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PNNL-38452

Lower Snake River Dams Contribution to Grid Services

September 2025

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U.S. DEPARTMENT of ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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Abstract

Hydroelectric generation and water storage have long been components of the energy mix, providing both reliable steady output and operational flexibility. As demand for energy increases, the role of all flexible resources—including hydropower—in balancing supply and demand continues to evolve. This study examined the contribution of the Lower Snake River (LSR) Dam plants to Bonneville Power Administration grid services in maintaining power system reliability within the Western Interconnection. By analyzing publicly available data, the study evaluated various reliability services through performance metrics including energy capacity, balancing and ramping, voltage and reactive power support, frequency response, and transmission impact. Results indicated that the LSR plants deliver services as expected based on their size, contributing to the balancing process, ramping capabilities, and operational reserves, particularly during peak load conditions and weather events, while also providing measurable frequency and voltage support to the grid.

Executive Summary

Electrical power is produced, transported and utilized at the same instance of time, with limited storage ability. To meet the system load, produced power needs to be transported over transmission lines. At every moment, power produced must match the load of the system. As the system load (or supply) changes, electrical power produced (or consumed) needs to change as well to keep the supply-demand balance intact. To keep a system stable and deliver the necessary power to load centers, various grid services are needed.

The study summarized by this report analyzes the historical role and contribution of Lower Snake River (LSR) Dam plants to grid services within the Western Interconnection, focusing on their contributions to the Bonneville Power Administration's (BPA) operations. The LSR system comprises of four hydroelectric plants: Ice Harbor (IHR), Little Goose (LGS), Lower Monumental (LMN), and Lower Granite (LWG) Dams. By leveraging publicly available data, simulations, and statistical analyses, the study evaluates various grid services provided by LSR plants, including capacity, load balancing, ramping, flexibility, voltage and reactive power support, and frequency stabilization (Table S.1). These are part of the essential reliability services defined by the Federal Energy Regulatory Commission.[1]

Table S.1 LSR contribution to grid services

Grid service	Metrics		Contribution	
Capacity/Energy	Average generation by LSR plants	~700 MW	Share of total BPA hydro generation	~10%
	Maximum generation by LSR plants	2000–2500 MW	Share of total BPA hydro generation	Up to 18%
Flexibility: Inter-hour Ramping & Balancing	Average LSR 3-hour ramps	High water season ±250 MW	Share of total BPA hydro generation	~20–25%
		Low water season ±100 MW		~10%
	Maximum LSR 3-hour ramps	High water season ±1000 MW		~25%
		Low water season ±400 MW		~10%
	LSR Mileage	~250000 MW per year		~15%

[1] https://www.ferc.gov/reliability-explainer

Grid service	Metrics		Contribution	
Flexibility: Intra-Hour Ramping & Balancing	Due to the lack of detailed data on LSR participation in AGC[1] regulation actions, an analysis of 5-minute LSR generation data was performed. This analysis extracted 5- and 15-minute ramp participation metrics, which can be compared to total BPA hydro fleet ramps to evaluate the contribution of LSR plants to intra-hour balancing process. On average, LSR 5-minute ramps are approximately 5 MW, with peak values reaching 30 MW.			~10%
Voltage/Reactive power support	Average reactive power in MVAR[2] provided by LSR plants	±1000 MVAR	The metric represents a local service and is not quantified as a share of total BPA reactive support	
Frequency Response: Inertia and Primary Frequency Response	LSR FRM[3]	70 MW/0.1Hz	Share of total BPA FRM	~10–15%

[1] automatic generation control
[2] megavolt-ampere reactive
[3] frequency response measures

The study finds that LSR plants account for approximately 10–15% of the total grid services that BPA provides.[1] Notably, this contribution has a seasonal component (Figure S.1), as LSR operations are influenced by multiple factors including water conditions, electrical grid operational constraints, environmental considerations, fish management, and flood control requirements. Furthermore, LSR operations are part of the complex optimization process of the entire BPA hydro fleet.

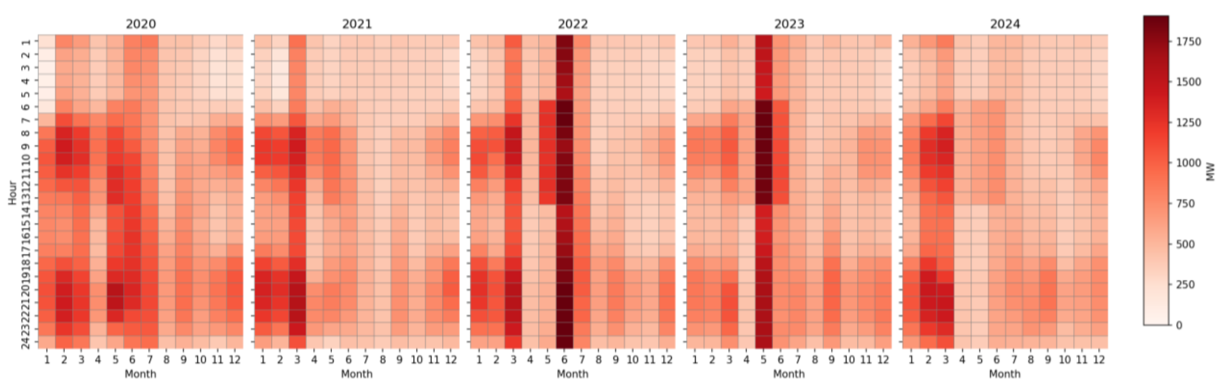

Figure S.1. Aggregated LSR plants average hourly generation by month (2020–2024).

Based on statistical analyses of ramping and MW-mileage,[2] LSR plants' operations support flexibility needs for both intraregional and interregional grid operations. The aggregated flexibility of LSR plants, as measured using their ramping capabilities and mileage, are leveraged to respond to a dynamically changing load and generation mix (Figure S.2).

[1] The share can be meaningfully measured only for certain services; however, there are local grid services for which precise quantification in this context is not feasible.
[2] Mileage is a commonly used metric to estimate the flexibility of a power plant. It is defined as the total "work" performed by electricity generation assets, calculated as the sum of all upward and downward ramps made at specified intervals over a given period. Source: https://www.energy.gov/sites/prod/files/2021/01/f82/us-hydropower-market-report-full-2021.pdf

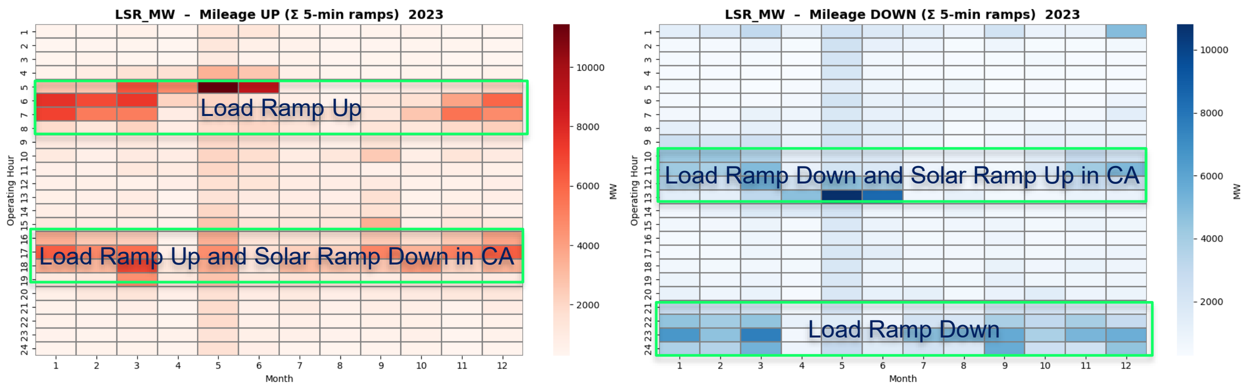

Figure S.2 Aggregated LSR plants hourly mileage Up and Down by month (2023).

LSR plants, along with the rest of the federal hydro fleet, also play a role in the intraregional and interregional balancing process, which has become more complex over the years due to variability in renewable output. For example, during afternoon hours, when solar generation in California rapidly declines, LSR plants tend to ramp up their output to meet load requirements, facilitating interregional power transfers through major interfaces like the California-Oregon Intertie and the Pacific DC Intertie. Another example is the combination of load and BPA wind generation shifting in opposite directions, which creates large net-load ramps that can only be addressed by deploying fast, flexible reserves—an area where the federal hydro fleet, including the LSR plants, contributes to grid stability (Figure S.3, ramping from 05:00 to 08:00). For comparison, the generation output of Grand Coulee (GCL) and Chief Joseph (CHJ)—two major BPA hydro plants—is also shown.

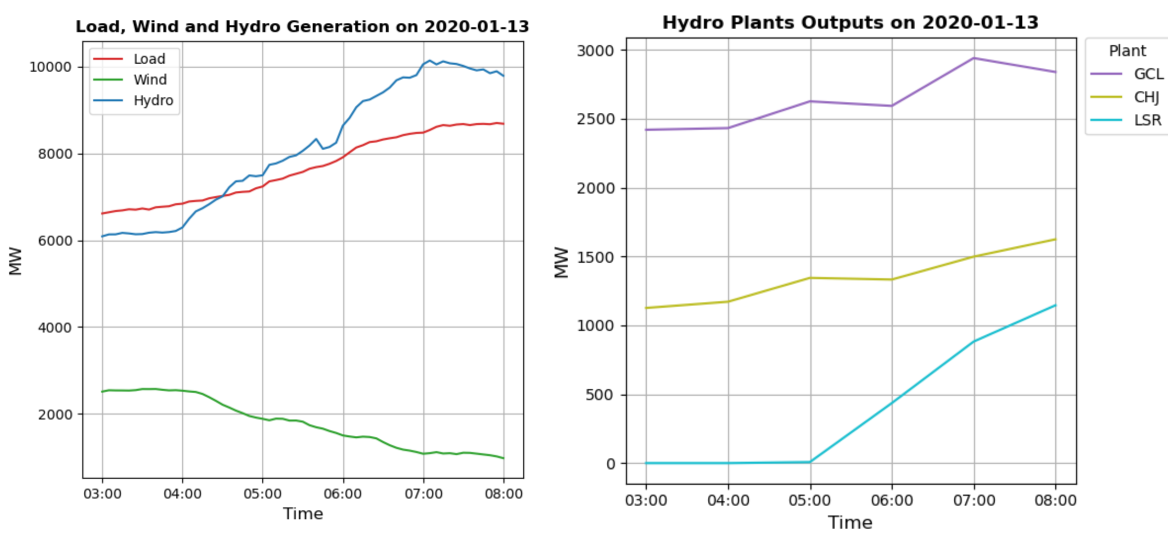

Figure S.3 BPA Generation Ramps on January 13, 2020:
(1) BPA Total Load, Wind, and Hydro Generation
(2) GCL, CHJ, and Aggregated LSR Plant Generation

LSR plants contribute to frequency support, offering both inertia and governor responses to prevent large frequency excursions during system disturbances throughout the Western Interconnection (Figure S.4). Frequency support service helps mitigate underfrequency load shedding risks and preserves system integrity when large generation units are lost. Additionally, their secondary response, enabled through AGC, further aids in stabilizing system frequency and returning it to its nominal value of 60 Hz.

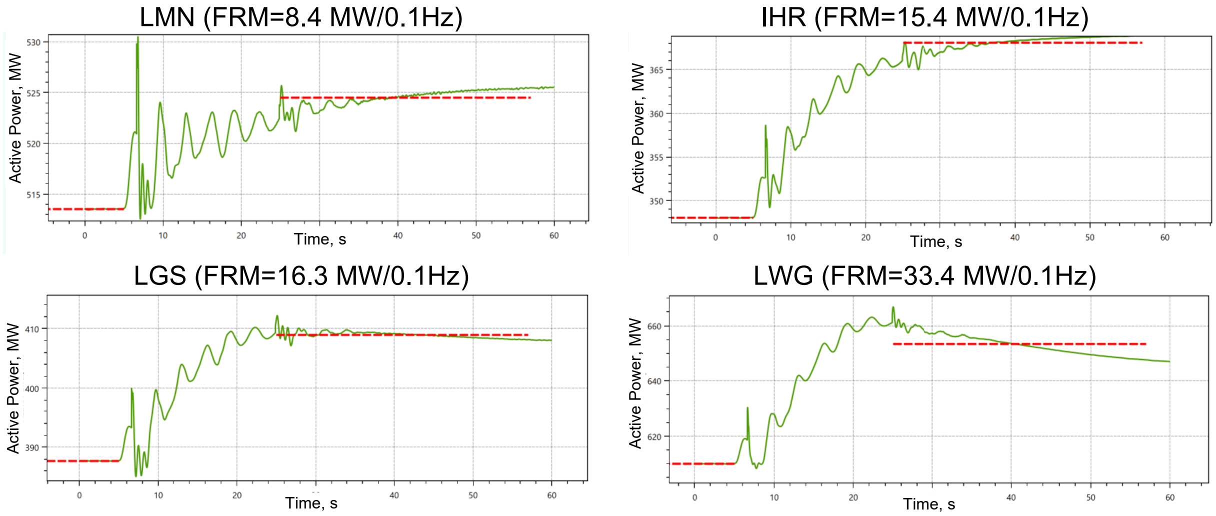

Figure S.4 Double Palo Verde outage simulation (LSR plants response) and calculated FRM metrics.

In addition to load balancing and operating reserves, LSR plants provide voltage and reactive power support. LSR plants provide voltage regulation during both normal operating conditions and under system contingencies. During light loading conditions, LSR plants absorb reactive power to prevent over-voltages, while at peak load periods, they supply reactive power to stabilize transmission networks.

During a few historical meteorologically driven grid stress events LSR plants have been observed to respond to adverse conditions. These periods often witness elevated system loads while renewable generation, particularly wind, tends to underperform due to adverse weather conditions. Figure S.5 illustrates BPA’s response to the September 6, 2022, heat-wave event, when California’s electrical demand reached a historic peak. During this period, wind generation was coincidentally near zero, and BPA’s hydro fleet—including the LSR plants—increased output to support California in maintaining system reliability.

Figure S.5 BPA total generation, net interchange, and LSR plants generation during peak load in California.

In summary, this report quantifies the reliability and flexibility contributions of LSR plants to BPA and Western Interconnection-wide operations. The number of services provided are proportional to their generating capacities, specifically measured for load balancing, ramping, voltage support, frequency stabilization, and interregional energy transfers. In a few instances of past weather driven events, LSR plants have been observed to provide additional energy, flexibility, and reserves to support operations. The contributions of LSR dams to energy, power, and grid services as a share of BPA's total contributions are summarized in Table S.1.

It should be noted that given the significant changes in the power system of the Western Interconnection over the past decade, the historical performance of these plants does not necessarily determine their potential future contribution to grid services. It is anticipated that changes in grid services due to changes in resource mix, addition of large loads, such as data centers, will change the nature and volume of grid services, the assessment of which is outside the scope of this report.

Acknowledgments

This work was supported by the U.S. Department of Energy's Grid Deployment Office and the Washington State Department of Commerce. We would like to thank the members of the Technical Committee for their valuable guidance and feedback throughout the study.

We are also grateful to Bonneville Power Administration and the U.S. Army Corps of Engineers for sharing data, as well as to our colleagues at Pacific Northwest National Laboratory for their technical input, valuable advice, and continued support.

Special thanks to Frank Tuffner and Jim Follum for reviewing the document and providing insightful comments.

Acronyms and Abbreviations

ACE	Area Control Error
AGC	Automatic Generation Control
BA	Balancing authorities
BON	Bonneville Dam
BPA	Bonneville Power Administration
CAISO	California Independent System Operator
COI	California–Oregon AC Intertie
CHJ	Chief Joseph Dam
FR	Frequency response
FRAT	Frequency Response Analysis Tool
FRM	Frequency Response Measure
FRO	Frequency Response Obligation
GCL	Grand Coulee Dam
HV	High voltage
IHR	Ice Harbor Dam
JDA	John Day Dam
LGS	Little Goose Dam
LMN	Lower Monumental Dam
LMP	Locational marginal price
LSR	Lower Snake River
LWG	Lower Granite Dam
MCN	McNary Dam
MVA	Megavolt-ampere
MVAR	Megavolt-ampere reactive
NERC	North American Electric Reliability Corporation
PDCI	Pacific DC Intertie
PF	Power factor
PMU	Phasor measurement unit
PNNL	Pacific Northwest National Laboratory
POI	Point of interconnection
RTD	Real-time dispatch
SCADA	Supervisory control and data acquisition
TDA	The Dalles Dam
TSAT	Transient Security Assessment Tool
UF	Underfrequency
UFLS	Underfrequency load shedding
USACE	United States Army Corps of Engineers
VAR	Volt-ampere reactive
WECC	Western Electricity Coordinating Council
WEIM	Western Energy Imbalance Market

Contents

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1.0 Introduction

Hydroelectric generation has traditionally been a reliable energy resource, providing baseload power and meeting peak demands. Hydropower's flexibility is enhanced by its ability to store water, which can be utilized during periods of low generation or high energy demand, including prolonged atypical weather events. Even run-of-river projects can provide short-term energy reserves for peak periods (typically 1-4 hours). These resources have played a key role in grid balancing as new variable energy sources, such as wind and solar, are integrated. For instance, the Federal Columbia River Power System adjusts hydroelectric output to complement fluctuating wind energy, while pumped storage systems in California were initially designed to balance excess nuclear energy generated at night. A map of the major hydro power projects in the Pacific Northwest region is shown in Figure 1-1.

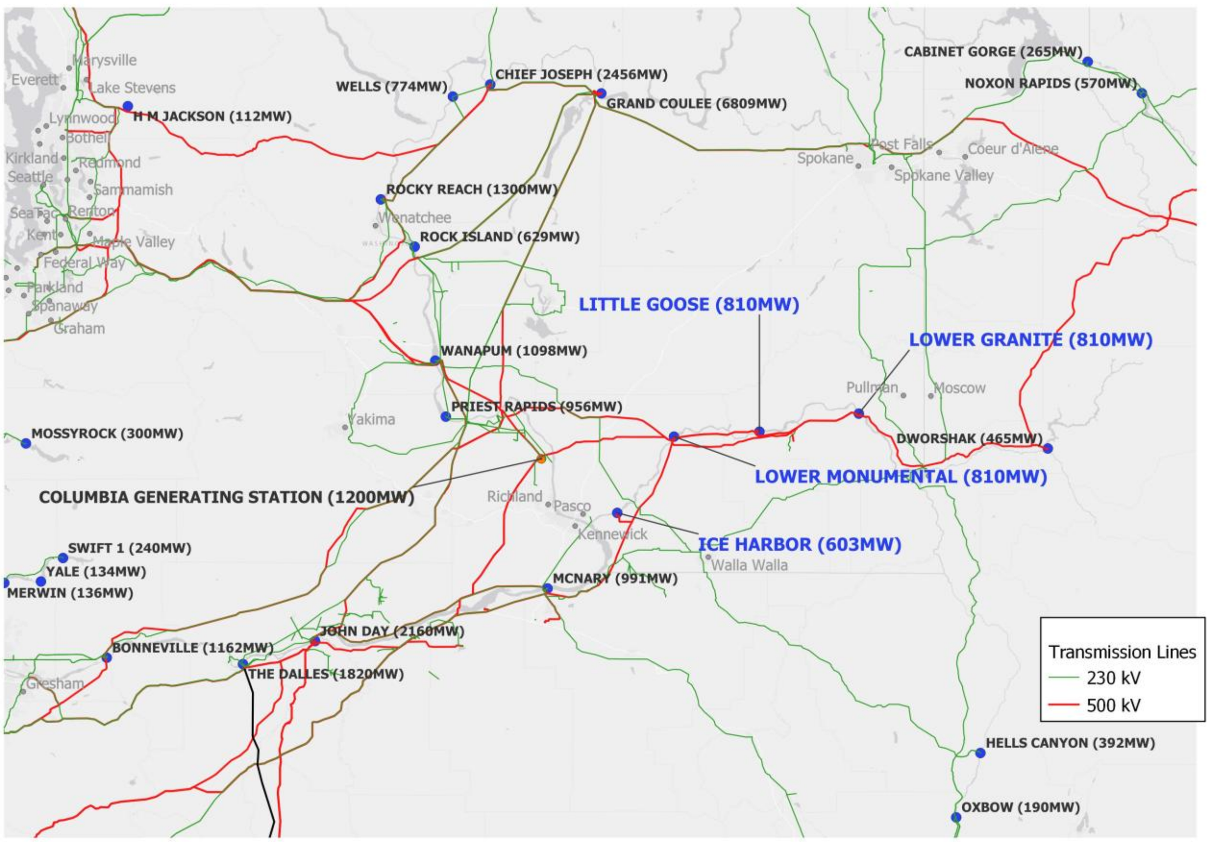

Figure 1-1. Major hydro power plants in the Pacific Northwest region (LSR plants in blue text).

Over the last decade, the Western Interconnection has experienced significant changes in its generation mix, with large amounts of solar and wind energy integrated into the grid. As a result, the region's net load profile has shifted noticeably, especially in California, with a pronounced midday drop in net load due to high solar generation, followed by a steep evening ramp as solar output declines while demand remains high. Consequently, this has led to significant power swings during sunset and sunrise. Traditionally, power transfer along the west coast occurred from north to south, moving from the Pacific Northwest to California. However, power transfer patterns fluctuate. During the day, power flows from south to north due to surplus solar generation in California. After sunset, power transfers shift back to flowing from north to south to compensate for the reduction in solar generation during nighttime conditions. Additionally, variations and intermittency of wind generation need to be accounted for. To manage these fluctuations and balance load with generation, controllable and predictable generation resources are essential. In the Western Interconnection, these balancing services are currently provided primarily by conventional hydroelectric and gas-fired power plants. In the Pacific Northwest, hydropower has played a key role in supporting resource adequacy and grid reliability.[1]

In this study, we focus on the contribution of the four Lower Snake River (LSR) hydroelectric plants to grid services provided by the Bonneville Power Administration (BPA). It is important to emphasize that we are examining only the historical contributions of these four plants to various grid services. Given the significant changes in the power system of the Western Interconnection over the past decade, the historical performance of these plants does not necessarily determine their potential future contribution to grid services. It is anticipated that changes in grid services due to changes in resource mix, addition of large loads, such as data centers, will change the nature and volume of grid services, the assessment of which is outside the scope of this report.

The goal of this research was to develop a methodology for evaluating the contribution of LSR plants and to evaluate their contributions, primarily based on historical measurements and data, to various grid services required for the reliable and resilient operation of the electric power system. The following reliability services have been identified for further evaluation:

- Energy and capacity: This involves examining the baseload energy provided by LSR plants over various periods, during both normal and extreme conditions.
- Balancing, regulation, and ramping: At all times, load and generation must be balanced, including variable renewable generation. For instance, when wind generation unexpectedly decreases or increases, other generation sources must be ramped up or down accordingly to adjust the power produced. A similar concept applies to load changes (i.e., as load changes, generation needs to be adjusted to meet demand). In this context, we investigate the historical contributions of LSR plants to balancing, frequency regulation, and ramping services. Regulation refers to the continuous adjustment of interchange and frequency through automatic generation control (AGC) action, while load following involves adjustments in generation to accommodate changes in load. Interchange is defined as transactions between balancing authorities (BAs) that allow an importing BA to balance its own demand and generation.
- Voltage and reactive power support: Voltage and reactive power support are needed because reactive power supports bus voltages within permissible limits, thereby ensuring correct equipment operation, maintaining power-quality criteria—such as minimal deviation from nominal voltage—and preventing voltage instability or collapse that could trigger widespread outages. Steady-state voltage support is offered during normal load changes. During light loading conditions (overnight), reactive power is absorbed to prevent overvoltages, while during the day, when transmission lines are heavily loaded, generators supply reactive power to support voltages in load centers and over transmission lines. Dynamic voltage support is offered by the fast action of the excitation circuit, which is essential during system contingencies.[2] We examine the contribution of LSR plants to voltage support in the transmission system and neighboring load centers under steady-state and contingency scenarios.

[1] Western Powerpool. "Exploring a Resource Adequacy Program for the Pacific Northwest," source: https://www.westernpowerpool.org/resources/exploring-a-resource-adequacy-program-for-the-paci

[2] The excitation system of a synchronous generator provides a controlled DC current to the rotor's field windings to control the magnetic field inside the generator. By adjusting this magnetic field, the system helps regulate the generator's voltage and supports the stability of the power grid.

- Frequency support: This includes inertia response, primary (governor response), and secondary frequency response (AGC). Following the loss of a large generation unit, the system experiences a frequency dip. If the dip is too large, it can lead to underfrequency load shedding (UFLS) or even additional generation underfrequency (UF) protection trips. Every generator with rotational mass provides an inertia response, which influences the rate of frequency decline. A power system lacking sufficient inertia would exhibit a faster frequency decline, potentially leading to UFLS because governors might not have enough time to respond. To prevent large frequency excursions, units that are not base-loaded[1] (governor blocked) will increase power output to balance load and generation. Primary response is achieved by hydro generation and gas-fired units; however, gas-fired units have limited governor response due to temperature increases within the turbine. Nuclear power plants usually have blocked governors and do not participate in primary frequency response. The secondary (AGC) response helps return frequency to 60 Hz and correct interchange deviations according to schedule. Generating units without governor block can be utilized for AGC, although only some units are used for this purpose. We will investigate the participation of LSR plants in frequency response.
- Transmission congestion management: Transmission lines are constructed to deliver generated power to load centers. Changes in the generation mix (retirements and additions) can lead to congestion in some parts of the system and underloading in others. We examine the role of LSR plants in helping manage transmission congestion.
- System restoration and black start: Each BA/transmission operator must provide specific, detailed procedures for system restoration, approved by Reliability Coordinators. Due to the sensitivity and confidentiality of these procedures, we cannot comment on the use of LSR plants for black start since we do not have access to detailed BPA protocols on the system restoration. However, it is confirmed by BPA and United States Army Corps of Engineers (USACE) that some or all generators installed in LSR plants have black start capabilities and can play an important role in the system restoration. We would refer readers to BPA/USACE for more specific information on this topic due to the confidentiality of black start procedures.

For each of the above-mentioned reliability services, we define specific metrics to estimate the impact of LSR hydropower plants on these services. It is important to note that some capabilities, such as balancing, regulation, and frequency response, have BA-wide and even interconnection-wide impacts and can be evaluated in terms of each plant's contribution (share or percentage) to the total BA reliability requirements. Other capabilities, like voltage support or transmission congestion relief, have primarily local impacts, though they remain essential for overall system reliability. These require different types of metrics to evaluate contributions to local reliability needs, such as a required reactive power generation for voltage support or active power generation to supply local load centers and relieve congested transmission lines.

This study is primarily based on publicly available information collected from the BPA, Energy Information Administration (EIA), and USACE websites. It includes data on BPA load and generation, transmission flows, and the dispatch of individual hydroelectric power plants. The data sources used are listed in Table 1-1. We downloaded data covering the period from January 2020 to December 2024, created a dedicated project database, and developed analytical scripts in Python to analyze various grid services. A planning Western Electricity Coordinating Council (WECC) case available at Pacific Northwest National Laboratory (PNNL),

[1] If unit is base-loaded (governor blocked), it cannot change generation output, but its output stays constant following disturbances. Nuclear and coal fired plants are typically base loaded. Solar and wind generation also do not change output following system disturbances.

which includes power flow and dynamic data, was used to simulate information that is not publicly available but necessary for this study.

The rest of this document is structured as follows: Chapter 2 examines the contribution of LSR plants to BPA's total generation, with a focus on their role in BPA's generation capacity. Chapters 3 and 4 explore the role of LSR plants in providing inter-hour and intra-hour flexibility, focusing on ramping and balancing services. Chapter 5 addresses the role of LSR plants in providing voltage support under both steady-state and dynamic conditions. Chapter 6 analyzes the contributions of LSR plants to frequency response within the Western Interconnection. Finally, Chapter 7 discusses the historical contributions of LSR plants to the reliability of the Western Interconnection during specific weather driven events (e.g., heat waves and cold snaps) when the power system becomes stressed and increasingly vulnerable.

Table 1-1. Public data sources used in the study

Data	Resolution	Source	Source Link
BPA total BA Loads, Resources (Generation: wind, solar, hydro, nuclear), Net Interchange, wind and solar forecast	5-minute	BPA Transmission (Public)	https://transmission.bpa.gov/Business/Operations/Wind/default.aspx
Federal Columbia River Project Operation Data	5-minute	USACE	https://www.nwd-wc.usace.army.mil/dd/common/dataquery/www/
US BA-level loads, generation by fuel type, net interchange	Hourly	EIA 930/EIA Electric Grid Monitor API	https://www.eia.gov/electricity/gridmonitor/dashboard/electric_overview/US48/US48
BPA BA Area Control Error	2-minute	BPA Transmission (Public)	https://transmission.bpa.gov/Business/Operations/ACE_FERC784/
Intercontinental Exchange Wholesale Hub Prices	Daily	EIA	https://www.eia.gov/electricity/wholesale/
EIM[1] Exchanges and LMPs[2] for Pacific Northwest Nodes	5-minute	CAISO[3] OASIS	http://oasis.caiso.com/mrioasis/logon.do
Paths and interties	15-minute	BPA Transmission (Public)	https://transmission.bpa.gov/Business/Operations/Paths/default.aspx
BPA reserve deployed and max reserve available	5-minute	BPA Transmission (Public)	https://transmission.bpa.gov/Business/Operations/Wind/

[1] Energy Imbalance Market; [2] Locational Marginal Price; [3]California Independent System Operator

2.0 Capacity and Energy

In this chapter, we will examine the historical data on BPA generation and contribution of LSR plants to BPA capacity and balancing capabilities. The installed capacity of the LSR dams is shown in Table 2-1. The total installed capacity of all four plants is about 3 GW.

Table 2-1. LSR dams and other major hydro plants installed capacity

Plant name	Code	Capacity, MW
Lower Granite	LWG	810
Little Goose	LGS	810
Lower Monumental	LMN	810
Ice Harbor	IHR	603
Aggregated LSR Dams	LSR	3033
Grand Coulee	GCL	6809
Chief Joseph	CHJ	2456
John Day	JDA	2160
The Dalles	TDA	1820
Bonneville	BON	1162
McNary	MCN	991

BPA BA generation by type (e.g., hydro, nuclear, wind, solar), load, and interchange data are available on the BPA website, and information on individual hydro plant generation is available at the USACE data portal. A time span of five years (2020–2024) was analyzed. Detailed information, including time-series plots and basic statistics (monthly averages, boxplots, etc.), is provided in Appendix A for BPA BA information and Appendix B for LSR power plant data.

The average monthly BPA hydro generation for the years 2020–2024, along with the corresponding share from the LSR plants, is shown in Table 2-2 and Figure 2-1. The share of LSR generation in the total BPA hydro generation depends on the month of the year and has been consistent over the last five years, averaging around 8–10%. LSR generation tends to be highest in May–July and lowest in April, September, and October.

Table 2-2. Major BPA hydro plants annual statistics

Plant	Metric	2020	2021	2022	2023	2024
Total BPA Hydro	average, MW	8373	7468	8488	6453	6399
	maximum, MW	14198	13302	14915	14175	11165
LWG	average, MW	196	155	198	177	146
	maximum, MW	753	538	842	738	499
	average, %	2	2	2	3	2
LGS	average, MW	193	154	186	178	165
	maximum, MW	634	527	560	699	549
	average, %	2	2	2	3	3
LMN	average, MW	189	154	193	178	146
	maximum, MW	684	521	823	855	479
	average, %	2	2	2	3	2
IHR	average, MW	182	162	169	155	154
	maximum, MW	475	477	478	444	469
	average, %	2	2	2	2	2

Plant	Metric	2020	2021	2022	2023	2024
LSR	average, MW	761	624	746	687	611
	maximum, MW	2324	1943	2650	2497	1918
	average, %	9	8	9	11	10
GCL	average, MW	2556	2316	2699	1929	1922
	maximum, MW	4706	4630	5395	4881	4311
	average, %	31	31	32	30	30
CHJ	average, MW	1359	1255	1431	1075	1052
	maximum, MW	2331	2399	2375	2393	2275
	average, %	16	17	17	17	16
JDA	average, MW	976	857	1020	785	796
	maximum, MW	1758	1699	1813	1600	1334
	average, %	12	11	12	12	12
TDA	average, MW	767	687	777	622	704
	maximum, MW	1381	1447	1437	1320	1138
	average, %	9	9	9	10	11

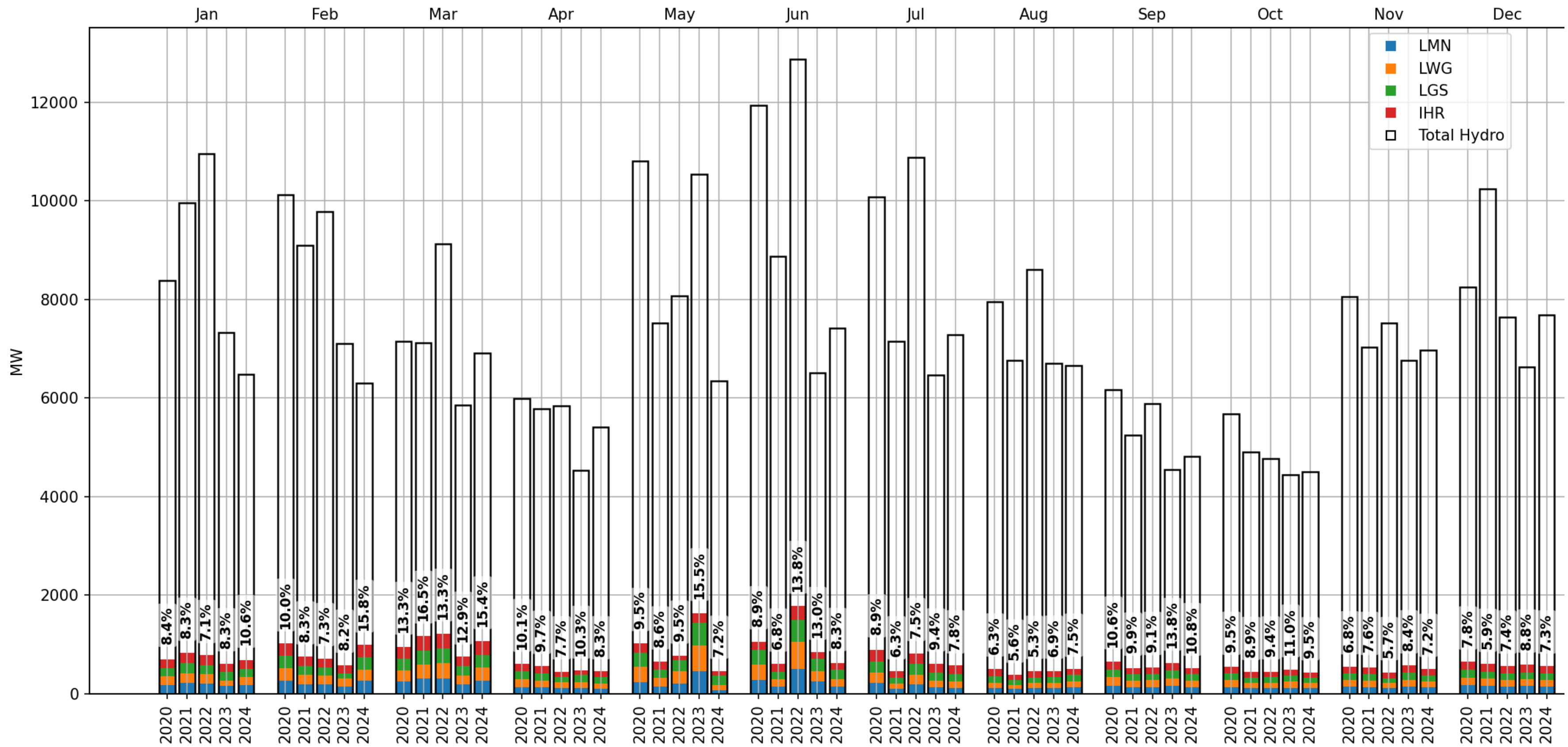

Figure 2-1. Average monthly generation by LSR plants and their contribution to BPA total hydro generation for 2020–2024.

Analysis of total BPA hydro generation by month for the years 2020 through 2024 is shown in Figure 2-2, while the aggregated generation from LSR plants is depicted in Figure 2-3. Boxplots, which are commonly used in statistical analyses, are utilized to illustrate the distribution of the values.[1] As seen in the figure, clear seasonal patterns in hydro generation emerge, remaining consistent across the analyzed years except for several instances explained by varying water conditions (low- or high-water years). Hourly analysis for each season in Figure 2-4 and Figure 2-5 also shows hourly patterns (varying by season) in LSR generation dispatch due to participation in the system balancing process.

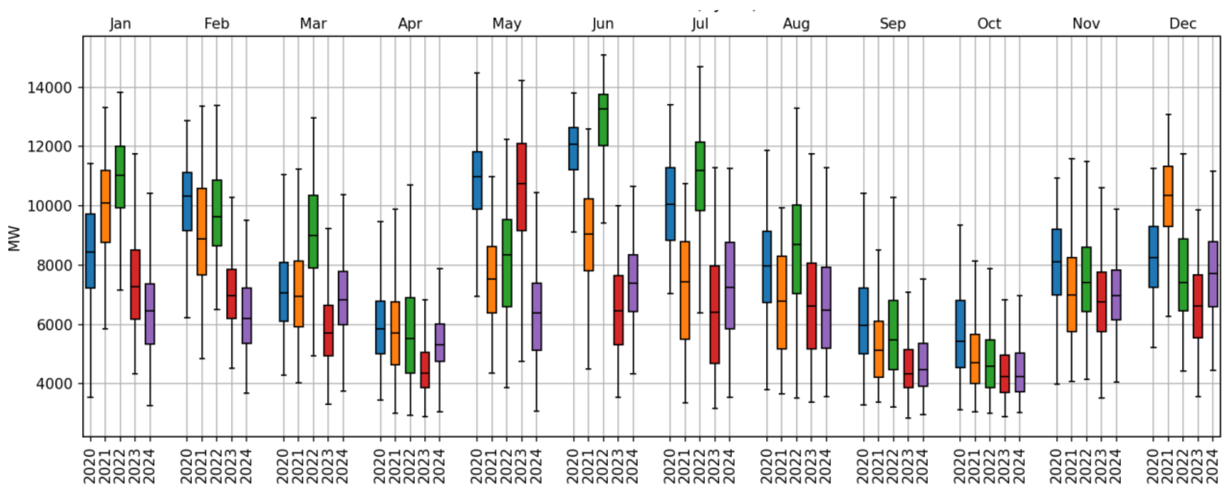

Figure 2-2. Monthly BPA total hydro generation statistics for 2020–2024.

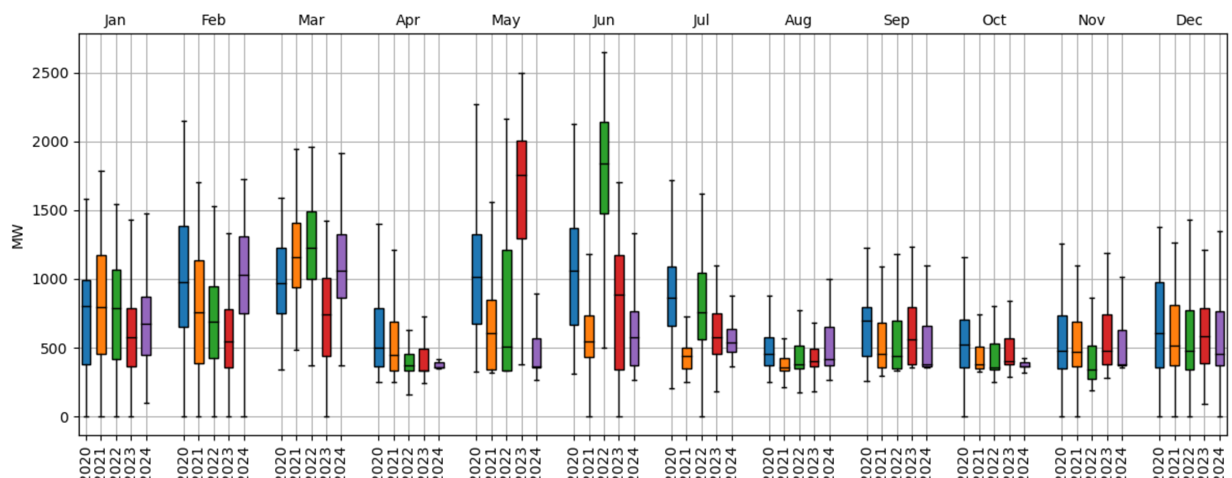

Figure 2-3. Monthly aggregated LSR statistics for 2020–2024.

[1] A boxplot, also known as a box-and-whisker plot, is a graphical representation that summarizes the distribution of a dataset by displaying key statistical measures. Specifically, it illustrates the median (middle line within the box), the first quartile (lower edge of the box), the third quartile (upper edge of the box), and whiskers extending to the smallest and largest data points within 1.5 times the interquartile range (IQR). The IQR is calculated as the difference between the third quartile (Q3) and the first quartile (Q1), representing the middle 50% of the data. Typically, data points beyond 1.5 times the IQR from the quartiles are marked as outliers. However, in our analysis, outliers are not displayed to maintain clarity and readability of the plots. Boxplots effectively visualize data variability, central tendency, and skewness, allowing straightforward comparisons between different datasets or conditions.

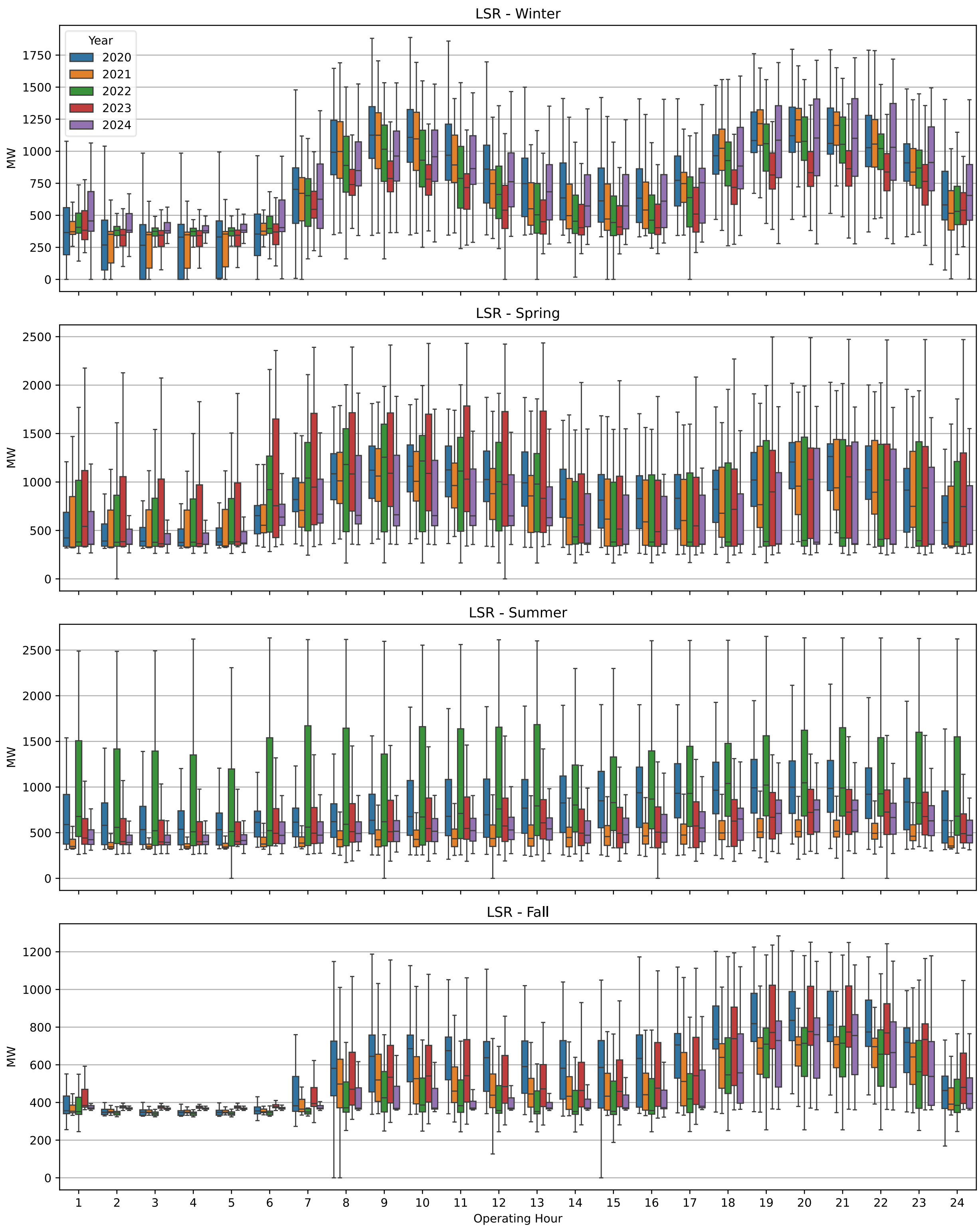

Figure 2-4. Hourly aggregated LSR statistics by season for 2020–2024.

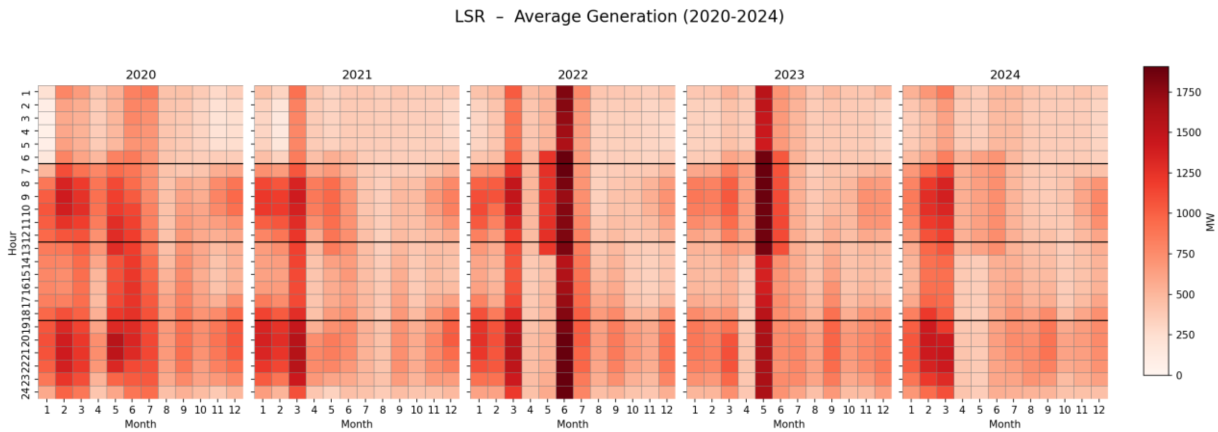

Figure 2-5. Hourly average LSR generation (2020–2024).

Figure 2-6 shows the correlation in 2024 between LSR plants, GCL, CHJ, and BPA load, total wind generation, net interchange, and net-load accounting for interchange (calculated as load−wind−solar+interchange). The figure indicates that the generation patterns of all four LSR plants are highly correlated, suggesting that many analysis cases can be simplified by using an aggregated representation of the LSR plants. It is also evident that BPA hydro generation is highly correlated with net load (correlation = 0.98), confirming that the hydro fleet is the primary resource for balancing in BPA. GCL, as the largest plant, also plays a major role, with a correlation of 0.79 with net load.

Additionally, monthly correlation analyses for 2020–2024 were performed between BPA hydro generation and load, net interchange, wind generation, and net load to identify consistent patterns across years and months (Figure 2-7). These results demonstrate that BPA uses hydroelectric plants in the balancing process and in mitigating variability from wind generation (as indicated by the negative correlation).

Figure 2-8 presents correlation analysis for 2020–2024 between the aggregated LSR plant and individual plants (GCL, CHJ, JDA) with total BPA hydro generation. The analysis highlights the complexity of hydro dispatch: hydro plants do not operate in a uniform manner, and dispatch patterns are influenced by multiple factors, including month, season, and water year. For instance, LSR generation is correlated with total BPA hydro generation during the January–March period; however, the correlation decreases in the April–June timeframe. This decline can be attributed to water being spilled at LSR plants to meet environmental (fish passage) requirements during that period (see Figure 2-9 and Figure 2-10).

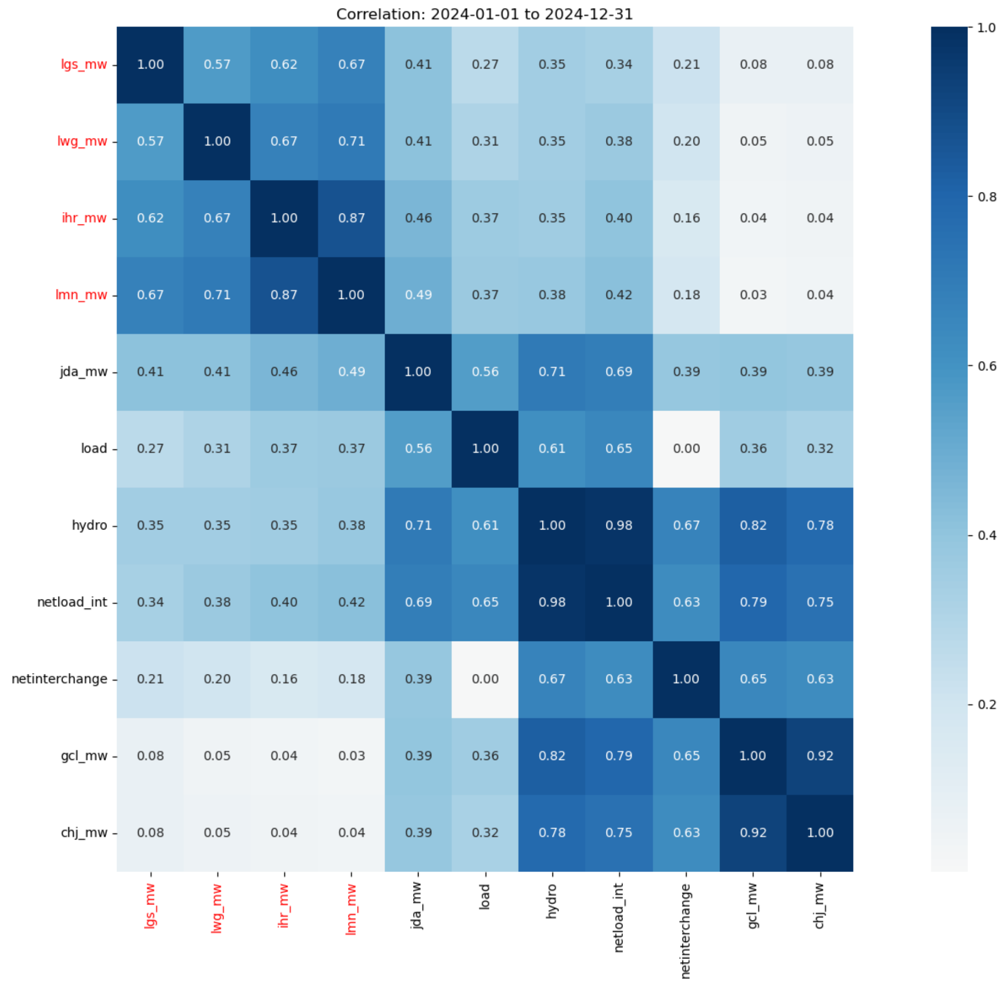

Figure 2-6. Correlation in 2024 between LSR plants, GCL, CHJ, and BPA load, total wind generation, net interchange, and net load

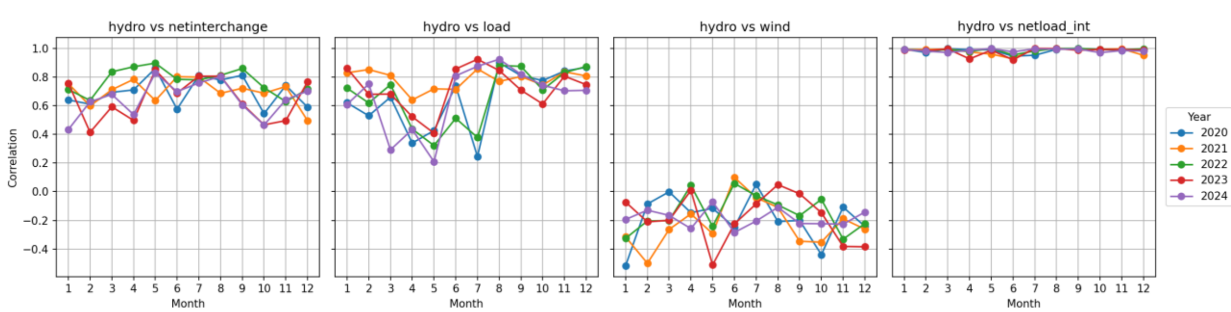

Figure 2-7. Monthly correlation of BPA hydrogeneration with net interchange, load, wind generation, and net load for 2020–2024.

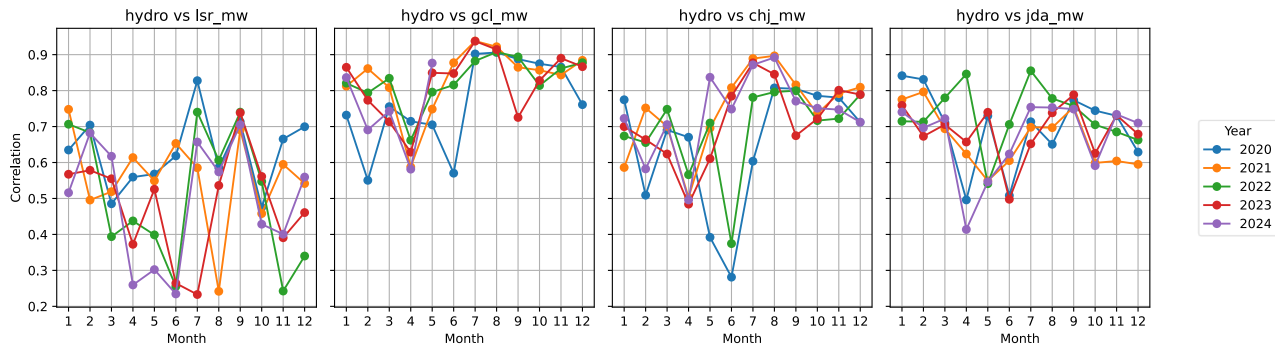

Figure 2-8. Monthly correlation of BPA hydrogeneration with LSR, GCL, CHJ, and JDA for 2020–2024.

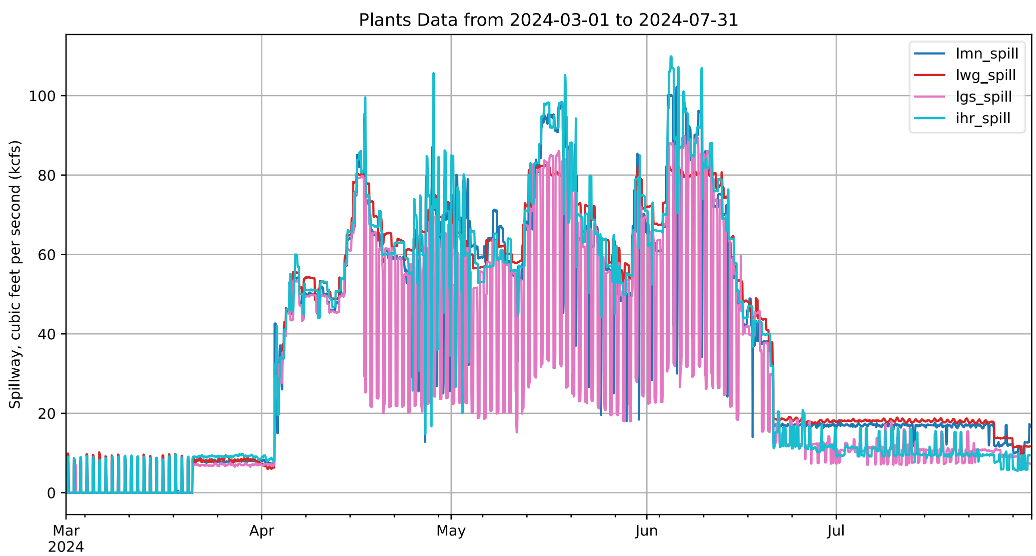

Figure 2-9. LSR plants spillway (March 2024–July 2024).

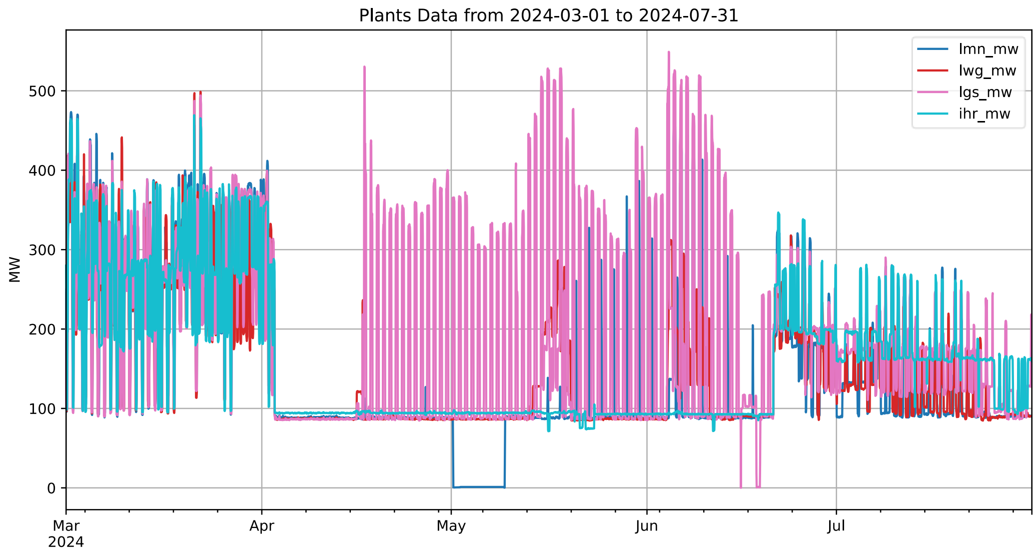

Figure 2-10. LSR plants generation (March 2024–July 2024).

3.0 Flexibility: Inter-Hour Ramping & Balancing

To quantify LSR dams' capacity flexibility analysis, we applied an approach similar to the CAISO Flexible Capacity Needs Assessment, which CAISO performs annually[1]. CAISO estimates the amount of flexible capacity needed each month to manage changes in electricity demand and supply, particularly during rapid ramping periods, such as mid-morning and late afternoon. These estimates are published each year to assess resource adequacy—ensuring there is sufficient generation capacity and ramping capability to meet demand and maintain system balance—and are based on the largest expected three-hour ramps in net load.

3.1 Methodology

The following data were used in the analysis (see Table 1-1 for details on the data source):

- BPA BA time series for load, generation by resource class (including hydro), and net interchange (California–Oregon AC Intertie [COI] and PDCI), at hourly resolution for 2020–2024.
- Individual hydro plant dispatch from USACE, aggregated to the LSR plants and selected benchmark projects (e.g., GCL, CHJ, JDA).
- CAISO solar output for correlation with interchange behavior.

Derived variables and ramp definitions:

- Net load at time t is defined as: NL(t) = Load(t) − WindGeneration(t) − SolarGeneration(t).
- Inter-hour ramp (Δ1h): $R_1(t) = X(t) - X(t-1h)$, where X is a variable such as BPA total hydro or an individual plant's generation.
- Three-hour ramp (Δ3h): $R_3(t) = X(t) - X(t-3h)$.

Analytical approach:

- Time series were grouped by month and by season to assess temporal patterns. Descriptive statistics (median, interquartile range, and 5th/95th percentiles) were computed and visualized using box plots to illustrate distributions and variability.
- Relationships among variables (e.g., interface flows vs. BPA hydro generation, BPA/CAISO net load, and CAISO solar) were evaluated using correlation analysis.
- Heat maps were used to visualize monthly and hourly characteristics on a single plot, highlighting seasonal and hourly patterns.

3.2 Net Load

Figure 3-1 shows three-hour ramps in the net load for the BPA, calculated for the years 2020–2024, along with marks for the top ten positive and negative ramps during this period, as listed in Table 3-1. The maximum positive ramp, approximately 2,800 MW, occurred on January 13, 2020, at 7 a.m. The maximum three-hour downward ramp of 2,574 MW occurred on January 30, 2022, at 10 p.m. As seen in Table 2, all maximum ramps occurred during coincident, opposite-direction shifts in load and wind generation. An example of such an unfavorable

[1] CAISO. 2023. Final Flexible Capacity Needs Assessment for 2024. Folsom: CAISO. https://stakeholdercenter.caiso.com/InitiativeDocuments/Final-2024-Flexible-Capacity-Needs-Assessment-v2.pdf.

combination, corresponding to the largest net load ramp, is presented in Figure 3-2. Hydro generation ramped up from 6 GW at 4 a.m. to 10 GW at 7 a.m., with LSR plants contributing approximately 1 GW to the total ramp-up.

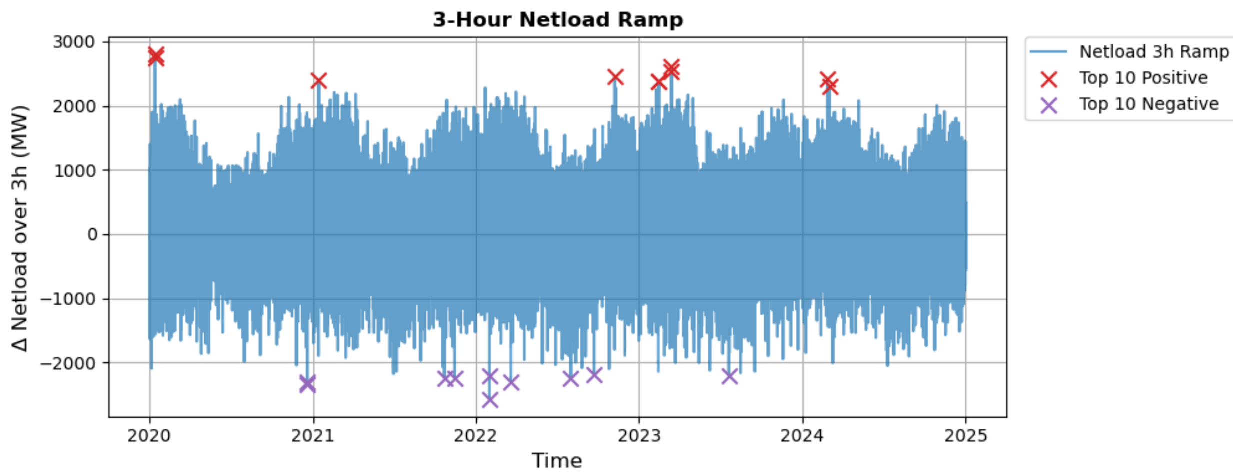

Figure 3-1. Net load 3-hour ramps in 2020–2024

Table 3-1. Positive and negative 3-hour net load ramps in 2020–2024

Timestamp	Net Load 3h Ramp	Load 3h Ramp	Wind 3h Ramp	Solar 3h Ramp
1/13/2020 7:00	2800	1629	−1171	0
1/13/2020 6:00	2755	1548	−1206	0
3/14/2023 7:00	2608	1784	−824	0
3/14/2023 6:00	2525	1567	−958	0
11/7/2022 7:00	2450	1653	−803	6
2/26/2024 6:00	2424	1686	−748	10
1/13/2021 17:00	2405	790	−1615	0
2/14/2023 6:00	2382	1509	−873	0
2/14/2023 7:00	2378	1610	−773	6
3/1/2024 18:00	2304	477	−1806	−20
9/21/2022 23:00	−2192	−938	1254	0
7/20/2023 22:00	−2207	−1159	1103	−54
1/30/2022 23:00	−2213	−848	1365	0
10/22/2021 0:00	−2247	−746	1501	0
11/14/2021 0:00	−2248	−803	1444	0
7/31/2022 23:00	−2256	−1356	955	−54
3/19/2022 13:00	−2301	−368	1876	57
12/19/2020 0:00	−2307	−990	1317	0
12/18/2020 23:00	−2354	−1059	1295	0

Timestamp	Net Load 3h Ramp	Load 3h Ramp	Wind 3h Ramp	Solar 3h Ramp
1/30/2022 22:00	−2574	−829	1745	0

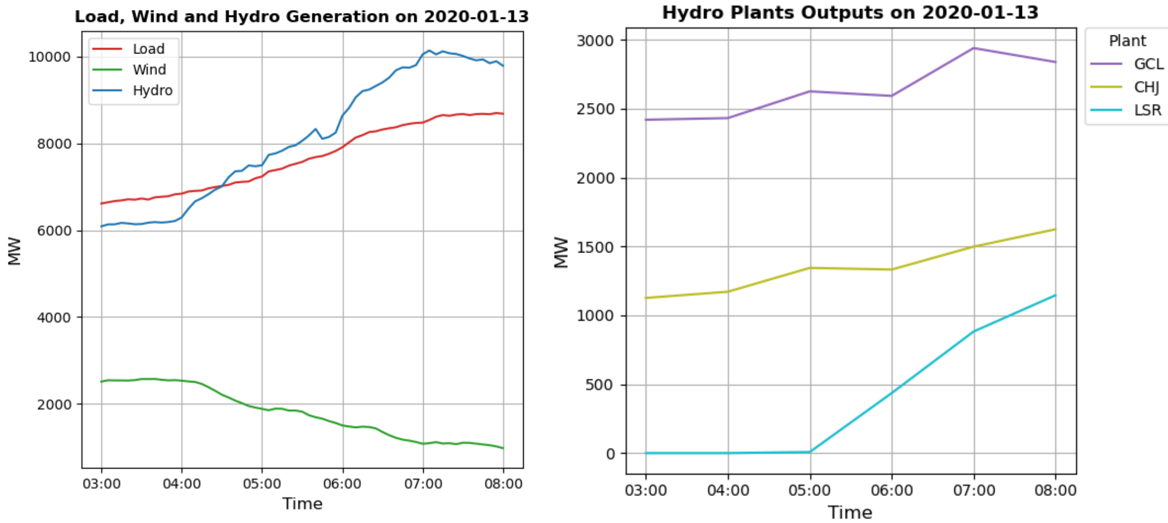

Figure 3-2. BPA generation ramps on January 13, 2020: (1) BPA total load, wind, and hydrogeneration, (2) GCL, CHJ, and aggregated LSR plant generation

Figure 3-3 presents the monthly distributions of 3-hour net load ramps from 2020 to 2024, with the upper panel showing ramp-up statistics and the lower panel displaying ramp-down statistics. On average, 3-hour ramp-up magnitudes range between 500 MW and 1,200 MW, with extreme ramp-ups exceeding 2,500 MW, particularly during the winter and early spring months (January–March). Ramp-down magnitudes follow a similar range, generally between −500 MW and −1,200 MW, with extreme downward ramps reaching below −2,000 MW, most frequently in April and May, indicating strong seasonal variability. The distributions reveal that ramp variability is higher in spring and winter, likely due to water availability, weather conditions, and fluctuations in renewable generation. In contrast, the summer months (July–September) exhibit more stable and moderate ramping behavior. Year-to-year variations are relatively small, with consistent patterns observed across all five years, suggesting these ramping characteristics are driven primarily by seasonal operational factors rather than interannual differences.

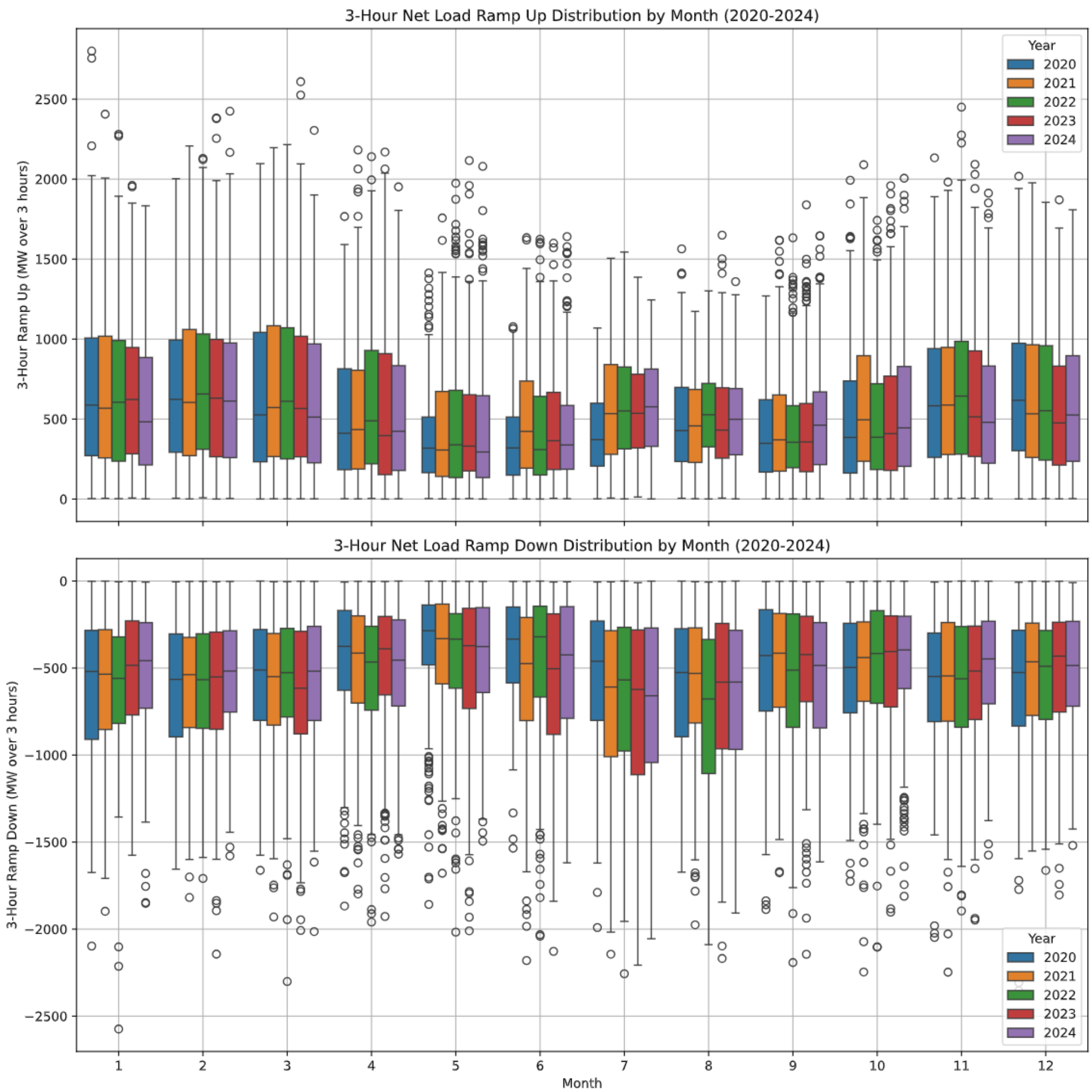

Figure 3-3. Net load 3-hour ramps monthly distribution in 2020–2024

To evaluate the ramping performance of the BPA hydro fleet and the participation of LSR plants, three-hour ramps were calculated and analyzed. Figure 3-4 shows the monthly distribution of three-hour ramps in BPA hydro generation, which has a noticeable seasonal pattern. The movement (ramping) of the hydro generation fleet significantly exceeds net load variation, and in extreme cases, exceeds 5,000 MW of ramp-up and ramp-down over a three-hour period. This can be attributed to interchange flows (exports) to neighboring systems (Figure 3-5), which helps maintain the supply demand balance during solar ramps, both in the mornings (solar ramps up) and afternoons (solar ramps down).

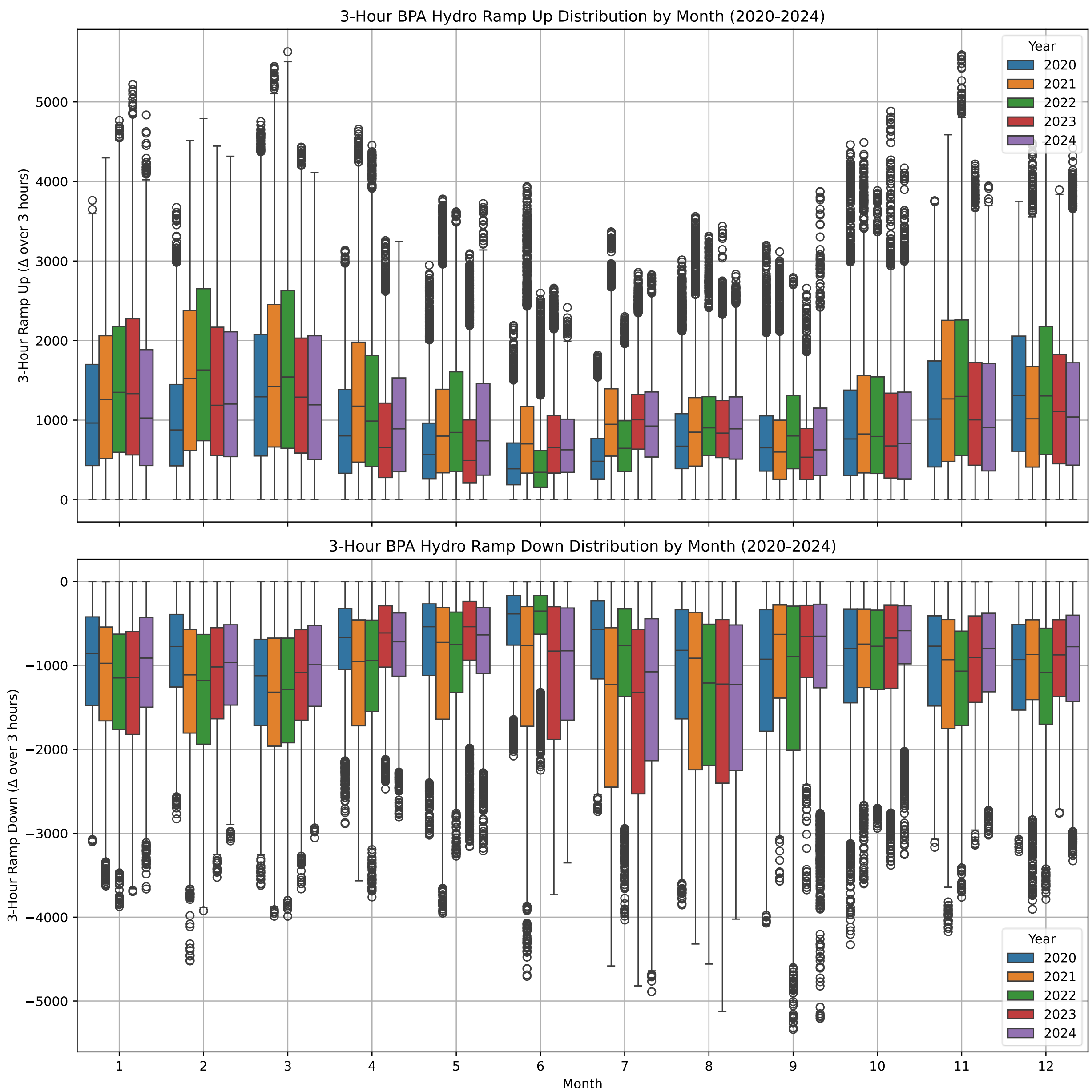

Figure 3-4. BPA hydro generation 3-hour ramps monthly distribution in 2020–2024

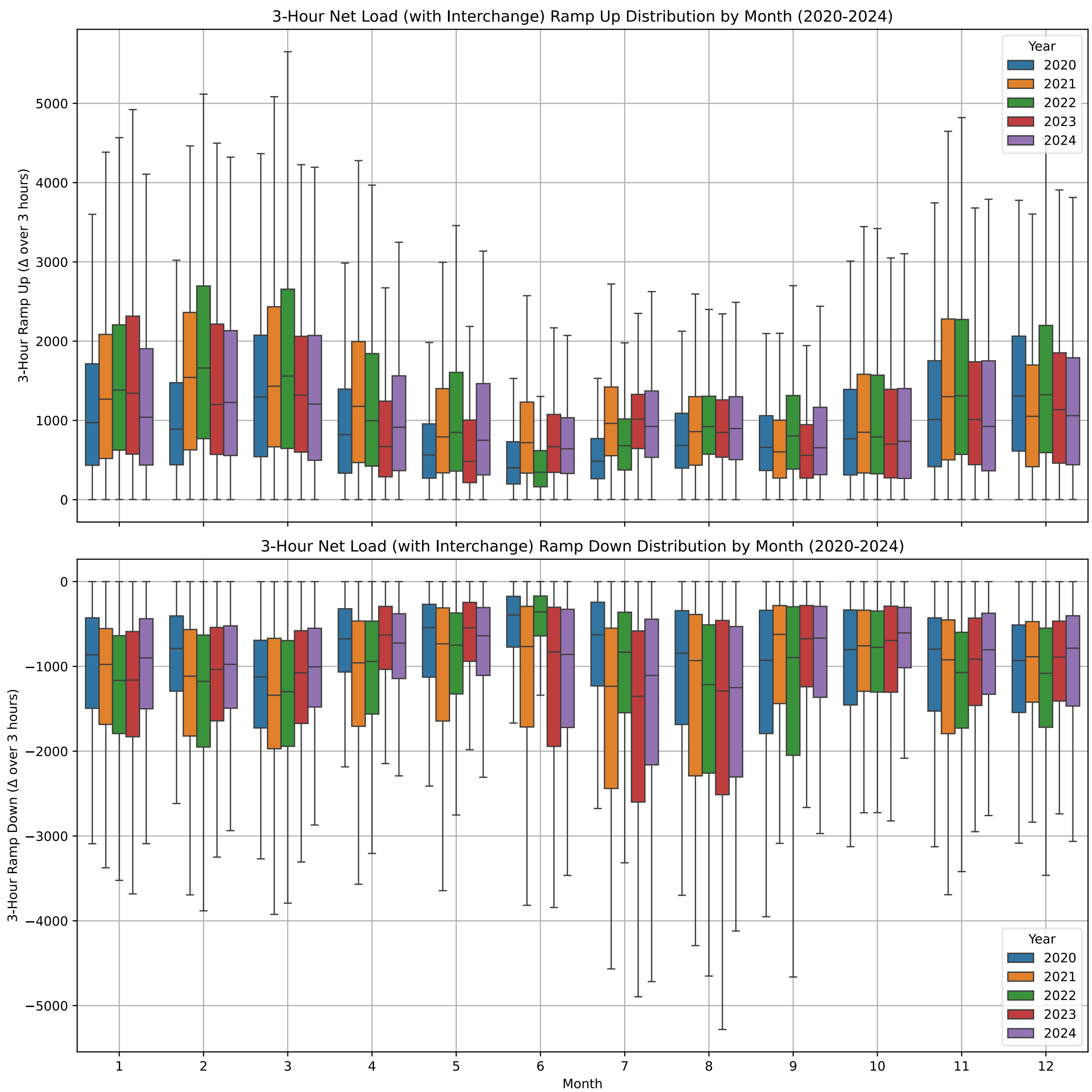

Figure 3-5. Net load with Interchange 3-hour ramps monthly distribution in 2020–2024

Figure 3-6 depicts the distribution of three-hour ramps for aggregated LSR plants (plots for individual LSR plants are given in Appendix B.3). It shows highly distinct seasonal and interannual patterns. From January to March, the LSR plants actively contribute to hydro generation dispatch. However, during the May to October period, their movement is limited, growing again in the November to December period.

For comparison, Figure 3-7 and Figure 3-8 present the monthly distribution patterns of the CHJ and JDA plants. Unlike the LSR plants, CHJ and JDA exhibit more consistent ramping behaviors throughout the year. Specifically, CHJ ramps are heightened in July and August, while JDA shows increased movements in May—periods when ramping by LSR plants is constrained. These differences underscore the distinct operational strategies employed by each plant, which are shaped by various factors, including water availability, regional ecological requirements, and the overall energy market dynamics. This necessitates complex optimization of hydro plant dispatch, influencing each plant's contribution to the grid balancing process and its ability to adapt to changing seasonal conditions.

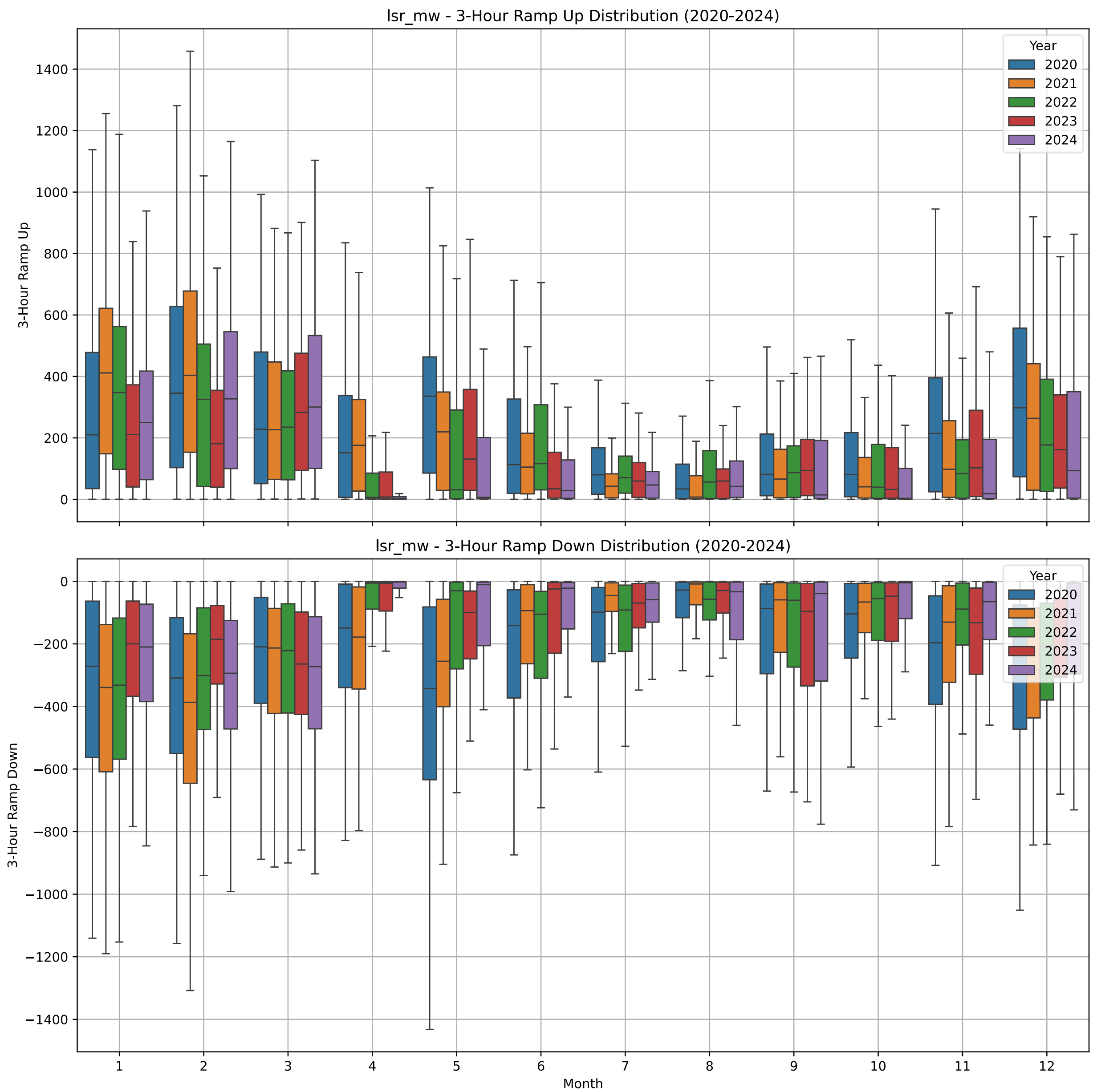

Figure 3-6. Aggregated LSR plant 3-hour ramps monthly distribution in 2020–2024

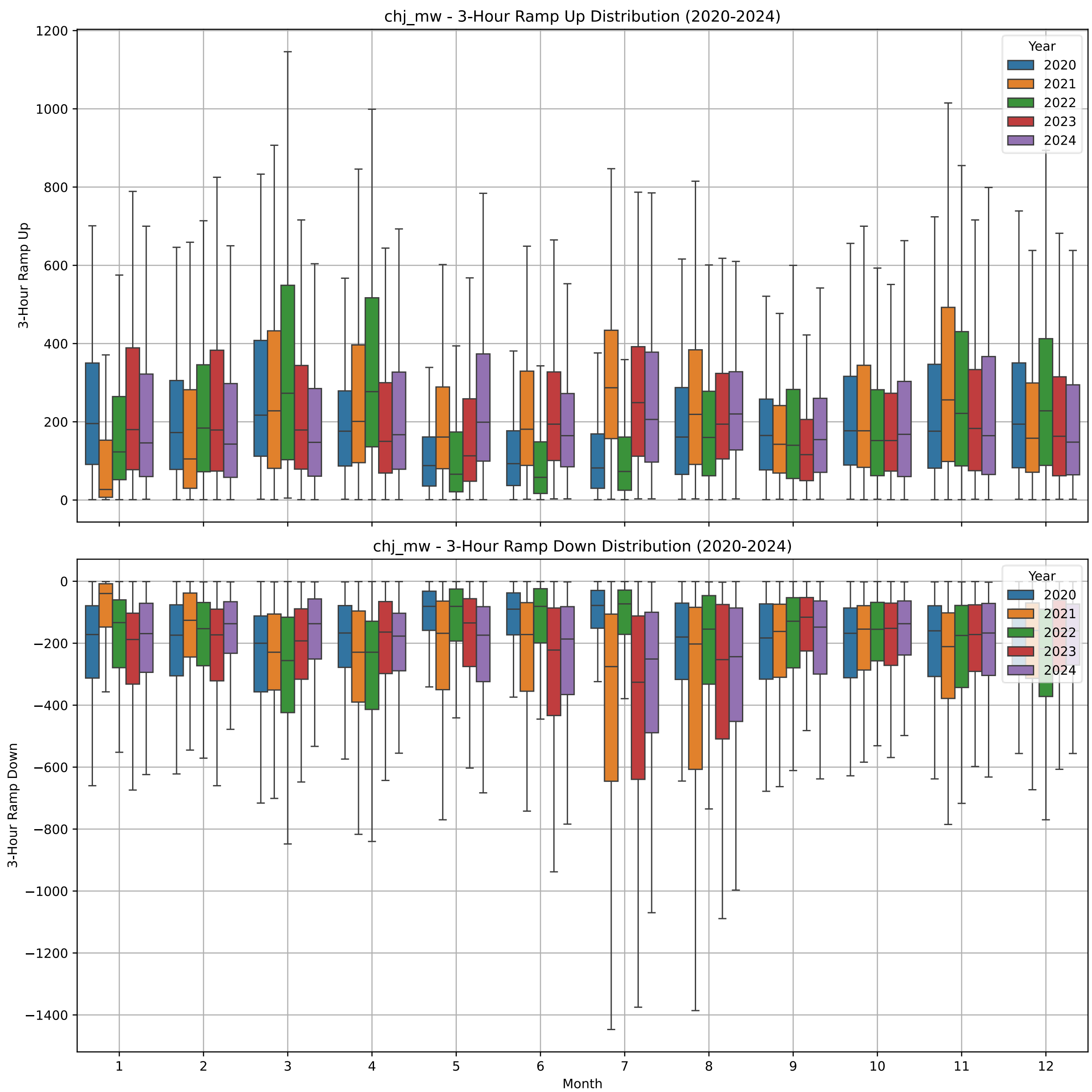

Figure 3-7. CHJ 3-hour ramps monthly distribution in 2020–2024

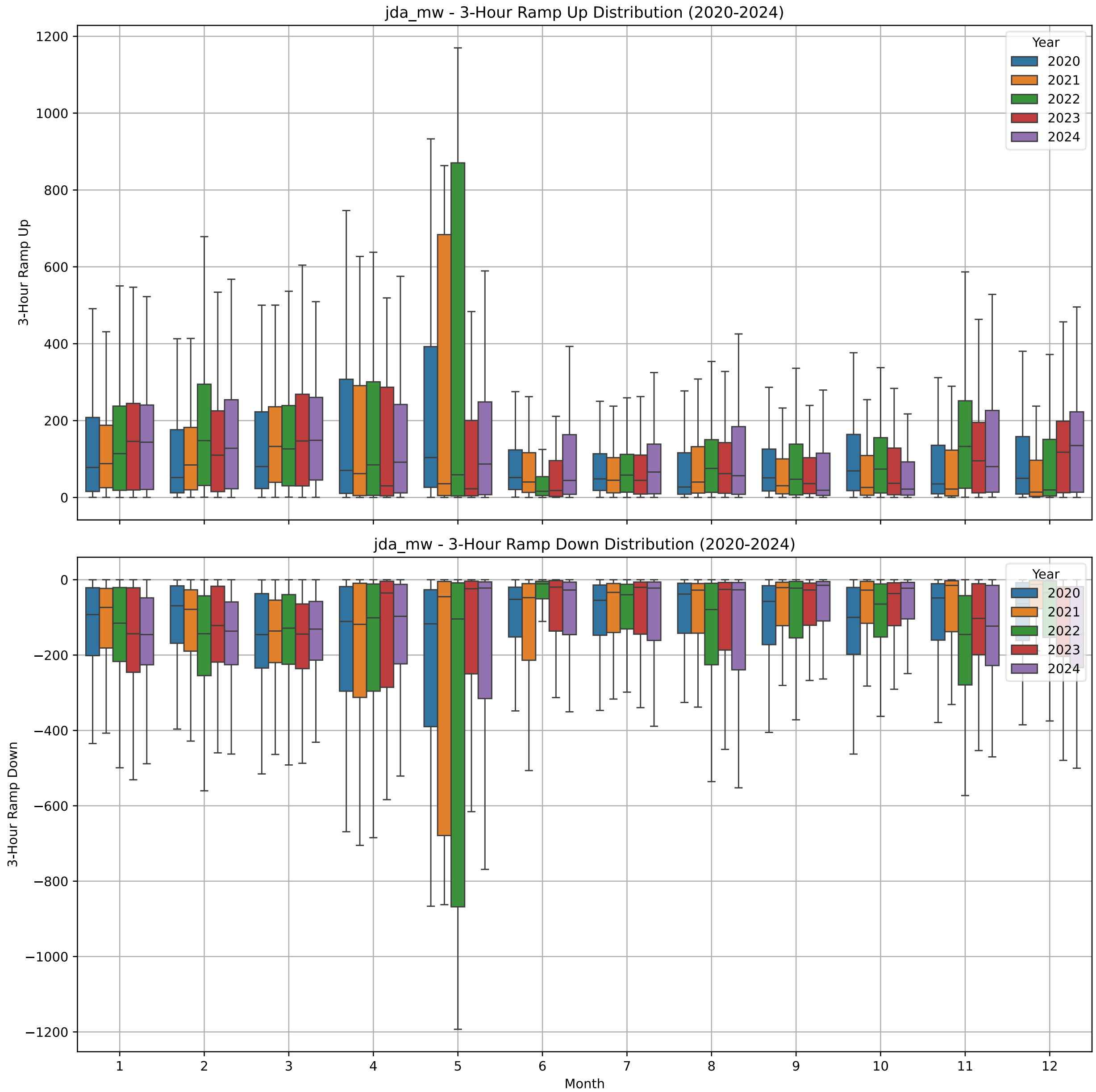

Figure 3-8. JDA 3-hour ramps monthly distribution in 2020–2024

3.3 Results

3.3.1 Interchange with CAISO and Transmission Impact

WECC defines a set of major transmission interfaces in the Western Interconnection, known as "paths." For each path, transmission limits are calculated, updated, and published annually.[1] Key interfaces between BPA and CAISO include the COI (also known as Path 66) and the Pacific DC Intertie (PDCI, Path 65), both shown in Figure 3-9. Other major WECC Paths in the

[1] WECC: Path Rating Catalog (Public Version). Source: https://www.wecc.org/sites/default/files/documents/meeting/2024/2024%20Path%20Rating%20Catalog%20Public_v2.pdf.

Northwest include West-of-Cascades North/South (Paths 4 and 5), Idaho–Northwest (Path 14), and Montana–Northwest (Path 8).

In addition to external paths, BPA monitors internal interfaces (referred to as “flowgates”), such as south of Allston, west of JDA, west of MCN, north of Hanford, north of Echo Lake, and west of LMN—the closest flowgate to the LSR plants. These flowgate limits define the available transmission capacity for importing to and exporting from the BPA system.

BPA’s entry into the Western Energy Imbalance Market (WEIM) on May 3, 2022, significantly changed flow patterns between BPA and CAISO. Figure 3-10 and Figure 3-11 show COI and PDCI flow distributions from 2020 to 2024. The data illustrate a shift from predominantly north-to-south flows before 2022 to bidirectional flows after BPA joined the WEIM.

This shift is driven in part by California’s rapid deployment of solar generation. According to the California Energy Commission, installed solar photovoltaic capacity grew from 13,865 MW in 2020 to 22,325 MW in 2024 and continues to rise.[1] This growth creates strong midday export pressure and evening import needs for CAISO, which the WEIM addresses in part by leveraging the flexibility of BPA’s hydro fleet and reversing flows on the COI (and, at times, the PDCI).

[1] https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/electric-generation-capacity-and-energy

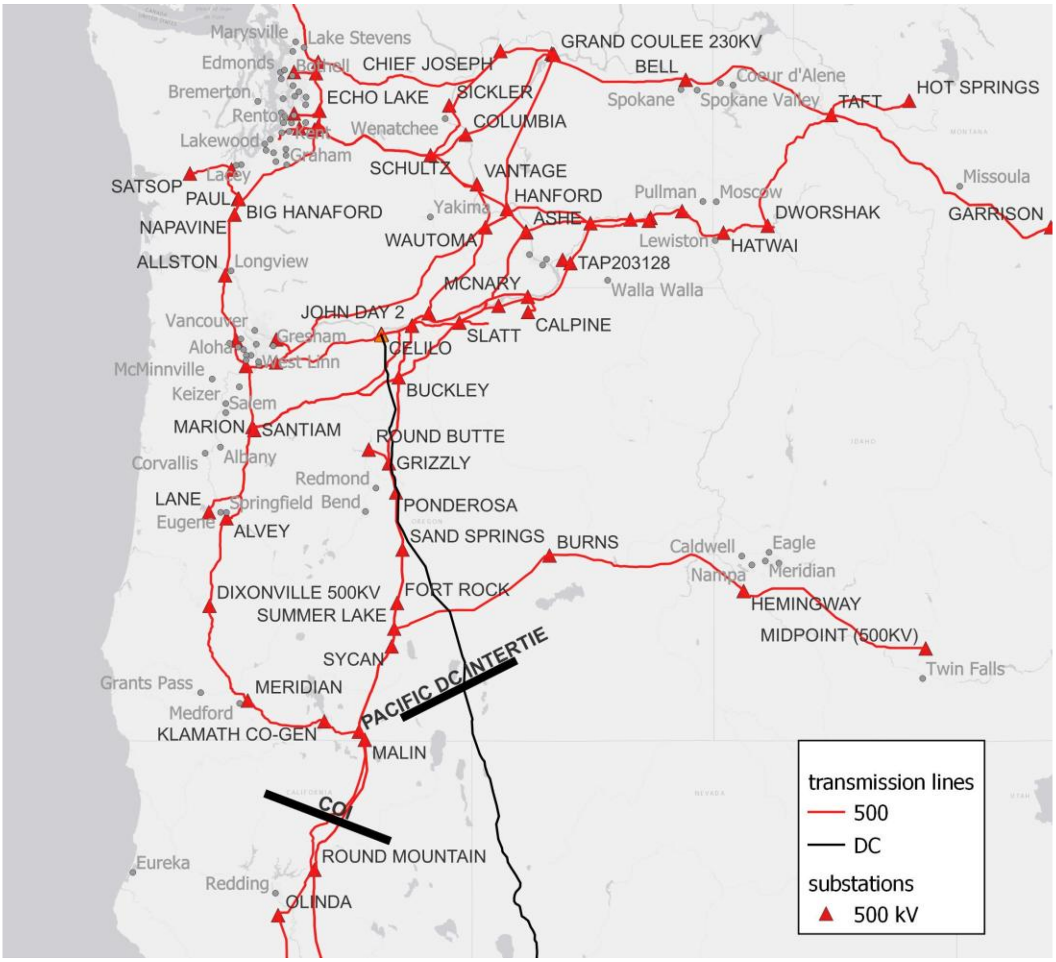

Figure 3-9. COI and PDCI transmission interfaces between BPA and CAISO

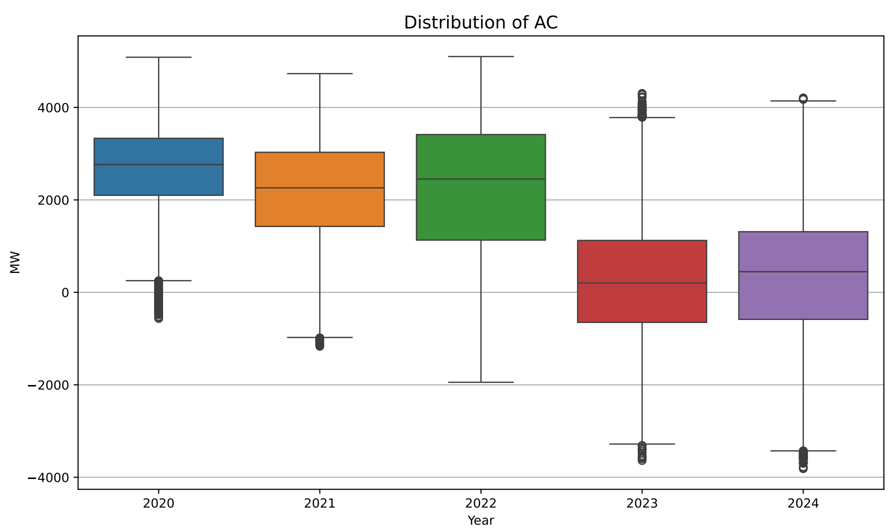

Figure 3-10. Distribution of COI flow in 2020 - 2024

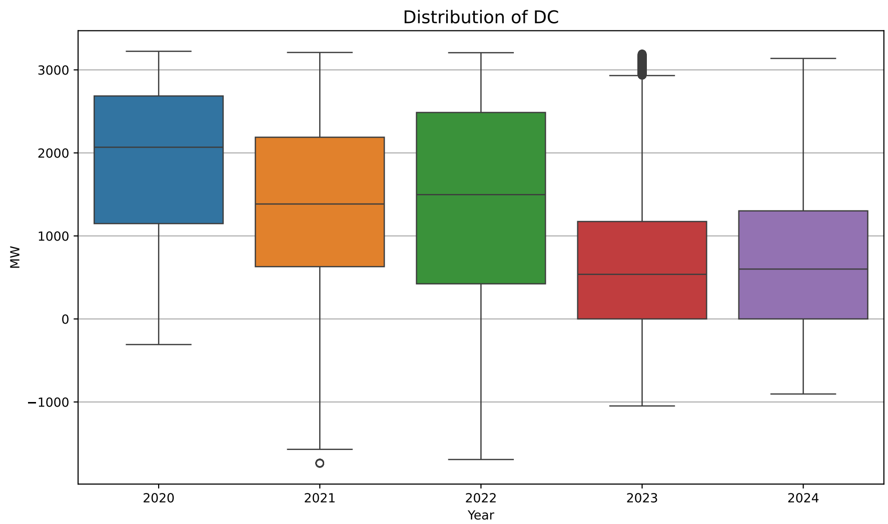

Figure 3-11. Distribution of PDCI flow in 2020 – 2024

The heat map in Figure 3-12 illustrates how average hourly power flows on the COI evolved from 2021 to 2023 monthly. In 2021, every month and hour are shaded red, signifying consistent north-to-south exports of Northwestern hydro to California. After BPA joined the WEIM, daytime colors begin to fade, and by 2023, the pattern flips: mid-morning through late afternoon blocks turn blue in nearly every month, indicating substantial south-to-north transfers as California's surplus solar energy flows into the Northwest. Meanwhile, early-morning and evening hours remain red, reflecting the traditional north-to-south pattern.

This figure confirms that WEIM participation, combined with California's rapid solar expansion, has transformed the intertie from a one-way export path into a bidirectional interface. This more dynamic flow behavior adds complexity not only to transmission congestion management and monitoring, but also to BPA generator fleet operations and overall system flexibility.

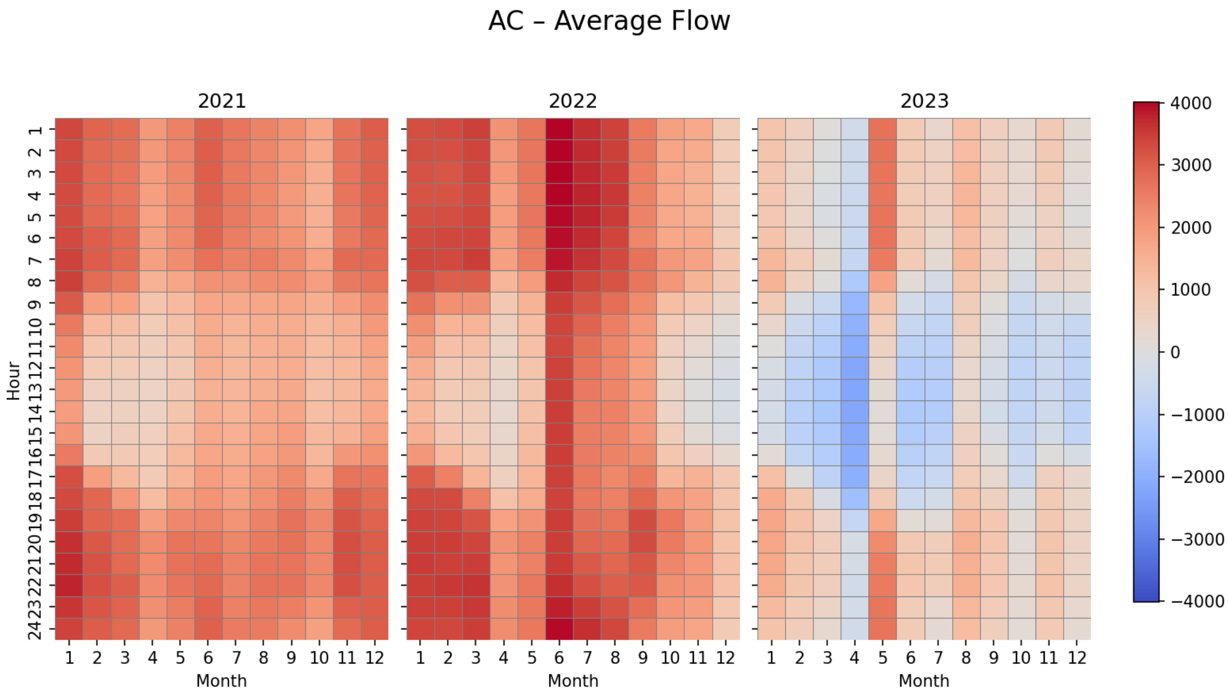

Figure 3-12. COI average hourly flows in 2021 – 2023

To analyze the impact and contribution of the LSR plants to power flows on the interfaces to California, it is important to consider the broader system context. Interface flows on the COI and PDCI are influenced by a complex interplay of factors, including BPA hydro generation, regional load levels in both California and the BPA balancing area, and solar generation in California. These flows reflect the net power balance across the Western Interconnection, making it difficult to isolate the specific role of LSR plants' generation. It is challenging to determine whether the energy produced by the LSR plants serves local demand or is exported to external markets. While a zonal energy flow model, such as one based on the Power Transfer Distribution Factor, could potentially estimate the LSR plant contributions more precisely, it requires comprehensive system data that is not always available. Therefore, we adopt a statistical correlation analysis approach to explore interdependencies between LSR plant generation and key variables such as COI and PDCI flows, providing insight into the broader patterns of interaction.

Figure 3-13 and Figure 3-14 illustrate the monthly correlation between interface flows (COI and PDCI) and BPA total hydro generation, net load, and CAISO solar generation. It can be observed that these flows are primarily influenced by BPA net load and CAISO solar generation, showing a significantly negative correlation, i.e., when BPA's net load increases and/or solar generation in CAISO increases, the interchange flow from north to south decreases. However, interchange flows are positively correlated with CAISO net load, indicating an increase in north–south flows when CAISO's net load increases, such as during even solar ramp downs. This pattern has been consistently observed over multiple years, with a seasonal component contributing to the variability, but the overall trend remains stable and consistent.

The correlations between LSR, as well as GCL, CHJ, and JDA plants, and COI and west of LMN flows are presented in Figure 3-15 and Figure 3-16. Figure 3-15 shows that the correlation between plant generation and COI flow is not particularly strong and varies significantly depending on the year and month, reflecting the complex interplay of multiple factors. In contrast, Figure 3-16 reveals a strong correlation between LSR plant generation and west of LMN flow. Additionally, the figures highlight that during periods of high generation, LSR plants show a greater correlation with both west of LMN and COI interface flows. However, during historically typical generation levels, the correlations are not as pronounced. This observation indirectly suggests that under average LSR plant generation levels (approximately 1,000 MW), LSR plants predominantly serve loads locally in the Tri-Cities area. When water conditions and EIM market conditions are favorable, LSR plants also contribute to BPA exports.

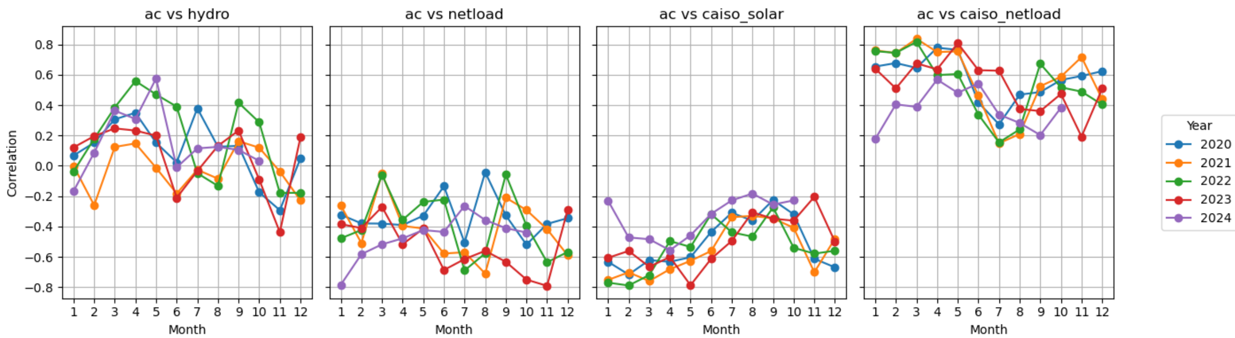

Figure 3-13. Monthly Correlation of COI flow with BPA total hydro generation, BPA netload, CAISO solar generation and CAISO netload for 2020–2024.

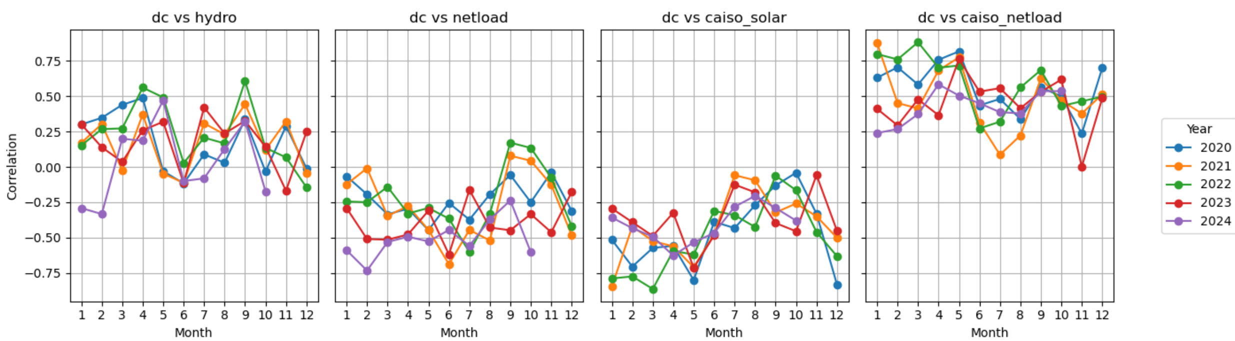

Figure 3-14. Monthly Correlation of PDCI flow with BPA total hydro generation, BPA netload, CAISO solar generation and CAISO netload for 2020–2024.

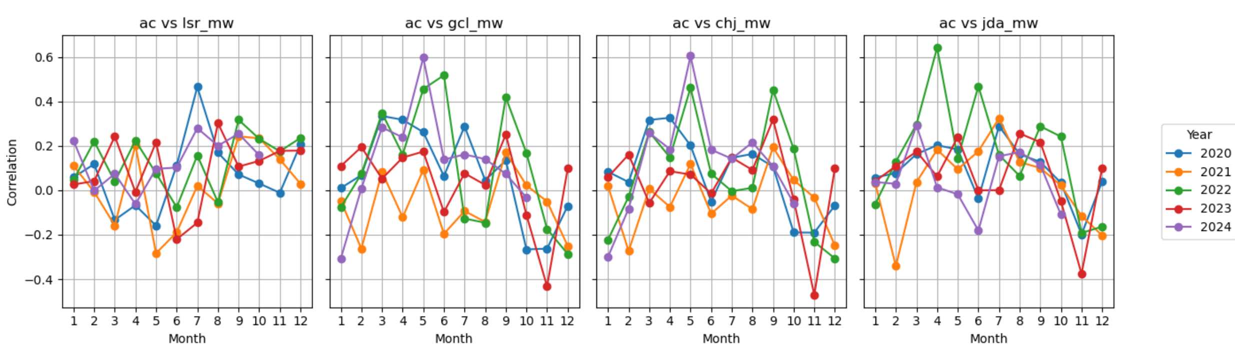

Figure 3-15. Monthly Correlation of COI flow with LSR, GCL, CHJ and JDA generation for 2020–2024.

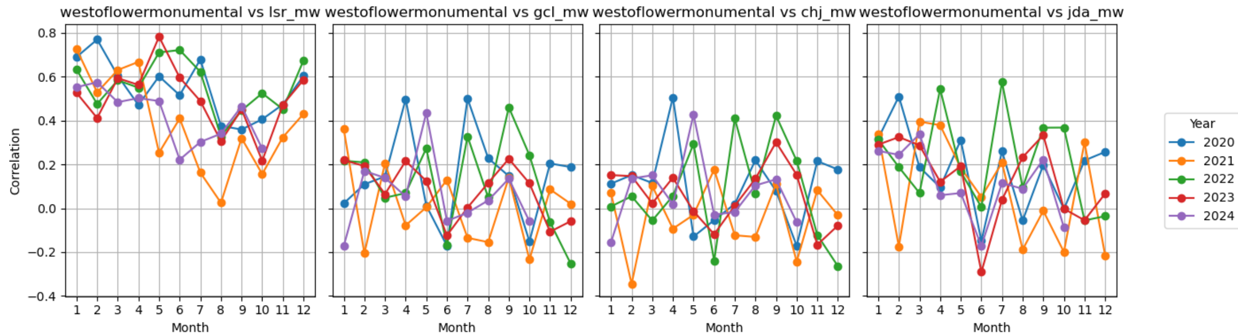

Figure 3-16. Monthly Correlation of West of Low Monumental flow with LSR, GCL, CHJ and JDA generation for 2020–2024.

One of the notable periods of high LSR plant generation occurred in May 2023. As shown in Figure 2-5, LSR plant generation reached its peak levels during this month. Figure 3-17 provides time-series data for various parameters across April to June 2023, enabling a deeper analysis of this period. The data reveals that in May, BPA significantly increased hydro generation, with GCL, as the largest hydro plant, making a substantial contribution. Additionally, LSR plants almost doubled their generation compared to typical levels. A strong correlation between LSR plant generation and west of LMN flow can be observed in May, contrasting sharply with the patterns seen in April and June. This increased hydro generation also contributed to higher interchange flows and elevated transfers through COI and PDCI interfaces.

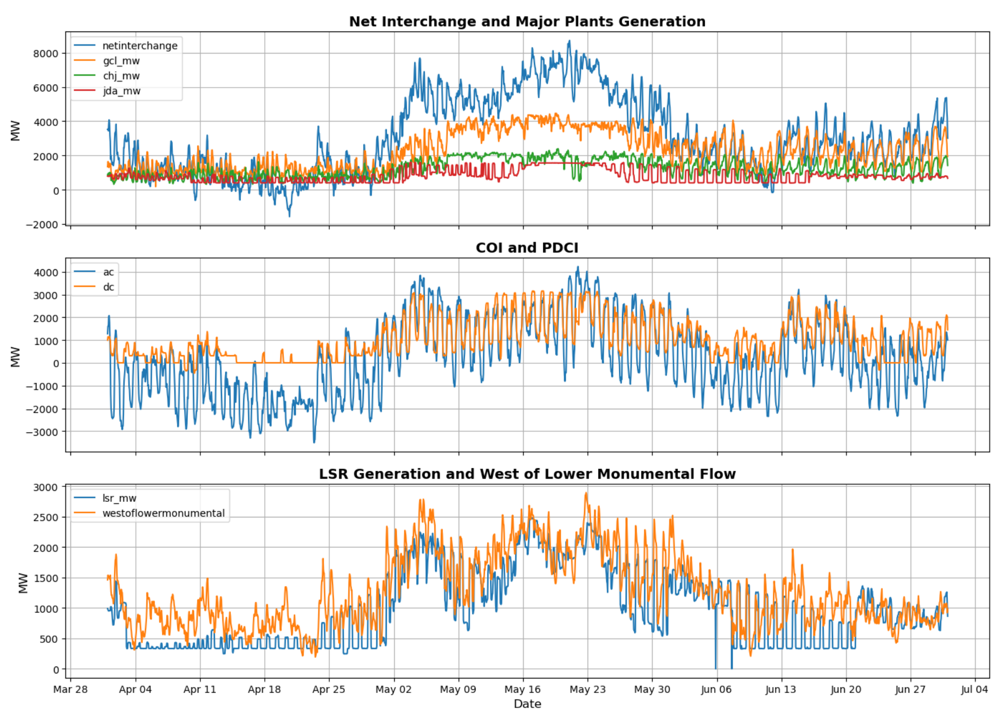

Figure 3-17. BPA generation and flows in April–June 2023.

4.0 Flexibility: Intra-Hour Ramping & Balancing

The typical real-time (intra-hour) balancing process has two interrelated control layers:

- Load Following—5-minute dispatch that adjusts generator output to follow the net load
- Regulation—fast AGC actions that adjust selected units every 2–4 seconds in response to Area Control Error (ACE).

BPA joined the WEIM in 2022 (Figure 4-1). The WEIM, based on the CAISO real-time market design, operates a 15-minute market followed by a 5-minute Real-Time Dispatch (RTD). In the RTD process, participating generators receive updated base-point instructions every five minutes to continuously adjust their output in response to real-time fluctuations in system demand—a function commonly referred to as "load following."

Across North America, regulation reserves refer to online capacity that moves continuously under AGC to correct second-by-second deviations between generation and load. The Balancing Area Authority's Energy Management System recalculates ACE every few seconds and issues raise/lower pulses via AGC to keep ACE within reliability limits defined by the North American Electric Reliability Corporation (NERC) BAL-001-2 Control Performance Standard.[1]

Source: CAISO
https://www.westerneim.com/Pages/About/default.aspx

Figure 4-1. WEIM map

Only ten Federal Columbia River Power System dams are wired directly to AGC, according to BPA. Referred to as the "Big Ten," these plants can follow the ACE signal in real time. They

[1] https://www.nerc.com/pa/stand/reliability%20standards/bal-001-2.pdf

include BON, TDA, JDA, MCN, CHJ, GCL, IHR, LGS, LWG, and LMN. Together, these plants form the backbone of BPA's regulation reserve stack.[1]

According to BPA, the LSR plants collectively can supply up to one-quarter of BPA's total operating reserves, due to their fast-response Kaplan turbines and the ability to store water for several hours to adjust power output when needed.[2] BPA does not publish plant-specific AGC deployments or reserve allocations, making in-depth analysis of each LSR project's regulating contribution challenging. However, 5-minute dispatch data for the LSR plants provided by USACE for this study—combined with system-wide series on total hydro generation—enable the assessment of overall behavior, including 5-minute and 15-minute ramp magnitudes, generator mileage, and LSR share of fast-ramping capacity. As reported by USACE,[3] during the June 2021 heatwave, BPA shifted reserve requirements to the Snake River, and at one point, the four LSR dams held 15 percent of all reserves (approximately 220 MW) while simultaneously providing up to 1,118 MW of power.

In the analysis that follows, we compute five- and fifteen-minute ramps for the LSR plants and compare them with aggregate hydro ramps to quantify the LSR contribution to BPA's fleetwide totals, and calculate mileage metrics to characterize the balancing services provided by the LSR plants.

4.1 Methodology

The following data were used in the analysis (see Table 1-1 for details on the data source):

- BPA BA total hydrogeneration, 5-minute data
- 5-minute dispatch for individual LSR plants
- Hourly dispatch for major BPA plants for mileage calculation

Ramp and mileage definitions:

- 5-minute ramp: $R5(t) = X(t) - X(t - 5\text{ min})$
- Upward and downward components: $R5\uparrow(t) = \max\{0, R5(t)\}$, $R5\downarrow(t) = \max\{0, -R5(t)\}$
- 15-minute ramp: $R15(t) = X(t) - X(t - 15\text{ min})$; similarly $R15\uparrow(t)$, $R15\downarrow(t)$
- Mileage from 5-minute data over period T: $M5\uparrow(T) = \Sigma t \in T\ R5\uparrow(t)$, $M5\downarrow(T) = \Sigma t \in T\ R5\downarrow(t)$

Analytical approach:

- Monthly distributions: For R5 and R15 (upward and downward), the median, interquartile range, and 5th/95th percentiles by month are computed, and box-and-whisker plots are used to visualize distributions and tails.
- Daily profiles: Hour-of-day statistics of upward and downward ramps are computed to identify morning and evening ramp windows and to assess LSR plants' performance in upward and downward movement.

[1] https://proceedings.bpa.gov/Home/OpenDoc?fileId=2977 (page 5–6)
[2] https://www.bpa.gov/-/media/Aep/about/publications/fact-sheets/fs-201603-A-Northwest-energy-solution-Regional-power-benefits-of-the-lower-Snake-River-dams.pdf
[3] https://www.nww.usace.army.mil/Media/News-Stories/Article/3999344/dont-bet-on-the-weather-the-role-hydropower-plays-in-balancing-the-grid-during/)

- Mileage statistics: Mileage is computed for individual plants to assess their participation in the overall generation movement required to balance the system.
- Heat maps: Heat maps are used to visualize monthly and hourly characteristics on a single plot, highlighting seasonal and diurnal patterns.

4.2 Results

4.2.1 BPA Hydro Fleet's Intra-Hour Ramping Performance

Figure 4-2 presents statistics for five-minute ramping for the entire BPA hydro fleet. The data indicates that ramping behavior has remained relatively consistent over the five-year period from 2020 to 2024, with no significant month-to-month variation. Median five-minute ramp values are approximately 30-50 MW, while maximum ramp magnitudes range from 150 to 175 MW, depending on the year and season. Comparable statistics for 15-minute ramps are shown in Figure 4-3. Median 15-minute ramps are around 100 MW, with maximum values reaching 350–400 MW.

Appendix C provides results from a separate ramping analysis based on deployed balancing reserves, using data published by BPA. While Figure 4-2 and Figure 4-3 reflect total system movement, Figure C-2 and Figure C-3 isolate the incremental contribution of regulation. This distinction explains the slightly lower ramping values observed in the balancing reserve analysis in Appendix C.

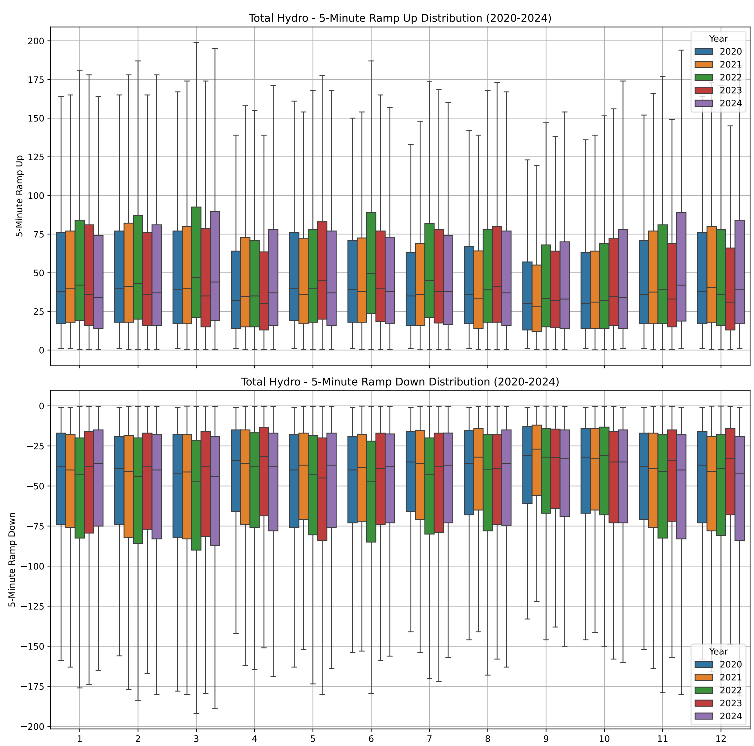

Figure 4-2. BPA total hydro generation 5-minute ramp monthly statistics (2020–2024)

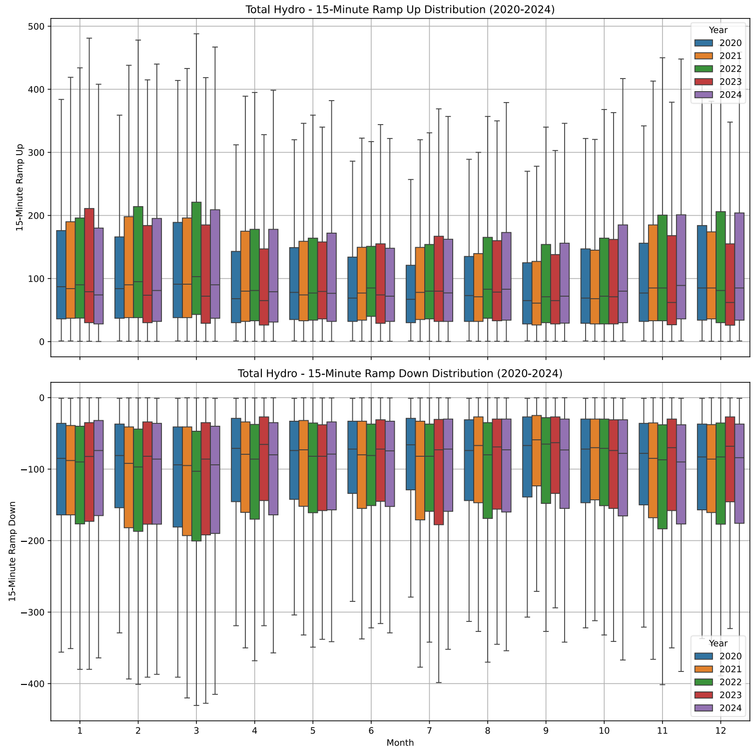

Figure 4-3. BPA total hydro generation 15-minute ramp monthly statistics (2020–2024)

4.2.2 LSR Plants' Intra-Hour Ramping Performance

The 5- and 15-minute ramping performance of aggregated LSR plants is presented in Figure 4-4 and Figure 4-5. The performance exhibits strong seasonal variation, dependent on water conditions and environmental constraints. Ramping activity typically peaks between January and March, becomes limited in April due to water spill requirements, slightly increases during May and June, and remains modest from July through October before growing again in November and December. This recurring pattern has been consistently observed over the years 2020 through 2023. It should be noted that 5-minute LSR plant generation data were not available for the year 2024 in this study.

On average, LSR plants provide 5 MW 5-minute ramps, with peaks reaching up to 30 MW during 5-minute ramping events. Given that LSR plants participate in both dispatch and frequency regulation but only total dispatch data is available, it is not possible to accurately separate their contributions to the regulation process. However, based on comparison with total hydro ramps, it can be conservatively estimated that LSR plants account for approximately 10–15% of the total BPA BA intra-hour ramping.

Hourly statistics on maximum 5-minute ramps of the LSR plants are presented in Figure 4-6 and Figure 4-7. Peak ramping values are observed during the morning load ramp-up period, typically between 5 a.m. and 7 a.m., as well as during the evening load ramp and coinciding solar ramp-down in California, which occurs between 4 p.m. and 7 p.m. The peak ramp-down periods are observed between 9 a.m. and 11 a.m., aligning with the load ramp-down and solar ramp-up in California.

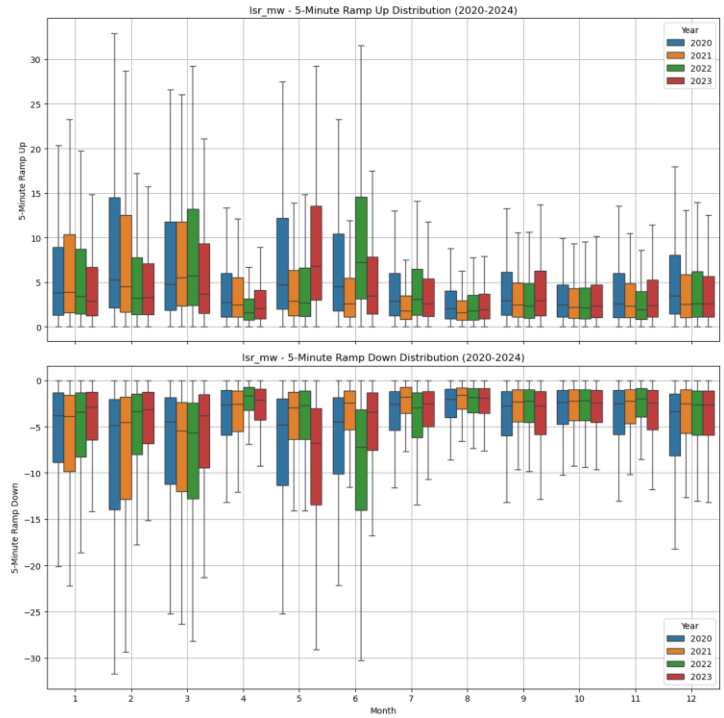

Figure 4-4. LSR 5-minute ramp monthly statistics (2020–2023)

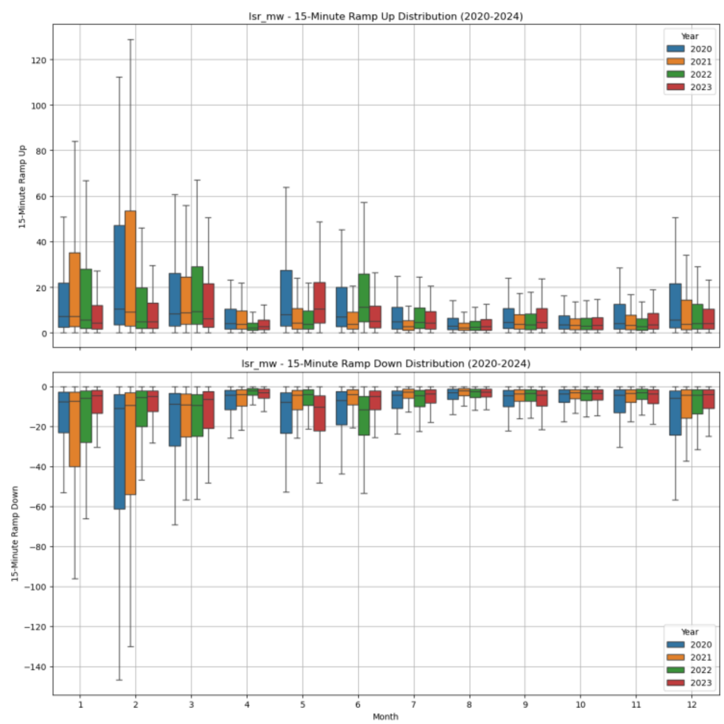

Figure 4-5. LSR 15-minute ramp monthly statistics (2020–2023)

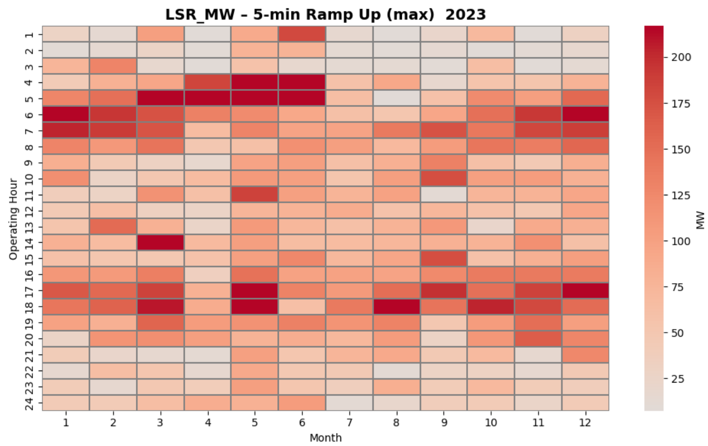

Figure 4-6. LSR 5-minute ramp-up maximum hourly statistics (2023)

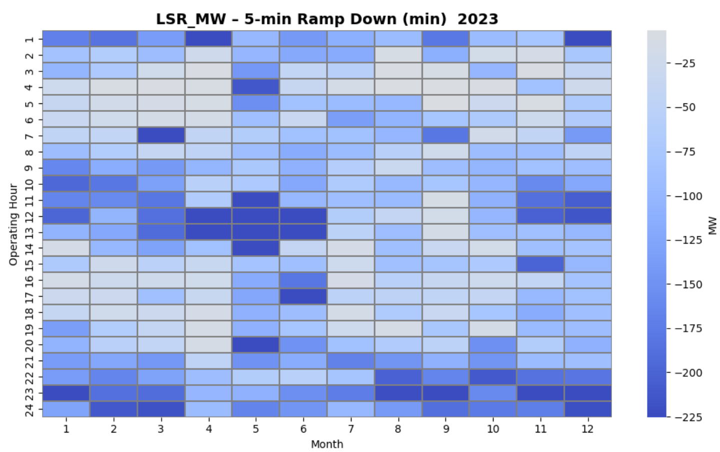

Figure 4-7. LSR 5-minute ramp-down maximum hourly statistics (2023)

4.2.3 Hydro Plants Mileage

In power system dispatch, “mileage” refers to the total change in generation output over time. It quantifies the movement of a power plant’s output as it is dispatched upward and downward, capturing both ramping up and ramping down activities. This metric serves as an indicator of how maneuverable and flexible a power plant is in contributing to the overall system power balancing process. Higher mileage indicates more flexibility.

The aggregated mileage of LSR plants, based on 5-minute dispatch data, along with its hourly distribution for 2023, is presented in Figure 4-8 and Figure 4-9 for upward and downward mileage, respectively. The hourly “mileage profile” exhibits patterns similar to ramping distribution, highlighting the participation of LSR plants in the balancing and regulation processes of the power system.

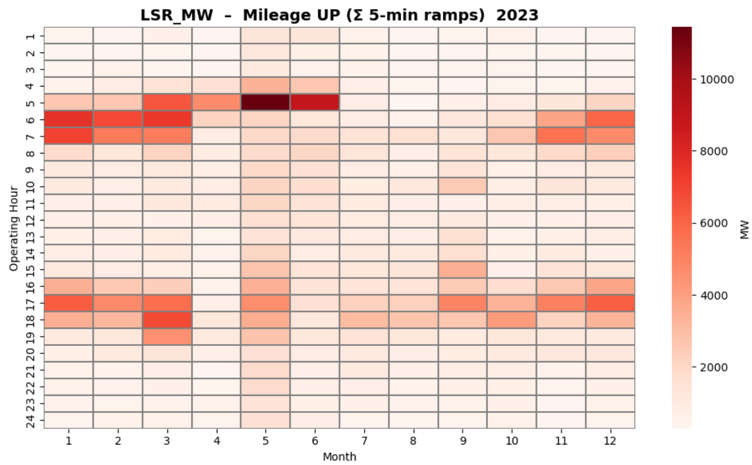

Figure 4-8. LSR mileage up hourly statistics (2023)

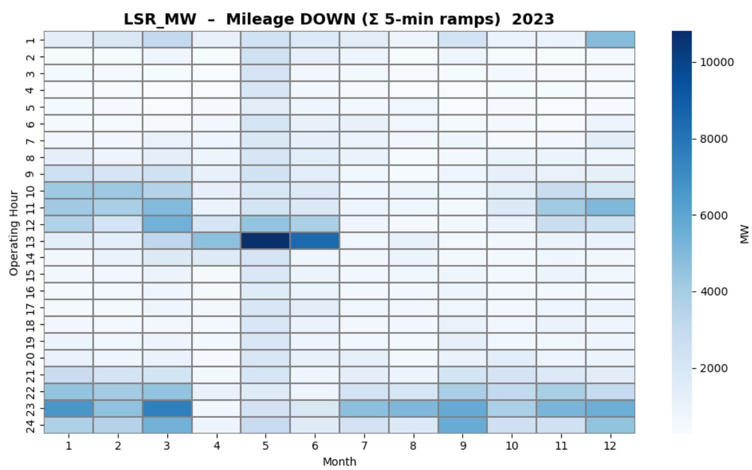

Figure 4-9. LSR mileage down hourly statistics (2023)

For this study, only hourly dispatch data for other major hydro plants was available. Consequently, to estimate the share of LSR plants in the total system motion and compare their mileage with other plants, mileage statistics for major plants were calculated using hourly data. While hourly data cannot capture intra-hour motion, it effectively characterizes overall movement on an hourly scale. Table 4-1 and Figure 4-10 present the calculated upward mileage for LSR plants alongside CHJ, GCL, and other plants, as well as the total upward hydro generation mileage based on BPA total hydro generation data.

It is important to note that upward and downward mileage values are equal, differing only by the distance between the starting and ending operating points within the time window used for the analysis. Additionally, due to the possibility of individual plants moving in opposite directions simultaneously, the sum of individual plant mileage is not equivalent to the mileage derived from the total hydro dispatch statistics published by BPA. In Table 4-1, the contribution of individual plants is normalized relative to the total hydro dispatch mileage. As a result, the sum of normalized contributions can exceed 100%, illustrating the quantification of each plant's respective share in total hydro dispatch mileage.

The aggregated total movement share of LSR plants is approximately 15%, placing them behind the two largest contributors, GCL and CHJ plants, which dominate the hydro fleet's motion. Despite their size being smaller compared to GCL and CHJ, the LSR plants demonstrate a significant contribution to system movement and flexibility. This is particularly noteworthy when compared to other hydro plants of similar size, JDA and TDA, which exhibit lower overall shares of total movement.

Table 4-1. Major hydro plants' annual upward mileage

Year		2020	2021	2022	2023	2024
DWR	MW	7726	8737	9901	5025	847
	%	0%	0%	1%	0%	0%
LWG	MW	115482	95503	83101	72837	58122
	%	7%	5%	4%	4%	3%
LGS	MW	99399	85487	78786	72670	78823
	%	6%	5%	4%	4%	5%
LMN	MW	107383	81062	91495	75811	63217
	%	7%	4%	5%	4%	4%
IHR	MW	105870	93068	68255	61261	52619
	%	7%	5%	4%	4%	3%
LSR	MW	385918	334965	306762	266485	241045
	%	25%	18%	16%	16%	14%
MCN	MW	129472	107286	83023	92651	80842
	%	8%	6%	4%	5%	5%
JDA	MW	208082	198540	237193	202401	208798
	%	13%	10%	13%	12%	12%
TDA	MW	142539	134288	166430	134951	68916
	%	9%	7%	9%	8%	4%
BON	MW	58231	62887	49464	36030	37488
	%	4%	3%	3%	2%	2%
GCL	MW	697345	929632	970771	848104	809357
	%	45%	49%	52%	49%	48%
CHJ	MW	394237	444743	415805	443499	436957
	%	25%	23%	22%	26%	26%
LIB	MW	10860	16207	29374	9522	1667
	%	1%	1%	2%	1%	0%
Total BPA Hydro[1]	MW	1565380	1895239	1868313	1718391	1691949

[1] Total BPA hydro mileage is based on BPA data for total hydro generation, not on the sum of individual generator mileage values provided in the table.

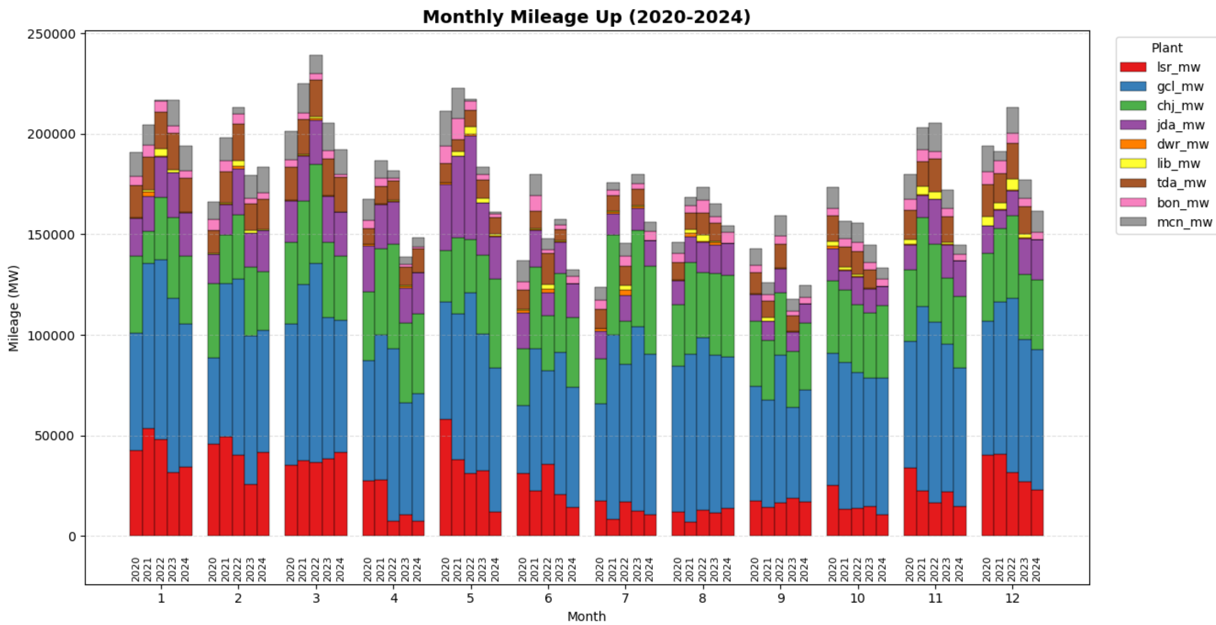

Figure 4-10. Major hydro plants' mileage (2020–2024)

5.0 Voltage and Reactive Power Support

Reactive power control and voltage support are important ancillary services for power system operations. Hydro plants provide reactive power and voltage control, and they can provide both steady-state and dynamic voltage support. Reactive power and voltage support are, and must be, provided locally. Synchronous condensers and other local voltage support devices may be used in areas needing additional support. Hydro generation is typically commissioned with 0.95 Power Factor (PF) meaning that it is designed to be capable of absorbing/generating reactive power in steady state. If PF is 1, then the generator is not rated to provide any reactive power during normal operation.

Steady-state voltage support is provided to regulate voltages under normal loading conditions. Voltage support for transmission lines depends on power transfer over the line. Voltage on heavily-loaded transmission lines will sag. To support power transfer and prevent voltage collapse, reactive power support needs to be provided over the line length. If the line is lightly loaded, voltage over the line will rise and reactive power needs to be absorbed to prevent dangerous over-voltage conditions. Load centers typically need voltage support and reactive power injections; load increases require more reactive power support.

During contingencies (loss of line, reactive power device, generator, etc.) dynamic voltage support is required (fast voltage support). Hydro-based generators can provide fast voltage support by changing excitation current. Conventional voltage support/control devices (e.g., shunt capacitors) typically cannot provide dynamic voltage support. Dynamic voltage support is necessary to prevent voltage instabilities and transient instabilities during contingencies.

5.1 Methodology

This section discusses the methodology that allows establishment of the impact and contribution of LSR plants on supporting system voltages. The developed methodology must account for steady-state and dynamic voltage support contributions. Voltage regulation is achieved by controlling reactive power produced/absorbed by generators. When voltage boost is needed, generators inject reactive power, measured in megavolt-ampere reactive (MVAR). To decrease voltage, generators need to absorb reactive power. Reactive power control is a function of a generator’s excitation circuit. When excitation voltage increases above the voltage at the point of interconnection (POI) of a generator with the system, generators produce reactive power. When absorption of reactive power is needed, excitation voltage is decreased below the voltage at the POI. As the excitation voltage can be changed automatically and rapidly, generators are capable of fast dynamic voltage control. Most, if not all synchronous generators operate in Automatic Voltage Regulation mode. Apart from excitation, voltage control by synchronous generators is a function of a generator’s capability. Generator capability is a function of the generator design. It determines how much active power (MW) and reactive power (MVAR) can be provided at the same time. The major limitation is the amount (intensity) of current that can flow through generator windings, and it depends on a generator’s MVA rating. Larger MW output means lower MVAR can be provided/absorbed.

To determine the contribution of LSR plants to voltage support in a steady state, the following approach was used:

- Use capability curves from WECC planning/operation model to evaluate plant capability to provide and absorb reactive power.

- Use historical data to calculate hourly contribution of MVAR from LSR plants.
- Use historical cases to plot MVAR vs. voltages in the neighboring load centers.
- Plot MW vs. MVAR from historical data to see how much generation capability is used to provide voltage support (for online generators—what is the PF they operate under).
- Estimate reactive power needs in steady state during major outages.

The following approach was used to evaluate dynamic voltage support provided by the LSR plants:

- Use WECC base cases and historical cases to investigate how much dynamic voltage support is provided by LSR plants during contingencies.
- Evaluate sensitivities through system studies using future planning cases that consider forecasted load growth.
- Evaluate voltage sensitivities for major outages.

The following metrics were used to quantify voltage support contributions from LSR plants:

- Historical MVAR provided by LSR plants. This metric provides insight on how much reactive power is provided/absorbed in steady state to regulate voltages.
- Voltage sensitivity (impact of LSR plants) of high voltage (HV) neighboring buses (kV/MVAR) and load centers. Larger sensitivity means that voltage support provided by given reactive source is more efficient. Low voltage sensitivity implies voltage support provided by LSR plants is not very efficient.
- Reactive power requirements for local voltage support under heavy and light loading conditions to keep voltages under the reliability limits.

Data required to analyze the impact of LSR plants on voltage support are listed below:

- MVARs and MW historical output of LSR plants provide insights into the historical role of LSR plants' voltage support.
- Major outages that affect neighboring systems, for correlating MVAR needed for voltage support with outages.
- Study cases (WECC base cases) to analyze voltage sensitivities. Voltage sensitivity can be estimated as a change of reactive power from LSR plants vs. change in voltage on neighboring HV buses.
- State Estimation cases if available (WECC cases are only snapshots for specific loading conditions). Sensitivities may change with loading conditions and during system outages.

5.2 Results and Findings

5.2.1 Steady-State Reactive Power Support from LSR Plants

The first set of results show the historical dispatch of reactive power from the LSR plants and its correlation with voltage support at a critical nearby substation. Figure 5-1 shows the scatterplot of the steady-state reactive power output of the LSR plants and the corresponding per-unit voltage at the generator substation. It can be observed that the LSR plants provide reactive power to support the local voltages. However, most LSR plants operate in an under-excited mode in steady state to prevent overvoltages that can damage equipment. The positive correlations show that the level of under-excitation reduces at intervals where the voltage levels are closer to nominal values.

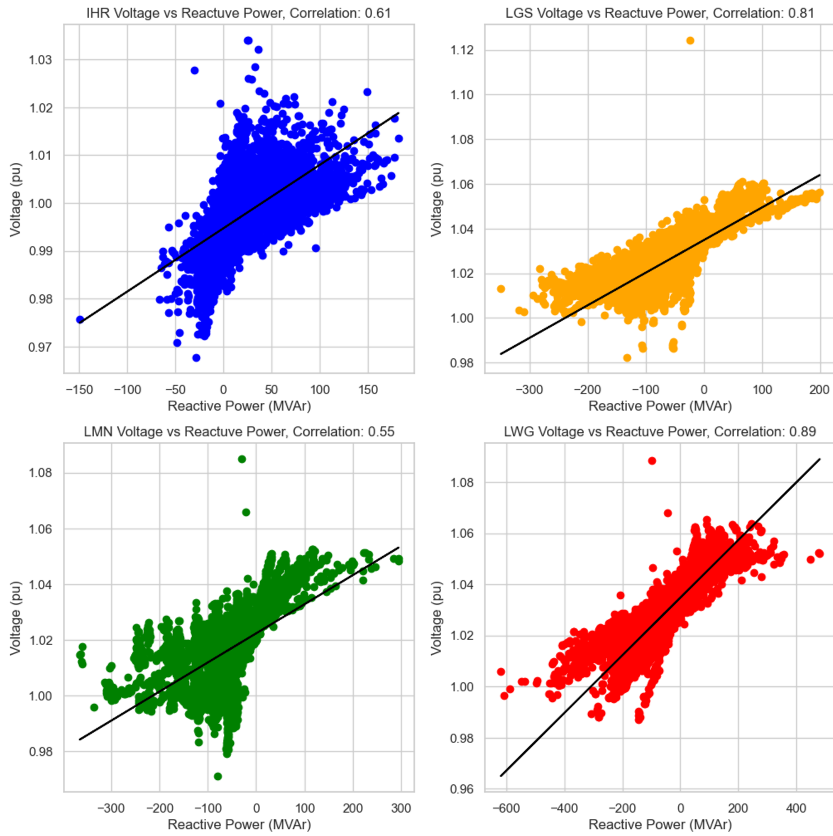

Figure 5-1. Scatterplot of the reactive power from LSR plants vs. the voltage at the local plant substation

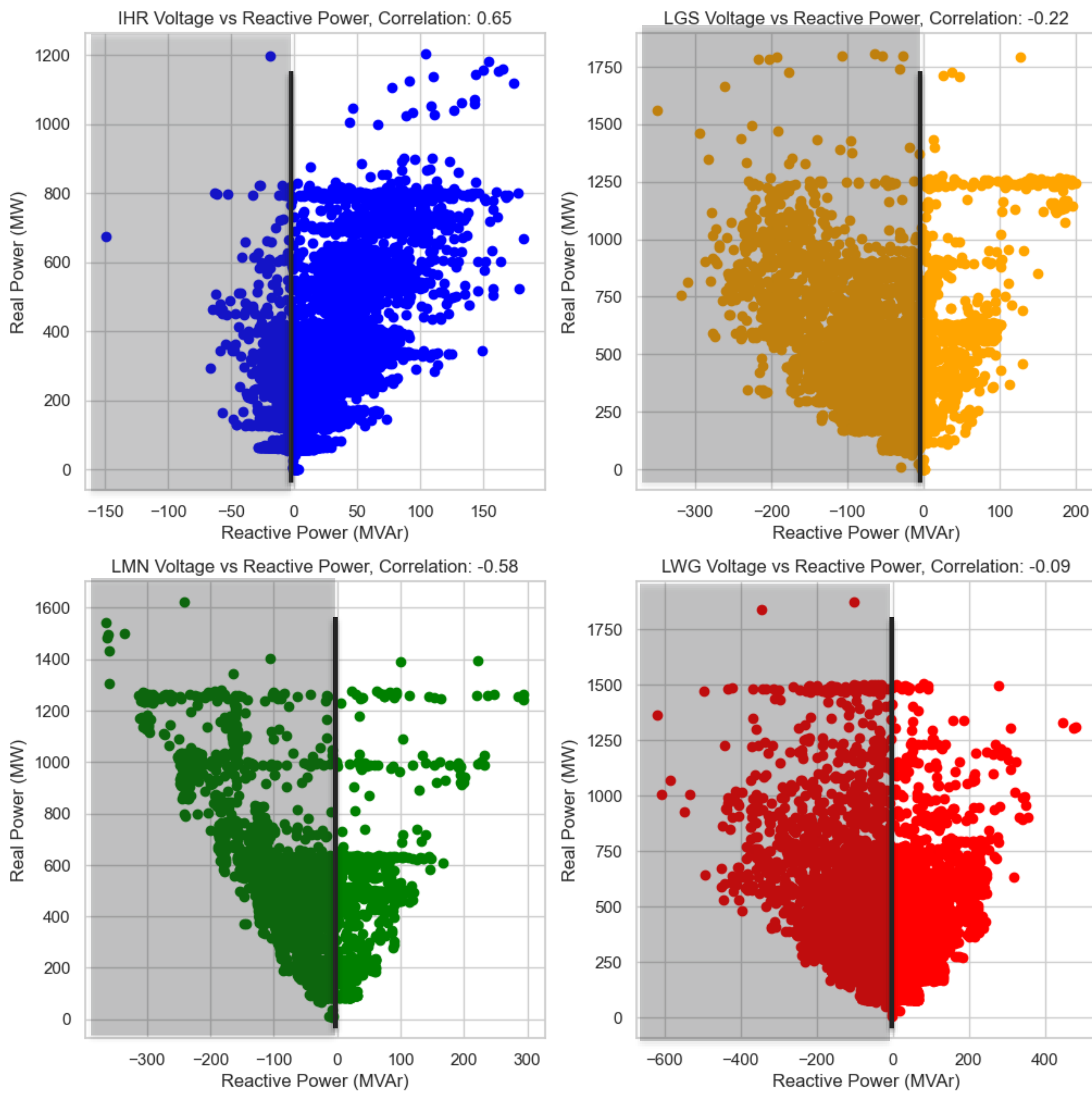

Figure 5-2. Scatterplot of the reactive power from LSR plants vs. active power (shaded region shows under-excitation or reactive power absorption by LSR plants)

Figure 5-3 shows the box-bar chart of the actual steady-state, hourly MVAR output of the LSR plants. All the LSR plants except IHR operate in the under-excited mode, meaning that they absorb reactive power to prevent overvoltages. The IHR hydro plant is the closest to a larger load center (Tri-Cities, Washington) and load centers typically need voltage support to prevent low voltages. From Figure 5-2, it can be seen that only this plant predominantly supplies reactive power. The reactive power support of the other LSR plants changes with their line loading, increasing slightly during the morning and evening ramps, indicating they regulate the voltage of transmission lines wheeling the power from these plants.

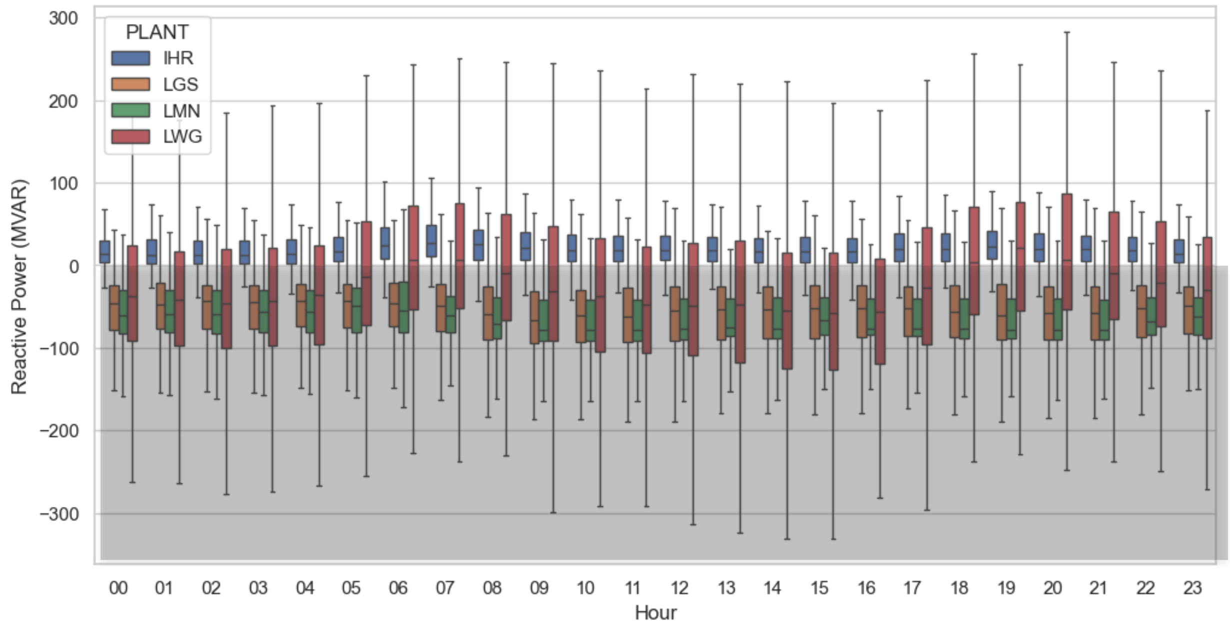

Figure 5-3. Box-bar chart of the hourly steady-state reactive power output of the LSR plants (Jan–July 2018). The shaded region shows under-excitation or reactive power absorption by LSR plants.

Figure 5-4 shows the same box-bar chart but on a monthly basis. It shows that reactive power output from some of the LSR units was elevated in May, likely due to spring runoff and hydro facilities operating at higher output.

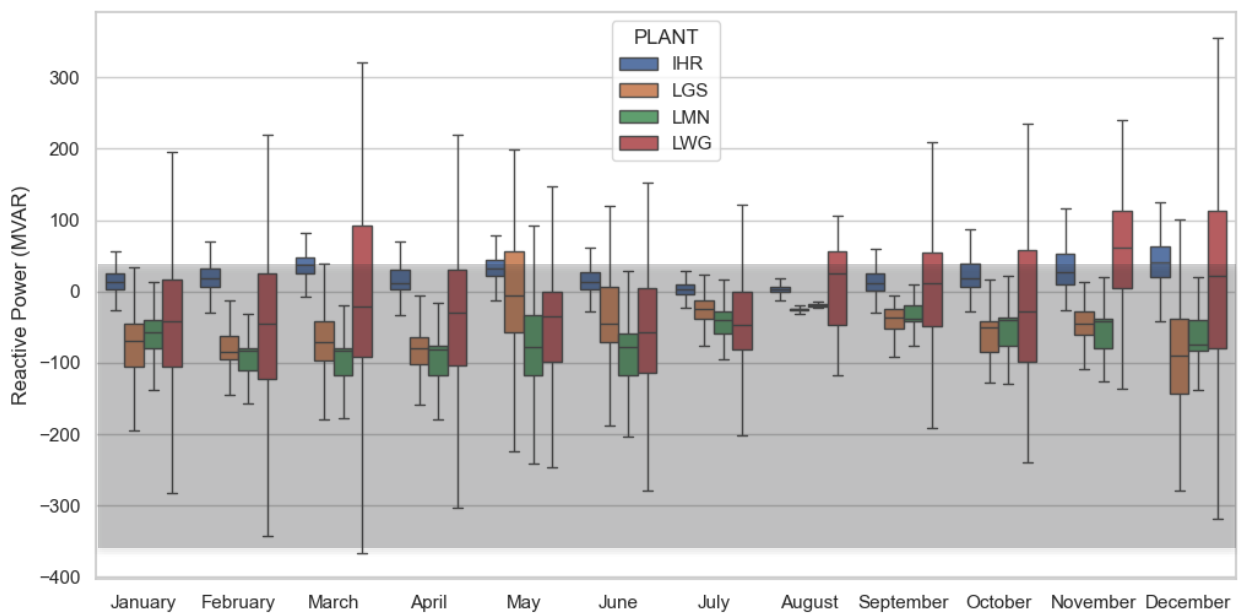

Figure 5-4. Box-bar chart of the monthly steady-state reactive power output of the LSR plants (Jan–July 2018). The shaded region shows under-excitation or reactive power absorption by LSR plants.

5.2.2 Dynamic Reactive Power Support from LSR Plants

In this section, we review the dynamic reactive power contribution of the LSR plants. This study used WECC operational cases and positive sequence time domain dynamic simulations with different disturbances to record the reactive power response of the LSR plants together with the voltage profile at a nearby 500 kV crucial substation.

Figure 5-5 shows the scatterplot of the dynamic reactive power support from the LSR plants with the 500kV substation voltages for three disturbances:

A. Outage of the two Palo Verde Nuclear Power Plant generators in AZ—**2,630 MW outage from two units with total capacity of 2,750 MW.** This is the largest credible contingency in the Western Interconnection.
B. Outage of the MCN Hydro Power Plant in BPA—**711 MW outage from 14 units with total capacity of 1,185 MW.**
C. A three-phase fault at the Columbia Generating Station (CGS) Nuclear plant.

The two contingencies at the MCN hydro plant and CGS are significant because they are in the same region as LSR plants. It can be observed that for the three-phase fault at the CGS plant, the reactive power support from the LSR plants increases substantially to provide reactive power support to maintain voltages and prevent voltage instability in the region.

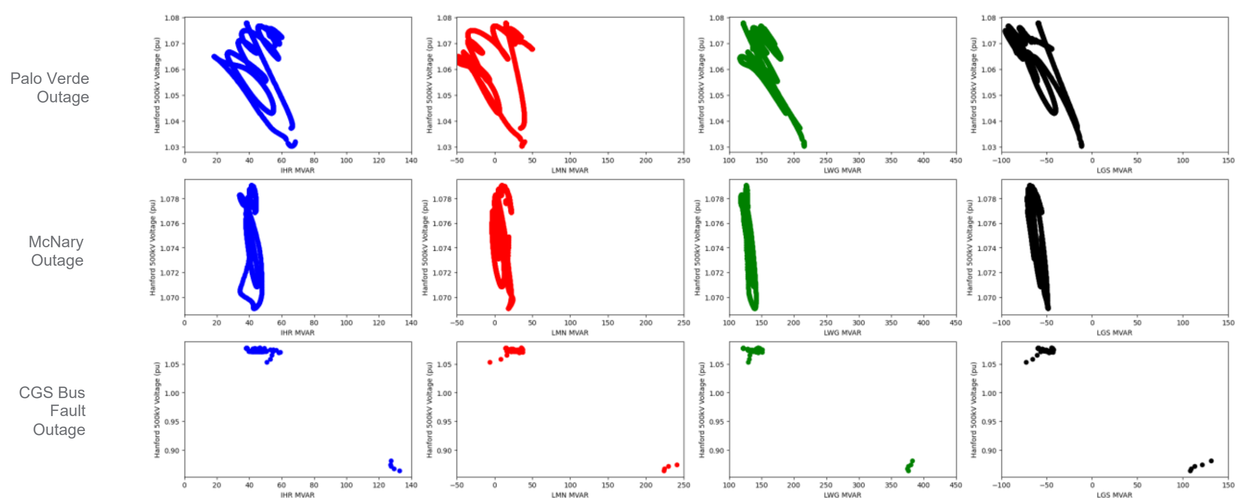

Figure 5-5. Dynamic reactive power support and voltage sensitivity of LSR plants for multiple disturbances

Figure 5-6 shows the dynamic reactive power response from all LSR plants aggregated for the Palo Verde outage, and the corresponding voltage profiles at the observed 500kV substation. The plots also illustrate the Hanford 500 kV substation voltage when the LSR units are offline. Although the Hanford 500 kV voltage does not show a lot of difference for the Palo Verde outage, when the outage is the close vicinity of the LSR units as seen in Figure 5-7 for the MCN outage case, they absorb reactive power to maintain the voltage levels at local buses. When the resources are removed, it can lead to high voltage problems in the vicinity of the LSR plants.

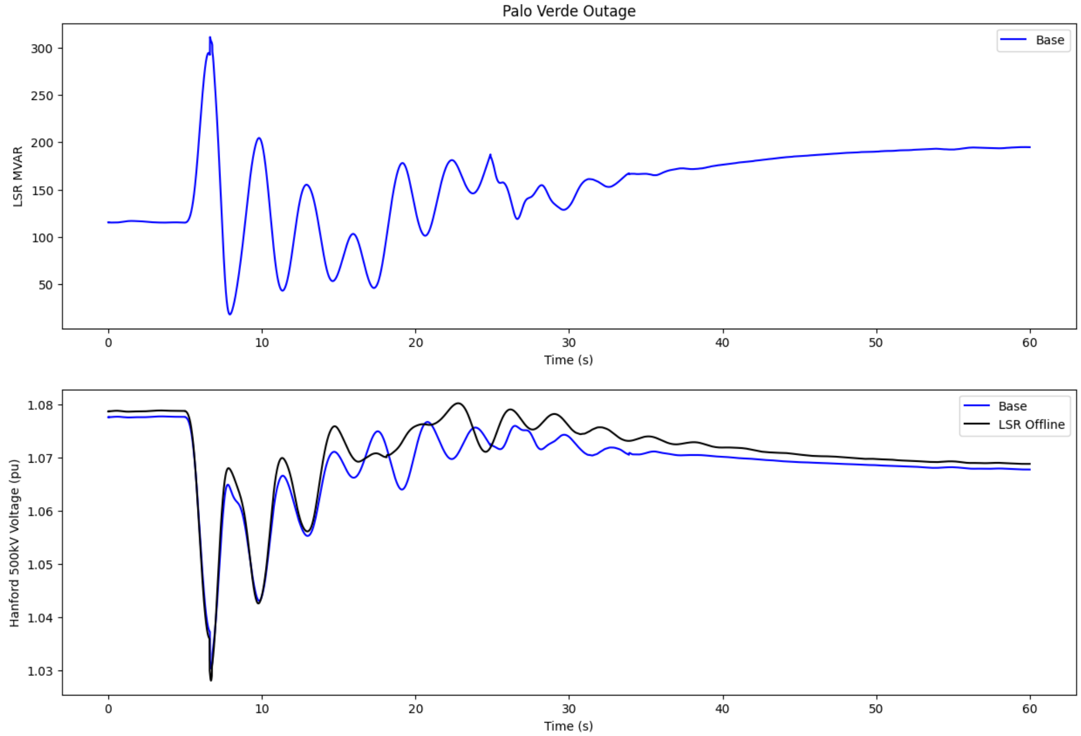

Figure 5-6. Dynamic reactive power support from LSR plants for Palo Verde outage. Upper: reactive power from LSR plant; Lower: voltage profile at Hanford 500kV substation

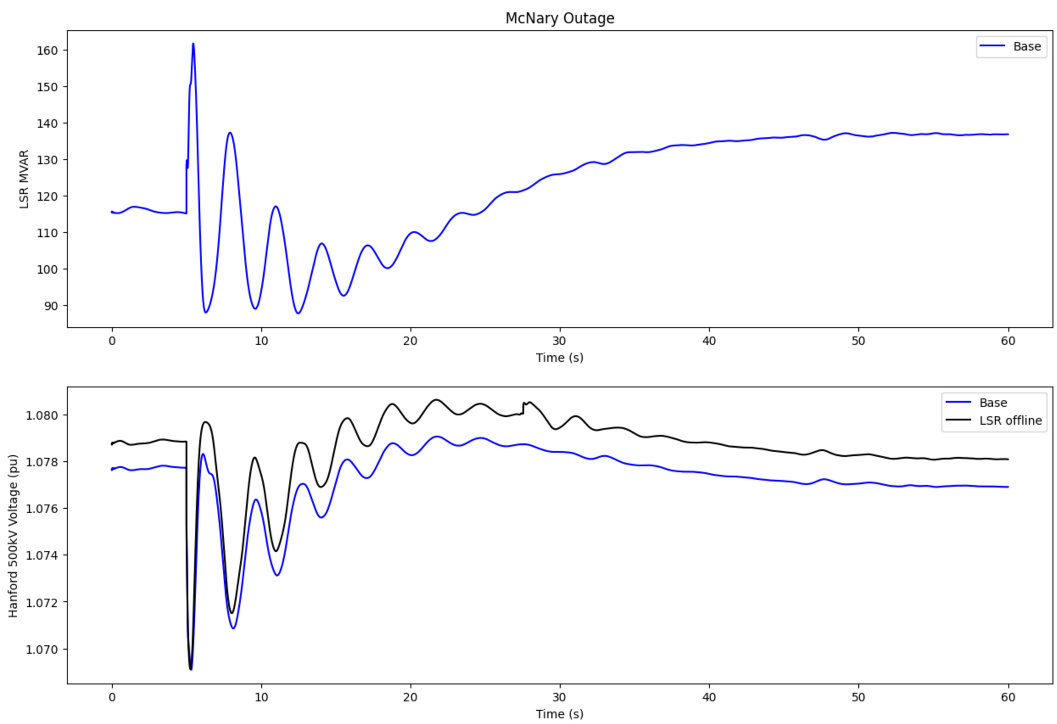

Figure 5-7. Dynamic reactive power support from LSR plants for MCN outage. Upper: reactive power from LSR plants; Lower: voltage profile at Hanford 500kV substation

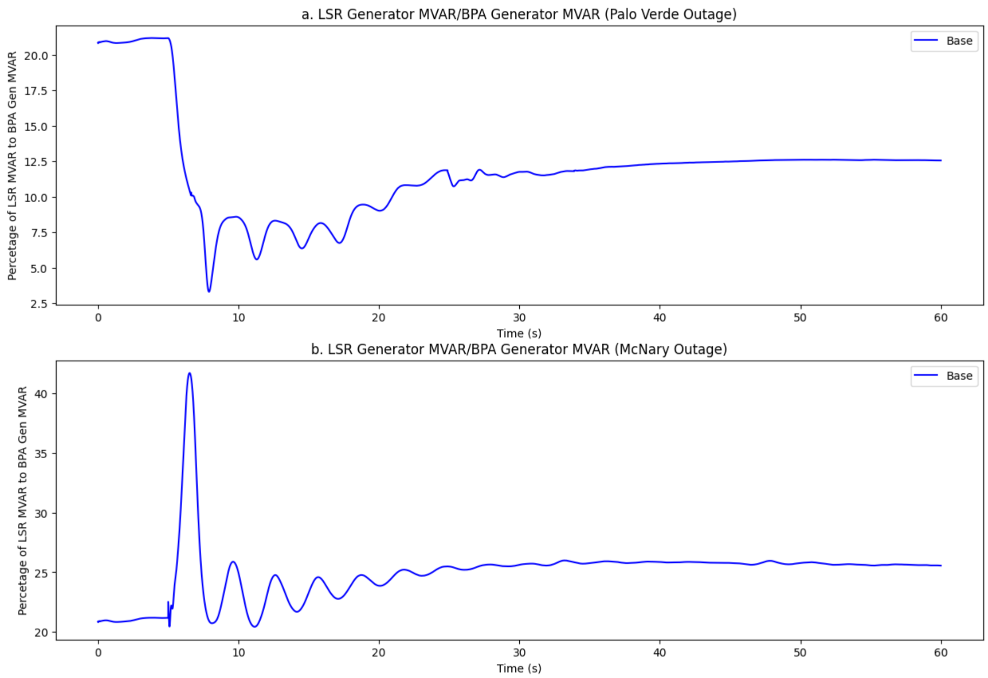

Figure 5-8. LSR reactive power as percentage of BPA reactive power from generators. Upper: Palo Verde outage; Lower: MCN outage

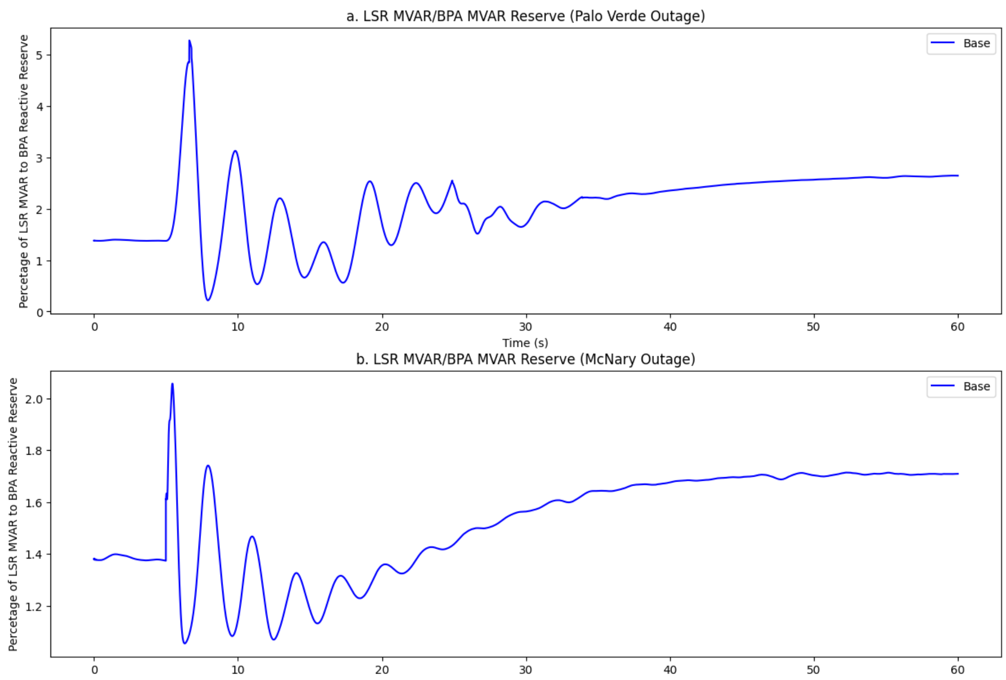

Figure 5-9. LSR reactive power as percentage of BPA reactive reserve. Upper: Palo Verde outage; Lower: MCN outage

Figure 5-8 and Figure 5-9 show the percentage of the dynamic LSR reactive power generation to the reactive power generation of all BPA generators. LSR plants contributed ~12% of the total reactive power produced by BPA for the Palo Verde Outage, while the LSR plants' reactive power contribution to a nearby outage in the MCN plant resulted in ~25% of the reactive power required to maintain voltage stability for the region.

Figure 5-10 shows the dynamic reactive power output of the LSR plants as a percentage of the total BPA reactive reserve which is approximately 2–3%. This chart shows the BPA region's reactive power reserve for the base case compared to the case with all LSR units offline. Taking LSR resources offline reduces the BPA reactive reserve by approximately 900 MVAR. Similarly, Figure 5-11 shows that removing the LSR plants can increase the total reactive power production in the BPA region by approximately 300 MVAR, leading to high voltage problems, especially during light load conditions.

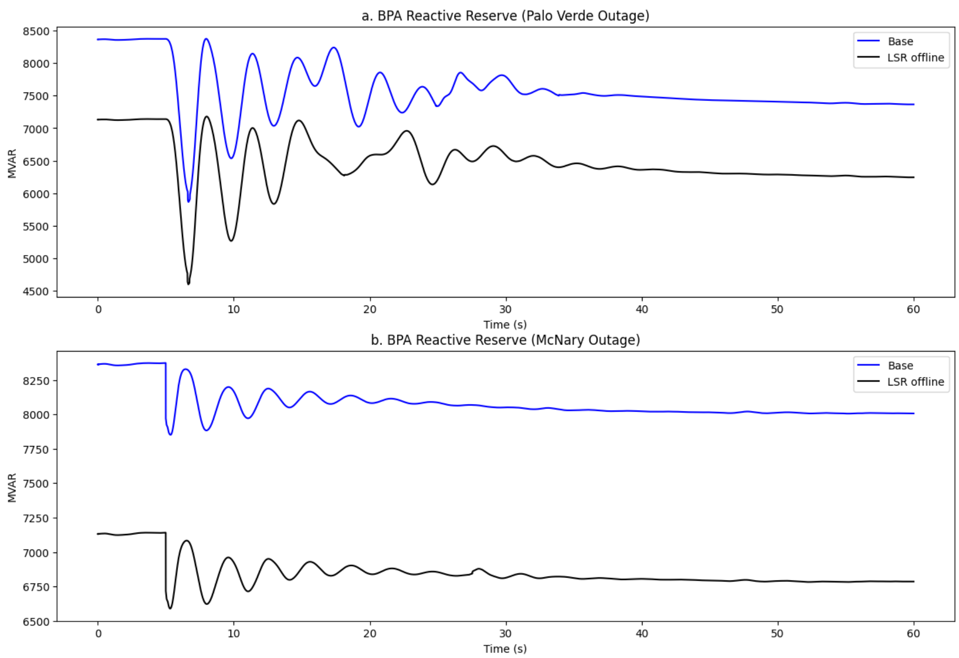

Figure 5-10. BPA reactive power reserve with LSR units online and offline. Upper: Palo Verde outage; Lower: MCN outage

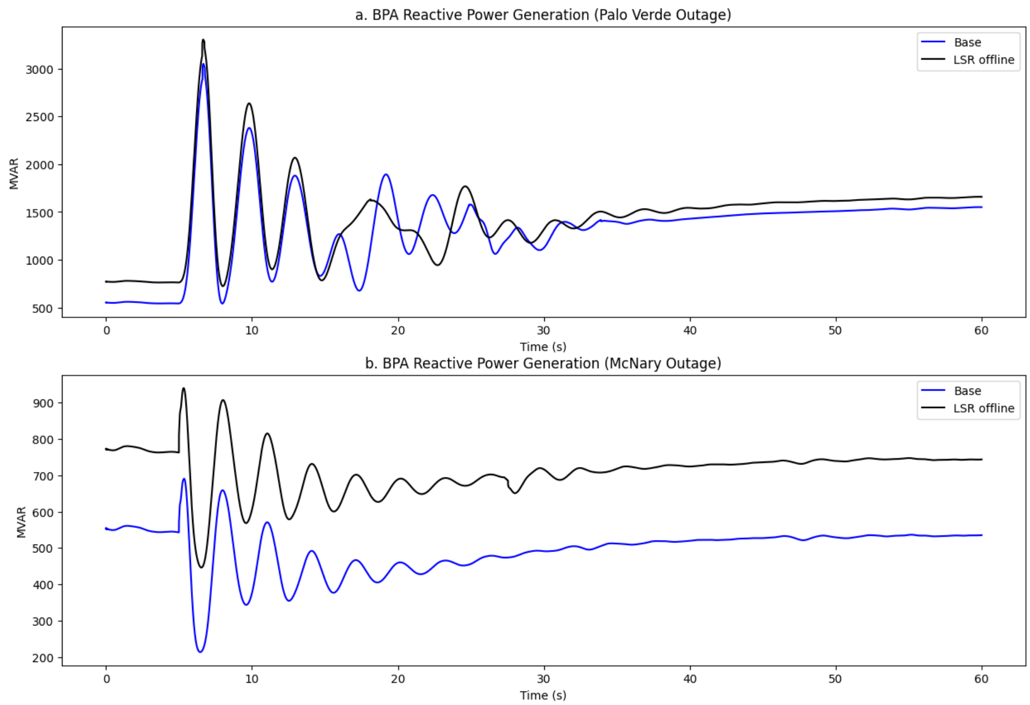

Figure 5-11. BPA reactive power generation with LSR units online and offline. Upper: Palo Verde outage; Lower: MCN outage.

5.3 Key Takeaways from Reactive Power Study

The key takeaway from this reactive power analysis is that LSR plants contribute to BPA's reactive needs and help provide reactive support/voltage control of neighboring load centers and transmission corridors, both at steady state and dynamically during system disturbances. The LSR plants primarily operate in under-excited conditions and absorb reactive power to support the high voltage problems in the vicinity of the plants. Because reactive power requirements are generally local, the LSR plants provide dynamic reactive support during events that are geographically closer to the LSR units.

6.0 Frequency Response

Electrical interconnections must operate within a secure frequency range to maintain continuous balance between system demand, interchange, and generation. Deviations in interconnection frequency can significantly impact system reliability and control performance. Fast frequency response helps prevent UF load shedding following large generation contingencies. If the system frequency drops below specific thresholds, UF load shedding is initiated to prevent further decline of the frequency and to prevent additional generators tripping that could lead to blackouts.

Frequency response (FR) measures an interconnection's ability to stabilize frequency immediately after a sudden loss of generation or load. It is a crucial aspect of maintaining power system reliability, especially during disturbances and the subsequent recovery phases. The NERC BAL-003-2 Frequency Response and Frequency Bias Setting Reliability Standard specifies the required frequency response in each interconnection and allocates the frequency response obligation (FRO) among BAs.[1]

According to this standard, each BA should calculate its frequency response measure (FRM) to monitor frequency response and ensure compliance with its FRO. FRMs are calculated using frequency event records, referred to as Single Event Frequency Response Data in the standard.

6.1 Methodology

Figure 6-1 shows a typical frequency recording following a resource loss in the interconnection. Frequency A represents the frequency prior to the resource loss, calculated as an average over the 16 seconds preceding the event. Frequency B, the settling frequency, is calculated as an average from 20 to 52 seconds after the resource loss. Point C marks the minimum (or nadir) frequency. If the frequency drops further after point B, NERC defines point C' as the minimum frequency occurring after the settling time. According to the NERC BAL-003 standard, the FRM is calculated at point B.

The BA FRM for a single event can be calculated using the following formula:

$$FRM_{BA} = \frac{I_{netB} - I_{netA}}{10\left(f_B - f_A\right)}, \tag{1}$$

where:

- I_{net_B} is the value of interchange power flow B
- I_{net_A} is the value of interchange power flow A
- f_A is the interconnection frequency A
- f_B is the interconnection frequency B

The FRM is expressed in MW/0.1Hz.

[1] NERC. 2019. "Frequency Response and Frequency Bias Setting Standard (BAL-003-2)." Atlanta, GA. https://www.nerc.com/pa/stand/reliability%20standards/bal-003-2.pdf.

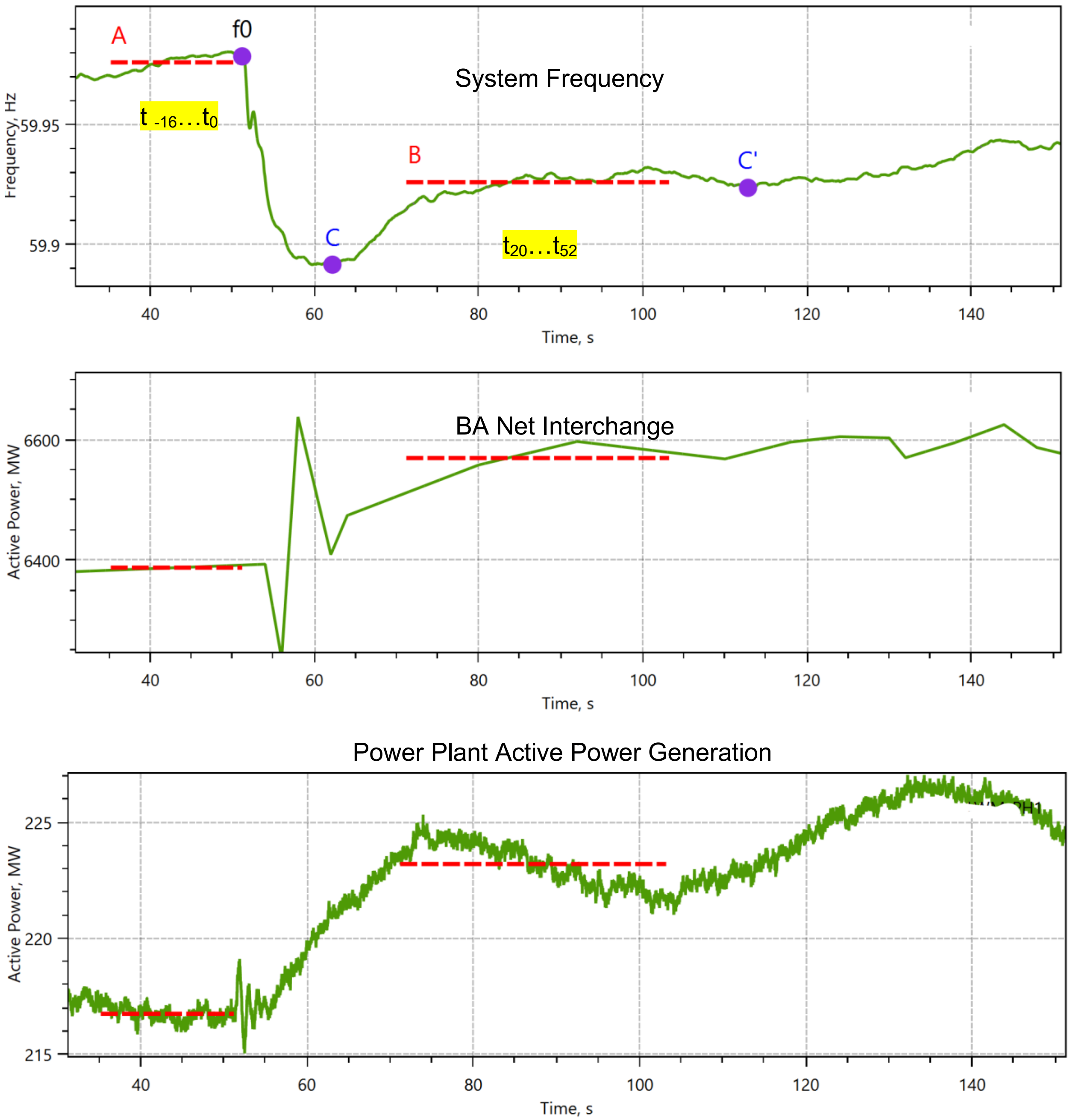

Figure 6-1. Frequency event—NERC Frequency A, Frequency B, and point C illustration.

The FRM for individual generators and plants is not defined in the standard but can be calculated as follows:

$$FRM_{plant} = \frac{P_{plantB} - P_{plantA}}{10(f_B - f_A)}, \quad (2)$$

The FRM for individual generators can be useful to evaluate the impact of the LSR plants to overall frequency stability on the WECC system.

6.2 Results

According to NERC standards, supervisory control and data acquisition (SCADA) measurements can be used to calculate FRM, as they are suited for 4-second resolution measurements. However, the best results for analysis, such as capturing point C, can only be achieved with phasor measurement unit (PMU) measurements. Due to the unavailability of PMU and SCADA event records, we substituted them with simulated data using WECC planning cases adjusted for realistic operating conditions (loads and generation). We also benchmarked the FRM results based on these simulations against publicly available reports on BPA FR.

Simulations were performed using the Powertech Labs Transient Security Assessment Tool (TSAT) software package,[1] and the simulated data were analyzed using the frequency response analysis tool (FRAT), developed by PNNL.[2] FRAT enables automated frequency response analysis according to the NERC BAL-003 standard and provides visualization tools.

The simulation of the outage involving the double Palo Verde units, which collectively represent approximately 2,600 MW of installed capacity, is depicted in Figure 6-2. This significant loss of power capacity, considered one of the biggest contingencies in the WECC, provides a crucial scenario for evaluating system stability and FR performance. During this event, the BPA FRM was calculated to be approximately 451 MW/0.1Hz.

The response of the LSR plants to this simulated event is illustrated in Figure 6-3. These plants, working together, contributed a combined FR of approximately 73.5 MW/0.1Hz. For comparative analysis, the FR provided by the CHJ (71 MW/0.1Hz) and GCL (147 MW/0.1Hz) plants, is depicted in Figure 6-4.

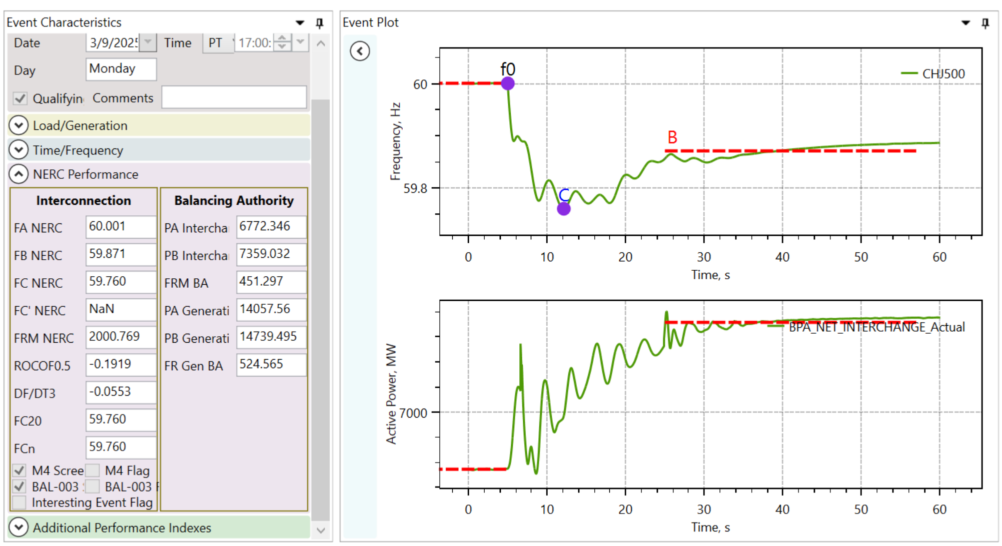

Figure 6-2. Double Palo Verde outage simulation (system frequency and BPA net interchange).

LMN (FRM=8.4 MW/0.1Hz) IHR (FRM=15.4 MW/0.1Hz)

[1] https://powertechlabs.com/tsat/

[2] P. Etingov, D. Kosterev, T Dai, "Frequency response analysis tool," PNNL-23954, 2014. Source: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23954.pdf

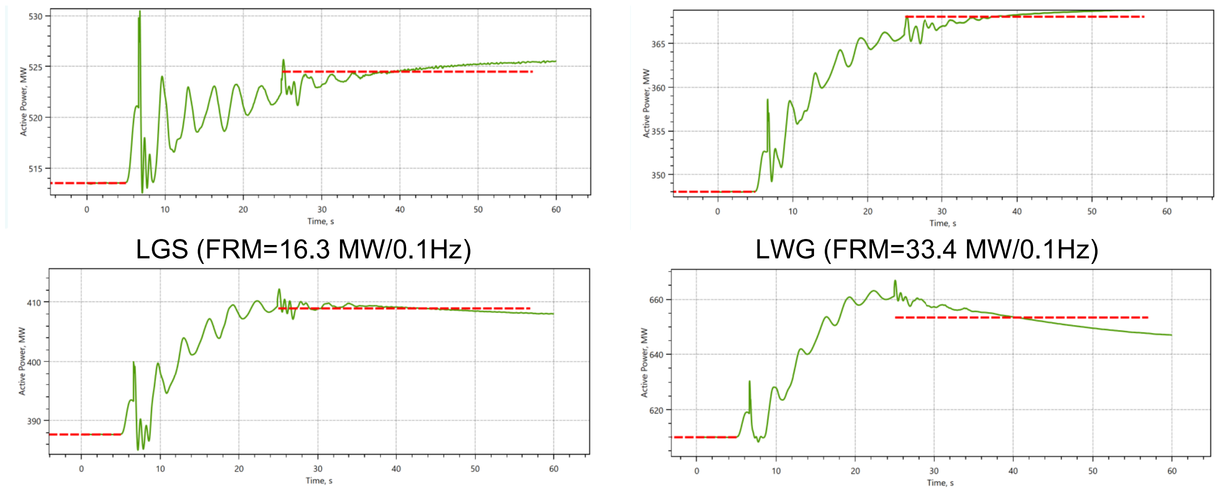

Figure 6-3. Double Palo Verde outage simulation (LSR plants response).

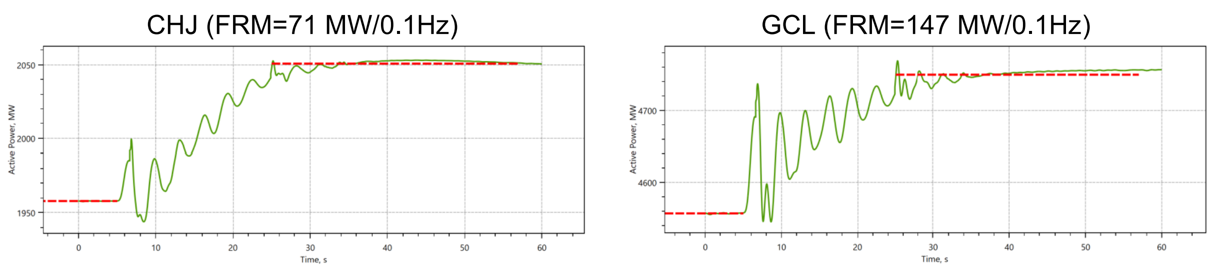

Figure 6-4. Double Palo Verde outage simulation (CHJ and GCL response).

The simulation of another frequency event, specifically the MCN power plant outage, is depicted in Figure 6-5, where approximately 700 MW of generation is lost. Since this event occurs within the BPA area, this generation loss should be included in the BPA FRM value calculation. Based on the analyses, the BPA FRM is computed to be about 474 MW/0.1Hz. The responses of the LSR plants, as well as the CHJ and GCL plants, are illustrated in Figure 6-6 and Figure 6-7. The combined response of the LSR plants is 74.2 MW/0.1Hz, while the CHJ and GCL responses are 73.4 MW/0.1Hz and 140.3 MW/0.1Hz, respectively.

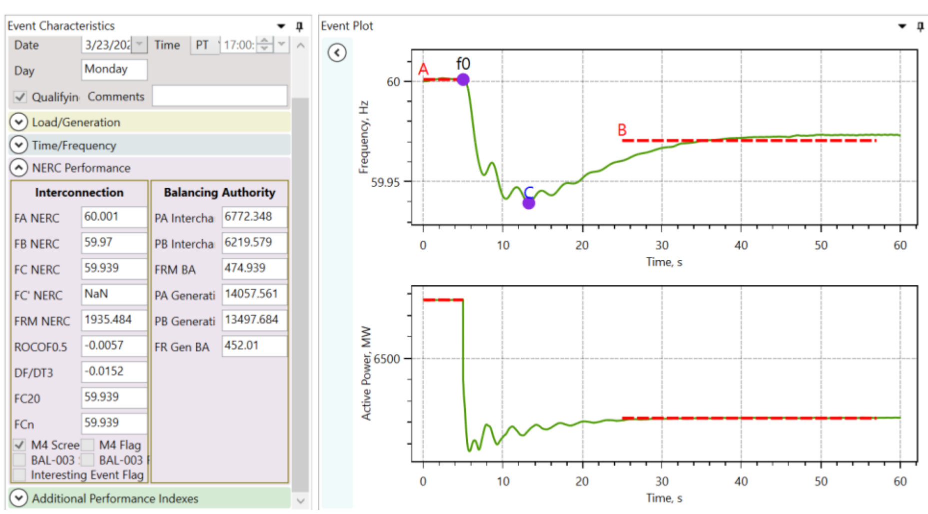

Figure 6-5. MCN outage simulation (system frequency and BPA net interchange).

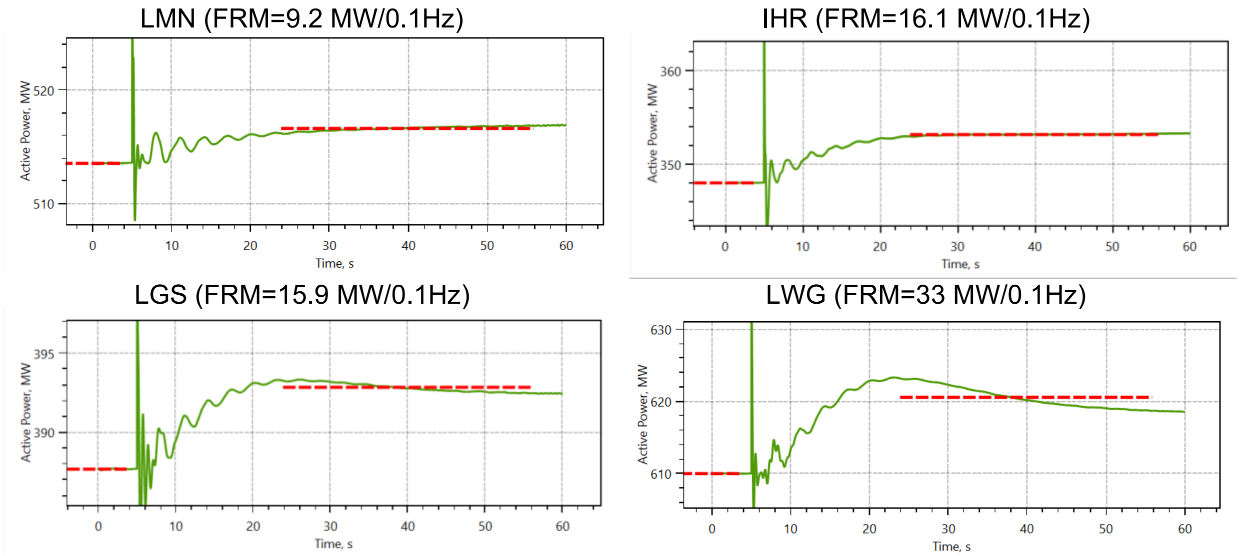

Figure 6-6. MCN outage simulation (LSR plants response).

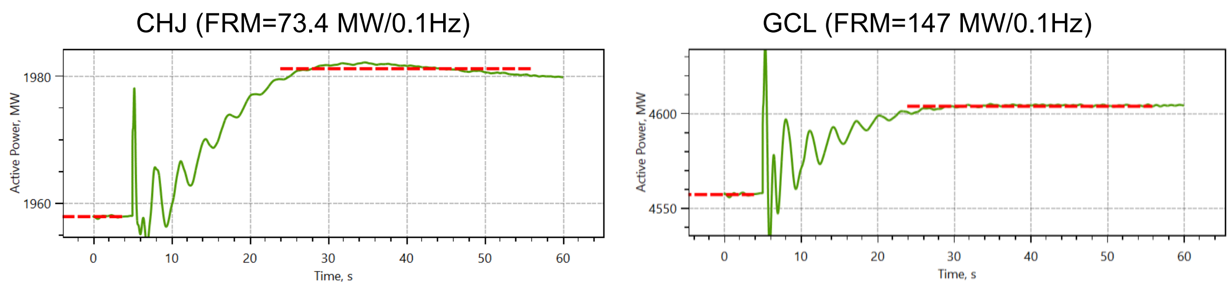

Figure 6-7. MCN outage simulation (CHJ and GCL response).

To analyze the impact of LSR plants on inertia, Palo Verde and MCN tripping faults were simulated under conditions where LSR plants were turned off. Inertia response, which influences the slope of the frequency signal following a fault, was characterized by calculating the Rate of Change of Frequency. Additionally, inertia directly affects the minimum frequency (Frequency at Point C) as defined by the NERC BAL-003 standard.

As shown in Figure 6-8, there is no noticeable difference in the frequency slopes between the scenarios with and without LSR plants. However, the Frequency at Point C drops slightly lower in the absence of LSR plants. Furthermore, BPA FRM values are also reduced in comparison to the base case, which includes the operational LSR plants.

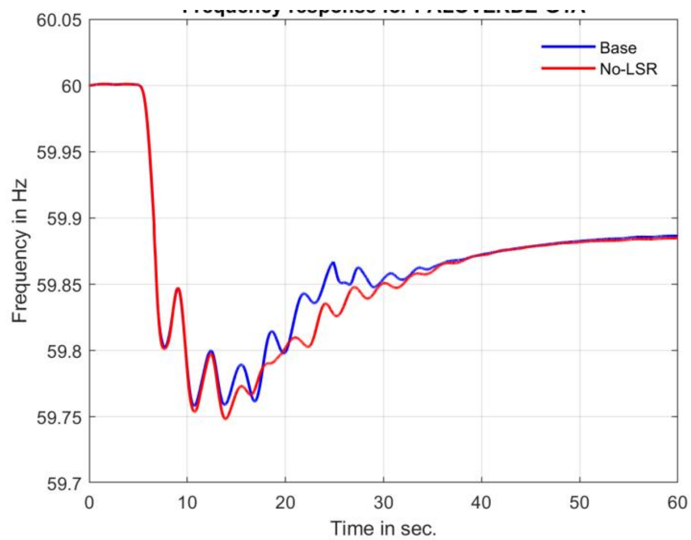

Figure 6-8. Double Palo Verde outage simulation—frequency base case and without LSR plants.

Table 6-1 summarizes the FR results for simulated events and some historical event PMU measurements available at PNNL. It is evident that the simulated FRM values are close to the actual data, with PMU measurements available only for the LMN plant. The BPA FRM values are also similar to the results presented by BPA.[1] Figure 6-9 illustrates the contribution of individual plants to the overall BPA FR. It is important to note that the FR of individual plants depends on various factors, including the number of online units, operating point, available headroom for providing FR, and the mode of operation for the speed governors. According to NERC, BPA's FRO allocation for the operating year 2024 is 91.7 MW/0.1Hz.[2]

On average, BPA provides more than 300 MW/0.1Hz of response (Figure 6-9), significantly contributing to the overall reliability of the Western Interconnection in terms of maintaining system frequency. As shown in Figure 6-10, the LSR plants combined contribute, on average, up to 15% of the total BPA FRM.

Table 6-1. FRM statistics for various events

Event	BPA NERC FRM	LMN	LGS	LWG	IHR	LSR (combined response)	CHJ	GCL
PMU 1	376	13						
PMU 2	514	13.8						

[1] Kosterev D., P. Etingov. 2015. "PMU-based application for frequency response analysis and baselining." North American SynchroPhasor Initiative Working Group Meeting. March 23-24. https://naspi.org/sites/default/files/2016-09/bpa_kosterev_pmu-based_application_for_frequency_response_20150323.pdf.

[2] NERC. 2023. BAL-003-2 Frequency Response Obligation Allocation and Minimum Frequency Bias Settings for Operating Year 2024. Atlanta: NERC. https://www.nerc.com/comm/OC/RS%20Landing%20Page%20DL/Frequency%20Response%20Standard%20Resources/BA_FRO_Allocations_for_OY2024.pdf

Event	BPA NERC FRM	LMN	LGS	LWG	IHR	LSR (combined response)	CHJ	GCL
PMU 3	418	7.5						
Paloverde	451	8.4	16.3	33.4	15.4	73.5	71	147
MCN	474	9.2	15.9	33.0	16.1	74.2	76.8	154
Paloverde (LSR – offline)	390	0	0	0	0	0	72.5	149
MCN (LSR – offline)	410	0	0	0	0	0	76.7	153.3

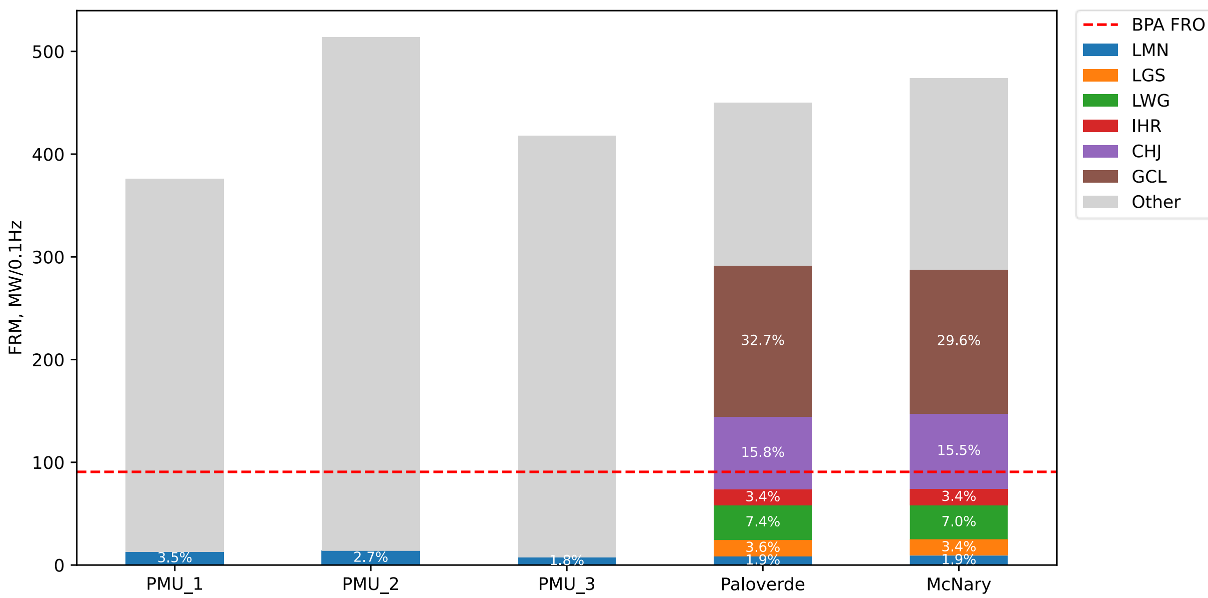

Figure 6-9. Individual plants contribution to FR for various events

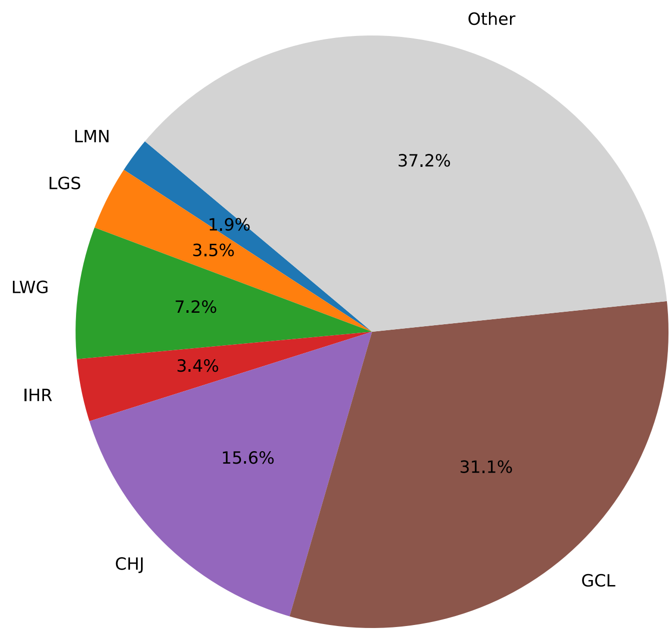

Figure 6-10. Summary statistics on average contribution of individual plants to BPA FRM.

6.3 Key Takeaways from Frequency Response Study

The key takeaway from the FR study is that LSR plants' contributions to FR is proportional to their capacity relative to the rest of the federal hydro fleet managed by BPA. They contribute to inertial and primary FR (inertia and governor response), and they can also provide secondary response (AGC) if needed.

7.0 Weather Events

In this section, we examine several weather events during which temperatures dropped below or exceeded typical seasonal levels and analyze how the power system performed under these conditions, and the role of LSR plants in supporting power system reliability under such prolonged stressed conditions. Analyzing specific extreme weather events is essential for accurately assessing power system reliability, as such events often push the system beyond normal operating limits and expose vulnerabilities that may remain hidden during typical operations. Heat waves and cold weather events can simultaneously affect generation, transmission, and demand, placing increased stress on the system and challenging its ability to maintain reliable operation. By studying these events in detail, we can evaluate the contribution of BPA's hydro fleet to the reliability of the BPA BA and its role in supporting the broader Western Interconnection.

7.1 January 2024 Arctic Storm Event

The winter storms Gerri and Heather, which swept across North America from January 10th to January 17, 2024, were reviewed by the Federal Energy Regulatory Commission and NERC to assess their impact on the U.S. electric grid.[1] Despite the severity of these events, the review highlighted strong emergency preparedness by electrical utilities, with no instances of load shedding reported during the storms. In this section, we will examine in greater detail the performance of BPA's generation fleet during this period, with a focus on the LSR plants, and analyze the role of interregional power transfers in maintaining reliable system operations.

Figure 7-1 shows the daily average temperatures in January for the years 2020 through 2024 in Richland, WA; Los Angeles, CA; and Seattle, WA. Notably, the purple lines representing 2024 indicate a sharp and prolonged temperature drop in mid-January in both Richland and Seattle, with daily averages falling below 20°F on January 13–14. This cold weather event was atypical for the region and resulted in a significant increase in electricity demand across the Pacific Northwest due to elevated heating loads. In contrast, California experienced relatively stable and mild temperatures during the same period, underscoring the regional nature of the cold front and its localized impact on system conditions in the Northwest.

Figure 7-2 presents BPA's load, hydro and wind generation, and net interchange for January 2024. A notable increase in load occurred between January 10 and 17, coinciding with the cold weather event shown in Figure 7-1. During this period, electricity demand rose sharply, reaching its monthly peak on January 13. At the same time, wind generation dropped from around 2,000 MW to near zero, significantly reducing the available generation capacity. To maintain system balance, BPA ramped up hydro generation. Additionally, the net interchange curve shows a shift from typical export patterns to substantial imports, indicating that BPA had to procure external power to support system reliability during this high-stress period.

Figure 7-3 shows the power output of LSR plants and other individual hydro power plants. It can be seen that GCL ramped its output from 2,000 MW to 3,500 MW during peak periods, while CHJ increased generation from 1,000 MW to 2,000 MW. Due to water constraints, the LSR plants were unable to significantly increase their output beyond typical levels but still contributed approximately 1,000 MW during peak generation. Forebay elevations at LWG and GCL, along with corresponding generation outputs, are shown in Figure 7-4 and Figure 7-5. The data

[1] https://www.ferc.gov/news-events/news/presentation-system-performance-review-january-2024-arctic-storms

indicate that low water conditions constrained power production at these plants during the event.

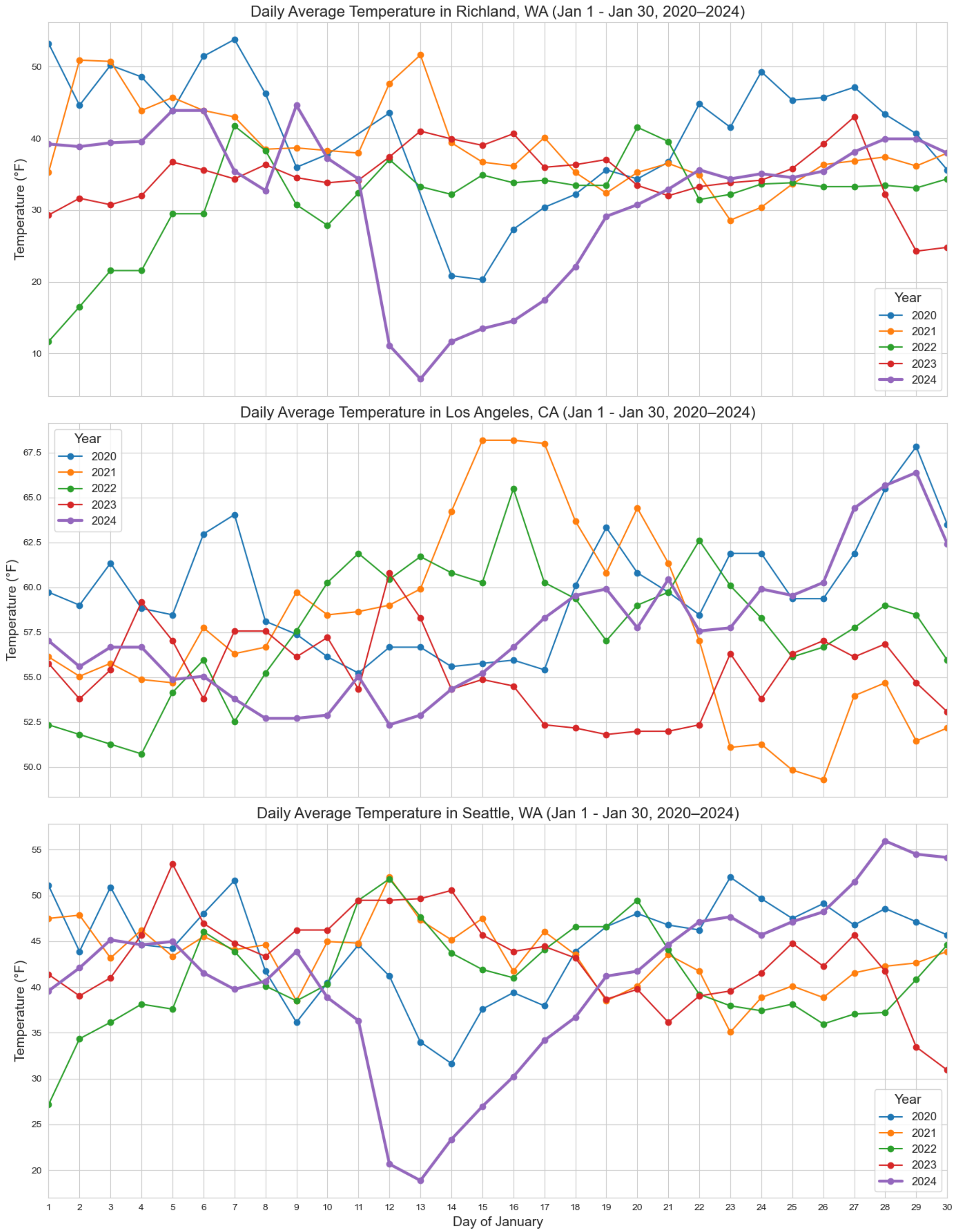

Figure 7-1. Daily average temperature statistics in January 2020–2024.

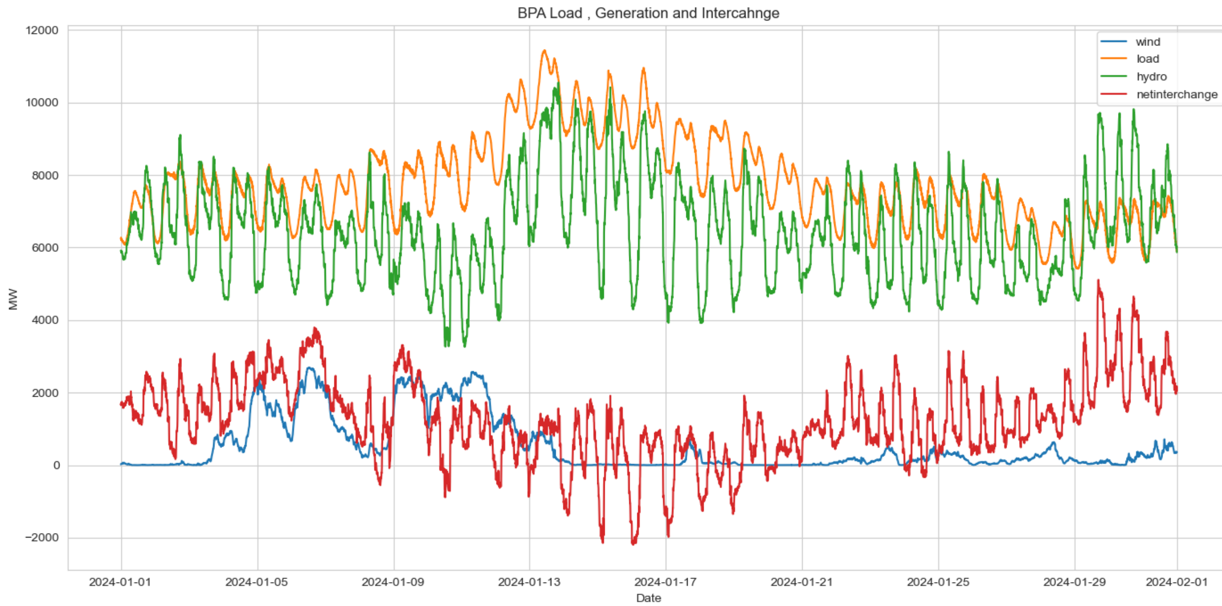

Figure 7-2. BPA load, wind and hydro generation and net interchange in January 2024.

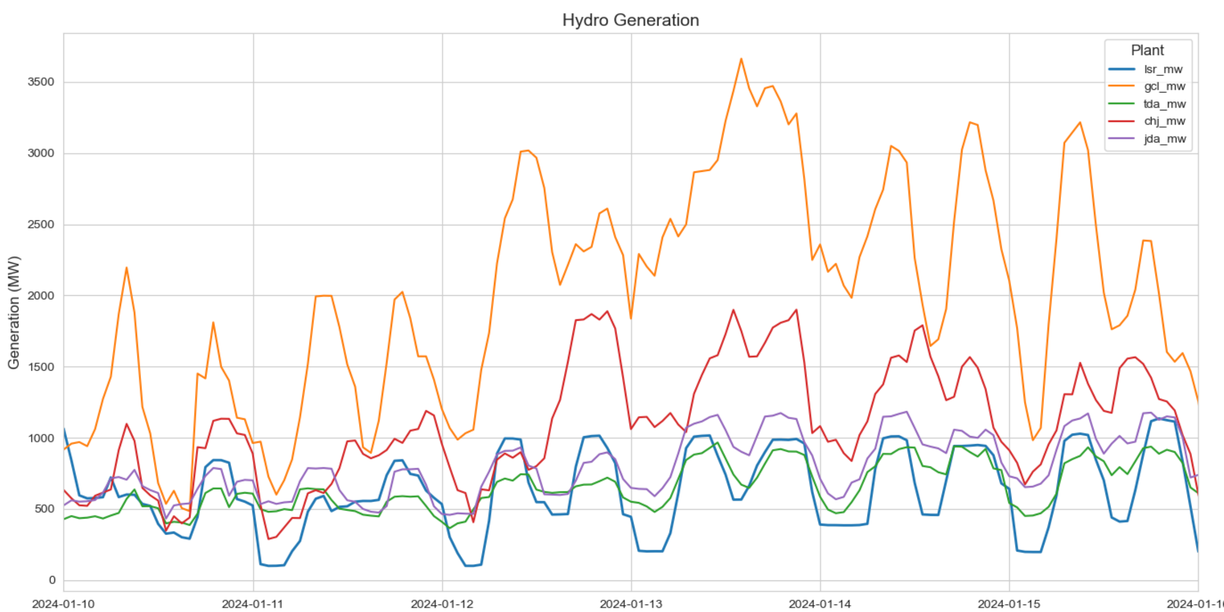

Figure 7-3. LSR, GCL, JDA, CHJ and TDA generation on Jan 10–Jan 16, 2024.

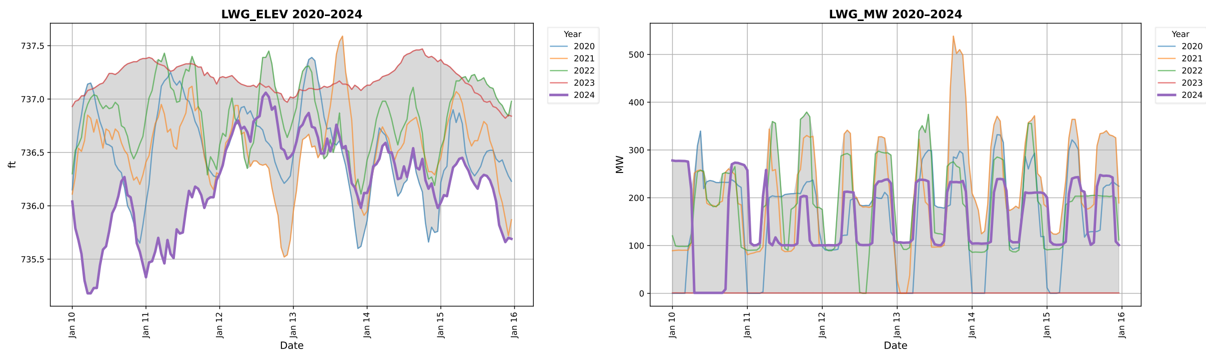

Figure 7-4. LWG elevation and generation on Jan 10–Jan 16, 2024.

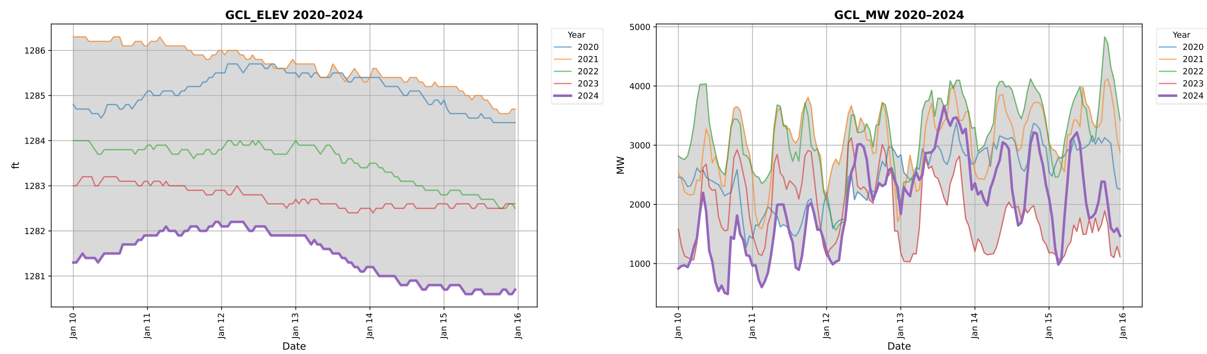

Figure 7-5. GCL elevation and generation on Jan 10–Jan 16, 2024.

Figure 7-6 shows power flows through the COI, the PDCI, and the internal BPA transmission path "West of Lower Monumental," which is located near the LSR plants. During the event, COI flow reversed to a south-to-north direction, enabling power transfers from California to support increased demand in the Pacific Northwest. The COI reached its operational transfer limit of -3,675 MW. At the same time, the PDCI transfer limit for south-to-north flow was set to zero, preventing any contribution from PDCI to the Pacific Northwest region during this period. Flows on the west of LMN path also dropped to low levels, indicating that power generated by the LSR plants was primarily used to serve local loads. These flow patterns are atypical for this time of year, as illustrated in Figure 7-7 and Figure 7-8, which shows historical COI and west of LMN flows from 2020 to 2024.

Thus, the January 2024 cold weather event demonstrated the contribution of flexible hydro resources and available transmission capacity in maintaining system reliability during extreme conditions. In the face of limited generation reserves and constrained transmission, the LSR plants contributed approximately 1,000 MW of generation, which is about the same as the average MWs provided by the LSR plants.

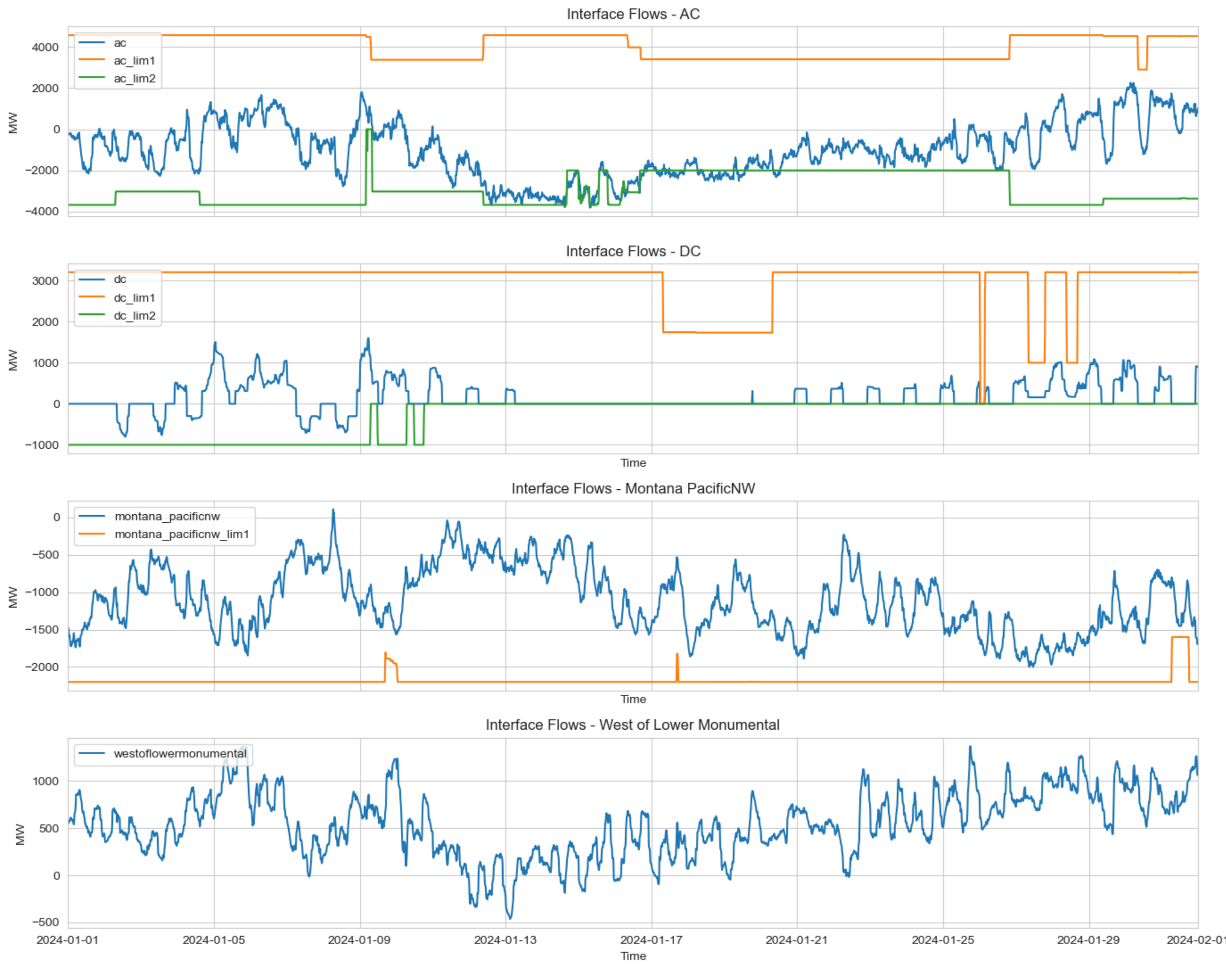

Figure 7-6. COI, PDCI, Montana–Pacific Northwest, and west of LMN interface flows in January 2024.

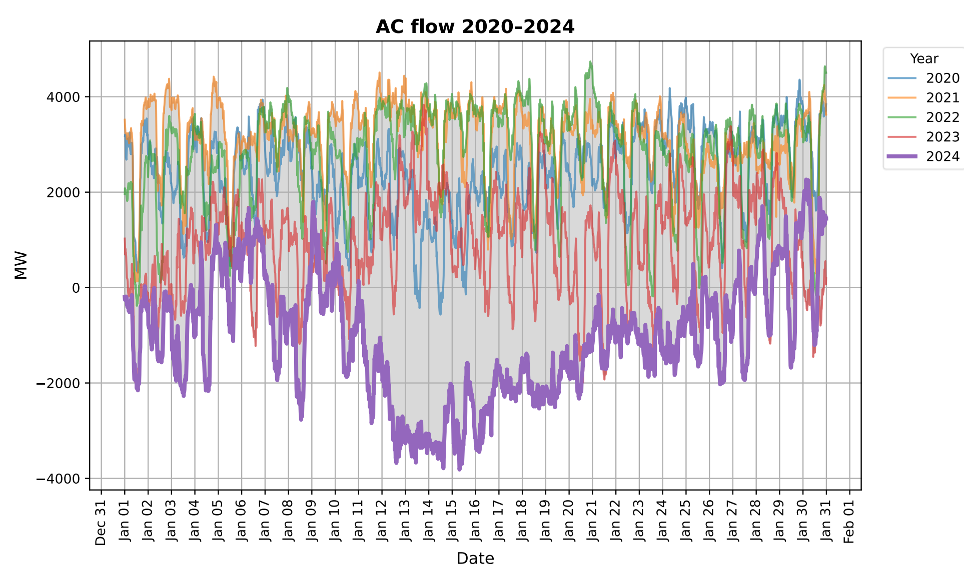

Figure 7-7. COI flow January 2020–2024.

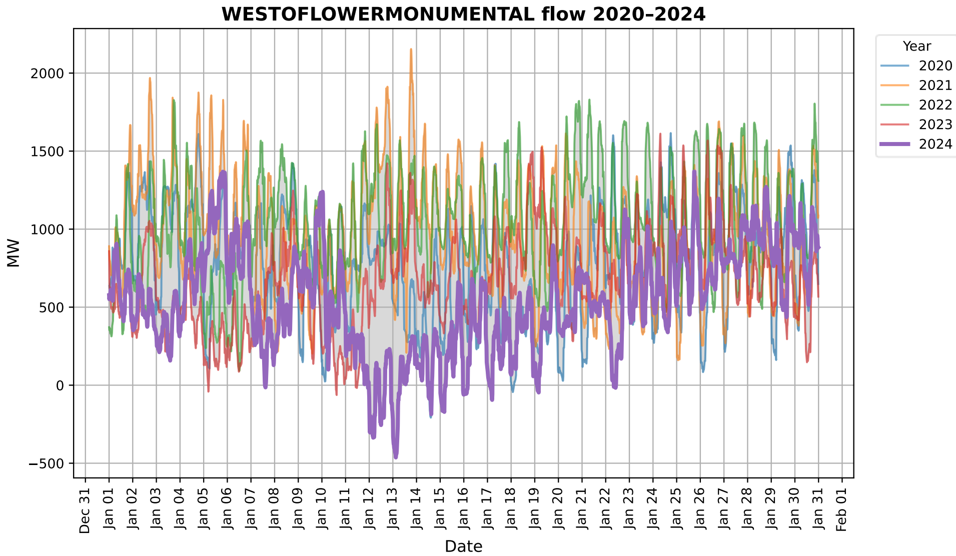

Figure 7-8. West of LMN flow January 2020–2024.

7.2 September 2022 Heat Wave in California

Figure 7-9 shows the historical daily average temperatures in the Pacific Northwest and Northern California during September from 2020 to 2024. On September 6, 2022, the temperature in Sacramento reached 92°F, which is significantly above the typical temperature for that time of year. As a result of the extreme heat and increased use of air conditioning—along with other contributing factors—CAISO's system load exceeded 50 GW, marking the highest load recorded in 2022.

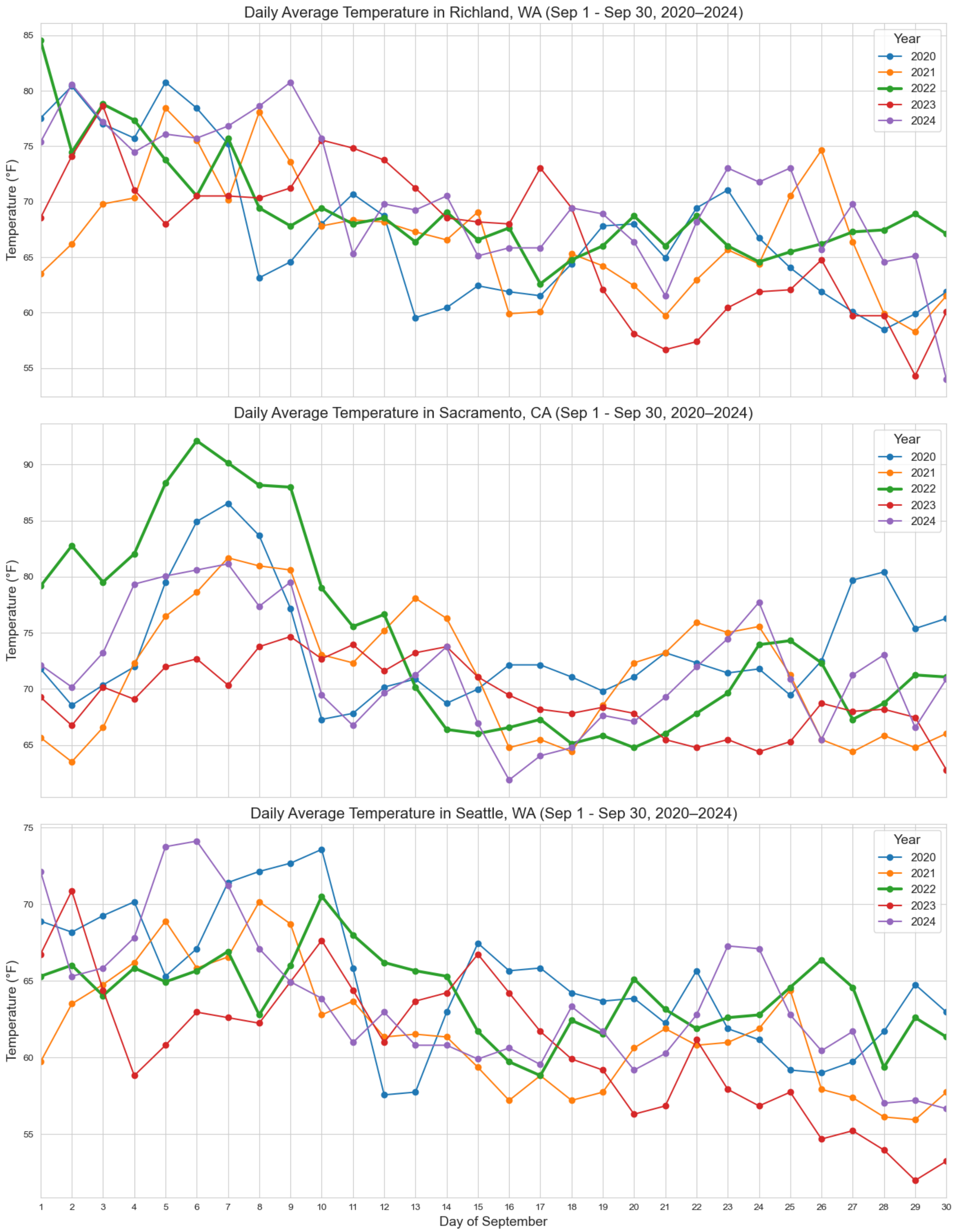

Figure 7-9. Daily average temperature statistics in September 2020–2024.

Figure 7-10 presents the CAISO load along with solar generation and net load. The peak net load of approximately 47,500 MW occurred at 7 p.m. on September 6th, when solar generation decreased from its peak of 12,000 MW at noon to about 1,760 MW. As shown in Figure 7-11, both the COI and PDCI interfaces were loaded to their transmission limits, transferring power from the Pacific Northwest to the south, assisting California in meeting its demand. Figure 7-12 and Figure 7-13 present historical flows through COI and PDCI during the same period from 2020 to 2024, showing that the flows in 2022 reached near-maximum levels across the five-year span.

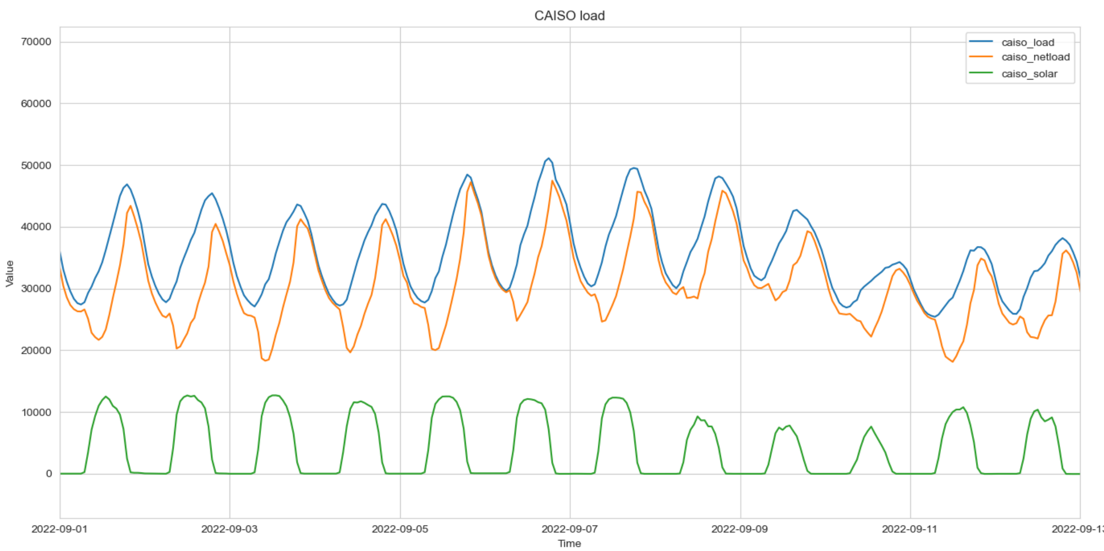

Figure 7-10. CAISO load, solar generation and netload in September 1–13, 2022.

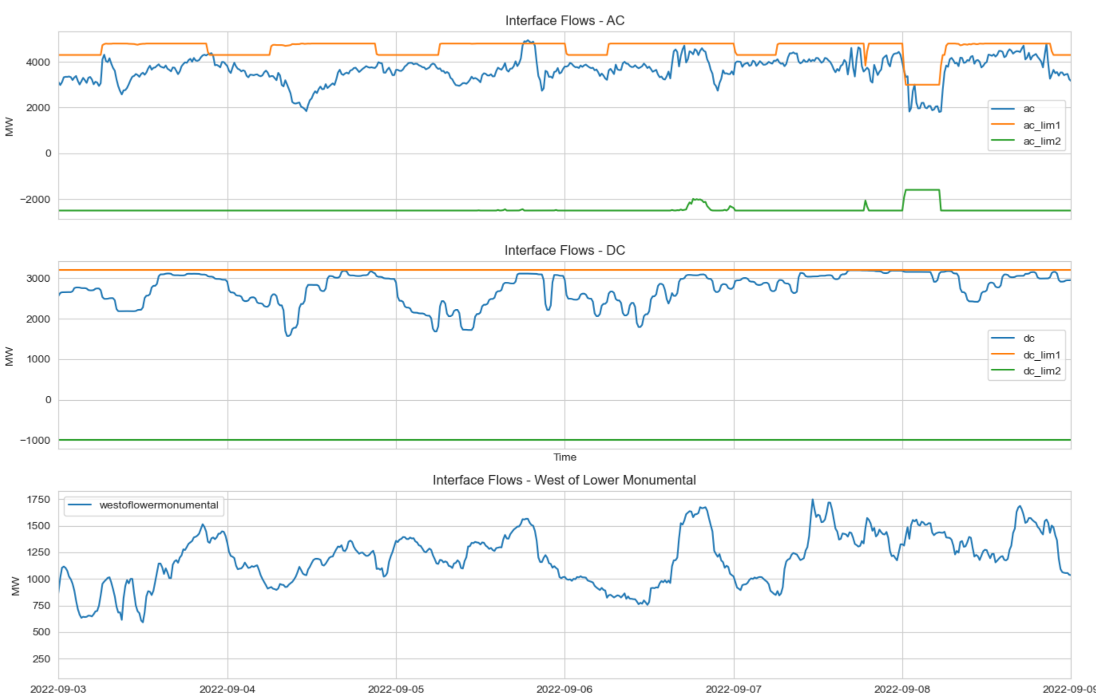

Figure 7-11. COI, PDCI, and west of LMN interface flows on Sep 3–Sep 9, 2022.

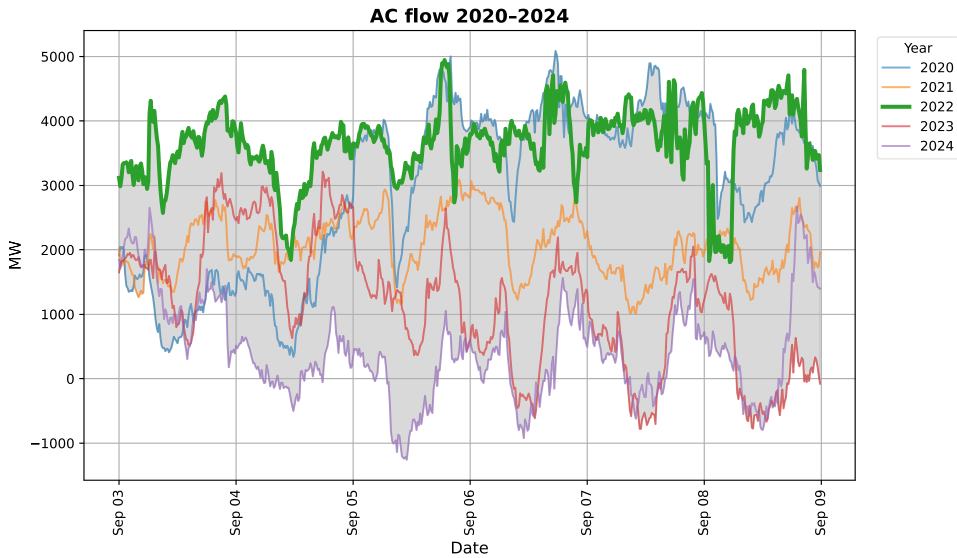

Figure 7-12. COI flow on Sep 3–Sep 9, 2022.

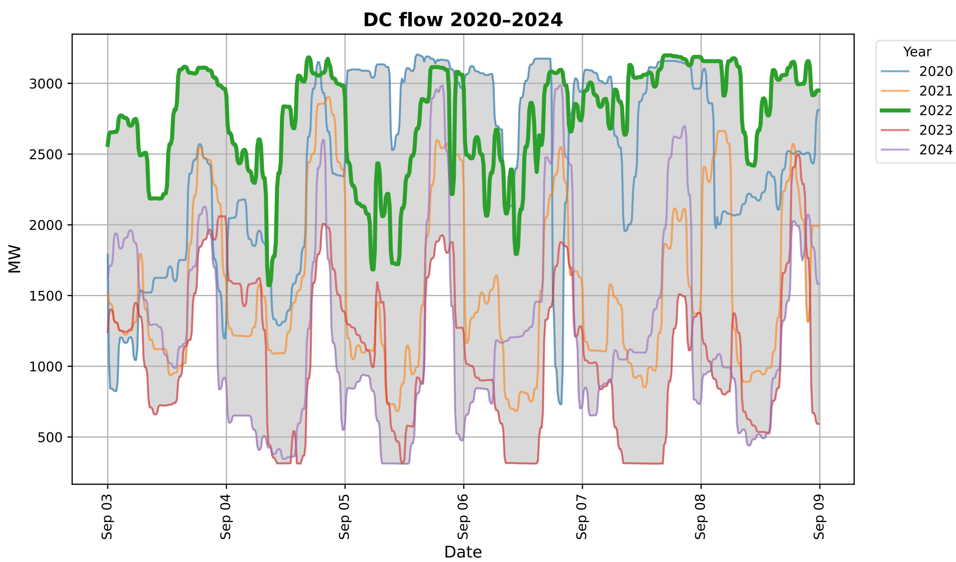

Figure 7-13. PDCI flow on Sep 3–Sep 9, 2022.

Figure 7-14 illustrates BPA wind and hydro generation, interchange, and load. During CAISO's peak load, BPA wind generation was close to zero. However, the flexibility of hydro generation allowed BPA to ramp up its hydro fleet to increase interchange flow. On September 6, LSR plants ramped up generation to 1,500 MW (see Figure 7-15), which is higher than the typical generation of around 1,000 MW. Major plants such as CHJ and GCL played significant roles and contributed to the increase in power generation during this challenging period. LSR plants made a measurable contribution to maintain balance between generation and loads in the WECC system during this event.

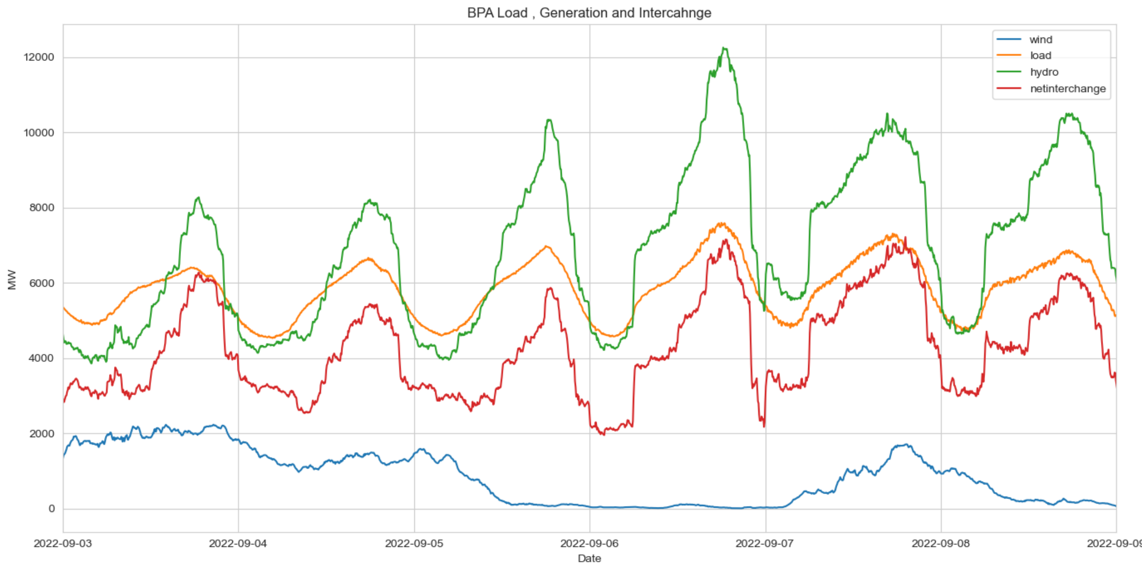

Figure 7-14. BPA load, wind and hydro generation and net interchange on September 3–9, 2022.

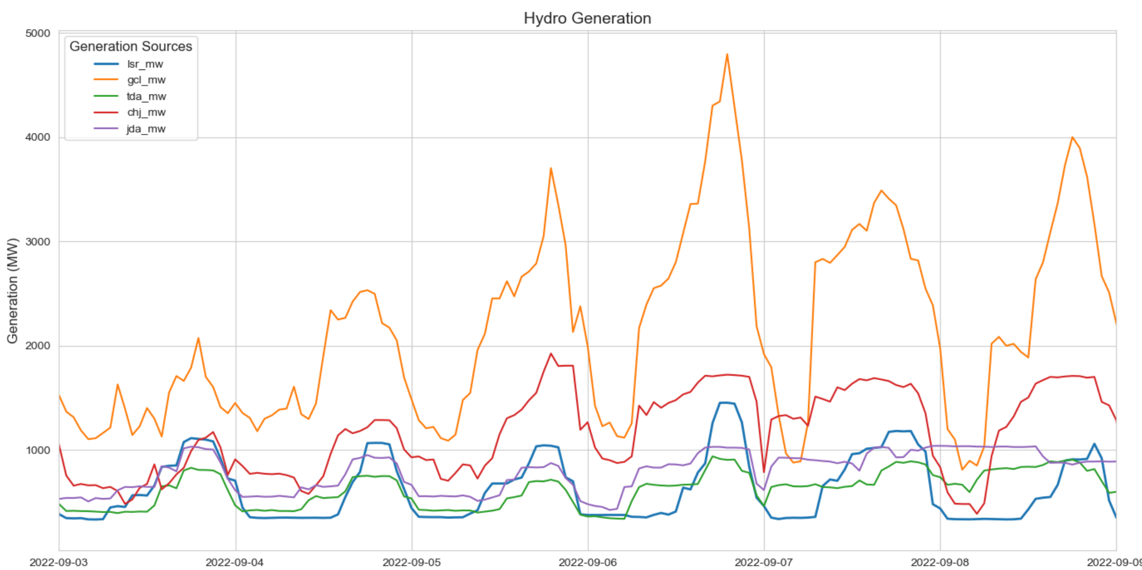

Figure 7-15. LSR, GCL, JDA, CHJ and TDA generation on Sep 3–Sep 9, 2022.

8.0 Conclusions

This report examines the historical role of LSR plants in ensuring system reliability. Their contributions have been proportional to their installed capacity, providing essential services such as incremental and decremental reserves, load-following support, and frequency and voltage stabilization. During meteorologically driven grid stress events such as heat waves or freezes, LSR plants have at times supplied extra generation and helped maintain overall system reliability. This analysis is based on historical data and events, and the power system is continually evolving, and the historical role of LSR plants may not necessarily represent their future contribution. Continual detailed operational and planning studies will be needed to assess the future role of LSR plants within the Western Interconnection as the power system evolves.

The key findings of this study are summarized in the table below. Table 8-1 presents a set of metrics identified for the analysis, along with brief descriptions, quantified values, contributions to total BPA services, and the associated impact of LSR plants on these services. This summary provides a concise reference for evaluating the role of LSR resources in supporting grid reliability. As illustrated in the table, LSR plants collectively account for approximately 10–15% for the total BPA grid services analyzed in the report.

Table 8-1. Key Grid Service Metrics

Grid service	Metrics		Contribution		Impact
Capacity/Energy	Average generation by LSR plants	~700 MW	Share to total BPA hydro generation	~10%	LSR plants provide moderate capacity under normal operating conditions, but potentially significant during peak load periods due to weather and other events when interchange flows may be constrained by transmission limitations.
	Maximum generation by LSR plants	2,000–2,500 MW	Share to total BPA hydro generation	Up to 18%	
Flexibility: Inter-hour Ramping & Balancing	Average LSR 3-hour ramps	High-water season ±250 MW	Share to total BPA hydro generation	~20-25%	LSR plants demonstrate measurable flexibility through their three-hour ramping capabilities, which contribute to BPA's ability to maintain reliable load-balancing operations. Additionally, these plants facilitate interregional energy trade and provide support (typically during high-water seasons), assisting CAISO in managing power balance and mitigating the impact of solar generation ramps on the grid.
		Low water season ±100 MW		~10%	
	Maximum LSR 3-hour ramps	High-water season ±1000 MW		~25%	
		Low-water season ±400 MW		~10%	

Grid service	Metrics		Contribution		Impact
	LSR Mileage	~250,000 MW per year		~15%	The aggregated LSR plants have exhibited substantial flexibility in terms of mileage, underscoring their active participation in the load-balancing process and their capability to dynamically adjust output in response to system net load demand.
Flexibility: Intra-Hour Ramping & Balancing	Due to the lack of detailed data on LSR participation in AGC regulation actions, an analysis of 5-minute LSR generation data was performed. This analysis extracted 5- and 15-minute ramp participation metrics, which can be compared to total BPA hydro fleet ramps to evaluate the contribution of LSR plants to intra-hour balancing process. On average, LSR 5-minute ramps are approximately 5 MW, with peak values reaching 30 MW.			~10%	According to BPA documents, LSR plants are connected to AGC and can provide regulation services. Based on the performed analysis, it can be reasonably assumed that LSR plants play a role in load-following and regulation processes.
Voltage/Reactive Power Support	Average MVAR provided by LSR plants	±1,000 MVAR	The metric represents a local service and is not quantified as a share of total BPA reactive support		LSR plants provide volt-ampere reactive (VAR) support as expected.
Frequency Response	LSR FRM	70 MW/0.1Hz	Share to total BPA FRM	~10-15%	LSR plants provide frequency support to the grid as expected.

Appendix A – BPA Annual Statistics on Generation and Load

A.1 Time Series Data

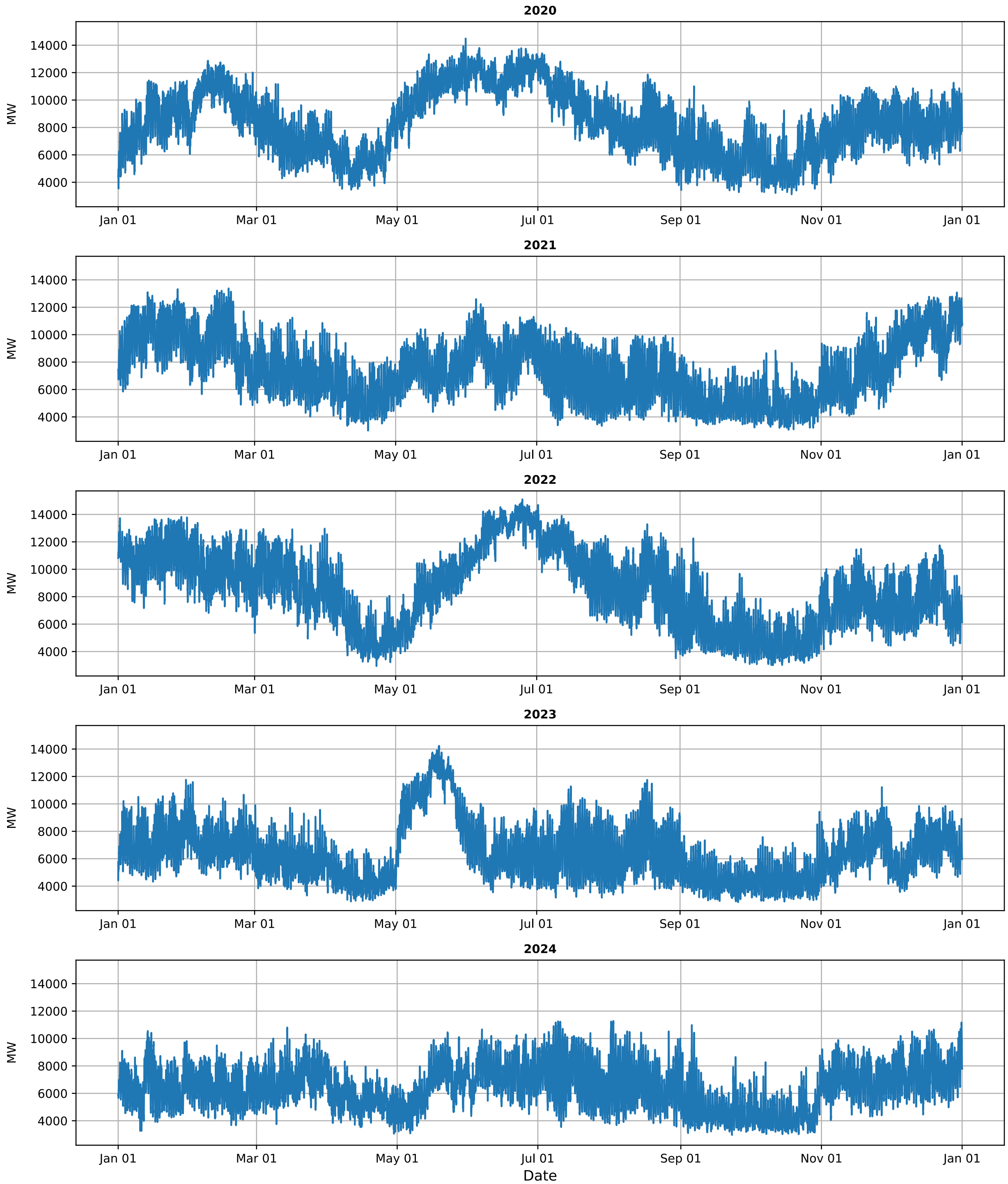

Figure A-1. BPA hydro Generation in 2020–2024.

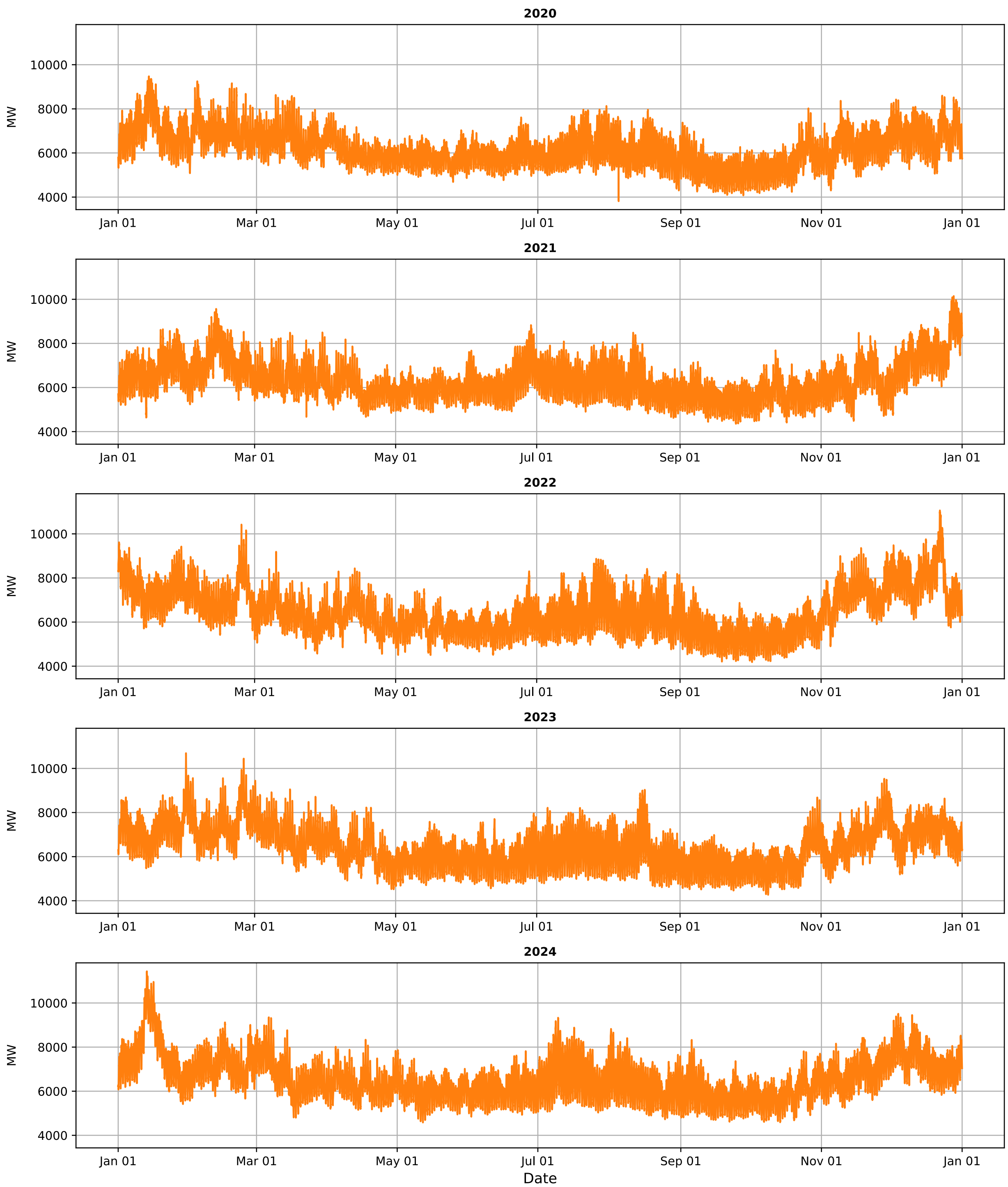

Figure A-2. BPA load in 2020–2024.

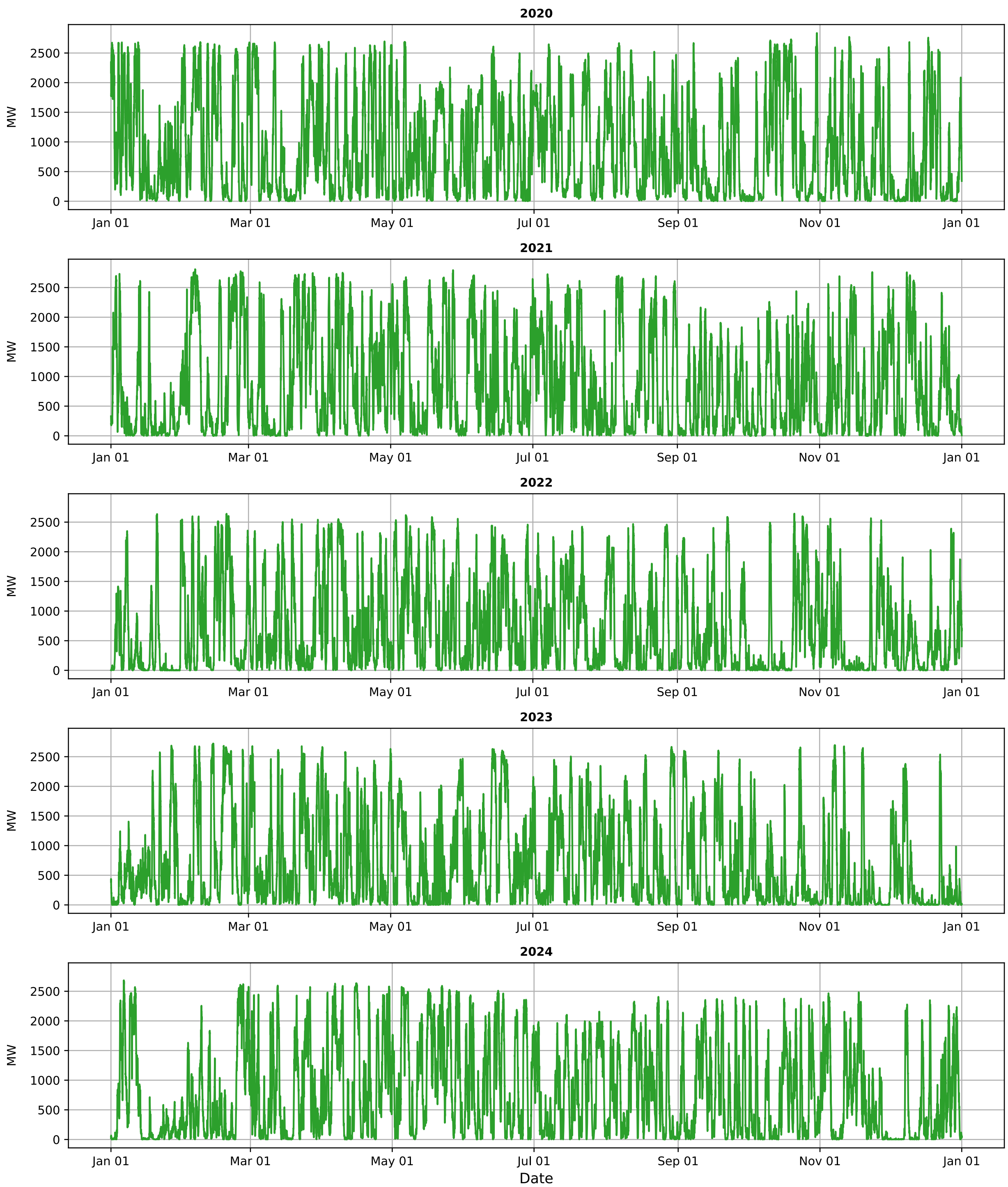

Figure A-3. BPA wind generation in 2020–2024.

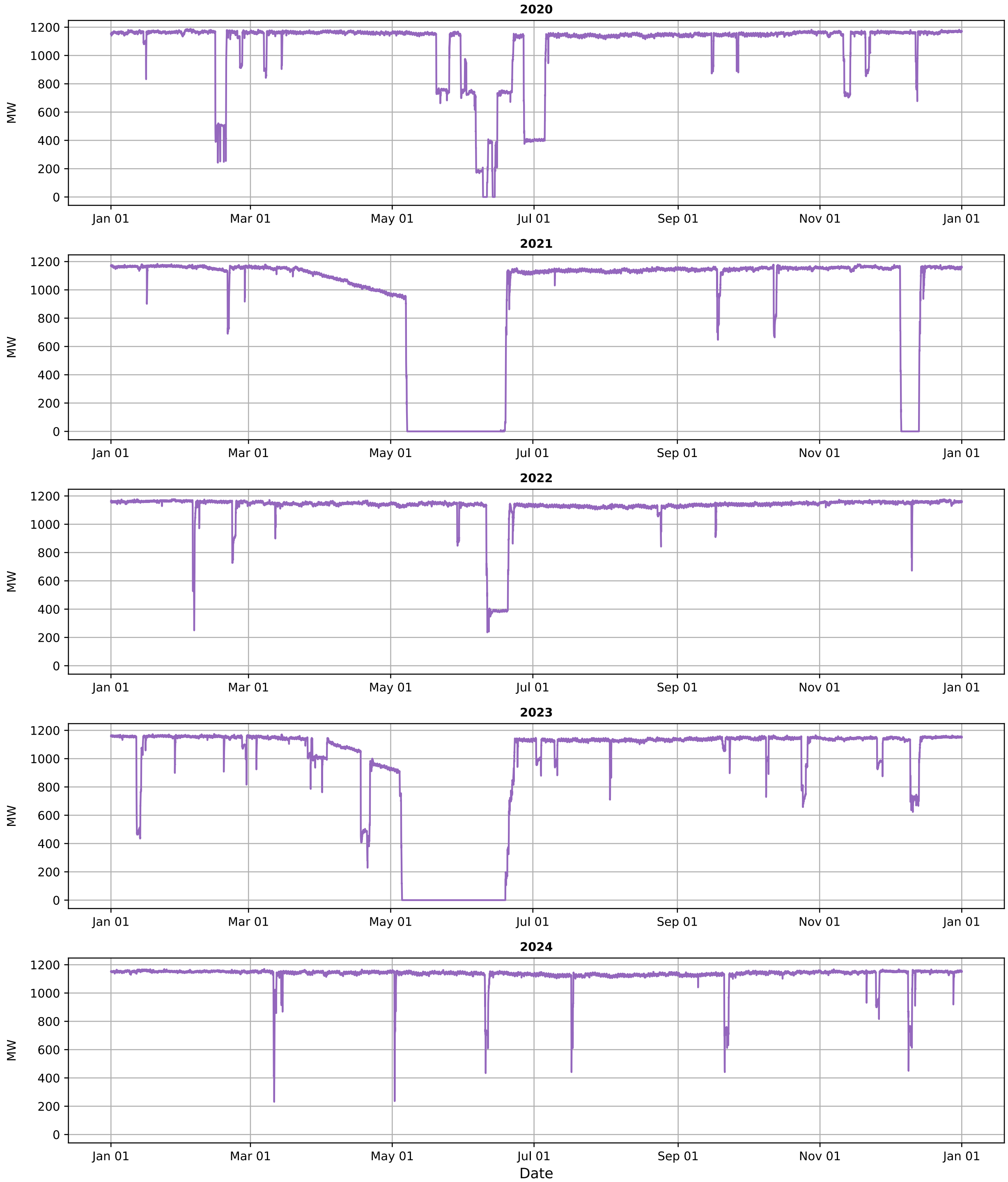

Figure A-4. BPA nuclear generation in 2020–2024.

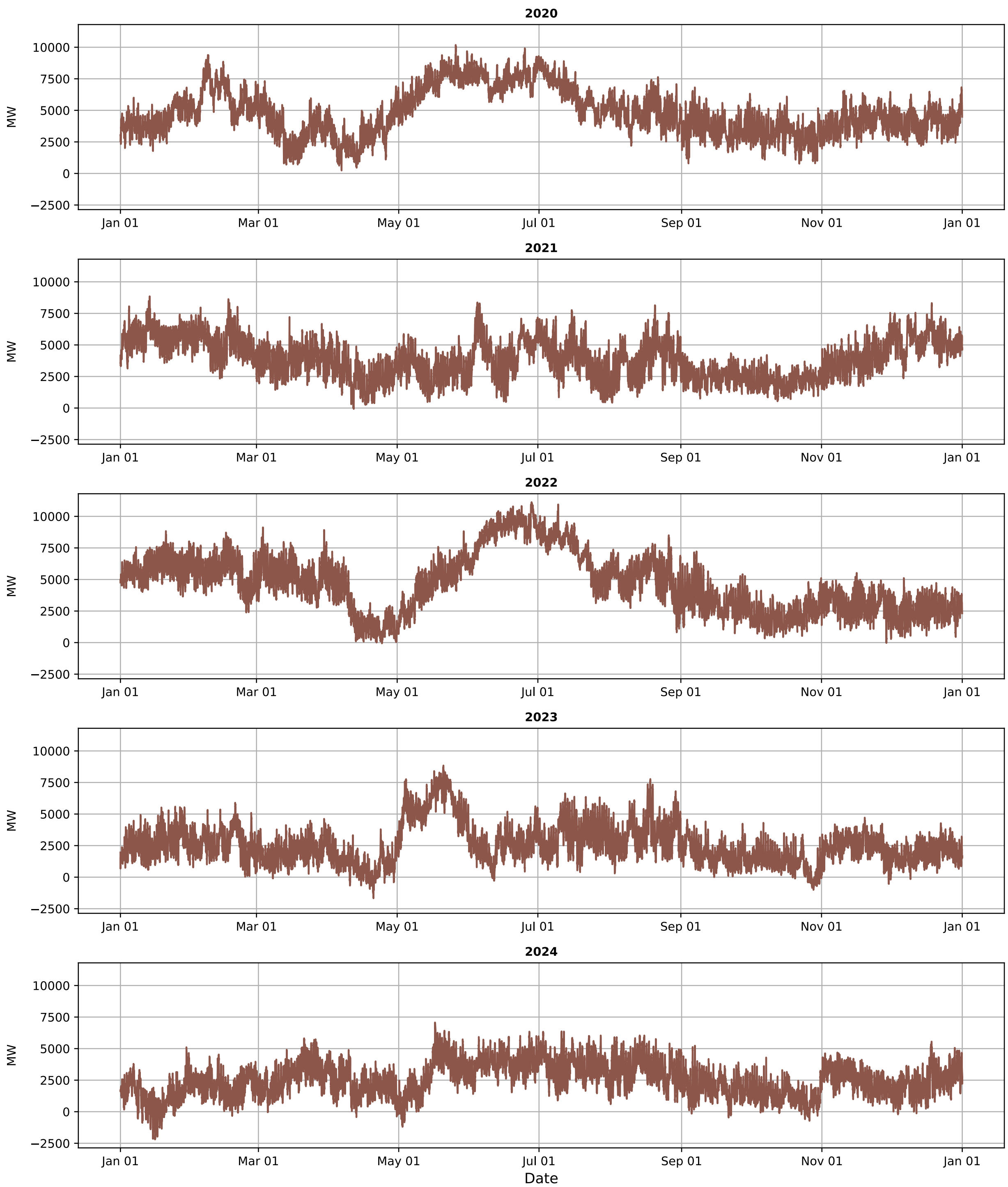

Figure A-5. BPA net interchange in 2020–2024.

A.2 Monthly Average

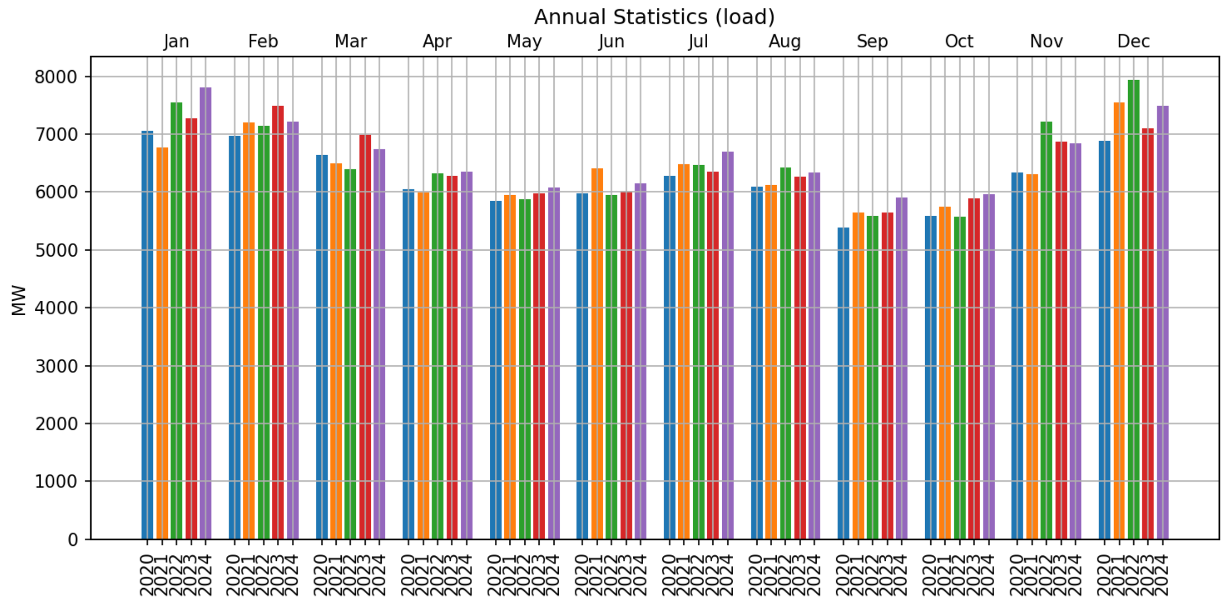

Figure A-6. Monthly average load for 2020–2024.

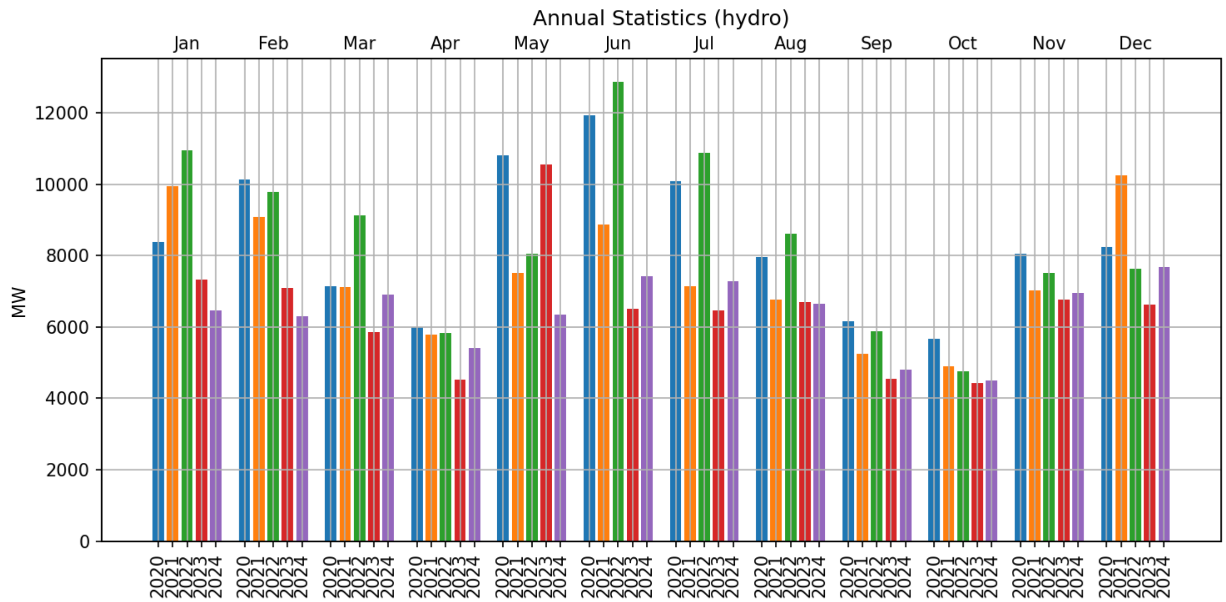

Figure A-7. Monthly average hydro generation for 2020–2024.

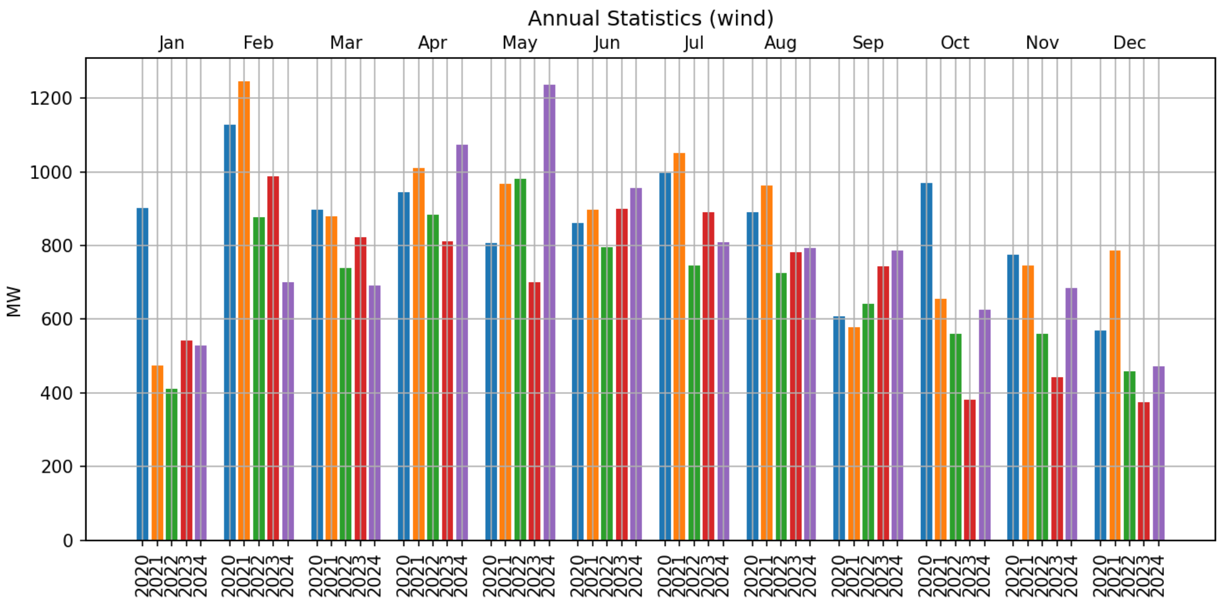

Figure A-8. Monthly average wind generation for 2020–2024.

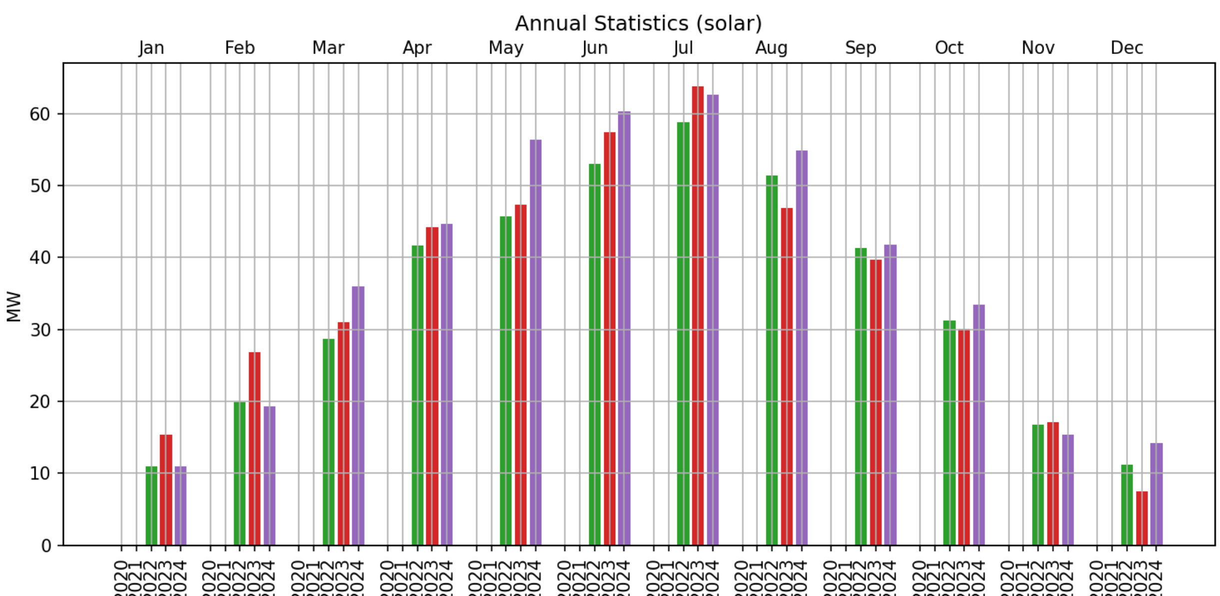

Figure A-9. Monthly average solar generation for 2022–2024.

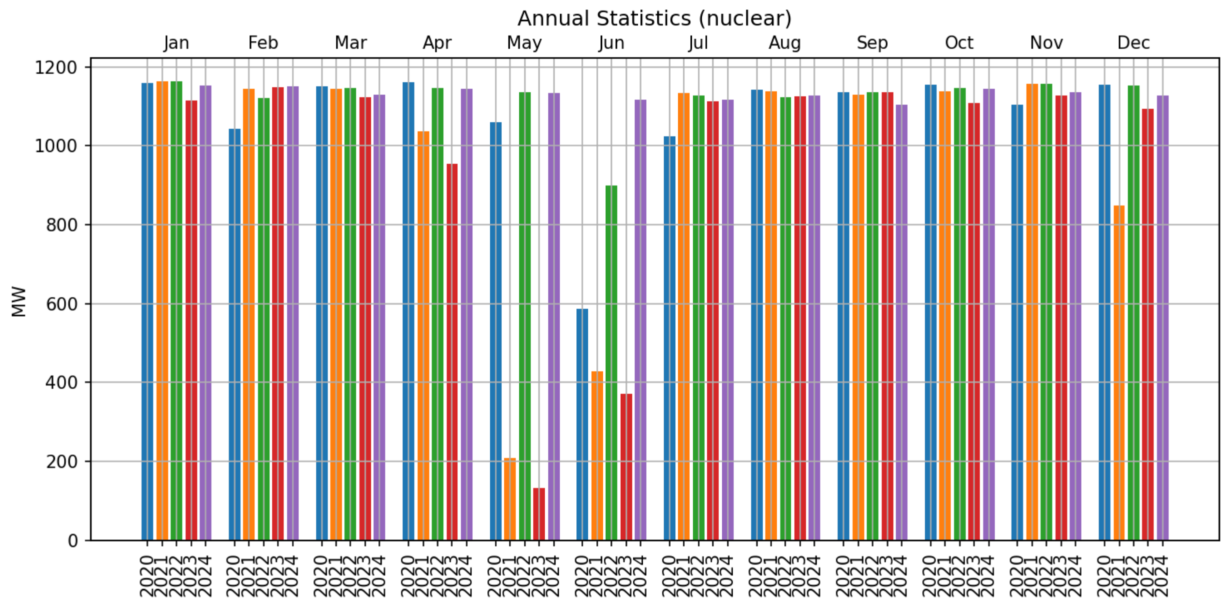

Figure A-10. Monthly average nuclear generation for 2020–2024.

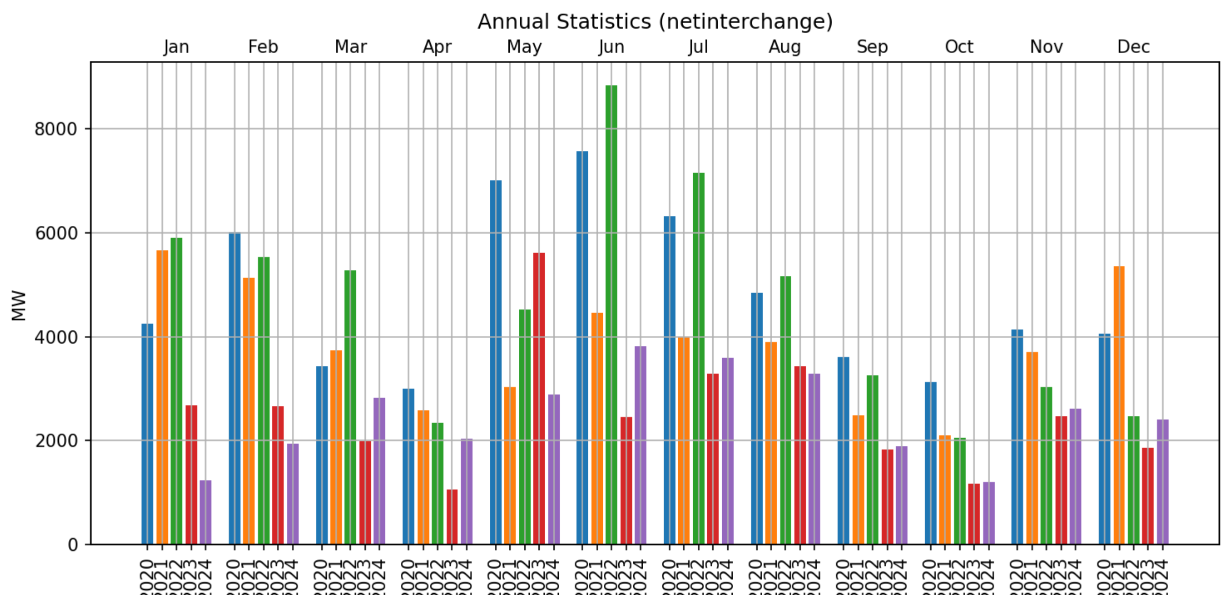

Figure A-11. Monthly average net interchange for 2020–2024.

A.3 Monthly Boxplots

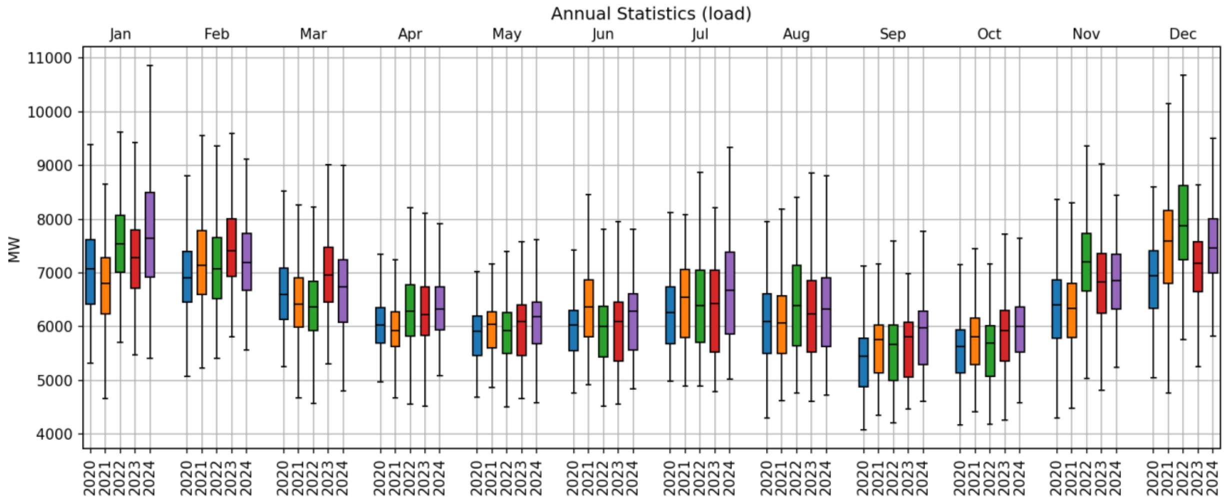

Figure A-12. Monthly load statistics for 2020–2024.

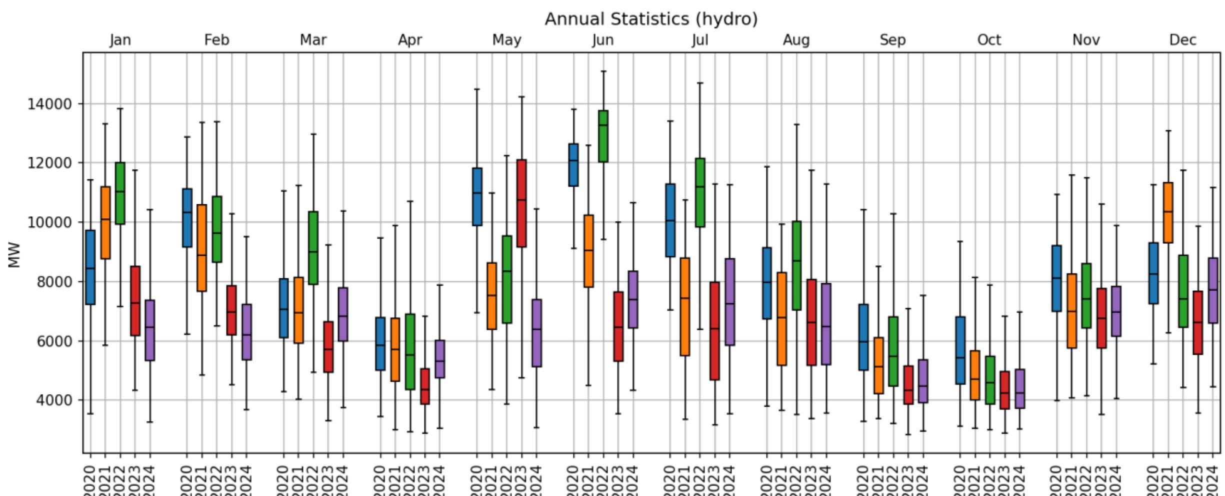

Figure A-13. Monthly hydro generation statistics for 2020–2024.

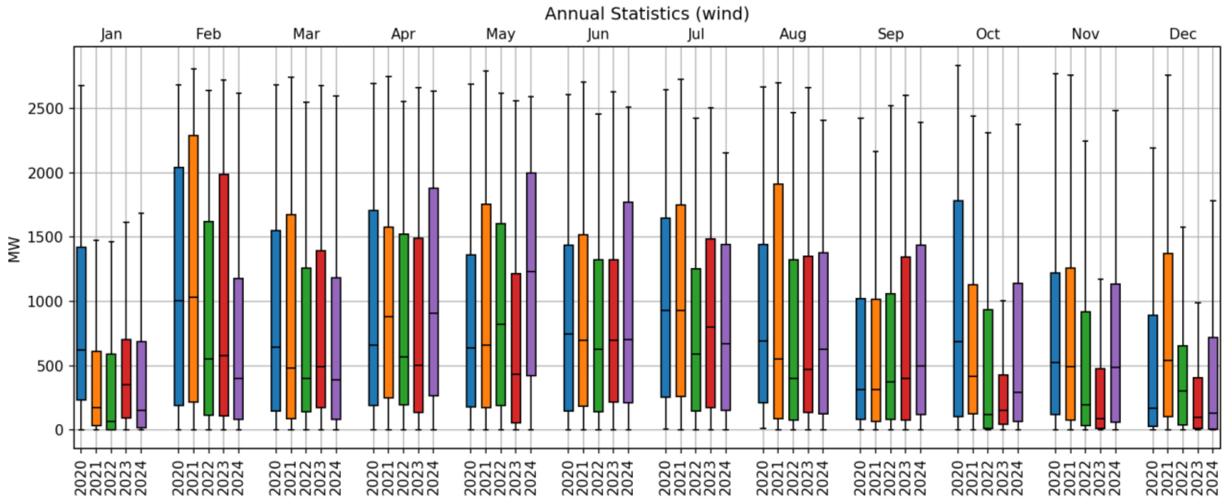

Figure A-14. Monthly wind generation statistics for 2020–2024.

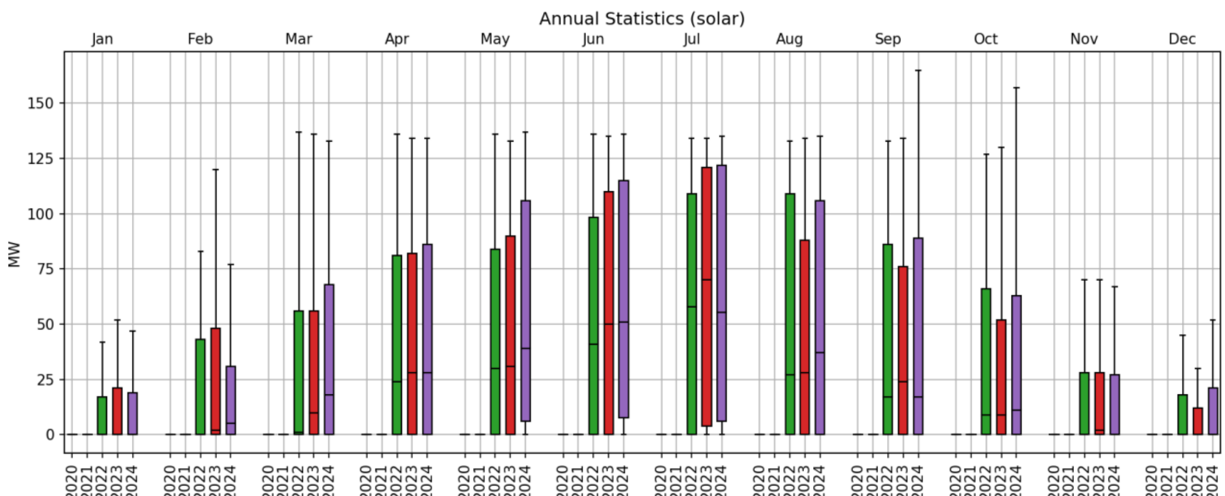

Figure A-15. Monthly solar generation statistics for 2020–2024.

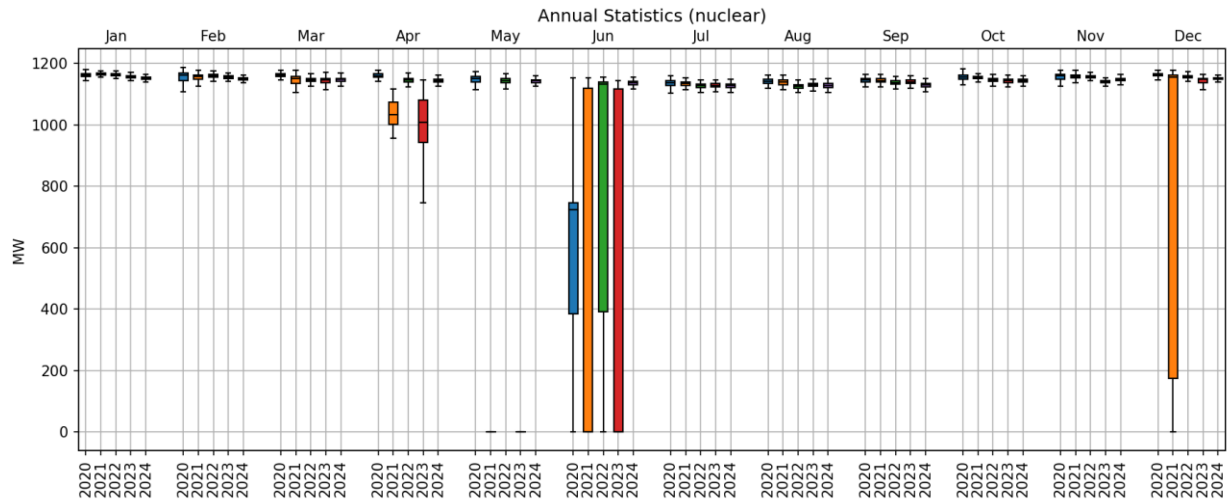

Figure A-16. Monthly nuclear generation statistics for 2020–2024.

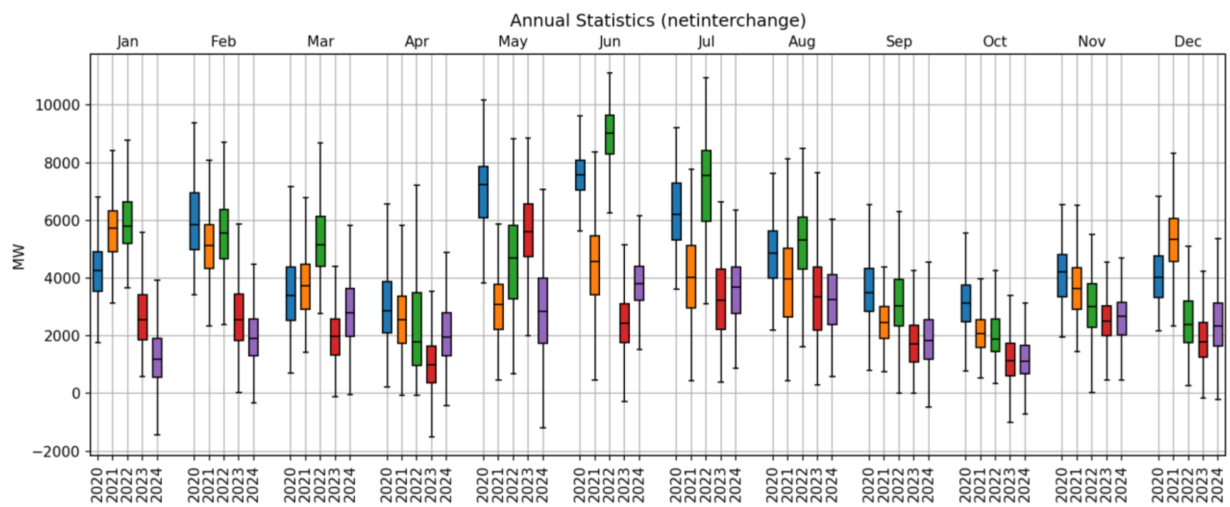

Figure A-17. Monthly net interchange statistics for 2020–2024.

Appendix B – LSR Dams Annual Statistics

B.1 Time Series

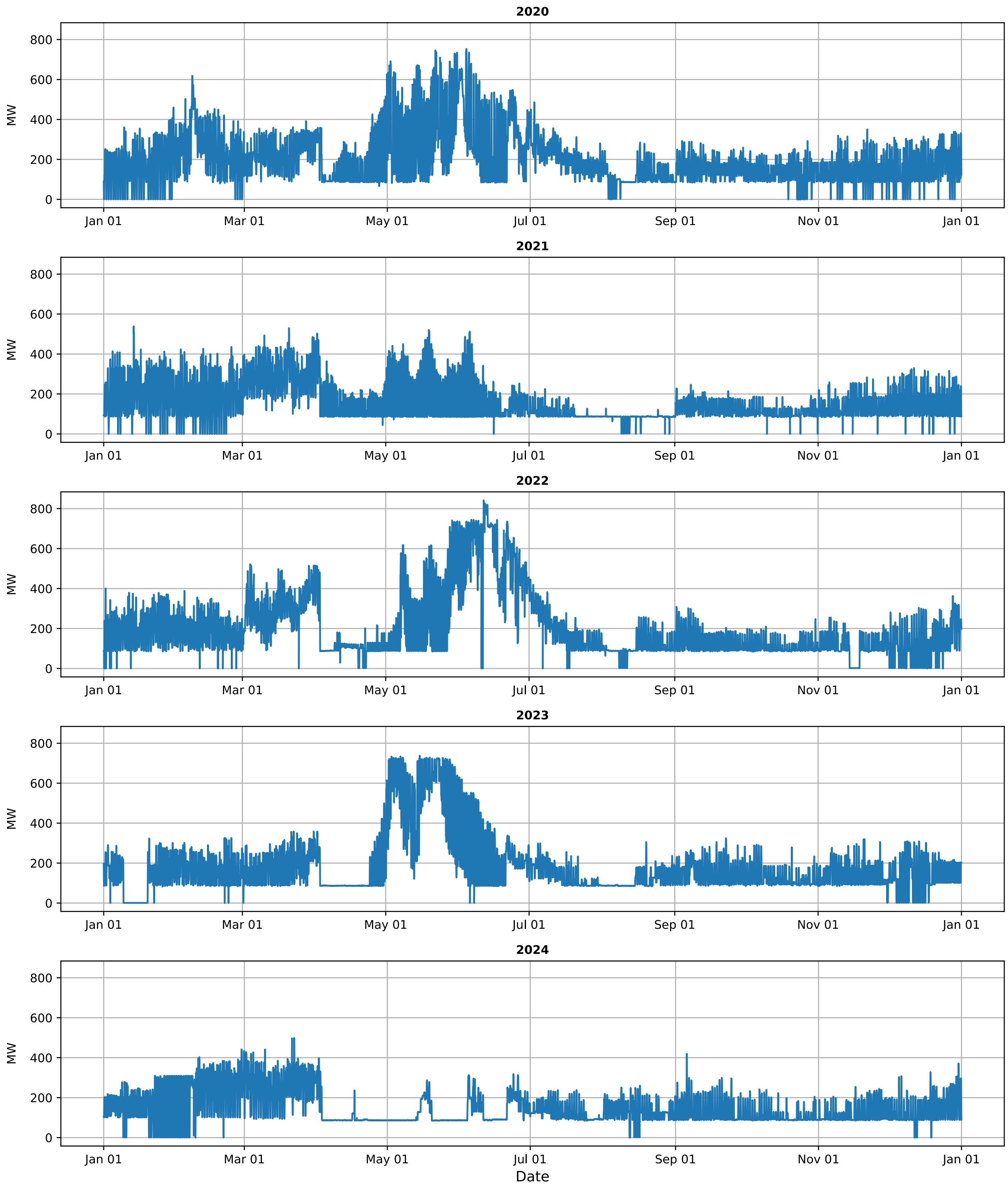

Figure B-1. LWG generation in 2020–2024.

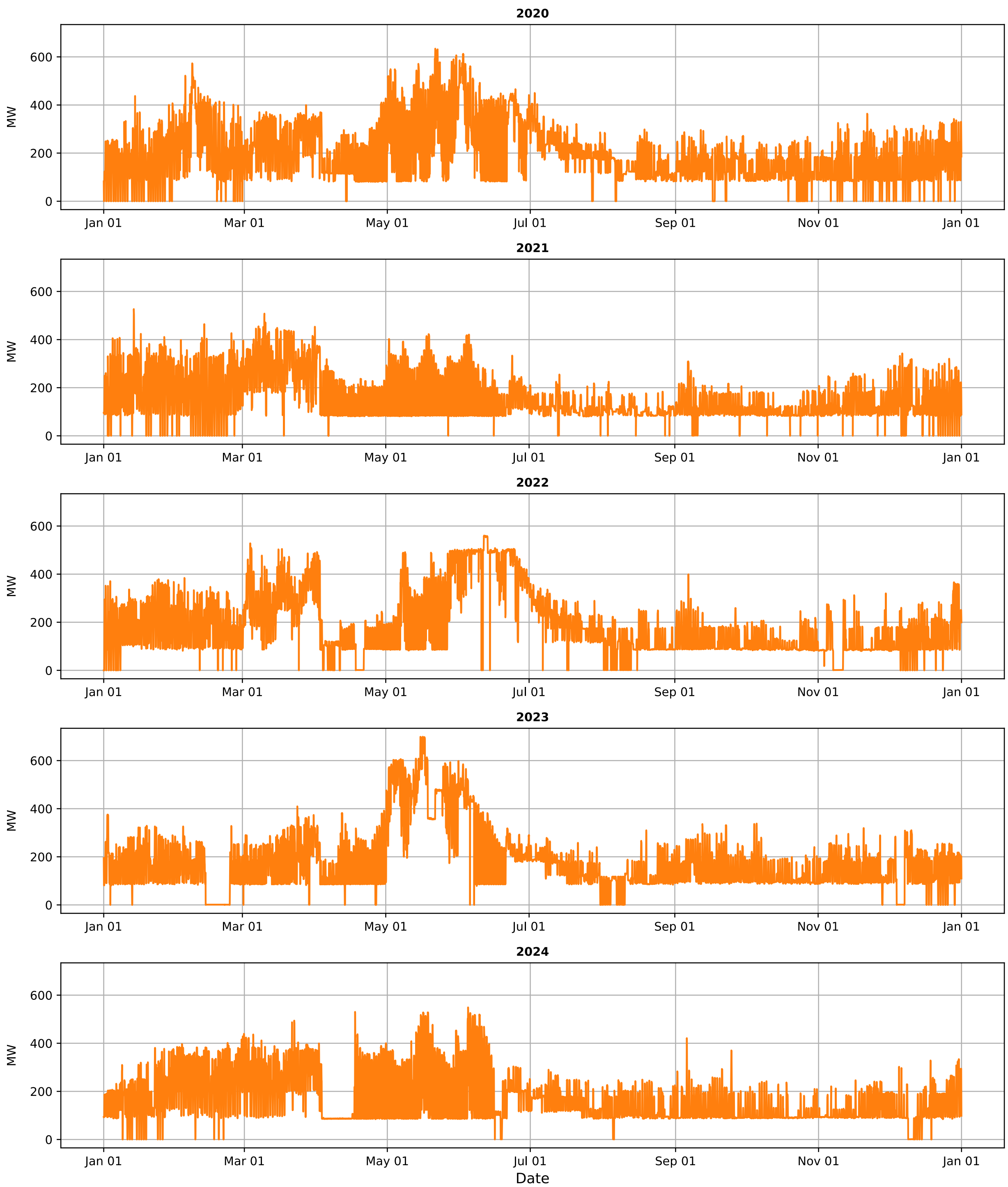

Figure B-2. LGS generation in 2020–2024.

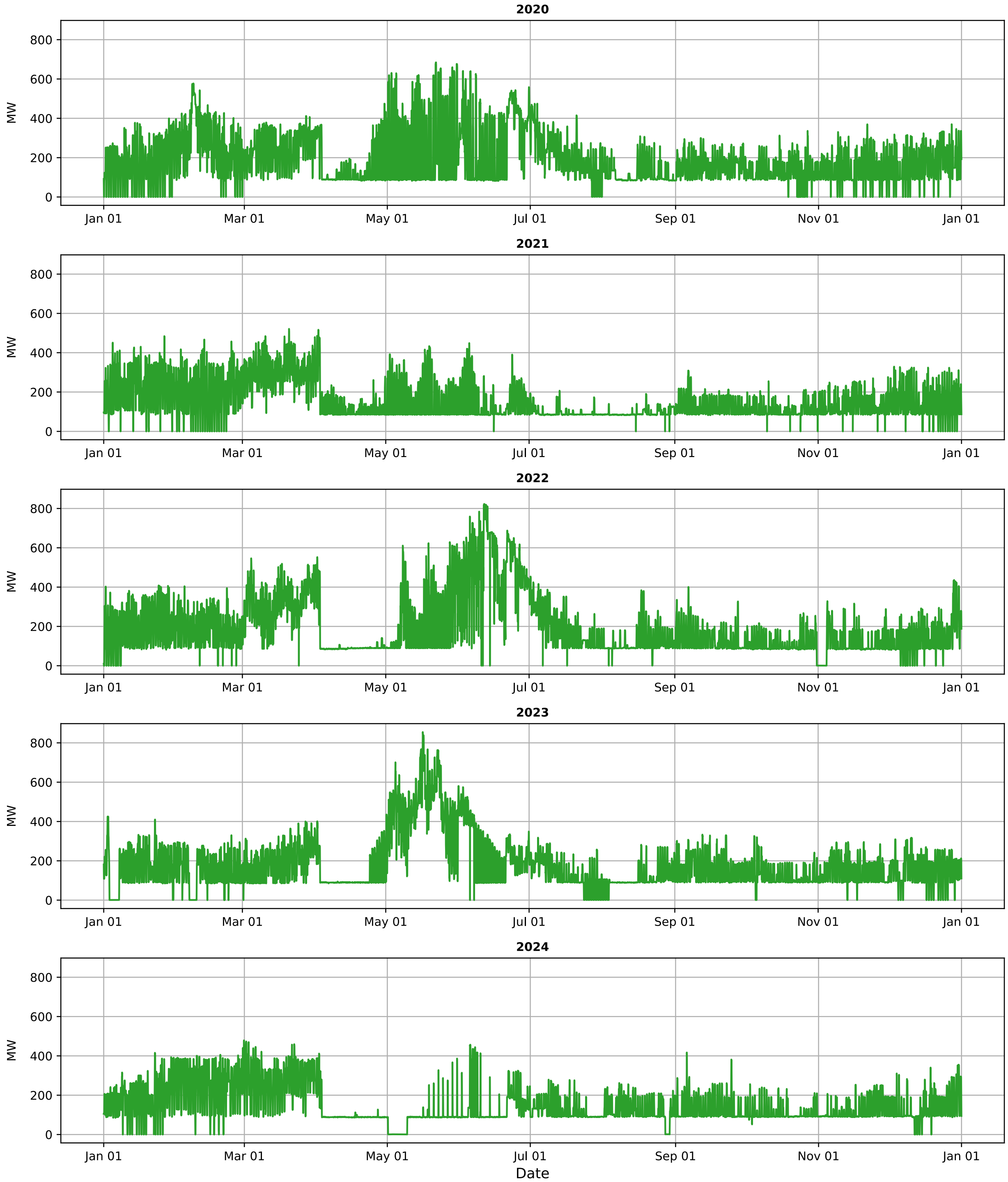

Figure B-3. LMN generation in 2020–2024.

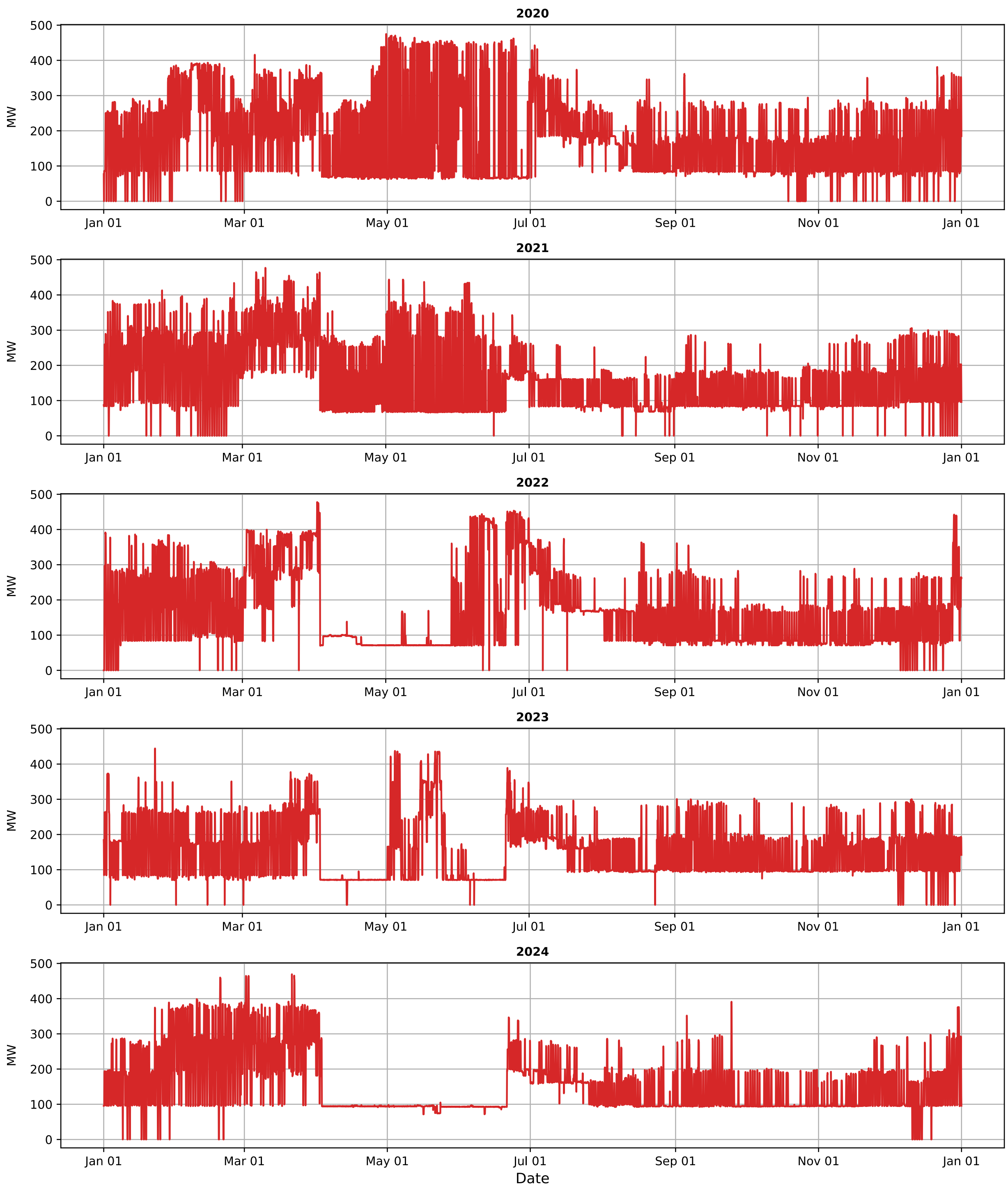

Figure B-4. IHR generation in 2020–2024.

B.2 Generation, Spillway and Elevation Monthly Boxplots

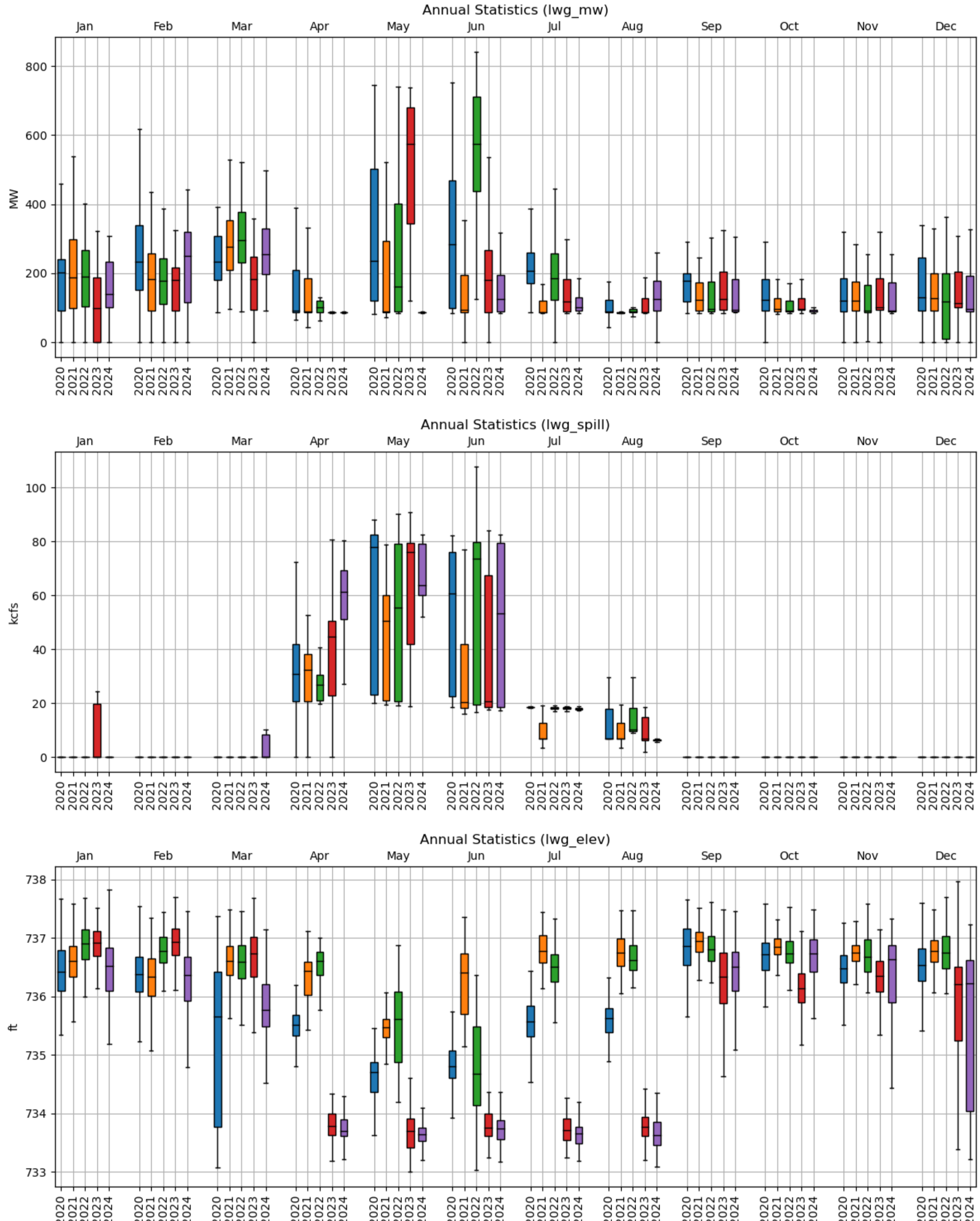

Figure B-5. Monthly LWG statistics for 2020–2024.

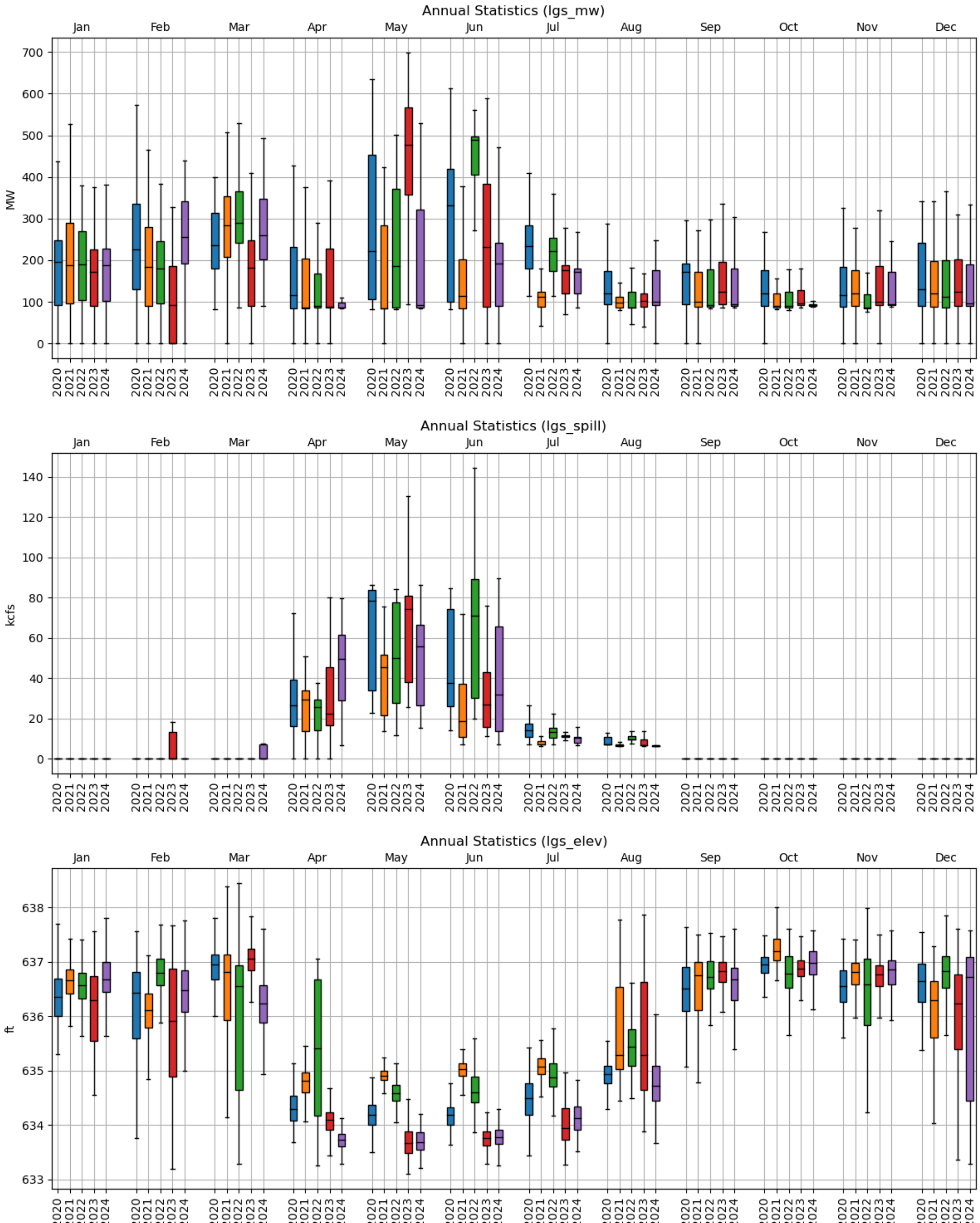

Figure B-6. Monthly LGS statistics for 2020–2024.

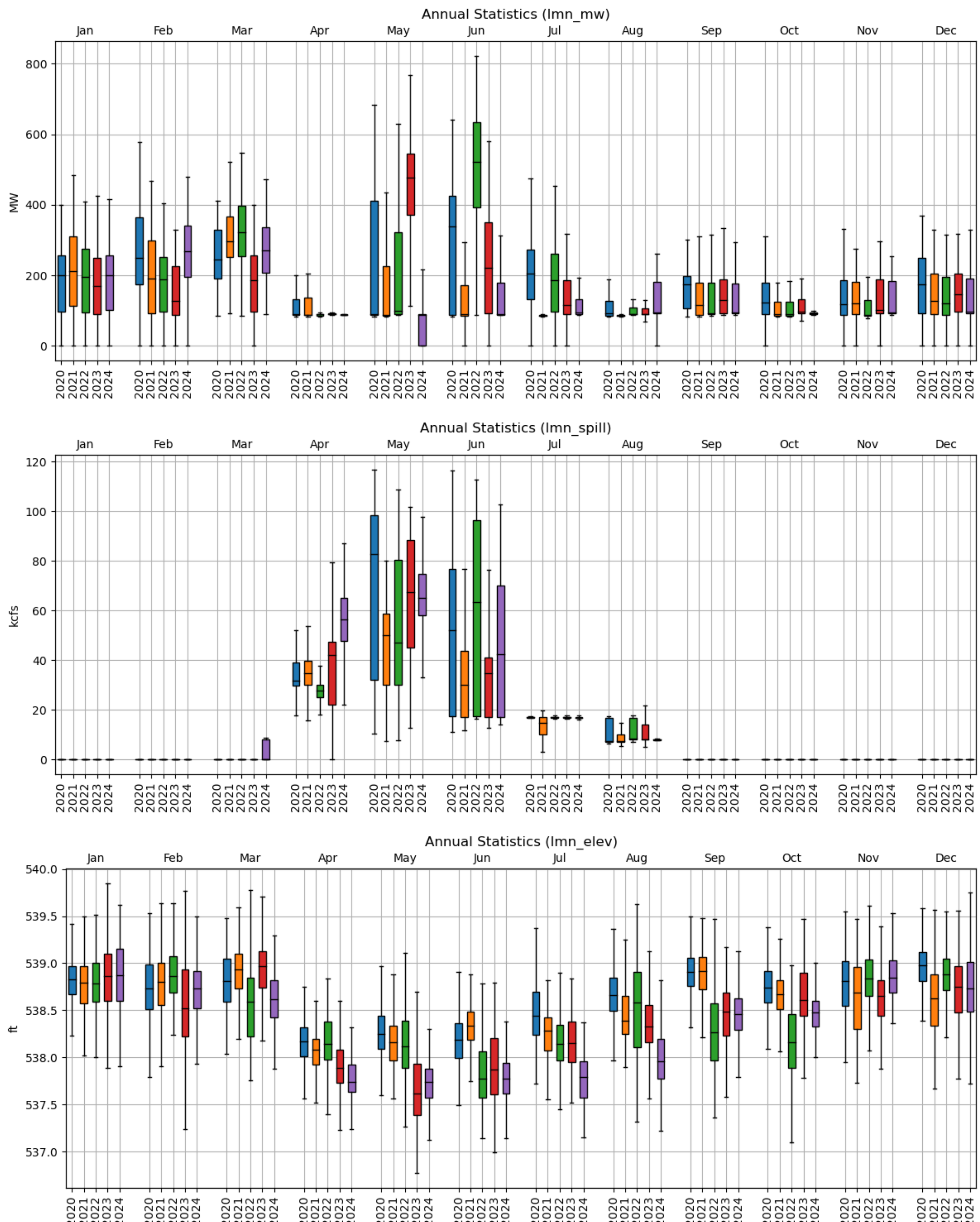

Figure B-7. Monthly LMN statistics for 2020–2024.

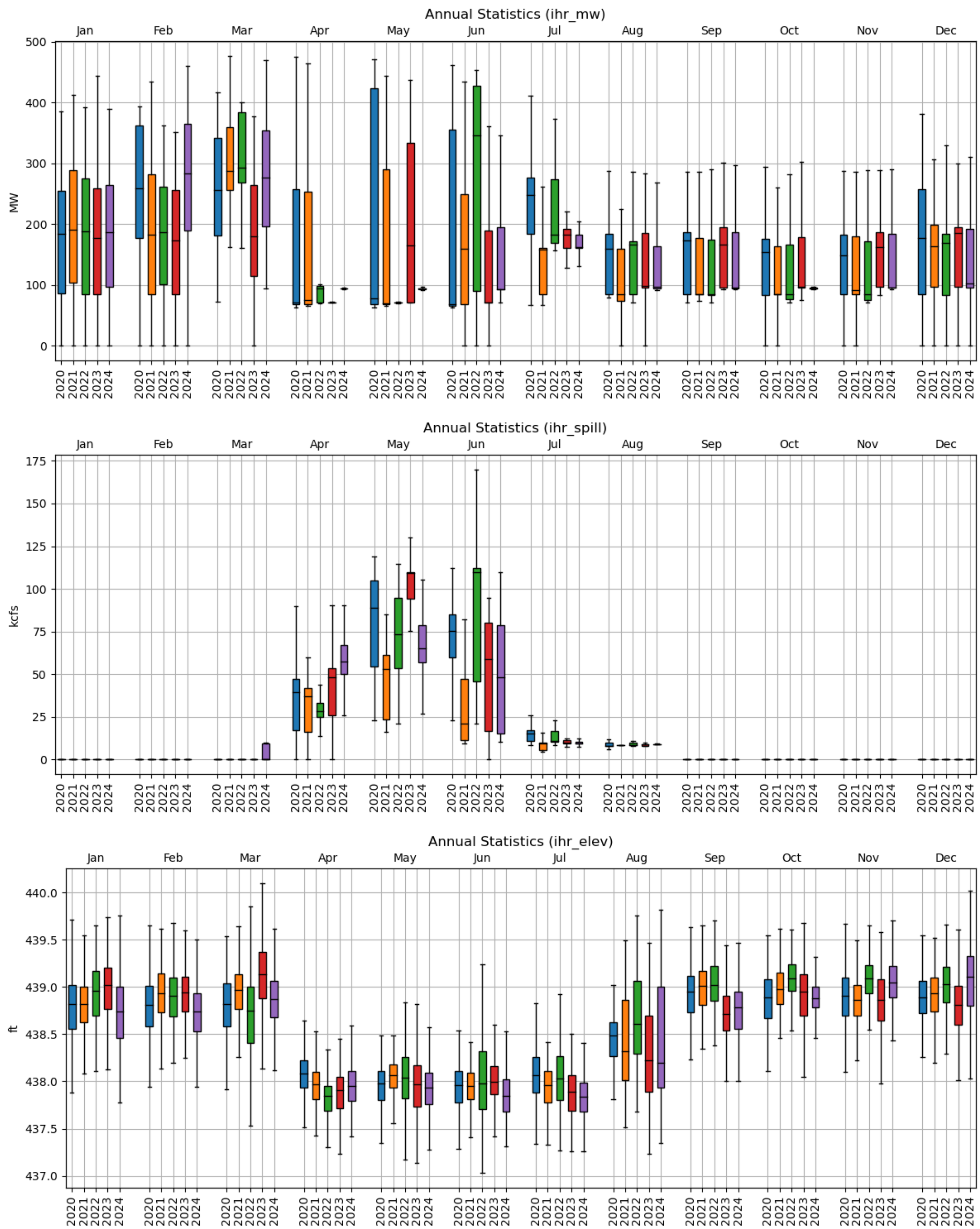

Figure B-8. Monthly IHR statistics for 2020–2024.

B.3 3-hour Ramp Distribution Boxplots

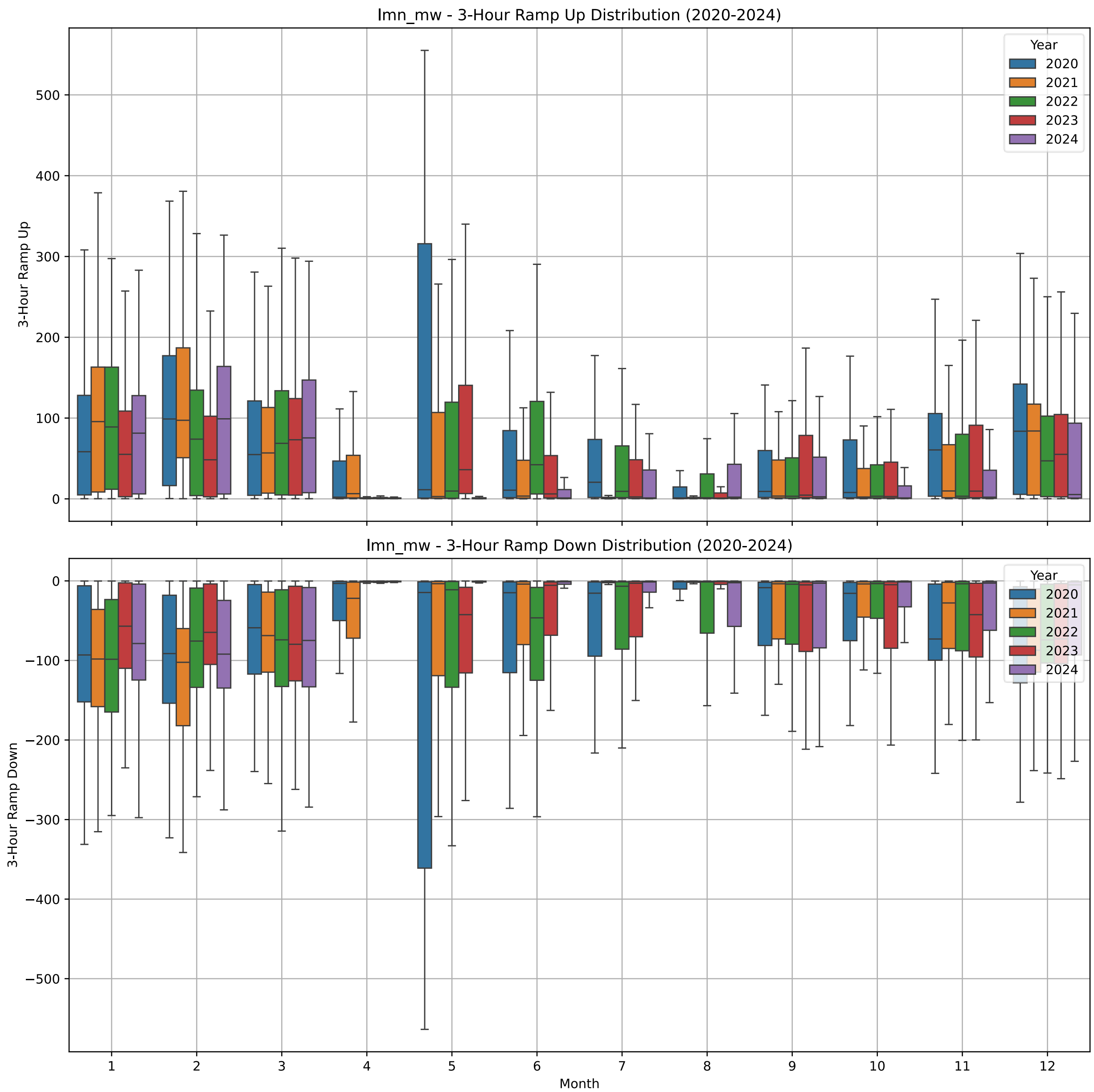

Figure B-9. Monthly LMN 3-hour ramps statistics for 2020–2024.

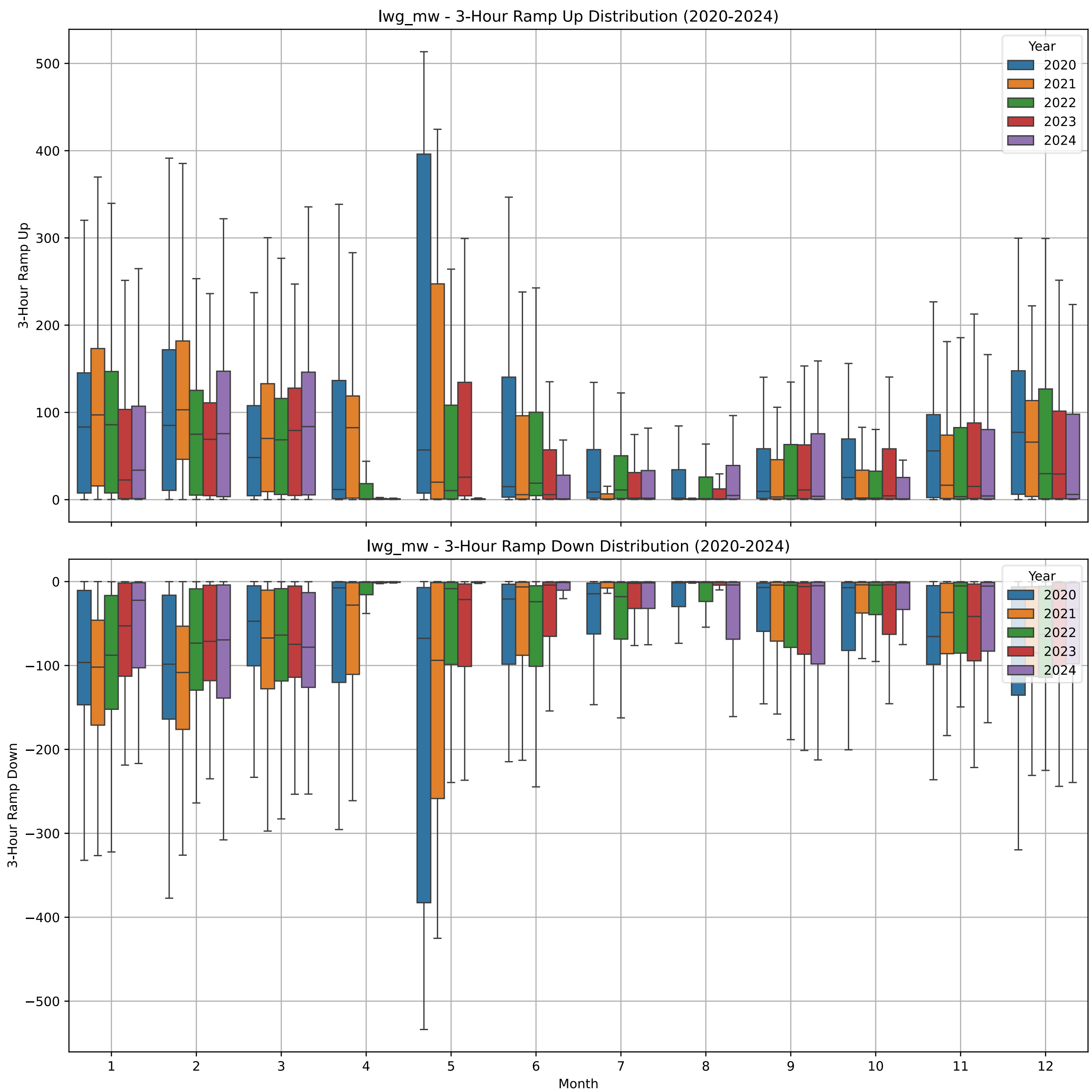

Figure B-10. Monthly LWG 3-hour ramps statistics for 2020–2024.

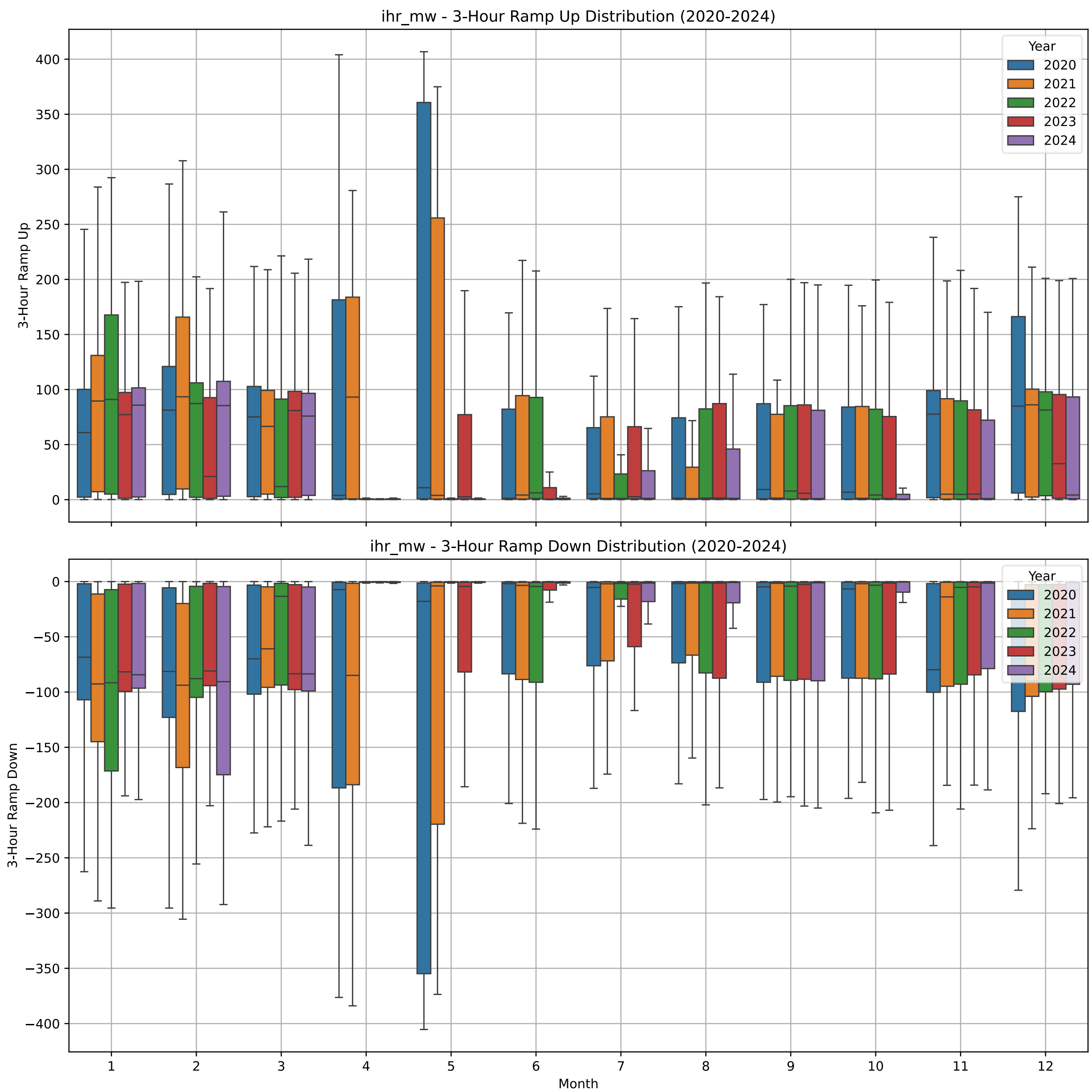

Figure B-11. Monthly IHR 3-hour ramps statistics for 2020–2024.

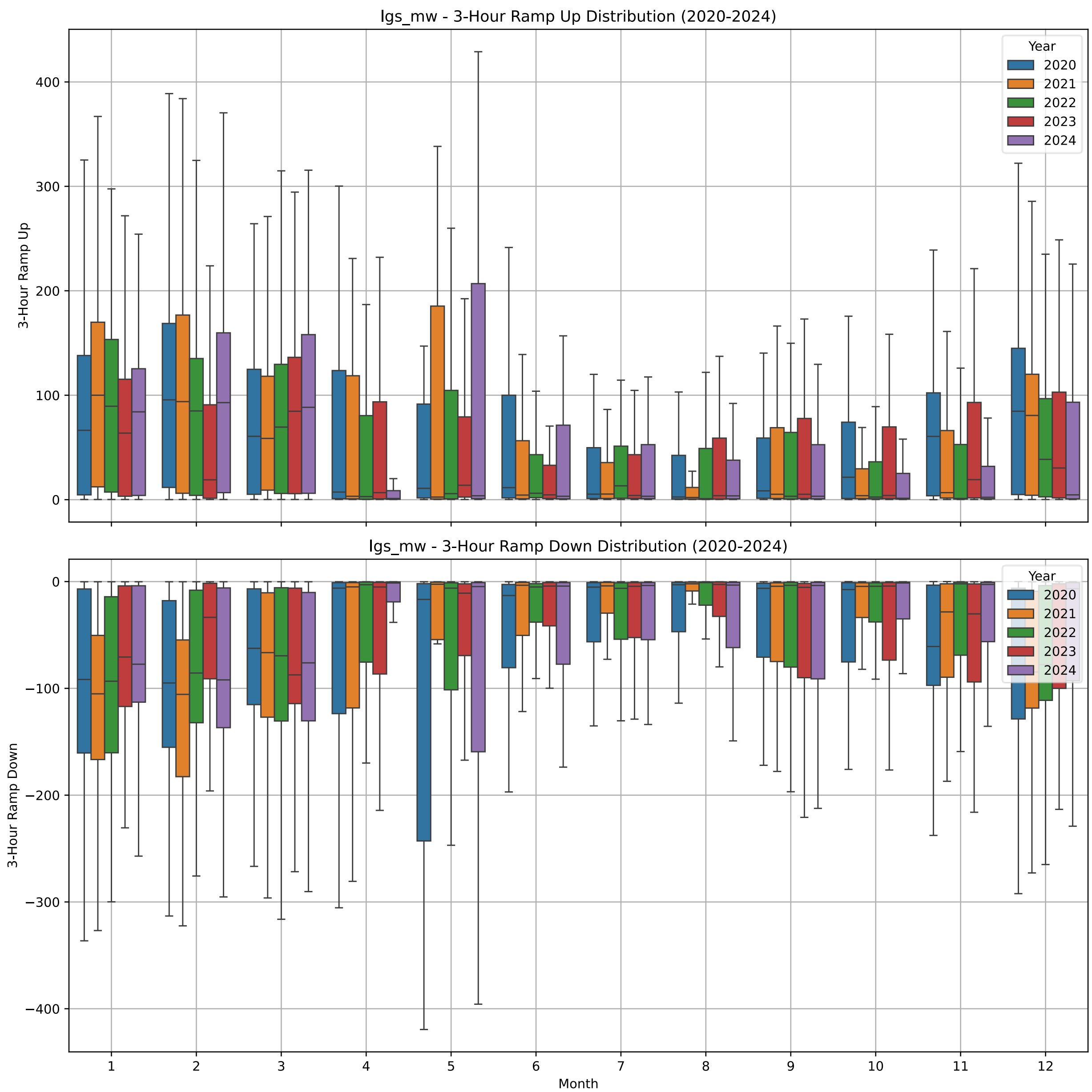

Figure B-12. Monthly LGS 3-hour ramps statistics for 2020–2024.

Appendix C – Deployed Balancing Reserve Analysis

Figure C-1 presents monthly boxplots of deployed regulating reserves from 2020 to 2024, illustrating the distribution of up and down regulation deployment for each year.[1] A noticeable trend emerges after 2022, when Bonneville Power Administration (BPA) joined the Western Energy Imbalance Market (WEIM): the median and interquartile ranges of deployed regulation narrow, particularly in the second half of the year, indicating a general reduction in the magnitude of deployed reserves. This trend may suggest more efficient balancing operations under WEIM participation, but it could also reflect other factors—such as a growing number of self-supplied operating reserve customers for whom BPA no longer provides balancing services.

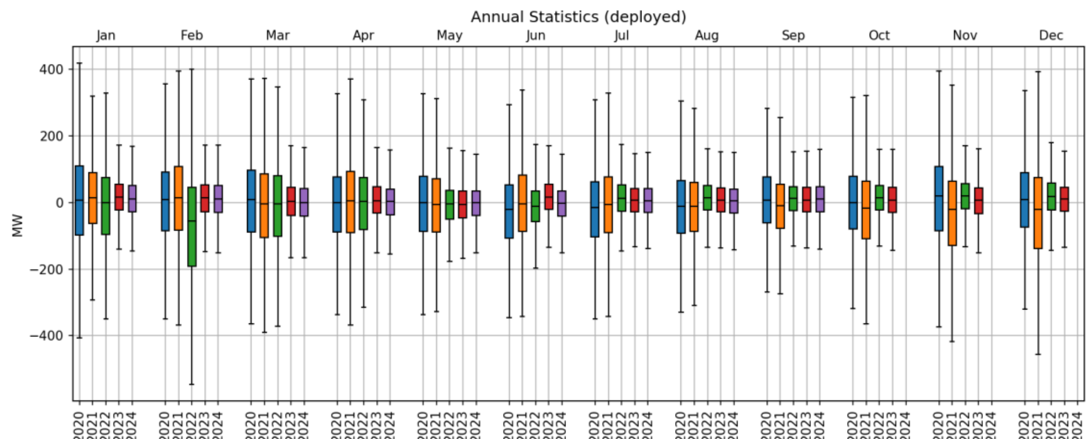

Figure C-1. BPA Deployed regulation monthly statistics (2020–2024)

Figure C-2 illustrates the distribution of 5-minute ramps, with typical values ranging between 20 MW and 60 MW and peaks reaching up to 120 MW for both upward and downward ramps. Additionally, the data show that 5-minute ramp patterns remain highly consistent across seasons.

Figure C-3 presents the statistics for 15-minute duration ramps, which, on average, range between 25 MW and 100 MW, with peaks reaching 200 MW to 250 MW. Furthermore, it can be observed that there is a tendency toward smaller ramp sizes following BPA's entry into the WEIM market in May 2022, reflecting changes in system operations and market dynamics.

[1] https://transmission.bpa.gov/Business/Operations/Wind/reserves.aspx

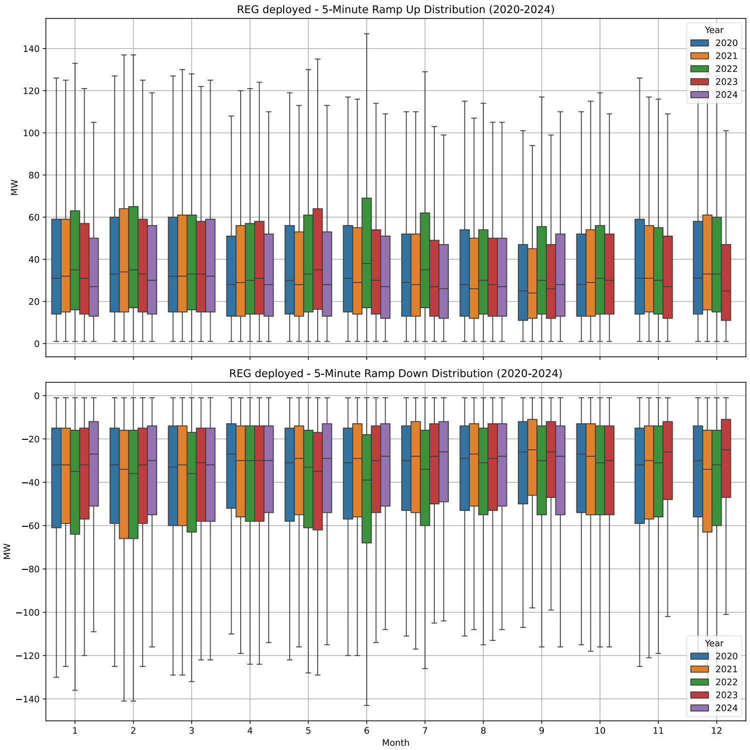

Figure C-2. BPA deployed regulation 5-minute ramp monthly statistics (2020–2024)

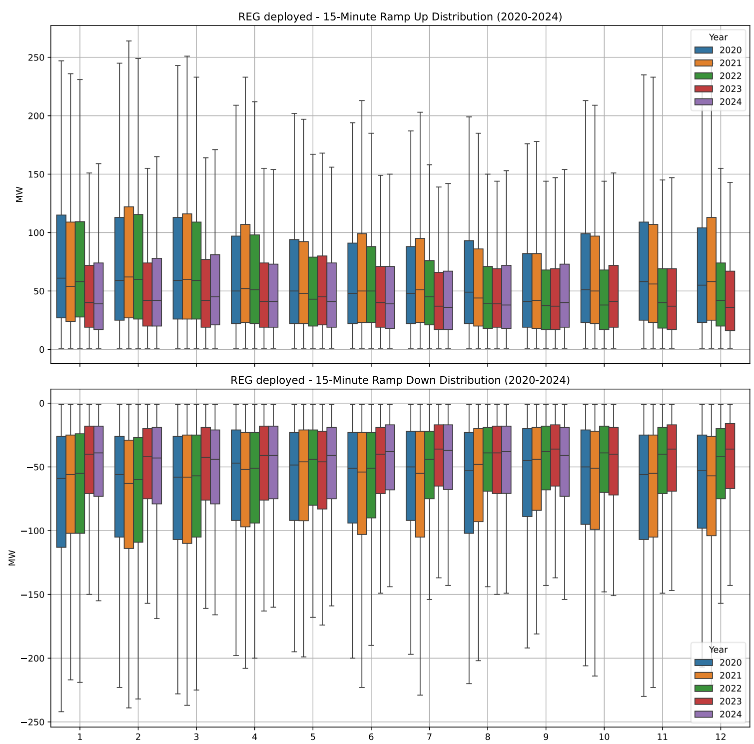

Figure C-3. BPA deployed regulation 15-minute ramp monthly statistics (2020–2024)

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