H

2017 PSE Integrated Resource Plan

Operational Flexibility

This appendix summarizes the operational flexibility study performed for PSE by E3 Consulting for the 2017 IRP.

Contents

1. OVERVIEW

A wide variety of conditions place demands on system flexibility. These include load fluctuations, integration of intermittent resources like wind, Balancing Authority obligations to integrate scheduled interchanges and unexpected events like forced outages. Balancing Authorities also require flexibility for maintaining contingency reserves to assist other balancing authorities that may have sudden needs for assistance in balancing loads.

This 2017 IRP analysis examines the issue of operational flexibility, specifically looking at the ability of PSE resources to balance load and variable energy resources such as wind on a sub-hourly basis. This analysis simulates the dispatch of PSE's existing portfolio in five-minute intervals using a two-stage production simulation model. It also compares how the portfolio's sub-hourly dispatch changes when potential new gas or storage resources are added.

The appendix is divided into five sections.

SYSTEM BALANCING discusses the role of balancing capacity, the Control Performance Standard 2 (CPS2) metric used to gauge PSE's ability to reliably balance the system and how PSE defines variability and uncertainty as they relate to balancing.

FLEXIBILITY SUPPLY AND DEMAND covers how PSE evaluates the availability of balancing capacity from PSE resources in light of the demands placed on the system for that capacity and discusses how that capacity is procured and deployed.

MODELING METHODOLOGY reviews the two models used to assess how PSE will meet its balancing obligations in 2018. The first model determines how to best set aside balancing reserves prior to an operating hour; the second simulates deployment of those reserves at 5-minute intervals.

Finally, we present the analysis **RESULTS** and offer a **CONCLUSION AND NEXT STEPS**.

In addition to the current PSE portfolio, the analysis considered the independent addition of eight different gas-fired resources, as well as five storage resource configurations.

The results of this work indicate that, at PSE's current level of load and wind balancing needs, the current portfolio's existing resources are able to balance sub-hourly changes in load with only small and infrequent challenges. Adding the new resources to the simulation typically lowers the total system dispatch cost on an hourly basis. In addition, the new resources provide incremental sub-hourly cost savings related specifically to 5-minute dispatch (incremental to hourly savings) ranging from $200,000 to $900,000 per year, depending on the resource evaluated. Most of the flexible new resources considered create small reductions in the amount of sub-hourly flexibility challenges, but the relative differences are small due to the already low level of issues identified with the current portfolio. It is possible that if PSE assumed responsibility for balancing more wind resources, the sub-hourly flexibility issues could become more challenging.

2. SYSTEM BALANCING

The PSE Balancing Authority

A Balancing Authority (BA) is an entity that manages generation, transmission and load; it maintains load-interchange-generation balance within a geographic or electrically interconnected Balancing Authority Area (BAA), and it supports frequency in real time. The responsibility of the PSE Balancing Authority is to maintain frequency on its system and support frequency on the greater interconnection. To accomplish this, the PSE BA must balance load with generation on the system at all times. When load is greater than generation, a negative frequency error occurs. When generation is greater than load, a positive frequency error occurs. Small positive or negative frequency deviations are acceptable and occur commonly during the course of normal operations, but moderate to high deviations require corrective action by the BA. Large frequency deviations can severely damage electrical generating equipment and ultimately result in large-scale cascading power outages. Therefore, the primary responsibility of the BA is to do everything it can to maintain frequency so that load will be served reliably throughout the BAA.

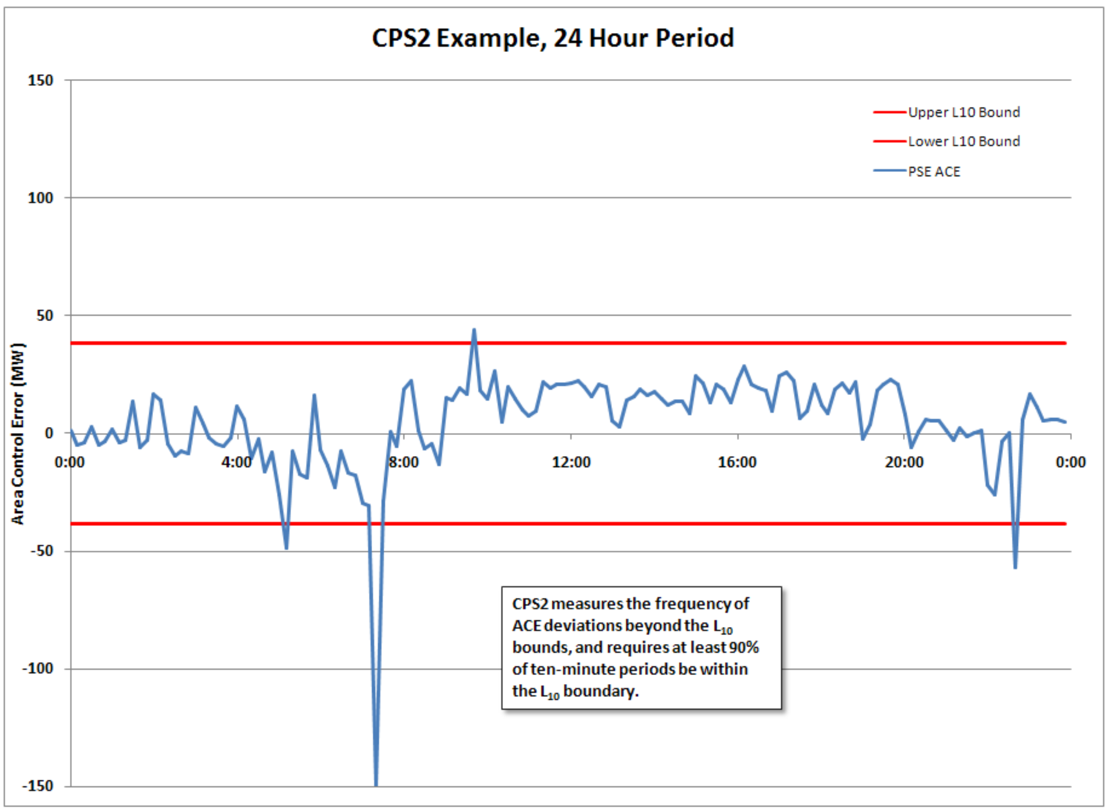
The Area Control Error (ACE) metric has been used for many years to track the ability of a BA to meet its reliability obligation. ACE is the instantaneous difference between actual and scheduled interchange, taking into account the effects of frequency. It reflects the balance of generation, load and interchange. Balancing Authority ACE determines how much a BA needs to move its regulating generation units (both manually and automatically) to meet mandatory control performance standard requirements.

By properly managing its ACE, PSE meets several key objectives: it reliably serves its customers, it maintains regulatory compliance, and it minimizes frequency excursions originating within its own BA that could impact other BAs or Transmission Operators (TOP) within the interconnection. PSE's CPS2 metric sets a requirement for how far and often its system can stray from load and generation being in balance. CPS2 measures whether the average ACE stays within a given boundary over a 10-minute period; this is the L10 value. At least 90 percent of the 10-minute periods in each month must be within the +/- L10 boundary to meet the CPS2 requirement. The L10 value is provided to PSE by the North American Electric Reliability Corporation (NERC). The PSE system responds to ACE every four seconds to ensure that PSE's average CPS2 score exceeds the required 90 percent for compliance. CPS2 is a concrete benchmark for assessing system reliability, and it is one of the metrics used to determine the adequacy of PSE's portfolio in this analysis.

BALANCING RESERVES refer to capacity held back on the PSE system to respond to negative and positive frequency errors. These can be incremental (INC) or decremental (DEC). Incremental capacity adds energy to the grid, decremental capacity reduces power to the grid. Balancing reserves can be in the form of regulating reserves, which are capable of adjusting dispatch to balance load within 5-minute time period, down to within one minute, and "load following" or "flexibility" reserves, which are often held to balance the variations of load and wind at a 5-minute level relative to an hourly ahead forecast.

CONTINGENCY RESERVES are also required in addition to balancing reserves; these are capacity reserved in spinning and non-spinning forms for managing a large negative frequency event such as a sudden loss of generation in PSE's BA or a neighboring BA. Contingency reserves are used for the first hour of the event only.

Figure H-1: Example of Control Performance Standard 2



Impact of Variability and Uncertainty on System Volatility

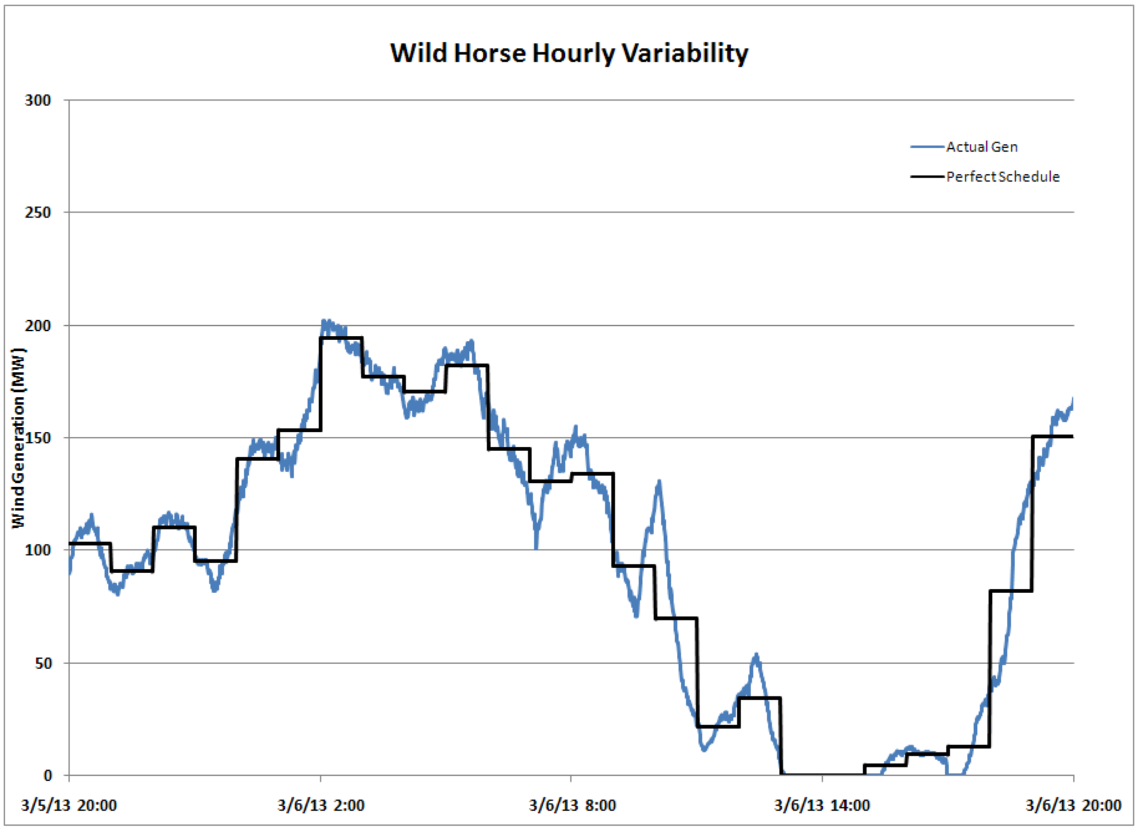
VARIABILITY is the moment to moment, natural fluctuations in loads and generating resources and is always present on the electric system. **UNCERTAINTY** is the inability to perfectly predict the hourly values for loads and generating resources. **VOLATILITY** refers to the collective variability and uncertainty observed system-wide.

Understanding the distinction between variability and uncertainty is essential when discussing ways to manage and potentially reduce volatility across the entire PSE system. Variability is a smaller component of volatility than uncertainty. It is largely uncontrollable, since it is caused by random changes in loads, generating resource power output and fuel availability (such as wind). Uncertainty is the larger component of system volatility, but there are tools that can be used to reduce this uncertainty. For example, improvements in load and wind forecasting can increase the accuracy of load and wind generation schedules, reducing the need to provide balancing energy. Also, shortening scheduling windows can reduce the impact of both variability and uncertainty on system volatility.

Prior to October 2016, the PSE BA managed system volatility over 60-minute scheduling periods. To help address system flexibility needs PSE joined the voluntary, within-hour Energy Imbalance Market (EIM) operated by the California Independent System Operator (CAISO) effective October 1, 2016. At present, CAISO, PacifiCorp, NV Energy, and Arizona Public Service are the other EIM entities. Within the EIM, PSE is able utilize purchases and sales with the market to fulfill energy flexibility requirements on a 5-minute and 15-minute basis, but as a BA, PSE retains final responsibility for balancing its loads and resources. Due to the short time period of actual data regarding PSE's EIM experience and its effect on PSE's sub-hourly balance, this analysis for the 2017 IRP did not consider the EIM when evaluating sub-hourly dispatch. Future studies will reflect the impact of the EIM.

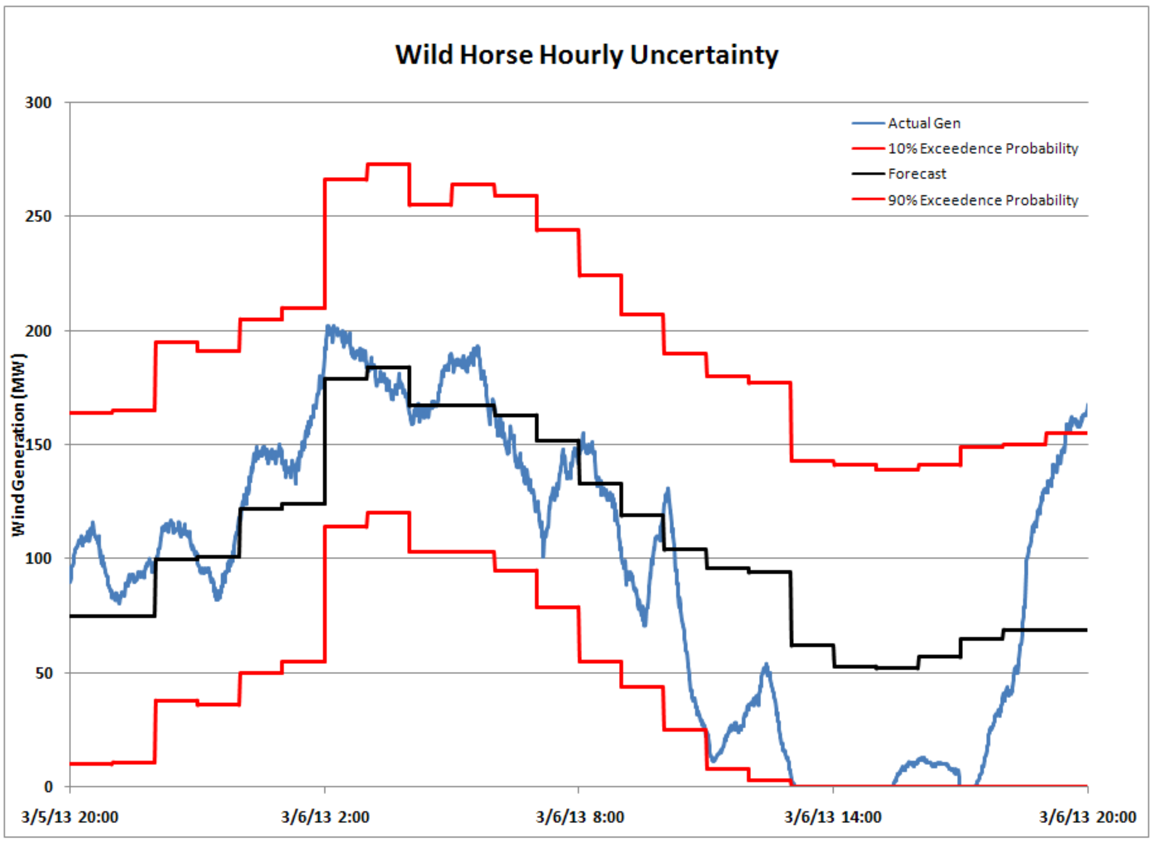
Figures H-2 through H-4 use a 24-hour period at the Wild Horse wind facility to illustrate examples of variability, uncertainty and volatility. In Figure H-2, the variability of Wild Horse is shown as the moment-to-moment generation relative to a perfect hourly schedule (a perfect hourly schedule equals the hourly average actual generation). It shows that even equipped with a perfect schedule, PSE must still manage fluctuations in wind generation within the hour, along with other deviations on the system.

Figure H-2: Hourly Variability in Wind Generation



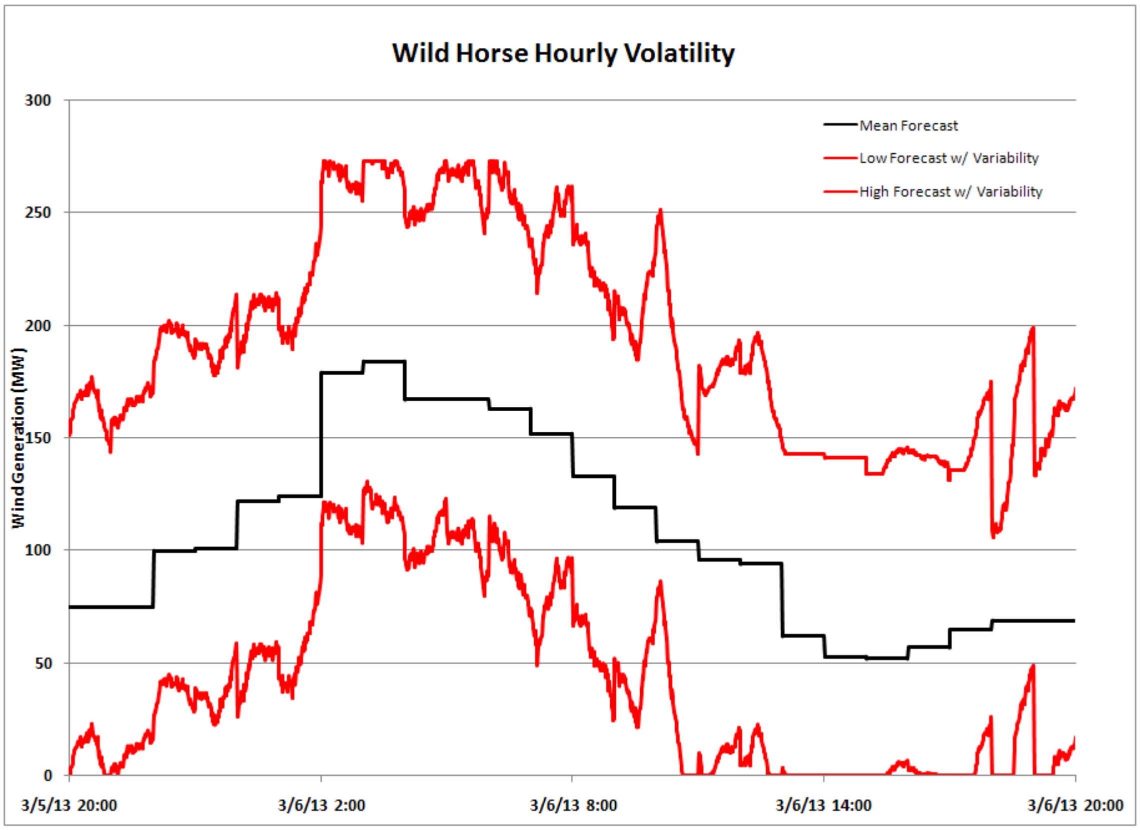
In reality, perfect foresight of wind generation or load for each upcoming operating hour is not possible. In Figure H-3, future wind generation is presented as an expected forecast for the next several hours, along with two additional forecasts that provide the probability of wind generation exceeding those values. At the 10 percent exceedence forecast, we would expect actual wind generation to be above this value only 10 percent of the time, whereas at the 90 percent exceedence forecast we would expect actual wind generation to be above this value 90 percent of the time. Actual wind generation may come in above or below the forecast, or, as is the case in HE 20 of March 6, 2013, it can exceed the forecasted bounds.

Figure H-3: Hourly Uncertainty in Wind Generation



The variability and uncertainty at Wild Horse are combined in Figure H-4 to illustrate the volatility that may be expected each hour. The actual variability observed around each perfect hour in Figure H-2 is imposed on the upper and lower probability forecasts from Figure H-3. It shows how PSE must balance potentially large blocks of energy related to forecast error (uncertainty) while simultaneously balancing within-hour fluctuations (volatility) in order to maintain system reliability. Addressing volatility from sources other than wind requires similar action on PSE's part.

Figure H-4: Hourly Volatility in Wind Generation



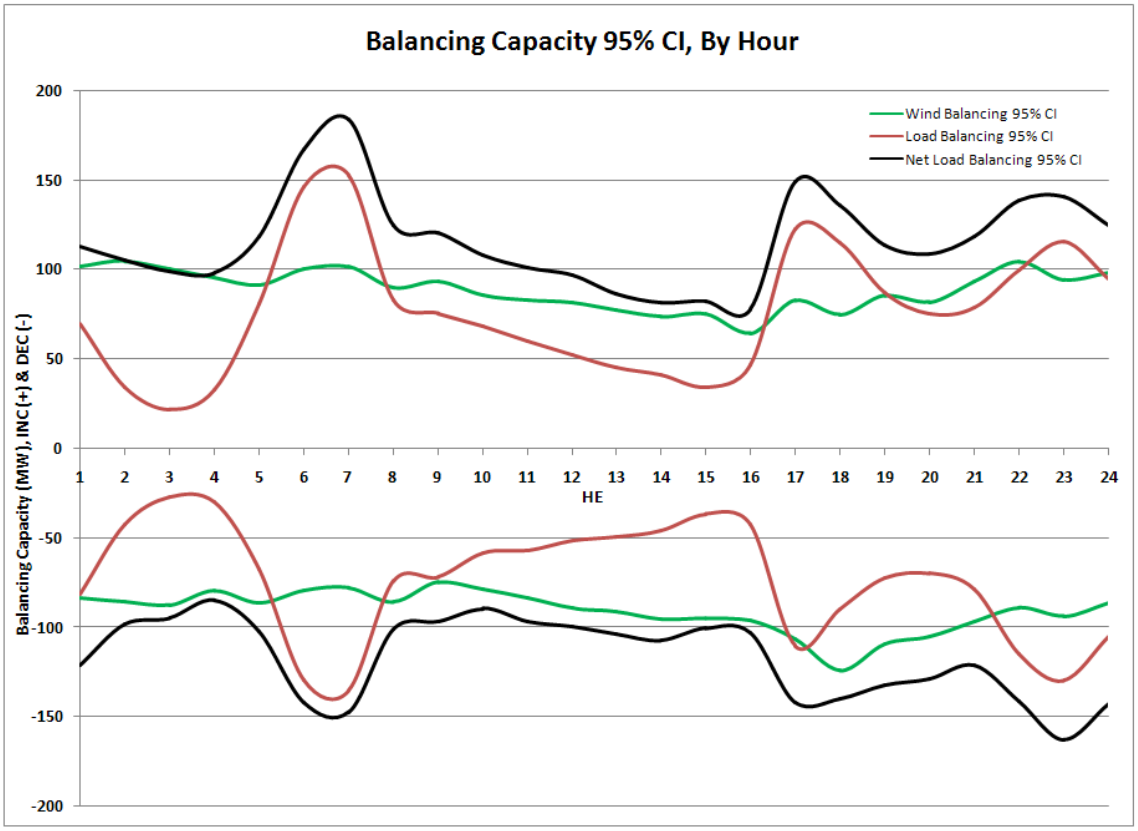
Managing Volatility

System volatility (variability and uncertainty) is managed with balancing reserves. Balancing reserves are generating capacity available to respond to changes in system conditions by either increasing generation (INC capacity) or decreasing generation (DEC capacity). The amount of balancing reserve capacity at PSE is determined by examining historical balancing capacity needs, and then establishing the amount of reserves necessary to cover 95 percent of the historical deviations in net load. This amount of balancing capacity is referred to as a 95 percent Confidence Interval level (95% CI) of reserves.

An overall 95 percent CI can be calculated that covers all time periods, but developing multiple 95 percent CIs can provide greater insight into balancing capacity needs. PSE develops 24 distinct 95 percent CIs for the entire day's operation. As Figure H-5 shows, the hourly 95 percent CI values can vary a great deal through the day for both load and wind resources. Large amounts of balancing capacity can be needed to manage strong load ramps to meet the 95 percent CI during morning and evening peaks.

For PSE wind resources, the 95 percent CI is more constant throughout the day, with a slight transition to more DEC capacity required in the evening hours and more INC capacity in the morning hours. The fixed range of potential wind generation, from 0 MW to full capacity, suggests the wind forecast can be a criterion for developing additional 95 percent CI. Taking the extremes, at a 0 MW wind forecast the only potential forecast error (forecast generation minus actual generation) PSE would need to balance is a negative error (forecast is less than actual generation), which would require only DEC capacity reserves. Conversely, when wind generation is forecast at full output, PSE would need to manage positive forecast errors only where the forecasted generation is greater than actual generation. In this case, INC capacity reserves are required.

Figure H-5: Hourly PSE Balancing Capacity at a 95 Percent Confidence Interval



It is important to note that contingency reserves are accounted for separate from balancing reserves. Contingency reserves are dedicated to addressing short-term reliability in the event of forced outages; they cannot be deployed to address hourly system volatility unless a qualifying event occurs, such as a unit tripping offline.

3. FLEXIBILITY SUPPLY AND DEMAND

System flexibility is the capability of PSE resources to manage system volatility over varying time periods, rates of change and overall magnitude. Flexibility is supplied by PSE generating resources, primarily PSE's share of the Mid-Columbia hydroelectric generating facilities (Mid-C), but also PSE's fleet of peaking and baseload gas-fired units. Flexibility demand is created by the volatility observed in load, generation and transmission curtailments, and the uncertainty inherent in predicting loads, wind generation and unexpected events. Load and wind volatility are the two primary drivers of the demand for flexibility on the PSE system. Regional consensus on flexibility metrics is still developing, but PSE has begun to try to quantify the flexibility supply it has available to meet demand.

Flexibility Supply

All resources provide some measure of flexibility; however, the ability of a resource to supply flexibility is constrained by unit-specific characteristics including availability, operational or environmental limitations, maximum and minimum operating range, and ramp rate. These characteristics, coupled with economic dispatch generation set points, affect PSE's total supply of system flexibility.

AVAILABILITY depends on whether the resource is online, the speed with which it can be dispatched if offline, and whether it is out of service due to planned maintenance or unplanned outage.

In terms of **OPERATIONAL LIMITATIONS**, the speed with which a resource can transition from offline to generating and synced to the system is a distinguishing feature of the resources needed to supply flexibility. Resources that take several hours to properly prepare for dispatch, like baseload gas units, are limited in their availability to respond to short-term system balancing needs.

RESOURCE RANGE refers to the physical and environmental (temperature) constraints that dictate the maximum and minimum levels at which a resource can generate. For any given resource, the difference between this maximum and minimum at any given time is referred to as its operating range. For conventional thermal resources, this range remains fairly constant, but the range for hydro resources changes dramatically during certain times of the year. A portion of PSE's capacity share of the Mid-C is available to meet PSE flexibility needs for most of the year, but during the spring runoff, high stream flows on the Columbia River reduce the available operating range on the Mid-C. At these times, hydro projects must generate at or near full capacity to avoid flowing excess water over spillways to meet water quality requirements for downstream fish migration. PSE's supply of flexibility is severely reduced at this time of year.

RESOURCE RAMP RATES describe the speed at which a unit can increase or decrease its generation. The ramp rate determines the ability of a resource to respond to all, some or none of the system's deviations. Slow ramp rates effectively limit the balancing capacity of a resource during a given time increment. A resource with a large operating range but very slow ramp rate may be insufficient to address sudden changes in load and wind generation, while a resource with a small operating range and faster ramp rate can quickly respond to system needs but may not be able to sustain such a rate for an extended period, so multiple resources may need to respond simultaneously.

Flexibility Demand

The demand for flexibility is created primarily by system volatility, the need to manage the scheduled interchange ramp period between hours and potential system contingencies.

Volatility

Continuous demands for flexibility are placed on the system by volatility – the variability of loads and generating resources that fluctuate from moment to moment combined with the uncertainty inherent in forecasting load and wind resources hour by hour.

PSE addresses the demand placed by all system loads and resources simultaneously, rather than responding to each deviation individually. The relationship between load and wind is especially important. Because wind generation serves system load, load and wind scheduling errors in the same direction offset each other. The BA does not need to respond to an increase in load if there is an equal increase in wind generation. Load and wind schedule deviations in opposite directions create greater demands on system balancing resources. On a probabilistic basis, the fact that PSE load and wind may often move in the same direction or at the same rate places a smaller total demand for flexibility on PSE than if each were measured individually and then added together.

Scheduled Interchange

In addition to managing loads and resources throughout each operating hour, PSE's BA must integrate hourly imports and exports. This is known as a scheduled interchange. Little volatility is associated with scheduled interchanges (they are generally a flat, hourly amount of energy), but the magnitude of scheduled interchanges can vary each hour, often by several hundred megawatts. To accommodate these large changes, resources are ramped in over a 20-minute period beginning 10 minutes prior to the start of the operating hour and ending 10 minutes after. Even with planned ramps, integrating such large changes in power can be demanding, both in the range required of resources and the speed with which they must respond.

System Contingencies

Forced outages place significant demands for flexibility on the system because they create an immediate need for large increases in energy to replace the resource lost to the outage. Forced outages occur when a generating unit, transmission line or other facility becomes unavailable for unforeseen mechanical or reliability reasons.

PSE also faces forced outage-type events as other BAs manage their own system volatility. For example, all wind resources within the BPA BA, of which PSE has 500 MW, are subject to dispatcher instructions meant to address BPA's need for system flexibility at times when its system reserve capacity is exhausted. One notable BPA business practice is Dispatch Standing Order 216 (DSO-216). DSO-216 states that if wind plants are under-generating and BPA is supplying INC balancing reserves, BPA will have the ability to curtail transmission schedules for each plant, relative to the plant's actual generation. A schedule cut within the hour is like a forced outage in that the PSE BA must respond instantaneously to a potentially large loss of energy. In addition to wind schedule cuts, PSE's thermal resources located outside the company's BA can also be cut due to regional transmission congestion and maintenance requirements. Transmission congestion can mean within-hour schedule cuts of several hundred megawatts.

Procuring and Deploying Balancing Reserve Capacity

The balancing reserves required to manage system operations within every operating hour can be thought of in two stages, each of which are simulated in this analysis:

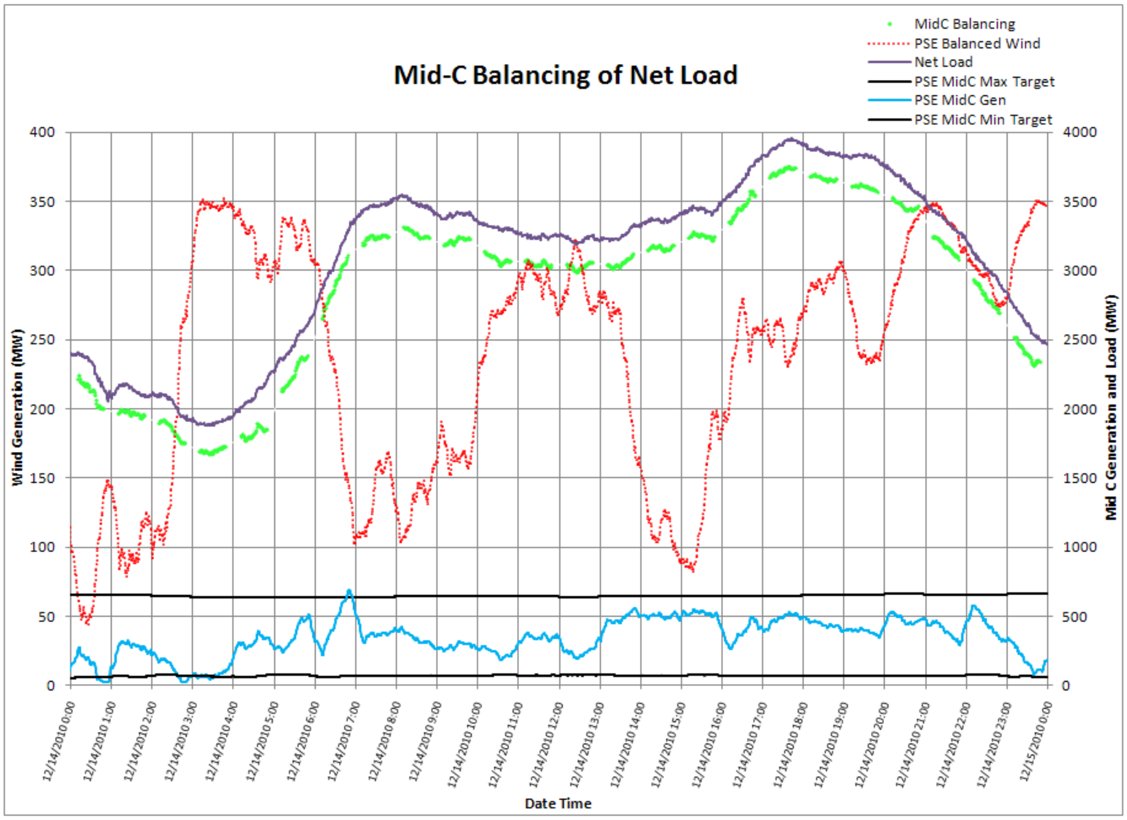
- In the day-ahead schedule (DA stage) PSE procures balancing reserve capacity ahead of the operating hour; and
- In real-time operations (RT stage), PSE deploys reserves and moves its generators to balance energy within the hour.

Procuring balancing capacity in the day-ahead stage ideally consists of positioning hydro assets to allow sufficient room to increase generation (INC capacity) or decrease generation (DEC capacity) as needed within the operating hour. Thermal resources (gas and coal) can also be dispatched to provide balancing capacity. It should be noted that procurement of the needed balancing reserve capacity does not always guarantee that sufficient flexibility is available to meet actual net load deviations on the system in real time. Meeting the demand for flexibility also requires unit ramp rates that can effectively deploy the capacity procured.

Figure H-6 depicts all aspects considered for balancing capacity and addressing system flexibility. In this 24-hour example, PSE's Mid-C generation is the source of balancing capacity. The moment-to-moment changes in net load (load minus wind generation) are represented by the purple trace. The blue line representing Mid-C generation is bounded by black minimum and maximum generation targets.

The green trace labeled "Mid-C Balancing" represents the slope (or rate of change) in Mid-C generation for each hour. It is presented just below the net load trace in order to highlight how the Mid-C generation is changing within the hour relative to the change in net load. This trace shows that during each hour, the Mid-C is responding in unison with changes in net load. The flexibility of the Mid-C is most evident during the 6:00 to 7:00 a.m. period as it manages an extreme load ramp of nearly 500 MW (over 8 MW per minute through the entire hour).

Figure H-6: Balancing of Net Load with Mid-C Generation



Note how the Mid-C reacts during the 20-minute schedule interchange period, from 5:50 to 6:10 am and from 6:50 to 7:10 am. During these periods Mid-C generation is being pushed down to accommodate new imports and to provide incremental balancing services for the next hour. In these instances, Mid-C frequently changes generation levels by 500 MWs over a 20-minute period (25 MW per minute ramp rate). No other resource in PSE's fleet is capable of this combination of speed and range. This is why Mid-C hydro is such an important flexibility resource in PSE's portfolio.

4. MODELING METHODOLOGY

This analysis focuses on whether PSE's portfolio has enough flexibility supply to meet its current system balancing needs on a 5-minute basis and how the cost of this balancing changes when different resources are added.

The flexibility analysis has two goals:

1. **Identify Physical Needs, addressing these questions**:
    - Will PSE have adequate ramp up/down capability?
    - If not, PSE may need to add an additional dimension to its planning standard or operational guidelines to ensure PSE can meet its operational needs.

2. **Reflect Sub-hourly Flexibility Analysis in Portfolio Analysis (Financial Impacts):**
    - Different resources have different sub-hourly operational capabilities.
    - Even if the portfolio has adequate flexibility, different resources can impact how the entire portfolio operates and also impact costs.
    - For example: Batteries could avoid dispatch of thermal plants for some ramping up and down.
    - A way to monetize those values is needed in order to incorporate these costs in the portfolio analysis, to ensure lowest reasonable cost decisions.

Model Framework and Input Methodology

PLEXOS is an hourly and sub-hourly chronological production simulation model that utilizes mixed-integer programming (MIP) to simulate unit commitment of resources at a day-ahead level, and then simulate the re-dispatch of these resources in real-time to match changes in supply and demand on a 5-minute basis. In more detail:

1. **In the day-ahead schedule (DA stage)**
    - Utilities schedule resources on an hourly basis in the day-ahead market.
    - On the next day, load and resources in every hour will probably deviate from the schedule.
    - The portfolio must have the flexibility to adjust to those differences.
    - Costs will be different than those predicted by the day-ahead schedule.

2. **In real-time operations (RT stage)**
    - Within each hour, resources will ramp up and/or down.
    - The day-ahead view alone will miss those cost impacts.

The Current Portfolio Case

For the sub-hourly cost analysis using PLEXOS, PSE, with support from its consultant E3, first created a Current Portfolio Case based on PSE's existing resources for the time period of this IRP analysis.

The Current Portfolio Case begins by creating a simulation that reflects a complete picture of PSE as a BA and PSE's connection to the market. This includes representation of PSE's BAA load and generation on a 5-minute basis, as well as contracts with neighboring BAs, and opportunities to make purchases and sales at the Mid-C trading hub in hourly increments.

This simulation reflected all three types of reserve requirements:

- Contingency reserves, required to be equal to 3 percent of PSE load, and 3 percent of PSE generation. These include spinning reserves, which can be deployed within 10 minutes, and non-spinning reserves, which are available for up to a 60-minute period;
- Regulating up and down reserves, which must be able to adjust to movements in load and wind in a period of less than 5 minutes and down to sub-minute level; and
- Balancing up and down reserves (also termed flexibility reserves, or load following) which are used to address differences at the 5-minute level compared to the hour-ahead forecast.

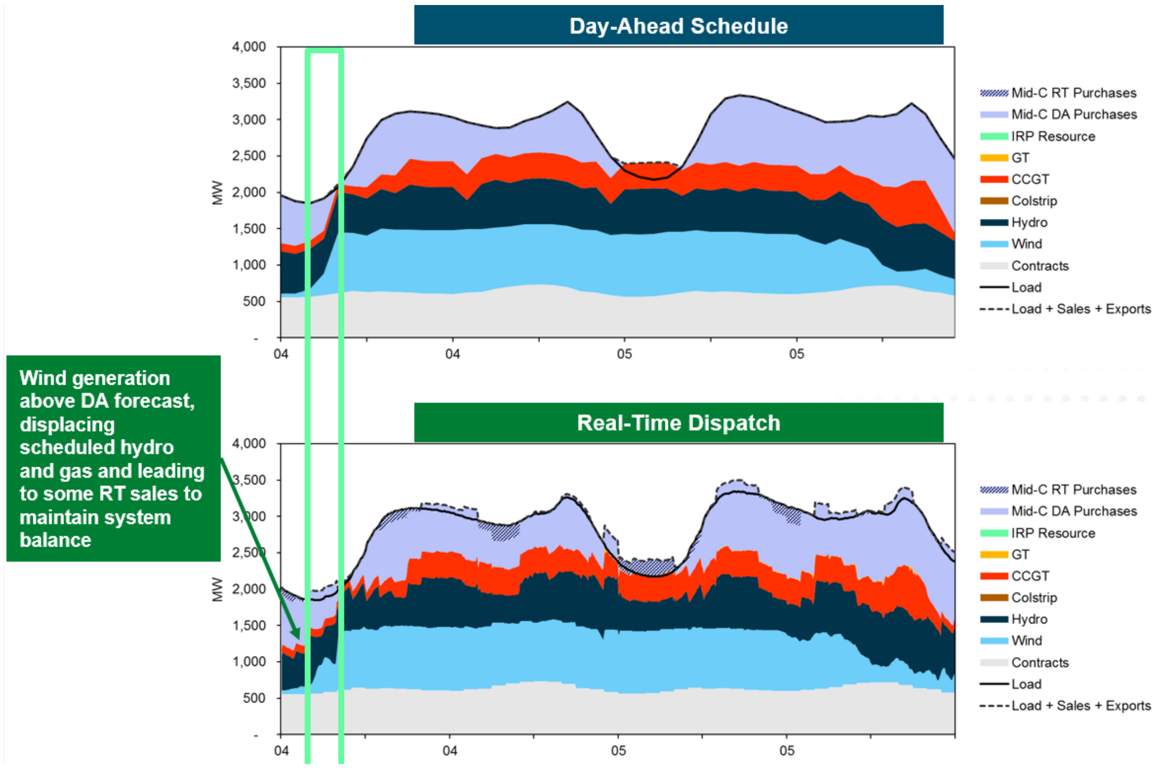
For this analysis, PSE used actual 5-minute demand data from 2016 for load, scaled to the demand forecast for 2022. The analysis also uses 2016 actual 5-minute data for wind and run-of-river hydro in PSE's BA, and 2016 daily total Mid-C energy generation. PLEXOS then optimized the Mid-C generation within the day, allocating the daily total to different hours and 5-minute intervals.

The analysis also used information consistent with PSE's 2017 IRP Base Scenario, including the base natural gas and CO_2 prices for generation and forecast Mid-C power prices from AuroraXMP for PSE hourly energy purchases and sales, which PLEXOS utilized when economic.

Figure H-7, below, illustrates the dispatch of PSE's system in the day-ahead and real-time stages over a two-day period, April 4 through April 5, 2022.

The highlighted area notes a time period of particularly high “downward deviation” of net load in the real-time stage compared to the day-ahead stage, because wind resources (in bright blue) were higher than expected in the first part of the hour. As a result, PSE's flexible resources respond in the real-time stage by reducing dispatch on hydro generation (dark blue), reducing gas dispatch (red area) and making real-time energy sales at Mid-C on an hourly basis. The shifts in generation required to accommodate these sub-hourly variations in real time may carry a cost resulting from the reduced efficiency of generation that is required to quickly adjust to balance the system.

Figure H-7: PSE System Dispatch, Day-ahead and Real-time



New Resource Cases

PSE tested the impact of a range of potential new resources, each of which is individually added to the current portfolio. If the dispatch cost of the portfolio with the new addition is lower than the Current Portfolio Case cost, the cost reduction is identified as a benefit of adding the new resource.

Modeling Assumptions and Limitations

Some key assumptions made in these modeling efforts should be noted.

- EIM participation by PSE was not included in this study, but may be included in future flexibility analyses.
- Contingency analysis of generators going offline in real-time (but not anticipated at the day-ahead stage) was not directly represented.
- Wind resources are modeled at the day-ahead level on an hourly basis using the 30-minute persistence forecast. This forecast uses, for each hour, the value of the wind output that occurs in the 5-minute interval 30 minutes prior to the operating hour.
- PSE load was modeled at the day-ahead level with perfect foresight of average conditions in the real-time stage.
- Balancing or “flexibility” reserves that were required to be held in the day-ahead stage are calculated on a month-hour basis based on the anticipated deviation of net load (PSE BAA load net of wind balanced by PSE) at the real-time 5-minute interval level compared to the day-ahead hourly value. These reserves, which average approximately 90 MW but can range up to 150 MW in some month-hour windows, are held as upward and downward room on thermal and hydro generators at the day-ahead stage, and “released” in the real-time stage. This means that the model can use the withheld generation capacity to increase or reduce energy output to respond to real-time changes in net load.

5. RESULTS

For this analysis, the real-time sub-hourly simulation shows a limited number of flexibility violations in upward and downward directions. The small size and frequency of flexibility issues reflect a relatively high amount of overall flexibility modeled for the PSE system from hydro and gas generation and hourly market transactions.

Most cases with potential generation resource additions show a small reduction in real-time flexibility issues and cost compared to already low level of flexibility issues in the Current Portfolio Case. IRP resource additions also provide small reductions in real-time dispatch costs compared to the Current Portfolio Case, with batteries providing highest value per kW.

Figure H-8 summarizes key details of the 13 new resources that were considered in the analysis, in addition to the Current Portfolio Case.

Figure H-8: Overview of Resource Additions Analyzed

Description	Capacity (MW)	Heat Rate (Btu/kWh)	Energy Storage (MWh)	Roundtrip Efficiency (%)
1x1 GE 7F.05	359	6,650	-	-
1x1 GE 7F.05 (Duct Firing)	413	8,500	-	-
1x1 GE 7HA.01	405	6,515	-	-
1x1 GE 7HA.01 (Duct Firing)	466	8,500	-	-
3x0 Wartsila 18V50SG	55	8,425	-	-
6x0 Wartsila 18V50SG	111	8,425	-	-
12x0 Wartsila 18V50SG	222	8,425	-	-
1x0 GE LMS100PA	114	8,986	-	-
2x0 GE LMS100PA	228	8,986	-	-
1x0 GE 7F.05	239	9,823	-	-
Li-Ion Battery 2-hr	25	-	50	85%
Li-Ion Battery 4-hr	25	-	100	85%
Flow Battery 4-hr	25	-	100	75%
Flow Battery 6-hr	25	-	150	75%
Pumped Storage Hydro	25	-	250	81%

Current Portfolio Case Results

Flexibility issues (defined as "violations" in the model) represent hours when the model faces constraints in moving resources upward or downward to follow load and wind. The model can include two categories of flexibility challenges.

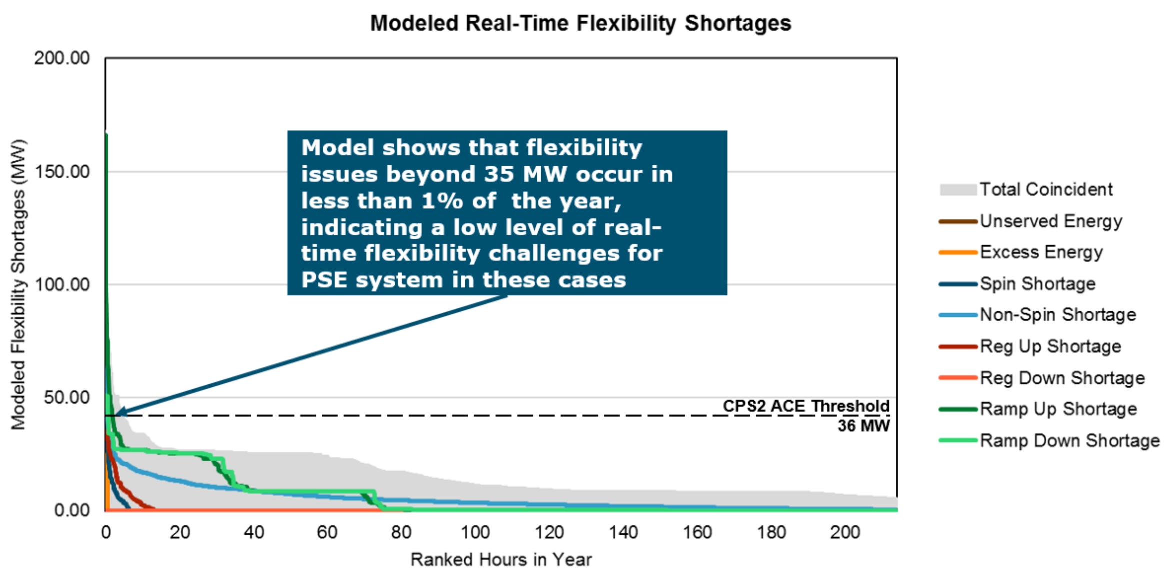
- **Upward flexibility issues** occur in certain real-time 5-minute intervals, including times of implied unserved energy, shortage of ramping response or reserves, or positive area control error (ACE) compared to scheduled interchange with neighboring systems.
- **Downward flexibility issues** occur in real-time 5-minute intervals in which the model identifies excess energy (which indicates the potential need to curtail wind or hydro output), shortage of downward reserves, challenging downward ramping constraints, or negative ACE with neighboring BAs.

The day-ahead analysis did not result in any flexibility issues, indicating that PSE's current portfolio has sufficient flexibility to balance on an hourly basis when conditions are well-known for the day, even while holding flexibility reserves.

In the real-time analysis, flexibility issues occurred but were relatively small. Some issues of very small magnitude may also be model-related noise rather than implying challenges that would actually appear in practice. The relatively small flexibility issues identified through PLEXOS modeling suggest there may be times when PSE could have ACE deviation from schedule or constrained reserves, but the small size of these deviations does not point to a need for procuring new resources.

Figure H-9 summarizes the size and frequency of flexibility issues identified when simulating the real-time stage for the Current Portfolio Case. The PLEXOS model shows flexibility issues occurring that are larger than 36 MW (the CPS2 L10 ACE threshold for PSE) in fewer than one percent of real-time 5-minute intervals in the year – with coincident issues occurring in fewer than 10 total hours per year.

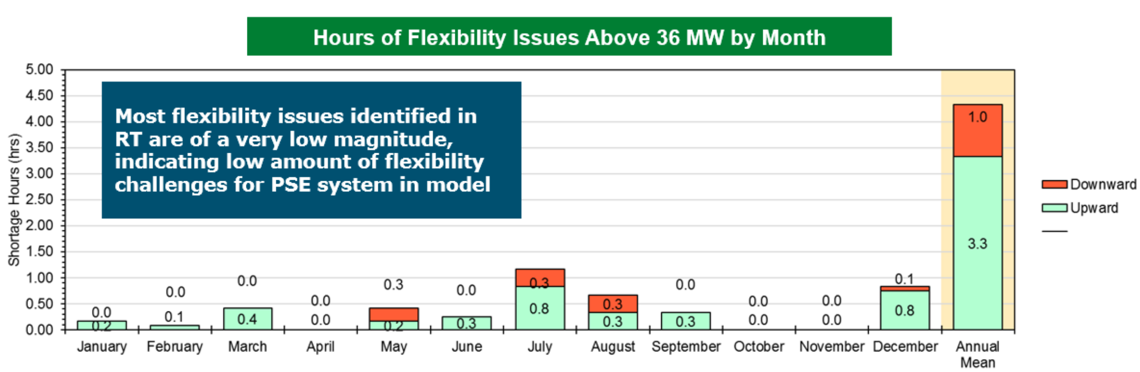
Figure H-9: Real-time Flexibility Shortages Modeled



Most of the flexibility issues shown above are still of a small magnitude (in MW) compared to PSE's 2,866 MW average load.

Figure H-10 summarizes the number of hours each month (in 5-minute intervals) in which upward or downward flexibility issues exceed 36 MW.

Figure H-10: Monthly Hours of Flexibility Issues above 36 MW



The flexibility issues occur in both the upward (green) and downward (red) direction across the year, most significantly in July, August and December – however, the frequency of these issues totals less than 5 hours. This represents less than 0.02 percent of PSE's total annual load.

New Resources Comparative Results

The figures below compare the frequency and total annual volume of flexibility issues that occur in real-time in the Current Portfolio Case, as well as in the separate simulations that include additional new resources. Figure H-11 shows that the number of hours of flexibility issues above the 36 MW threshold is lower in many of the cases with additional resources added compared to the Current Portfolio Case, though the relative size of the issues in each case is very close. Overall, the low level of flexibility issues in the Current Portfolio Case leaves little room for definite improvement in flexibility performance when adding new resources; as a result, all cases have similar performance. The small increase in some cases (including the 2x0 GE LMS 100PA case) is likely driven by changes in how generation across PSE's portfolio is committed in the day-ahead stage. Because the day-ahead stage does not anticipate directly what will occur in the real-time stage, adding certain resources may cause price improvements in the day-ahead stage, but happen to set up a commitment that encounters marginally more issues in real-time.

Figure H-11: Annual Flexibility Shortage Hours, 36 MW Threshold

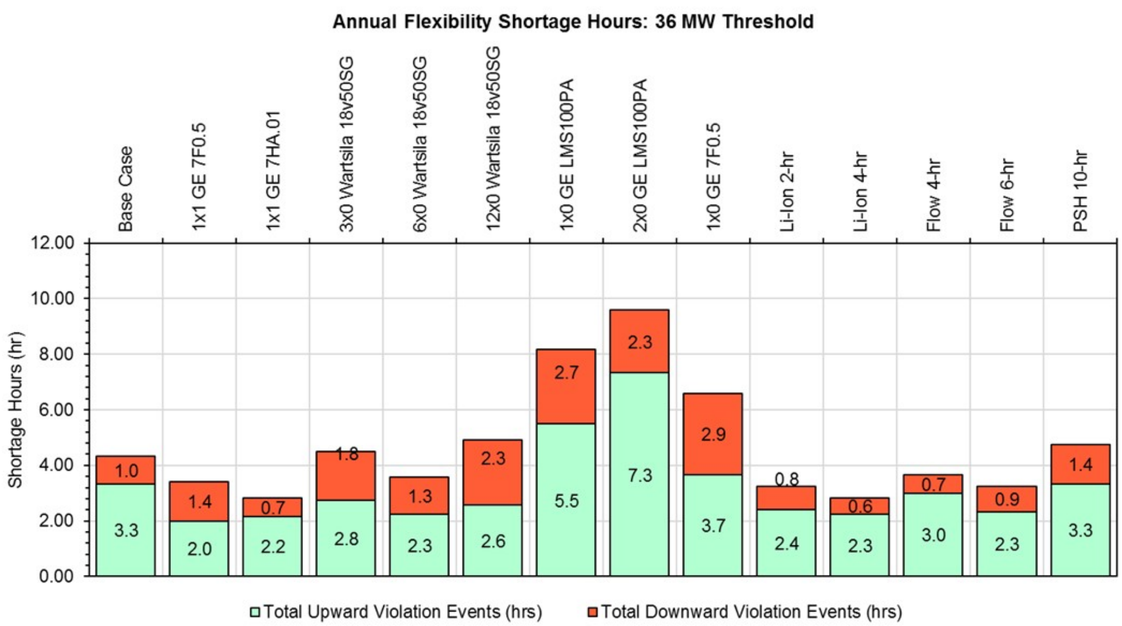
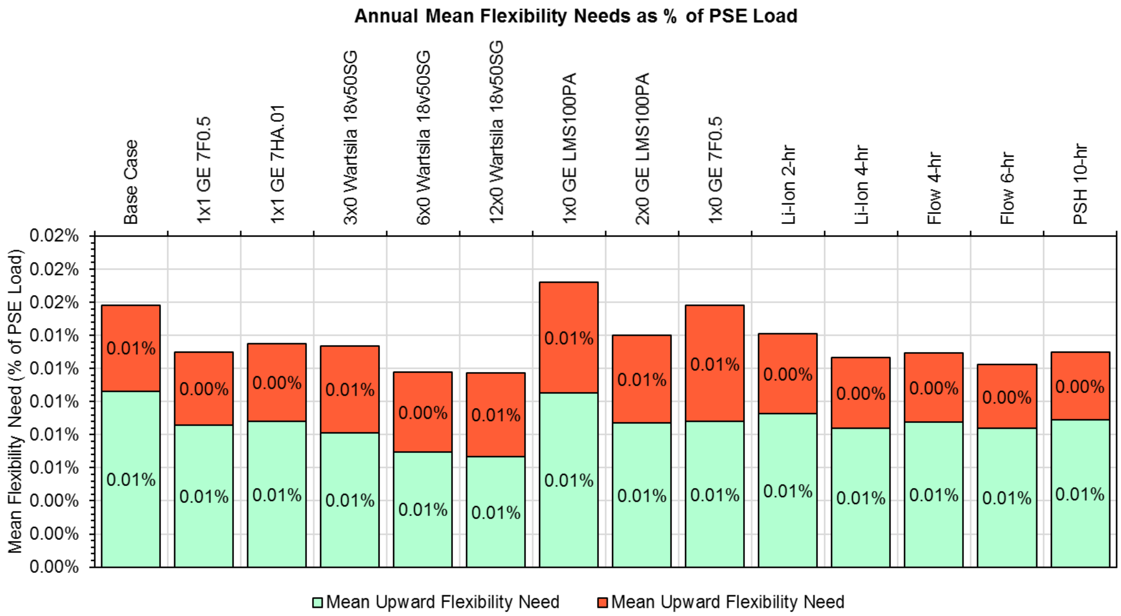


Figure H-12 presents the changes in impact on flexibility issues as a percentage of total PSE load across different portfolio resources. The Current Portfolio Case encounters upward or downward issues equivalent to less than 0.02 percent of total PSE system load. In most cases, new resources reduce the total annual volume of flexibility issues relative to the Current Portfolio Case, but the overall size of these differences is small due to the low starting level of flexibility issues in the Current Portfolio Case.

Figure H12: Annual Mean Flexibility Needs as Percentage of PSE Load

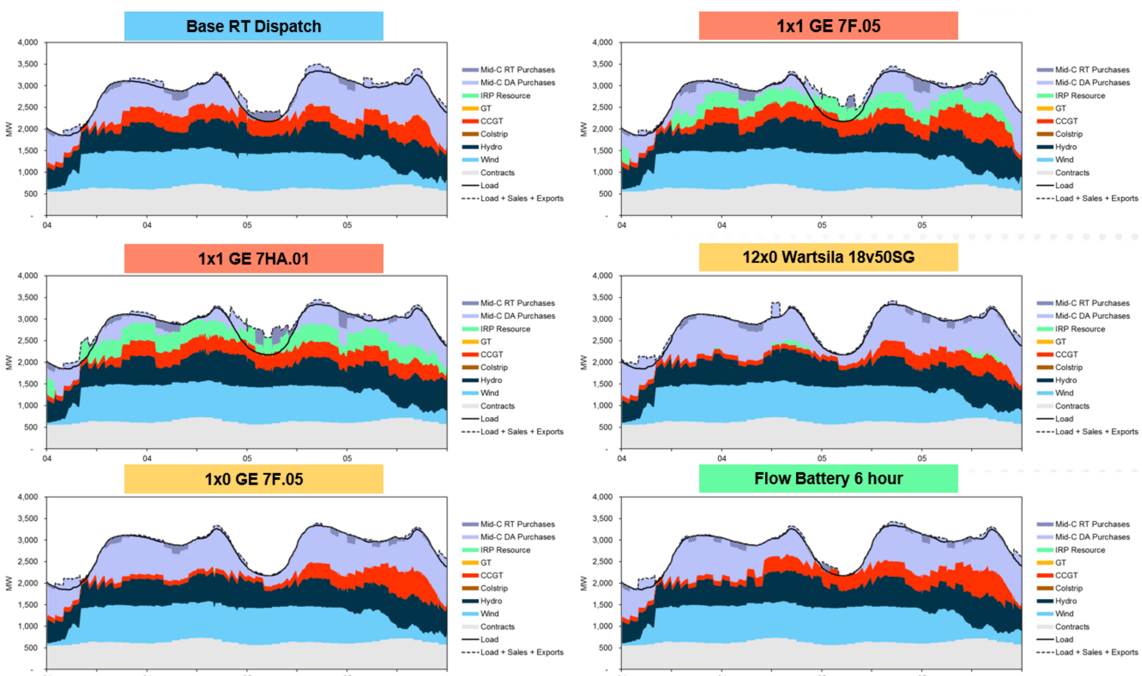


Sub-hourly Dispatch Cost Impact

Even in cases where adding new resources does not substantially change the total frequency of flexibility issues, new generators can improve the total variable cost of dispatching the portfolio to address flexibility movements at a sub-hourly level.

Figure H-13 illustrates how selected new resource additions (represented in green) move to address the real-time flexibility needs identified previously in the April 4, 2022 example.

Figure H-13: Real-time Impact of New Resources on Flexibility



The cost impact of these new resources can be represented by comparing the total portfolio cost (variable generation cost plus net purchases) across the different simulations.

Figure H-14 presents the total annual cost by generation category for PSE's system (including energy purchases and sales at Mid-C) under the Current Portfolio Case (first column) and the different simulations that model resource additions.

Figure H-14: Total Annual Cost by Generation Category

	Real-Time System Cost for Each IRP Resource Addition Scenario ($MM)	Base Portfolio	1x1 GE 7F0.5	1x1 GE 7HA.01	3x0 Wartsila 18v50SG	6x0 Wartsila 18v50SG	12x0 Wartsila 18v50SG	1x0 GE LMS100PA	2x0 GE LMS100PA	1x0 GE 7F0.5	Li-Ion 2-hr	Li-Ion 4-hr	Flow 4-hr	Flow 6-hr	PSH 10-hr
Generation	Wind	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Hydro	12	12	12	12	12	12	12	12	12	12	12	12	12	12
	CCGT & Colstrip	185	169	167	187	185	180	187	187	188	185	185	185	186	185
	GT	24	20	19	28	27	26	29	29	29	26	26	26	26	26
	IRP Resource	-	73	84	2	6	17	1	7	7	-	-	-	-	-
	Subtotal	*222*	*275*	*282*	*229*	*231*	*236*	*230*	*236*	*237*	*224*	*224*	*224*	*225*	*224*
Mid-C	Purchases	248	192	183	239	237	233	238	234	233	245	245	245	244	245
	Sales	(22)	(36)	(38)	(26)	(28)	(31)	(27)	(30)	(29)	(24)	(24)	(24)	(24)	(25)
	Subtotal	*226*	*156*	*145*	*213*	*209*	*202*	*211*	*204*	*204*	*221*	*221*	*221*	*220*	*220*
Contracts	Aggregated	208	208	208	208	208	208	208	208	208	208	208	208	208	208
	DSM	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Subtotal	*208*	*208*	*208*	*208*	*208*	*208*	*208*	*208*	*208*	*208*	*208*	*208*	*208*	*208*
Total		**656**	**639**	**635**	**650**	**648**	**646**	**649**	**647**	**649**	**653**	**652**	**653**	**652**	**652**

For example, the Current Portfolio Case shows a total dispatch cost of $656 million (this includes generation fuel and CO_2 cost, variable operations and maintenance, and startup cost). In the second column, the addition of a baseload gas resource (1x1 CCCT) results in annual operating costs of $73 million on the new plant, but this also displaces the dispatch (and cost) of other PSE resources. Adding the unit also reduces the volume and cost of PSE's annual energy purchases at Mid-C and increases PSE's sales.

In total, the new baseload gas generator results in a PSE variable dispatch cost of $639 million, a reduction of $17 million compared to the $ 656 million cost with the Current Portfolio Case. These cost changes are characterized in subsequent columns for each of the new resources considered. It is important to note that the size of new resources covers a very wide range, from 25 MW batteries up to baseload gas plants of over 400 MW. Therefore, the total impact in $/kW-yr may provide a more useful direct comparison across resources. Figure H-15 identifies the resulting cost changes in each scenario compared to the Current Portfolio Case, and also provides the estimated impact in $/kW-yr.

It is also important to note that, consistent with the current Clean Air Rule for the State of Washington, larger resources (including the baseload gas units in this study) incur a CO_2 adder on fuel costs; peaking resources in this study were assumed to be smaller than the threshold for the carbon rule, which may increase their relative dispatch in these cases.

Figure H-15: Cost Impact of Added Resources Compared to the Current Portfolio Case

	Total Real-Time System Cost Delta from Base Portfolio for Each IRP Resource Addition Scenario ($MM)														
		Base Portfolio	1x1 GE 7F0.5	1x1 GE 7HA.01	3x0 Wartsila 18v50SG	6x0 Wartsila 18v50SG	12x0 Wartsila 18v50SG	1x0 GE LMS100PA	2x0 GE LMS100PA	1x0 GE 7F0.5	Li-Ion 2-hr	Li-Ion 4-hr	Flow 4-hr	Flow 6-hr	PSH 10-hr
Generation	Wind	1	0	0	0	0	0	0	0	0	0	0	(0)	0	0
	Hydro	12	0	0	0	0	0	0	0	0	0	0	0	0	0
	CCGT & Colstrip	185	169	167	187	185	180	187	187	188	185	185	185	186	185
	GT	24	(4)	(5)	4	4	3	6	5	6	2	2	3	2	2
	IRP Resource	-	73	84	2	6	17	1	7	7	-	-	-	-	-
	Subtotal	*222*	*53*	*60*	*7*	*10*	*14*	*8*	*14*	*15*	*2*	*2*	*2*	*3*	*2*
Mid-C	Purchases	248	(56)	(64)	(8)	(10)	(15)	(9)	(13)	(14)	(3)	(3)	(3)	(4)	(3)
	Sales	(22)	(14)	(16)	(4)	(6)	(9)	(5)	(9)	(7)	(2)	(2)	(2)	(2)	(3)
	Subtotal	*226*	*(69)*	*(81)*	*(13)*	*(17)*	*(24)*	*(15)*	*(22)*	*(22)*	*(5)*	*(5)*	*(5)*	*(6)*	*(5)*
Contracts	Aggregated	208	0	0	0	0	0	0	0	0	0	0	0	0	0
	DSM	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Subtotal	*208*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Total		**656**	**(17)**	**(20)**	**(5)**	**(7)**	**(10)**	**(6)**	**(8)**	**(6)**	**(3)**	**(3)**	**(3)**	**(3)**	**(4)**
Levelized Delta ($/kW-yr)			**(46)**	**(50)**	**(97)**	**(65)**	**(44)**	**(56)**	**(35)**	**(26)**	**(119)**	**(131)**	**(117)**	**(128)**	**(144)**

Adding new resources reduces the total portfolio cost of generation to a varying extent; however, much of the cost reduction occurs at the day-ahead (hourly) simulation stage. These changes in generation cost typically overlap with the impact of the resource additions that PSE models in Aurora. The exception is storage resources, which PSE did not incorporate directly into the Aurora model due to limited parametrization; thus there is not an overlap of these portfolio costs impacts and Aurora results for the five storage resources listed.

For the resource additions, the cost impact related specifically to sub-hourly flexibility, can be isolated from the overall hourly impact of the new resources by comparing the change in portfolio cost of the real-time stage versus the day-ahead stage. These results are presented in Figure H-16.

Figure H16: Cost Difference between Real-time Redispatch and Day-ahead Schedule for Each Resource Addition

Real-Time Redispatch Cost from Day-Ahead Schedule for Each IRP Resource Addition Scenario ($MM(															
		Base Portfolio	1x1 GE 7F0.5	1x1 GE 7HA.01	3x0 Wartsila 18v50SG	6x0 Wartsila 18v50SG	12x0 Wartsila 18v50SG	1x0 GE LMS100PA	2x0 GE LMS100PA	1x0 GE 7F0.5	Li-Ion 2-hr	Li-Ion 4-hr	Flow 4-hr	Flow 6-hr	PSH 10-hr
Generation	Wind	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
	Hydro	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
	CCGT & Colstrip	(5)	(5)	(5)	(5)	(4)	(4)	(4)	(4)	(5)	(6)	(5)	(6)	(5)	(5)
	GT	5	4	4	7	6	6	6	6	8	6	6	6	6	6
	IRP Resource	-	(1)	(2)	(0)	(1)	(0)	0	0	(2)	-	-	-	-	-
	Subtotal	*(0)*	*(2)*	*(3)*	*1*	*2*	*2*	*2*	*3*	*1*	*1*	*1*	*1*	*0*	*1*
Mid-C	Purchases	14	15	16	13	13	12	12	12	13	14	14	14	14	14
	Sales	(14)	(13)	(13)	(15)	(16)	(15)	(15)	(15)	(14)	(15)	(14)	(15)	(14)	(15)
	Subtotal	*1*	*2*	*3*	*(2)*	*(3)*	*(3)*	*(3)*	*(4)*	*(1)*	*(1)*	*(1)*	*(1)*	*(1)*	*(1)*
Contracts	Aggregated	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	0	(0)	(0)
	DSM	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Subtotal	*(0)*	*(0)*	*(0)*	*(0)*	*(0)*	*(0)*	*(0)*	*(0)*	*(0)*	*(0)*	*(0)*	*0*	*(0)*	*(0)*
Total		**0**	**0**	**(0)**	**(1)**	**(1)**	**(1)**	**(1)**	**(1)**	**(0)**	**(0)**	**(0)**	**(0)**	**(0)**	**(0)**
Levelized Delta ($/kW-yr)			**0**	**(0)**	**(11)**	**(8)**	**(4)**	**(7)**	**(4)**	**(1)**	**(3)**	**(8)**	**(2)**	**(7)**	**(10)**

Overall, the impact of sub-hourly flexibility on portfolio costs with additional new resources produces smaller differences between cases – with the overall cost impact ranging from $200,000 to $900,000 per year. These flexibility differences are largest on a $/kW-yr basis for smaller resources, representing, for instance, up to 10 percent of the total value identified for the 3x0 Wartsila internal combustion engine ($11/kW-yr for sub-hourly flexibility, compared to $97/kW-yr total value for addition to the PSE system). These costs can be considered incremental or additive to the hourly cost impact that PSE identified with its Aurora simulation. In addition, since the hourly cost impact of storage resources was not modeled in Aurora, the full storage cost impact from PLEXOS can instead be used.

6. CONCLUSION AND NEXT STEPS

The analysis indicates that PSE's current portfolio appears to have sufficient flexibility to balance the movements of load and wind in its BA on a 5-minute basis. The addition of new resources typically provides a small reduction in the frequency and magnitude of flexibility issues identified in the real-time stage at a 5-minute level. In addition, the additional resources typically provide modest incremental reductions in the variable cost of dispatching PSE's portfolio over the year on a 5-minute basis.

This two-stage PLEXOS simulation approach for modeling sub-hourly flexibility on the PSE system can be used to address a wide range of scenarios. Future analysis by PSE could evaluate the impact of PSE balancing a larger amount of wind resources internally to its BA, which could increase the demand for flexibility. This framework can also be used to examine the sub-hourly flexibility of fast-response demand response measures. In addition, PSE could model participation in the EIM market by including an opportunity to purchase and sell energy on a 5-minute basis in the real-time stage at an external market price.