Option 15 regression analysis 95% Prediction Interval ranges and Coefficients.

Table 27: Option 15 Regression Analysis Values

Limit	95% Prediction Interval Range (MW)	Coefficient (MW)	Significant
All Lines In SHEI Voltage + B20	88.6 to 101.2	94.9	Yes
All Lines In SHEI Thermal + B20	64.3 to 92.5	78.0	Yes

4.4.16 Option 16: Upgrade 1.7 Miles of B22 Line for 39 MVA LTE Rating

Option 16, upgrading 1.7 miles of 34.5 kV line B22, with a 39 MVA LTE rating, was included as a component of four of the upgrade cases studied. It was always bundled with Option 1, the upgrade of line B20. In the process of diverting more flow down the 34.5 kV, the B20 reconductoring does show an impact on the B22 line, which becomes a subsequent thermally-limiting element. Upgrading B22 allows for further offloading of the 115 kV K42 line.

From a SHEI voltage limit perspective, similar to the B20 line upgrade, the reconductoring of the B22 line helps avoid a possible line trip due to overloading, thus providing additional voltage support to the region. As shown in the voltage results, a trip of the B22 line, assumed due to thermal overloading, tended to degrade voltage stability in the Highgate / St. Albans area. Thus, the thermal limit increase of B22 due to reconductoring showed an improvement to SHEI voltage limits. It also provided improvement to the thermal limit, but less than the voltage limit.

Table 28 summarizes Option 16 regression analysis 95% Prediction Interval ranges and Coefficients.

Table 28: Option 16 Regression Analysis Values

Limit	95% Prediction Interval Range (MW)	Coefficient (MW)	Significant
All Lines In SHEI Voltage + B20	17.6 to 29.3	23.5	Yes
All Lines In SHEI Thermal + B20	0.9 to 27.9	14.4	Yes

4.4.17 Option 17: Open B20 Line at Johnson

Option 17, opening the 34.5 kV B20 line at Johnson, was included as a component of two of the upgrade cases studied. It was bundled with the 46 kV closure Options 12 and 13, as well as previously observed favorable upgrade options (Cases 40 and 42).

Table 29 summarizes Option 17 regression analysis 95% Prediction Interval ranges and Coefficients. Opening B20 is not significant for the SHEI+B20 All Lines In SHEI Voltage limit, because it has mixed results—it removes the limiting B20 line, however, it shifts power flow onto the 115 kV system, which may aggravate voltage issues. Opening B20 is significant for the SHEI+B20 All Lines In Thermal limit, because it eliminates a thermally-limiting element, thus increasing SHEI+B20 thermal transfers.

Table 29: Option 17 Regression Analysis Values

Limit	95% Prediction Interval Range (MW)	Coefficient (MW)	Significant
All Lines In SHEI Voltage + B20	-12.4 to 10.1	-1.1	No
All Lines In SHEI Thermal + B20	18.0 to 69.8	43.9	Yes