WWSIS III: Western Frequency Response and Transient Stability Study

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TRC Call
March 26, 2014

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Today's Call

- Purpose:

Review final analysis steps in project, since 3-26-14 TRC, with specific emphasis on review of new sensitivity and mitigation investigation.

- Items:

1. Headroom depletion
2. Frequency responsive wind and solar controls
3. Energy storage
4. Coal retirements/weak grid

Since Last Call

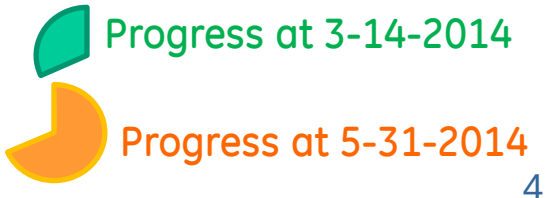
(Next Steps from 3-26-15 TRC call plus 2-4-2014 meeting Notes)

- The main part of the frequency response and transient stability analysis, which focused on the four light spring and heavy summer study scenarios, is nearing completion. The remaining work ~~will focus~~ has focused on further analysis of the simulations run to-date, and additional sensitivity cases. Please keep in mind that WWSIS 3 is an applied research study, rather than a comprehensive transmission planning study. Therefore, the objective of the sensitivity analysis is to define a band of potential responses, indicate general impact (e.g., better or worse), and provide insight into specific dynamic performance questions raised by the TRC. The further investigation of cases and new sensitivities under consideration are:.....

Mitigation of FRO Concerns

progress

- Apply frequency controls to wind plants
  - Multiple tests. 5% of possible production reserved on:
  - (a) All new wind plants (i.e. those added to case to create Hi-Mix (case 3), for Light Spring '22
  - (b) Only new wind plants in areas short of FRO
  - Look at impact on total WECC FR and individual area performance.
  - Governor response, inertial response and combination of both to be tested.
- Apply frequency controls to solar plants
  - Partly done, when we added governor response to CSP
  - Will add 5% FR to new utility scale PV
- Add energy storage for Frequency Response
  - Add inverter based energy storage (e.g. battery system) to areas short of FR
  - Determine (approximately) the amount of ES required to bring FR = FRO in those areas
- Illustrate impact of changes to dispatch and/or commitment
  - This 2nd part will enable responsive generation in areas that are deficient.



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Sensitivity/causality of FRO Concerns

- Headroom depletion as described in the TRC meeting.
  - Duck plots (in back up of this deck)
- Evaluate system response to a large distributed generation outage alone, and compare that to an equivalent but more localized outage of a conventional generation plant.
  - We will trip approximately 2700 MW of DG (PV) via the complex load model, and check the FR
  - This test also relates to other stability investigation, so will check on other stability impacts (see below)
- Illustrate impact of changes to dispatch and/or commitment (e.g. replace non responsive units with governor responsive units, replace 1000MW wind with hydro)
  - This first part will focus on illustrating sensitivities under the Hi-Mix cases
  - Will execute selected one-to-one changes in commitment and dispatch … think partial derivatives

Progress at 3-14-2014

Progress at 5-31-2014

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Further Investigation of Stability

progress

- Discuss/analyze retirements. Any coal plants de-committed in a snap shot power flow could be considered retired. Explore impact on system performance.
  - Check for changes/concerns on transient stability…
  - These cases will use the light spring extreme case, in which there are acute changes in dispatch and commitment of thermal plants -- from perspective of this study, having units decommited is largely indistinguishable from them being retired
  - Will report on changes in unit commitment, with particular attention to coal plants.
  - Expect to test fault scenarios, especially in Northeast and Desert Southwest regions,
  - Will look for conditions of low short circuit strength
  - Investigate sensitivity to wind plant controls… baseline modeling of newly added wind plants will be tested for credible other behavior …e.g. less aggressive voltage regulation; attempt to capture aspects of recent "mix" of wind generation added.
  - Ditto for utility scale PV plants.

A bit left to do here

- Investigate possible relay impacts/issues.
  - This will be primarily screening of impact on key relay variables with high renewables. Will also focus on sensitivity/comparisons marginal impact on current, apparent impedance, voltage trajectories at COI and other nodes for one-to-one substitution of wind (or solar) for synchronous generation.
- Additional fault scenarios, e.g. Grizzly transfer trip. **Please provide detailed description of fault and any associated RAS.**

Didn't happen, but we worked extensively on Aeolus fault

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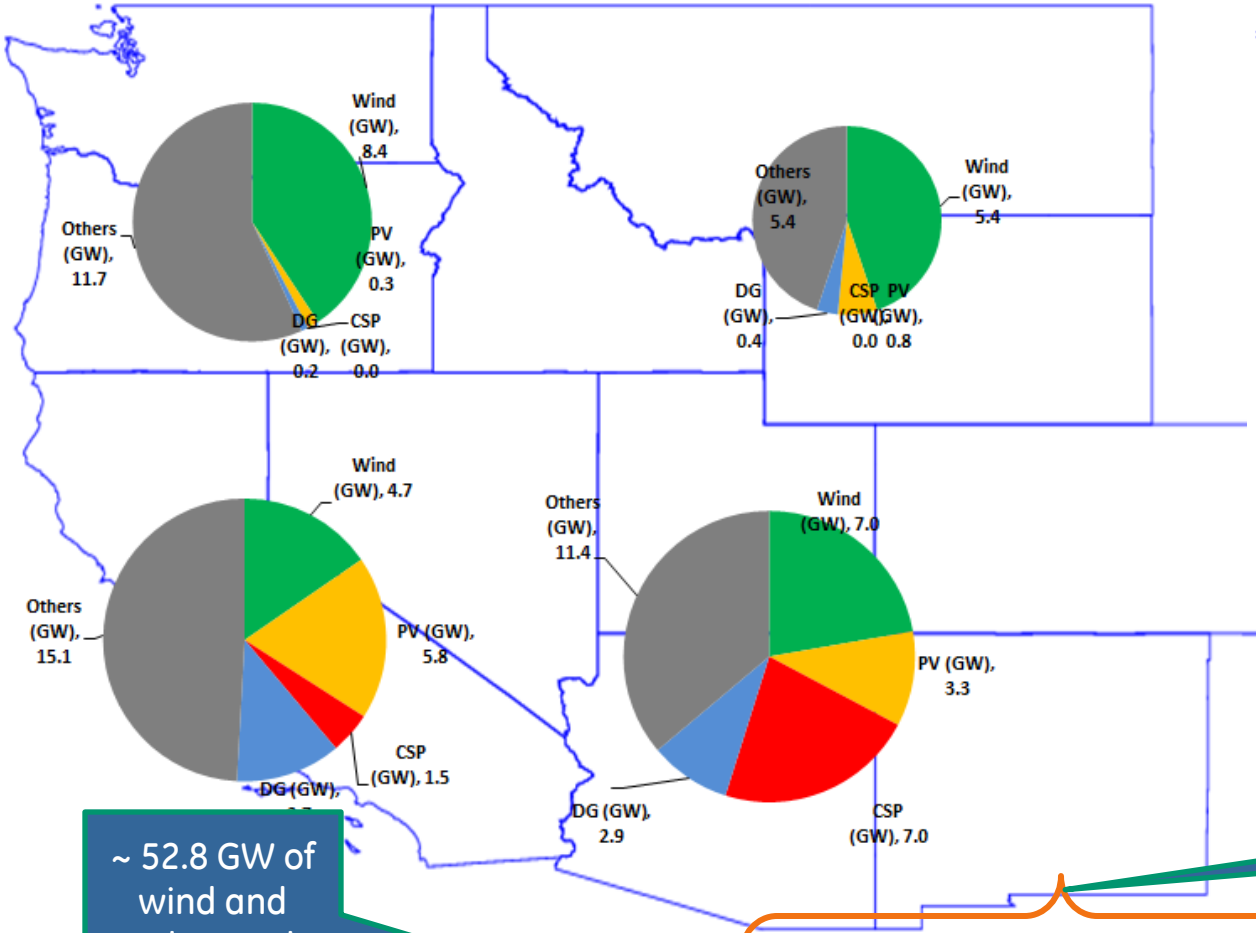
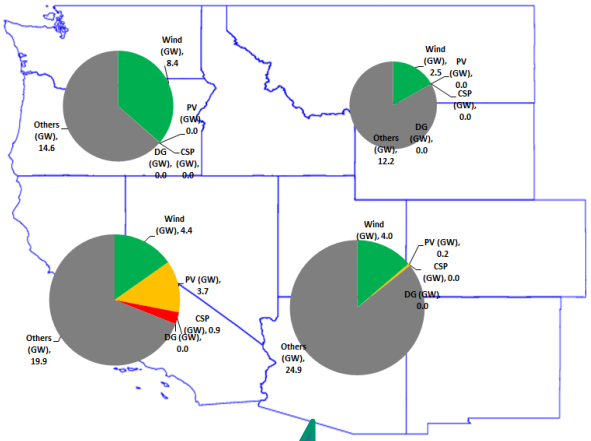
2022 LSP HiMix Case – Renewable Conditions





~ 25 GW of wind and solar total in Base Case

US only

~ 52.8 GW of wind and solar total

	WECC	CALIFORNIA	DSW	NORTHEAST	NORTHWEST
Wind (GW)	27.2	4.7	7.0	5.4	8.4
PV (GW)	10.2	5.8	3.3	0.8	0.3
CSP (GW)	8.4	1.5	7.0	0.0	0.0
DG (GW)	7.0	3.7	2.9	0.4	0.2
Others (GW)	65.7	15.1	11.4	5.4	11.7
total (GW)	118.6	30.8	31.6	12.0	20.5

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Preliminary Results: Not for Further Distribution or Citation

Headroom Depletion / Exhausting Primary Reserves

Loss of headroom: Ducks

This slide from TRC 2-4-14

- Discussion with CAISO (thanks Clyde Loutan)
- Recent concern over emerging net load profile with strong mid-day solar…Duck Curves
- Commitment and dispatch to accept high solar can leave system short of responsive resources in the evening when solar drops off and before wind picks up
- Particular concern that FRO will not be met, especially for some individual BAs

Spring Ducks

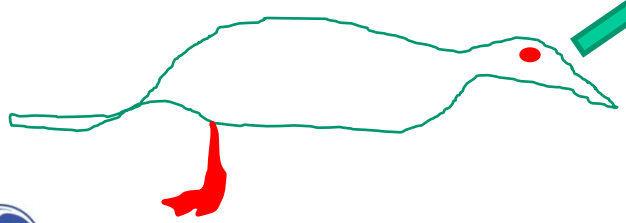
This slide from TRC 2-4-14

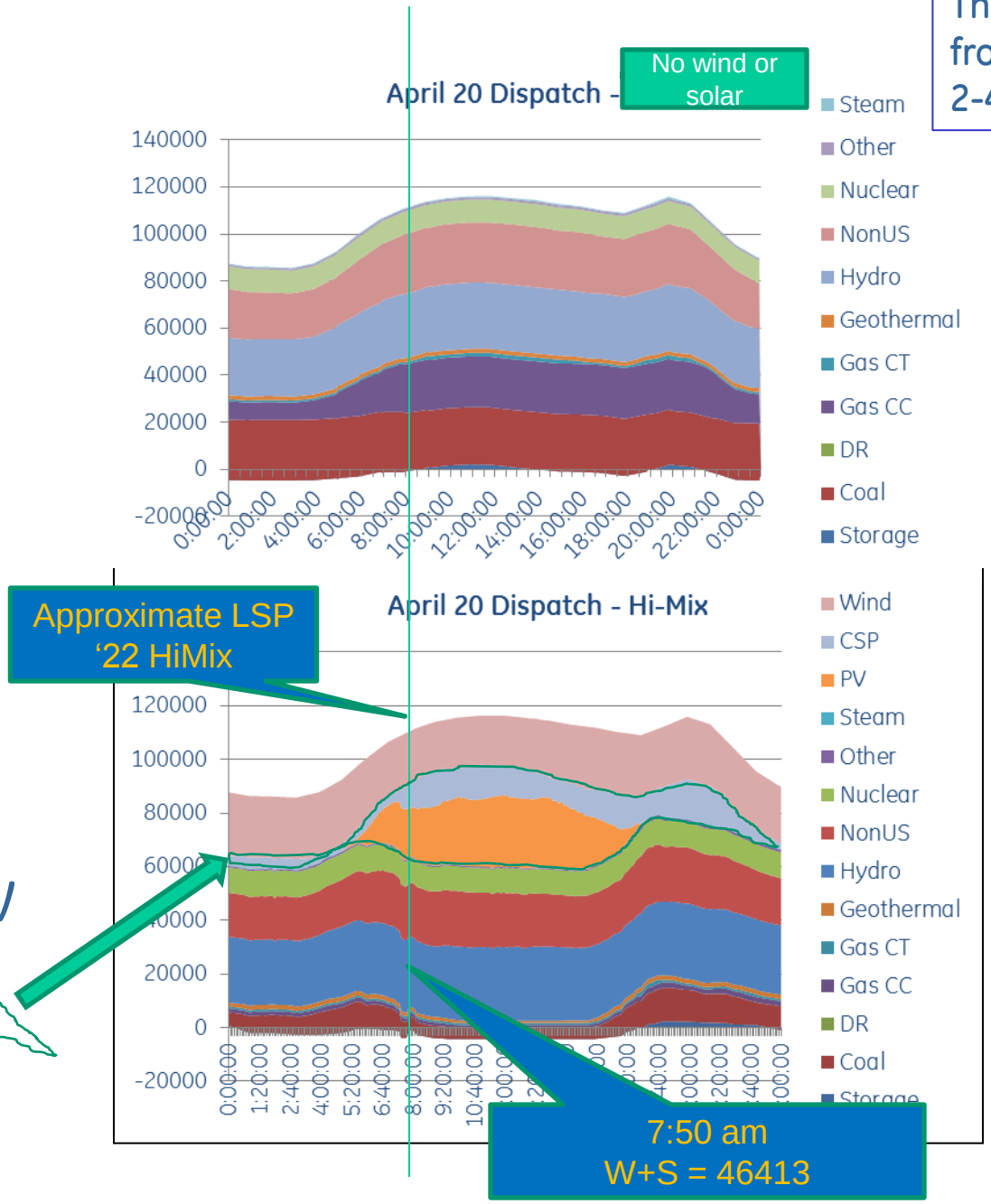
- These are from PLEXOS
- LSP HiMix was developed to investigate high instantaneous penetration:

Load = 109.5GW

W+S = 52.8 (48% penetration)

Headroom = 21.9GW





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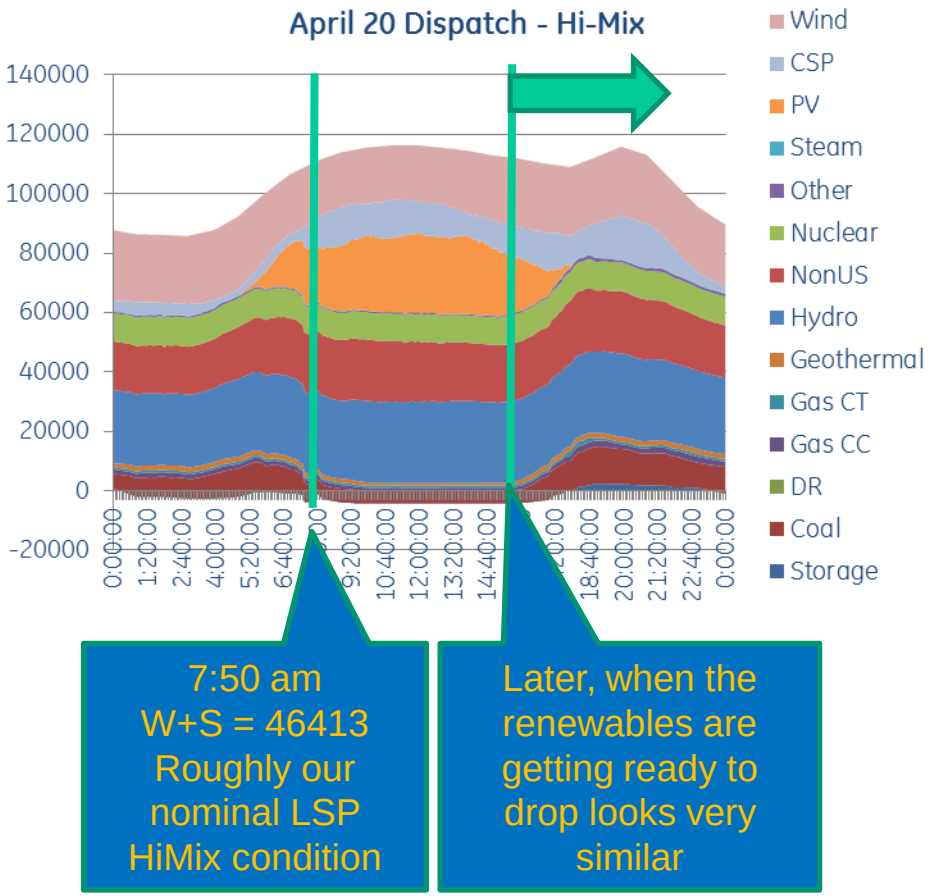
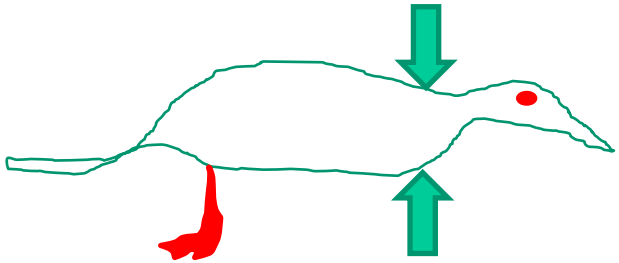
Squeezing the Duck: Headroom experiments

Proposed investigation

- Fix Commitment
- In steps (of say 4000MW)
  - Decrease wind & solar
  - Dispatch up units (identified by Plexos dispatch sensitivity
  - Recalculate headroom, Kt, etc.
- Run Palo Verde 2 event
  - Observe frequency
  - Calculate FR
- Repeat until UFLS or other fail
- Plot performance
  - vs. renewable power
  - vs. headroom





Headroom Depletion Cases

Case	Description
HiMix	2022 LSP HiMix case
DGoff	Starting from HiMix case, DG is turned completely off (≈ 7.2 GW), based on PLEXOS results units were dispatched up; hydro in Northwest (responsive), and coal and combined cycle (mostly unresponsive)
PVoff	Starting from DGoff case, utility scale PV is switched off (≈6.4 GW) pumped storage units switched to generating mode, hydro units in CA dispatched up the rest of PLEXOS list units dispatched up. Phase shifters (BLGS PHA, RMRK PHA and , CROS PHA) adjusted and limit increased. Valmont capacitor bank added and BLACKWTR DC increased from 50 to 200 MW.
1.2BL	1.2 GW of California hydro units with governor switched to baseload units
1.8BL	1.8 GW of California hydro units with governor switched to baseload units
2.1BL	2.1 GW of California hydro units with governor switched to baseload units
2.8BL	2.8 GW of California hydro units with governor switched to baseload units
3.2BL	3.2 GW (All) of California hydro units with governor switched to baseload units

Many intermediate steps (>30) …requires trimming voltages, flows, etc.

Final steps of re-dispatch squeezed remaining on-line resources

Contribution of hydro in California is important (in this case), and also rather uncertain.
This sequence tests consequences of loss of primary response from committed hydro with headroom

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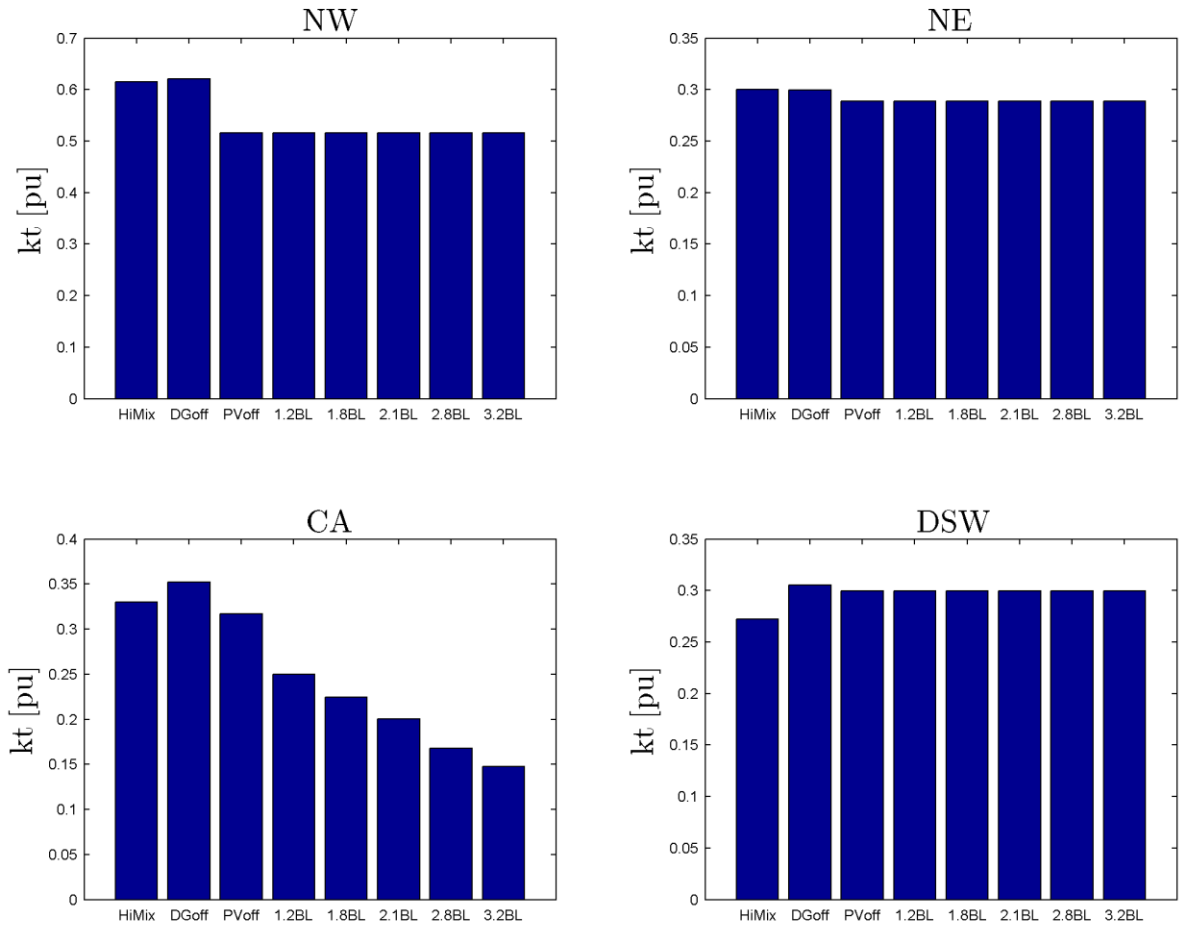
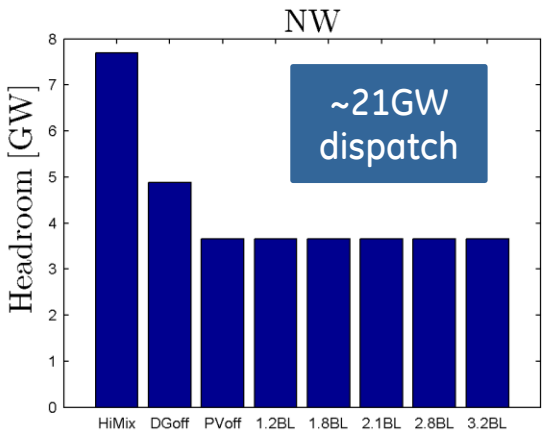
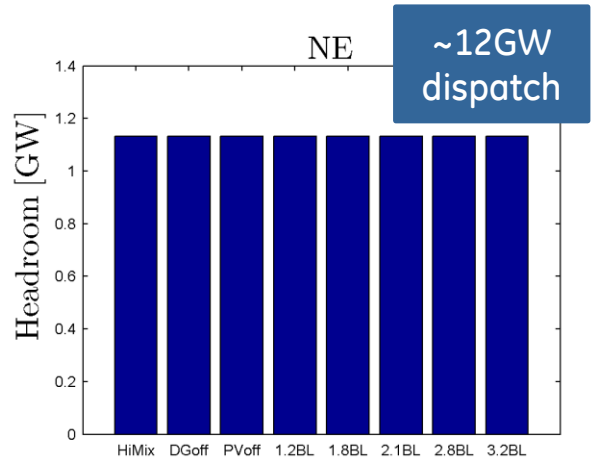
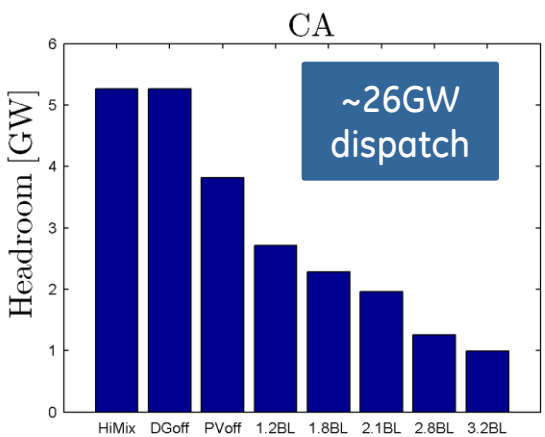
Headroom Depletion: Kt – 4 regions

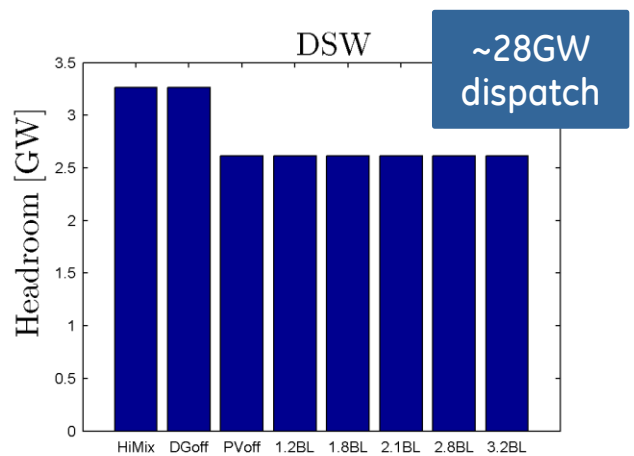


Headroom









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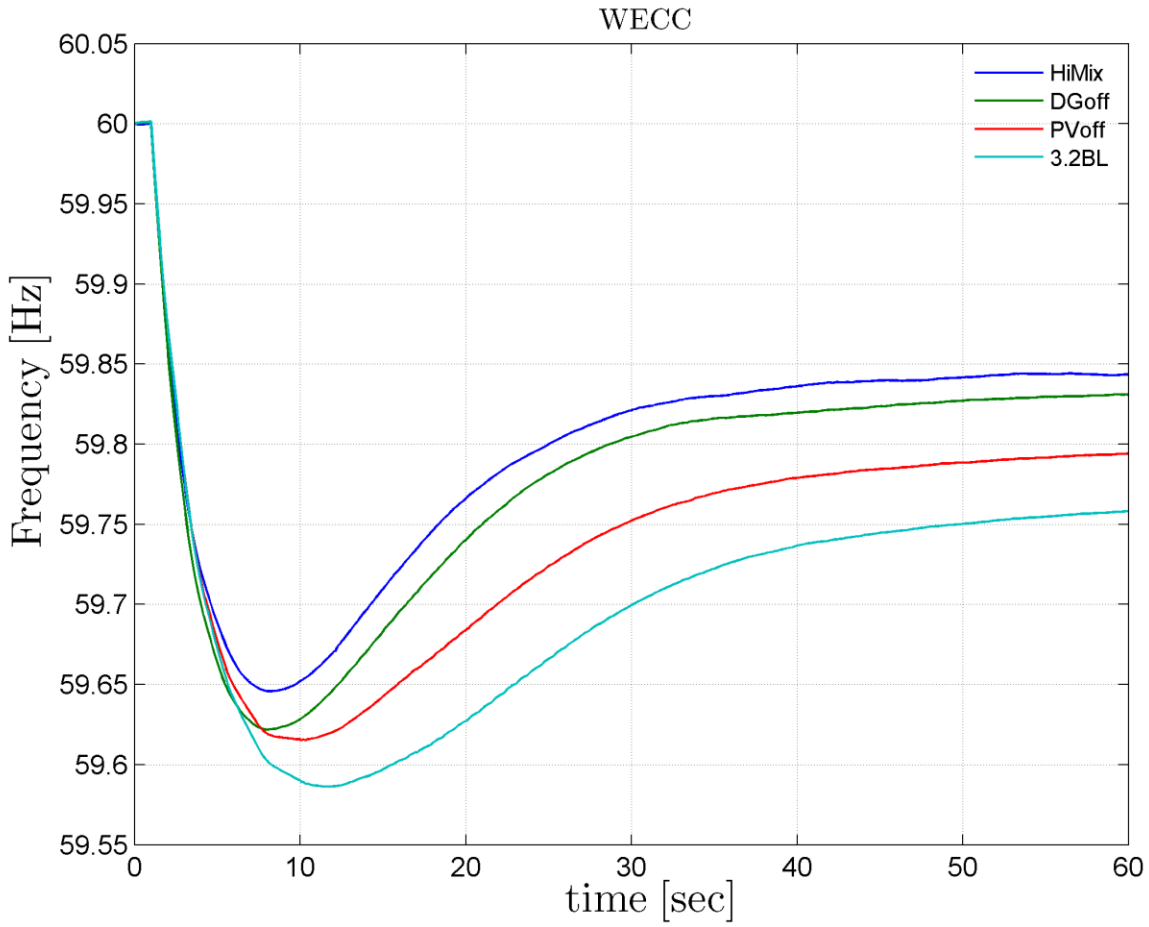
WECC Frequency Response



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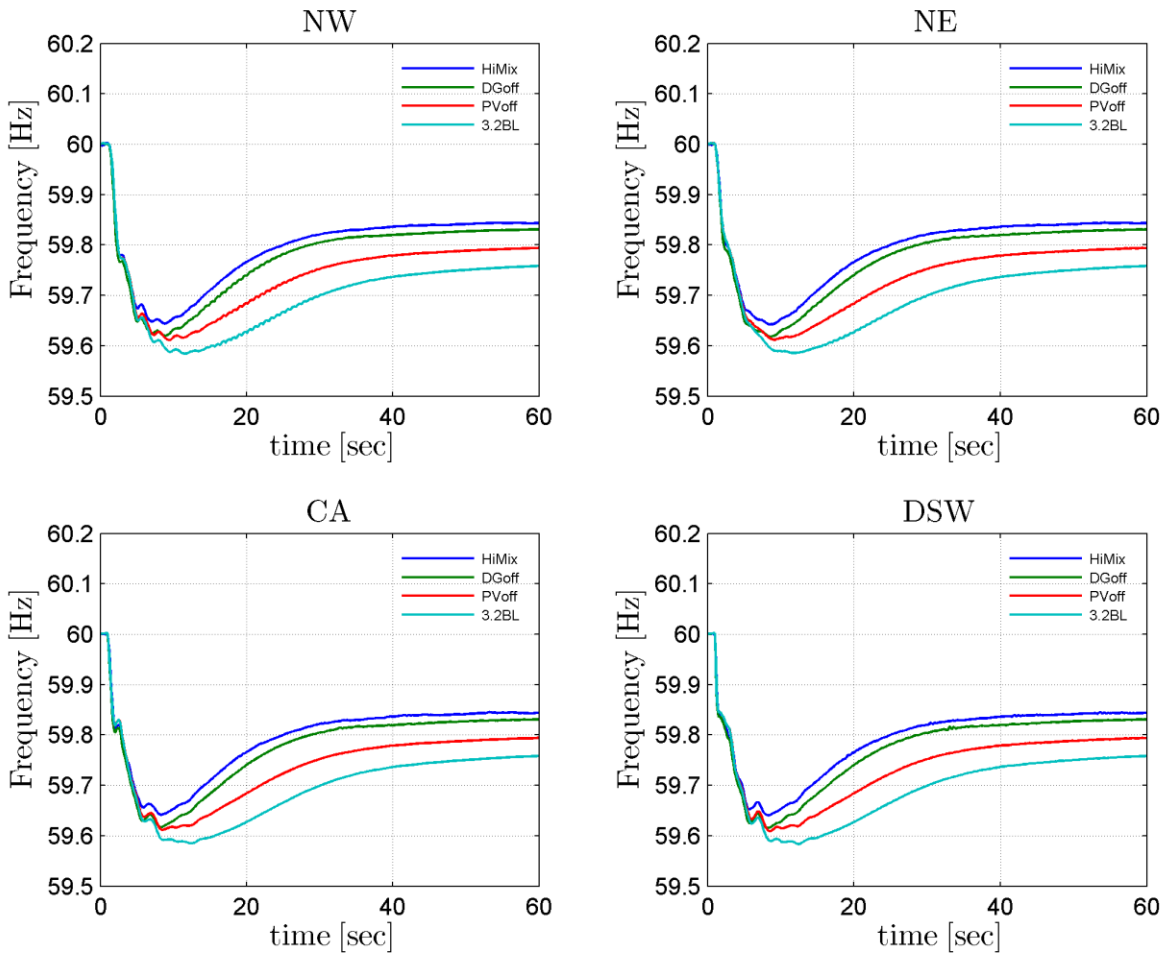
WECC Frequency Response



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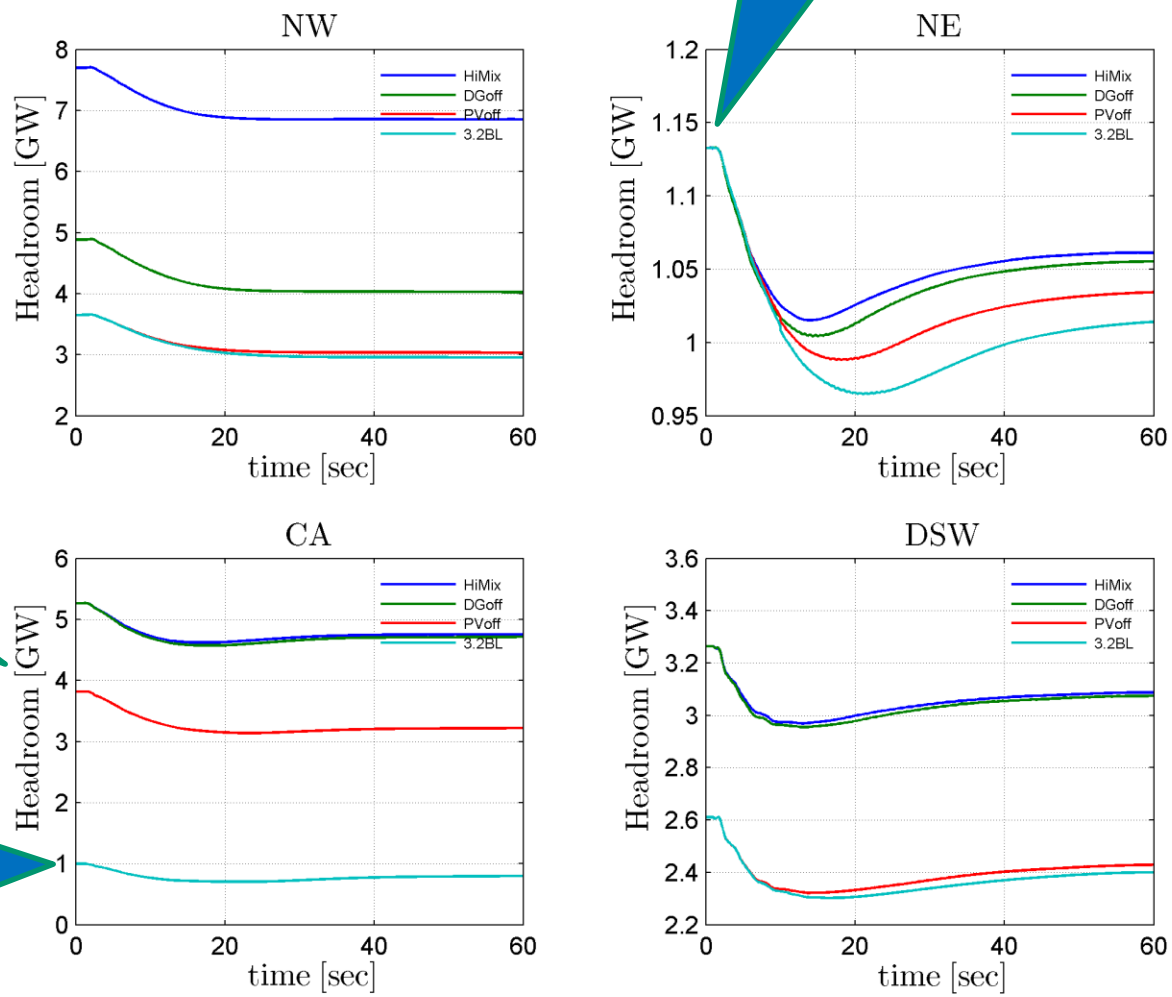
Headroom

Initial Hi-Mix case already has very limited headroom



Most of California's headroom and frequency response in this case comes from hydro

Only ~1 GW headroom from non-hydro

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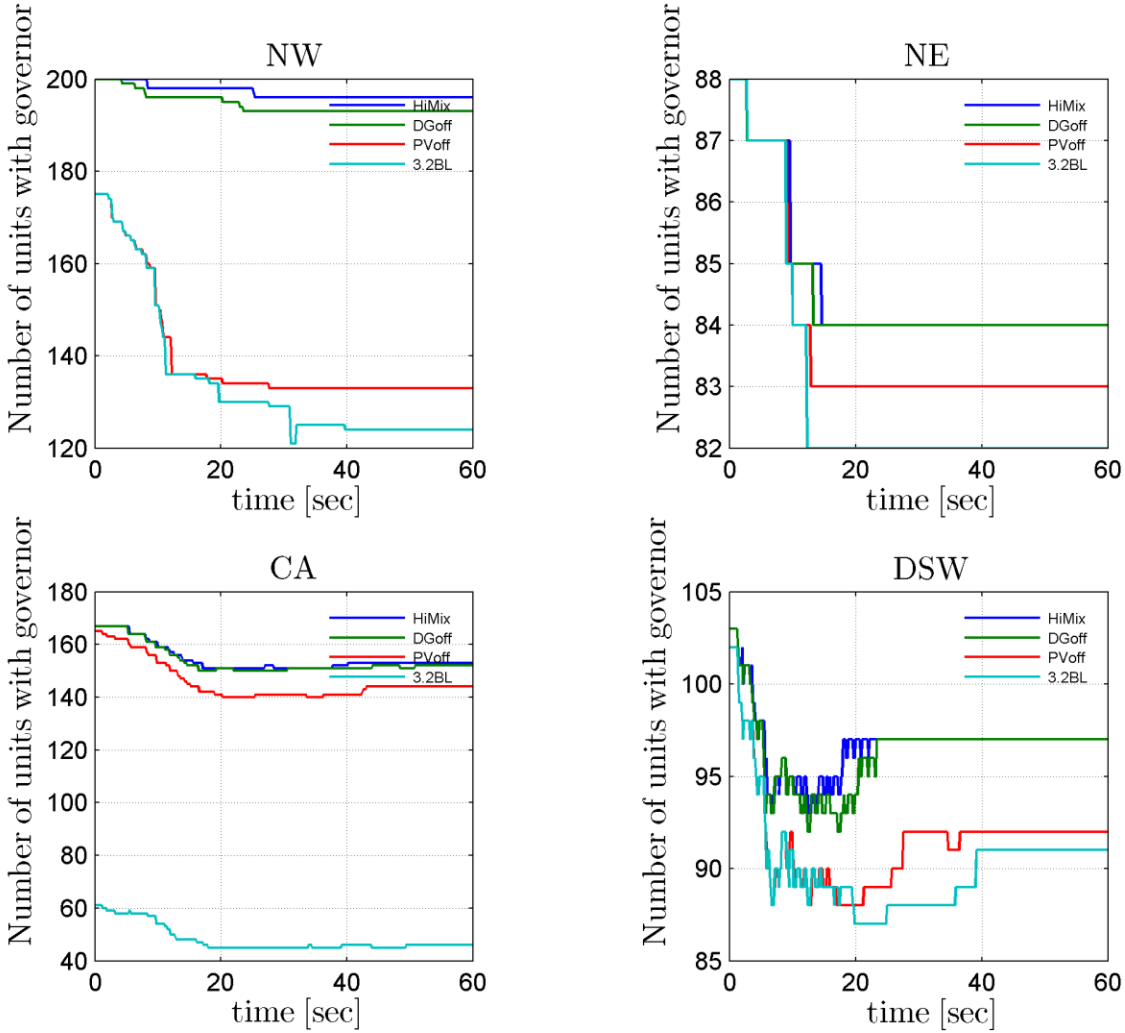
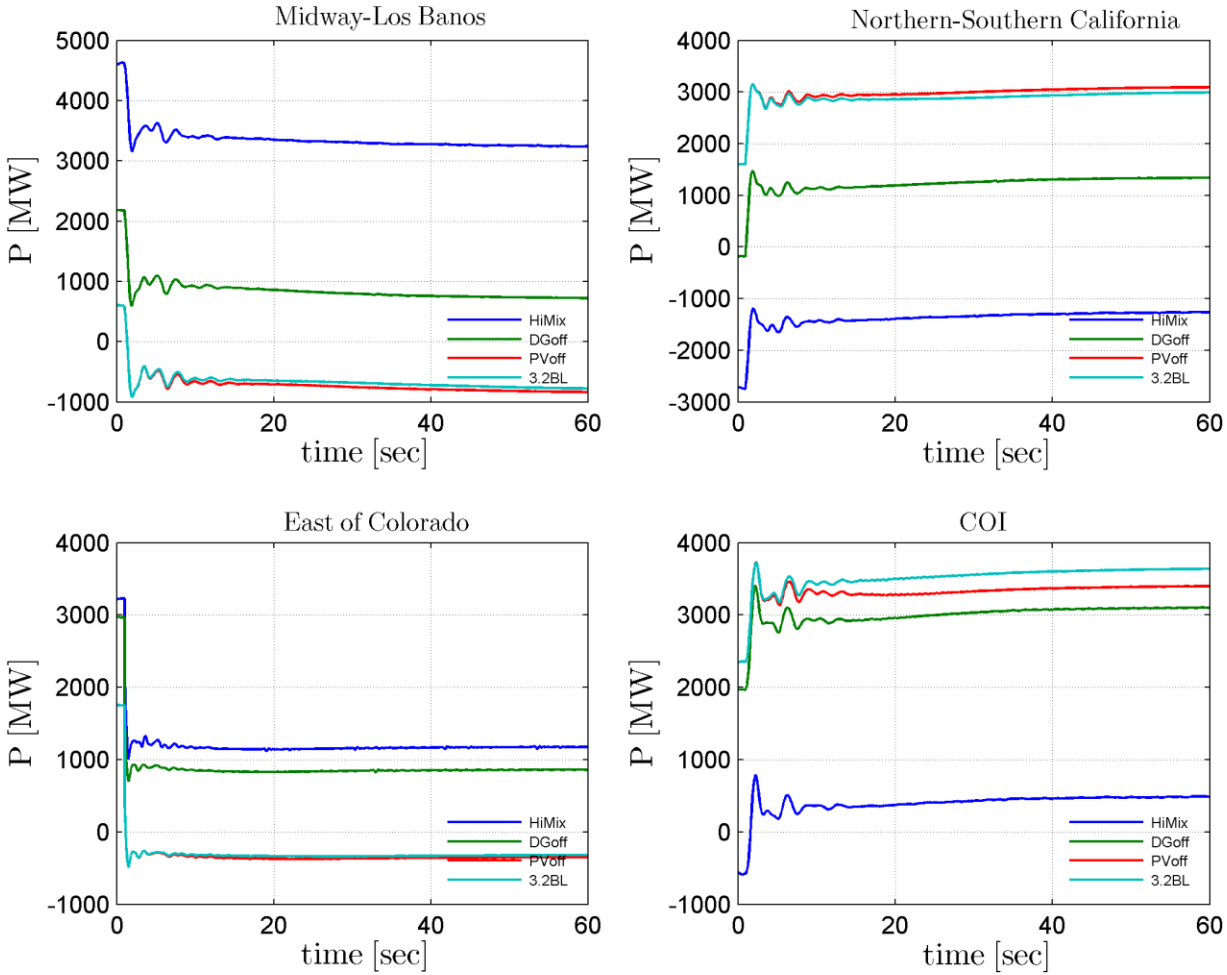
Number of units with governors (and non-zero headroom)



Interface Flows



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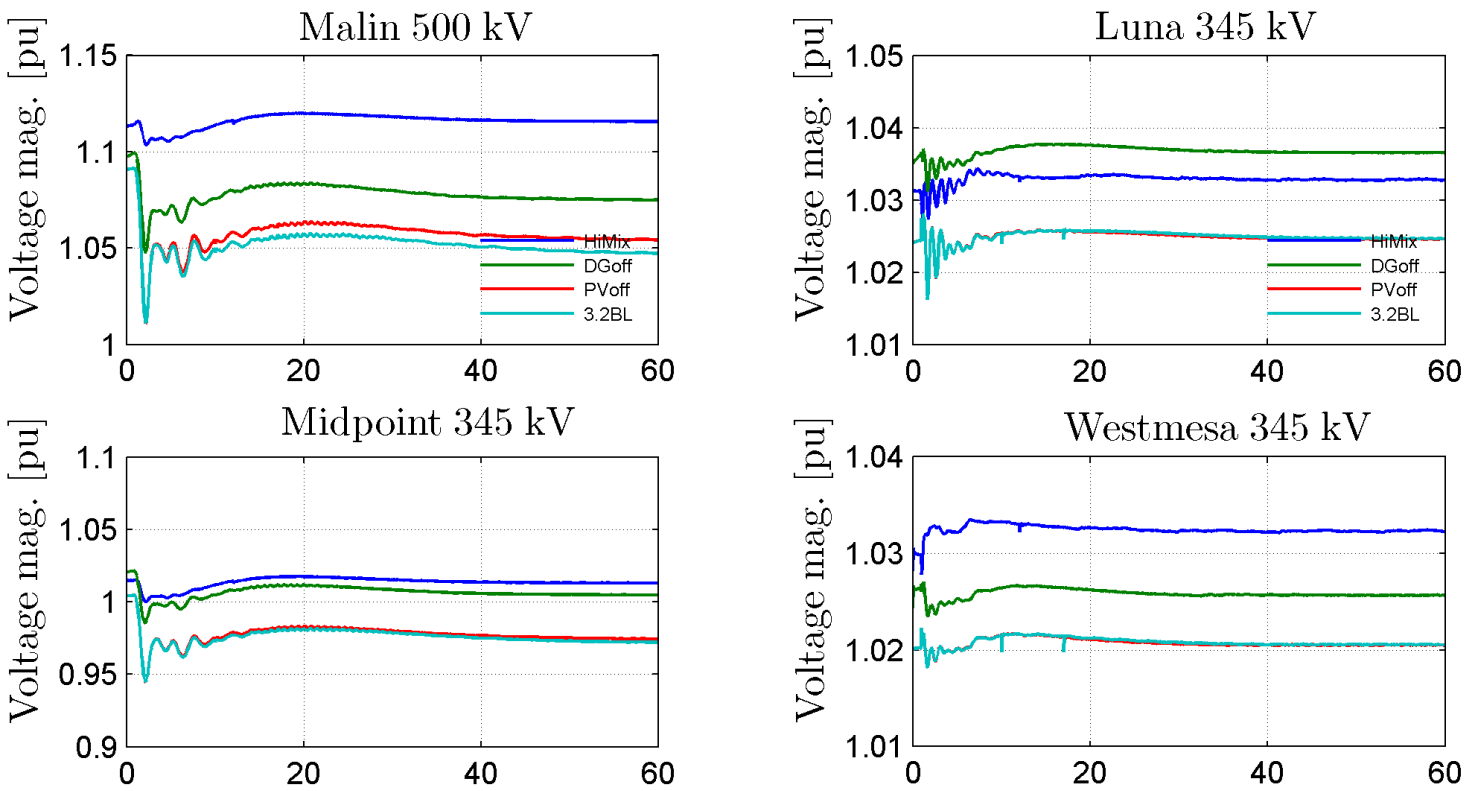
Some Bus Voltages



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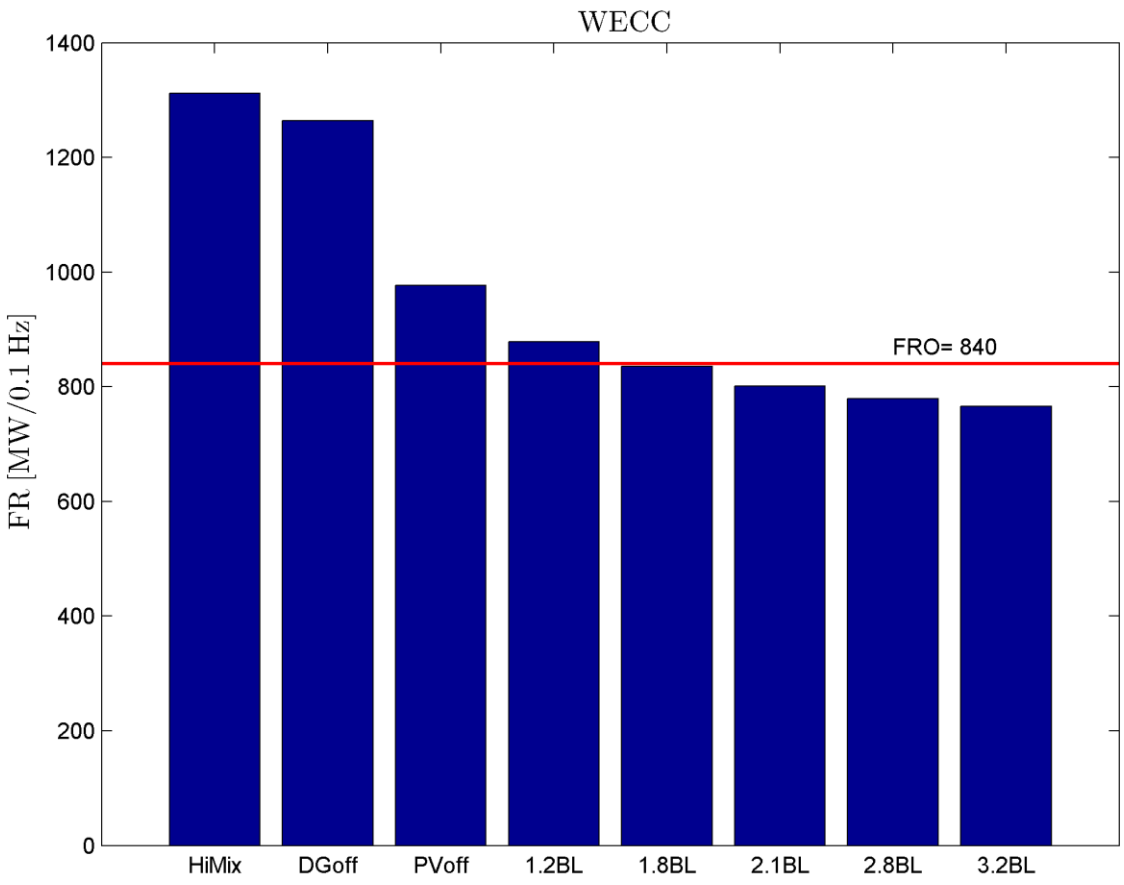
WECC Frequency Response



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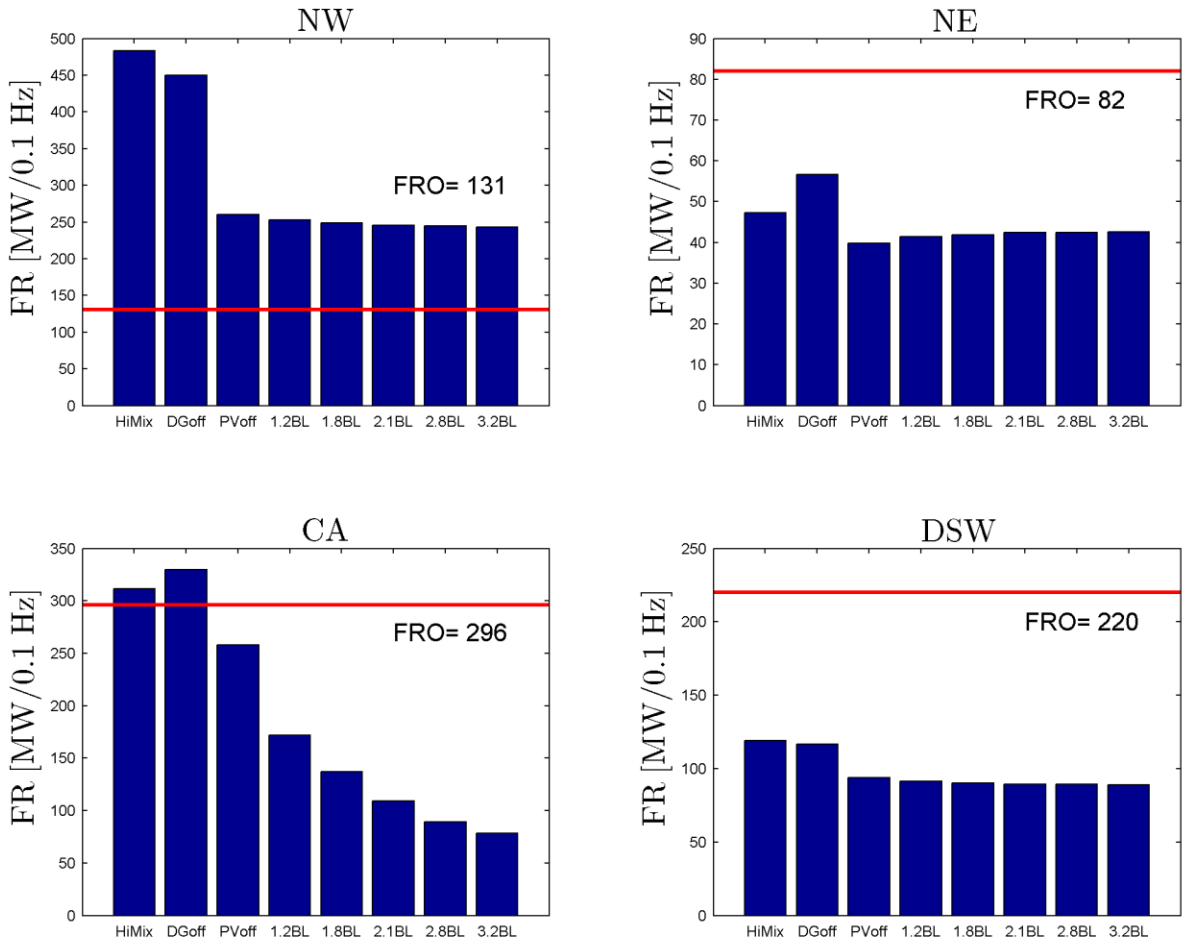
WECC Frequency Response – 4 Regions



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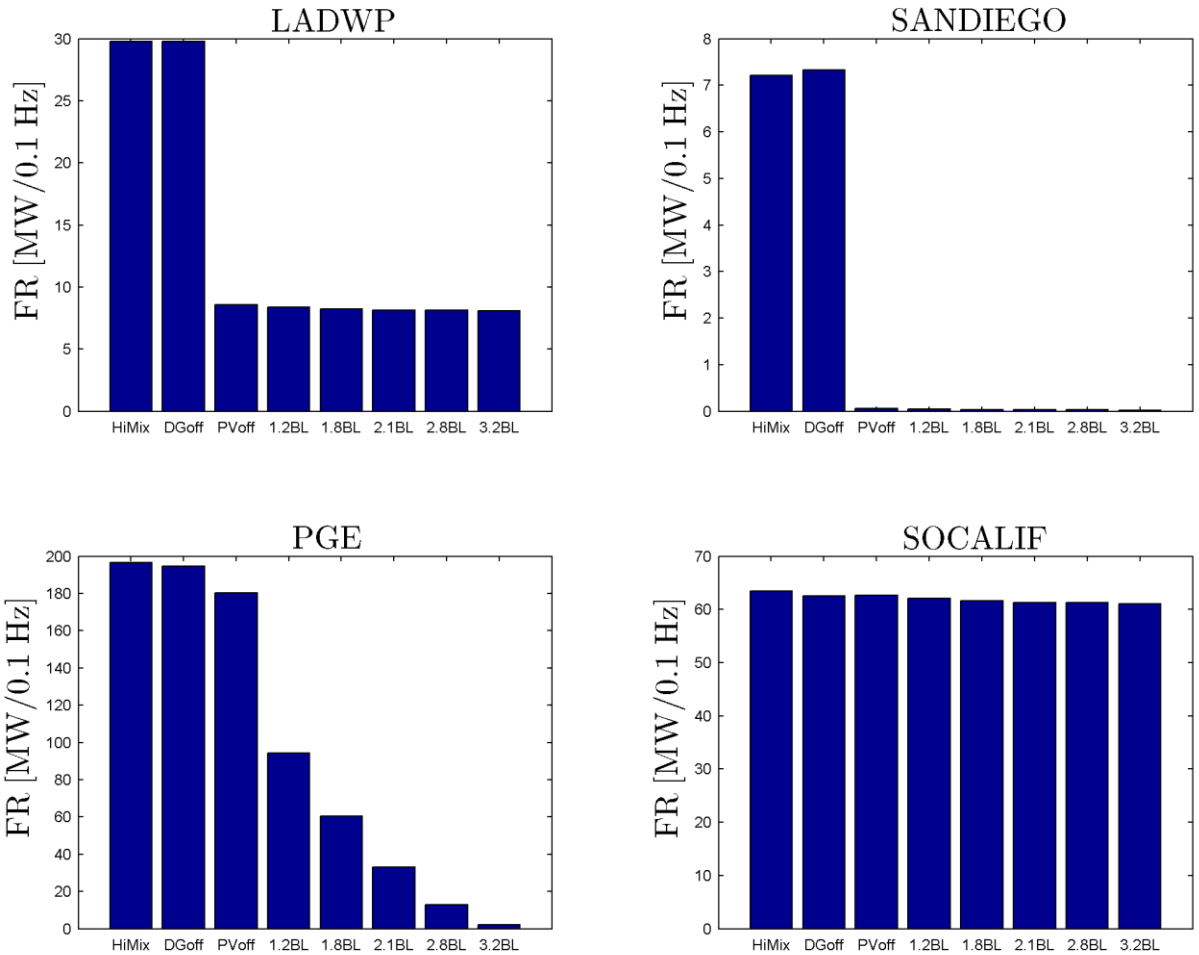
CA Area Frequency Response



Hydro in California is in PG&E area

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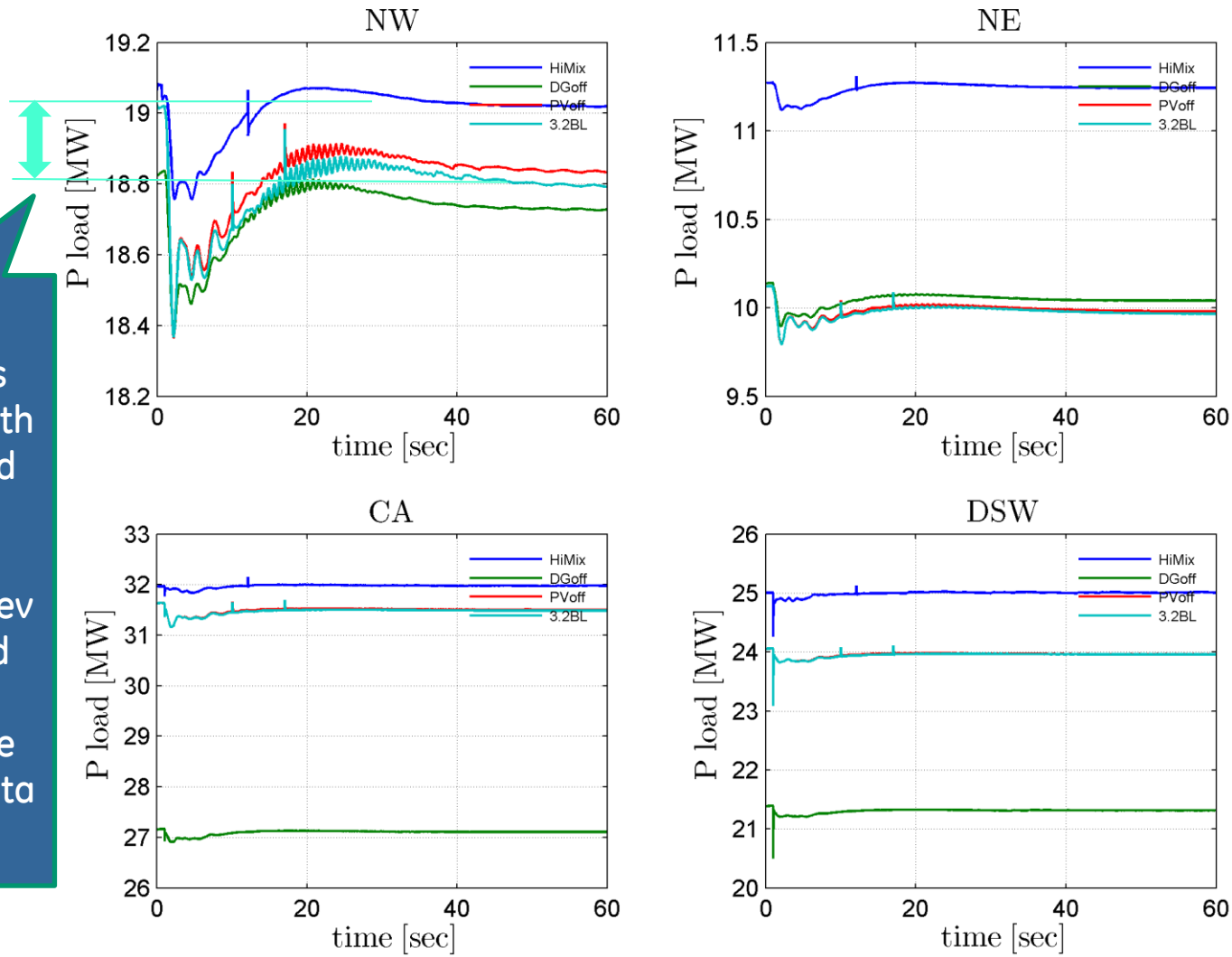
Load Behavior



Some complexities associated with Complex load model…But deltas are interesting…several hundred MW of load response due to Voltage delta .

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Observations on Headroom Depletion

- No dramatic cliff observed…degradation of FR is steady, monotonic.
- Overall WECC FR is marginal, even with signficant contribution for CA hydro
  - Fails to meet FRO with about ½ of hydro becoming unresponsive
- Many local stress points, e.g. poor voltage, as PV drops output
- Suggests need to commit/recommit units could be driven as much by local constraints as overall stability
- Minor local stress related stability issues, e.g. individual units having stability problems (poor voltage, units dispatched at P_{max} losing synch, etc.)
- Suggests locational issues may drive some local/secondary (?) constraints on FR

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Observations on Headroom Depletion (cont)

- Kt = .30 is not obviously sufficient criteria
  - Good indicator in California
  - But both NE and DSW regions come up short with Kt about 30%
  - Enough headroom is needed across enough machines

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High Stress and Path Loadings

Three Cases

- 2022 LSP Base
- 2022 LSP HiMix
- 2022 LSP HiMix Extreme

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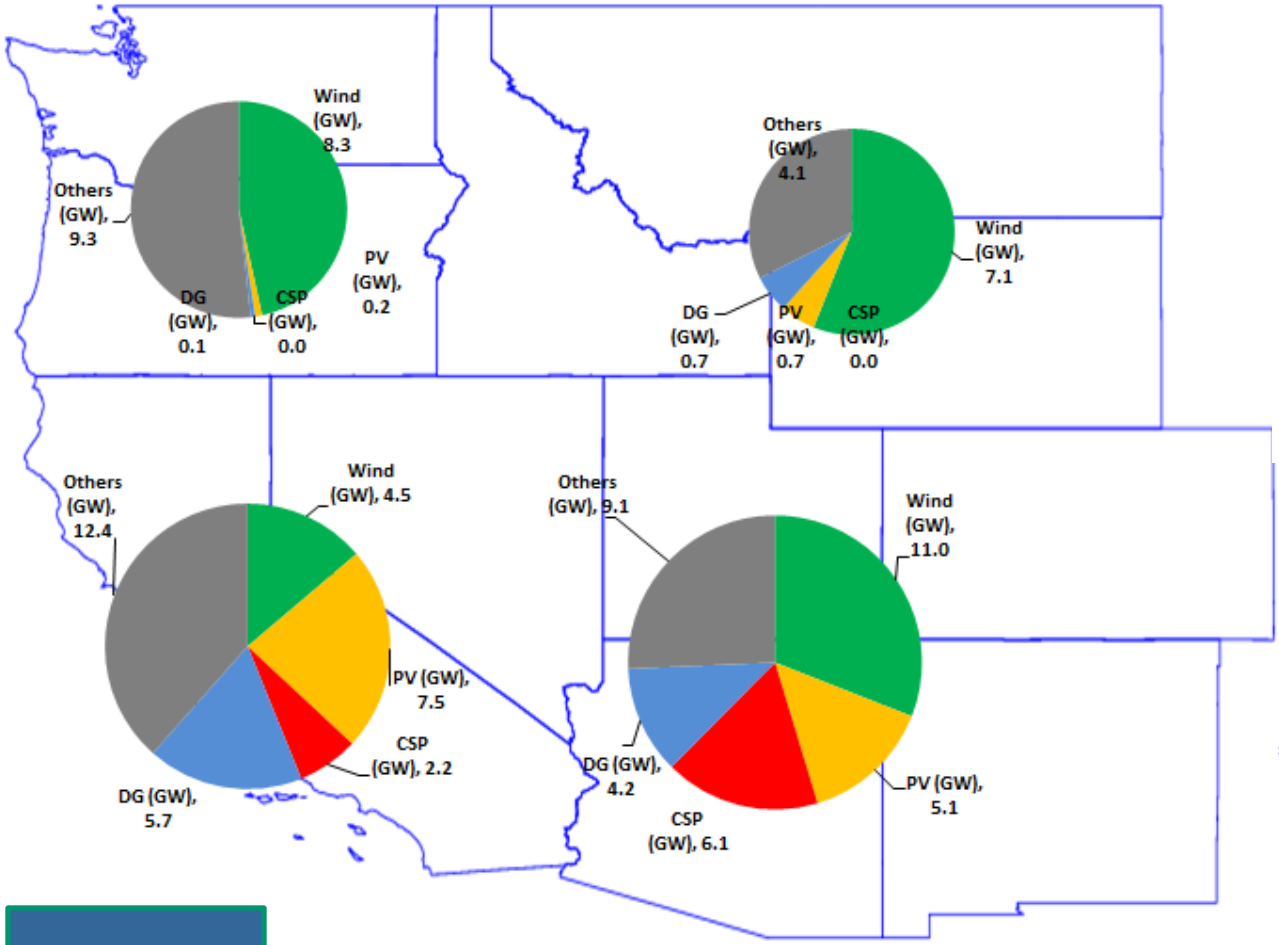
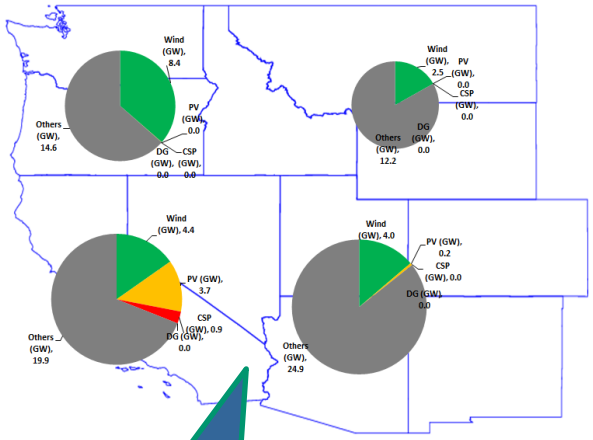
Preliminary Results: Not for Further Distribution or Citation

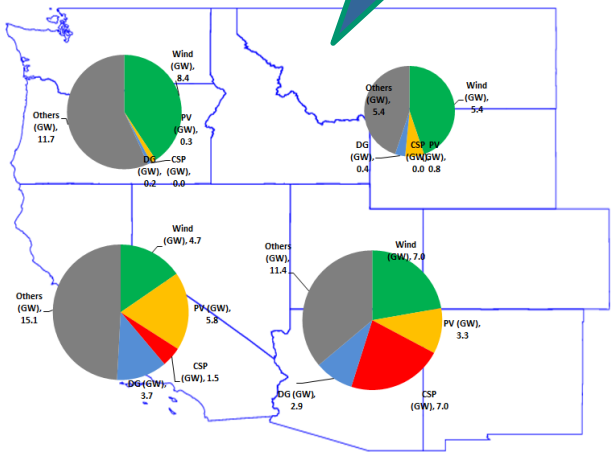
LSP HiMix Extreme Case - Renewable Conditions





~ 25 GW of wind and solar total in Base Case

~ 52.8 GW of wind and solar total in HiMix Case



~ 64.8 GW of wind and solar

	WECC	CALIFORNIA	DSW	NORTHEAST	NORTHWEST
Wind (GW)	32.6	4.5	11.0	7.1	8.3
PV (GW)	13.5	7.5	5.1	0.7	0.2
CSP (GW)	8.3	2.2	6.1	0.0	0.0
DG (GW)	10.4	5.7	4.2	0.7	0.1
Others (GW)	56.6	12.4	9.1	4.1	9.3
total (GW)	121.4	32.3	35.6	12.6	17.9

Preliminary Results: Not for Further Distribution or Citation

Path Ratings

Interface number	Interface name	22'LSP Base case	22'LSP HiMix	22'LSP HiMix Extreme	Rating
		[MW]			
10	WEST OF COLSTRIP	2024.5	297	-193	2598
15	MIDWAY - LOS BANOS	1467	4545.1	5997.4	4800-5400
22	SOUTHWEST OF FOUR CORNERS	1829.4	-338.8	485.2	2325
26	NORTHERN - SOUTHERN CALIFORNIA	1139.9	-2653.9	-4180.5	4000
30	TOT 1A	414.4	154.1	874.7	650
37	TOT 4A	357.2	258.9	1088.4	810
43	NORTH OF SAN ONOFRE	664.4	1018.4	-681.8	2440
46	WEST OF COLORADO RIVER (WOR)	4204.4	7126.3	7364.5	10623
48	NORTHERN NEW MEXICO (NM2)	-18.3	-357	-1789.7	-1970
49	EAST OF COLORADO RIVER (EOR)	3099.5	3588.3	4062.2	9300
66	COI	2346.2	-266.8	-1593	4800/-3675

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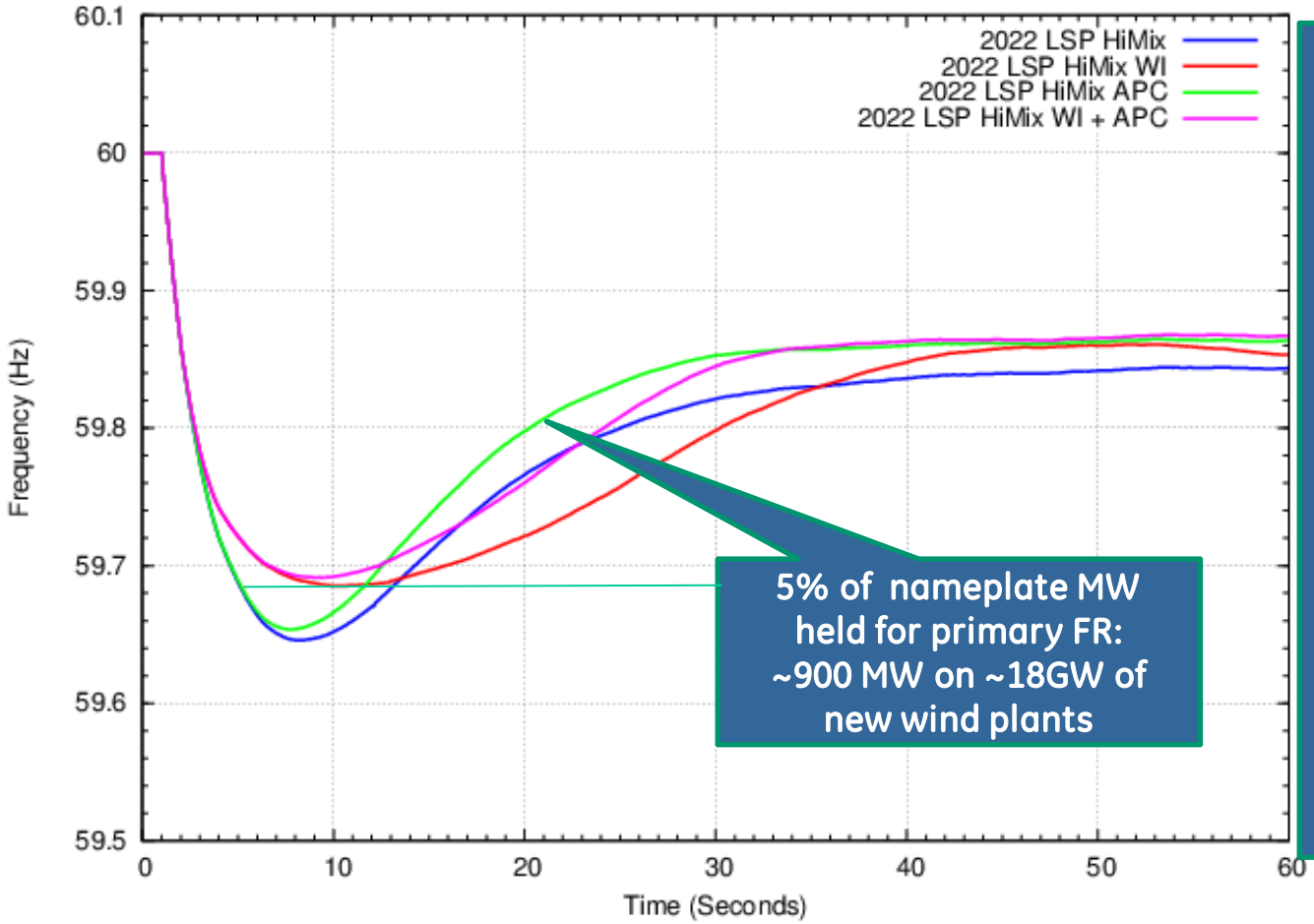
Apply Frequency Controls to Wind Plants

TwoCases

- 2022 LSP HiMix
- 2023 HS HiMix

WECC Frequency Response – 2022 LSP HiMix



Loadflow and initial dispatch are identical in all cases.

For governor response (APC), wind speed is assumed to be such that all new wind plants dispatched at <=95% of rating have enough wind to deliver 5% more power, on their rating base.

That extra power is headroom, that is used to increase the power output when the frequency drops below the deadband

.

Apply frequency controls to all <u>new</u> wind plants with initial loading <= 95% of rating

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Frequency Response: LSP HiMix Wind FR Controls

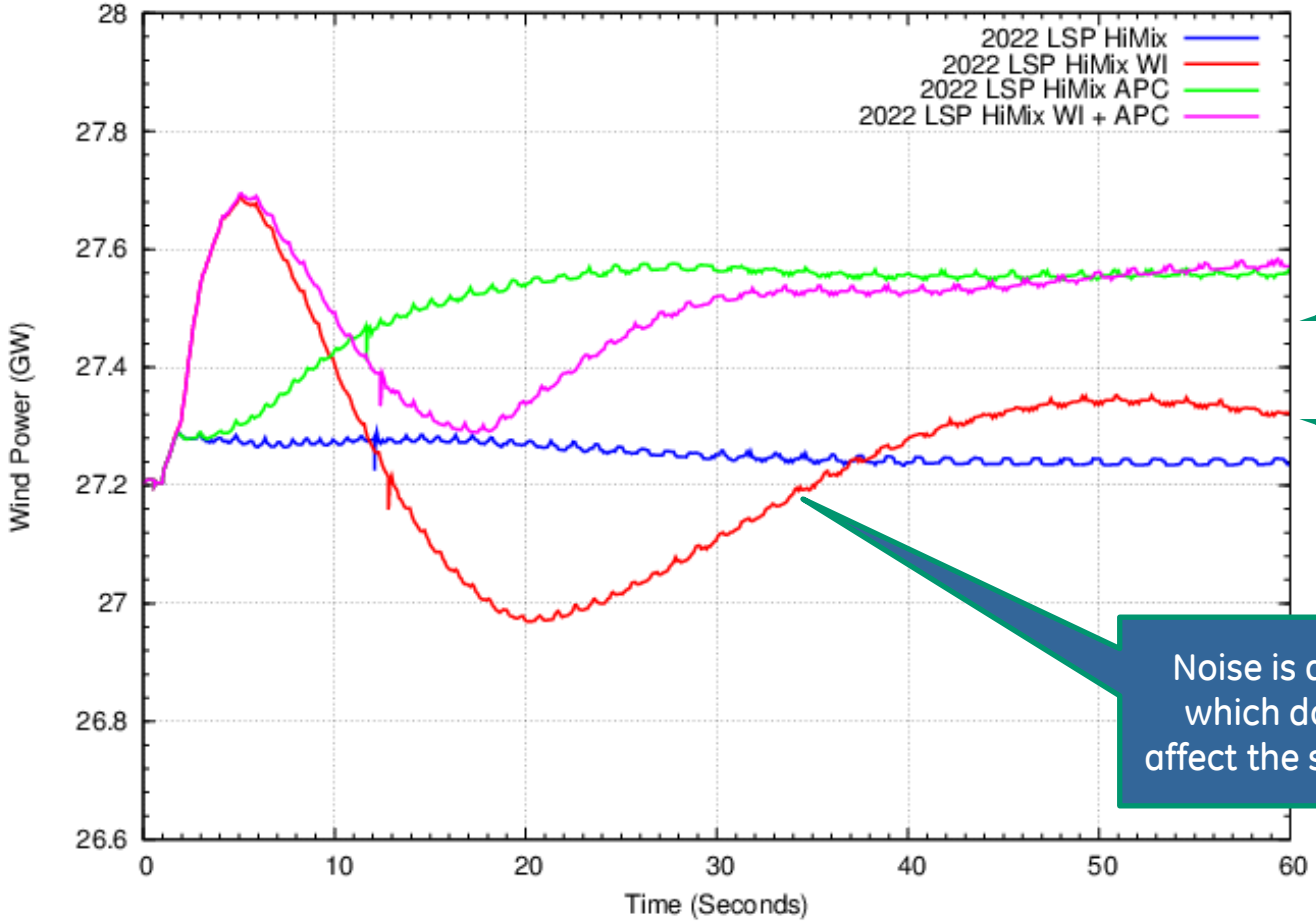
						WI		WI+APC		APC	
Name	ID	PGEN [GW]	FRO [MW/0.1Hz]	FR [MW/0.1Hz]	FR margin [MW/0.1Hz]	FR [MW/0.1Hz]	FR margin [MW/0.1Hz]	FR [MW/0.1Hz]	FR margin [MW/0.1Hz]	FR [MW/0.1Hz]	FR margin [MW/0.1Hz]
WECC	WE	203.7	840.0	1311.2	471.2	1324.4	484.4	1369.9	529.9	1371.0	531.0
CALIFORNIA	CA	68.8	295.7	334.8	39.1	314.9	19.2	525.6	229.9	562.9	267.2
DSW	DS	53.9	220.0	118.6	-101.4	117.8	-102.2	132.3	-87.6	134.9	-85.1
NORTHEAST	NE	19.7	81.5	54.2	-27.3	39.7	-41.8	140.0	58.5	164.1	82.6
ALBERTA	AL	12.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ARIZONA	AZ	27.5	104.4	49.7	-54.7	49.8	-54.5	51.1	-53.2	51.1	-53.3
B.C.HYDRO	BC	11.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EL PASO	EL	1.7	8.6	3.8	-4.8	3.6	-5.0	4.3	-4.3	4.5	-4.1
IDAHO	ID	4.3	17.9	21.8	3.9	22.0	4.1	22.7	4.9	23.0	5.1
IMPERIALCA	IV	1.5	4.0	14.4	10.5	14.6	10.7	14.7	10.7	14.6	10.6
LADWP	LA	6.3	29.3	29.8	0.5	29.0	-0.3	40.4	11.2	42.7	13.4
MEXICO-CFE	MX	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MONTANA	MT	3.3	11.3	10.3	-1.0	10.5	-0.8	10.1	-1.2	10.2	-1.1
NEVADA	NV	6.1	27.9	33.6	5.7	28.5	0.6	68.5	40.7	77.3	49.4
NEW MEXICO	NM	3.5	14.3	1.8	-12.6	1.8	-12.6	1.8	-12.5	1.9	-12.5
NORTHWEST	NW	33.3	130.8	490.2	359.3	496.2	365.4	517.1	386.3	517.6	386.7
PACE	PC	9.4	41.8	25.4	-16.4	25.4	-16.4	26.1	-15.6	26.2	-15.6
PG AND E	PG	32.4	132.7	196.2	63.5	196.8	64.1	252.6	119.9	255.0	122.3
PSCOLORADO	CO	8.3	35.5	5.2	-30.3	5.2	-30.3	5.3	-30.2	5.2	-30.3
SANDIEGO	SD	4.4	21.3	7.4	-14.0	7.3	-14.0	7.6	-13.7	7.7	-13.7
SIERRA	SP	2.6	10.6	7.0	-3.6	7.3	-3.3	6.8	-3.8	6.4	-4.2
SOCALIF	SC	24.2	108.4	63.6	-44.8	65.3	-43.1	65.9	-42.5	64.6	-43.8
FORTISBC	FB	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WAPA R.M.	WR	6.9	27.4	24.2	-3.2	24.4	-3.1	25.4	-2.0	25.6	-1.9
WAPA U.M.	WU	0.1	0.1	2.5	2.3	-10.6	-10.8	75.0	74.9	95.3	95.1

900 MW curtailment at 5% droop governor control (APC) yields about 350 MW of response which adds about 60 MW/0.1Hz = ~5% to the FR for WECC

imagination at work

TRC Call: Do not Cite - Not for Further Distribution

WECC Wind Generation– 2022 LSP HiMix



~350MW of response

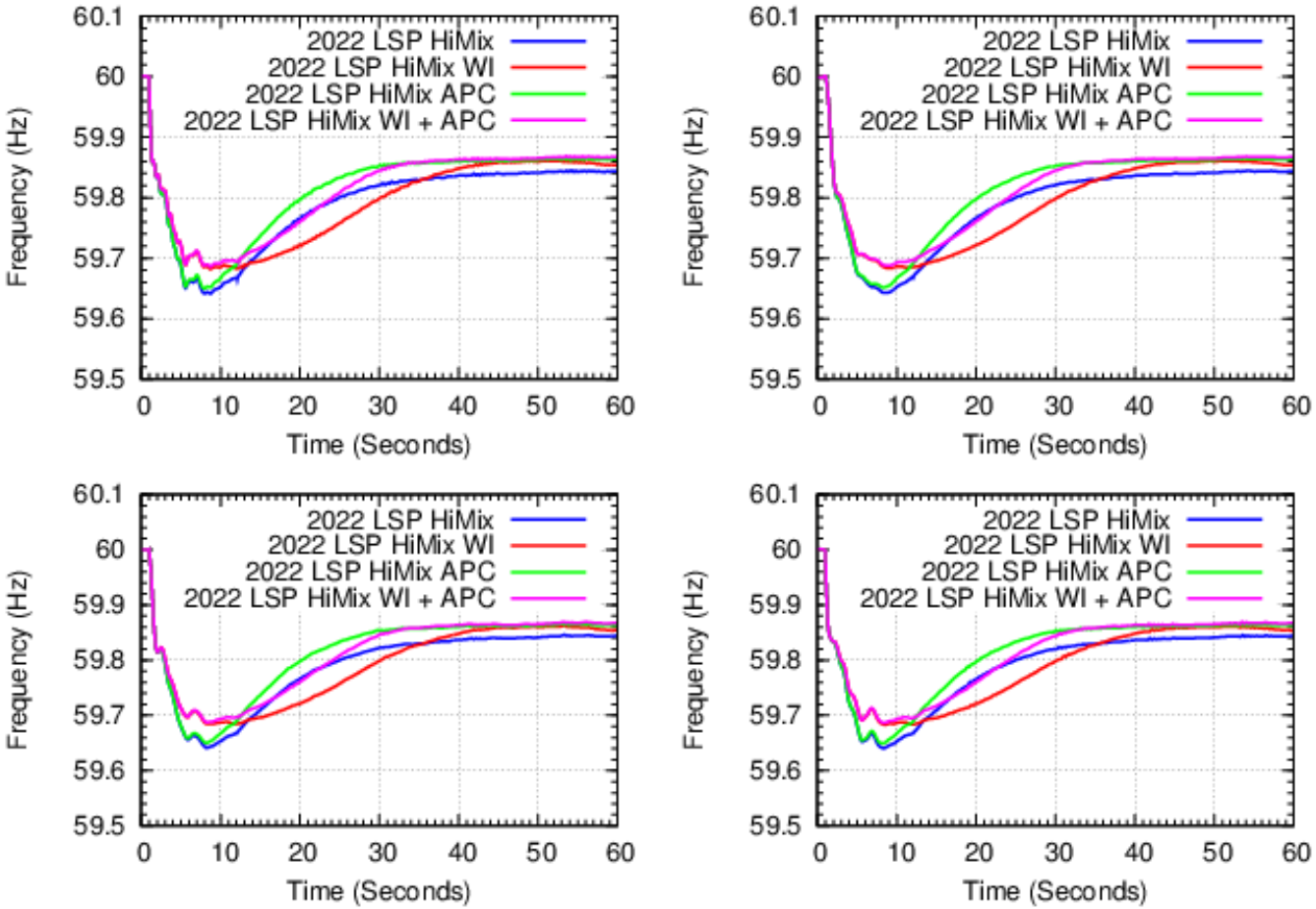
Noise is a numeric issue which doesn't actually affect the simulation much.

Apply frequency controls to all new wind plants

imagination at work

TRC Call: Do not Cite - Not for Further Distribution

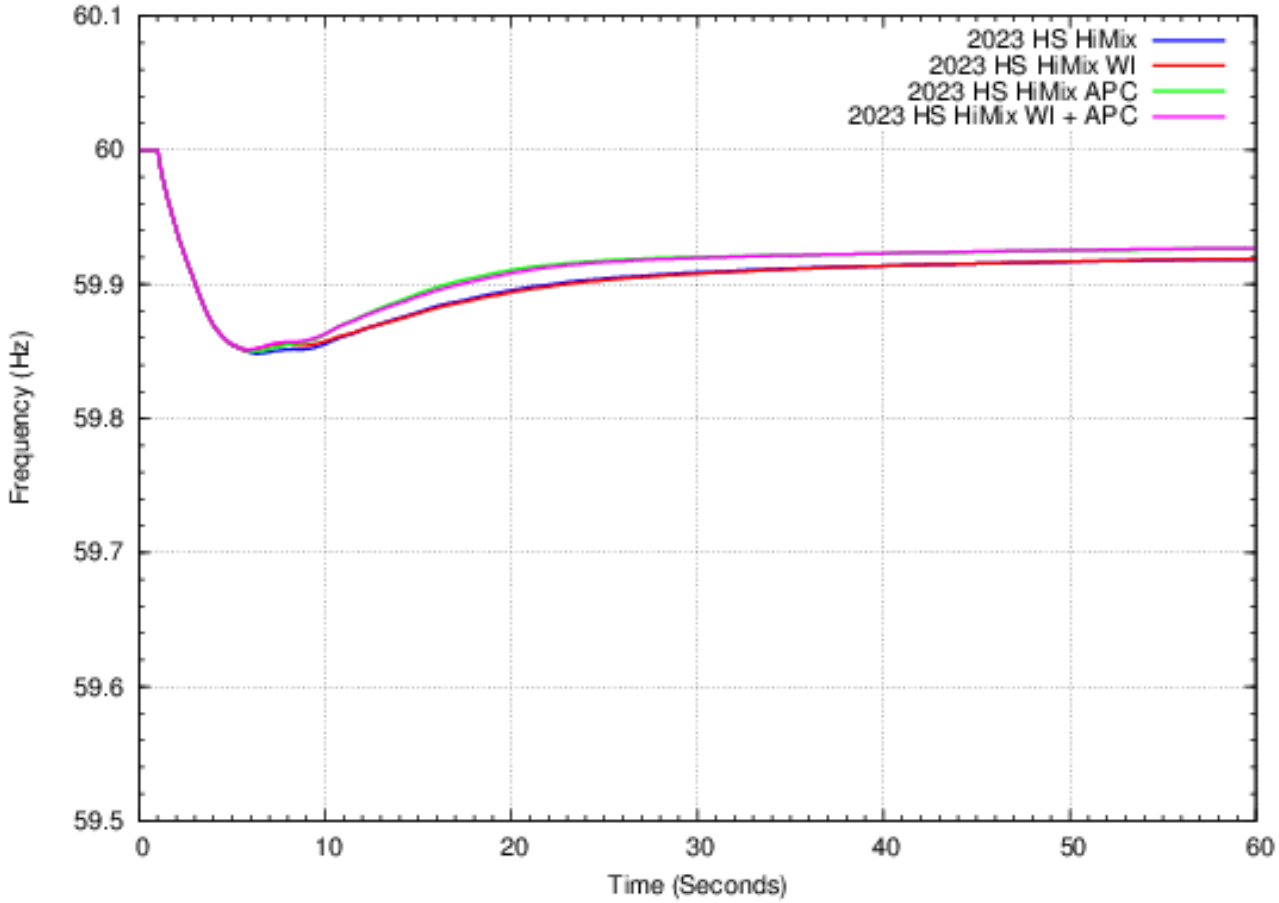
WECC Regional Frequency Response – 2022 LSP HiMix



Apply frequency controls to all new wind plants

TRC Call: Do not Cite - Not for Further Distribution

WECC Frequency Response – 2023 HS HiMix

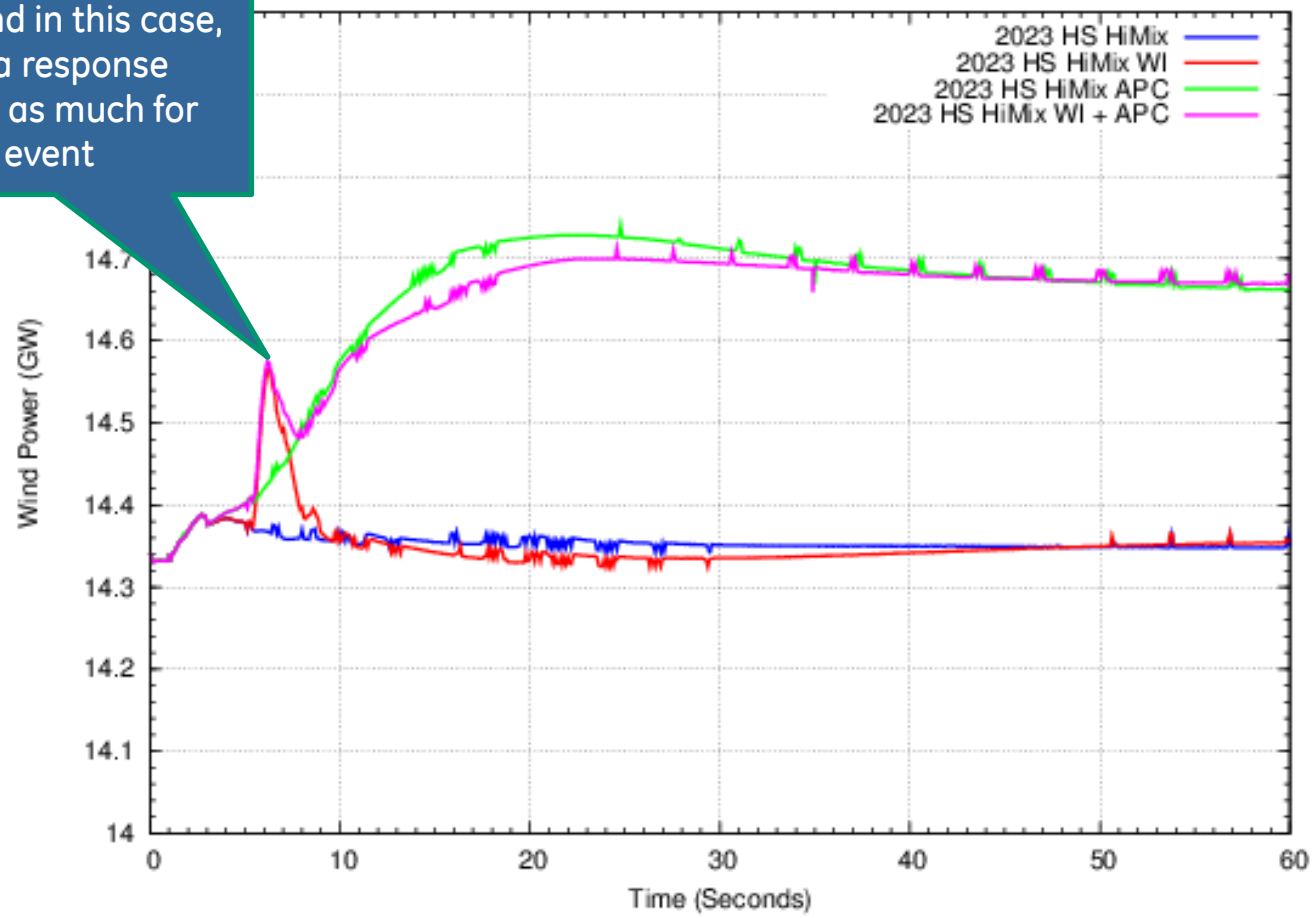


Apply frequency controls to all new wind plants

TRC Call: Do not Cite - Not for Further Distribution

WECC Wind Generation– 2023 HS HiMix

System has more synchronous generation and less wind in this case, so inertia response doesn't do as much for this event



Apply frequency controls to all new wind plants

imagination at work

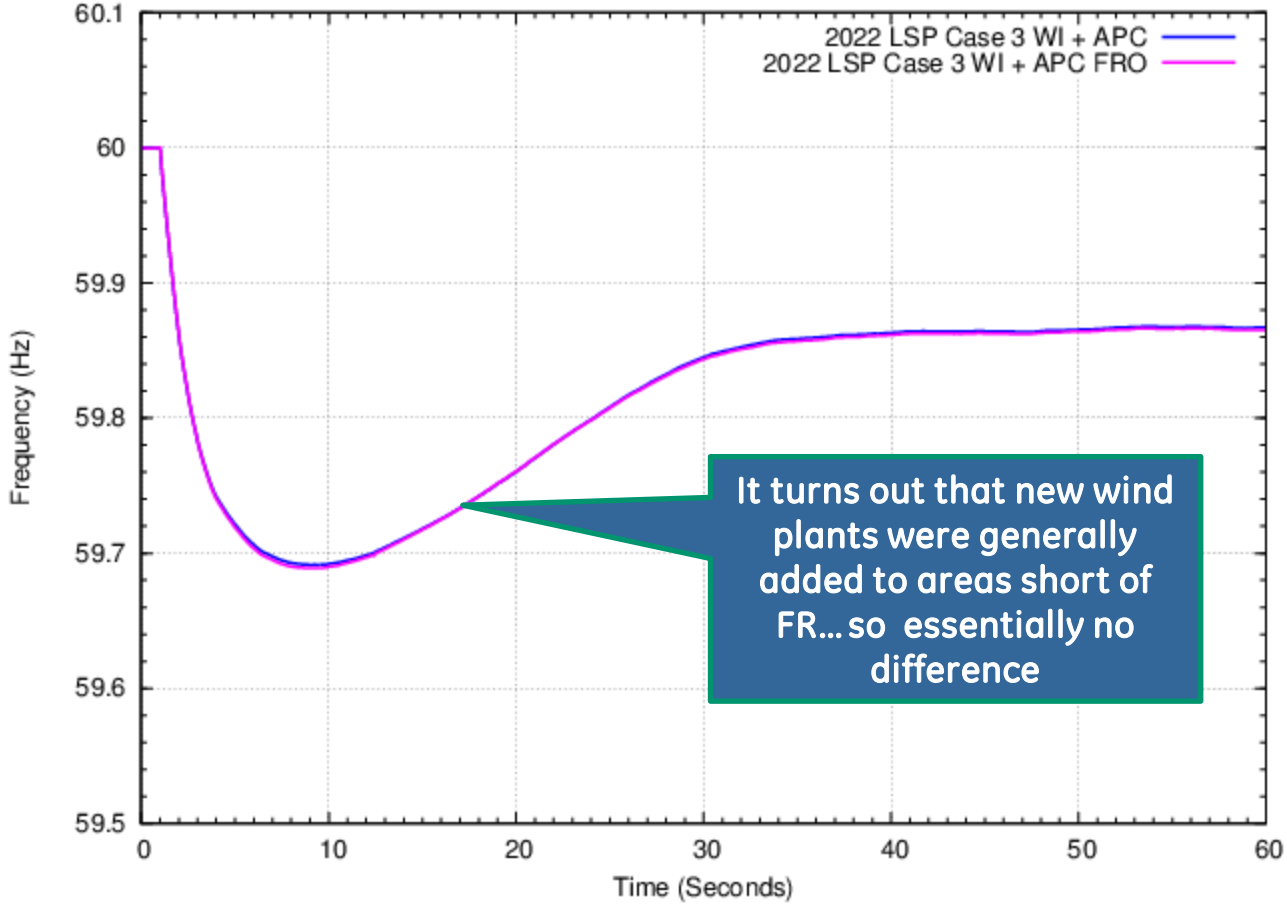
TRC Call: Do not Cite - Not for Further Distribution

Frequency Response – HS HiMix Wind FR Controls

							WI		WI+APC		APC	
ID	Name	ID	PGEN [GW]	FRO [MW/0.1Hz]	FR [MW/0.1Hz]	FR margin [MW/0.1Hz]	FR [MW/0.1Hz]	FR margin [MW/0.1Hz]	FR [MW/0.1Hz]	FR margin [MW/0.1Hz]	FR [MW/0.1Hz]	FR margin [MW/0.1Hz]
1	WECC	WE	203.7	840.0	2671.8	1831.8	2668.5	1828.5	2729	1889	2722.0	1882.0
2	CALIFORNIA	CA	68.8	295.7	773.5	477.8	761.9	466.2	1214	918	1226.7	931.0
3	DSW	DS	53.9	220.0	661.2	441.2	660.1	440.1	676	456	674.8	454.9
4	NORTHEAST	NE	19.7	81.5	59.3	-22.2	55.1	-26.4	122	41	131.2	49.6
54	ALBERTA	AL	12.9	0.0	0.0	0.0	0.0	0.0	0	0	0.0	0.0
14	ARIZONA	AZ	27.5	104.4	382.4	278.0	382.2	277.8	389	285	388.6	284.3
50	B.C.HYDRO	BC	11.3	0.0	0.0	0.0	0.0	0.0	0	0	0.0	0.0
11	EL PASO	EL	1.7	8.6	33.3	24.6	33.2	24.6	35	26	34.7	26.1
60	IDAHO	ID	4.3	17.9	22.8	4.9	22.7	4.9	24	7	24.3	6.4
21	IMPERIALCA	IV	1.5	4.0	19.8	15.8	19.7	15.8	21	17	21.7	17.7
26	LADWP	LA	6.3	29.3	75.4	46.1	74.9	45.6	79	50	78.9	49.6
20	MEXICO-CFE	MX	2.7	0.0	0.0	0.0	0.0	0.0	0	0	0.0	0.0
62	MONTANA	MT	3.3	11.3	14.5	3.2	14.5	3.2	14	3	14.4	3.1
18	NEVADA	NV	6.1	27.9	59.9	32.1	58.8	31.0	93	65	97.5	69.6
10	NEW MEXICO	NM	3.5	14.3	33.0	18.6	32.8	18.5	36	22	36.4	22.0
40	NORTHWEST	NW	33.3	130.8	830.5	699.7	828.1	697.3	856	725	853.0	722.2
65	PACE	PC	9.4	41.8	11.3	-30.5	6.1	-35.7	329	287	326.1	284.4
30	PG AND E	PG	32.4	132.7	478.5	345.8	477.8	345.0	503	370	504.7	372.0
70	PSCOLORADO	CO	8.3	35.5	79.1	43.6	79.1	43.6	80	44	79.5	44.0
22	SANDIEGO	SD	4.4	21.3	55.1	33.8	55.1	33.8	55	34	55.3	34.0
64	SIERRA	SP	2.6	10.6	4.8	-5.8	4.8	-5.8	5	-5	5.3	-5.3
24	SOCALIF	SC	24.2	108.4	151.7	43.3	151.8	43.4	155	47	154.7	46.3
52	FORTISBC	FB	1.1	0.0	0.0	0.0	0.0	0.0	0	0	0.0	0.0
73	WAPA R.M.	WR	6.9	27.4	86.9	59.5	86.5	59.1	89	61	88.8	61.4
63	WAPA U.M.	WU	0.1	0.1	2.6	2.4	-0.3	-0.4	56	56	65.3	65.2

TRC Call: Do not Cite - Not for Further Distribution

WECC Frequency Response – 2022 LSP HiMix



It turns out that new wind plants were generally added to areas short of FR… so essentially no difference

Apply frequency controls to only new wind plants in areas short of FRO

imagination at work

TRC Call: Do not Cite - Not for Further Distribution

Observations on Frequency Response from Wind Plants

- Inertial response (in LSP HiMix) produces a 41mHz (~12%) improvement in nadir, and stretches out recovery
  - Saturation of inertial response not high enough to cause double-dip problem in this case
- Governor response improves settling frequency
  - ~350 MW response from ~900 MW of headroom
  - Suggests that 5% droop underutilizes this resources…
  - More to follow below
- Combined response is good
  - System wide FR improves

TRC Call: Do not Cite - Not for Further Distribution

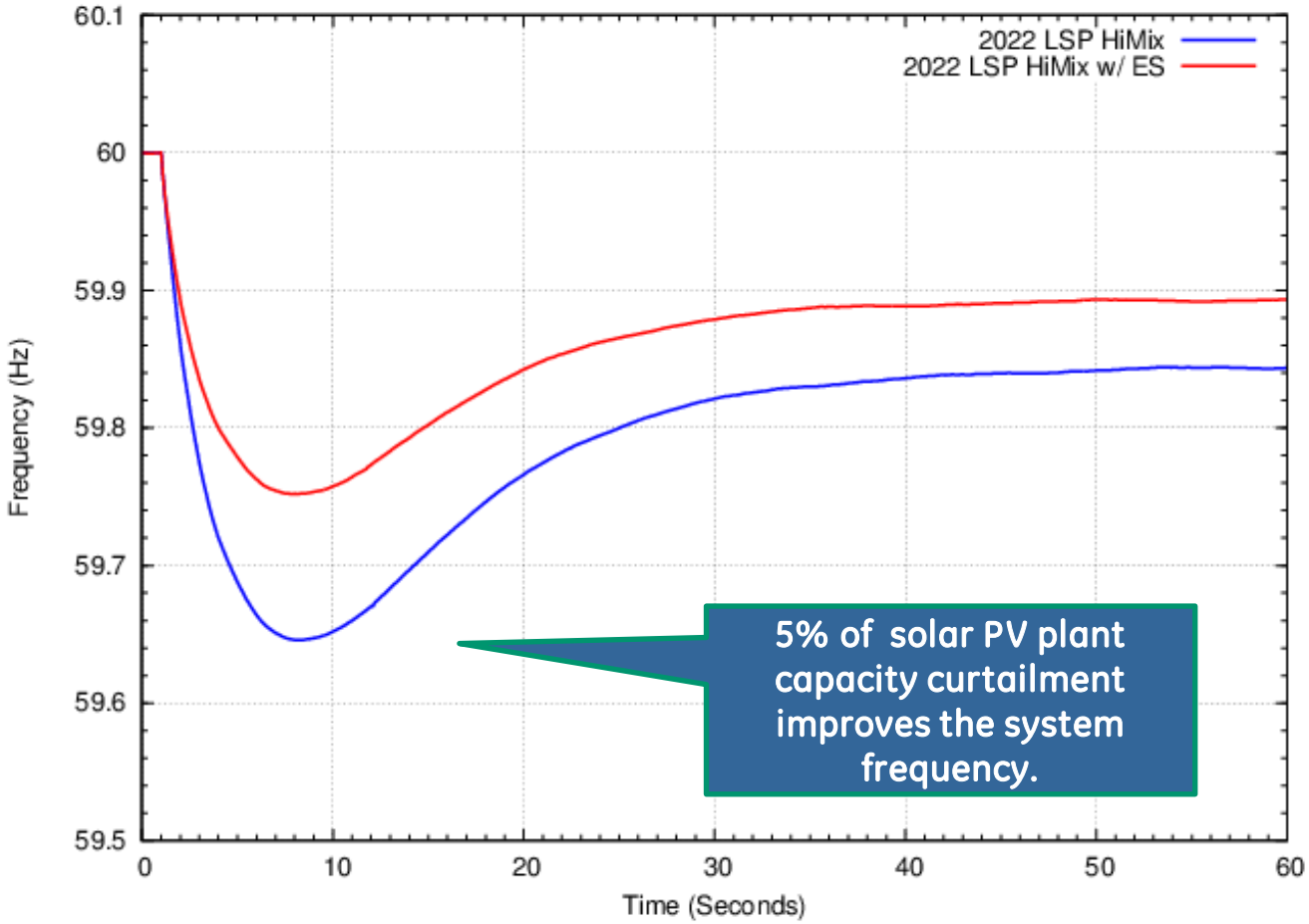
Apply Frequency Controls to Solar Plants

- Add 5% primary frequency response (on plant rating) to new utility scale PV
- ~900 MW curtailment leaving ~10.2GW production on ~18GW nameplate
- Aggressive control (fast, gain selected to saturate for this design-basis disturbance)
- No mechanical risk or penalty for fast response
- No inertial response tests (PV has no inertia to access)
- One case: 2022 LSP HiMix

imagination at work

TRC Call: Do not Cite - Not for Further Distribution

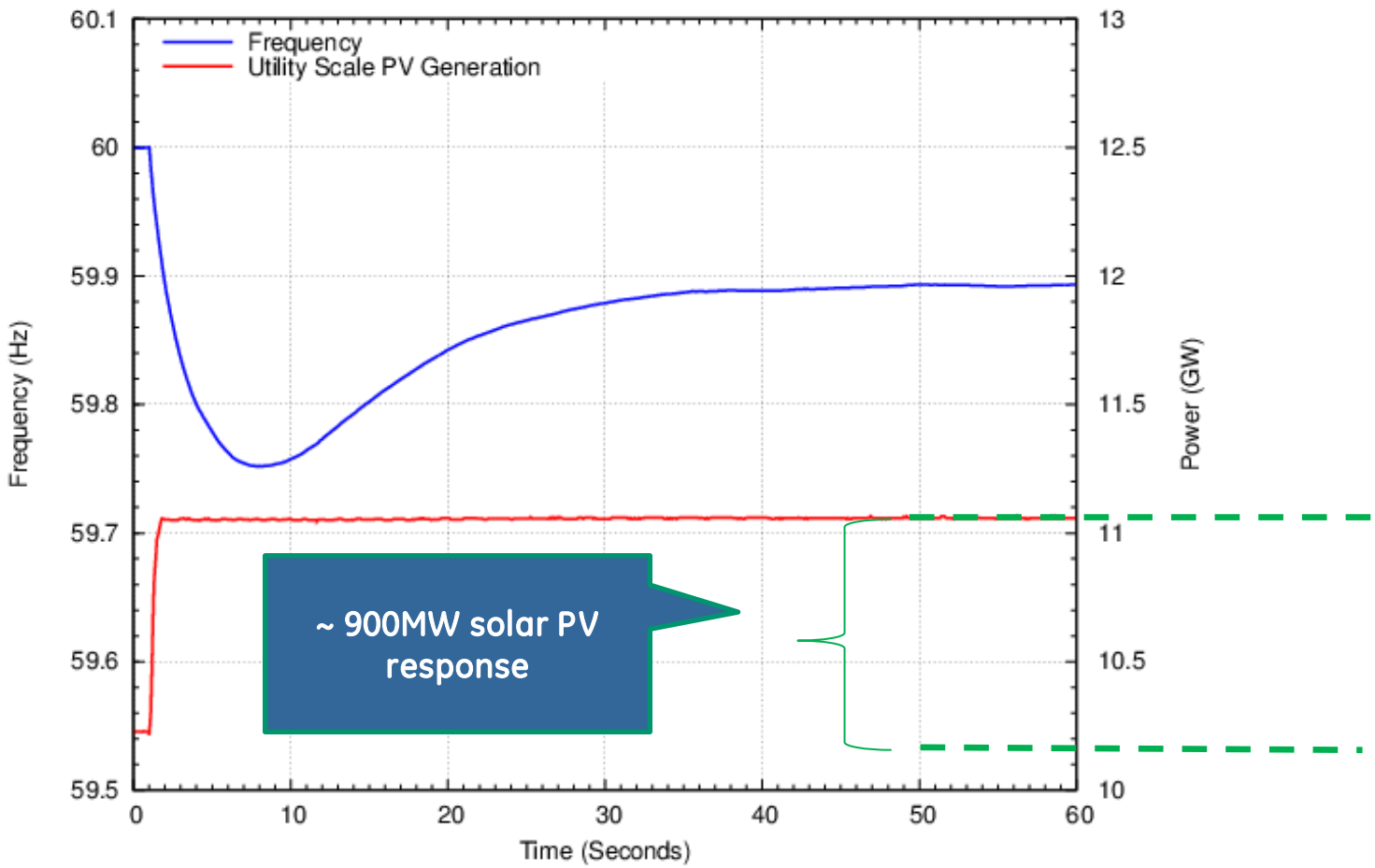
WECC Frequency Response – 2022 LSP HiMix



imagination at work

TRC Call: Do not Cite - Not for Further Distribution

WECC Utility Scale PV Response - 2022 LSP HiMix



imagination at work

TRC Call: Do not Cite - Not for Further Distribution

Frequency Response: LSP with PV Solar FR

TRC Call: Do not Cite - Not for Further Distribution

Observations on Frequency Response from PV Solar

- Primary response (with this control) is very effective at improving both nadir and settling frequency
  - Nadir improves ~40mHz
  - Settling frequency improves
  - FR improves
  - Suggests best use of this class of resource is highly non-linear….raises some interesting questions of practice and reliability
  - More below
- (Reminder: We already looked at FR from CSP earlier)

TRC Call: Do not Cite - Not for Further Distribution

Add Energy Storage for Frequency Response

Add inverter based energy storage (e.g. battery system) to areas short of FR

Determine (approximately) the amount of ES required to bring FR = FRO in those areas.

Two cases

- 2022 LSP HiMix
- 2022 LSP HiMix Extreme

imagination at work

TRC Call: Do not Cite - Not for Further Distribution

Energy Storage - 2022LSP HiMix

ID	Name	ID	FR [MW/0.1Hz]	%of WECC FR	FR margin [MW/0.1Hz]	Pbess for LSP C3	FR/FRO %
1	WECC	WE	1311.4	100.0	471.4	0.0	156.1
2	CALIFORNIA	CA	311.7	23.8	15.9	0.0	105.4
3	DSW	DS	119.2	9.1	-100.8	157.3	54.2
4	NORTHEAST	NE	47.3	3.6	-34.2	53.6	58.0
54	ALBERTA	AL	0.0	0.0	0.0	0.0	
14	ARIZONA	AZ	49.7	3.8	-54.7	85.3	47.6
50	B.C.HYDRO	BC	0.0	0.0	0.0	0.0	
11	EL PASO	EL	3.8	0.3	-4.8	7.6	43.8
60	IDAHO	ID	21.8	1.7	3.9	0.0	122.1
21	IMPERIALCA	IV	14.4	1.1	10.5	0.0	364.5
26	LADWP	LA	29.8	2.3	0.5	0.0	101.8
20	MEXICO-CFE	MX	0.0	0.0	0.0	0.0	
62	MONTANA	MT	10.3	0.8	-1.0	1.6	91.1
18	NEVADA	NV	33.9	2.6	6.0	0.0	121.7
10	NEW MEXICO	NM	1.8	0.1	-12.6	19.6	12.4
40	NORTHWEST	NW	483.4	36.9	352.6	0.0	369.5
65	PACE	PC	8.2	0.6	-33.6	52.6	19.6
30	PG AND E	PG	196.5	15.0	63.8	0.0	148.0
70	PSCOLORADO	CO	5.8	0.4	-29.7	46.7	16.5
22	SANDIEGO	SD	7.2	0.6	-14.1	22.0	33.8
64	SIERRA	SP	7.0	0.5	-3.6	5.6	66.1
24	SOCALIF	SC	63.5	4.8	-45.0	69.9	58.5
52	FORTISBC	FB	0.0	0.0	0.0	0.0	
73	WAPA R.M.	WR	24.2	1.8	-3.2	5.1	88.2
63	WAPA U.M.	WU	2.7	0.2	2.5	0.0	1795.0
						316.0	

Remember that these are estimated FRO for these areas. FRO applies to BAs

Areas with negative FR margin have ES added with rating sufficient to make-up deficit <u>for this settling frequency</u>

Sample math:

- Actual FR = 49.7 MW/0.1Hz
- FRO = 104.4 MW/0.1 Hz (estimated!!)
- Deficit = 54.7 MW/0.1Hz
- Settling freq = -0.156 Hz
- Extra response needed = 54.7MW x 1.56
- (any questions?)

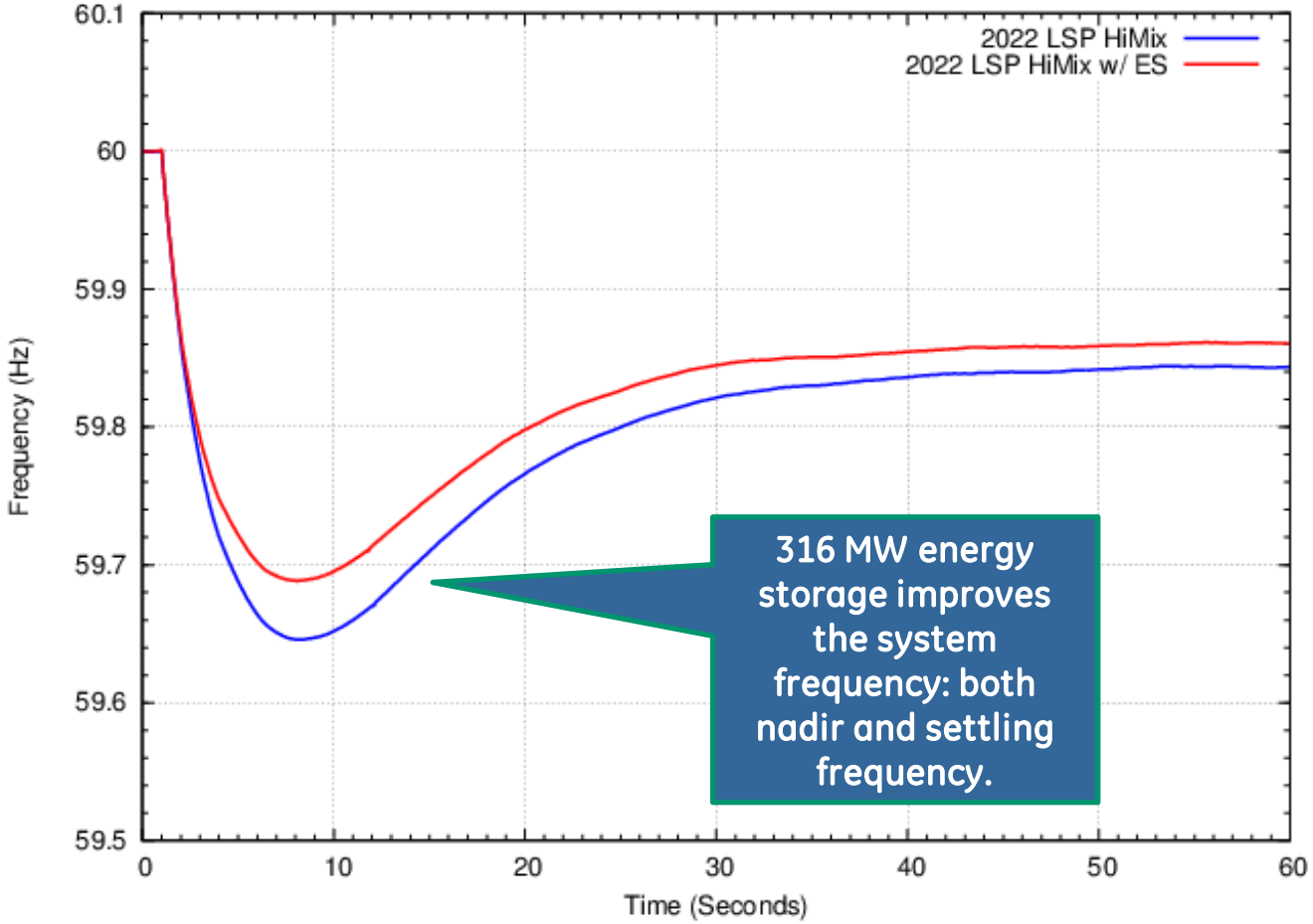
Estimated total 316 MW energy storage required to bring short areas to 100% FRO

imagination at work

Apply energy storage to areas short of FR

TRC Call: Do not Cite - Not for Further Distribution

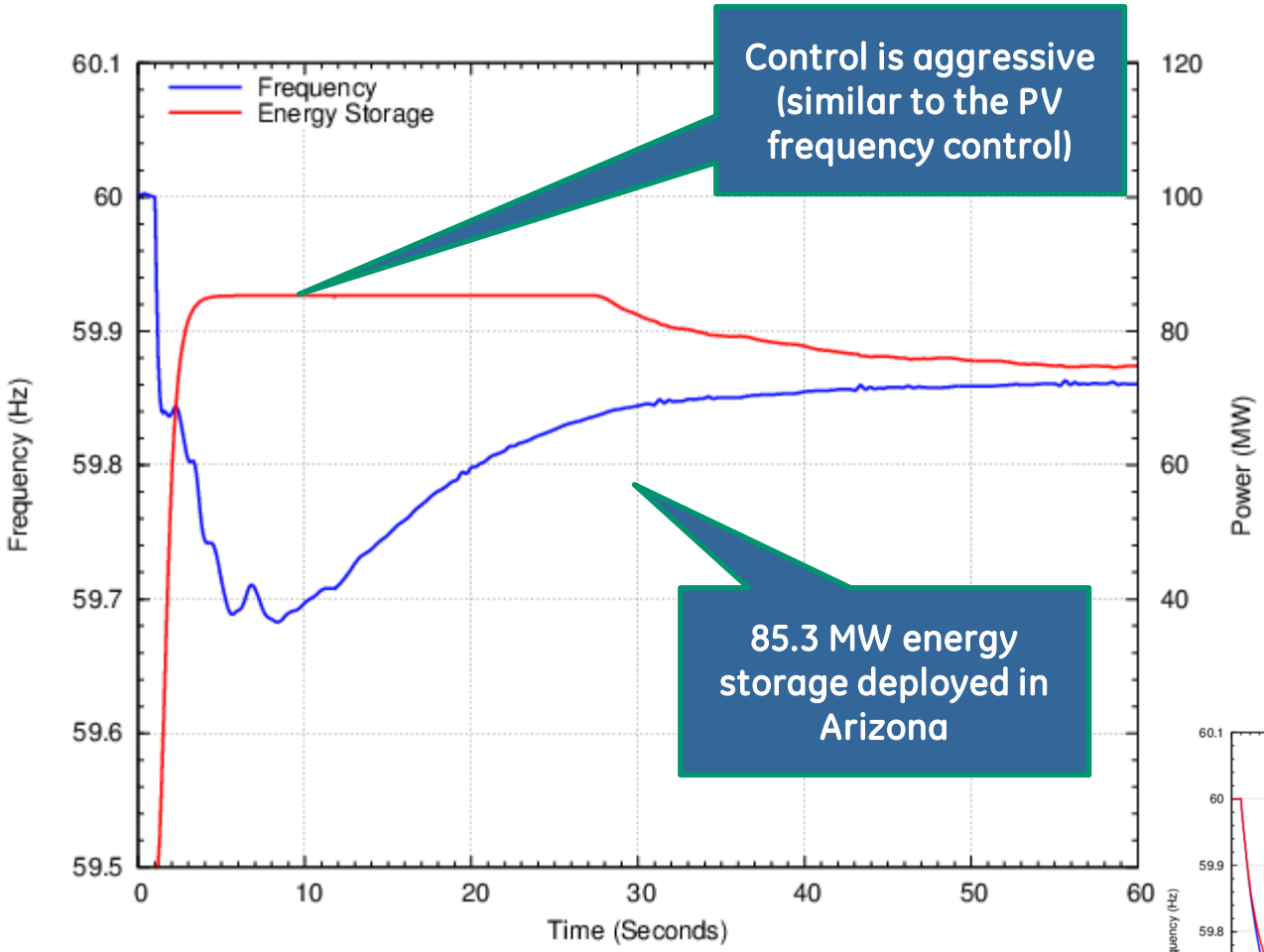
WECC Frequency Response – 2022LSP HiMix

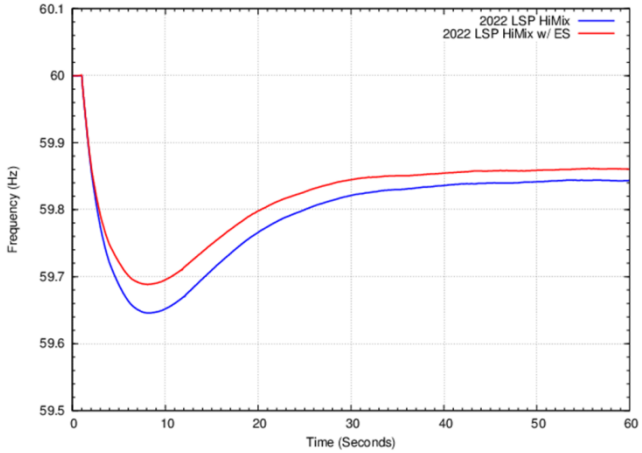


imagination at work

TRC Call: Do not Cite - Not for Further Distribution

Arizona Energy Storage Response - 2022LSP HiMix





imagination at work

Frequency Response Table with Energy Storage

ID	Name	ID	PGEN [GW]	PLOAD [GW]	FRO [MW/0.1Hz]	FR [MW/0.1Hz]	%of WECC FR	FR margin [MW/0.1Hz]	Pbess [MW]	FR [MW/0.1Hz]	%of WECC FR	FR margin [MW/0.1Hz]
1	WECC	WE	203.7	184.6	840.0	1311.2	100.0	471.2	0.0	1512.6	100.0	672.6
2	CALIFORNIA	CA	68.8	67.9	295.7	334.8	25.5	39.1	0.0	369.2	24.4	73.5
3	DSW	DS	53.9	47.8	220.0	118.6	9.0	-101.4	157.3	223.9	14.8	4.0
4	NORTHEAST	NE	19.7	18.0	81.5	54.2	4.1	-27.3	53.6	85.3	5.6	3.8
54	ALBERTA	AL	12.9	12.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	ARIZONA	AZ	27.5	20.8	104.4	49.7	3.8	-54.7	85.3	105.4	7.0	1.0
50	B.C.HYDRO	BC	11.3	8.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	EL PASO	EL	1.7	2.3	8.6	3.8	0.3	-4.8	7.6	9.0	0.6	0.3
60	IDAHO	ID	4.3	3.9	17.9	21.8	1.7	3.9	0.0	21.8	1.4	4.0
21	IMPERIALCA	IV	1.5	0.3	4.0	14.4	1.1	10.5	0.0	14.4	1.0	10.4
26	LADWP	LA	6.3	7.2	29.3	29.8	2.3	0.5	0.0	29.7	2.0	0.4
20	MEXICO-CFE	MX	2.7	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
62	MONTANA	MT	3.3	1.9	11.3	10.3	0.8	-1.0	1.6	10.3	0.7	-1.0
18	NEVADA	NV	6.1	6.8	27.9	33.6	2.6	5.7	0.0	33.9	2.2	6.0
10	NEW MEXICO	NM	3.5	3.1	14.3	1.8	0.1	-12.6	19.6	13.8	0.9	-0.6
40	NORTHWEST	NW	33.3	27.2	130.8	490.2	37.4	359.3	0.0	487.3	32.2	356.4
65	PACE	PC	9.4	9.9	41.8	25.4	1.9	-16.4	52.6	40.1	2.7	-1.7
30	PG AND E	PG	32.4	29.0	132.7	196.2	15.0	63.5	0.0	196.9	13.0	64.2
70	PSCOLORADO	CO	8.3	8.1	35.5	5.2	0.4	-30.3	46.7	33.4	2.2	-2.1
22	SANDIEGO	SD	4.4	5.5	21.3	7.4	0.6	-14.0	22.0	20.6	1.4	-0.7
64	SIERRA	SP	2.6	2.3	10.6	7.0	0.5	-3.6	5.6	10.3	0.7	-0.3
24	SOCALIF	SC	24.2	25.9	108.4	63.6	4.8	-44.8	69.9	103.3	6.8	-5.1
52	FORTISBC	FB	1.1	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
73	WAPA R.M.	WR	6.9	5.8	27.4	24.2	1.8	-3.2	5.1	25.8	1.7	-1.6
63	WAPA U.M.	WU	0.1	0.0	0.1	2.5	0.2	2.3	0.0	2.7	0.2	2.5

316 MW ES gives ~200 MW/0.1 Hz FR improvement

Most deficient areas at or near FRO

TRC Call: Do not Cite - Not for Further Distribution

Energy Storage – 2022LSP HiMix Extreme

ID	Name	ID	FR [MW/0.1Hz]	%of WECC FR	FR margin [MW/0.1Hz]	Pbess for LSP Ext	FR/FRO %
1	WECC	WE	1054.7	100.0	214.7	0.0	125.6
2	CALIFORNIA	CA	295.1	28.0	-0.6	1.2	99.8
3	DSW	DS	96.6	9.2	-123.4	230.5	43.9
4	NORTHEAST	NE	50.7	4.8	-30.8	57.3	62.2
54	ALBERTA	AL	0.0	0.0	0.0	0.0	
14	ARIZONA	AZ	44.7	4.2	-59.7	111.3	42.8
50	B.C.HYDRO	BC	0.0	0.0	0.0	0.0	
11	EL PASO	EL	3.1	0.3	-5.6	10.4	35.4
60	IDAHO	ID	21.1	2.0	3.2	0.0	118.0
21	IMPERIALCA	IV	14.2	1.3	10.2	0.0	357.8
26	LADWP	LA	29.1	2.8	-0.1	0.2	99.6
20	MEXICO-CFE	MX	0.0	0.0	0.0	0.0	
62	MONTANA	MT	10.9	1.0	-0.3	0.6	97.0
18	NEVADA	NV	18.6	1.8	-9.3	17.5	66.5
10	NEW MEXICO	NM	1.7	0.2	-12.7	23.6	11.6
40	NORTHWEST	NW	280.4	26.6	149.5	0.0	214.3
65	PACE	PC	11.3	1.1	-30.5	56.8	27.0
30	PG AND E	PG	188.5	17.9	55.8	0.0	142.0
70	PSCOLORADO	CO	5.7	0.5	-29.8	56.0	16.0
22	SANDIEGO	SD	7.0	0.7	-14.4	26.7	32.8
64	SIERRA	SP	7.4	0.7	-3.2	5.9	70.0
24	SOCALIF	SC	56.1	5.3	-52.3	95.0	51.8
52	FORTISBC	FB	0.0	0.0	0.0	0.0	
73	WAPA R.M.	WR	22.9	2.2	-4.5	8.4	83.6
63	WAPA U.M.	WU	2.7	0.3	2.5	0.0	1790.1
						412.4	

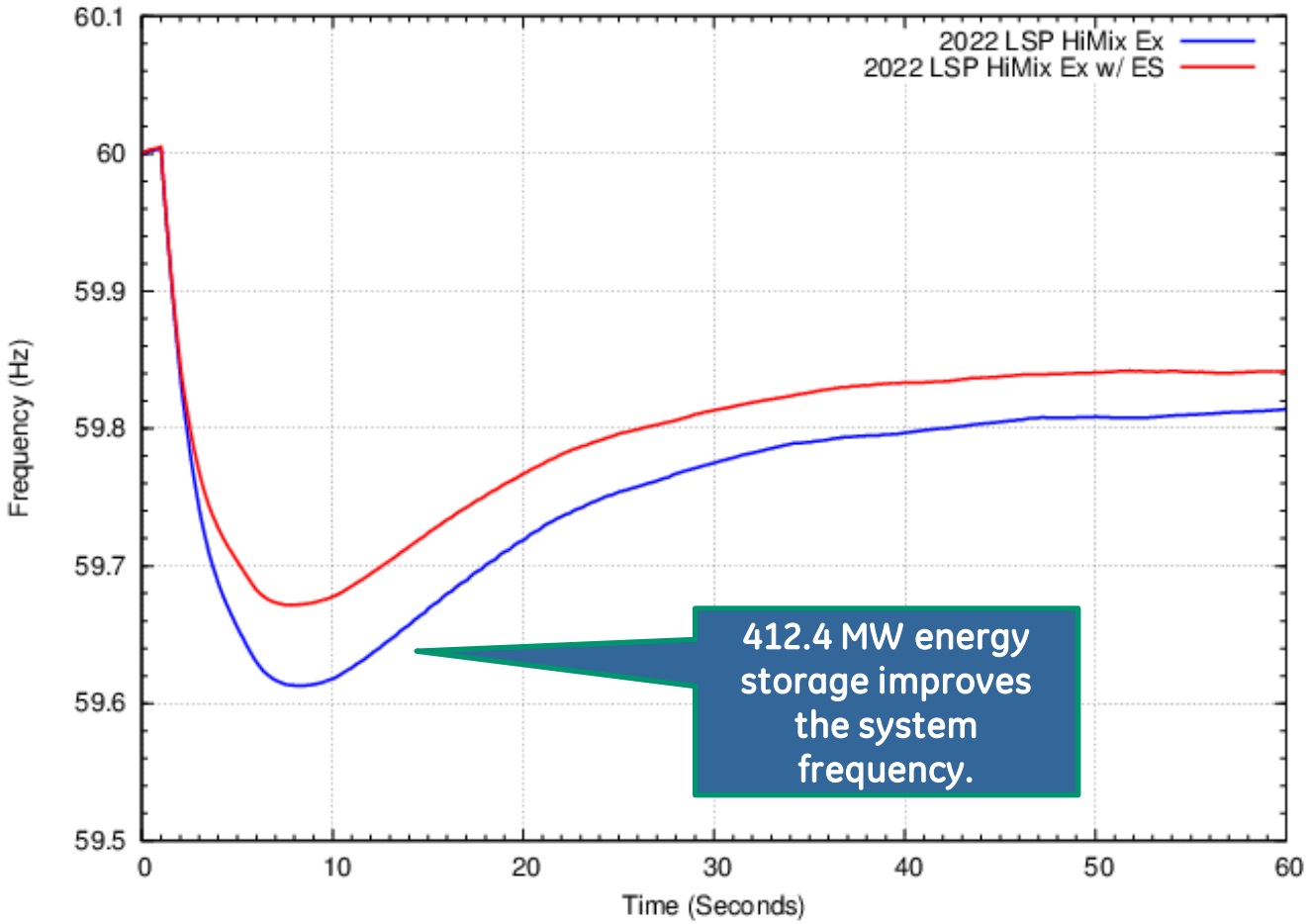
Totally 412.4 MW energy storage

Apply energy storage to areas short of FR

imagination at work

TRC Call: Do not Cite - Not for Further Distribution

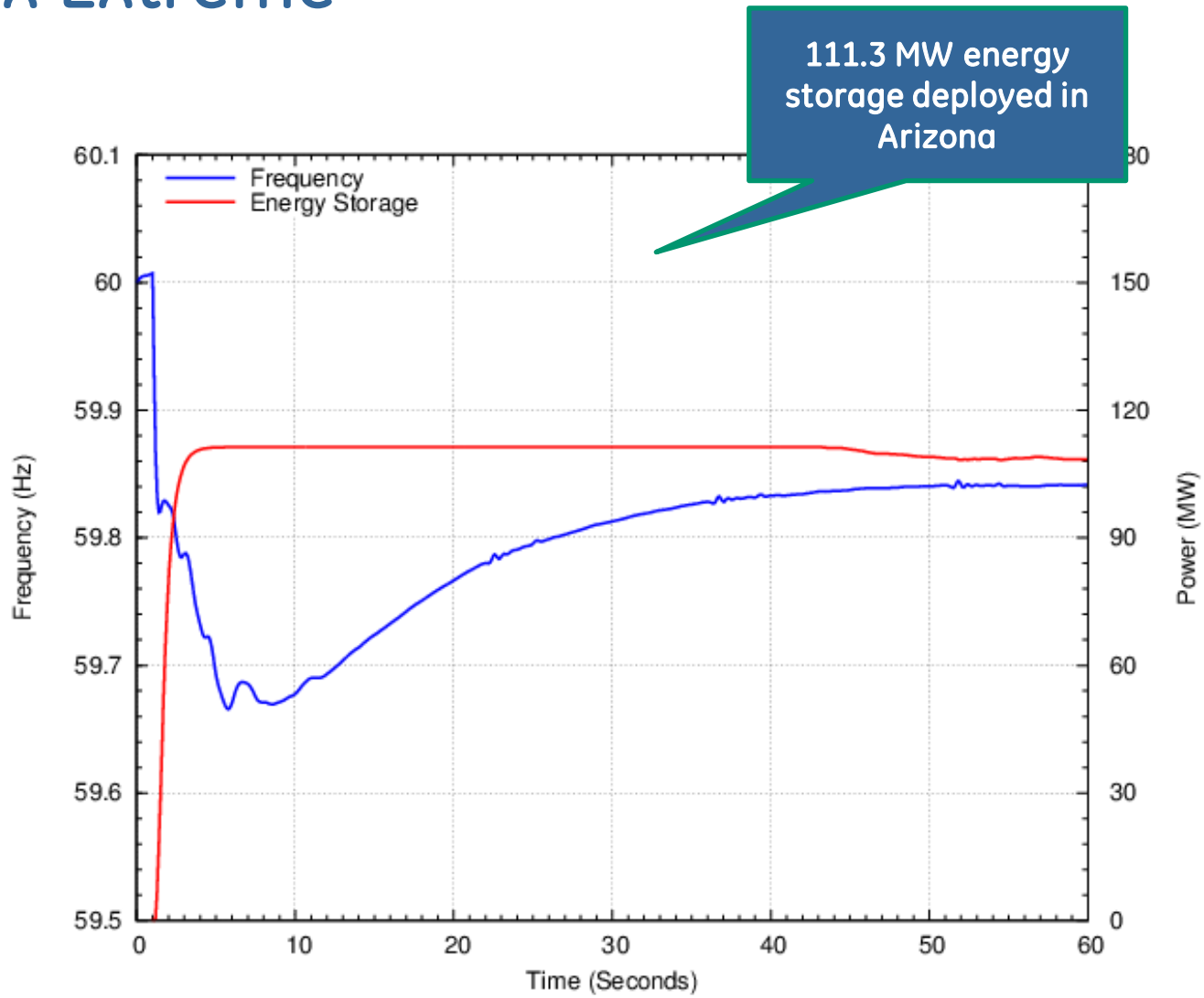
WECC Frequency Response – 2022LSP HiMix Extreme



imagination at work

TRC Call: Do not Cite - Not for Further Distribution

Arizona Energy Storage Response - 2022LSP HiMix Extreme



imagination at work

TRC Call: Do not Cite - Not for Further Distribution

Frequency Response – Extreme Case with Energy Storage

ID	Name	ID	PGEN [GW]	PLOAD [GW]	FRO [MW/0.1Hz]	FR [MW/0.1Hz]	%of WECC FR	FR margin [MW/0.1Hz]	Pbess [MW]	FR [MW/0.1Hz]	%of WECC FR	FR margin [MW/0.1Hz]
1	WECC	WE	203.7	184.6	840.0	1054.8	100.0	214.8	0.0	1307.3	100.0	467.3
2	CALIFORNIA	CA	68.8	67.9	295.7	332.7	31.5	37.0	1.2	368.4	28.2	72.7
3	DSW	DS	53.9	47.8	220.0	96.2	9.1	-123.8	230.5	229.0	17.5	9.0
4	NORTHEAST	NE	19.7	18.0	81.5	62.9	6.0	-18.6	57.3	87.9	6.7	6.4
54	ALBERTA	AL	12.9	12.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	ARIZONA	AZ	27.5	20.8	104.4	44.8	4.2	-59.6	111.3	110.7	8.5	6.3
50	B.C.HYDRO	BC	11.3	8.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	EL PASO	EL	1.7	2.3	8.6	3.1	0.3	-5.6	10.4	9.5	0.7	0.9
60	IDAHO	ID	4.3	3.9	17.9	21.1	2.0	3.2	0.0	21.1	1.6	3.2
21	IMPERIALCA	IV	1.5	0.3	4.0	14.5	1.4	10.6	0.0	14.2	1.1	10.3
26	LADWP	LA	6.3	7.2	29.3	29.1	2.8	-0.1	0.2	29.4	2.2	0.1
20	MEXICO-CFE	MX	2.7	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
62	MONTANA	MT	3.3	1.9	11.3	10.9	1.0	-0.3	0.6	10.0	0.8	-1.2
18	NEVADA	NV	6.1	6.8	27.9	18.7	1.8	-9.2	17.5	28.4	2.2	0.5
10	NEW MEXICO	NM	3.5	3.1	14.3	1.7	0.2	-12.7	23.6	14.9	1.1	0.6
40	NORTHWEST	NW	33.3	27.2	130.8	292.5	27.7	161.6	0.0	286.7	21.9	155.9
65	PACE	PC	9.4	9.9	41.8	35.9	3.4	-5.9	56.8	42.1	3.2	0.3
30	PG AND E	PG	32.4	29.0	132.7	188.9	17.9	56.1	0.0	191.6	14.7	58.8
70	PSCOLORADO	CO	8.3	8.1	35.5	5.3	0.5	-30.2	56.0	30.5	2.3	-5.0
22	SANDIEGO	SD	4.4	5.5	21.3	7.1	0.7	-14.3	26.7	20.9	1.6	-0.5
64	SIERRA	SP	2.6	2.3	10.6	7.4	0.7	-3.2	5.9	10.0	0.8	-0.6
24	SOCALIF	SC	24.2	25.9	108.4	56.1	5.3	-52.3	95.0	96.4	7.4	-12.0
52	FORTISBC	FB	1.1	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
73	WAPA R.M.	WR	6.9	5.8	27.4	22.9	2.2	-4.5	8.4	25.0	1.9	-2.4
63	WAPA U.M.	WU	0.1	0.0	0.1	2.5	0.2	2.4	0.0	2.7	0.2	2.5

412 MW ES gives ~250 MW/0.1 Hz FR improvement

imagination at work

TRC Call: Do not Cite - Not for Further Distribution

Observations on Energy Storage

- Primary response from fast energy storage (e.g. batteries, flywheels, etc.) is very effective at improving both nadir and settling frequency
- Relatively small amounts (total ~400MW for all WECC) “fixed” all area FRO deficiencies in these cases
- Similar character (not surprising) to Solar
- Further suggests best use of this class of resource is highly non-linear
- Fast control of loads would very likely produce similar improvements

TRC Call: Do not Cite - Not for Further Distribution

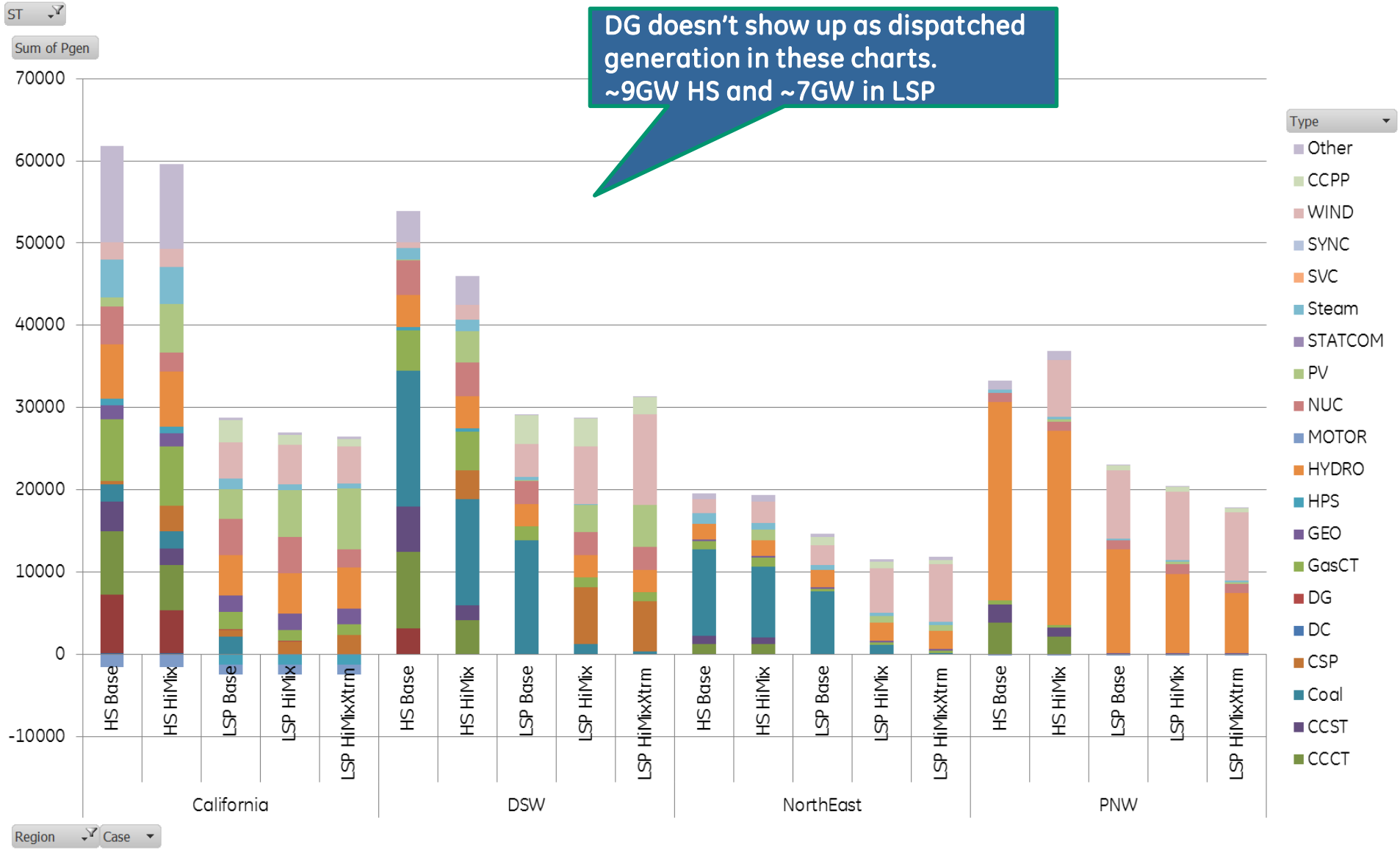
Weak Grid/Coal Displacement-Retirement

- Evolution from LSP-Base to LSP-HiMix to LSP-HiMix-Extreme displaces thermal generation in NE and SW regions
- Major new transmission under construction to provide for export from the NE introduces new stability concerns
- Termination of new 500kV line at Aeolus in heart of major wind region of Western Wyoming

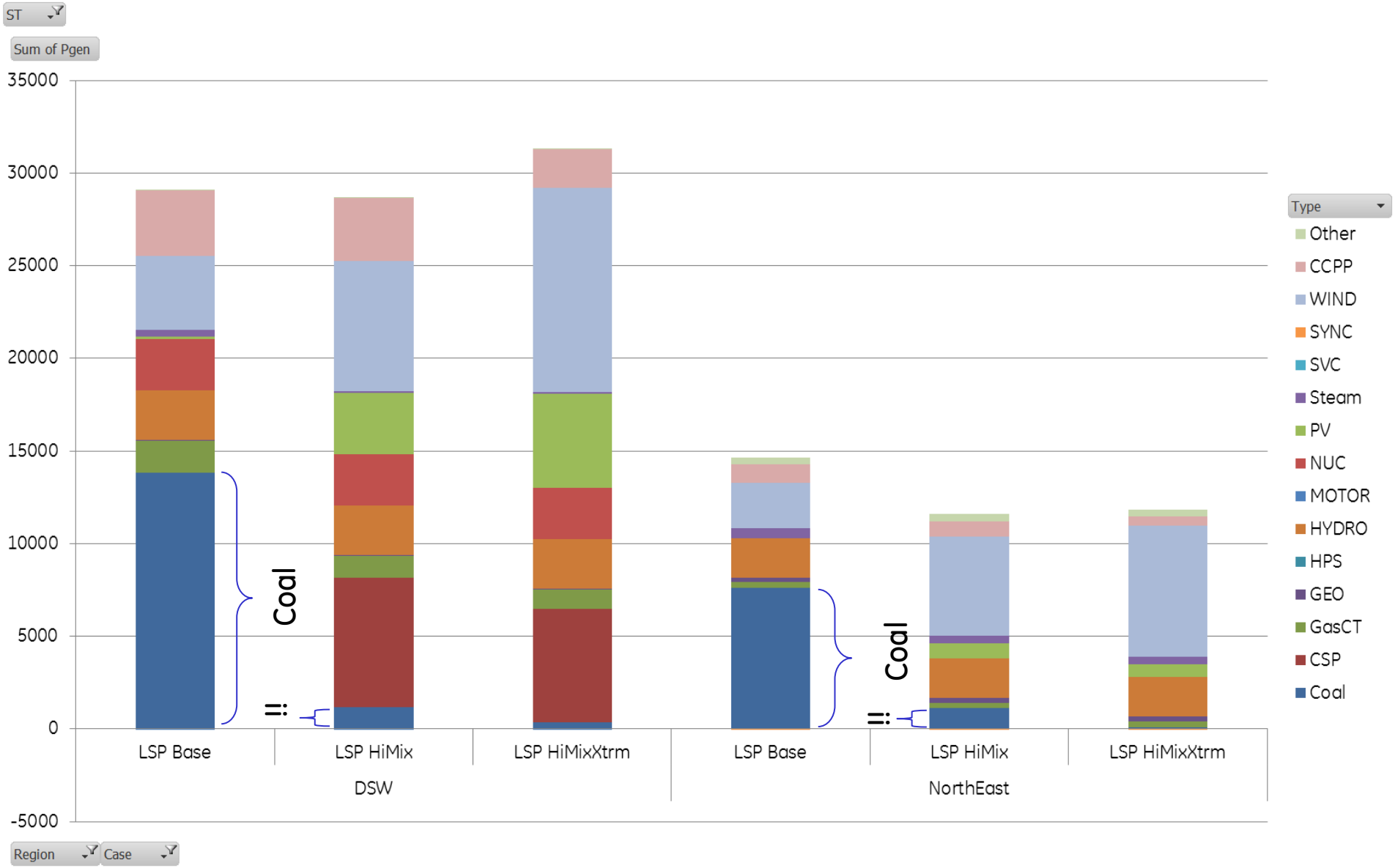
imagination at work

TRC Call: Do not Cite - Not for Further Distribution

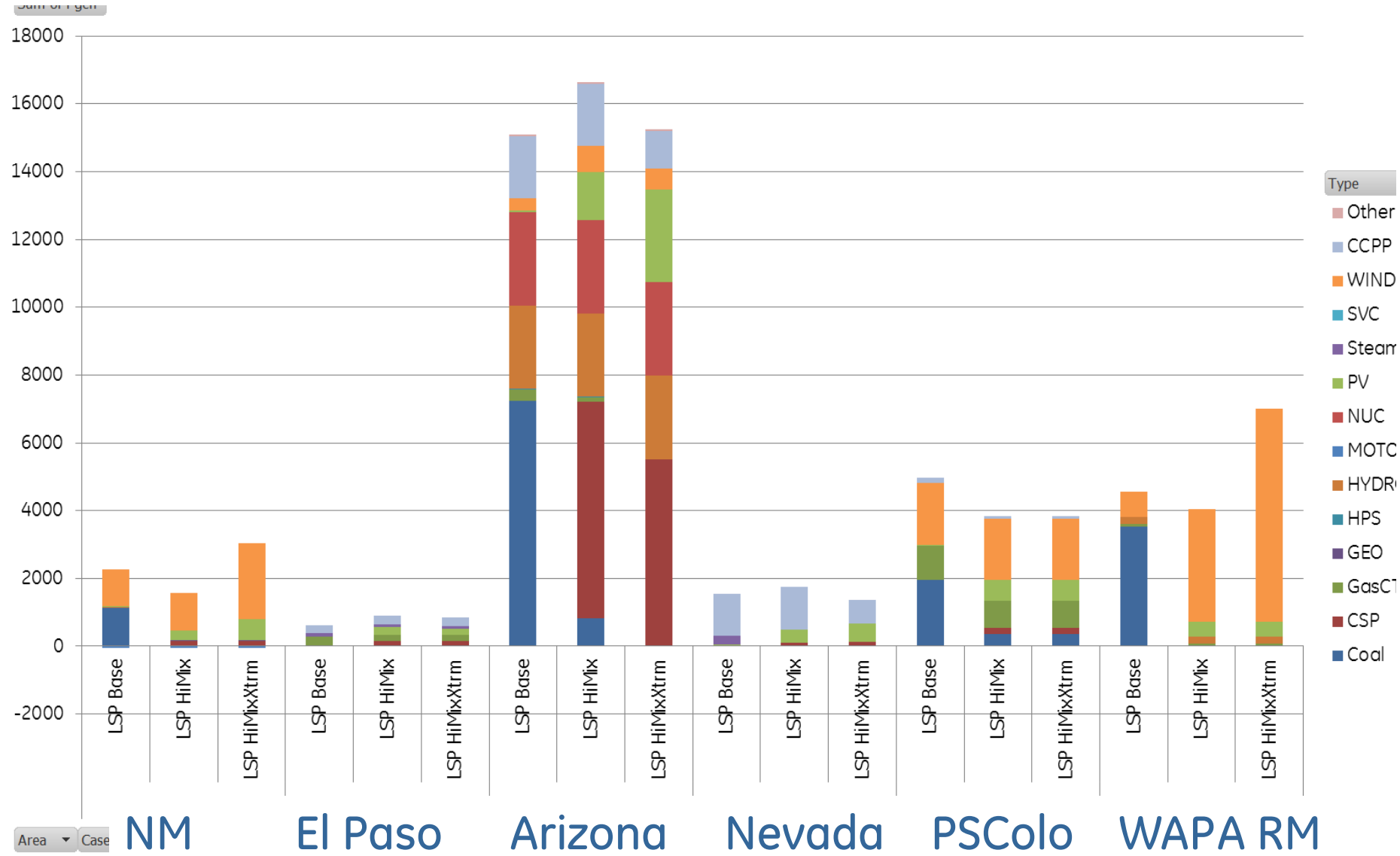
Regional Dispatch



Coal Off-line/Retired in the East

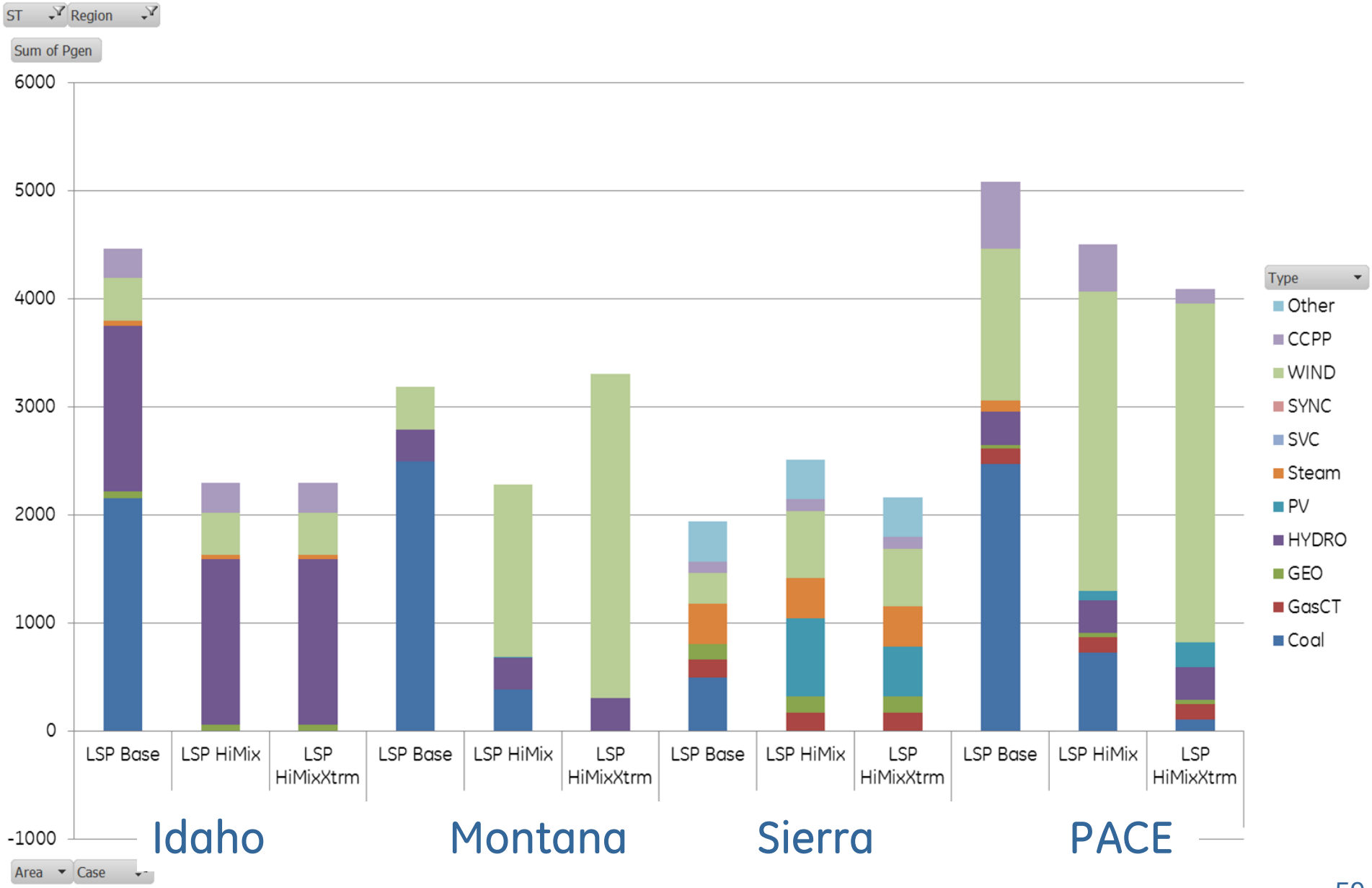


DSW Areas

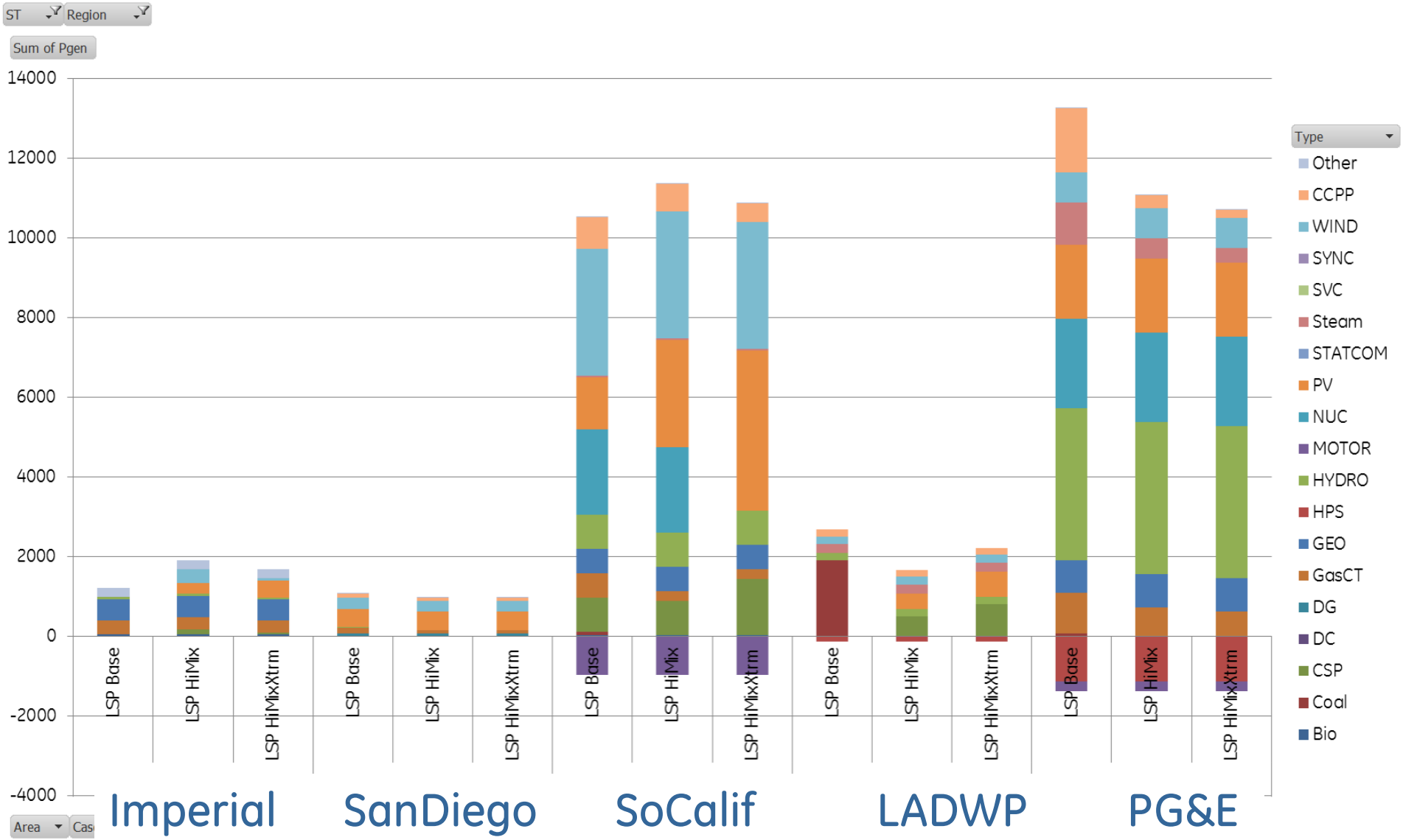


imagination at work

NE Areas

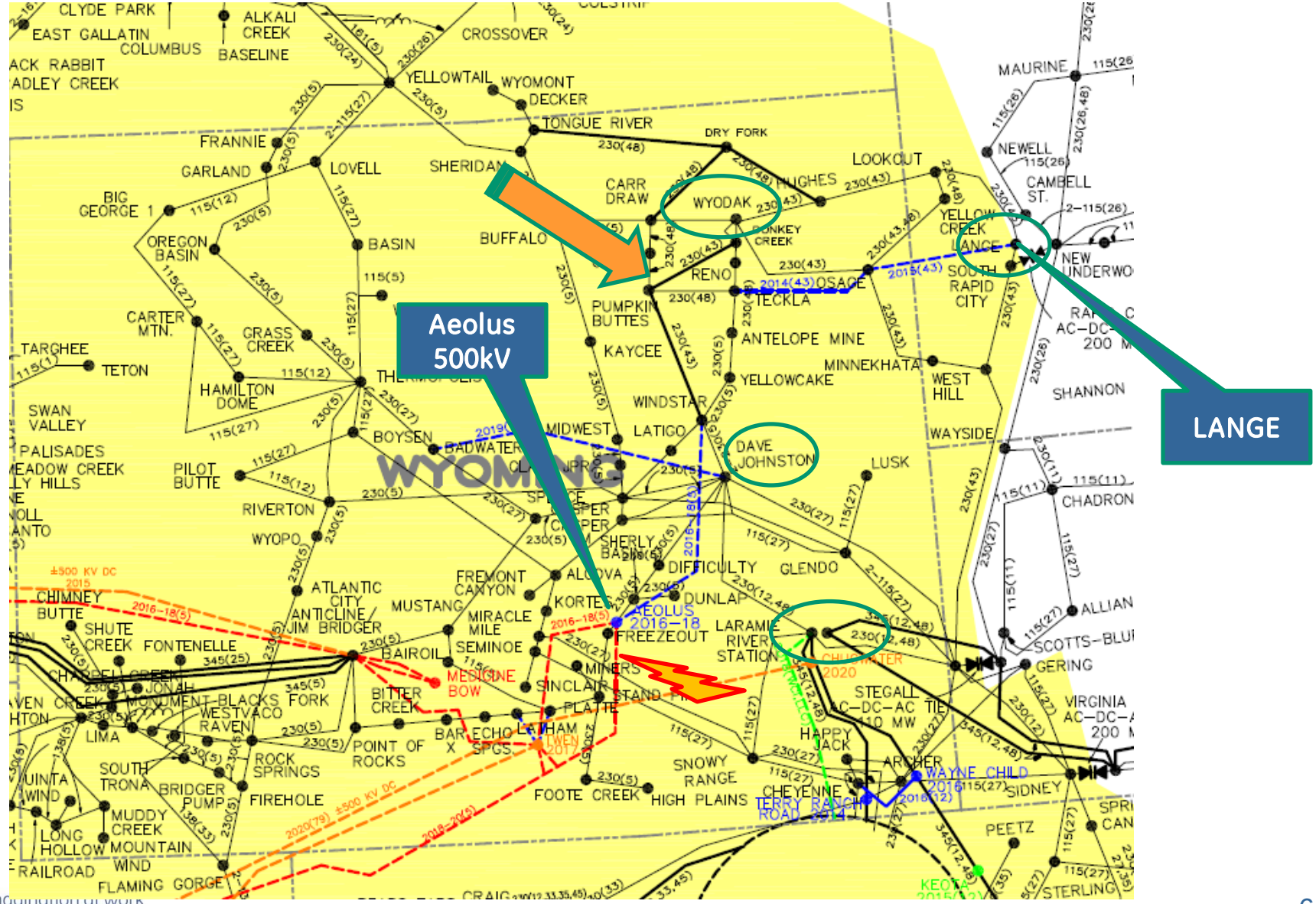

ST
Region
Sum of Pgen
6000
5000
4000
3000
2000
1000
0
-1000
LSP Base
LSP HiMix
LSP HiMixXtrm
LSP Base
LSP HiMix
LSP HiMixXtrm
LSP Base
LSP HiMix
LSP HiMixXtrm
LSP Base
LSP HiMix
LSP HiMixXtrm
Idaho
Montana
Sierra
PACE
Type
Other
CCPP
WIND
SYNC
SVC
Steam
PV
HYDRO
GEO
GasCT
Coal
Area
Case

CA Areas



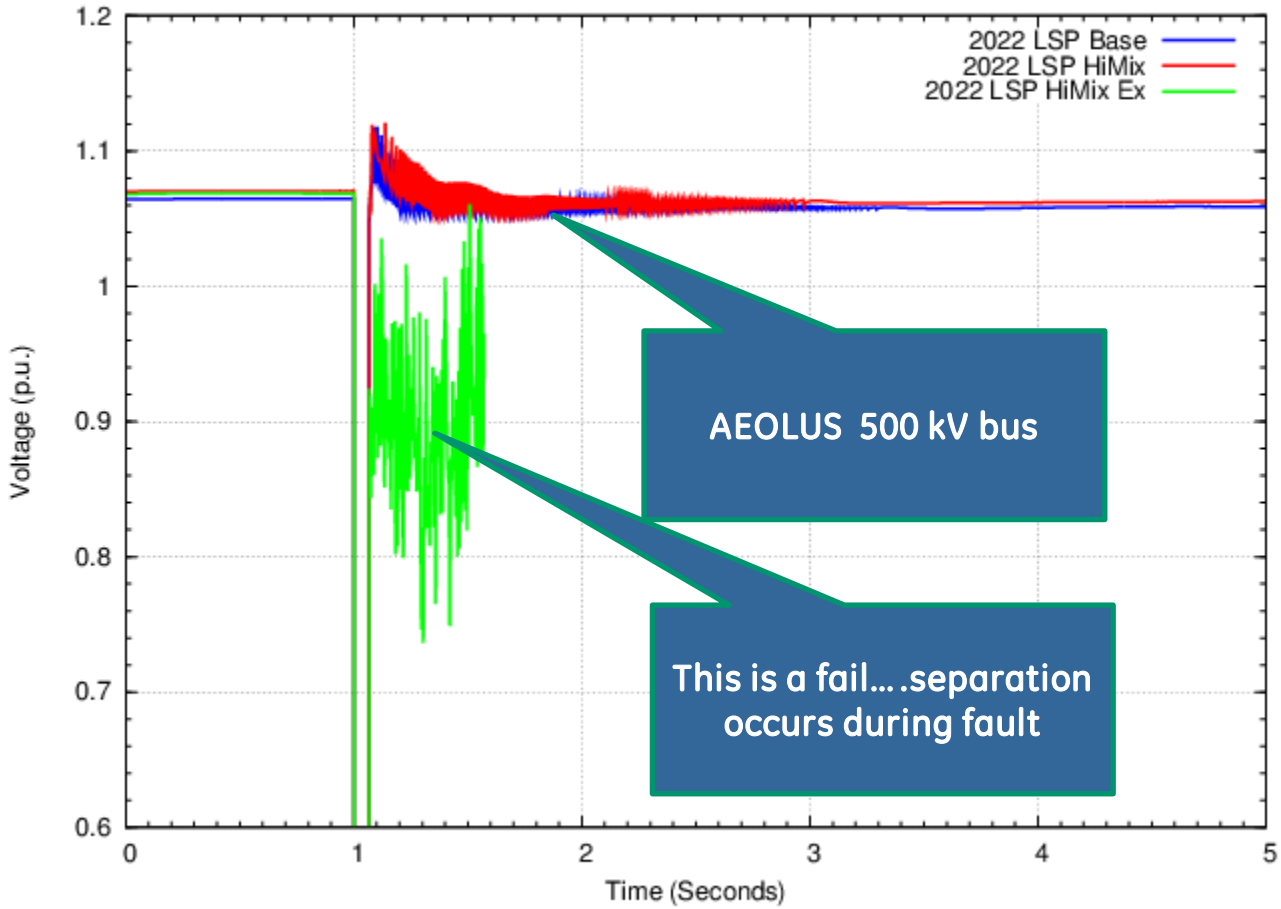
imagination at work

Investigation of Stability in Northeast Region



TRC Call: Do not Cite - Not for Further Distribution

AEOLUS Fault – 3 Cases

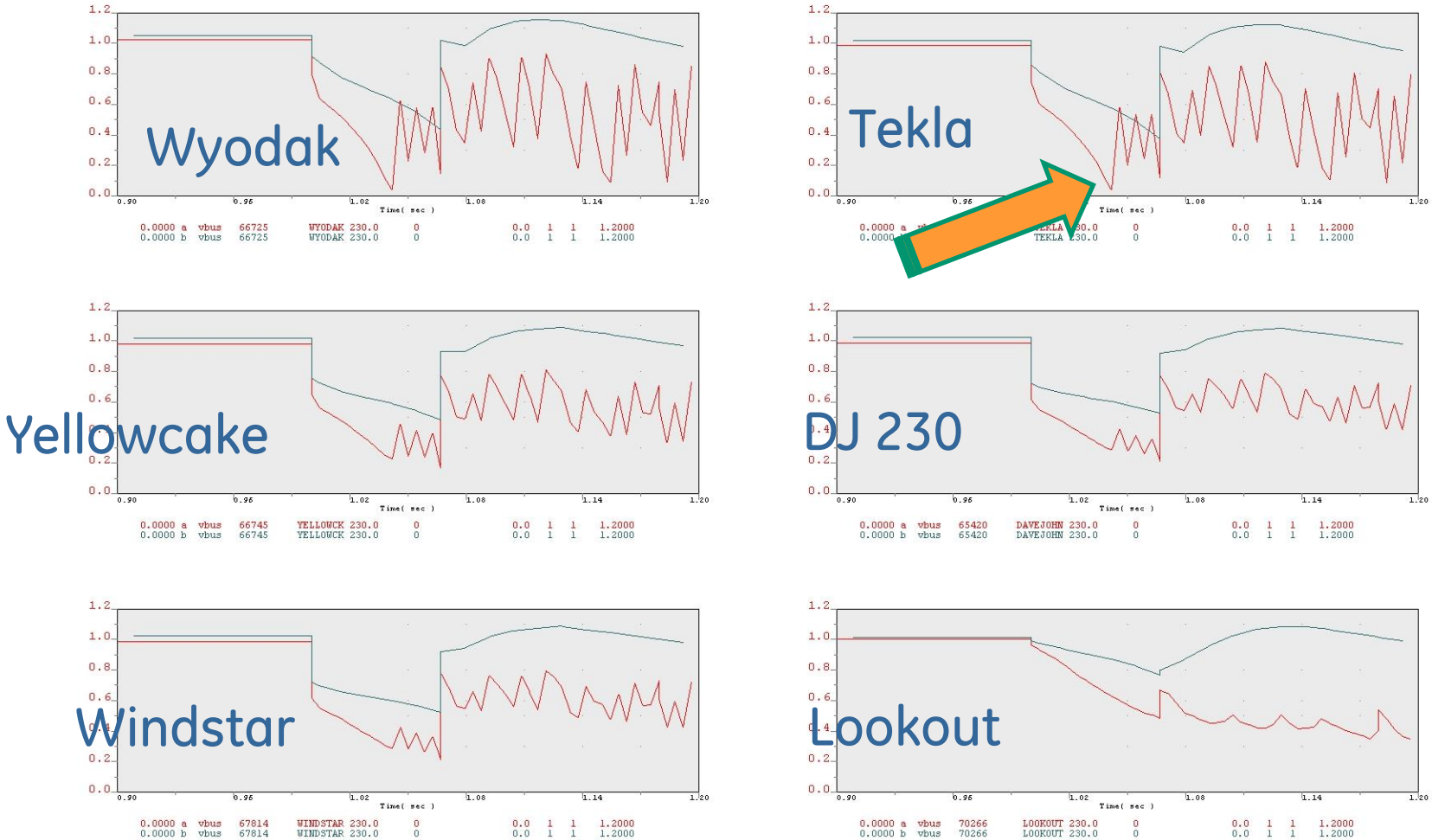


AEOLUS 4-cycle 3 phase to ground fault; clear one of 2 500kV circuits

imagination at work

TRC Call: Do not Cite - Not for Further Distribution

AEOLUS Fault – LSP HiMix Extreme vs Fix

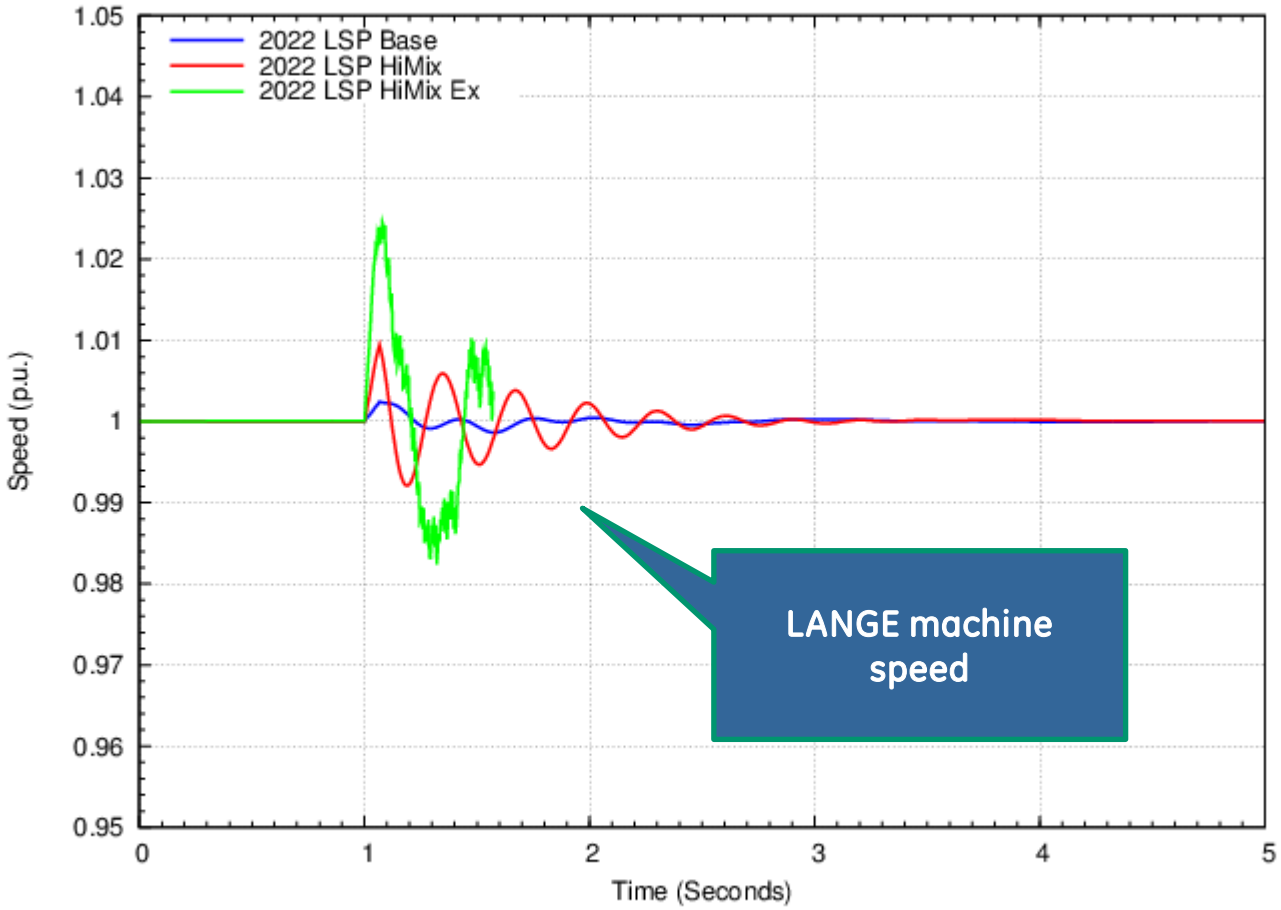


Voltage collapses between the fault and Rapid City area: system has separated during the fault

imagination at work

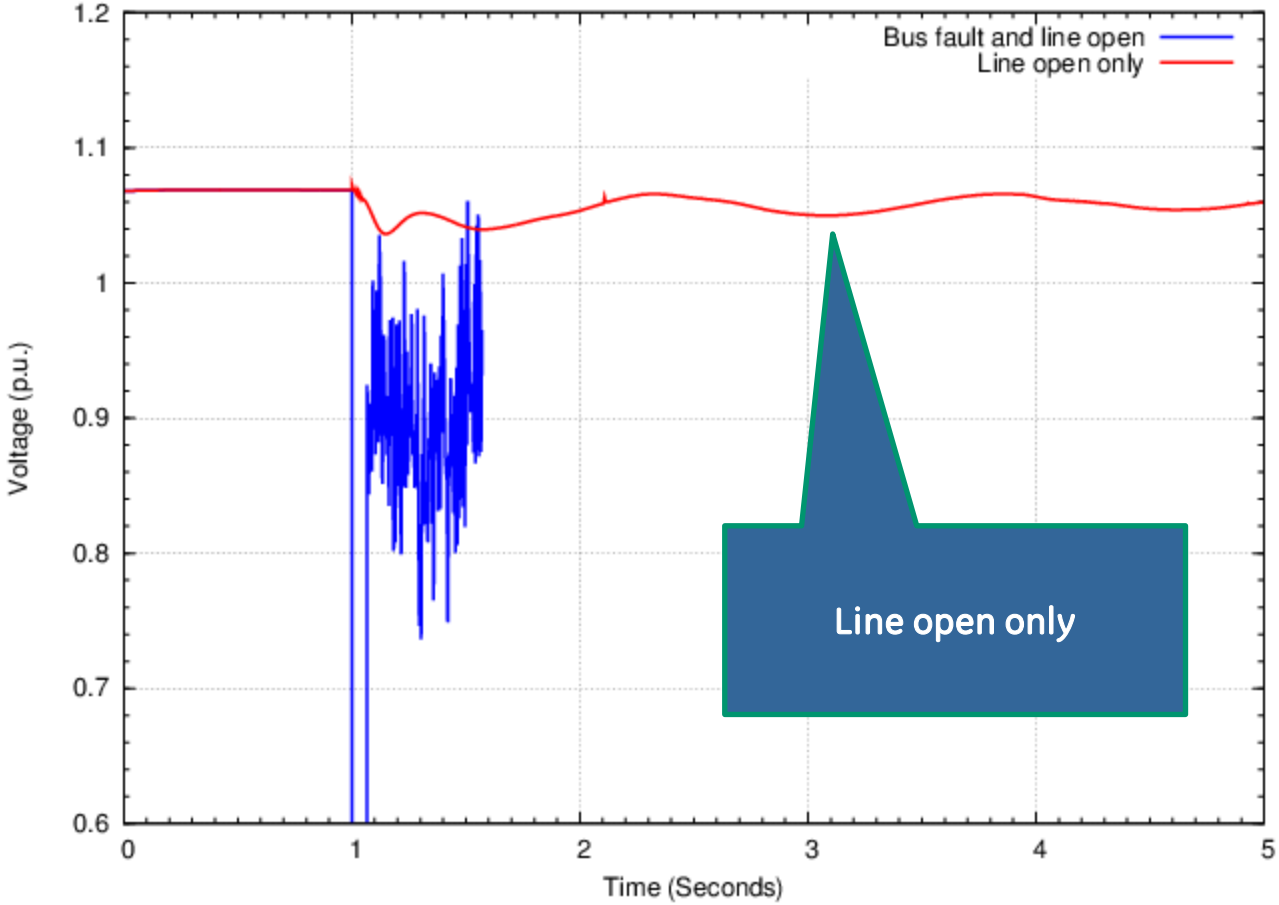
TRC Call: Do not Cite - Not for Further Distribution

AEOLUS Fault – 3 Cases



TRC Call: Do not Cite - Not for Further Distribution

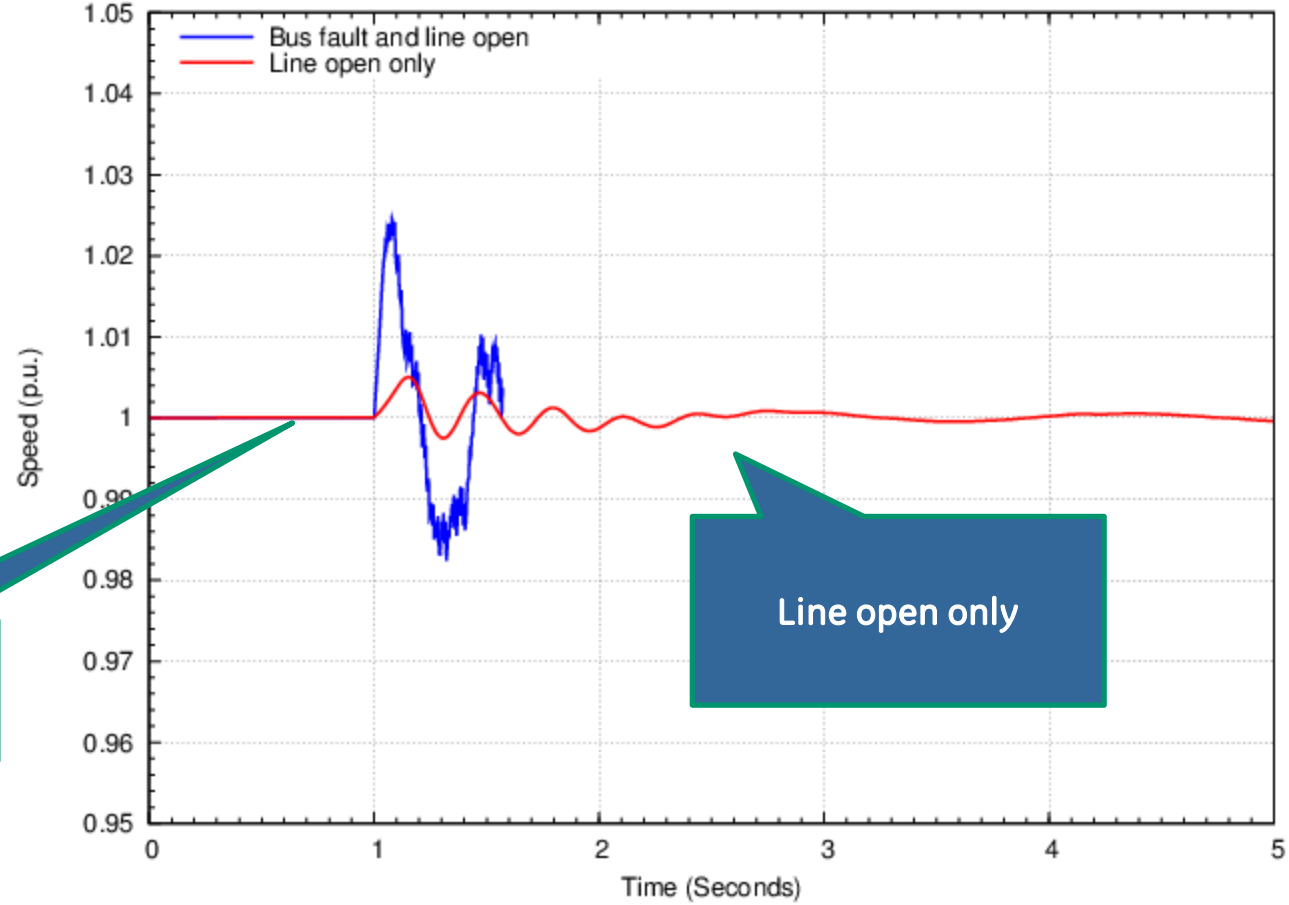
AEOLUS Fault Sensitivity Analysis – with and without Bus Fault



2022 LSP HiMix Extreme Case

TRC Call: Do not Cite - Not for Further Distribution

AEOLUS Fault Sensitivity Analysis – line trip - with and without Bus Fault



Lange CT Speed

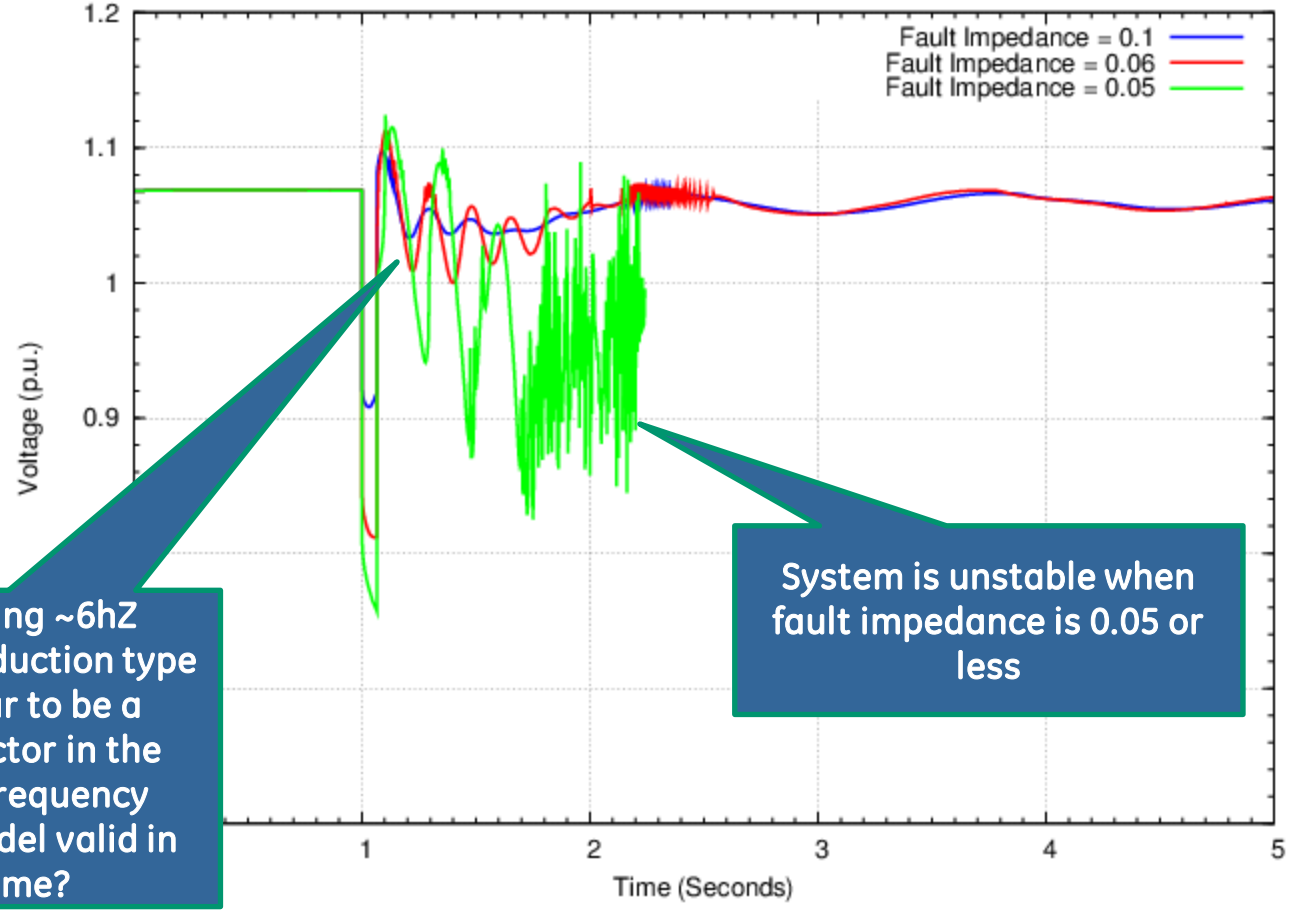
Line open only

2022 LSP HiMix Extreme Case

imagination at work

TRC Call: Do not Cite - Not for Further Distribution

AEOLUS Fault Sensitivity Analysis – Fault Impedance



Note emerging ~6hZ oscillations… induction type WTGs appear to be a significant factor in the rather high frequency swings… is model valid in this regime?

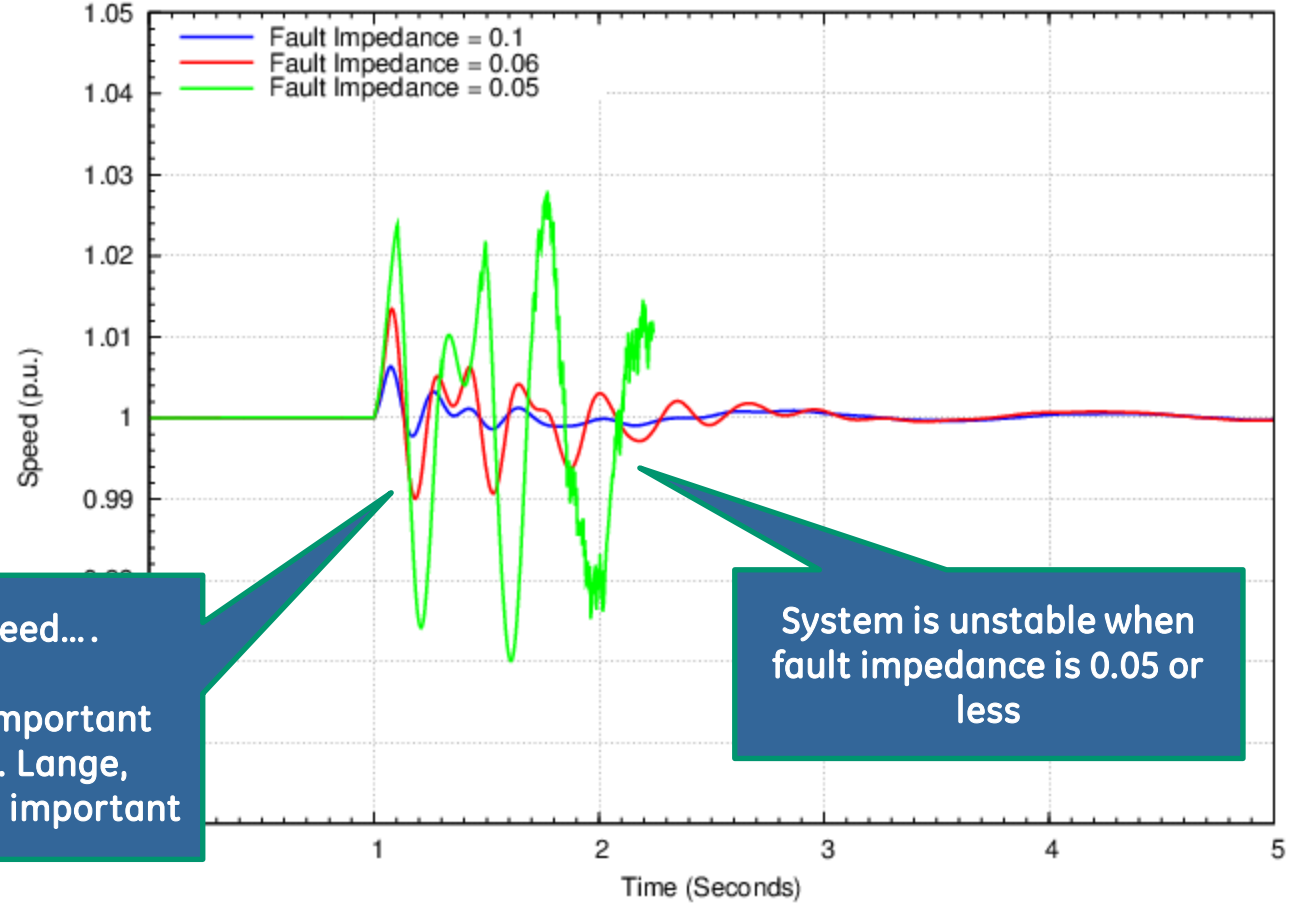
System is unstable when fault impedance is 0.05 or less

2022 LSP HiMix Extreme Case

imagination at work

TRC Call: Do not Cite - Not for Further Distribution

AEOLUS Fault Sensitivity Analysis – Fault Impedance



Lange CT speed….

Normally less important machines, e.g. Lange, Osage, … become important

System is unstable when fault impedance is 0.05 or less

2022 LSP HiMix Extreme Case

TRC Call: Do not Cite - Not for Further Distribution

2022 LSP HiMix Extreme Fix Case System Reinforcement

Synchronous condenser:

65445 DAVEJON4	400 MVA
66730 WYODAK 1	402.3 MVA
73129 MBPP-1 (LARAMIE RIVER)	690 MVA

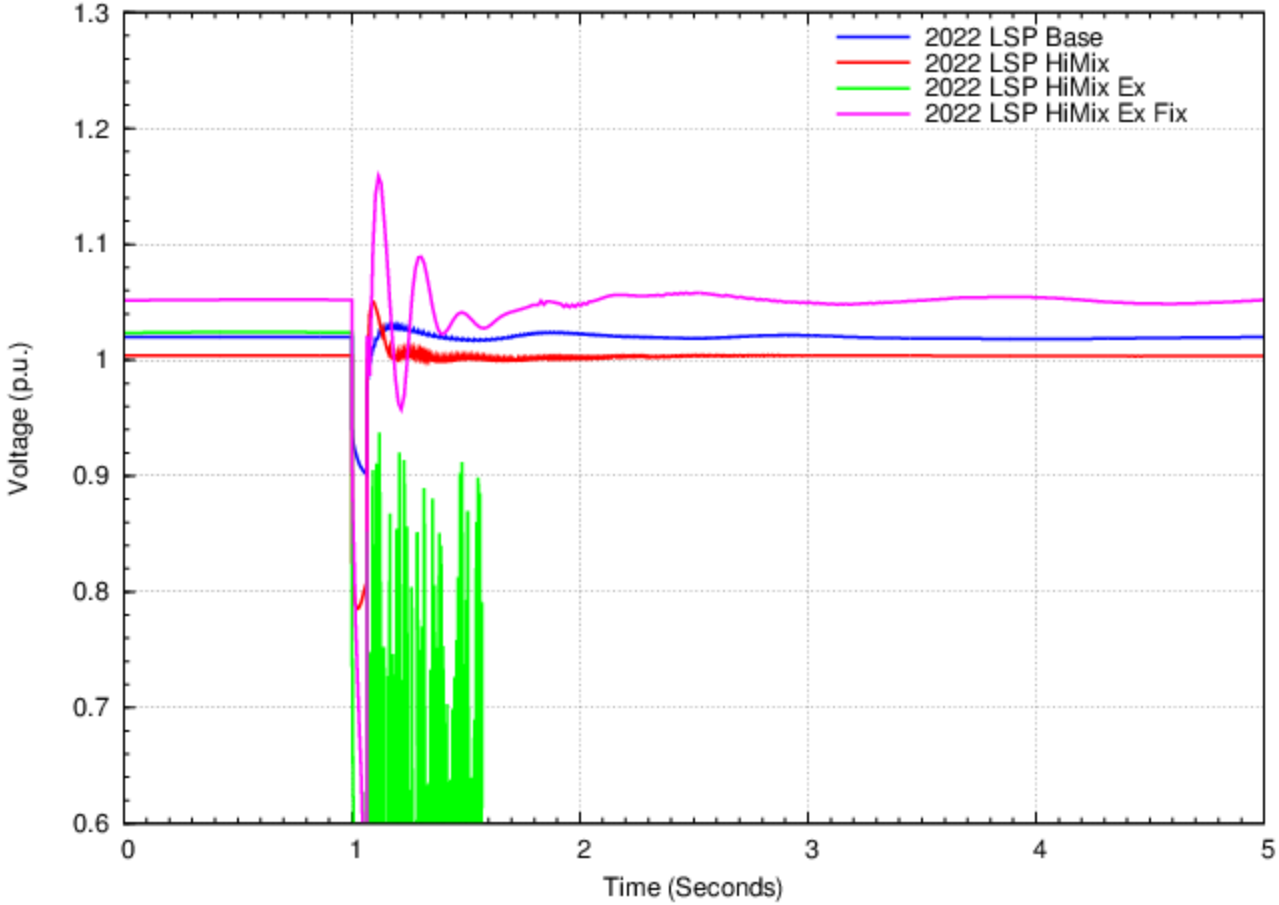
Shunt capacitor:

65420 DAVEJOHN	230.00	100 MVAr
65425 DAVEJOHN	115.00	100 MVAr
70122 COMANCHE	230.00	60 MVAr
70821 CEDARCRK	230.00	150 MVAr
76400 PUMPKIN BTS	230.00	100 MVAr

Minimum transmission build out for AEOLUS Fault for 2022 LSP HiMix Extreme case

TRC Call: Do not Cite - Not for Further Distribution

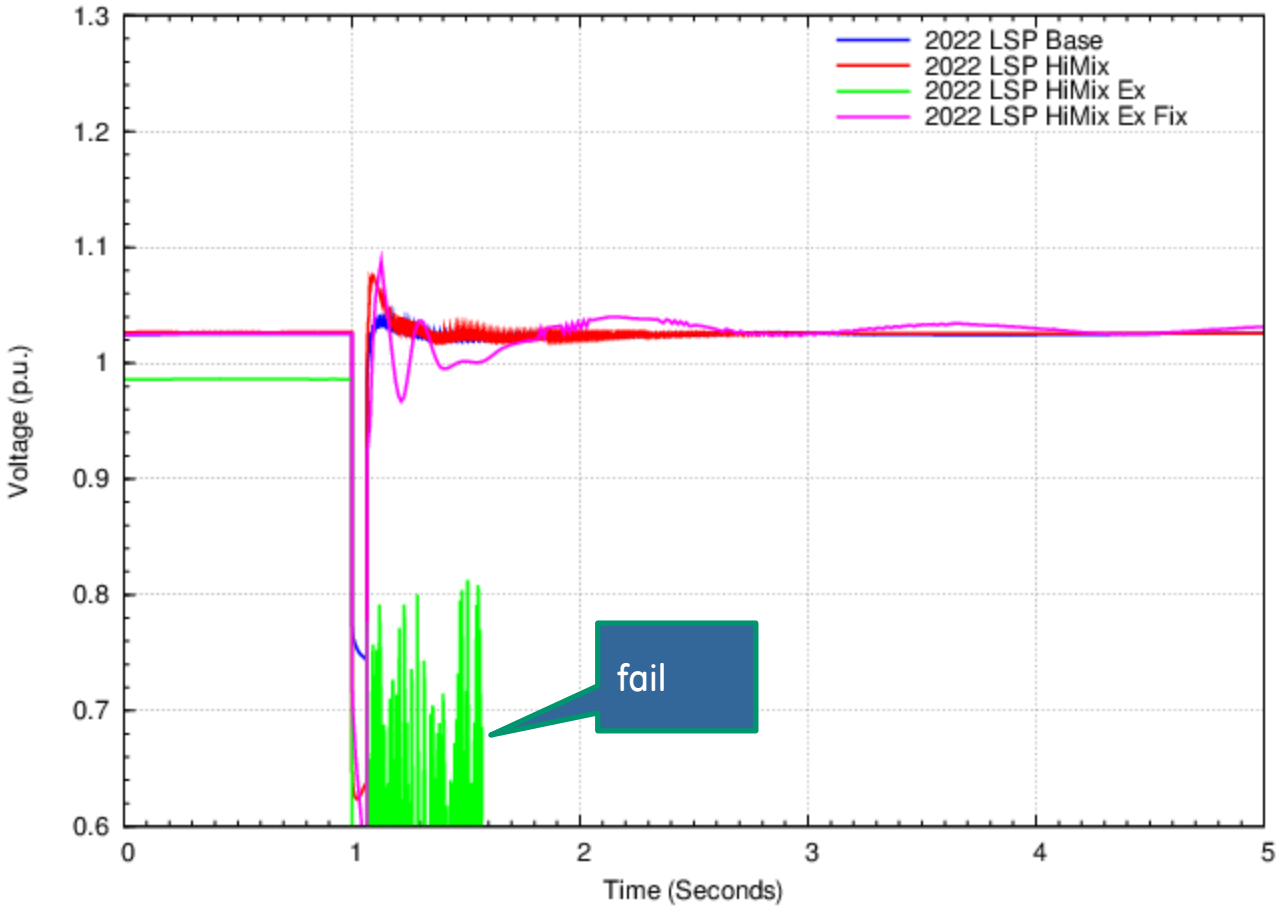
AEOLUS Fault – WYODAK 230 kV Bus



imagination at work

TRC Call: Do not Cite - Not for Further Distribution

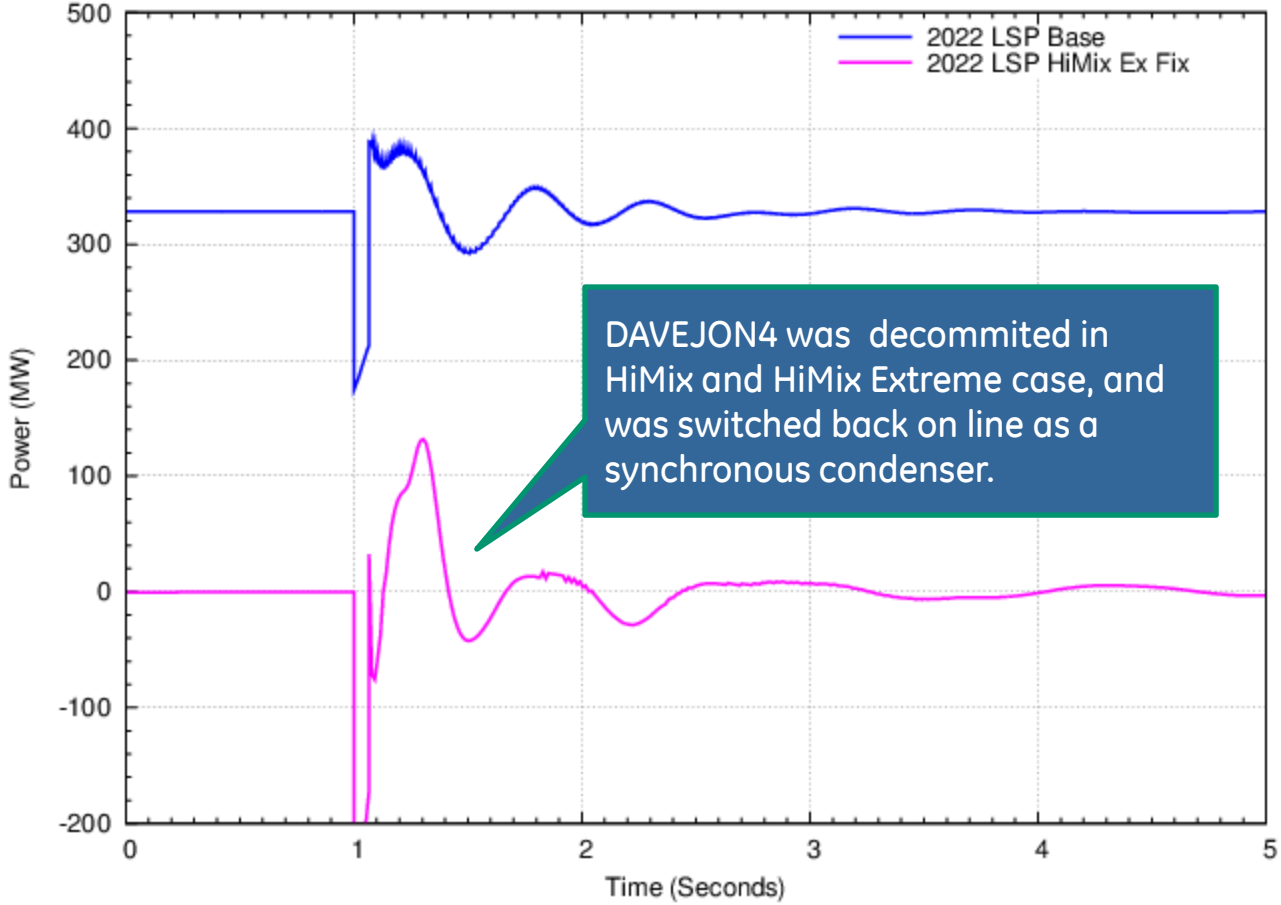
AEOLUS Fault – DAVEJOHN 230 kV Bus



imagination at work

TRC Call: Do not Cite - Not for Further Distribution

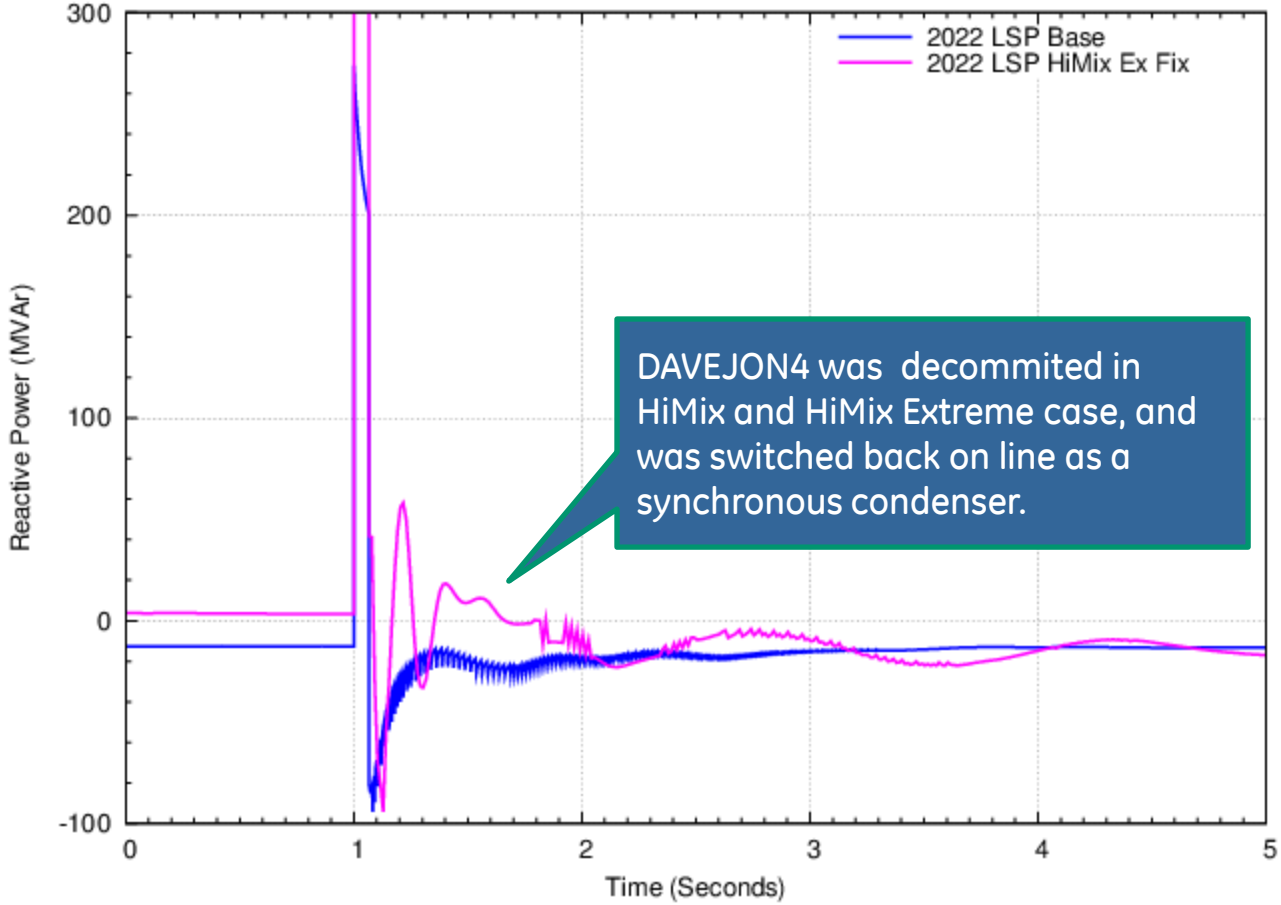
AEOLUS Fault - Real Power Output (P) at DAVEJON4 Units



DAVEJON4 was decommited in HiMix and HiMix Extreme case, and was switched back on line as a synchronous condenser.

TRC Call: Do not Cite - Not for Further Distribution

AEOLUS Fault - Reactive Power Output (Q) at DAVEJON4 Units

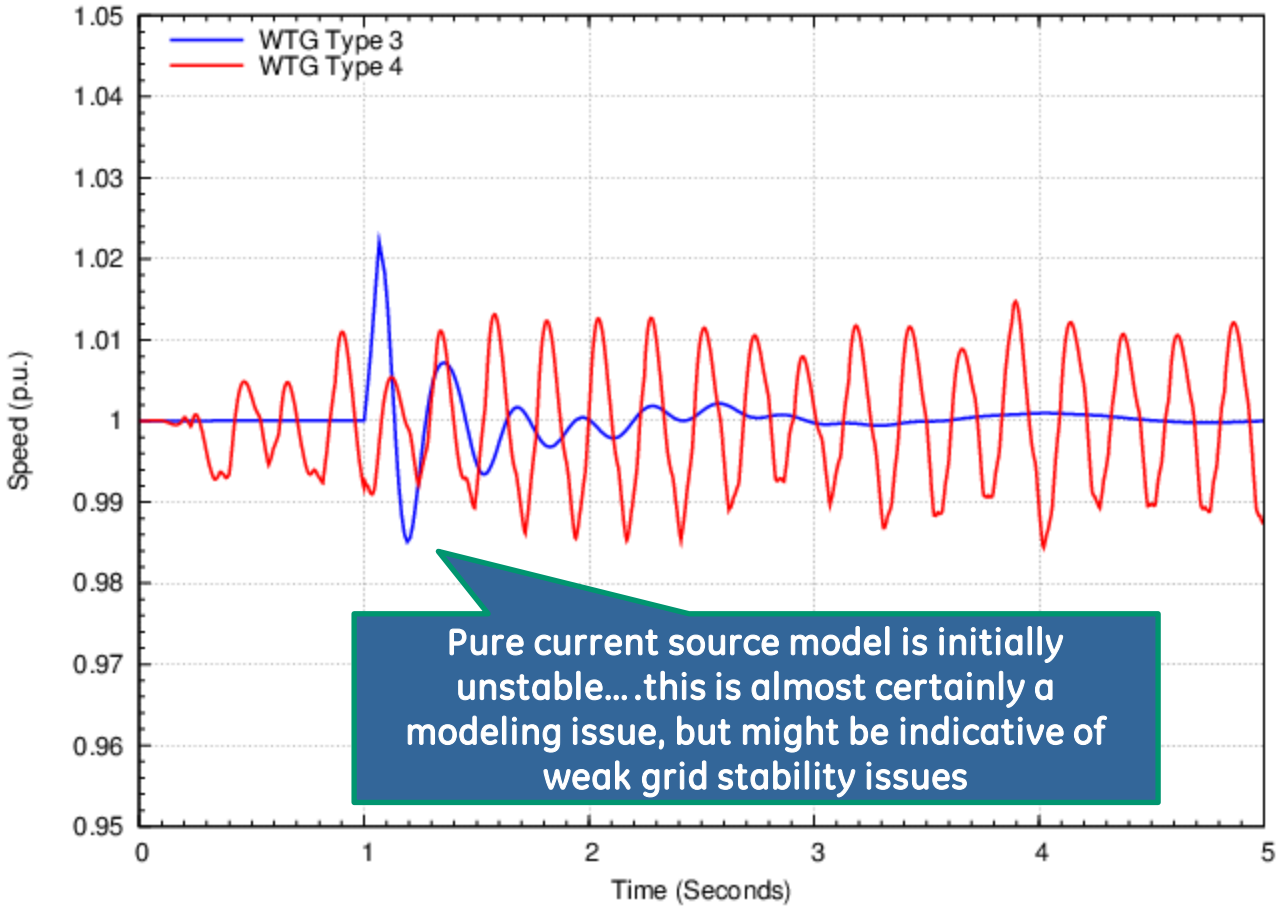


DAVEJON4 was decommited in HiMix and HiMix Extreme case, and was switched back on line as a synchronous condenser.

imagination at work

TRC Call: Do not Cite - Not for Further Distribution

AEOLUS Fault – WTG part Thevinen (Type 3) model vs current source (Type 4) model



2022 LSP HiMix Extreme Fix Case

imagination at work

TRC Call: Do not Cite - Not for Further Distribution

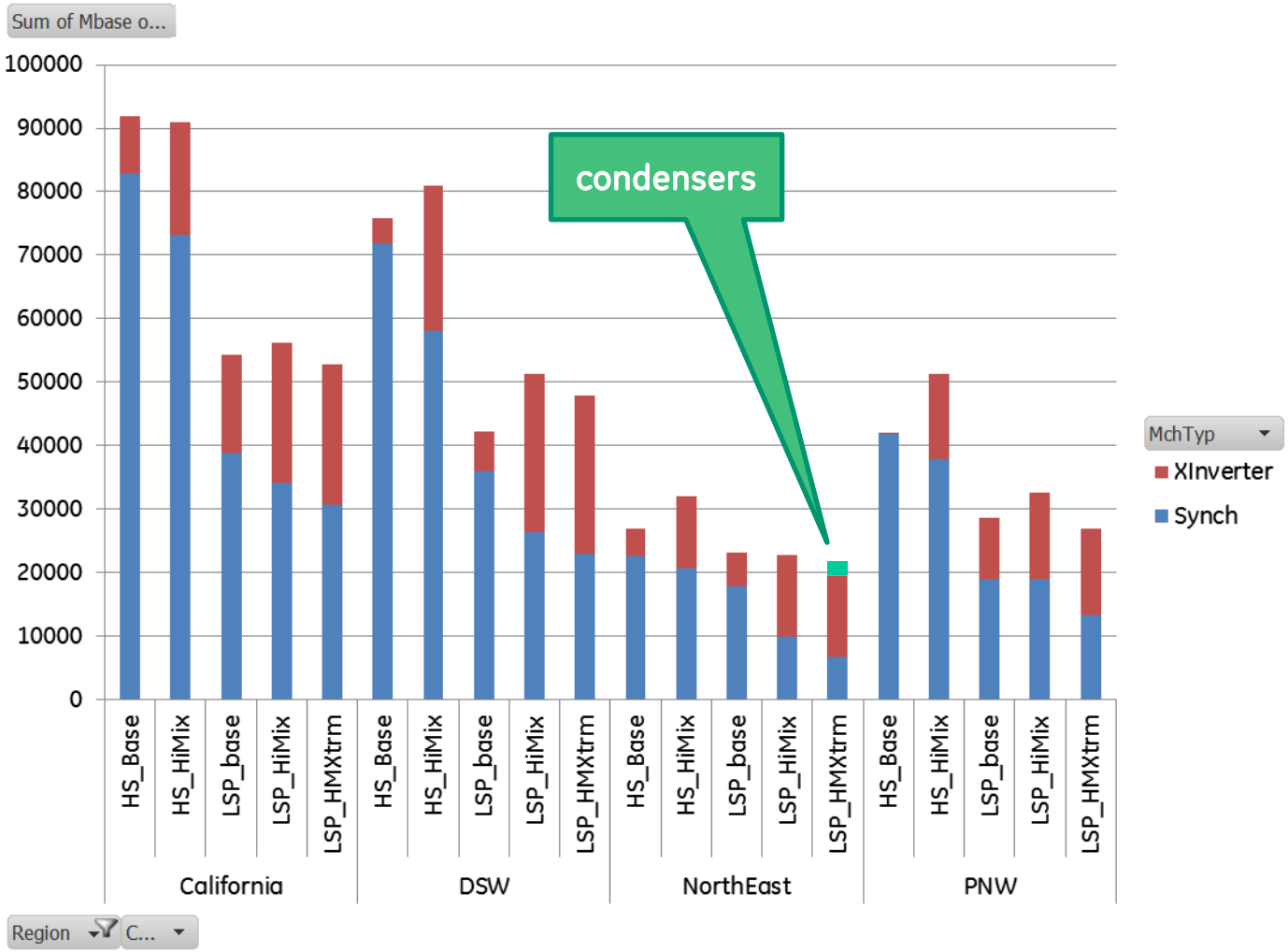
System Strength / Non-synchronous Generation

- Systemic concerns about evolution to low fraction of total generation coming from synchronous generation
  - E.g EirGrid monitors SNSP – "system non-synchronous penetration"
  - Currently limited to <50%, with near-term plans to raise limit to <75%
- Also an issue in west Texas, Brazil, Australia…

TRC Call: Do not Cite - Not for Further Distribution

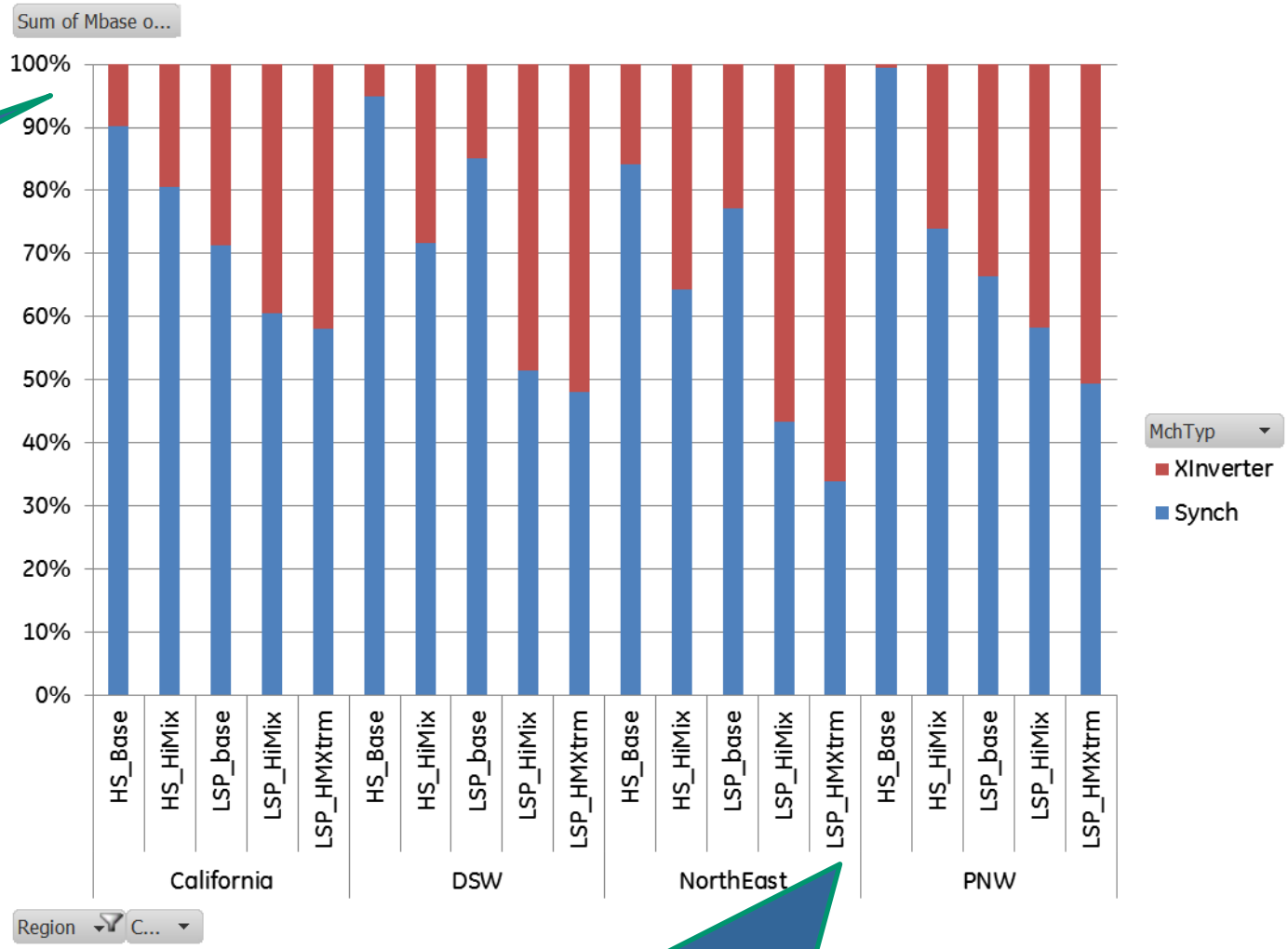
Synchronous vs. Non-synchronous Commitment

This is the MVA (not dispatch) of committed units



System Strength/Short Circuit

This is one way to calculate SNSP for WECC regions… based on MVA.



- ~66% SNSP… not counting condensers
- Improves to about 61% with 1600MVA of condensers added

imagination at work

Fault Currents

Location	LSP_Base	LSP_HiMix Extreme
Dave Johnson 230 kV	19.7 kA/7730 MVA	10.7 kA/4260 MVA
Populus 345	25.1 kA/15,000 MVA	20.1 kA/12,000 MVA

- Short circuit levels declined significantly in 230kV system when majority of coal generation is decommitted.
- Stability results suggest that weak grid problems are manageable, but more investigation is warranted.
- Inspection of details of protection at reduced SC levels will behave properly is recommended.

Observations on high coal displacement / weak grid

- High decommitment of coal does not obviously over-stress system
  - >80% reduction of coal commitment from LSP base case (NE region)
- Localized voltage and thermal problems
  - "Fixed" mainly with shunt capacitors, a few 230 line upgrades or transformer additions
  - OK for conditions investigated, but questions of voltage stability and "brittleness" need closer investigation
  - Relatively straightforward reinforcements…Ohms Law still applies; good planning practice needs to be followed.
  - Regional transmission system evolved with coal plant at "anchor" nodes…displacement by wind and solar that is more dispersed results in those nodes being less well supported
- System dynamics for EHV fault stable

TRC Call: Do not Cite - Not for Further Distribution

Observations on high coal displacement / weak grid – (continued)

- Extreme decommitment further stresses system
  - >90% reduction of coal commitment from LSP base case
  - Additional shunt compensation needed
- Some dynamic reactive compensation needed (to stabilize Aeolus fault)
  - Conversion of some coal plants to synchronous condensers (assuming retirement) works well to stabilize system
  - In the event of no retirements, raises questions of minimum commitment
- Results suggest that substantial displacement of coal can probably be tolerated
  - And that, the last few steps, i.e. decommiting the final 1 or 2 GW in the eastern half of WECC, while possible, will need to be carefully examined

TRC Call: Do not Cite - Not for Further Distribution

Observations on high coal displacement / weak grid – (continued)

- Results suggest (not surprisingly) that when wind and solar are the predominant source of generation throughout the region, that care to get the dynamic models right is acute
  - WECC has longstanding (best) practice to keep dynamic models up-to-date
  - Wind (and solar) plant modeling needs to be held to the same level of accountability in very high penetration future
- Localized problems will occur
  - Good transmission planning practice is needed, especially for voltage management
  - There is no obvious reason why voltage and thermal problems can't be solved by conventional methods – but they will need to be solved!
- Further investigation of weak grid aspects warranted
  - More on investigation of sensitivity to WTG control specifics (and of modeling implications)

TRC Call: Do not Cite - Not for Further Distribution

Final Steps

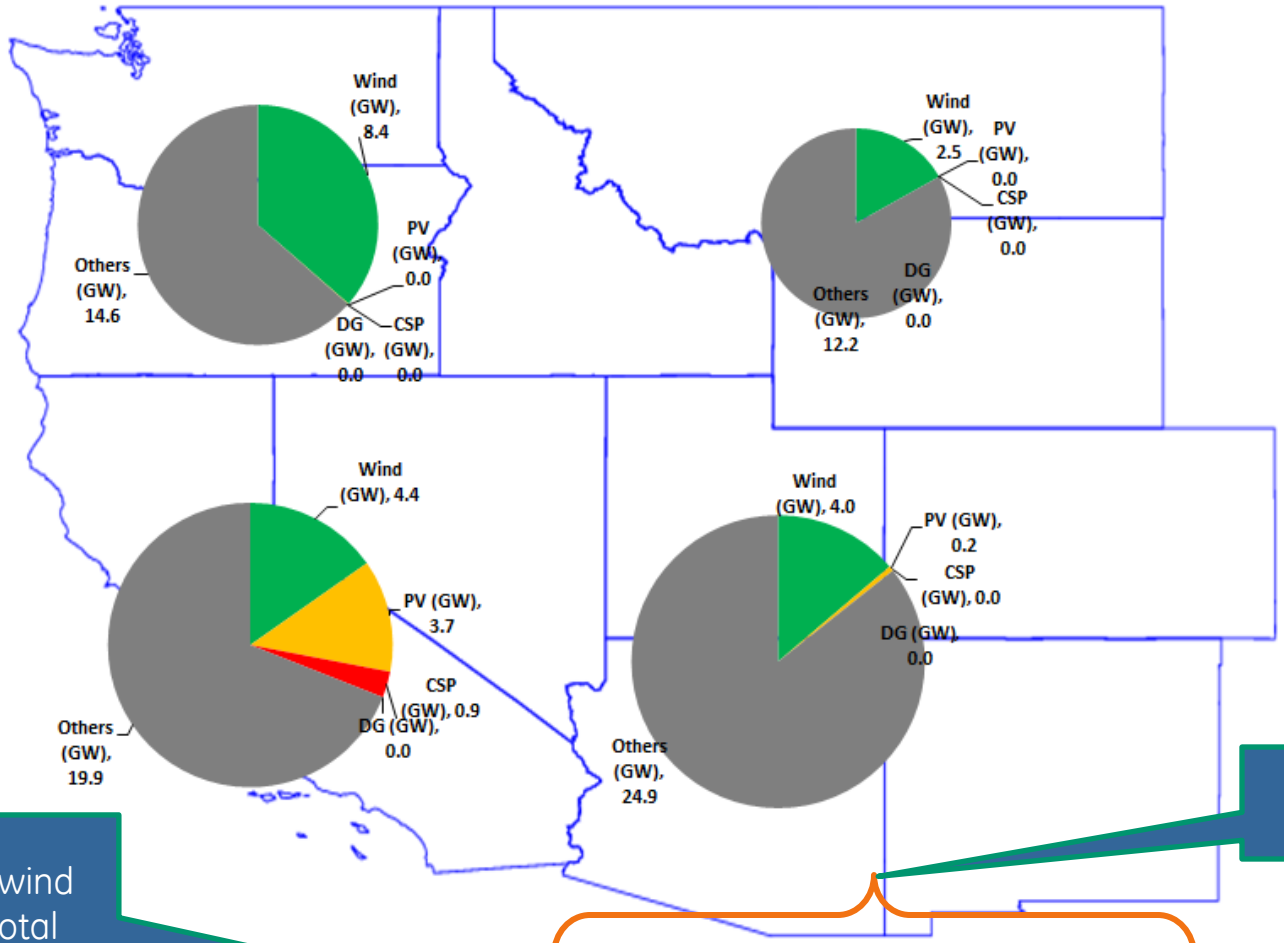
- A few additional analytical steps
  - Uniform DG trip case
  - Sensitivity on governor response
  - Further diagnostics/output on the dynamic behavior of the complex loads
  - Some further checks on the weak grid performance, particularly sensitivity to WTG modeling
- Draft report
  - Early summer
- Final TRC meeting – in person at NREL
  - Late summer/early Fall
- Final report
  - After receiving comments

Thanks

Backup

TRC Call: Do not Cite - Not for Further Distribution

2022LSP Base Case – Renewable Conditions



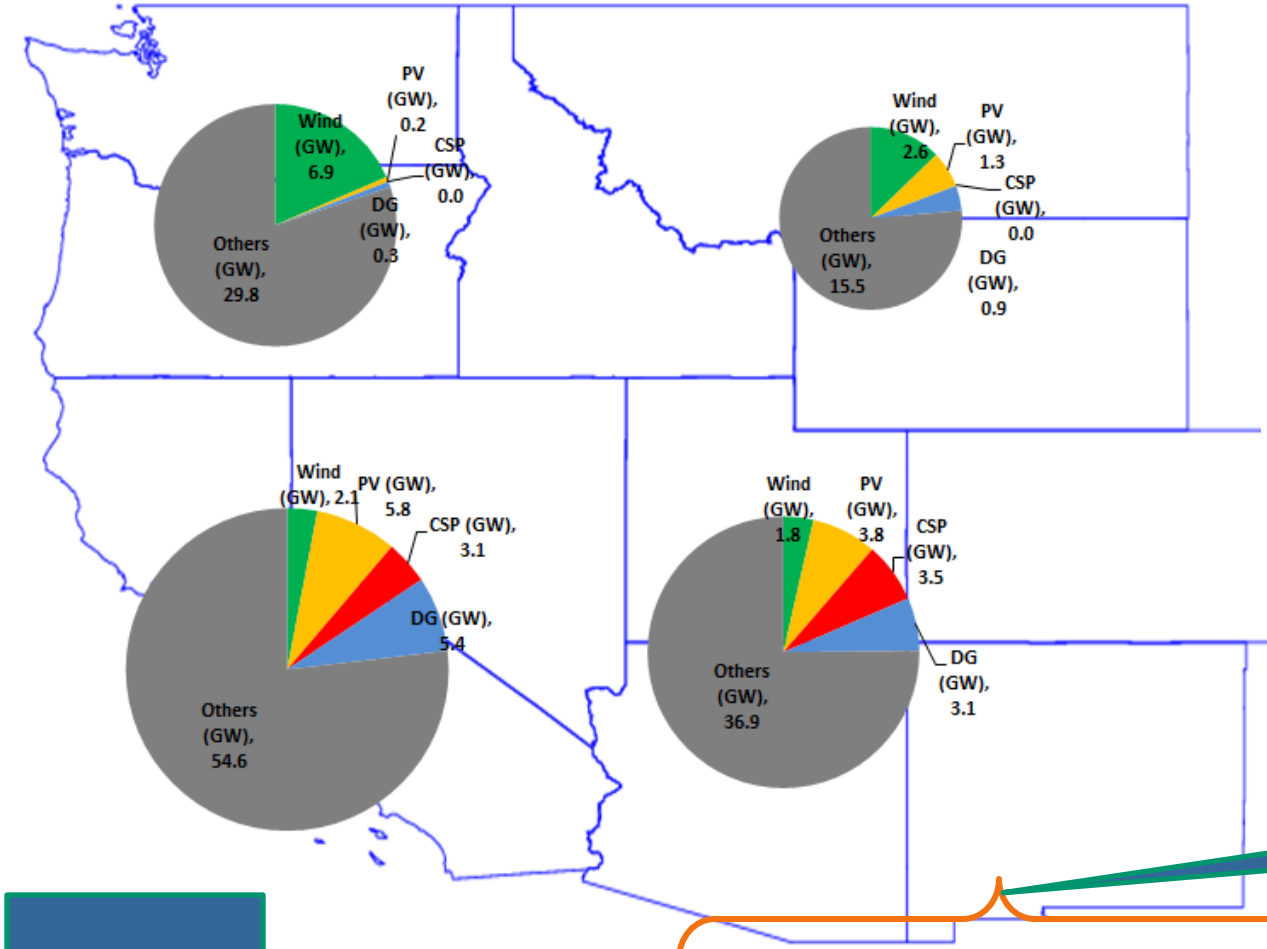
US only

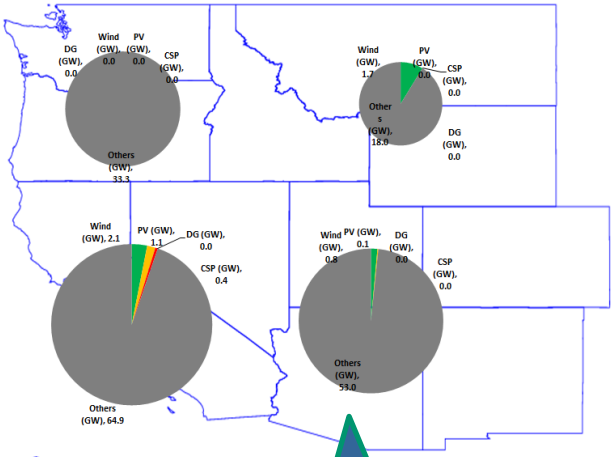
~ 25 GW of wind and solar total

	WECC	CALIFORNIA	DSW	NORTHEAST	NORTHWEST
Wind (GW)	20.9	4.4	4.0	2.5	8.4
PV (GW)	3.9	3.7	0.2	0.0	0.0
CSP (GW)	0.9	0.9	0.0	0.0	0.0
DG (GW)	0.0	0.0	0.0	0.0	0.0
Others (GW)	94.7	19.9	24.9	12.2	14.6
total (GW)	120.3	28.9	29.1	14.7	22.9

Preliminary Results: Not for Further Distribution or Citation

2023HS HiMix Case - Renewable Conditions





~ 7.2 GW of wind and solar in US in Base Case

US only

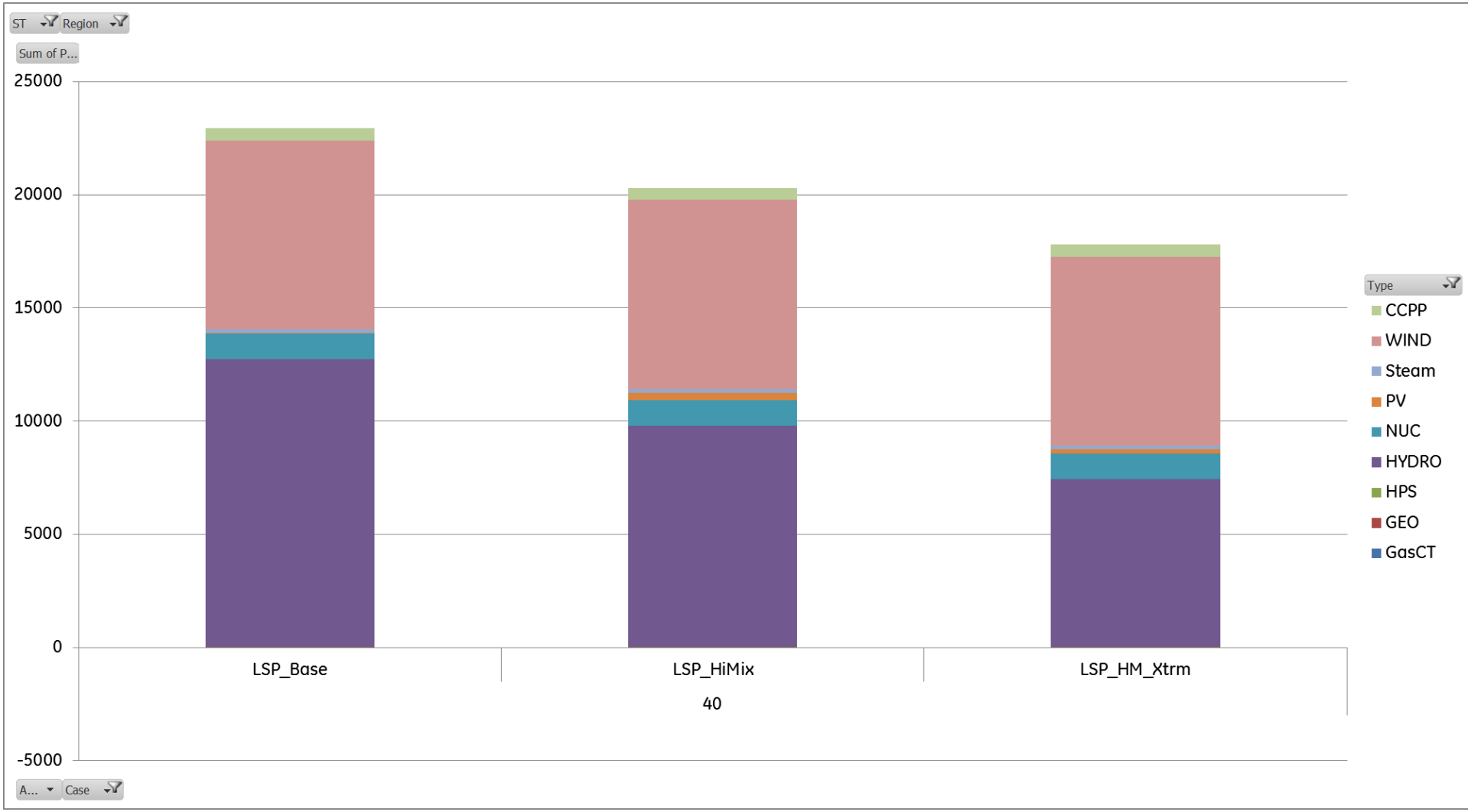
~ 41.5 GW of wind and solar

	WECC	CALIFORNIA	DSW	NORTHEAST	NORTHWEST
Wind (GW)	14.3	2.1	1.8	2.6	6.9
PV (GW)	11.2	5.8	3.8	1.3	0.2
CSP (GW)	6.6	3.1	3.5	0.0	0.0
DG (GW)	9.4	5.4	3.1	0.9	0.3
Others (GW)	162.7	54.6	36.9	15.5	29.8
total (GW)	204.2	71.0	49.1	20.3	37.2

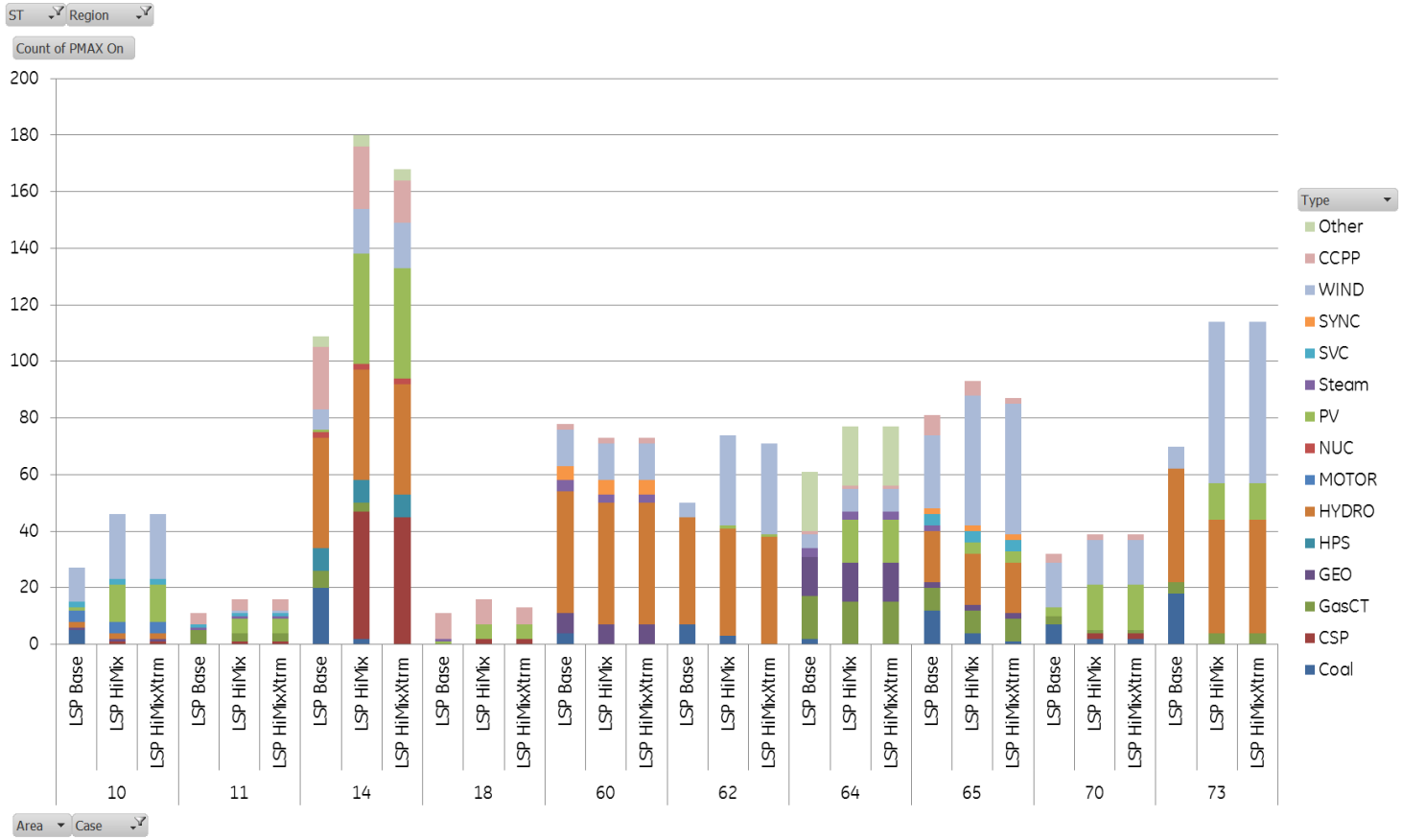
imagination at work

Preliminary Results: Not for Further Distribution or Citation

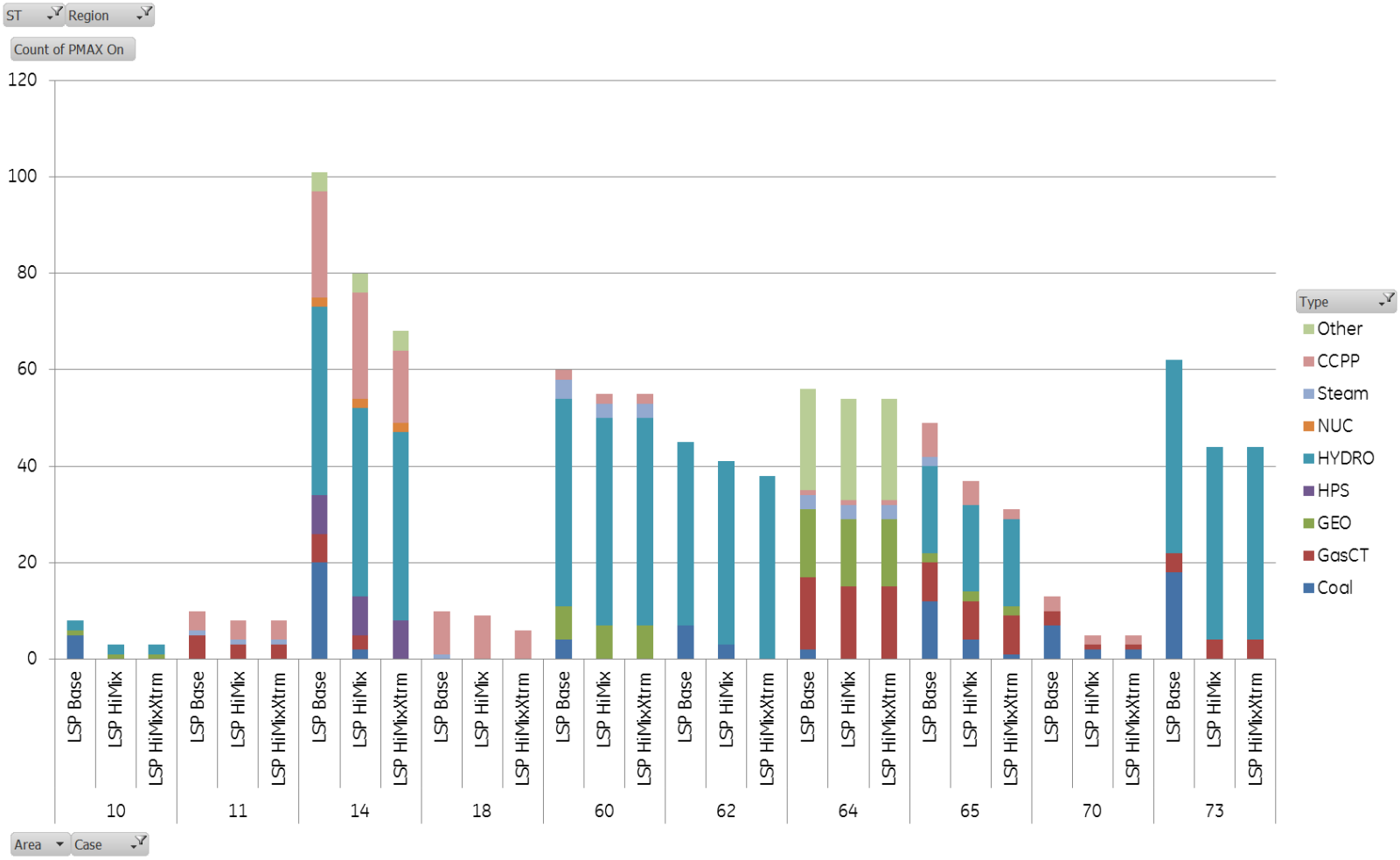
PNW


ST
Region
Sum of P...
25000
20000
15000
10000
5000
0
-5000
LSP_Base
LSP_HiMix
LSP_HM_Xtrm
40
Type
CCPP
WIND
Steam
PV
NUC
HYDRO
HPS
GEO
GasCT
A...
Case

Sum of Pmax in East (all generation)

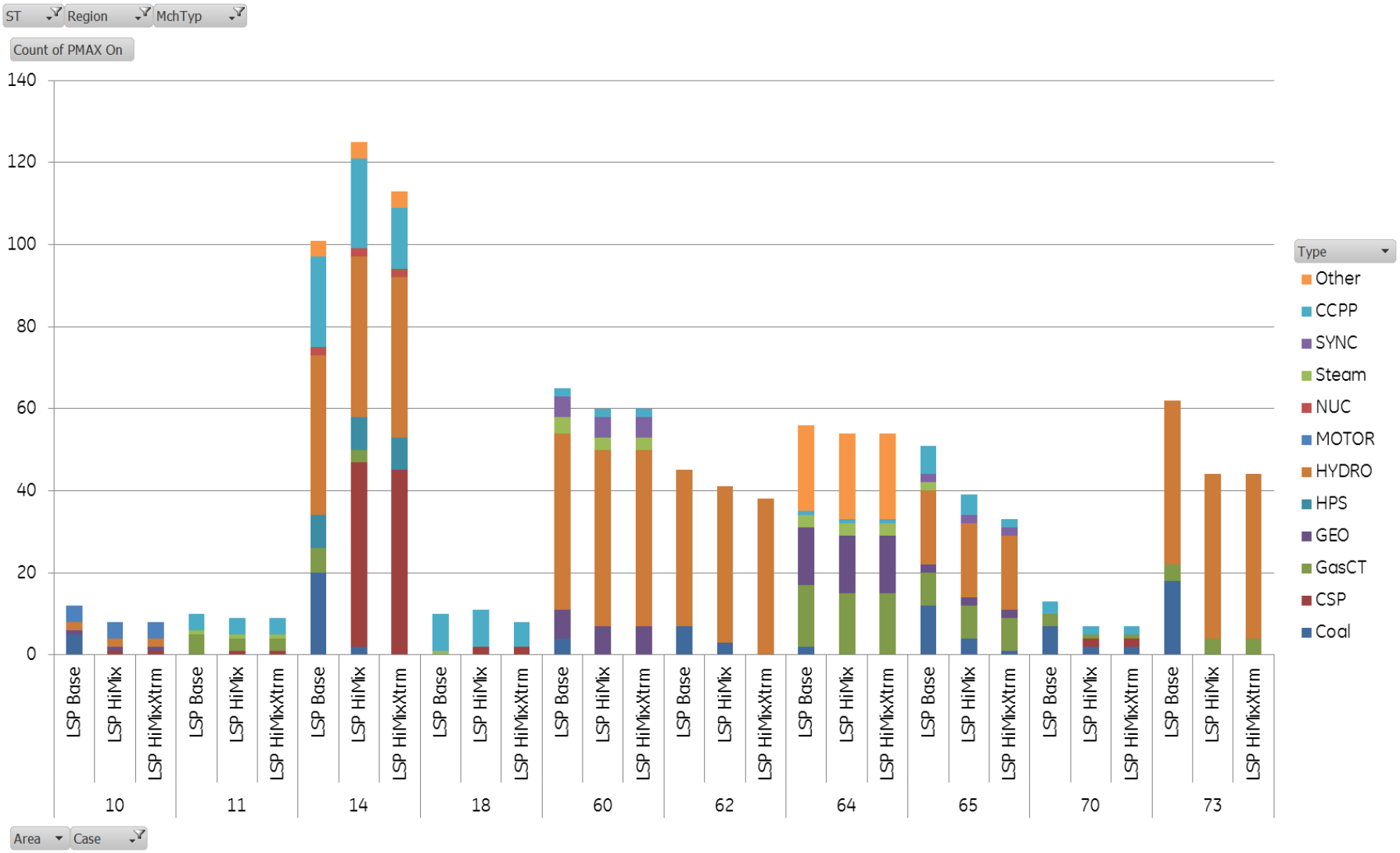


Pmax in east – non-renewable synch gen



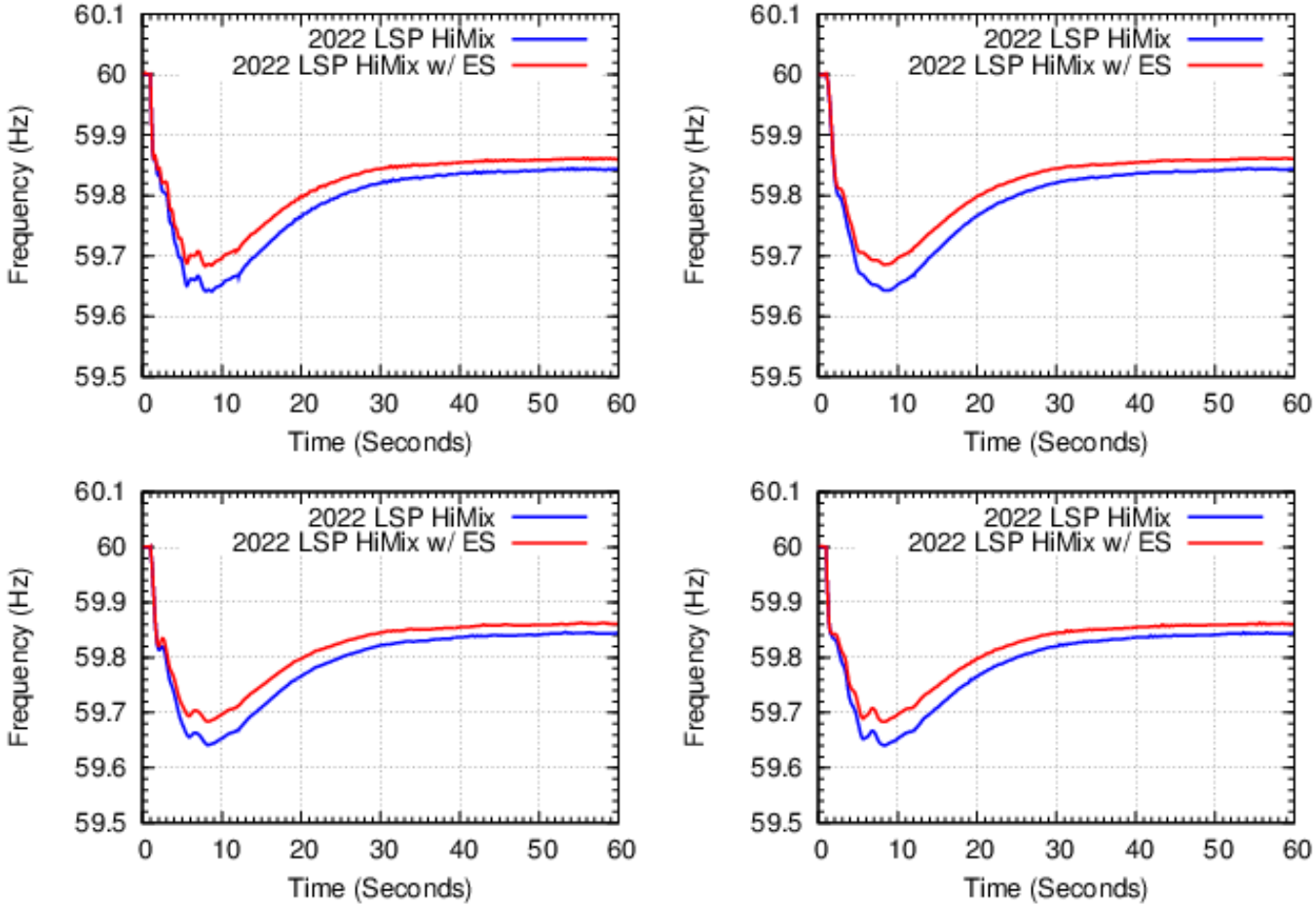
imagination at work

Pmax in east of all synch gen (incl CSP)



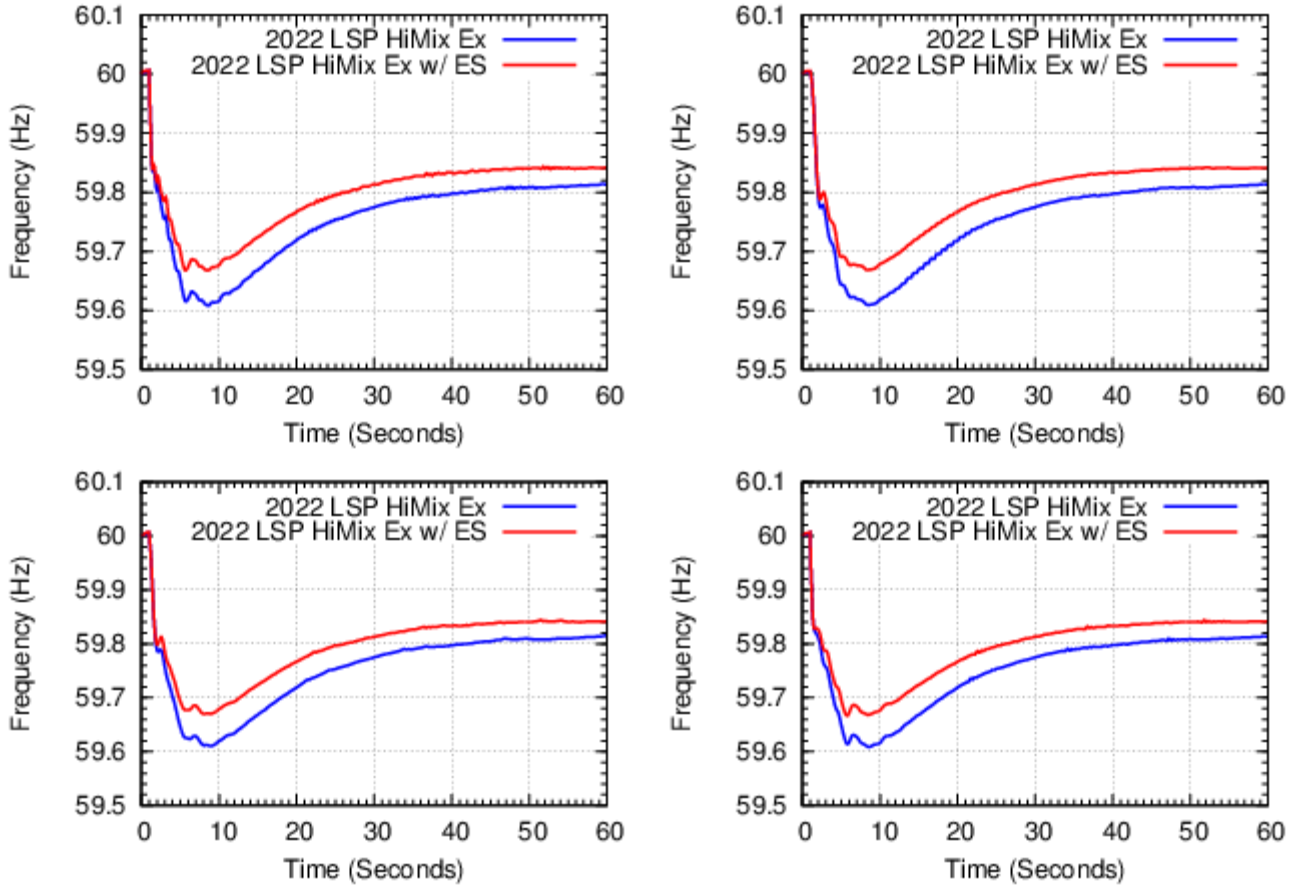
imagination at work

Regional Frequency Response – 2022LSP HiMix



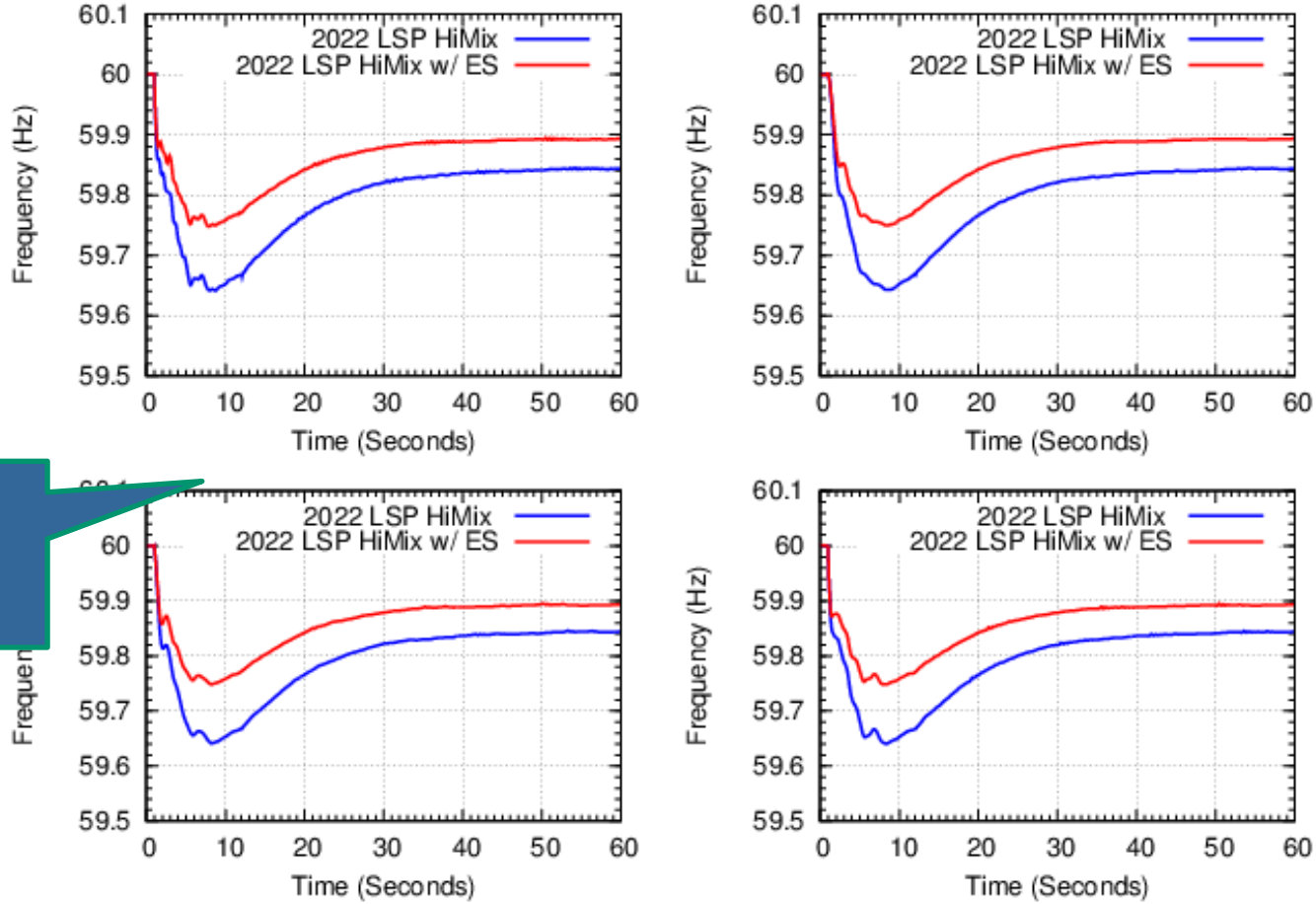
TRC Call: Do not Cite - Not for Further Distribution

Regional Frequency Response – 2022LSP HiMix Extreme



TRC Call: Do not Cite - Not for Further Distribution

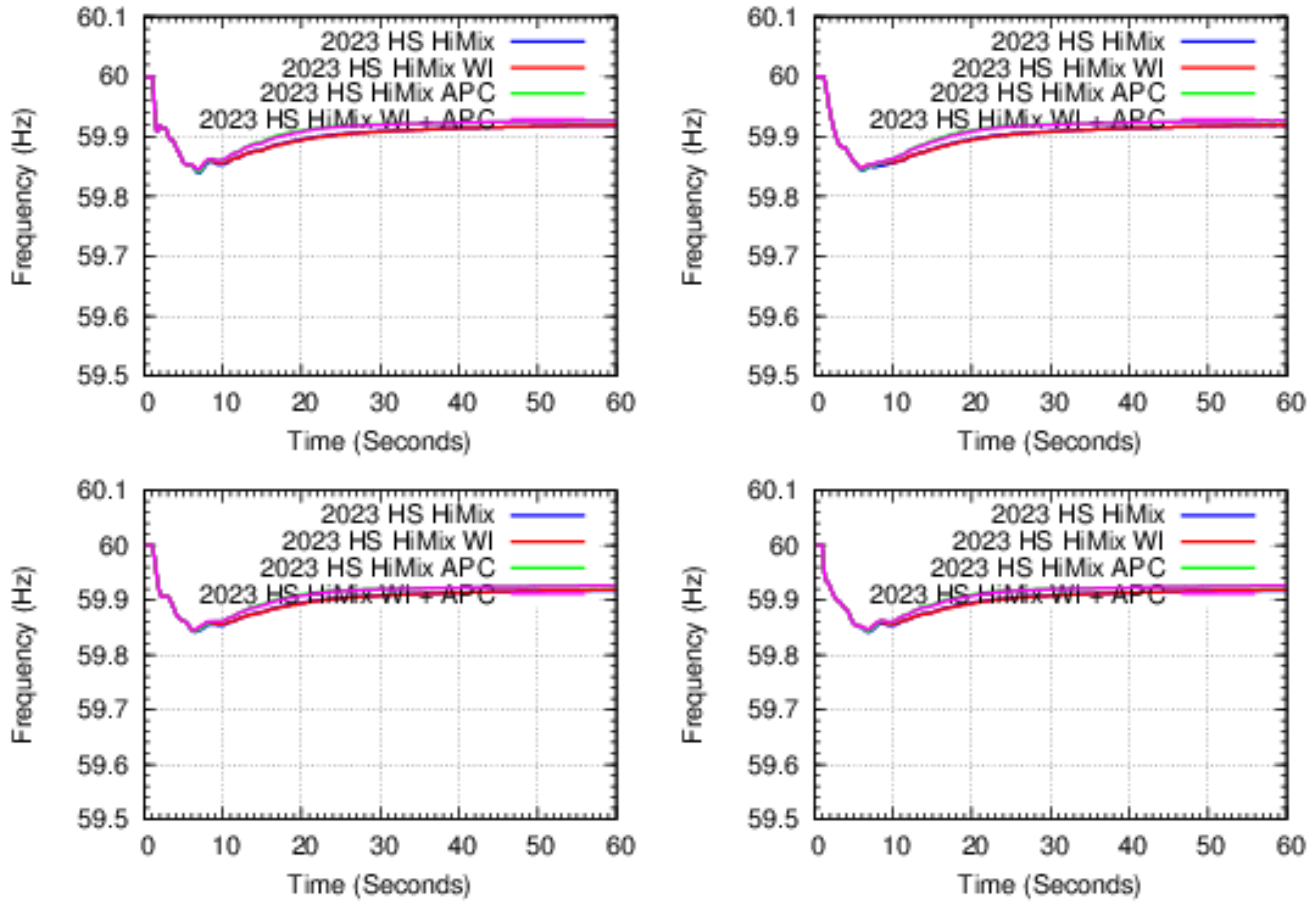
Regional Frequency Response – 2022 LSP HiMix



With Energy Storage

TRC Call: Do not Cite - Not for Further Distribution

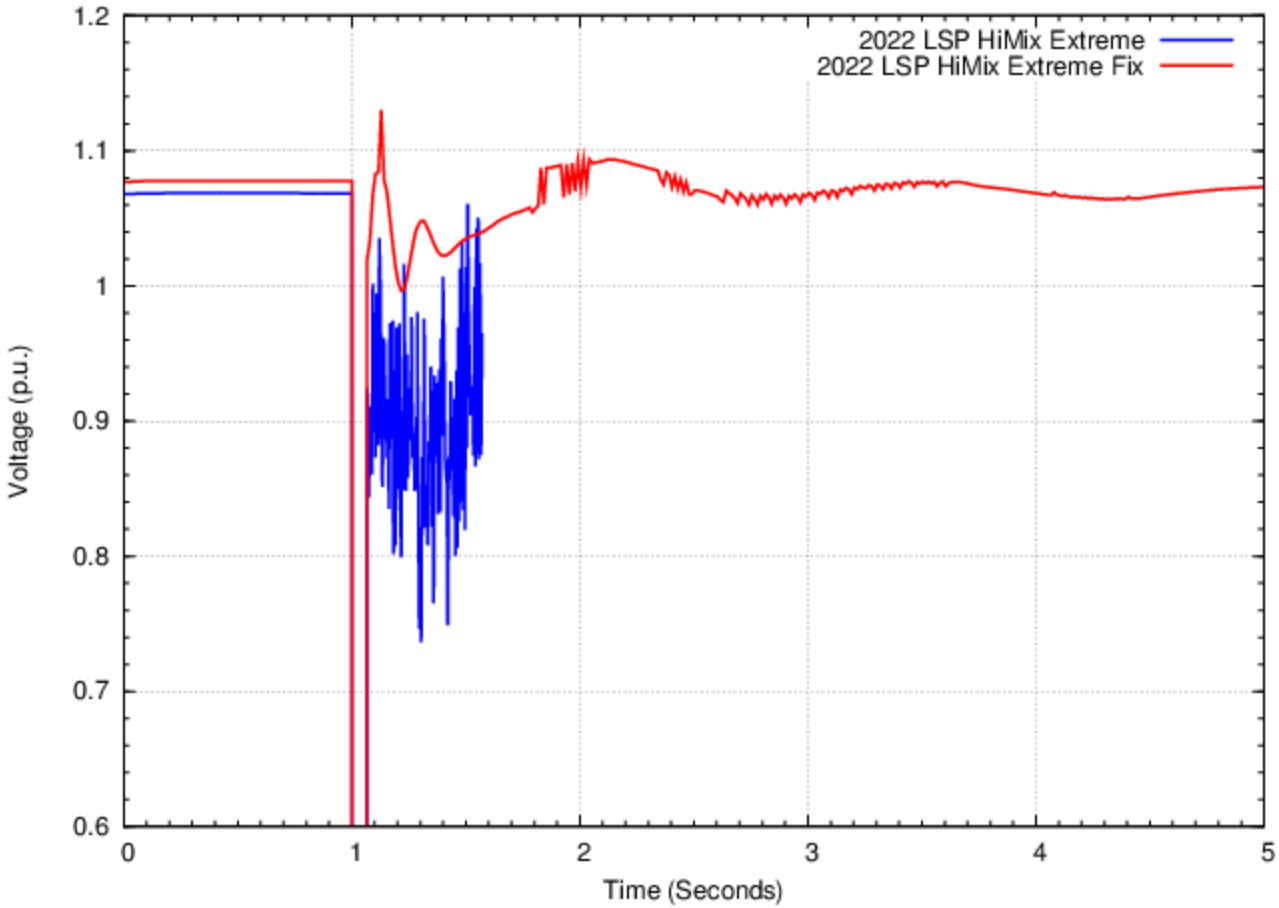
WECC Regional Frequency Response – 2023 HS HiMix



Apply frequency controls to all new wind plants

TRC Call: Do not Cite - Not for Further Distribution

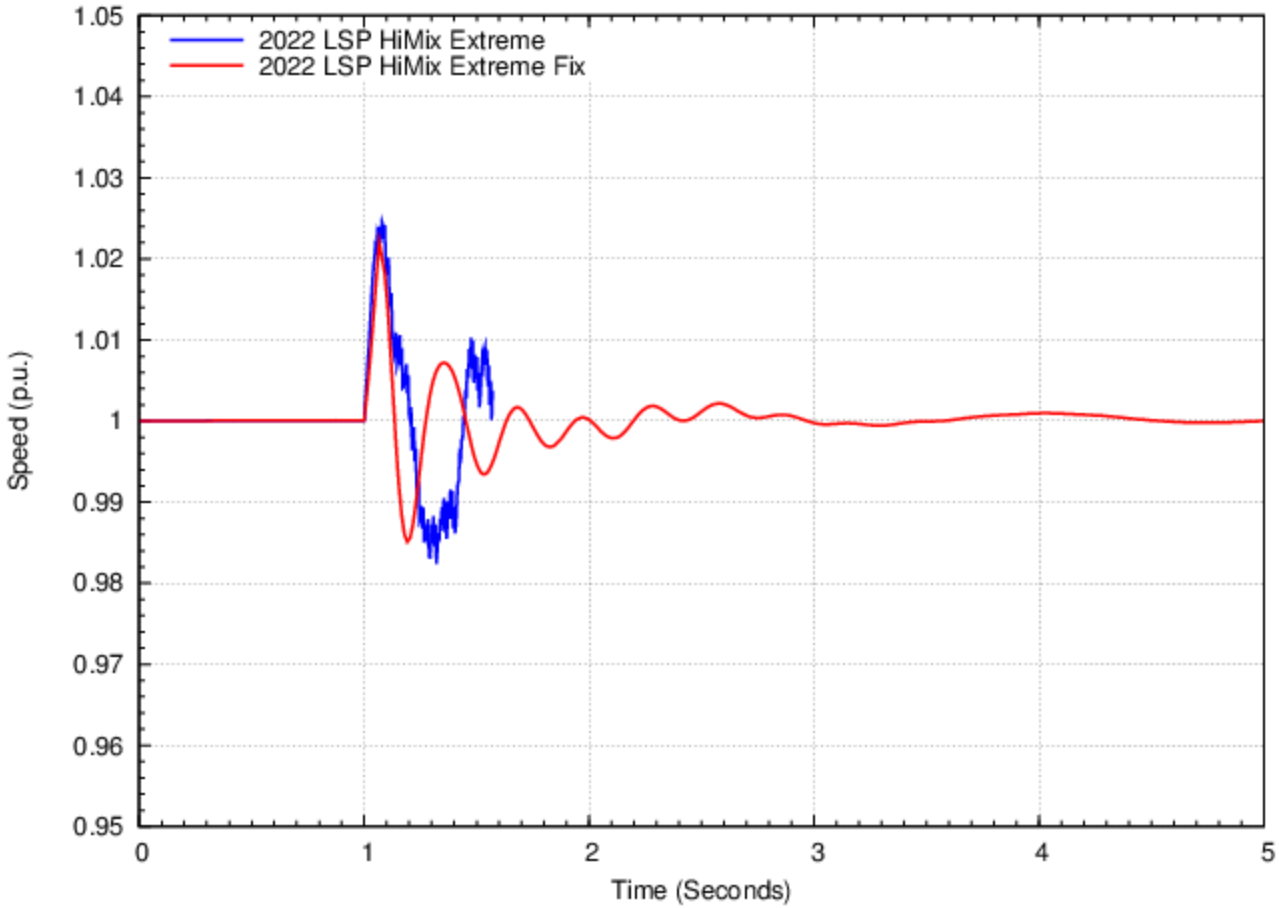
AEOLUS Fault – 2022 LSP HiMix Extreme Fix Case



imagination at work

TRC Call: Do not Cite - Not for Further Distribution

AEOLUS Fault – 2022 LSP HiMix Extreme Fix Case



imagination at work

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