WECC

Changes to System Inertia with High Renewable Implementation Assessment

Jon Jensen, Kent Bolton, Dick Simons

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Executive Summary

This study analyzed impacts on the potential future of the Western Interconnection (WI) with decreased inertia due to a retirement of thermal resources and a high implementation of renewables. For this study, the assumption was to retire all the existing coal resources and replace that generation with inverter-based resources (IBR), with a few exceptions. In developing the case, our assumption was to limit the unserved energy, but not to optimize the system relative to economics. Other similar studies may have different results. The results of this study are only based on the scenarios and conditions of this study, this is not an all-inclusive study for all hours or conditions:

To create a generation/load balance for the SITF case. It took about six times the MW in IBR to replace coal MW for our study due to the lower capacity factors and time of day dependencies for replacement resources.

This study resulted in about 62% of the inertia of the case that was referenced for the study. Inertia associated with hydro-electric plants, combined cycle gas, or other synchronous plants were kept intact in the study, besides coal. With decreased inertia, the power system experienced a steeper frequency decline and a lower frequency nadir[1] and a slower frequency recovery. Seven different outages listed below which are not inclusive of the entire WECC transmission system were studied for frequency performance. However, with the scenario and the limited outages studied, the system recovered to a stable state without shedding load due to Under Frequency load Shedding (UFLS).

This study did not enable frequency response and voltage regulation capability for the added IBR.

The results of this assessment are informational only. This assessment has only studied the standard outages that are considered for the base case creation and validation. This assessment has not considered all the outages that might become critical to the WECC transmission system under the changed resource portfolio. This study does address the need for more localized studies on the system to identify local impacts on reliability. The base case used to conduct the study has all the Regional Projects such as, the 500 kV Energy Gateway projects, West and South and others that directly impacts the power flow in the Western Interconnection. There is a significant amount of coal resources being retired in Wyoming, Montana, Colorado and New Mexico and being replaced with IBR resources which could change the criticality of the local outages in the Western Interconnection. For example, with the significant amount of IBR based resources added in Wyoming and the Gateway West and South regional projects, a 3-phase fault at Aeolus could be more critical as compared to the outages simulated in this study which was not analyzed as part of this study.

[1] Frequency Nadir – Please see Appendix B – Glossary.

WECC Standard Disturbances:

- Chief Joseph Brake insertion
- Double Palo Verde Outage
- Colorado River-Red Bluff 500kV Line Outage
- Gates – Midway and Two Diablo – Midway 500kV Line Outage
- Brownlee – Hells Canyon 230kV Line Outage
- Daniel Park – Comanche 345kV Line Outage
- Pacific DC Intertie (PDCI) 500kV DC Intertie Block

For more information on the WECC standard disturbances, please see the Dynamic and Transient analysis section of this report.

The SITF used the 2028 ADS Phase 2 V2.0[2] as a starting case to the create SITF case. The results of the SITF case may have been different if different transmission assumptions were included in the starting case of 2028 ADS Phase 2 V2.0. The transmission project assumptions included in the starting case may have had significant affects to the results of this SITF study.

Based upon the amount of resources added for this study, the total capital cost of only the added resources came to about $147 billion for around 115 GW of added generation capacity. No power flow analysis to determine thermal issues and voltage performance was conducted to determine transmission congestion due to addition of large amount of IBR resources. This capital cost does not include plant retirement cost, any transmission improvements or new transmission necessary to transmit these newly added IBR.

Short circuit analysis showed a decreased fault current in the areas where the coal resources were retired and review of the protection settings in those area may become necessary.

A significant observation in the path flow comparison of our study was the reversal of flow direction of Path 66 COI.

The future recommendations for this study are focused on a detailed analysis of the impact of decreased inertia on the system.

[2] Changes to 2028 ADS PCM from Phase 1 V1.0 to V2.2 and Phase 2 V2.0

Table of Contents

1. Introduction

The purpose of the Changes to System Inertia with High Renewables Implementation assessment is to assess the impacts on the reliability of the Bulk Electric System (BES) in the Western Interconnection (WI) as the system inertia changes due to the retirement of high-inertial resources such as coal-fired plants and increased implementation of inverter-based resources (i.e., energy storage, wind, and solar generation). The System Inertia Task Force (SITF) was made up of WECC staff and stakeholders to evaluate impacts of changes to BES inertia on the system by looking at the following: frequency response, transient voltage recovery, potential transmission congestion, system resource adequacy , potential inverter-based resource tripping under faulted condition, and potential impact to WECC path capacity and utilization in the year-10 horizon.

Estimated high-level capital cost is included for this study to get an idea of the cost magnitude associated with the resources added for this case.

Also, short circuit fault current analysis was performed to identify potential fault current impact associated with the retirement of coal generation.

Note: Because the "Changes to System Inertia with High Renewable Implementation" assessment was conducted by the SITF, it will be referred to as "SITF assessment/study" throughout this report. The case will be called the "SITF case".

This study seeks to answer the following questions as referenced in the Scope of Work:

1. Identify the change of system inertia and frequency response from increased levels of coal generation retirements with replacements coming from IBR;
2. Examine the impact that adding energy storage has on BES reliability (batteries/compressed air energy storage (CAES));
3. Evaluate the impacts of changes to short circuit fault duty and capture the impact on HVDC, protection scheme, and certain circuit breakers;
4. Analyze the reliability impacts of adding IBR with and without inverter frequency response capability;
5. Identify what capital costs might be required to mitigate reliability issues resulting from changes to BES inertia, based on "WECC 2019 Generator Capital Cost Tool – With E3 Updates (WECC's capital cost calculator);
6. Assess the ramping capability of the remaining generation fleet in the Western Interconnection for the loss of coal and thermal generation to be able to meet the demand based on system changes;
7. Identify the crucial contingencies in the Western Interconnection, and how changes to BES inertia would affect those contingencies;
8. Examine the impact of changes to BES inertia by looking at Transient and Voltage stability;

9. Identify the potential impacts of changes to the BES inertia by looking at WECC Path capacities (this assessment did not include a formal path rating study);
10. Identify potential transmission congestion or transmission loadability issues relating to the WECC Path Rating process;
11. Identify the impacts on system resource adequacy (i.e., Loads/Resources balancing, meeting state's and utility's established Planning Reserve Margin);

2. Participants

See Appendix A for full list of the SITF participants.

3. Assessment Approach

Assessment Approach Brief

The SITF assessment examined the impacts on the reliability of the Western Interconnection system caused by decreased inertia due to the retirement of high-inertial resources such as coal plants that are replaced by inverter-based resources such as wind and solar. To do this, we modeled an extreme case that retired 100% of the coal generation resources in the Western Interconnection and offset the reduced capacity by adding inverter-based resources including solar-tracking, onshore wind, and energy storage.

The SITF used the following Software programs:

- Power Flow [3]- Positive Sequence Load Flow (PSLF[4])
- Production Cost Model (PCM[5]) – GridView[6]
- Short circuit based on the power flow data - PowerWorld
- Capital cost – "WECC 2019 Generator Capital Cost Tool – With E3 Updates"

[3] Power Flow – Please see Appendix B – Glossary.

[4] PSLF – Please see Appendix B – Glossary.

[5] PCM – Please see Appendix B – Glossary.

[6] GridView – Please see Appendix B – Glossary.

To study the difference in fault duty current with the specified changes in the generation mix, PowerWorld was used to analyze Positive Sequence fault duty current differences. Neither zero nor negative sequence fault duty current were considered in this study.

The SITF used the WECC 2019 Generator Capital Cost Tool – With E3 Updates to evaluate the capital costs of newly interconnected inverter-based generation identified in the assessment.

The SITF modeled the case with the following process:

1. The task force started with the ADS Phase 2 V2.0, a yearly Production Cost Model (PCM) built in GridView.
2. Next, the PCM case was modified to remove all existing coal generation resources and replace that coal generation with enough wind and solar resources to offset the coal generation and to meet demand.
3. The PCM simulated the generation for every hour of the year in 2028 assuming no coal generation in the Western Interconnection. The PCM model hourly output was reviewed for hours of operational stress.
4. After the modified yearly PCM was complete, the SITF selected two hours for further analysis using a power flow model, Positive Sequence Load Flow (PSLF).
5. After the hour(s) were solved in PSLF, the task force performed dynamics (i.e., transient stability) studies to consider how the decreased inertia affected the Western Interconnection.
6. The team evaluated capital costs of added resources to the study.
7. The team also completed a short circuit analysis of fault current in positive sequence.

Assessment Approach Detail

The team executed this approach as follows:

The analysis began with the ADS Phase 2 V2.0 PCM as the foundational case for the study.

The study proceeded by retiring all the coal resources from the ADS Phase 2 V2.0 PCM and replacing that generation with inverter-based resources (IBR). The goal was to minimize unserved load to maintain an energy balance without optimizing the system by economics or location. Wind and solar resources were selected and placed in the WI in the Western Renewable Energy Zones (WREZ) which identify high quality resource areas that had underutilized transmission. Adding transmission to the case was not considered except for minor radial transmission to interconnect resources.

The SITF team modified the ADS Phase 2 V2.0 PCM by removing all the coal generation in the ADS and adding the following specific resources to minimize unserved load:

- Battery Storage - (Battery model in which a *shape* defines the charge/discharge times)
- Gas
- CAES (Compressed Air Energy Storage)

- Pumped Storage - (Battery model in which *prices* defines the charge/discharge times)
- Solar Photovoltaic (PV)-Tracking
- Wind Turbine (WT)-Onshore

The reason that battery storage is represented as "Battery Storage" (model defined by a shape) and "Pumped Storage" (model defined by prices) is because the PCM software did not provide a more realistic model at this time defined by both price and shape at the time of this study.

In summary, the following modifications were made to create the SITF case:

- 21,661 MW coal capacity (100% of remaining coal in the ADS Phase 2 V2.0 case) was retired.
- 2,685 MW of that 21,661 MW coal capacity in Alberta was converted from coal to natural gas fuel;

  and

- The remaining ≈18,976 MW of retired coal generation was not converted to another fuel. But replaced by 115,840 MW capacity of other resources were added, including battery storage (defined based on shape), gas generation, CAES, pumped storage (defined based on price), Solar PV-Tracking, WT-Onshore (Wind).

The following resources were modified from the ADS Phase 2 V2.0 to create the SITF Case:

Resource Conversions:

The following coal units in Alberta were converted to natural gas fuel for this study:

Table 1 – Alberta Coal Resources Converted to Gas

Unit Name	Capacity, MW
Sheerness_2_2	408
Sheerness1-1	408
Genesee_2_2	422
Genesee1-1	422
Genesee_3_3	527
Keephills3_1	498
Total:	2,685

Resource Retirements:

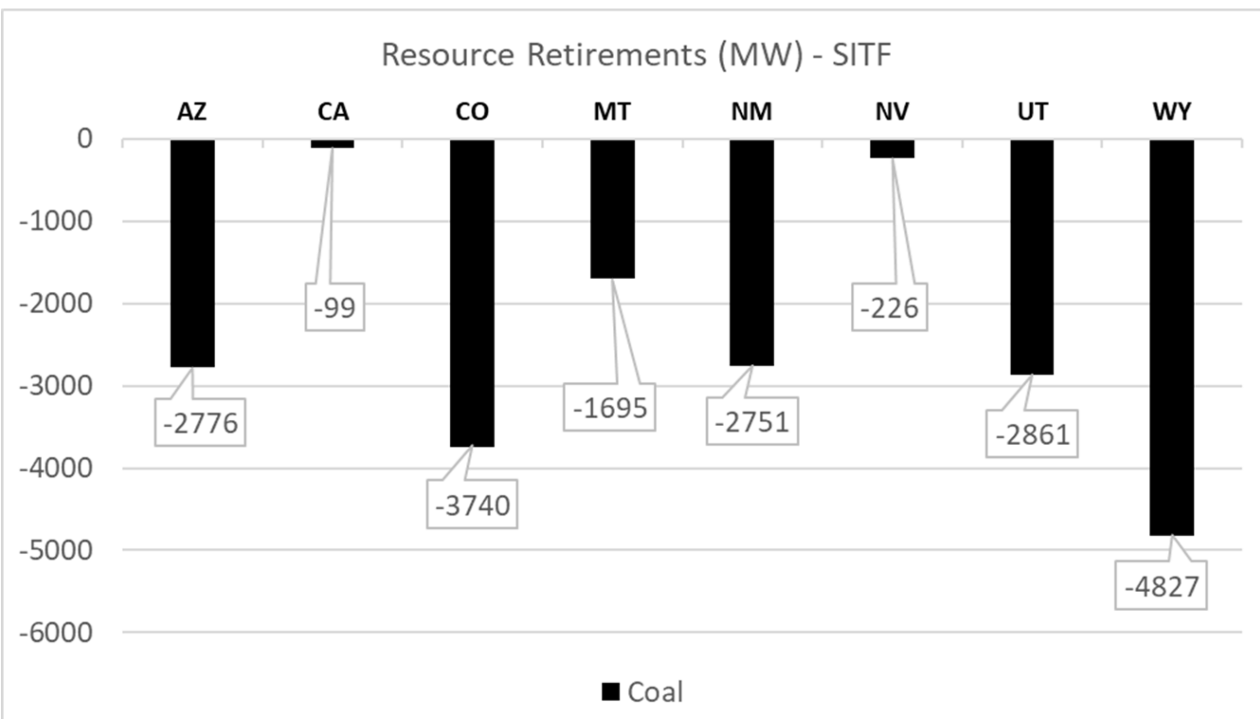
The following coal resources were retired for this study:

Table 2 – Coal Capacity Retired in Inertia Assessment

State	Coal Capacity, MW
AZ	2,776
CA	99
CO	3,740
MT	1,695
NM	2,751
NV	226
UT	2,861
WY	4,827
Total:	18,976 (including significant digits)

Total Retired Resource Capacity: ≈18,976 MW
Figure 1 shows the coal retirements in MW by state:

Figure 1 – Resource Deletions in System Inertia Assessment



Including the coal from Alberta, which we converted to natural gas, there was a total of 21,661 MW capacity of coal retired from the case.

Resource Additions:

The following resource were added to offset the coal retirement for this study.

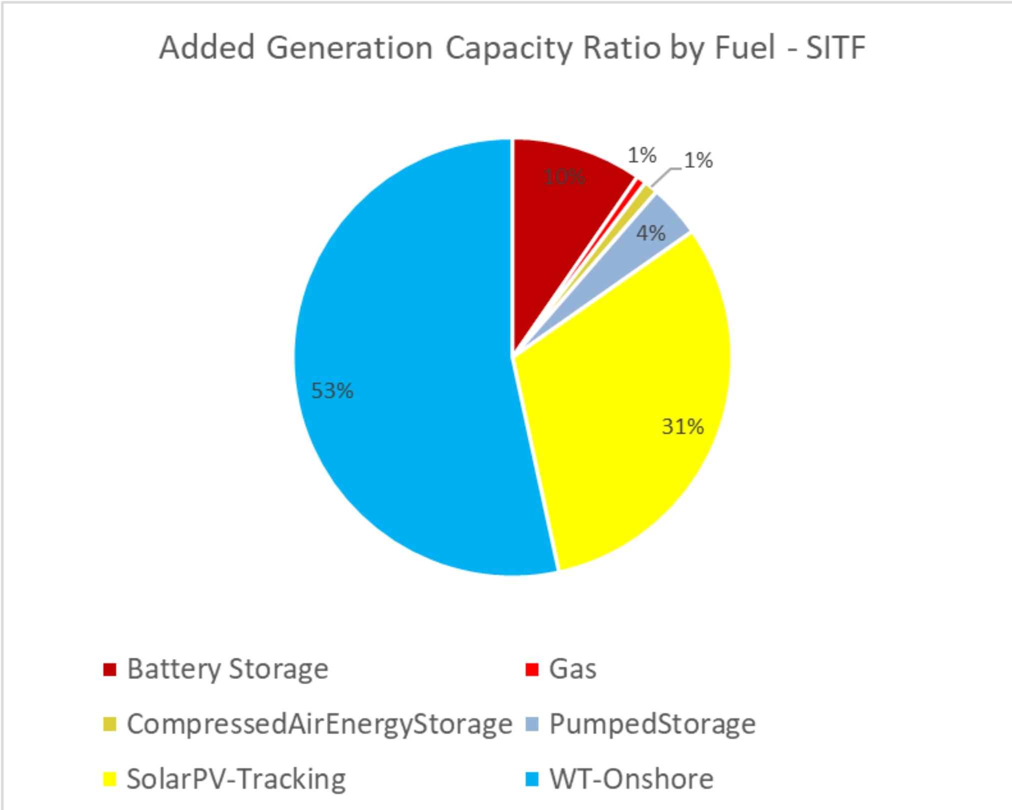
Table 3 – System Inertia Assessment Resource Additions, MW

State	Battery Storage	Gas	CAES	Pumped Storage	Solar PV – Tracking	Onshore Wind
AZ	1,000	-	-	-	15,000	500
CA	2	-	-	1,247	-	-
CO	3,050	-	-	250	12,400	26,200
ID	-	-	-	-	-	2,600
MT	2,000	-	-	200	-	11,650
NM	800	-	-	-	3,600	3,900
NV	300	-	-	-	2,901	-
UT	500	840	1,200	500	2,400	-
WY	3,500	-	-	2,300	-	17,000
Totals:	11,152	840	1,200	4,497	36,301	61,850

Total Added Resource Capacity: 115,840 MW

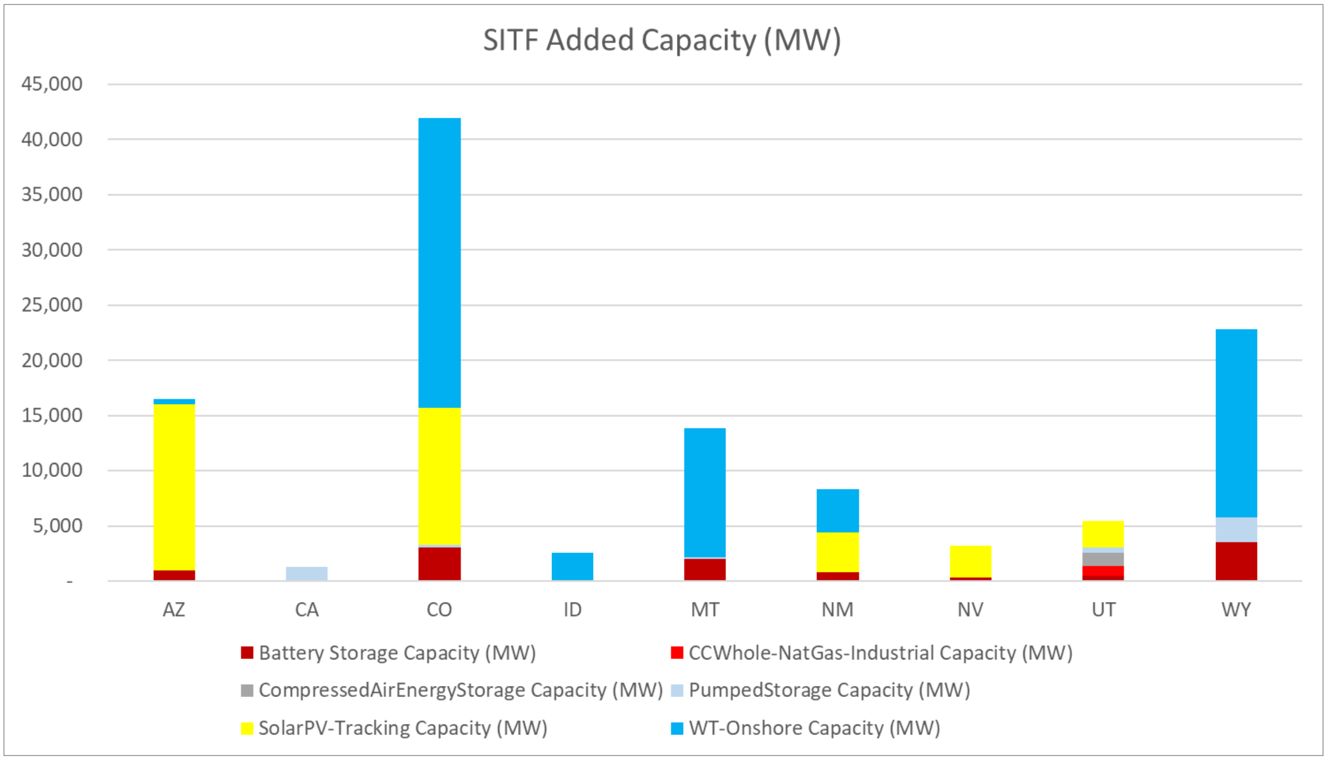
Figure 2 shows the ratio of resources added to the SITF case. Wind and solar make up most of the resources added to the case.

Figure 2 – Generation Additions by Fuel Type



Capacity Factor is the ratio of actual energy produced over a given time period divided by the theoretical maximum amount of energy output over that given time period that it could produce. Because coal has a higher capacity factor than wind and solar, it takes more wind and solar resources to create the same amount of power. For example, SolarPV-Tracking capacity factors are around 20-32%, and Onshore Wind capacity factors are around 21-35%. Coal capacity factors are around 60-85%. To minimize unserved load, the SITF case needed about six times more IBR to offset the retired coal resources. Another reason for such a high amount of renewables is the time of day dependency to the renewables. For example, there may be enough solar to handle load in the middle of the day because the sun is out, but not enough toward the evening peak because the sun is going down. Figure 3 shows resource additions to the SITF case by state:

Figure 3 – Resource Additions by State



Comparing the ADS Phase 2 V2.0 PCM and the SITF case.

Here are the differences between **Capacity** of the ADS Phase 2 V2.0 PCM and the SITF case.

Figure 4 shows the generation capacity differences between the ADS Phase 2 case and the Changes to System Inertia case. The latter case includes significantly higher wind and solar generation with a significant decrease in coal because we retired 100% of the coal resources in the SITF case.

Figure 4 – Resource Changes from ADS Case to SITF Case

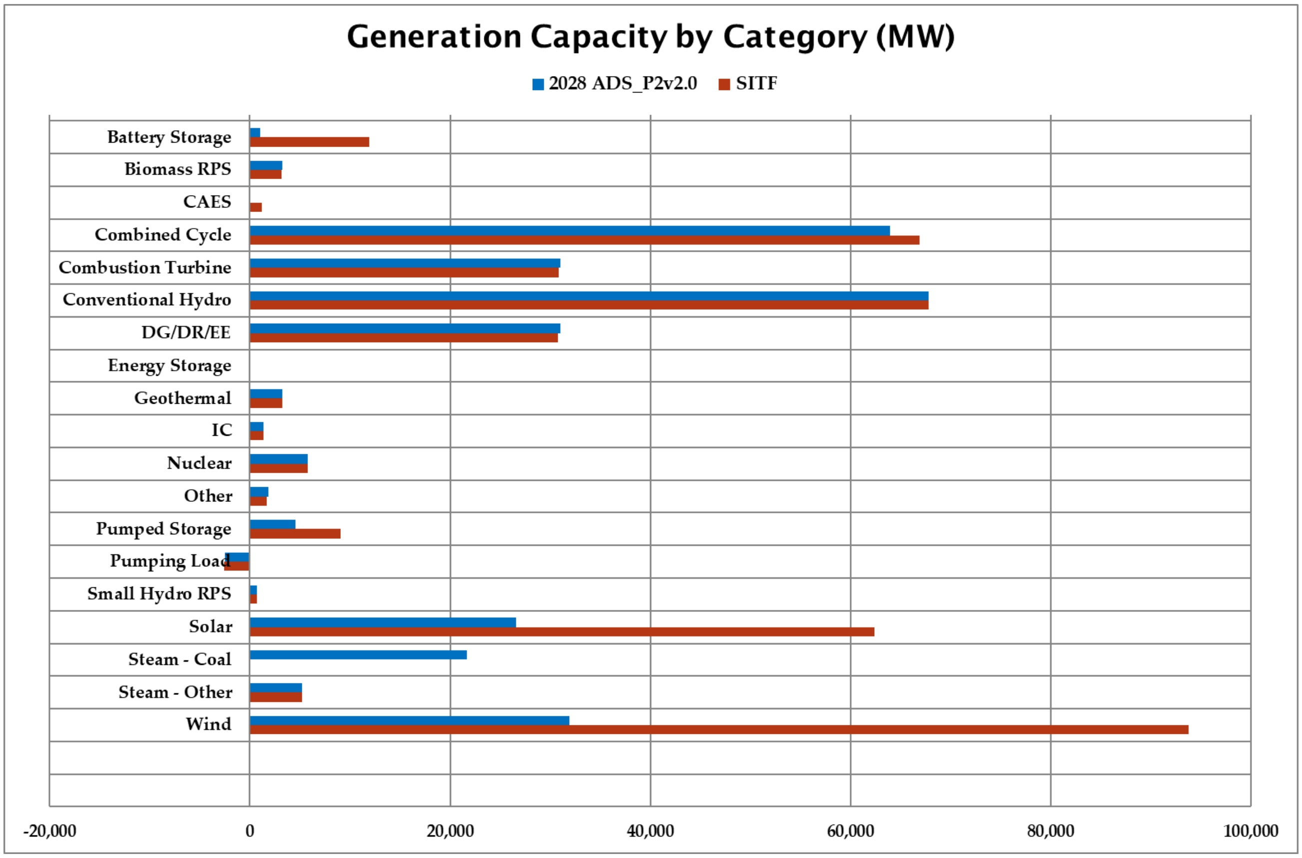
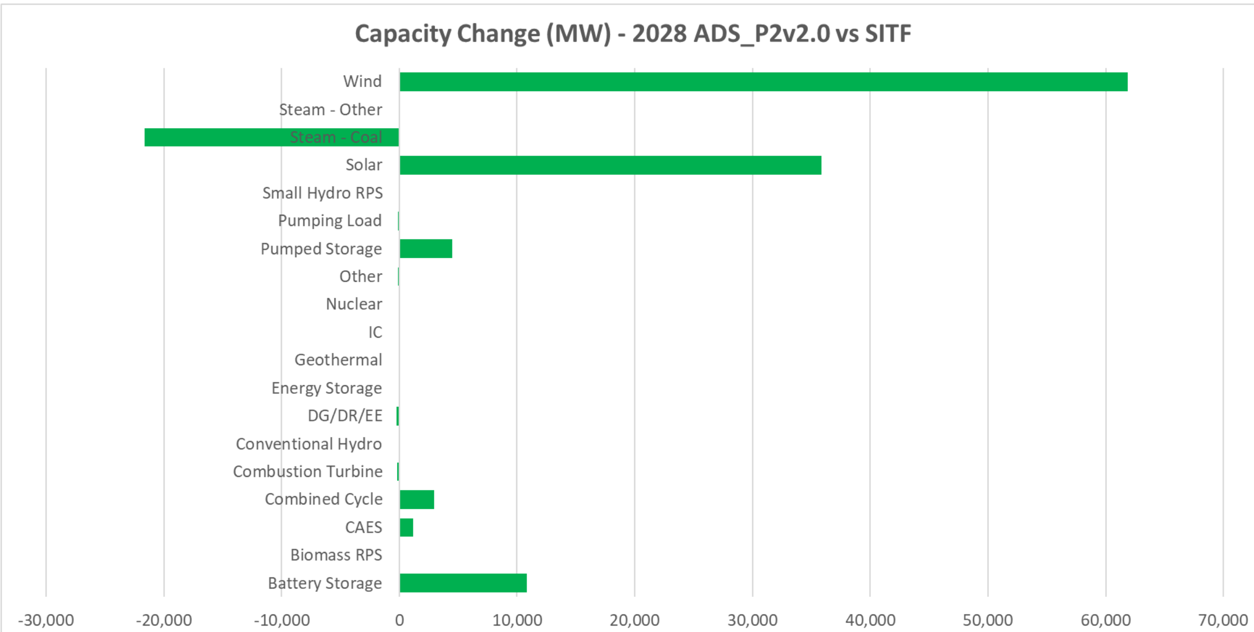


Figure 5 illustrates only the net changes in capacity of each resource that was added or retired. Note, the reduction in coal and increase in IBR.

Figure 5 – Net Changes to Capacity from ADS Case to SITF Case



The following figures depict the changes in **<u>Energy</u>** between the ADS Phase 2 V2.0 PCM and the SITF case. Note that the energy output resembles the change in capacity. There was no coal energy in the SITF case, but a significant increase in Wind and Solar.

Figure 6 – Changes to Energy Generation ADS Case to SITF Case, MWh

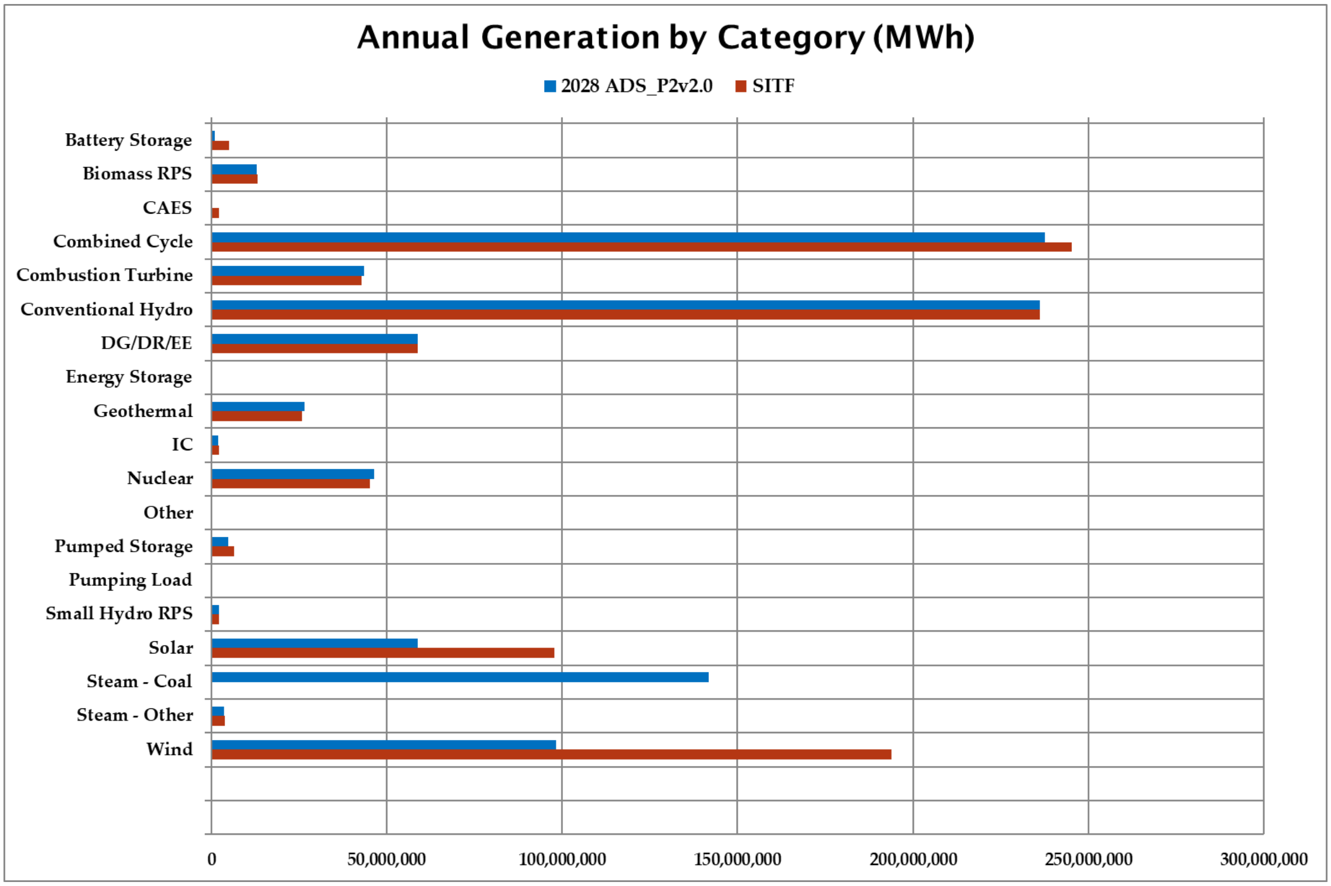


Figure 7 – Net Changes to Energy Generation ADS Case vs. SITF Case

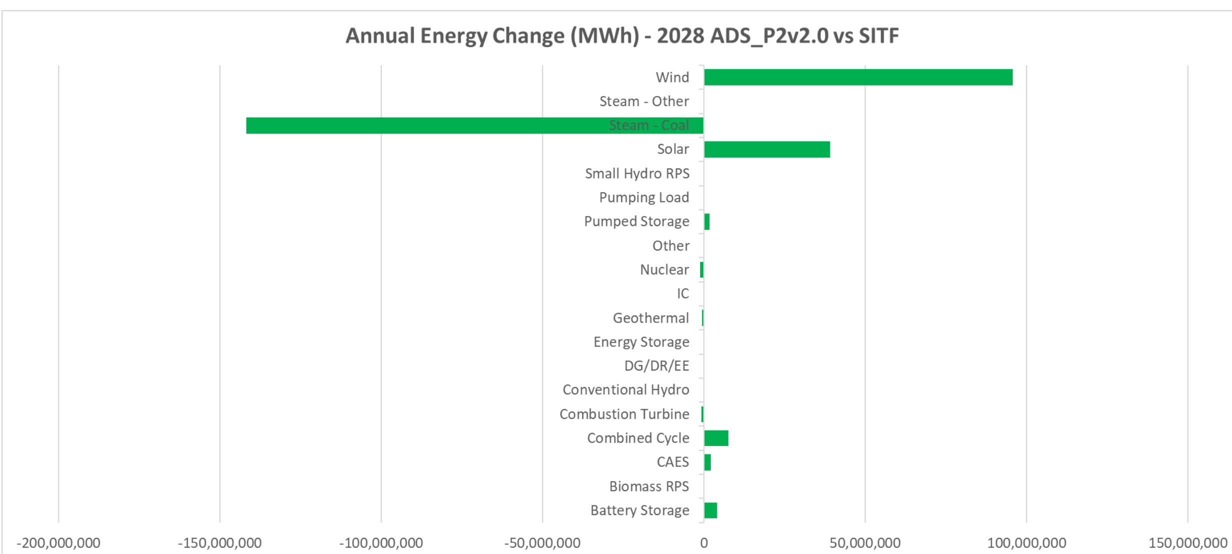


Figure 8 – Annual Energy Changes from ADS Case to SITF Case by State

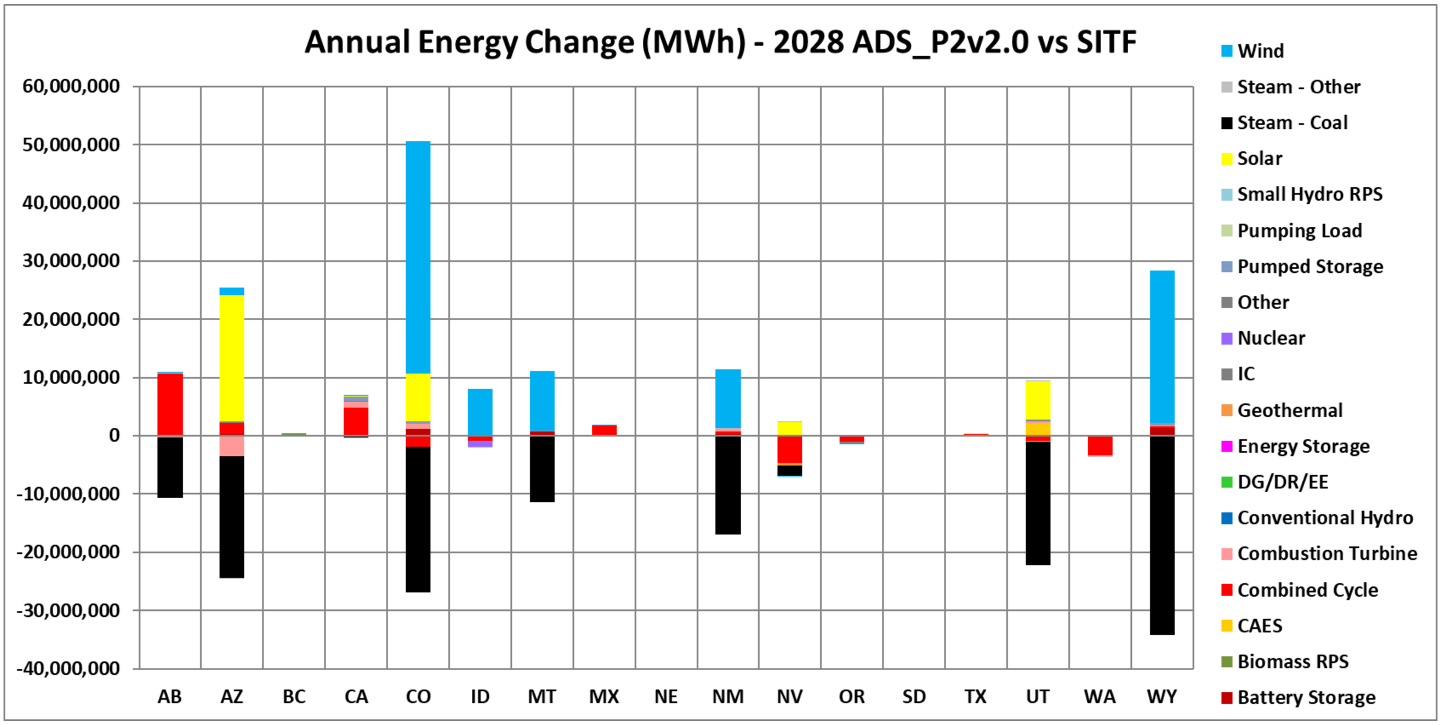
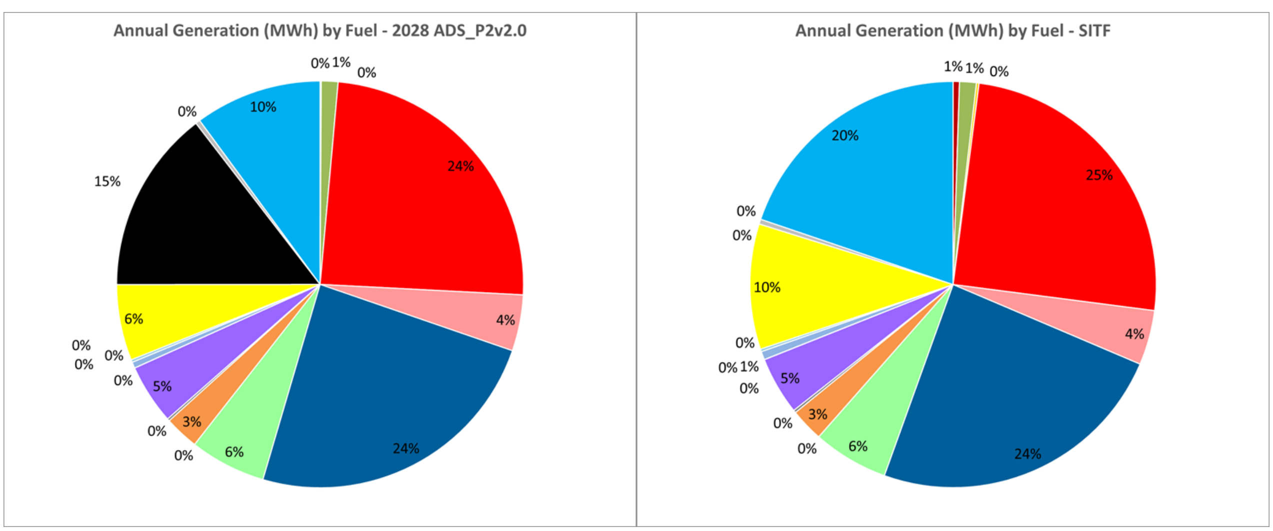
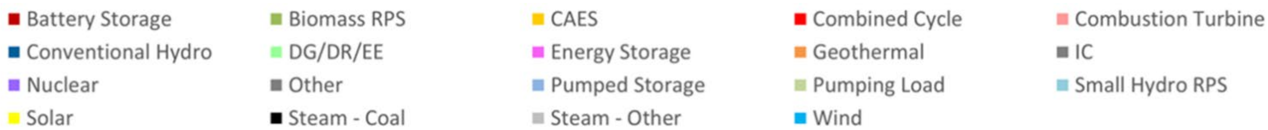


Figure 9 compares the generation mix shares of the 2028 Phase 2V2.0 and the SITF case. We see the coal (black) drop out from the annual generation from the 2028 Phase 2V2.0 case (left) and an increase in Wind (light blue) and Solar (yellow) in the SITF case (right).

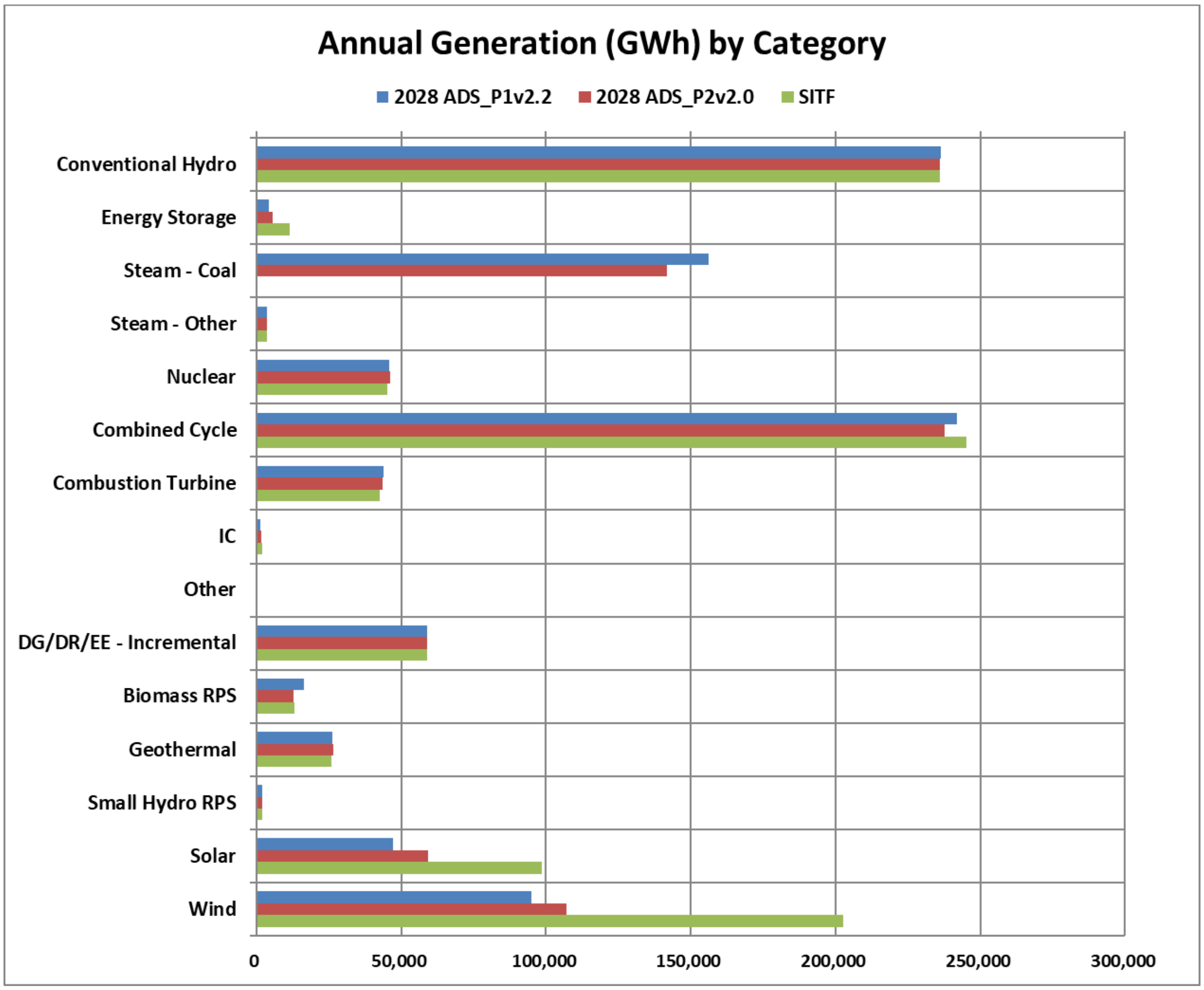
Figure 9 – Resource Mix Comparison ADS Case vs. SITF Case





The 2028 ADS Phase 2 V2.0 is a derivative of the 2028 Phase 1 V2.2. The chart below shows each step of the changes from Phase 1 to Phase 2 to the SITF PCM cases and the differences between each case.

Figure 10 – Annual Generation Comparison



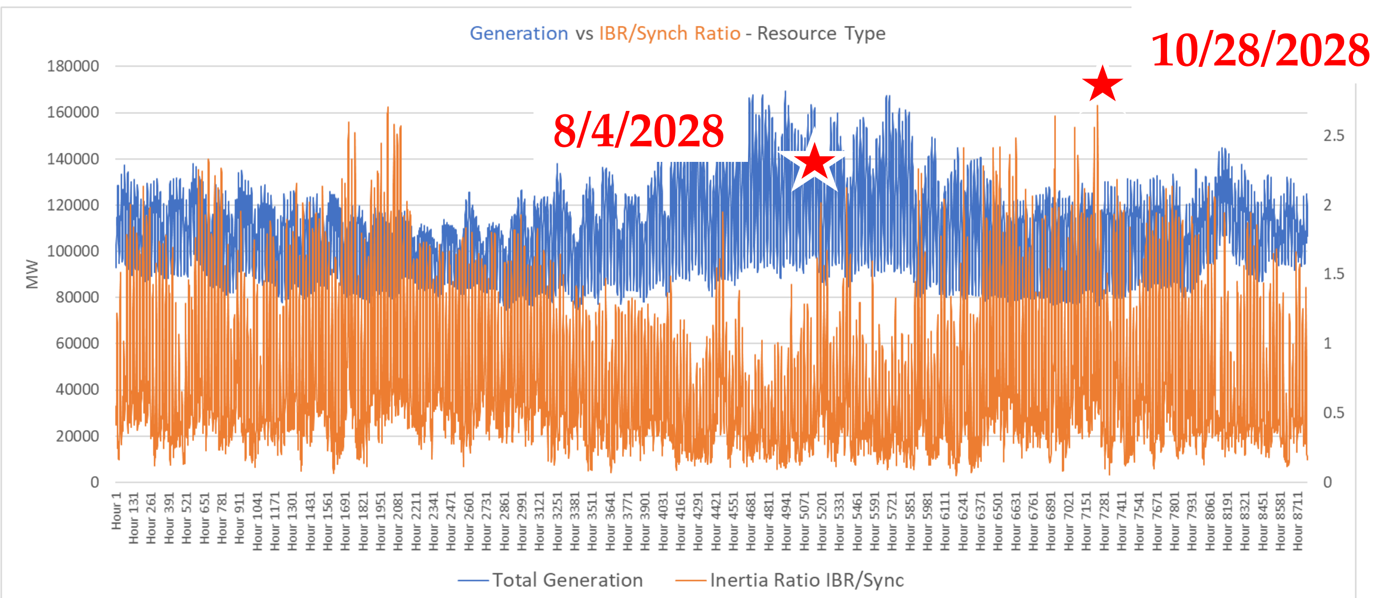
Power Flow Analysis

After updating the PCM case with the resources above, the SITF team looked for specific hours to perform a transient stability study with various disturbances.

The criteria to select the specific hours to study from the PCM in a power flow were based on high IBR-to-Synchronous-Machine ratios during periods of heavy and light generation levels. Two hours were chosen to study. Figure 11 shows the Generation(blue) and the IBR/Synchronous machine ratio(orange) for the whole year as well as which hours were chosen to analyze in power flow and dynamics.

Both hours chosen were mid-afternoon hours, generally solar has a higher output from mid-morning through mid-afternoon, where wind tends to have a higher output earlier in the morning and later in the evening.

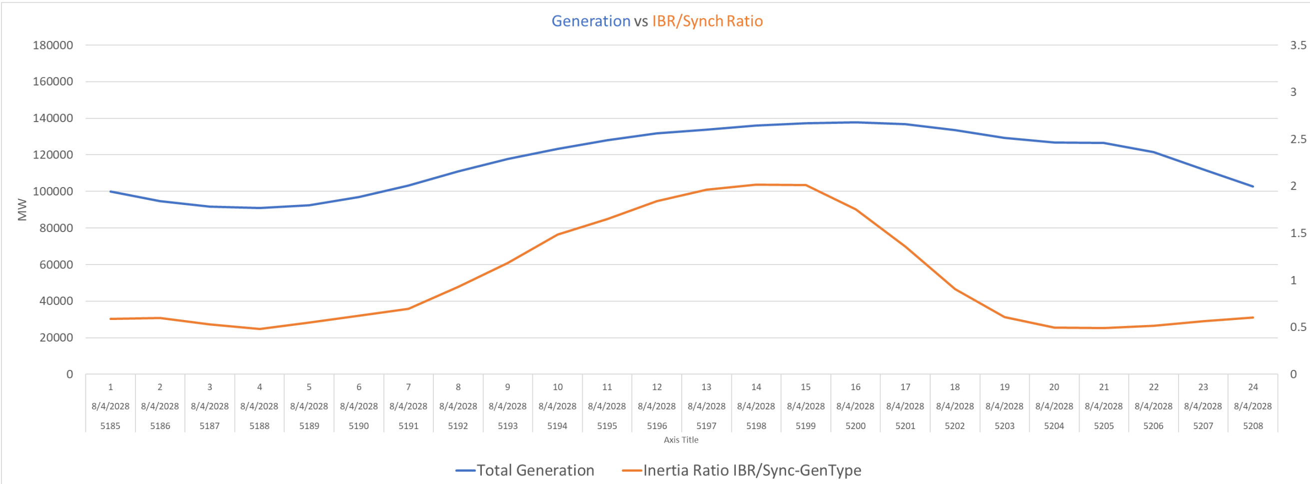
Figure 11 – Total Generation and IBR Ratio - 2028



- Hour 5198 (8-4-2028 hour 14)
    - Generation = 135,972 MW
    - IBR/Sync = 2.02

The hour shown in Figure 12 represents a high IBR/Synch ratio with high generation. This represents an hour where there is about twice as much IBR generation as synchronous machine generation.

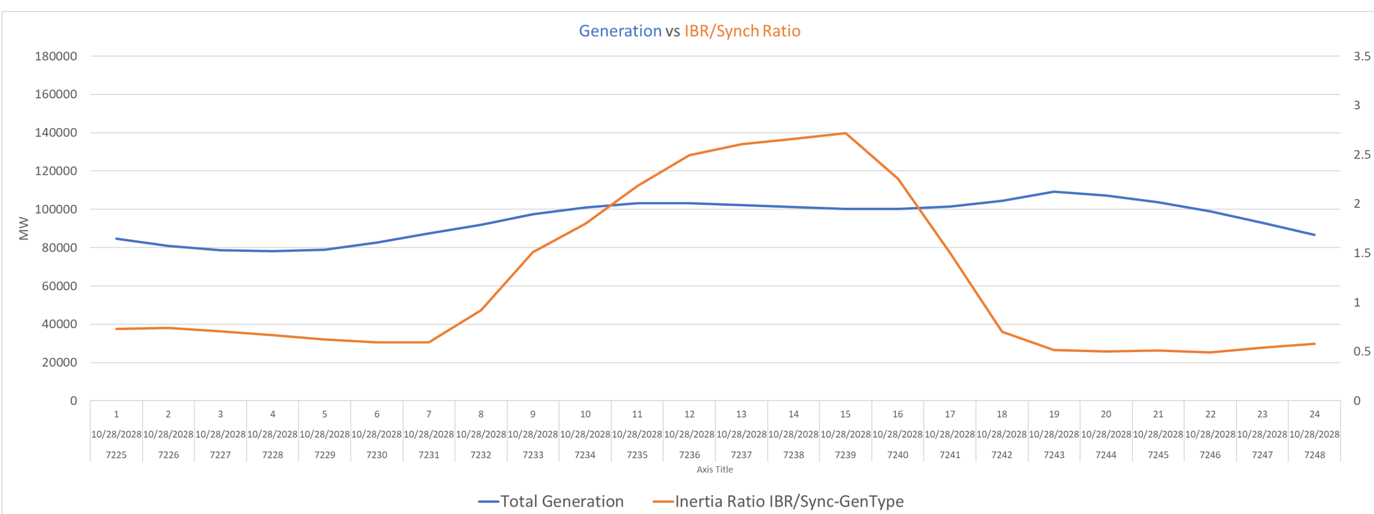
Figure 12 – Generation vs, IBR/Synch Ratio Hour 5198



- Hour 7239 (10-28-2028 hour 15)
  - Generation = 100,168 MW
  - IBR/Sync = 2.72

The hour shown in Figure 13 represents a high IBR/Synch ratio with lower total generation. This represents an hour where there is about 2.7 times as much IBR generation as synchronous machine generation.

Figure 13 – Generation vs. IBR/Synch Ratio Hour 7239



Hour 5198 was solved in PSLF as a power flow by exporting the generation and load tables out of the PCM, this included topology and dispatches for all generators and loads. Then the generation and load table information was implemented into the 2028 HS1 power flow (Phase 1) to create the SITF power flow (hour 5198). This process also accounted for any additional or removed generator or load that was made to the SITF PCM. The generation and load modifications were implemented in PSLF slowly using WECC tools to the 28HS1 power flow (Phase 1) case while maintaining a valid power flow solution until all modifications were made. Once all modifications were implemented and the case had a valid power flow solution, this new case became the SITF power flow case (hour 5198).

After the power flow case was created, the dynamic data was created for all the added resources through PSLF generic models, then added to the dynamic file. The dynamic information was then read into PSLF to start initializing the case. After the initialization issues were resolved, the case was ready to for dynamic runs. No-disturbance dynamic runs were initiated until the case ran a flat line no-disturbance run with no issues. After the case was clean and any erroneous data was resolved, it was then ready to run the WECC standard disturbances.

During hour 5198 (8-4-2028 hour 14), loads were scaled by 0.98 to account for the difference in calculated losses between GridView(PCM) and PSLF(PF).

Unfortunately, the power flow and dynamic and transient analysis for hour 7239 (10-28-2028 hour 15) was not completed during this study. However, it is mentioned as a recommendation for continued work.

Case Inertia

Inertia is measured in megawatt seconds (MW*s). The inertia for each case was calculated by the inertia constant (H) from each dynamic model multiplied by the megavolt-amperes (MVA) from each dynamic model. Figure 14 shows the inertia and MVA differences between the 2028 HS1 Phase 1 power flow and the SITF power flow case (hour 5198).

The Inertia in the SITF power flow (hour 5198, 8-4-2028 hour 14) case has about 62% of the Inertia in the 2028_ADSPhase1_V2.2 power flow and the MVA in the SITF power flow (hour 5198, 8-4-2028 hour 14) case has about 63% of the MVA in the 2028_ADSPhase1_V2.2 power flow case. This is primarily due to the fact that we retired the entire coal fleet and replaced those units almost exclusively by IBR, which does not provide inertia. Other contributors to this change in inertia are due to the nature of the cases. The Phase 1 case is a very heavy peak hour case which has more inertia providing thermal resources in the dispatch, versus the SITF case which is a lighter load mid-day august case that has fewer inertia providing thermal resources in the dispatch. Also, the mid-day high solar creates a reduced dispatch of these thermal resources that provide inertia, because the high solar is replacing these resources during the day. Thus, creating significantly lower inertia in the SITF case.

Figure 14 shows the amount of inertia and MVA from coal resources in the 2028 ADS Phase 1 V2.2 power flow case. Coal inertia in the Phase 1 case make up about 8% of the total inertia in the case and Coal MVA makes up about 10% of the total MVA in the case. All the coal was removed from the SITF case, hence no coal inertia or MVA in the SITF case.

Figure 14 – Inertia/MVA differences between cases

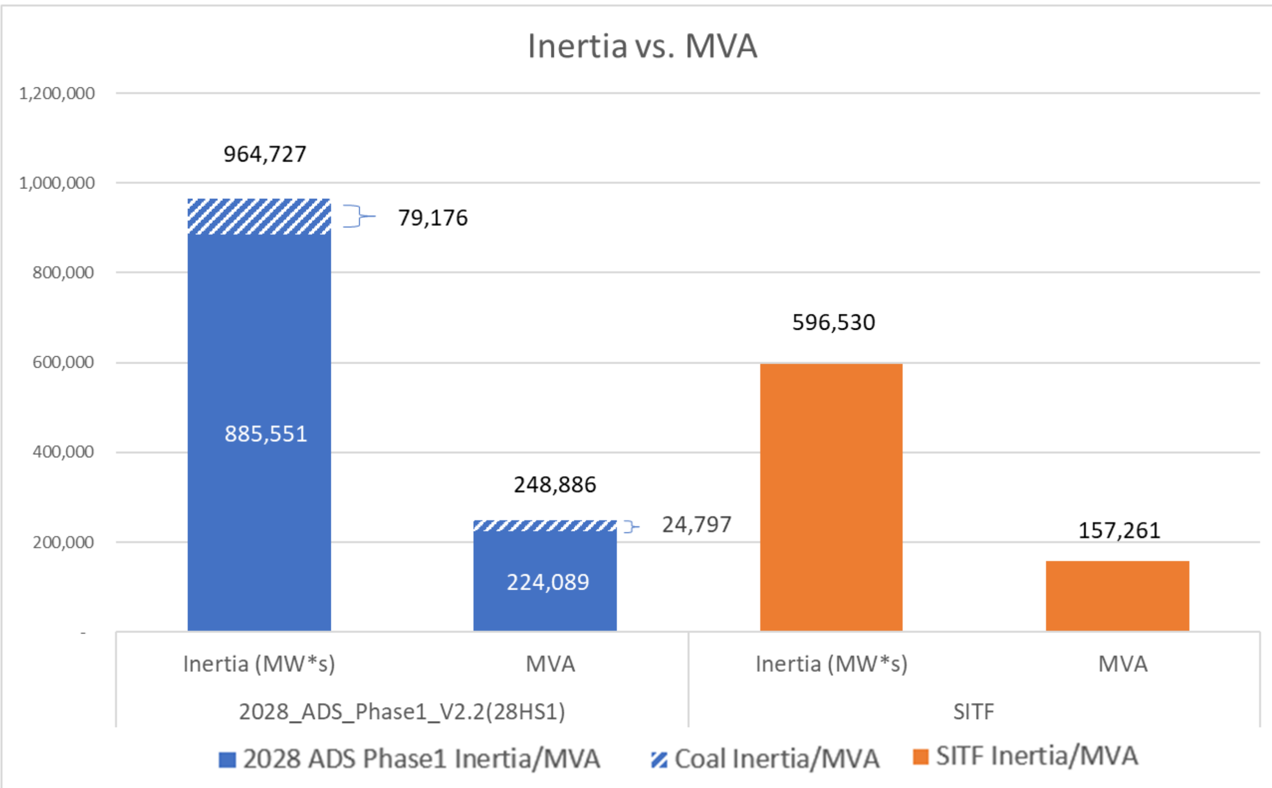
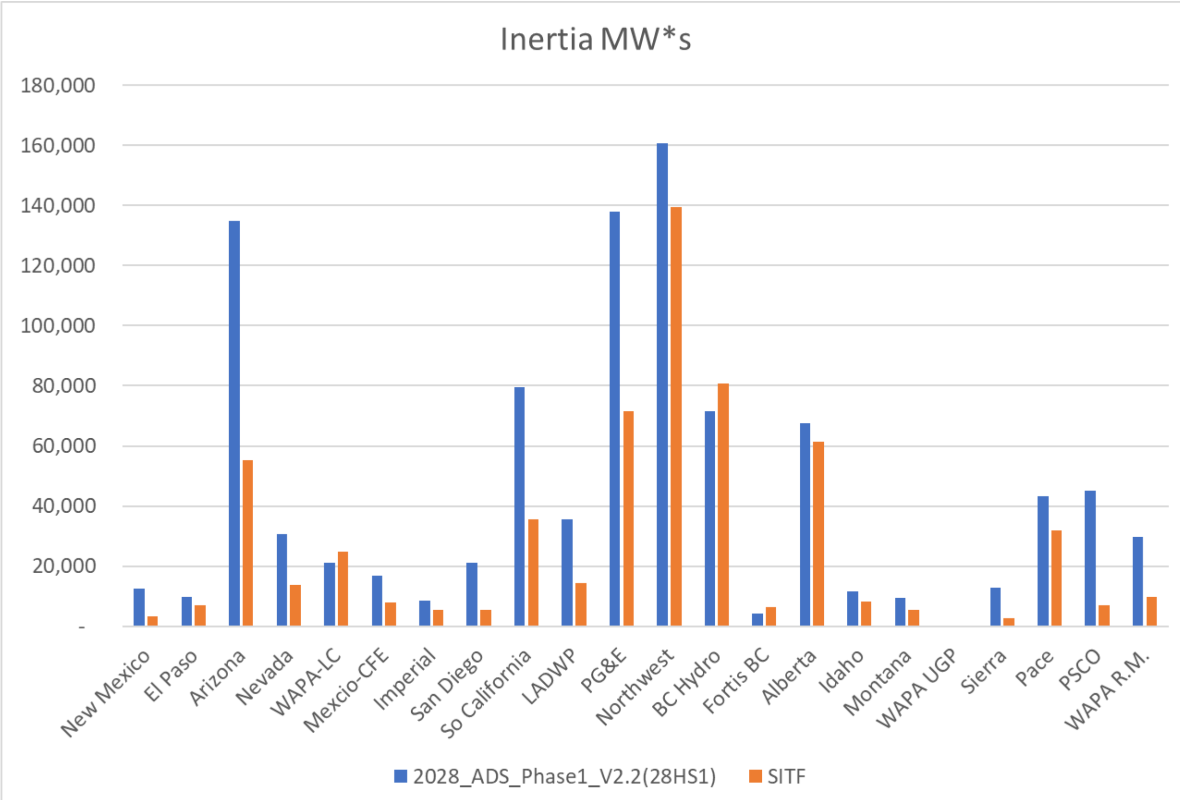


Figure 15 – Inertia differences by state



Other inertia differences are due to differences in the generation and load between the cases. The 2028 ADS Phase 1 case is a Heavy Summer case where all areas are peaking at the same time. The SITF case is an exported hour from the PCM where not all areas are peaking at the same time which would lead to a lower load. Fewer synchronous machines were dispatched in California in the SITF case because of these lower loads which explains the decreased inertia in California.

Dynamic and Transient Analysis

Dynamic simulations were run to observe the effects of decreased inertia on the system. One measure of system performance is frequency response after a system disturbance. There are standard disturbances that WECC uses with every base case [7]it compiles. This study used the same standard disturbances:

The WECC Standard Disturbances include the following:

- Chief Joseph Brake insertion
    - Insertion for 30 cycles, then removal of the large braking resistor in the Northwest

[7] Base Case – Please see Appendix B – Glossary.

- Double Palo Verde Outage
  - Simultaneous tripping of two Palo Verde generation units
- Colorado River-Red Bluff 500kV Line Outage
  - 3-phase fault with tripping of two transmission lines in Southern California
- Gates – Midway and Two Diablo – Midway 500kV Line Outage
  - 3-phase fault with tripping of three transmission lines in Northern California
- Brownlee – Hells Canyon 230kV Line Outage
  - 3-phase fault with tripping of one large transmission line in Idaho. This includes the approximation of an associated Remedial Action Scheme (RAS).
- Daniel Park – Comanche 345kV Line Outage
  - 3-phase fault, then tripping of two large transmission lines in Colorado
- Pacific DC Intertie (PDCI) 500kV DC Intertie Block
  - Simulates a block (removal of the lines from service) of the DC line from Celilo (in the Northwest) to Sylmar (in Southern California)

Since frequency is highly dependent on the balance between generation and load, we developed plots (figures 16 and 17) for the double Palo Verde outage disturbance. Differences in frequency response could also be observed in the other disturbances, but it was most pronounced in the double Palo Verde outage.

Figure 16 shows the frequency response at a major BES bus in the Pacific Northwest for a double Palo Verde outage disturbance simulation. The blue line represents the frequency observed at this bus in the 2028 ADS Phase 1 power Flow (28HS1). The orange line represents the frequency observed at this bus in the SITF power flow case (hour 5198). Figure 16 shows that frequency declines much more rapidly in the SITF case than in the Phase 1 power flow. The frequency nadir falls lower in the SITF case as well. We also notice that the frequency recovery is a little slower in the SITF case. However, both cases recover to a slightly off-nominal but stable frequency level with no shed load. According to the WECC Region frequency set points are generally as shown in Table 4:

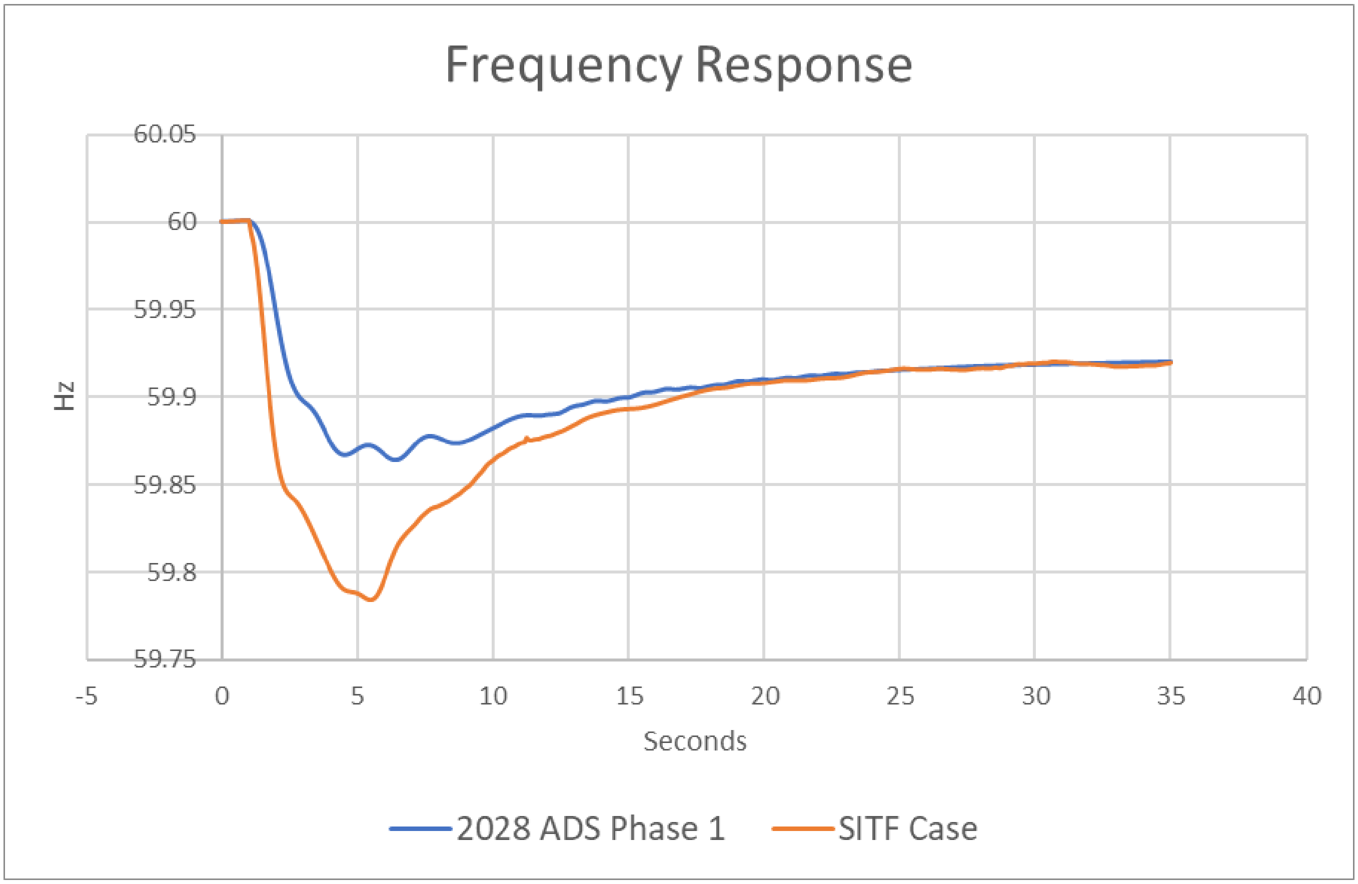
Table 4 – Frequency Load Shedding

Load Block Shedding	Frequency Set point
1	59.1
2	58.9
3	58.7
4	58.5

5	58.3

For more information on load shedding, please see the WECC Off-Nominal Frequency Load Shedding Plan[8]

Figure 156 – Frequency Response Major Bus



The F nadir is the lowest frequency at the bus. F delta is the difference between the pre disturbance frequency and the F nadir. F response is defined by how many MW of generation it takes to change the frequency by 0.1 Hz. The Rate of Change of Frequency (RoCoF)[9] as calculated here is how quickly the frequency declines during the first second of the disturbance.

We notice that the RoCoF is about four times greater in the SITF case which indicates that the frequency declines faster and drops farther in the SITF case than in the 2028 ADS Phase 1 power flow case.

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[8] WECC Off-Nominal Frequency Load Shedding Plan

[9] RoCoF – – Please see Appendix B – Glossary.

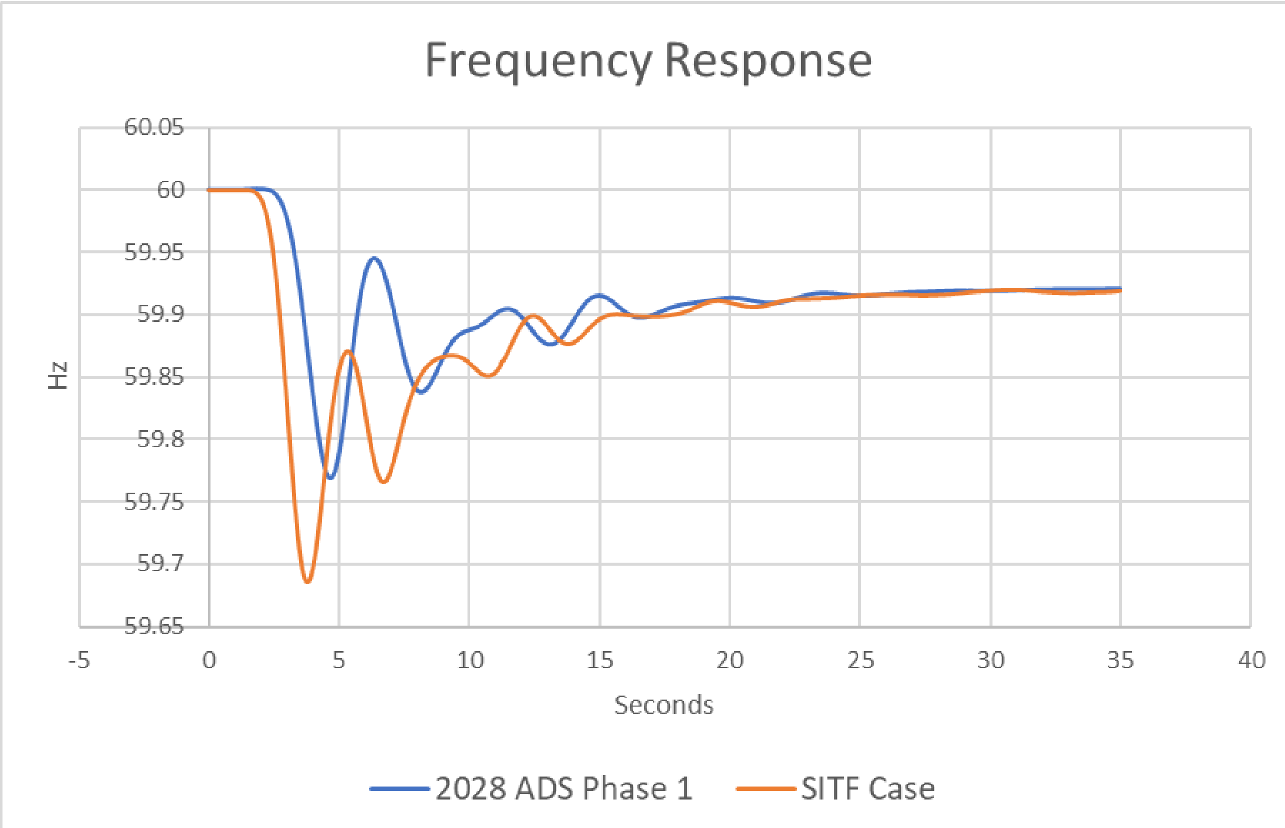
The F response in the SITF case is approximately half the size of the F response in the 2028 ADS Phase 1 power flow case. This means that if the same amount of generation is lost in each case, the F nadir in the SITF case would be nearly twice as low. This can also be observed in the F delta metric as shown in Table 5.

Table 5 – Frequency Metrics for Major Bus

Case	F nadir (Hz)	F Delta (Hz)	F Response (MW/0.1Hz)	RoCoF (Hz/Sec)
ADS Phase1	59.86461	0.136112	2018.335	-0.027
SITF (hour 5198)	59.78472	0.215878	1211.613	-0.11686

Figure 17 shows the frequency response at a generator terminal bus in Canada exhibiting the highest deviation for the double Palo Verde outage disturbance simulation. The blue line represents the frequency observed at this bus in the 2028 ADS Phase 1 power flow (28HS1). The orange line represents the frequency observed at this bus in the SITF power flow case (hour 5198). From figure 17, it can be seen that frequency declines much more rapidly in the SITF case than in the Phase 1 power flow. The frequency nadir (f nadir) falls lower in the SITF case as well. The frequency seems to recover about the same time for both cases and both cases recover to a slightly off-nominal but stable frequency level with no shed load.

Figure 17 – Frequency Response for Generator Terminal Bus



As shown in Table 6, the RoCoF is about two to three times bigger, not four times bigger as in the previous plot. This is due in part to the nature of the bus being observed, which is a generator terminal bus and the attached generator will try to resist frequency change whereas the previous plot did not have a connected generator to react to frequency change. Even though the generator helps prevent nearby frequency change, we still see that the frequency is much more effected in the SITF case.

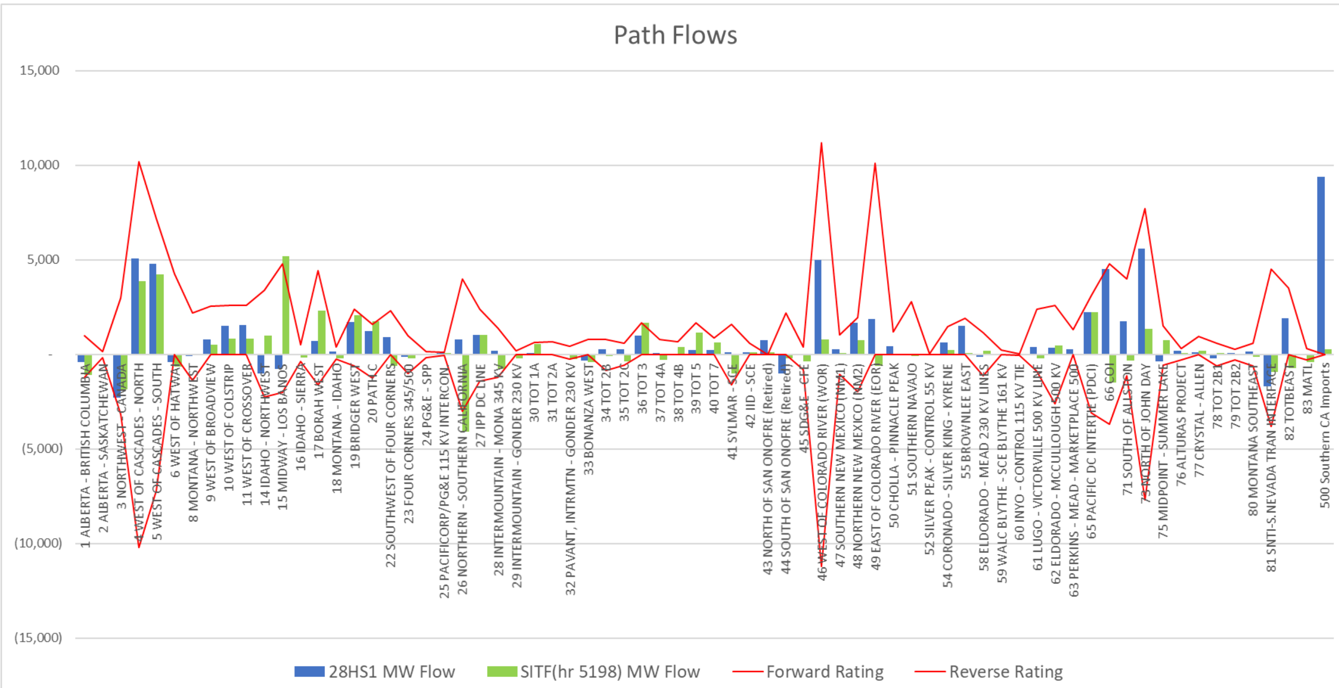
Table 6 – Frequency Metrics for Generator Terminal Bus

Case	F nadir (Hz)	F Delta (Hz)	F Response (MW/0.1Hz)	RoCoF (Hz/Sec)
ADS Phase1	59.76867	0.231941	1184.438	-0.00299
SITF (hour 5198)	59.68606	0.313927	833.1881	-0.00822

Path flow comparison between 2028HS1 (Phase1) vs SITF case hour 5198.

The chart below represents the existing WECC paths currently in service. The red lines are the forward and reverse Path ratings for each path. The blue bars are the path flows for the 2028 ADS Phase 1 V2.2 (28HS1) power flow and the green bars are the path flows for the SITF case (hour 5198) power flow.

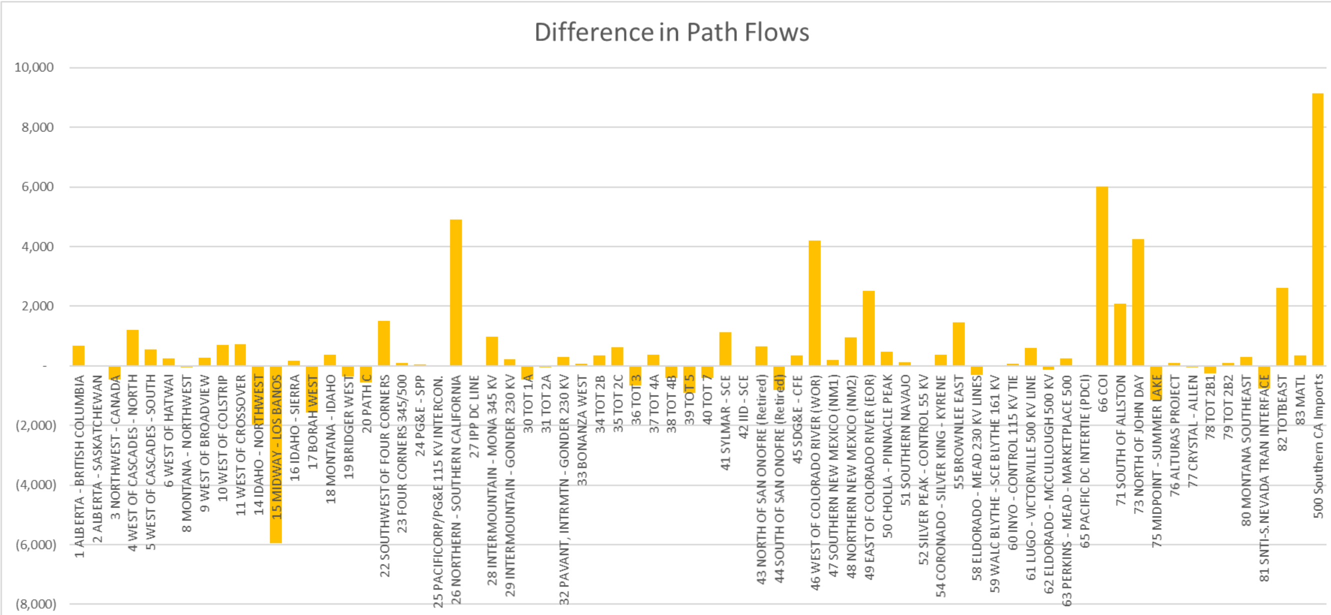
Figure 168 – Path Flows 2028 ADS vs. Hour 5198 Power Flow



The chart below shows the difference in path flows between the cases. The following path flows have the biggest differences between the cases:

- Path 500 – Southern CA Imports
- Path 66 – COI
- Path 15 – Midway – Los Banos
- Path 26 – Northern – Southern California
- Path 73 – North of John Day
- Path 46 – West of Colorado River (WOR)

Figure 1917 – Path Flow Differences ADS Case vs. Hour 5198



No outages were conducted in the power flow to determine reliability issues such as thermal overloads or post transient voltage performance due to absence of reactive support provided by synchronous machines with inertia.

Path flows may be directly related to the locational limitation of renewable resources placement. Further analysis may be needed.

The chart below represents Phase 3 paths that were part of the 2028 ADS base case. According to the Project Coordination, Path Rating and Progres Report Processes document "Phase 3 is the last part of the Path Rating Process. Phase 3 is a monitoring phase where major changes in assumptions and conditions are evaluated to assure the "Accepted Rating" is maintained. Phase 3 is completed when the Project is placed into service.[10]

[10] Project Coordination, Path Rating and Progres Report Processes

Figure 18 – Path Flows

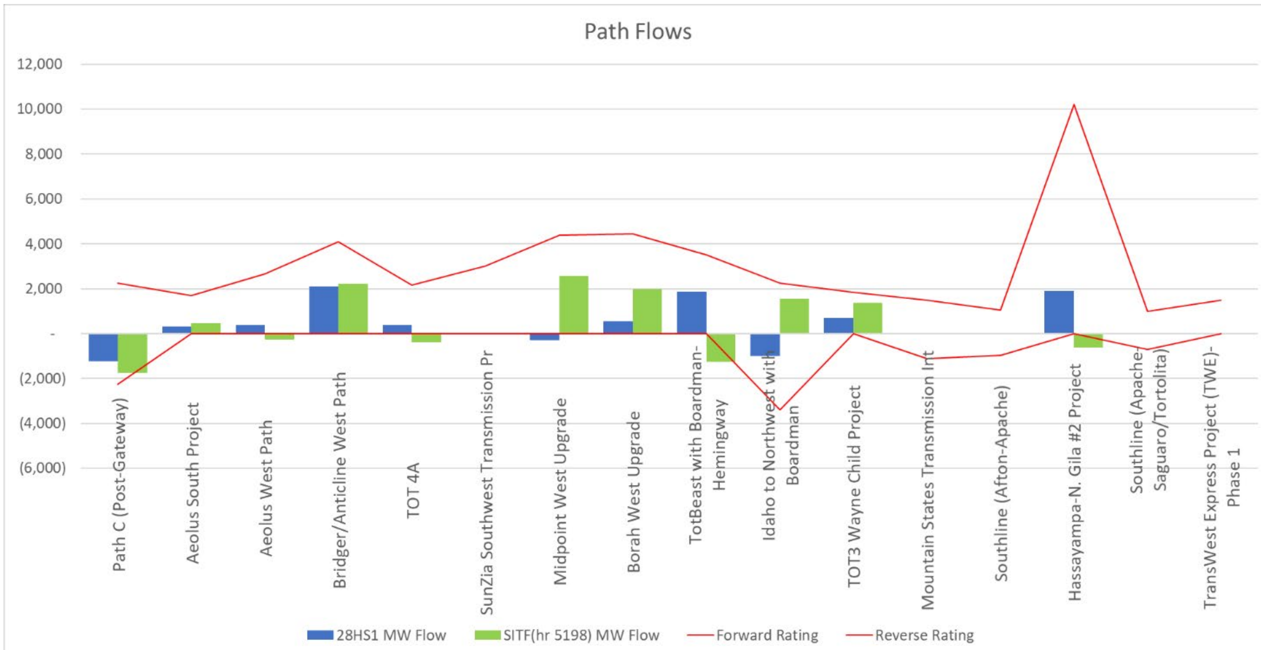
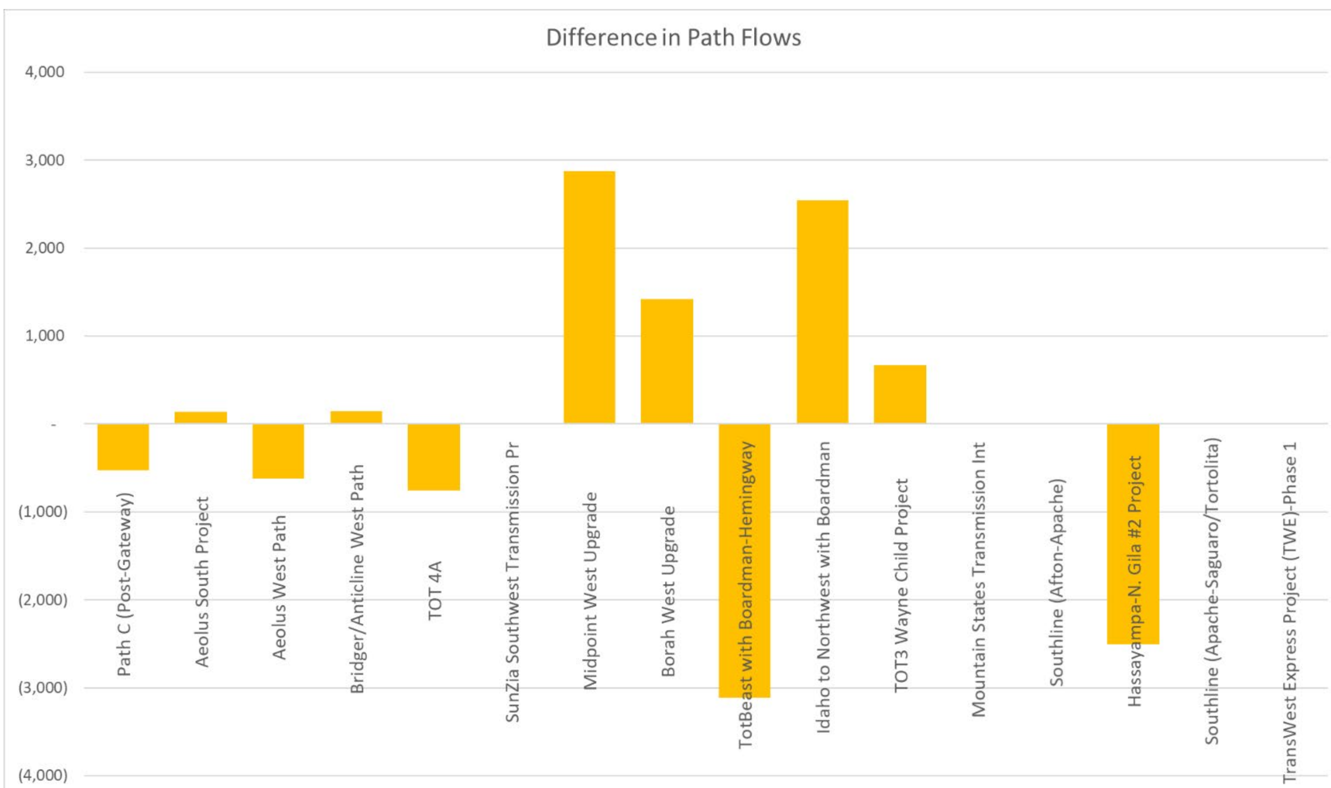


Figure 21 – Difference in Path Flows between the 2028HS1 and SITF Case (hour 5198)



Regarding the Phase 3 Paths, the following list shows the biggest path differences between the two cases.

- Path TotBeast with Boardman-Hemingway
- Path Midpoint West Upgrade
- Path Idaho to Northwest with Boardman
- Path Hassayampa-N. Gila #2 Project
- Path Borah West Upgrade
- Path TOT 4A

Figures 22 and 23 show the regional annual transfers for the 2028 ADS Ph 2 V2.0 PCM case and the SITF PCM case. In the SITF case, we see an increase in exports out of the Basin and Rocky Mountain regions and a decrease in imports into Southern California. The pink paths are the DC interties with the Eastern Interconnection, which were not modified.

Figure 192 – 2028 ADS Ph 2V2.0 Inter-regional transfers

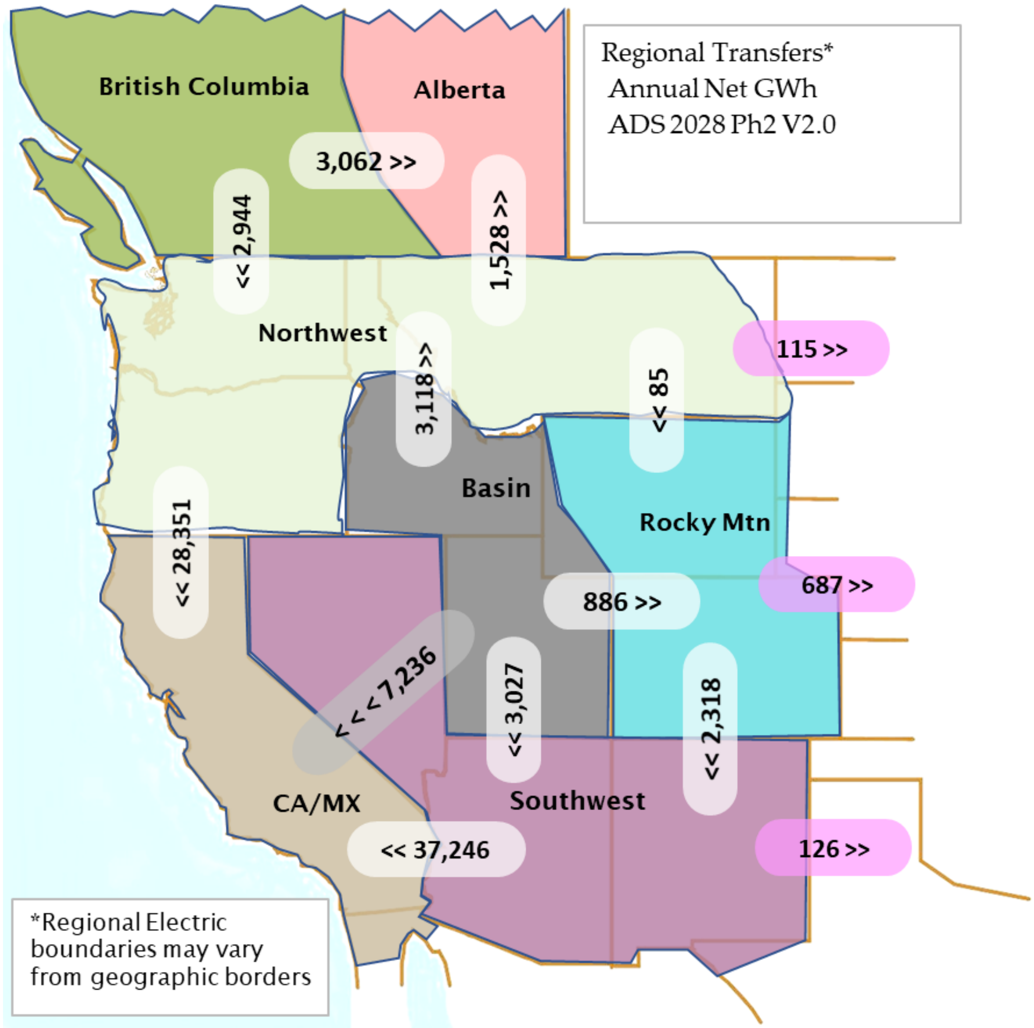
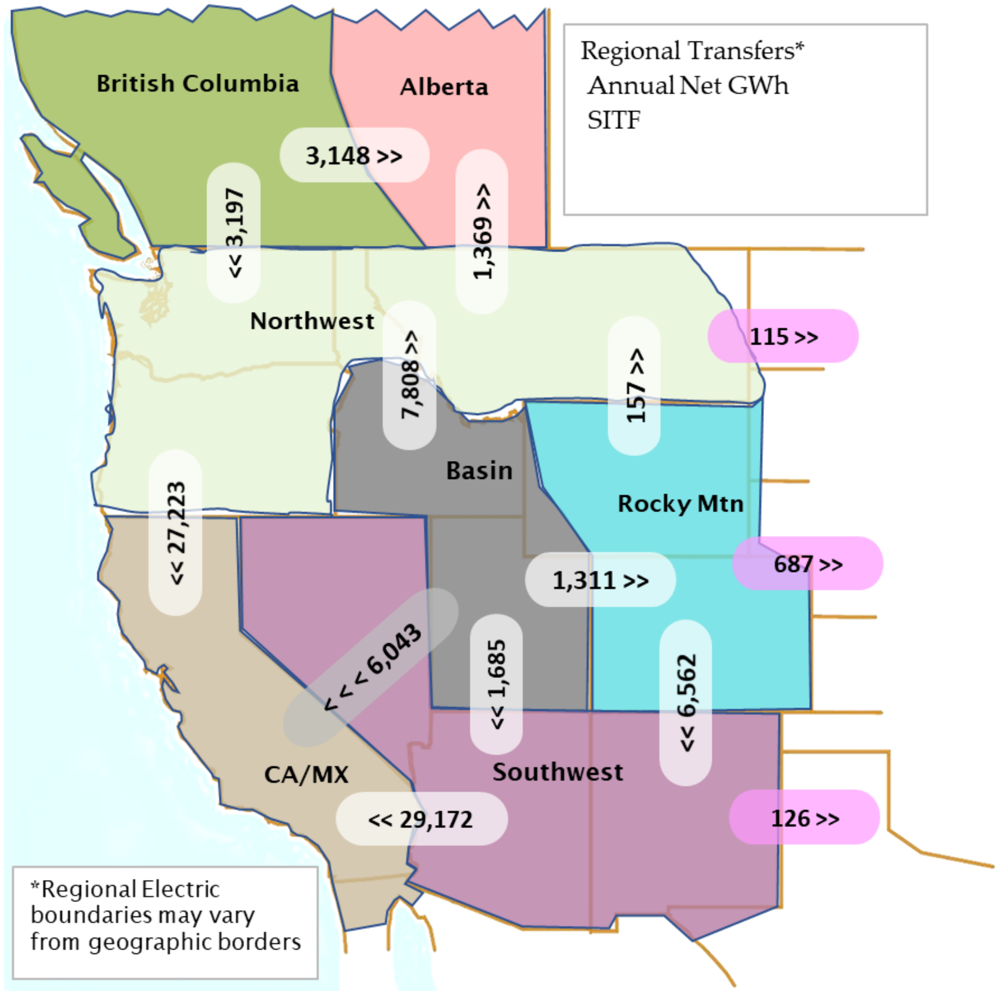


Figure 203 – SITF Inter-regional transfers



Fault Current

The team used Power World to complete a high-level fault current analysis on the SITF case. The solution compared the 2028HS1 ADS V2.2 (Phase1) power flow case to the SITF power flow case hour 5198 (8-4-2028 hour 14) to represent the differences in fault current with the decreased inertia. Fault current is only calculated using Positive Sequence in PowerWorld.

The reliability risk of decreased fault current is if the relay settings aren't adjusted for a lower fault current due to IBR in place of synchronous resources, the relays may not detect a fault on the system.

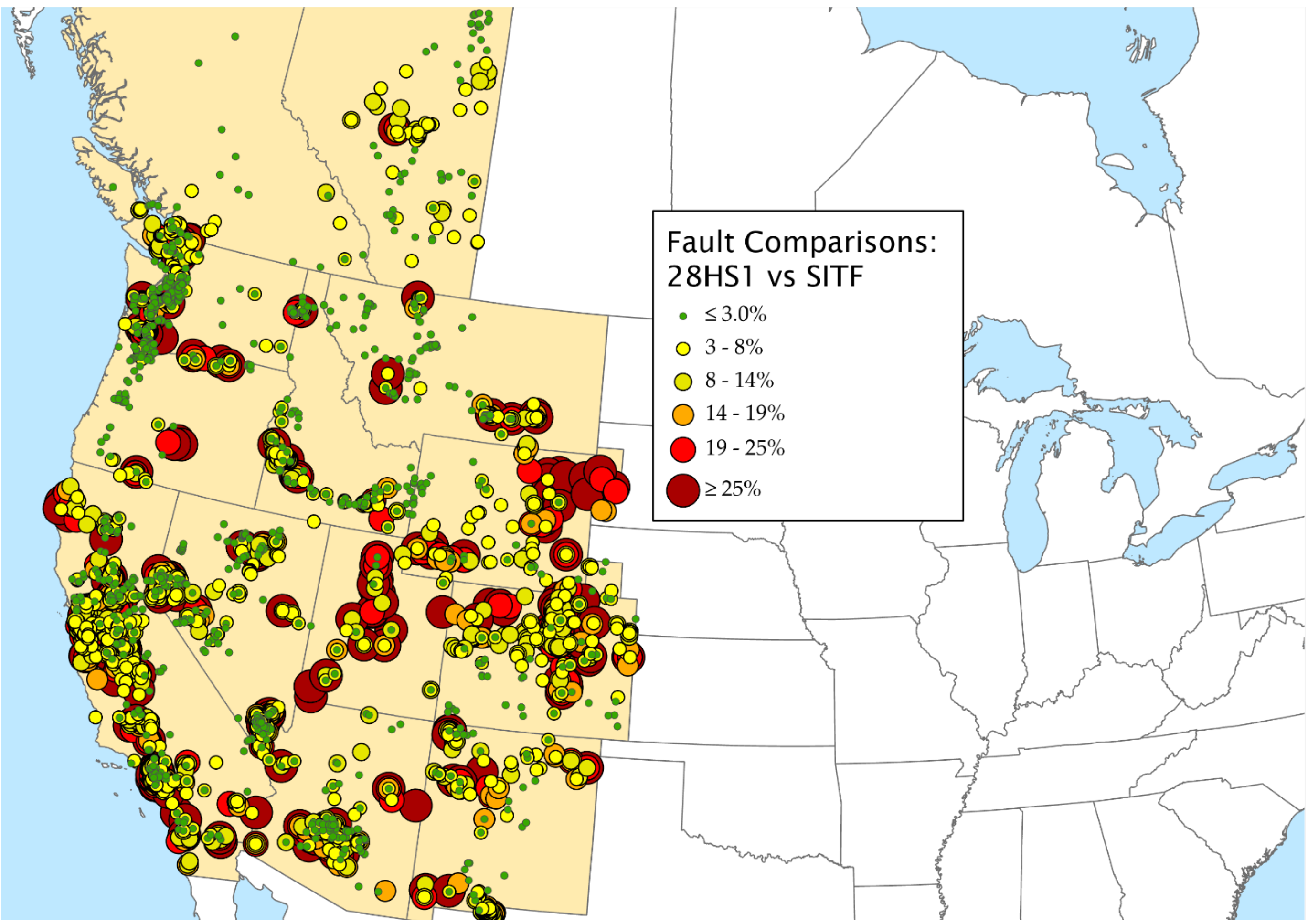
Figure 24 shows significant decreases in fault current in the areas where coal resources were removed in Arizona, Colorado, Montana, New Mexico, Utah and Wyoming. We also see decreased fault currents along the West Coast due to the generation and load differences between the cases. Fewer synchronous machines were dispatched in the SITF case, meaning not as much inertia was online along the West Coast in the SITF case (hour 598) due to the nature of the load levels at the time in the SITF case. As previously stated, the 2028 ADS Phase 1 case is a Heavy Summer case where all areas are peaking at the same time. On the other hand, the SITF case is an exported hour from the PCM in which all areas are *not* peaking at the same time.

Fault currents are usually represented as percentages to ensure proper protection during fault conditions. For example, if one removes several synchronous machines, one may need to decrease the relay current setting in an area to allow for correct relay operation during a fault with decreased fault current.

Figure 24 shows only decreasing fault current.

Note only about half of the busses used in the PowerWorld short circuit calculation have Geographic Information System (GIS) data.

Figure 24 – Fault Comparisons 2028 ADS vs. SITF Case



High-Level Capital Cost for Added Resources

The SITF assessment provided a system cost of the additional generation and energy storage units added to the SITF case to offset the coal generation. The capital cost information is based only on generation—no transmission costs are included even though minor radial transmission was added to the SITF case (i.e. collector system transformers) to interconnect the new IBR to the system.

The capital costs of the generation additions to the SITF case were calculated using the Independent Power Producer (IPP) pro forma in the WECC 2019 Generator Capital Cost Tool – With E3 Updates (WECC's capital cost calculator), as well as the data pertaining to the SITF case. The capital cost information was only calculated for added units with an installation year of 2023, signifying the value of money for this Capital Cost study will be in 2023 dollars.

In Figure 25, system cost ($) represents how much it would cost to build a 1 MW resource for each state. We notice that it is generally more expensive to build in California. We also notice that CAES is the most expensive, followed by Wind (WT)-Onshore, CC-Natural Gas, Solar-Tracking, Battery. However, this does not represent the efficiency of each resource type.

Figure 25 – System Cost for Capital Enhancements, $ - 1MW System

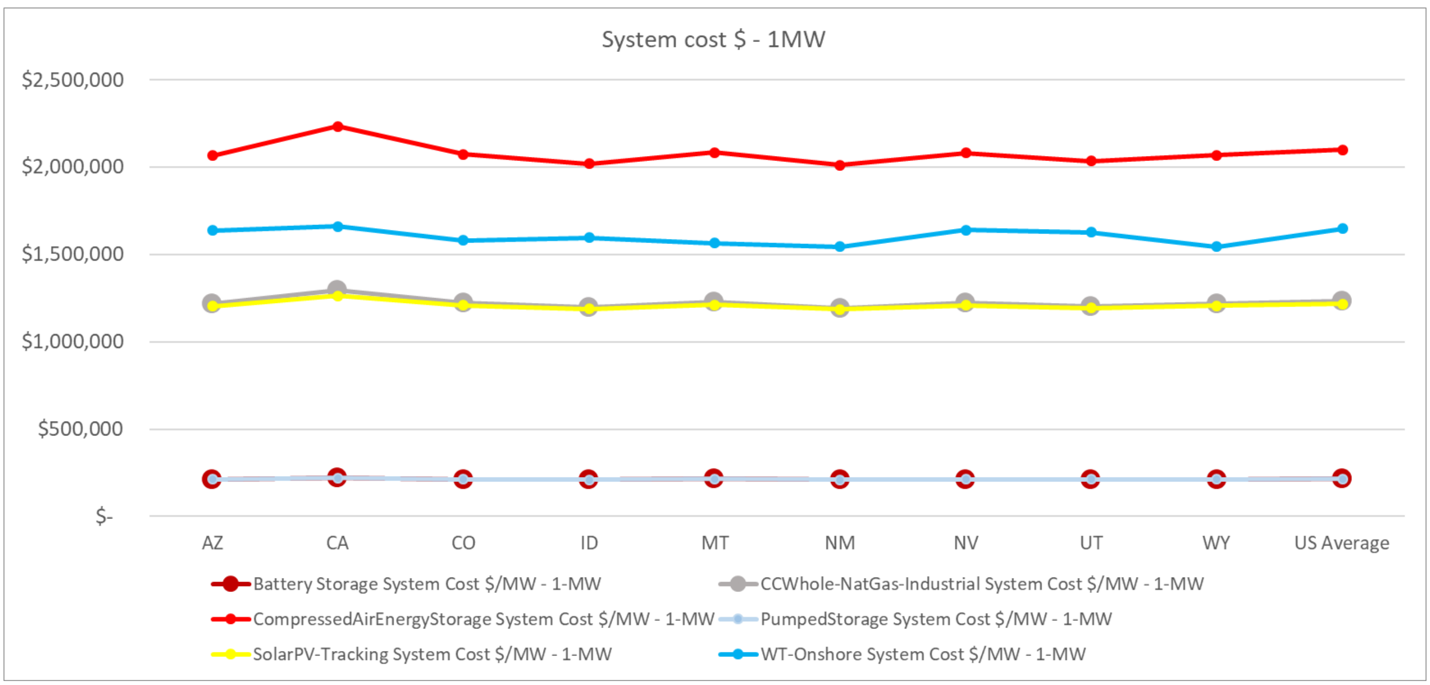


Figure 26 shows how much of each resource was added and where. This shows that a lot of wind additions were concentrated in the northeastern part of the Western Interconnection and solar additions concentrated in the southeastern part.

Figure 26 – SITF Case Resource Additions in MW by State

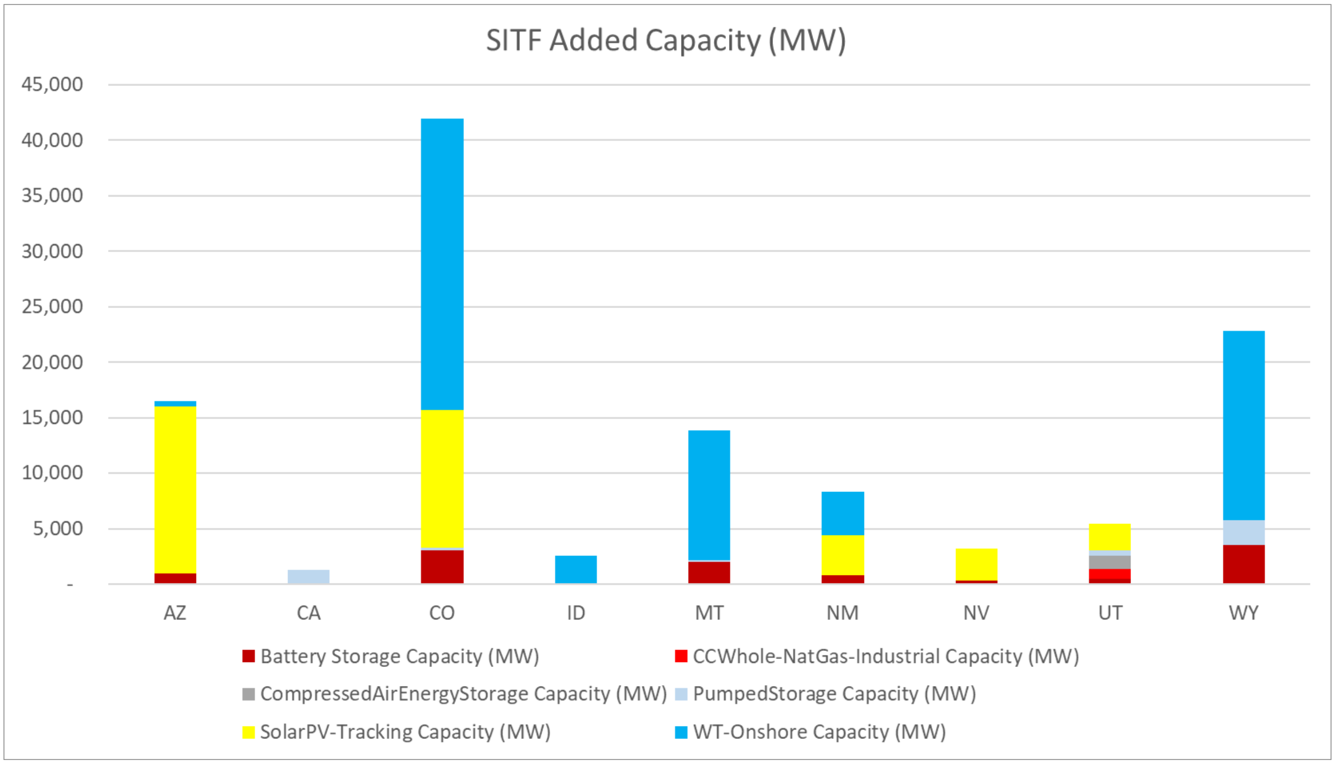
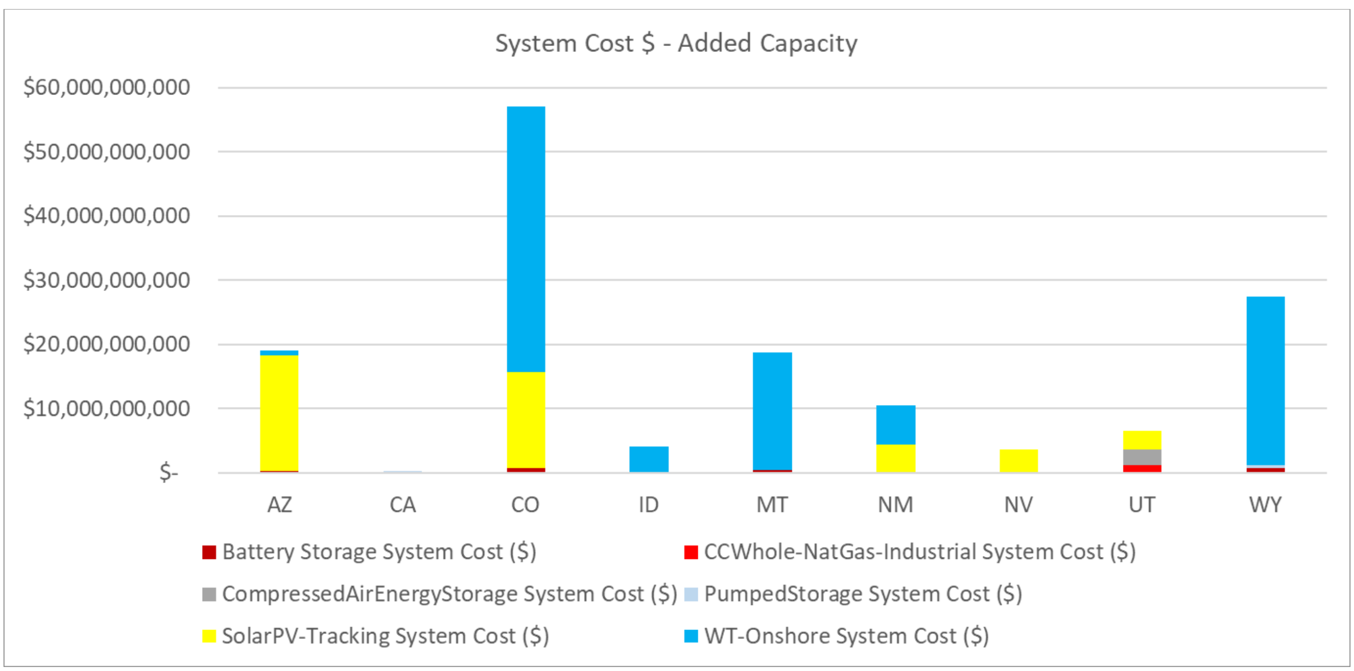
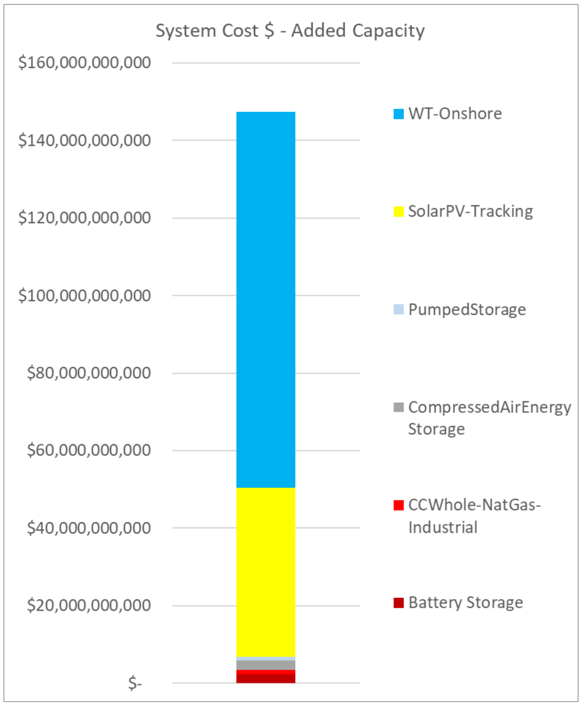


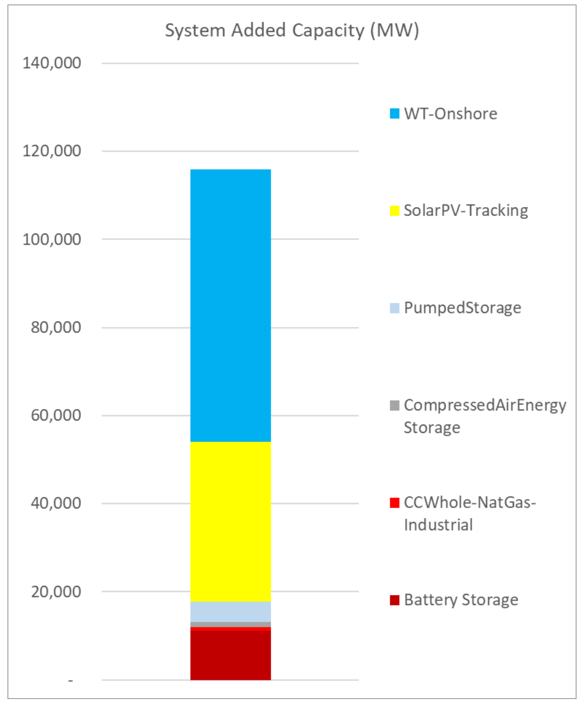
Figure 217 – Capital Costs of SITF Case Resource Additions



The system cost for capital additions of all 115,840 MW of added resources at the given capacities with an installation year of 2023 is about $147,418,088,000 based on the Independent Power Producer ((IPP) proforma Generation Capital Cost Calculator in the WECC 2019 Generator Capital Cost Tool – With E3 Updates. Figure 28 shows the breakdown is as follows:

Figure 28 – SITF Case Capital Costs and Capacity Additions





Totals: $147,418,088,000 115,840 MW

Levelized Fixed Cost $/kW-yr

Levelized Fixed Cost (LFC) represents an average payment required to pay off the capital costs over the resources lifetime. LFC does not include the reliability value of the plant, efficiency, or economic life of the plant, but relates only to the cost to pay for the plant.

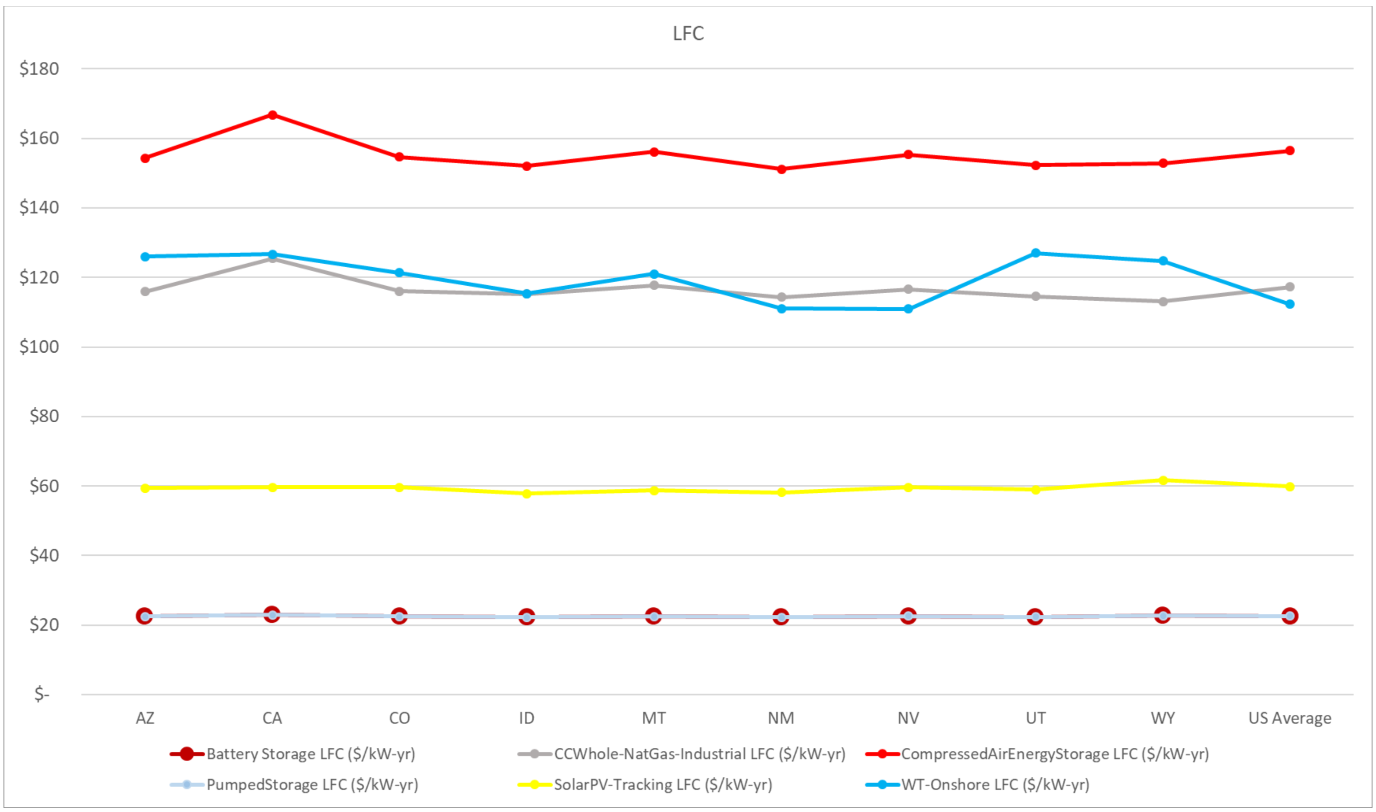
The following lifetimes according to the Independent Power Producer ((IPP) proforma Generation Capital Cost Calculator in the WECC 2019 Generator Capital Cost Tool – With E3 Updates are as follows:

Table 7 – Resource Lifetime

Resource	Lifetime (years)
Battery Storage	20
Gas	20
CAES	35
Pumped Storage	20
SolarPV-Tracking	35
WT-Onshore	25

Please note, the graph below shows the LFCs according to the lifetimes in the table above and the LFCs are not normalized to common lifetime. This means that some resources may appear more/less expensive in the chart below because the lifetimes are different.

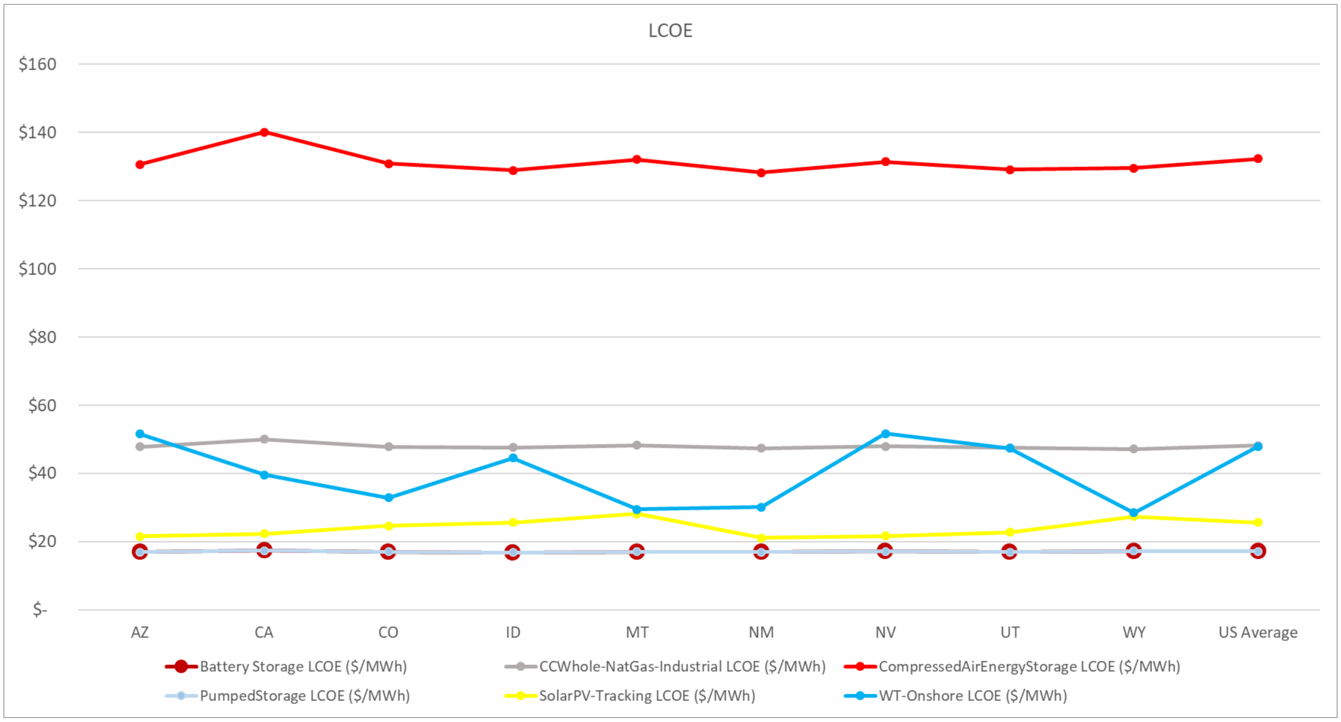
Figure 29 – LFC for Added Resources



Levelized Cost of Energy $/MWh

Levelized Cost of Energy (LCOE) represents the energy price output needed to recuperate the cost of the plant over its estimated lifetime. For instance, according to the chart below, SolarPV-Tracking would need an estimated LCOE of about $21 to break even for the cost of building the solar plant.

Figure 30 – LCOE for Added Resources



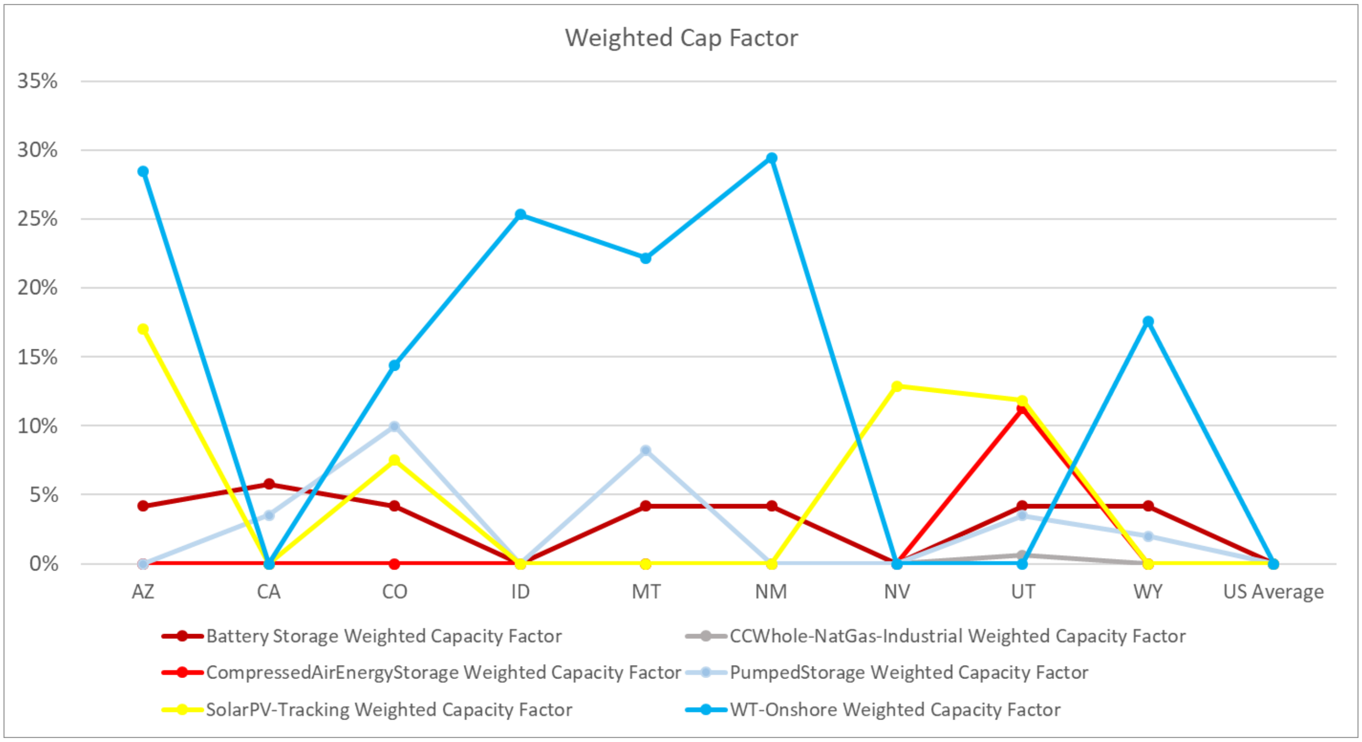
Weighted Capacity Factor

Since the Capacity Factor is the ratio of actual energy produced over a given time period divided by the theoretical maximum amount of energy output over that given time period that the machine could produce. The weighted capacity factor (WCF) is represented by

WCF = (Capacity*CapFactor)/(TotalCapacity).

This only relates to units that were added to the case. For example, the capacity factor for wind in California, Nevada, and Utah is 0, because no wind was added to those states.

Figure 221 – Weighted Capacity Factor for Added Resources



4. Assumptions

Station Service Load: NERC, FERC and WECC define load as power plant net metered generator output to the interconnected grid, plus metered net imports. Hence, station service 'load' is not included in the load forecast data and is not included in the base load data prepared for the PCM. Consequently, the power plant output calculated by the PCM understates thermal-based power generation. This understatement is ignored in the SITF cases as it is considered inconsequential to the study results.

Alberta Dispatch: The PCM generally dispatches thermal generation based on minimum-cost calculations. However, for Alberta, Canada, some thermal generation is dispatched based on pre-defined schedules. This Alberta dispatch process, which is common in WECC's long-term planning cases, was not changed for the SITF cases.

Load Netting: Both the PCM and the power flow program allow for a load-netting of generation. This load-netting removes the generator and an equivalent amount of load from the input data set. To a minor extent, the load netting of existing generation is widespread throughout the Western Interconnection but is generally not found in PCM future generation modeling. However, Alberta's future generation modeling incorporates several hundred megawatts of such netted load while southern Idaho modeling incorporates several hundred megawatts of netted load associated with existing renewables generation. Outside of Alberta, and southern Idaho, the load netting is insignificant. It is presumed that the Alberta and southern Idaho load netting is inconsequential for the SITF cases.

Load Scaling: The team scaled the load to account for the difference in losses between the PCM and the PF. The PF load was scaled to 98% of the PCM load.

Additional Resource Placements: The additional resources for the SITF case were represented as equivalenced/aggregated units on specific high-side buses in the PCM. In the power flow, the added resources were moved from the specific high side bus to a low side bus with a "collector system" in between. The "collector system" consisted of two step-down transformers.

Figure 32 – Collector System Example

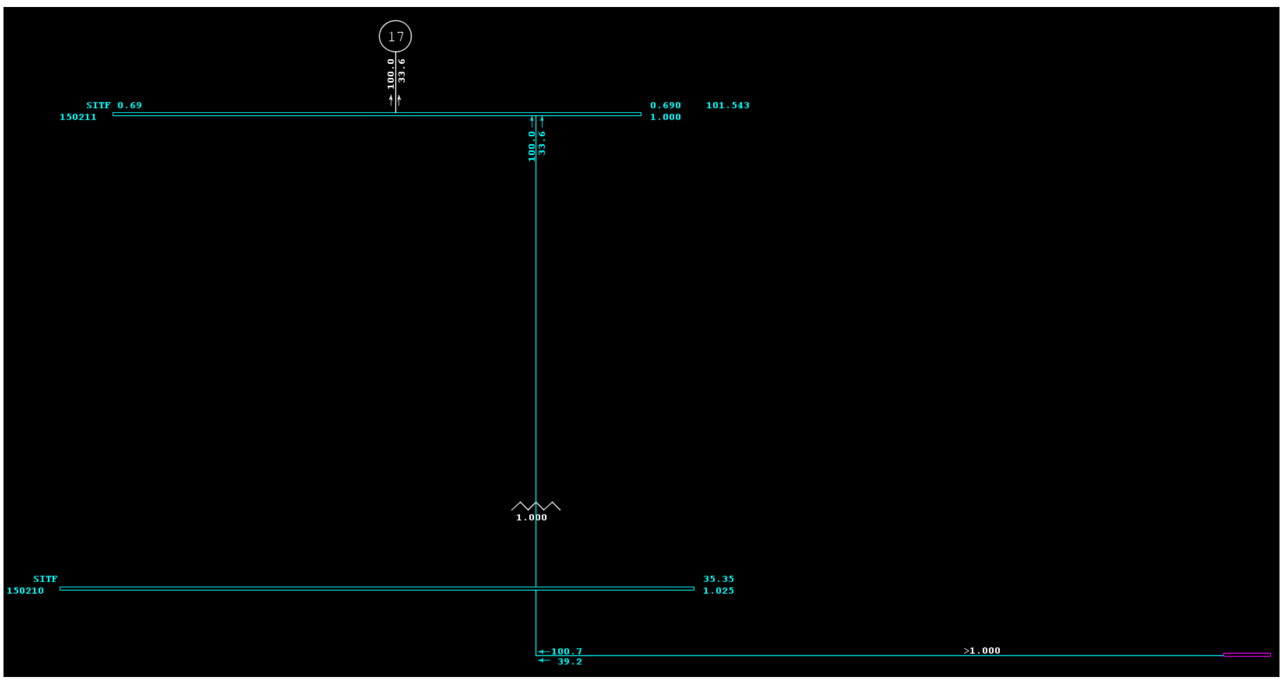
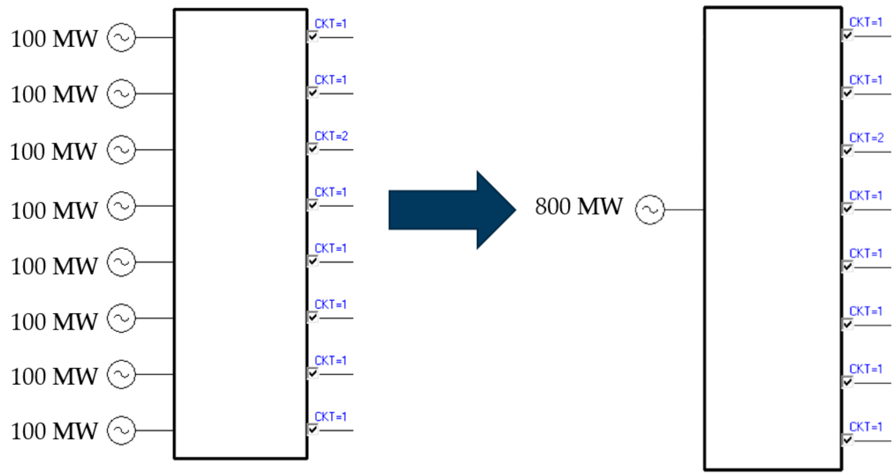


Figure 23 – Equivalenced/Aggregation Example



5. Observations and Conclusions

The following observations were made for this study. Note, this is not an all-inclusive study for all hours or conditions:

- It took about six times the MW in IBR to replace coal MW for our study due to the lower capacity factors and time of day dependencies for replacement resources.
- By changing the resource mix and locations, path flows may change to the point to cause critical contingencies to change. As a result, these contingencies may need to be reevaluated to more localized contingencies.
- By replacing synchronous machines with IBR, system inertia decreases. In an event of loss of resources, this causes frequency to decline faster, drop lower and recover more slowly. This may become a reliability concern if the frequency drops into the Under-Frequency Load Shedding (UFLS) region. However, for the disturbances and scenario that were run in this study for the summer power flow (hour 5198), the system did not collapse and there was no load shed. Study results are based on frequency response analysis, voltage performance analysis was not conducted for this study.
- Adding the resources that we did totaled 115,840 MW and cost $147,418,088,000. This capital cost does not include plant retirement cost, any transmission improvements or new transmission necessary to transmit the newly added IBR.
- With all coal resources retired, a significant decrease in fault current is observed which may require updated relay settings to reliably detect faults on the system.

6. Recommendations

Based on the assessment, the SITF recommends:

- Update all Short Circuit Model busses with GIS data to represent the system more fully on the map plot;
- Complete additional short circuit analyses in CAPE/Aspen where one case has all coal removed and the other includes coal to include zero and negative sequence;
- Complete autumn power flow and dynamic analyses; The results included in this report are for the selected summer case;
- Evaluate dynamic stability where frequency response and voltage regulation capability is enabled for all added IBR or all IBR (Since this study did not enable frequency response and voltage regulation capability for the added IBR).;
- Evaluate the differences in Path flow loading and run contingencies on related loaded paths;
- Analyze in greater depth the impact that the addition of energy storage (Batteries/CAES) has on reliability;
- Evaluate possible mitigations for path overloads; and
- Optimize the system for the best mix of energy storage and renewables.

7. Appendix A – SITF Membership

Table 8 – List of SITF Membership

Name	Affiliation	Membership
Afranji, Frank	Northwest Power Pool	Member
Aggarwal, Ravi	BPA	Member
Austin, Jamie	PacifiCorp	Member
Baklou, Hassan	SDG&E	Member
Basrai, Simrit	PG&E	Member
Black, Shannon	WECC	Member
Bolton, Kent	WECC	WECC Staff Liaison
Bond-Simpson, Angela	SRP	Member
Carr, Thomas	Western Interstate Energy Board	Member
Chakraborty, Tamojit	Mitsubishi	Member

Cichosz, Jonathan	PGE	Member
Ciniglio, Orlando	Idaho Power	Member
Cooper, Tyler	Black Hills Corporation	Member
Corral, Christopher	El Paso Electric	Member
Cramer, Taylor	Mitsubishi	Member
Delgado, Andres	Idaho Power	Member
Duncan, Camille	WECC	Member
Feltes, Jim	Siemens	Member
Freeman, Bryce	Wyoming Consumer Advocate	Member
Gearhart, Roy	WAPA	Member
Ghoudjehbaklou, Hassan	SDG&E	Member
Haagenson, Tessa	City of Burbank, CA	Member
Haralson, David	WECC	Member
Heutte, Fred	Northwest Energy Coalition	Member
Hosie, Bill	DATC	Member
Jensen, Jon	WECC	WECC Staff Liaison
Kara, Robyn	PacifiCorp	Member
Kosterev, Dmitry	BPA	Member
Le, David	CAISO	Member
Liu, Frank	PG&E	Member
Mackin, Peter	GridBright	Member
Miller, Mitchell	SRP	Member
Mitchell, Sarah	WECC	Member
Nansel, Gayle	WAPA	Member
Negash, Ahlmahz	City of Tacoma, WA	Member
Olson, Erik	PSE	Member
Rai, Dipendra	BC Hydro	Member

Ramasubramanian, Deepak	EPRI	Member
Reedy, Karen	PNM	Member
Reynolds, Michael	SRP	Member
Schmitt, Andreas	BPA	Member
Shah, Rikin	PacifiCorp	SITF Chair
Shao, Shengnan	PG&E	Member
Shenoi, Kavita	Siemens	Member
Simons, Dick	WECC	WECC Staff Liaison
Spacek, April	Avista	Member
Stringer, Brian	WAPA	Member
Tang, Eric	SRP	Member
Tesema, Berhanu	BPA	Member
Thornton, Jameson	PG&E	Member
Toppo, Shilpa	Mitsubishi	Member
Valdepena Delgado, Andres	Idaho Power	Member
Wyman, Jeff	ITC	Member
Xiong, Lei	AESO	Member
Xu, Xiaofei (Sophie)	PG&E	Member
Zargaryan, Hayk	SCE	Member
Zewe, Janice	SMUD	Member
Zhang, Wenjuan (Wendy)	PG&E	Member

8. Appendix B – Glossary

Table 9 – Glossary of terms

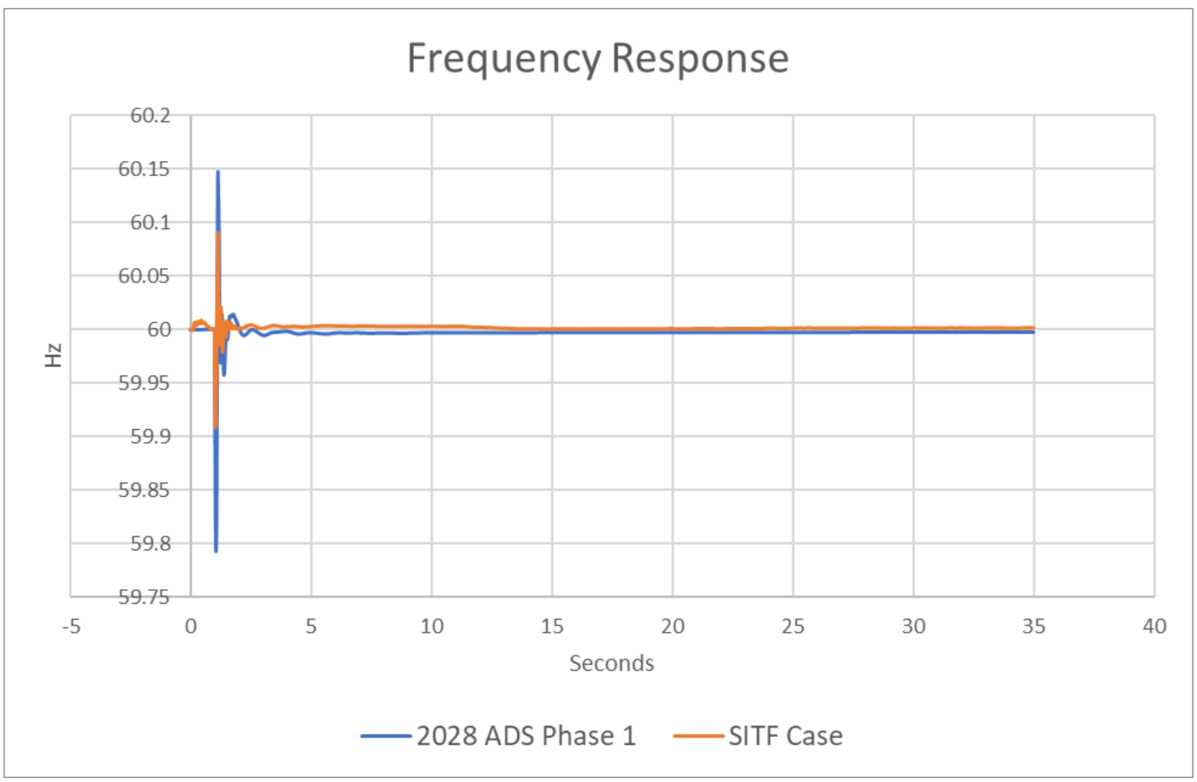
Term	Definition
2028_ADS_Phase1_V2.2	Phase 1 of the Anchor Data Set (ADS)
2028_ADS_Phase1_V2.2 – PowerFlow	2028HS1 base case (Year 2028 Heavy Summer 1 Case)
2028_ADS_Phase2_V2.0	Phase 2 of the Anchor Data Set (ADS) – PCM only for this assessment
2028_ADS_Phase1_V2.2 – PCM	PCM used for the 2028_ADS_Phase1_V2.2
Base case	A power flow case built by the WECC Compilation schedule (generation and load levels defined by a description, which are usually heavy or light loads to stress the system)
Frequency Nadir	Frequency Nadir measures the minimum post contingency frequency
GridView	A Production Cost Model simulates the least cost dispatch of generation to meet loads for every hour for the forecasted year 2028
PCM – Production Cost Model	A Production Cost Model simulates the least cost dispatch of generation to meet loads for every hour for the forecasted time period. For this assessment, we modeled the forecasted year of 2028. (DC only model)
Pmax	Refers to a value similar to a nameplate rating
Power flow (PF)	A model simulates a snapshot in time with whatever user input is defined in the model (AC/DC model).
PSLF	Positive Sequence Load Flow, power flow software

RoCoF	Rate of Change of Frequency is a measure of how fast the frequency declines
SITF case	The case that was created for the "Changes to System Inertia with High Renewable Implementation" assessment
SITF - PCM	PCM case representing the SITF assumptions
SITF (hour 5198)	A power flow case representing hour 5198 (8-4-2028 hour 14) from the SITF PCM
SITF (hour 7239)	A power flow case representing hour 7239 (10-28-2028 hour 15) from the SITF PCM

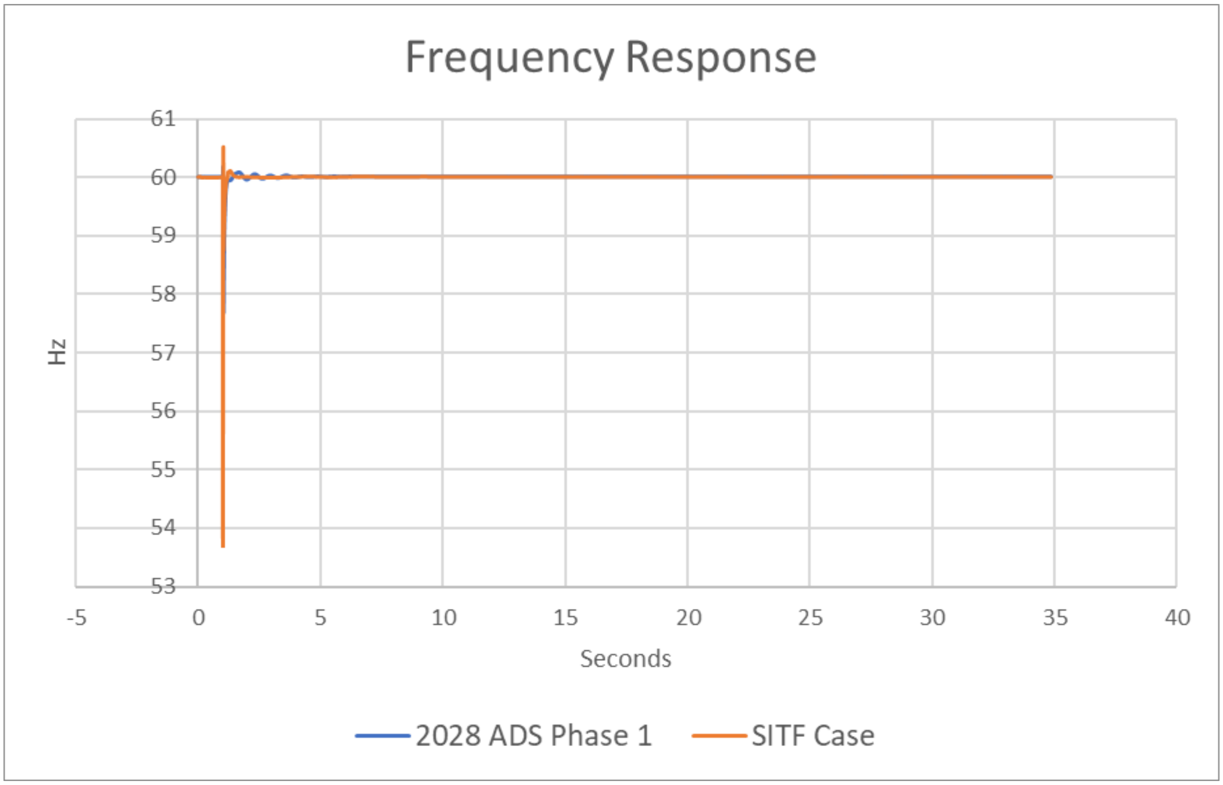
9. Appendix C – Additional Plots

Below are some additional dynamics plots showing the frequency response of the bus with the largest frequency deviation.

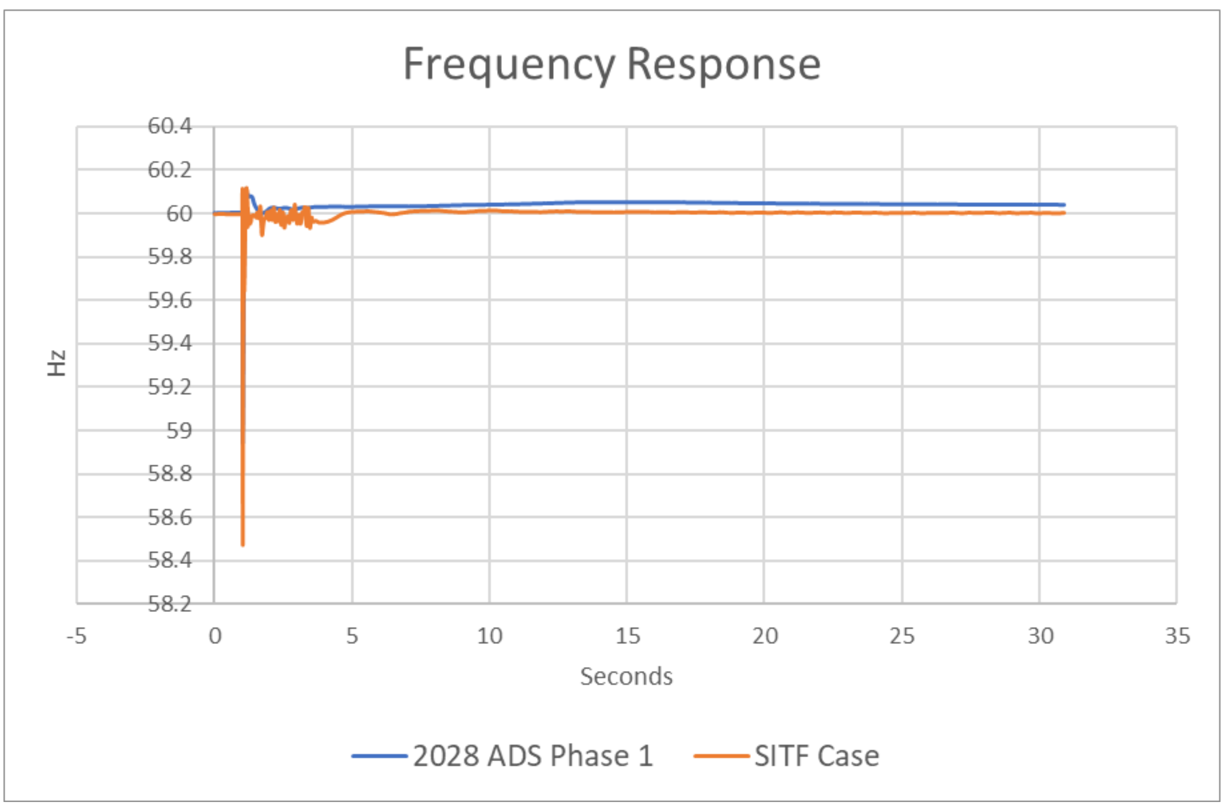
Brownlee – Hells Canyon 230kV Line Outage:



Colorado River-Red Bluff 500kV Line Outage:



Gates – Midway and Two Diablo – Midway 500kV Line Outage:



Chief Joseph Brake insertion: