

Understanding Operational Flexibility in the Federal Columbia River Power System

Hydro Research Foundation Final Report

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Roll on, Columbia, roll on!

— Woodie Guthrie, 1941

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Abstract

Operational flexibility describes a power system's ability to respond with controllable real power resources to rapid changes in power balance error. For balancing areas with high penetrations of stochastic generation, these changes can be large enough to cause operating problems. We create the tools to quantify and intuitively explore operational flexibility in any power system and apply those tools to analyze the Federal Columbia River Power System (FCRPS). We chose the FCRPS because it is a large system with complicated constraints, and because conflicting demands on operational flexibility have become a regional public issue. We inventory system obligations, map all obligations and forecasts to constraints in the form of power (MW) vs. time, create data structures and an algebra for unifying these time series, and assemble an original metric of operational flexibility. The metric quantifies a common but vague concept of flexibility, intuitively characterizes a power system, and yields actionable intelligence that dovetails with existing deterministic indicators of system state. The resulting information-dense summary can improve schedule quality both as a visualization tool for human schedulers and as a versatile formulation for dispatch algorithms.

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Part I

Foundations

Chapter 1

Introduction

1.1 Operational Flexibility

Modern power systems contort to match supply with demand. System operators must maintain that balance while meeting the evolving opportunities and obligations facing the system. These power system challenges have changed over time. Customer demand for electricity, known as load, once drove generation schedules. Load can be forecast with very little error, which allowed major dispatch decisions to be made days and weeks in advance about fossil fuel and hydropower plants. Now, even as load becomes more controllable, generation has become dramatically less so. Large amounts of wind energy, spot market opportunities, wildlife conservation efforts, abundant telemetry data, and other pressures increasingly squeeze dispatch decisions into the final hours and minutes before operation [3, 40, 88].

Operational flexibility is the power system’s ability to respond rapidly to changing conditions with controllable real power resources. Stochastic resources – dramatically more uncertain and variable than load – drive the need for more operational flexibility. Even as reliance on stochastic renewables like wind energy increases the need for flexible operation, many other obligations constrain that flexibility. Operators need to know exactly how much flexibility they can call upon in the coming minutes, hours and days.

We propose a new operational metric to quantify system wide operational flexibility. Our metric follows in the tradition of spinning reserve, an operational metric of theoretical and operational value. Where spinning reserve manages the risk of conventional generator outages with online

generation and interruptible load, our metric manages the risk of fluctuating stochastic resources and embraces controllable load. The generator specific concept of reserve no longer captures the complexities of the modern power system, rich with renewable energy and responsive demand. To operate the system economically, we require a new rigorous awareness of operational flexibility. Talking vaguely about flexibility, while measuring only capacity quantitatively, will suffice no longer. The system requires a new tool to understand, and properly balance, the risk of power outages and the risk of non-economic operation. The proposed operational flexibility metric, therefore, makes a valuable contribution to Power Systems Operation.

We define an obligation as anything that imposes an objective or constraint on the power system schedule. Our flexibility metric creates a framework to unify the constraints caused by all obligations, whether they be environmental regulations, river network topology or power plant nameplate specifications. In addition to quantifying the operational flexibility in a power system, this work innovates by presenting constraints as time series on the same axis with forecasts of stochastic resources, and by unifying diverse obligations for human and machine use to optimize power system schedules on the time scale of minutes to days.

Focusing on the practical realities of balancing a power system in real time in the face of uncertainty, this work will provide immediate insight for duty schedulers and inform future real time decision support algorithms.

1.2 Opportunities

We identify several big opportunities, summarized here and discussed in more detail in the following chapters.

Stochastic Generation: Reserve, the existing framework for managing generator outage risk, fails to handle stochastic renewable generation well. A new operating metric must support the modern operating paradigm.

Controllable Real Power: Segregating real power resources into load and generation hides their value to the operator. Classifying resources instead as controllable and uncontrollable sheds more light on the state of the system and the recourse available.

Unified Constraint Formulation: To date, constraints from diverse sources are not unified in one decision support framework. A human operator juggles obligations – and uncertainty.

Flexibility: No definition of operational flexibility yet completely describes the recourse available to a system operator, nor does a metric provide actionable intelligence on this timescale. In practice, operators have a sense of system flexibility, but that awareness is not yet complete or economic.

1.3 Problem Statement

Quantify operational flexibility – a power system’s ability to respond rapidly to changing conditions with controllable real power resources – as a metric of theoretical and operational value for power system schedulers. Provide a general theoretical framework along with practical examples for practical people.

1.4 Hydropower

Hydropower generators have sometimes been described as the ideal carbon neutral complement to intermittent and stochastic renewable energy sources such as wind and solar, thanks to their lack of startup constraints, steep ramp rates, and inherent energy storage in reservoirs [34, 57]. However, the services provided by hydropower’s operational flexibility on the very short term timescale (minute to day ahead) have never been in higher demand. Although the need for a flexibility metric is emerging throughout power systems, it emerged first as operationally relevant in hydropower.

The hydropower rich Federal Columbia River Power System (FCRPS) presents a particularly acute need to measure flexibility. The many uses of the river system impose diverse power and non-power obligations on operation. We explore the flexibility needs of this system in particular, and use it to demonstrate the applicability of our flexibility metric.

The Pacific Northwest has a spectacular energy resource in the Federal Columbia River Power System (FCRPS), an abundant and versatile source of inexpensive sustainable power. But the FCRPS serves many masters; it is managed for flood control, fish and wildlife, public safety, treaty

commitments, and many other uses. Transmission congestion, wind power generation, energy contracts, and hydropower generation at non-federal dams place further demands on the FCRPS hydropower schedule.



Figure 1.1: The Federal Columbia River Power System consists of the dams owned by the US Army Corps of Engineers (red circles) and the US Bureau of Reclamation (white triangles). The networked system, interspersed with dams owned and operated by other organizations, presents unique coordination challenges. Image courtesy of Northwest Power and Conservation Council

The Bonneville Power Administration (BPA), the U.S. Army Corps of Engineers, and the U.S. Bureau of Reclamation manage the FCRPS jointly. Figure 1.1 shows a map of the managed watershed, which spans Washington, Oregon, Idaho, Montana, and British Columbia. The constraints facing hydropower schedulers are sufficiently complicated and diverse that the modeling and analysis work performed here should be applicable to – and simpler in – other power systems with hydro in the United States and beyond.

Figure 1.2 lists many of the obligations the FCRPS must meet. All of the obligations influence the system’s deployment for power generation and introduce uncertainty. Together, power and

non-power constraints drive the system towards a less flexible operational schedule [33].

- ### Columbia River: Managed for
- **Beauty**
 - **Recreation**
 - **Retreat**
 - **Getting in touch with nature**
 - **Preserving diverse ecosystems**
 - **Bringing nutrients up from the ocean (salmon)**
 - **Education**
 - **Navigation**
 - **Commerce**
 - **International Treaties**
 - **Tribal Rights**
 - **Safety (flood control)**
 - **Safety (rescue divers)**
 - **Infrastructure protection (e.g. keep bridges, banks from eroding away)**
 - **Private business opportunities (e.g. hotel on the water, boat tours, swimming lessons)**
 - **Irrigation**
 - **Cooling**
 - **Cheap power**
 - **Balancing**

Figure 1.2: The Federal Columbia River Power System serves many masters. In practice and statute, all of the obligations listed here influence hydropower scheduling. In fact, power concerns – like serving the load at lowest cost and balancing variations in wind power – take a back seat to the other priorities when the hydropower duty scheduler controls generators.

Operators must wring more flexibility from the hydropower system to keep meeting the needs of all stakeholders. In fact, operational flexibility may best be defined in its absence: when the needs of any FCRPS stakeholders are not met by the river flow, as managed via power houses in the region’s network of federal dams, that constitutes an operational flexibility short fall. When such inevitable conflicts of interests arise, transparency becomes valuable so stakeholders can see that limited system flexibility has been allocated appropriately (according to the negotiated or mandated priority order).

1.5 Collaborators

This work stems from several collaborations.

- Steve Barton, Bonneville Power Administration (BPA)
- Hydropower Research Foundation (HRF)
- Adam Greenhall, University of Washington (UW)

BPA manages the FCRPS jointly with the Army Corps of Engineers and the Bureau of Reclamation. Given flow, generation, and reservoir depth constraints from the Corps, BPA is responsible for the day ahead and real time dispatch all of the federally owned hydropower on the Columbia and Snake rivers [3, 7]. Steve Barton, of BPA short term planning and operations, serves as liaison and mentor for this work. Mr. Barton has supplied historical data; detailed system constraints, objectives and procedure; and guided the effort toward pressing system operation and planning problems.

A fellowship from the Hydropower Research Foundation funded a portion of this work and fosters industry communication. Consultation with other HRF fellows, especially at the Hydrovision conferences in July 2012 and July 2013 proved helpful. Ever improving hydropower coordination optimization algorithms are being explored by another HRF fellow, Sue Nee Tan. Civil engineering HRF fellows Andre Dozier, Jonathon Lamontagne, and Ryan Morrison considered a subset of power system constraints in the upstream optimizations of their river flow and forecasting models. Fellow Lisa Dilley quantifies the value of pumped storage of a power system, and wishes to incorporate our flexibility metric in that model. Geologist, law student, and fellow Mark Cecchini-Beaver’s “model will be designed to communicate the goals of, and constrain[t]s on, this complex system in a way that diverse stakeholders can grasp and shape,” so we found some common ground working with FCRPS constraints and their consequences. Mitch Clement measured the economic impact of non-power constraints on a hydro-wind system [12]. Adam Greenhall – co-Christie-advisee, officemate and fellow HRF fellow – modeled stochastic energy scheduling in thermal-wind (ERCOT) and hydro-wind (FCRPS) systems for his 2013 PhD [29].

More information about the Hydropower Research Foundation Fellowship, including reports from the fellows mentioned above, can be found at the foundation’s website.

1.6 Reader’s Guide

Chapter 2 motivates the concept of operational flexibility in all power systems and discusses other early efforts to define and measure it in the literature. Chapter 3 discusses the set of hydropower scheduling problems; it also expands on the challenges and opportunities presented by the Federal Columbia River Power System (FCRPS). Chapter 5 formulates our new definition of operational

flexibility, and Chapter 6 discusses how disparate constraints can be unified and the feasibility problem formulated. We validate the new metric in Part III, using an innovative test data set in Chapter 7 and practical examples drawn from Power System Operations (Chapter 8) and the Federal Columbia River Power System in particular (Chapter 9). We conclude by summarizing the results in the FCRPS in Chapter 10 and more general impacts in Chapter 11.

Chapter 2

Operational Flexibility

2.1 Summary

This chapter explores the concept of operational flexibility – a power system’s ability to respond to rapidly changing circumstances. We motivate the need to explicitly quantify flexibility, and then explore the work others have done to define and address this need. In Section 2.6, we conclude the flexibility literature review by extracting design specifications for a new operational flexibility metric. Our solution, addressing those specifications, appears later in Chapter 5.

Operational flexibility describes a power system’s ability to respond with controllable real power resources to rapid changes in power balance error. For balancing areas with high penetrations of stochastic generation, these changes can be large enough to cause operating problems.

Progress has been made in the last four years toward defining a system’s operational flexibility, and quantitatively summarizing it for use in long term planning and eventual stochastic unit commitment [39, 41, 42, 46, 49]. However, an operational flexibility metric for optimization on a very short time horizon – minutes to days – has remained elusive.

2.2 Motivation

Scheduling decisions that were once made weeks in advance now occur days and even hours ahead of operation thanks to confining constraints, evolving forecasts of wind power, system telemetry data, and market conditions. These pressures motivate an explicit calculation of operational flexibility

for short term and real time dispatch.

2.2.1 Defining Operational Flexibility

The term “flexibility” has come into general use to describe a power system’s ability to respond quickly to changing operational conditions. The term describes the system’s aggregate controllable real power resources. Ramp rates, operating limits, and responsiveness to operator commands all contribute. A number of definitions have been proposed without consensus, or employed on a planning time frame without adapting well to operational practice.

The IEEE power systems literature has used the term “flexibility” in the sense that we use “operational flexibility” in this thesis for more than 30 years. The earliest examples we found in the literature date from 1980. Davidson et al. used the term “flexibility” to describe a concept very like generalized spinning reserve; they further propose that storage, when implemented correctly, will remove need for spinning reserve in their system [17]. In 1982, Daley and Castenschiold used the words “necessary flexibility” when discussing capacity reserves for unusually high peak loads [16].

The term “flexibility” has been widely used in recent papers. De Jonghe wrote in 2011 that “comparison of those different sources of system flexibility suggests that energy storage facilities better facilitate the integration of wind power generation [18].” In 2011, Kirschen, Ma, Silva and Belhomme devoted a paper to optimizing system flexibility with unit construction and unit commitment [36]. They observed that increasing operational flexibility means – so far in practice – “adding more peakers,” a simplification they found unsatisfying in summarizing the complexities of the modern power system, as do we¹. Storage continues to be touted as a great way to provide flexibility; in the context of storage, “flexibility” is still only qualitatively defined to mean something like the ability to time shift power [45]. Even with the emergence of the first flexibility metrics in the literature, (as in section 2.4), “flexibility” continues to be widely and imprecisely used in IEEE Transactions [74]. The persistent use of the term in the technical power systems literature underscores the demand for a useful quantitative definition.

¹This dissatisfaction probably motivated the group’s innovative “flexibility index” the next year, which we discuss in section 2.4.2

2.2.2 Acute Pressure on Operational Flexibility

Constricting Boundaries

Increasing transmission congestion, regulation of green house gas emissions, and many other constraints place increasing restrictions on the operation of power plants and the scheduling of power systems [33]. In chapter 3 we further discuss the specific obligations reducing operational flexibility on the Federal Columbia River Power System.

Renewable Integration

The need to incorporate increasing quantities of stochastic renewable generation is driving changes to the power grid [18]. Wind and solar generation provide energy, reducing the net load served by other generation; fluctuates dramatically in magnitude, requiring flexibility from balancing resources; and continues to evade confident forecasts, increasing reserve requirements [36].

Philbrick summarizes some relevant consequences: “Integration of wind power will require significant changes to traditional methods used for system planning and operations. In particular, the probabilistic nature of wind will require modifications of traditional unit commitment and economic dispatch tools ... to better incorporate uncertainty in the decision support tools available to operators. In all time frames, the goal is to make effective use of flexible resources by considering appropriate trade-offs between their costs and the capabilities they provide.” [63]

Systematic Operation

Electricity supply does not operate in isolation. Coordination with larger systems increasingly constrains the operation of new and existing hydropower and fossil fuel plants. The constraints imposed by these larger systems – fuel supply networks and pipelines, reliable transmission grid operation, natural ecosystems tied to power plant input and output - are only increasing in complexity.

2.2.3 Regional Demand for a Metric

In the Pacific Northwest, there is significant interest in a flexibility metric for both planning [10, 37, 41, 61, 63] and operations [3, 4, 7, 80]. Bonneville Power Administration, the US Army Corps

of Engineers, the Electric Power Research Institute, and independent analysts have all explicitly voiced their desire for an operational flexibility metric.

Ben Kujala leads an ongoing effort with the Northwest Power and Conservation Council to assess methods for quantifying flexibility [38, 39]. As of August 2014, this work takes the form of a survey of approaches to quantifying flexibility, as many utilities across the region are tackling the problem.

2.2.4 Renewable Energy Grid Integration Studies

Major integration studies in the past few years describe the critical role of operational flexibility as the grid accommodates increasing penetrations of variable generation [22, 28, 43, 50, 69]. We follow Lannoye et al. in defining variable generation as those real power resources whose “output is dependent on the prevailing environmental conditions” [43].

Grid integration studies with high stochastic renewable penetrations, all coordinated by the National Renewable Energy Laboratory (NREL), have been performed on the Western interconnect (Western Wind and Solar Integration Study) [28], the U.S. Eastern Interconnect (Eastern Wind Integration and Transmission Study) [22], and nation wide (Exploration of High-penetration Renewable Electricity Futures) [50, 69]. The analyses consider operational flexibility indirectly, modeling operating regimes under different configurations and inputs.

The studies have demonstrated that changing operational procedure (*i.e.* more flexible operating regimes for fossil fuel plants and markets) such as rolling unit commitment, increased use of forecasts in scheduling, and changing reserve requirement calculations have allowed more integration of stochastic renewable generation. All the studies saw a new utilization pattern of thermal generation: increases in transmission congestion, baseload startups/shutdowns, the use of flexible fossil fuel generation (*e.g.* natural gas burning peakers), and the demand for energy storage. The Eastern Wind Integration and Transmission Study allowed the model to build new quick ramping fossil fuel plants in response to high renewable penetration, and in fact the generation mixture shifted accordingly [22].

The studies agree: as generation from stochastic renewables increases, the demand for flexibility skyrockets.

2.2.5 Other Kinds of Power System Flexibility

To wrap up our discussion defining operational flexibility, we note a potential point of confusion. Flexibility means many things to many people, even within the power systems literature. A few definitions of flexibility we *do not* mean are:

- Design flexibility, allowing for configuration changes over time [19, 27, 32]
- Fuel switching flexibility [57, 82]
- Geographic flexibility (e.g. natural gas processing plants that can be moved around [83])
- The fleet’s ability to change sign quickly of injected power, generating or consuming as required [84]
- Long term capacity flexibility (i.e. fleet’s ability to respond to changes in load growth, regulation, fuel prices with minimal changes in production cost) [70]

2.2.6 Power Balance

Power balance error – the sum of actual generation (*e.g.* thermal, hydro, wind) minus the sum of delivered power (*e.g.* load, interchange with neighboring interconnected systems) – describes how far the system is out of balance. Equivalently, power balance error describes how much real time operation differs from operators expectations. Every electric power system must achieve a balance of supply and demand at every moment in time, so any power balance error must be immediately offset by drawing energy from (or sinking energy into) connected resources.

The part of the vast interconnected system which must absorb its own variations to achieve the power balance is called a balancing area. “The dual objectives [for a balancing area] will be to secure the correct total generation to match prevailing total demand and to allocate this total among alternative sources for optimum economy consistent with continuity of service,” wrote Nathan Cohn in his classic text on control in interconnected systems[14]. Figure ?? captures the essential power system scheduling problem. The most important constraint is the Power Balance: $\text{Supply} = \text{Demand} + \text{Losses}$ at every point in time, or equivalently, controllable plus uncontrollable minus losses equal zero at every point in time. The power balance error describes how far a system is out of balance, or equivalently, how much that constraint has been violated by the resulting

Classic Power System Scheduling

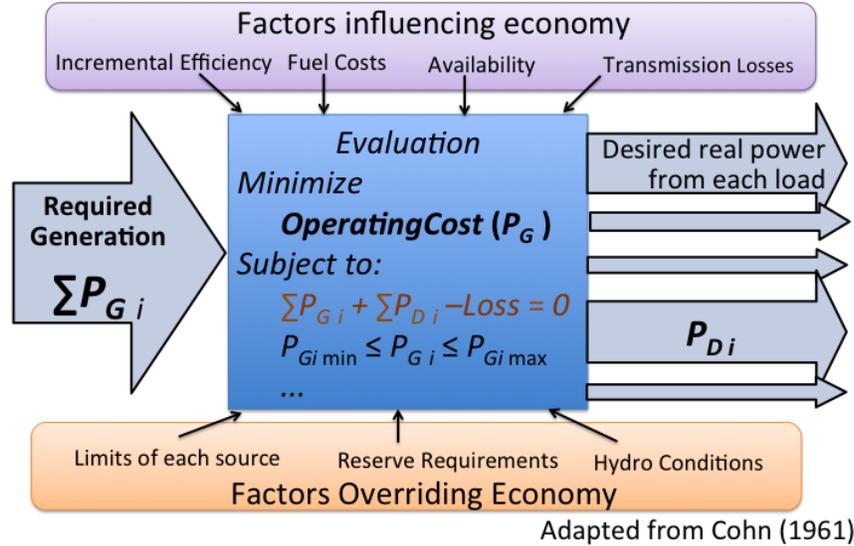


Figure 2.1: The central problem in power system operations and economics is scheduling controllable real power resources. Most often this is an economic dispatch, where the objective is lowest cost. Taking all the uncontrollable resources – demand, wind, collectively we get required generation ($\sum P_{U_i}$). All the factors influencing economy (e.g. fuel cost, unit availability, incremental unit efficiency, transmission losses) and all the factors overriding economy (e.g. reserve requirements, high and low limits of each source) pose constraints. Setting controllable generation to minimize operating cost subject to all constraints and evaluating yields a dispatch – desired real power from each controllable source P_{C_i} , where I is an index on sources.

dispatch. Figure 2.2 summarizes the resources available to achieve power balance in the face of variability and uncertainty that increases with forecast horizon.

2.3 Reserve

The existing framework for providing operational flexibility to a power system is spinning reserve. Ortega-Vasquez defines spinning reserve as “the capability of the power system to respond voluntarily to contingencies within the tertiary regulation interval with the already synchronized generation” [86]. During unit commitment, a fixed amount of available generating capacity – generally enough power to compensate for the unexpected loss of the single largest committed generator – is held in reserve. The ability to ramp generation quickly up or down by the amount of the reserve margin avoids load-shedding in case of a disruption to transmission or generation. Spinning reserves also absorb the smaller imbalances in supply and demand during regular operation.

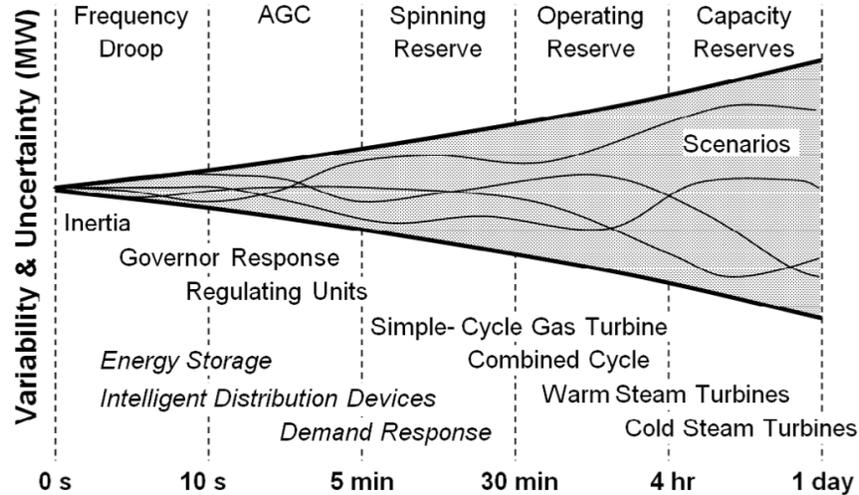


Figure 2.2: Philbrick observes that while the magnitude of variability decreases with shorter forecast horizons, so too do the ramping abilities of available resources decrease. Though this figure shows thermal generation resources, the minutes to days part of the figure captures the very short term scheduling time horizon we discuss. Controllable hydropower resources are often used for regulation, and should be considered “regulating units” in this context. The least responsive hydropower units have lead times like “Cold Steam Turbines.” Image from Philbrick 2011 [63]

Nathan Cohn dramatically improved the operational flexibility of power systems by creating the principal of automatic generation control, the control theory to coordinate bulk power transfers and frequency schedules among balancing areas. This allowed effective reserve sharing across balancing area boundaries [14, 15]. Cohn’s work has allowed reserve sharing among balancing areas to provide adequate operational flexibility for the last 53 years – no small achievement given the increasing complexity of the balancing problem.

2.3.1 Why Do We Need More Than This Classic Tool?

Reserve is a special case of operational flexibility, but incomplete. Using reserve to keep tabs on system flexibility is better than nothing, but the metric suits neither economy, security, nor a balance of the two. Reserve is maladapted to the prolonged excesses and shortfalls in power supply characteristic of stochastic renewable resources. As a practical matter, deployed reserve tracks the flexibility used already without shedding light on remaining operationally available flexibility.

In the modern power system, that operational awareness has become critical. System conditions fluctuate rapidly, and stochastic generation often aggregates to larger quantities than the largest conventional generating units. Reserve margins are being stretched to treat the uncertainty and

variability of renewable generation like conventional plants, protecting against outages, but keeping the true operational flexibility of the system hidden. Logging reserve deployed gives operators an indicator of what flexibility has been accessed rather than an awareness of what could be accessed in the future or whether upcoming dispatch schedules are feasible.

We need the next elegant and useful operational metric to fit the modern operating paradigm and manage the risk of stochastic renewable generation.

2.4 Other Assessments of Operational Flexibility

We are not the first to attempt to quantitatively define operational flexibility. A great deal of progress has been made to quantify flexibility from diverse planning perspectives; nevertheless, none of the proposed methods give the complete picture of flexibility necessary for power balancing operations.

The flexibility aware literature can be categorized as supporting planning or operations, and as describing either the flexibility requirements of a system, the flexibility of a specific resource, or flexibility of the system as a whole. Figure 2.3 shoes these categories, discussed in more detail in the remainder of this section. We stand on the shoulders of all of this scholarship. Our metric design stems from their clever insights, and of course the missed opportunities we recognize in their formulations.

2.4.1 Insufficient Ramp Rate Expectation

The most prominent flexibility metric, the Insufficient Ramp Rate Expectation (IRRE), was designed at University College Dublin by Lannoye, Flynn, and O'Malley [41, 42, 43]. The IRRE is formulated as the flexibility analog of capacity planning's Loss of Load Expectation (LOLE). IRRE is the, "expected number of up or down ramps for which there would be insufficient ramping resources available [42]."

The paper illustrates the time frame problem that a metric must capture, but falls short of capturing the time rich sensitivity of flexibility. "The main value of the IRRE is to highlight the time horizons for which ramping events may pose the most risk," asserts the paper [41]. The IRRE notably assumes available and required flexibility to be independant, but they are not. The IRRE

Flexibility Assessment Landscape

	Planning	Operations
Requirements	NERC (2011), Palmitier (2013)	Chavez (2012), Lu (2010), Clement (2013) Net Load Forecast, Wind Forecast Err.
Resource	Ma (2013)	ramp rate, P_{\min} , t_{startup}
System	Ma (2013), Lannoye (2012), IEA (2011)	frequency, Lannoye (2011), Menemenlis (2012), Studarus

Figure 2.3

assumes independence in the interest of faster computation for long term planning studies; even this could be too detailed for their purposes, and the authors consider using a priority list instead of UC. We suspect that the temporal disconnect will render the IRRE less effective than our flexibility metric at the operational timescale.

2.4.2 Flexibility Index

Ma, Silva, Belhomme, Kirschen and Ochoa define an elegant flexibility index that summarizes both system wide flexibility and the contribution of individual thermal generators. One feature of their index is that it is “non-time-specific” and not dependent on the status of any units; that feature may undermine its utility on the operational timescale [49]. This work also revealed that existing markets do reward flexibility, and market design can enhance or reduce system flexibility [36, 47, 48].

2.4.3 Flexibility Assessment Tool (FAsT)

The International Energy Agency has developed FAsT [34, 81] as an accounting system to track each resource’s ramping ability and then incorporates an operator’s judgment to determine how much of that ramping ability is available [81]. This approach is valuable but incomplete and slow.

2.4.4 Ramp Capability (Midwest ISO)

Navid, Rosenwald and Chatterjee created a definition of flexibility that can be applied to individual resources, with the goal of making flexibility an ancillary service [55]. Market participants bid their ramp rate (MW/min), output power limits (MW), and offer price (\$/MWh) into co-optimized up ramp capability, down ramp capability, and energy markets. The metric here is actually just unit ramp rate, but the resulting market design is flexibility aware.

2.4.5 Flexibility Index (ISO New England)

Zheng, Zhao, Zhao and Litvinov incorporate four elements into their flexibility index: response time, cost thresholds, available control actions, and target state deviations [91]. They aim to unify technical and economic feasibility, and the index describes the largest “change of state” the system can feasibly accommodate without exceeding a given cost threshold.

2.4.6 Reserve Adequacy for Wind Integration

Menemenlis, Huneault and Robitaille borrow a definition of flexibility from the process control literature, in which flexibility “refers to the design of control processes which with minimum alteration and changing costs can adapt to the production of new products.” Their work applies this process flow flexibility index to check the adequacy of reserves in the operational timeframe [53].

2.4.7 Existing Indicators

Some existing system metrics – like system frequency, deployed reserve, and the difference between total wind forecast and observed production – provide instantaneous feedback about the state of the system. Timeliness and level of granularity for these metrics are insufficient; they do not predict operational flexibility shortfalls.

2.4.8 Flexibility Aware Planning

Unit Commitment Considering Flexibility and Environmental Constraints (PNNL)

Shuai, Makarov, Zhu, Lu, Kumar, and Chakrabarti made great progress by explicitly incorporating flexibility and fish motivated flow constraints in their unit commitment formulation, and by thinking geometrically about flexibility [46]. Flexibility constraints are implemented on three axes: capacity, ramp rate, ramp duration. (The constraints are visualized as an allowable prism on these three axes, yielding the memorable term “flying boxes.”) The flexibility constraints are fixed parameters in the optimization, like traditional reserve requirement, rather than reflecting the state of the system.

Short Term Stochastic Models

Chavez, Baldick, and Sharma empirically analyze net load forecast error in ERCOT, developing a short term stochastic model that considers in particular the impact of wind noise, wind ramps, and wind forecast error on a regulation (5 minute) time horizon [11].

Clustered Unit Commitment in Long Term Planning

Bryan Palmintier, of the Engineering Systems Department at MIT, formalized a long term planning method. The method maintains the temporal link between available and required operational flexibility by including an elegantly simplified unit commitment simulation in planning simulations [60, 61]. The analysis explores whether a power system is flexible enough to meet its own constraints, but does not propose a metric to quantify flexibility in its own right. Flexibility aware planning largely means including operationally detailed simulations in long term planning, the finer grained the better.

2.4.9 Limiting Wind Capacity Studies

Failure mode analyses seek to identify extreme conditions under which the power system will fail. Bonneville Power Administration calls them “break studies” and estimates how much wind power the system could accommodate ???. Morales Pinson, and Madson used a transmission cost based stochastic optimization model to determine how much wind could be economically integrated in a

power system. They explore the “plausible frictions among the stochastic nature of wind generation, electricity markets, and the investments in transmission required to accommodate larger amounts of wind” [54]. Such studies provide valuable insight about the boundaries of feasibility, but are used as long term planning tools rather than as a guide for operations.

Worst Case Scenario Analysis

Worst case scenario analysis, as described by Lannoye, et al., identifies the time steps in historical data in which the difference between available ramp and maximum net load variation is the smallest, and qualitatively assesses whether the variation threatens to overtake ramping resources under similar circumstances in the future [41].

2.5 Innovation and Limitations of Existing Work

Chavez, Lu, and Clement have all made progress in including non-traditional constraints into the scheduling problem. Ma and Lannoye, and teams at National Electric Reliability Council and the International Energy Agency have tightened up the definition. Menemenlis proposed flexibility as a time series, maps it to balancing reserves, and provides a principaled definition of flexibility index from process control research. Ma created an elegant summary of flexibility at both the resource and system level. Lannoye led the charge to define operational flexibility, posing good questions, and suggesting metrics in several sectors.

Both Lannoye’s Expectation of Risk and Menemenlis reserve adequacy require extensive scenario generation and weighting, These are stochastic optimizations, even more established stochastic UC have not been adopted by any utilities or ISOs. And they leave the existing intelligence that’s currently used on the table. Ma and Lannoye, expressly decouple controllable and uncontrollable resources temporally, which makes them unsuitable for the operational timescale. ISO New England’s formulation is system specific and hasn’t published enough detail to judge (or reproduce). Net load forecast ignores the controllable resources and frequency provides a real time indicator rather than a predictor on which dispatch can be based.

In a nutshell, the existing flexibility metrics discussed in section 2.4 were designed to be computationally inexpensive summaries of a system for long term planning and resource adequacy

Flexibility Metrics: Appropriate?

○ = Yes, ✖ = No, ⊙ = Probably

	Ops	Tractable	Predictive	Unified	Reproducible
Our Metric	○	⊙	○	○	○
Menemenlis's	○	✖	⊙	○	⊙
Lannoye's E{Risk}	○	✖	○	○	✖
Ma's Flexibility Index	✖	⊙	⊙	✖	⊙
Lannoye's IRRE	✖	⊙	✖	✖	⊙
ISO NE's Flexibility Index	○	⊙	⊙	✖	✖
Net Load Forecast	○	○	○	✖	○
Frequency	○	○	✖	⊙	○

Figure 2.4: Where explicit operational flexibility metrics exist, are they appropriate to the task at hand? Space remains in this field for a new operational flexibility metric.

assessment. They give valuable insight about the system, but have not been shown to meet the needs of a real time duty scheduler. Figure 2.4 summarizes the applicability of the most relevant metrics.

2.6 Design Objectives

Informed by this literature survey, an ideal operational flexibility metric should meet several criteria:

- Resources should be grouped by their effect on flexibility (i. e. uncontrollable vs controllable generation) rather than their polarity (i. e. load vs generation)
- Measuring available capacity is not enough to describe available flexibility.
- Information should be presented as a time series extending forward from now out to an arbitrary horizon.
- Increases and decreases in system power are tabulated separately. The directions are fun-

damentally distinct in the human mind and in many system resources (*e.g.* wind can be curtailed, but not encouraged to blow harder).

- Information should be formulated both for humans and for Mixed Integer Programming solvers like those widely used for unit commitment [30].
- Information should be presented deterministically, even when constructed from stochastic sources. Long term planning can explore and set risk tolerance and perform statistical analyses of a system, stochastic unit commitments abound in the literature, but utilities and ISOs operate deterministically when scheduling at the short and very short time scales [35]. A real time duty scheduler values a clear threshold: Am I meeting my obligations or not? Am I well prepared to do so in the next hour, or not? Match the rest of the system telemetry data and spares a decision maker from aggregating uncertainty information from many sources while trying to make a quick decision.
- Reserve requirements – a deterministic solution to a stochastic problem – are a trusted way of ensuring that balancing resources are available when needed. This metric, then, should extend and refine the deterministic idea of reserve.
- Assessing flexibility for the long term planning timescale is not enough. The rubber meets the road in real time; every assumption in planning models that breaks the temporal connection between controllable and uncontrollable resources obfuscates the details of operational flexibility.

2.7 Conclusion

Modern power systems need an operational flexibility metric, and existing scholarship falls short. In this chapter we have explored the power systems requirements and existing literature, then given marching orders for the necessary innovation.

In chapter 3, we will detail the acute need and opportunity to measure operational flexibility in one hydropower system. In section 5 we propose a new operational flexibility metric that meets the requirements already spelled out in 2.6.

Chapter 3

Hydropower

3.1 Summary

The Pacific Northwest has a spectacular energy resource in the Federal Columbia River Power System (FCRPS), an abundant and versatile source of inexpensive sustainable power. But the FCRPS serves many masters; it is managed for flood control, fish and wildlife, public safety, treaty commitments, and many other uses. Transmission congestion, wind power generation, energy contracts, and hydropower generation at non-federal dams place further demands on the FCRPS hydropower schedule.

This chapter introduces current hydropower scheduling practices, discusses the operational flexibility requirements of the Federal Columbia River Power System (FCRPS), introduces the “very short term” time horizon, and identifies some challenges in hydropower operations modeling. These sections together paint a clear picture of why the FCRPS needs – and can showcase – a new operational flexibility metric.

3.2 Current Power Scheduling Practice

3.2.1 Power Balance with Hydropower

Balancing areas rich in hydropower, like the FCRPS, offer an interesting special case of the scheduling problem we introduced in section 2.2.6. Hydropower generators lack cost curves and therefore are not scheduled for optimum economy except when coordinated with thermal generators, where

they essentially allow time-shifting of thermal output for maximum economy.

While economy takes a back seat, the rest of the classic power system scheduling framework in figure 2.1 holds unyieldingly, especially the power balance. We can think of current practice as a power balance driven feasibility problem; Bonneville’s scheduling problem is all about satisfying the constraints imposed by diverse obligations on the river system. On operational timescales this evaluation is informal; in fact, the hydropower rich system is dispatched informally for optimal flexibility. A true operational metric of flexibility would allow formal scheduling for optimal flexibility instead of simply feasibility or optimal economy.

Figure 2.2 provides a conventional thermal scheduling backdrop against which hydropower scheduling can be considered. The responsiveness of many hydropower projects (e.g. Grand Coulee or Bonneville dams) places them as cheap “regulating units” in that framework, and makes them attractive balancing resources indeed.

3.2.2 Planning Timeframes

Hydropower scheduling in the literature and in practice is broken out into four time frames:

Long Term Years ahead, capacity planning

Mid Term Annual, considers climatological variation and historical usage patterns, results in monthly or weekly release targets

Short Term 1-2 week horizon, 1-8 hour intervals, considers forecast wind, hydro inflows, load, market prices, weather, and short term system usage

Real Time An operator with telemetry data from all hydropower projects tracks power balance error and fine tunes the dispatch to account for variation from forecasts. Historically, this has meant “steering” the system to keep it within the water release boundaries of the short term schedule, or – informally – maximizing flexibility.

3.2.3 FCRPS

The Federal Columbia River Power System (FCRPS) faces constricting operational requirements when balancing 16 GW of hydro, 4.4 GW of wind, and 6.3 GW of thermal generation capacity as of November 2012. Federal dams in the Pacific Northwest historically operated only for flood

control, irrigation and abundant hydropower – allowing a superfluity of system flexibility. Modern opportunities and obligations, however, consume that flexibility. Demands include balancing the variability of high penetrations of renewable generation, market opportunities, a strong regional commitment to low electricity rates, transmission bottlenecks between generation and load, and – most stringent of all – fish and wildlife conservation. Hydropower rich generation mixtures like the FCRPS, while conventionally considered to have flexibility too high to mention, must now quantify and allocate flexibility as carefully as capacity.

The FCRPS is jointly managed by the Army Corps of Engineers (Corps), the Bureau of Reclamation (Bureau), and the Bonneville Power Administration (BPA). The Corps takes the lead on mid term reservoir scheduling (driven by flood control) and BPA takes the lead managing the reservoirs on shorter timescales (balancing power). But diverse constraints are integrated at every level. “You used to have to take snow melt forecasts, power requirements, fishery requirements, treaty requirements, encapsulate them in your head ... and do it fast enough so that you can share it and implement it,” says Corps engineer George “Chan” Modini, a statement that just as easily could have come from a current BPA analyst [3, 9]. Planning has traditionally managed uncertainty by committee, but competing obligations and data availability are increasingly utilized. “You used to sit around and hear these oral traditions,” observes Modini. “Now data is replacing our oral traditions [9].”

Some of BPA’s current work flow on the very short term timescale is captured in Figure 3.1. The current Columbia Vista (CV) “optimal dispatch” decision support tool, a black box to its users, treats all constraints as soft and enforces them with penalty functions. The method returns infeasible solutions, and therefore is not part of the critical path of the process. Instead, a team of experienced planners gathers available information, draws on years of experience, and makes a good faith effort to meet all constraints and satisfy all parties. This approach draws on hard won intuition, avoids past problems, keeps reality-checking eyes on the process, and allows smooth integration of disparate information sources, modeling runs and priorities. The downsides are that this method is expensive, turn-around time can be slow, many people spend long hours in meetings doing this work every day, it relies on good group dynamics and the presence of experienced people, and priorities are tough to lock in except through legal action [3].

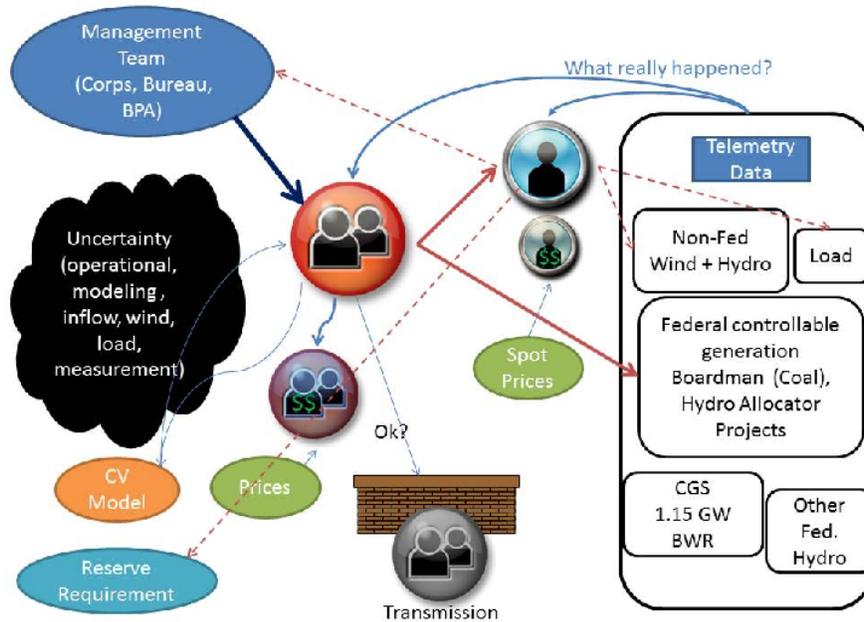


Figure 3.1: This figure captures some of the current hydro short term scheduling process. The core decision makers on this graph are the short term planning team (red icon) and the real time duty scheduler (blue icon) who poll all the other sources of information. Blue lines indicate the flow of information flow, red lines indicate the flow of control, and dotted red lines indicate emergency control [4, 5, 6, 7, 71, 76, 87].

Obligations¹ are known by the members of the group, and some are codified in the FCRPS governing documents including an annual Water Management Plan, Biological Opinions (that map current science to court mandated scheduling rules), and Dispatcher Standing Orders (DSO). Procedures for relieving transmission congestion are codified in DSO-300 series, while procedures for shedding wind are codified in DSO-200 series dispatcher standing orders [3, 5, 71, 72, 76, 77].

3.3 Very Short Term Time Horizon

Short term planners and the real time desk have an especially close relationship at the Bonneville Power Administration and other balancing authorities because they face similar pressures. The line blurs between short term and real time schedulers performing a function best described by its own time frame: very short term dispatch.

Hydropower systems regularly perform optimization and dispatch on a very short term time scale, where “very short term” means minutes to days ahead, in contrast to “short term” scheduling

¹defined in section 1.1

which traditionally implies day to week ahead. The timescale includes what other systems call “economic dispatch timescale” or “load following timescale.” “Very short term” also encompasses most of “Real Time” operations, but is not simply a relabeling of real time operations, which still should mean responding to observed system conditions and mitigating unforeseen problems as they arise. “Very short term” scheduling still focuses on reconciling forecast conditions with system observations, and on optimizing system performance on a regular ongoing basis.

3.3.1 Why is this time frame absent from the literature?

Very short term hydropower scheduling, by any name, is largely absent from the literature. There may be several reasons for this silence:

- The problem is messy, and therefore not appealing as a showcase for an elegant theory or optimization
- The constraints are highly specific to each balancing area with hydro. The oft heard mantra, “Every hydro system is different,” discourages generic solutions [89].
- Often, operational practice includes “steering to keep the needle in the middle” which does not lend itself to formal statement
- Those who truly understand how the system has been dispatched are too busy dispatching the system to formally state what they are doing.
- The constraints and objectives for the FCRPS have never all been gathered in one place before [4, 5, 7].
- Many hydropower plants are in systems dominated by thermal units. In the resulting hydro-thermal coordination, hydropower is scheduled to have near constant output (as a baseload regulating resource) while fossil fuel plants perform the load following. Perhaps this is why the very short term timescale has remained under the “economic dispatch” umbrella instead of finding a place in the hydropower scheduling literature as needed by hydro rich systems.

3.4 Flexibility in Very Short Term Hydropower Scheduling

3.4.1 Many Obligations

For use in dispatch, taking into account the limited bandwidth of the scheduler, constraints from diverse sources must be unified and intuitively presented. The scheduler must achieve continuity of service along with system specific objectives[14]. Wind variation and forecast error dominate the very short time scale, which also wrestles with load following, day ahead and spot market transactions, and spill requirements for fish passage.

Absent from the literature are any theoretical formulations that consider the full complement of operational objectives and constraints. The cascaded hydropower system presents difficult coordination challenges based on its topography. New obligations have arisen, as listed in section 1.2, long after the system was originally designed for power and flood control. Some of the interesting constraints are introduced in section ??.

John Bruner wrote a very accessible discussion in *Forbes* of the complex problem facing duty schedulers in the Federal Columbia River Power System, to which we direct interested readers [9]. *Cadillac Desert* describes how extensively dams were used to try to tame the hydrologically hostile American West. The complexities that were ignored historically during project construction reenter the picture as complicated constraints in current and power system future operation [67].

3.4.2 Systemwide Flexibility

Opportunities and obligations facing schedulers and balancing authorities have transformed over the life of the power system. Seasonal climate and electricity demand once drove generation schedules. Now, large amounts of wind energy, market opportunities, wildlife conservation efforts, abundant telemetry data, and many other pressures increasingly squeeze dispatch decisions into the final hours before operation. Non-power constraints drive the system towards a less flexible operational schedule [33].

The system simultaneously has more and less flexibility than we expect. On the one hand, there is a prevailing sense among stakeholders that “there is lots of spinning reserve floating around out there.” Some see that excess as an unnecessary expense; others observe that it varies based on operator style, and has cushioned otherwise dicey situations where all available reserve was

deployed. On the other hand, the highly constrained system does not have as much flexibility as the potential energy behind the dams would suggest. Demanding scenarios sometimes are absorbed without incident as operators mobilize resources to respond, and sometimes result in violated constraints (*e.g.* spilling the wrong amount of water over a dam and killing fish with high dissolved gas levels, curtailing wind, shedding load) [3, 8, 9]. A common thread among these opinions is that flexibility could be better quantified.

3.4.3 Oversupply

The need to measure and account for flexibility in the FCRPS was thrown into the spotlight in May of 2011. Abundant wind and record high spring snow melt resulted in an oversupply of electricity, and wind production was curtailed. Curtailment means that the wind farm had to forgo possible generation and revenue.

To the average observer and windfarm owners the reason for curtailment was unclear, and in fact the motivation was complicated. Because spilling water dissolves nitrogen gas at levels fatal for fish, limits on allowed dissolved gas have been implemented as spill limits on hydropower projects [1, 4, 65, 71]. Adherence to the spill limits is court ordered, and violations result in stiff financial fines. The system's reservoir capacity (though large compared to other regions) can only accommodate about 30% of annual inflow [23], making it infeasible to time shift the energy on a seasonal timescale. The first responsibility of the big upstream reservoirs is flood control, protecting the people and property in floodplains downstream. This means those upstream projects continue to release water early in the snow melt season to absorb the anticipated rapid inflows, and cannot operate full. Many of the dams cannot hold more than about 6 hours of runoff during the snow melt season. So, the flood control and fish protecting spill limits amount to a court mandated "must run" condition on the hydropower generators. Without enough regional demand, and lacking transmission capacity to move the abundant power to other markets, BPA ordered wind farms to curtail their output by 6% by its authority in the balancing area [9, 71, 72].

Wind producers were outraged, bringing federal law makers into the fight [66]. Their argument lept particularly on the economics of the situation: Bonneville got revenue from the energy they generated while denying wind farm producers income from both energy sales and Federal production tax credits. The production subsidies can drive energy spot market prices below zero, and in such

conditions Bonneville balked at paying wind farms to generate while simultaneously paying hefty fines for violating court ordered spill limits. Wind farm producers saw Bonneville's actions as financial self interest. Litigation continues over this high profile shortfall in operational flexibility which persisted intermittently through 2012 [3, 8, 9]. Fortunately, creative policy construction is ongoing as well, and a new 2014-2015 Rate Case which includes financial compensation for oversupply in cases of oversupply will resolve the issue between BPA and wind farm owners.

But similar problems will result from other conflicting obligations in any flexibility limited power system. The lack of a clear way to set, enforce and explain priorities in infeasible situations sparked bitter disagreement in the oversupply situation, and should be addressed by better understanding and reporting of the flexibility and obligations influencing generation schedules.

3.5 Ancillary Services

Historically, electricity has been largely traded "volumetrically" as MWh. Other aspects of energy delivery have been lumped into the term "ancillary services." The Federal Energy Regulatory Commission (FERC) defines ancillary services as six services "necessary for the transmission provider to offer transmission customers ... to accomplish transmission service while maintaining reliability within and among control areas affected by the transmission service:"

- scheduling and dispatch
- reactive power and voltage control
- loss compensation
- load following
- system protection
- energy imbalance

[85]

For flexibility to be explicitly traded and allocated as a service, it needs to be quantified and its value agreed upon. Ma et al. have made great progress on this front, with their flexibility index and market analysis but their index isn't time varying [49]. We think a time varying flexibility value

will help quantify and value flexibility as a tradable product in the context of FERC’s ancillary services and emerging market structures.

Hydropower is the primary supplier of balancing services in the pacific northwest region. Neglected by subsidies to encourage *new* carbon neutral generation like the production tax credit, for profit hydropower producers would do well in a flexibility market, except when existing constraints on the use of that flexibility (see 3.4.3) prevent it. Pizzimenti, Olsen, and Wilson further quantify the ability of hydropower to provide ancillary services [65]. Even not for profit hydropower operators, like BPA, would like an explicit valuation of the services provided when formulating rate cases.

3.6 Reserve

On this timescale, and in the context of wind rich systems, reserve requirements are getting new scrutiny in the literature and operations [2, 3, 21, 34, 58, 87]. Any operational flexibility metric would be a generalization of the concept of reserve.

3.7 Conclusion

The FCRPS provides an excellent context to explore flexibility limited power system operation: they are experiencing the problem right now, they make rich datasets publicly available, and a framework that can handle the difficult constraints in this system would be easy to adapt to other power systems. We propose just such a framework in the next part of this thesis.

Part II

Theory

Chapter 4

Real Power Resources: Seeing the Power Balance in a New Light

4.1 Summary

We simply but fundamentally reframe the power balance in terms that better capture the modern power grid. Considering controllable and uncontrollable real power resources lays the foundation for an operationally useful definition of flexibility, and captures the realities of managing an increasingly distributed electricity supply.

This reframing captures the first design objective for a flexibility metric (section 2.6), grouping resources by their effect on flexibility (i.e. uncontrollable vs controllable generation) rather than their polarity (i.e. load vs generation).

4.2 Generation and Load

Historically, the boundaries between supply and demand were stark. Large hydropower, nuclear, and fossil fuel generators produced power and delivered it over transmission and distribution grids to industrial, residential, and commercial customers.

Today, distributed energy resources...

stochastic renewable supply

demand response...

4.3 Real Power Resources

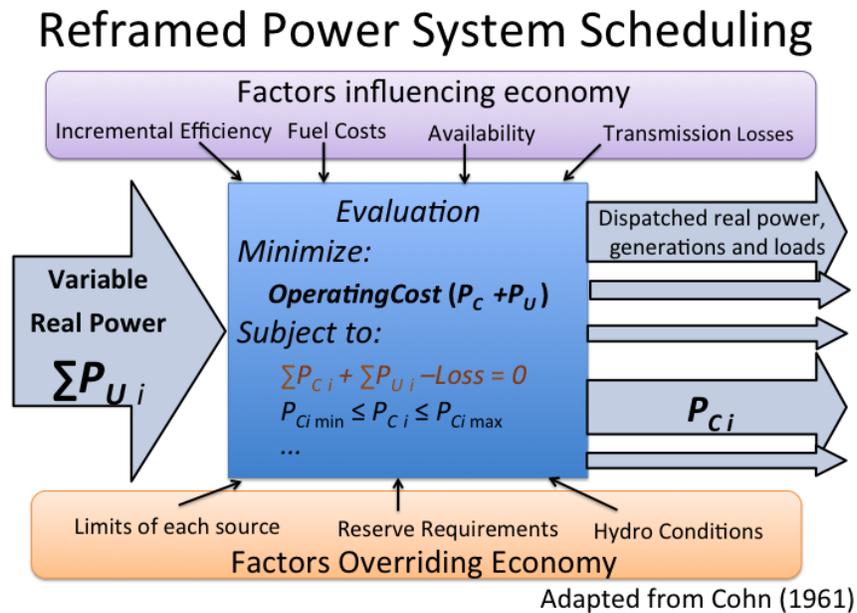


Figure 4.1: The central problem in power system operations and economics is scheduling controllable real power resources. Most often this is an economic dispatch, where the objective is lowest cost. Taking all the uncontrollable resources – demand, wind power, collectively we get the net uncontrollable real power resources ($\sum P_{U_i}$ or P_U). To serve and accommodate P_U . All the factors influencing economy (e.g. fuel cost, unit availability, incremental unit efficiency, transmission losses) and all the factors overriding economy (e.g. reserve requirements, high and low limits of each source) pose constraints. Setting controllable generation to minimize operating cost subject to all constraints and evaluating yields a dispatch – desired real power from each controllable source P_{C_i} , where i is an index on sources.

4.4 Defining Flexibility

Operational flexibility is a power system’s ability to respond with controllable real power resources.

4.5 Conclusion

Chapter 5

A New Metric of Operational Flexibility

5.1 Summary

In this chapter, we develop a new metric to quantify operational flexibility in power systems. This metric is designed to be useful to schedulers following the variations in uncontrollable power resources to minimize power balance error. The metric is information rich, but should fit intuitively with the scheduler's work flow.

5.2 Real Power Resources: Seeing the Power Balance in a New Light

We simply but fundamentally reframe the power balance in terms that better capture the modern power grid. Considering controllable and uncontrollable real power resources lays the foundation for an operationally useful definition of flexibility, and captures the realities of managing an increasingly distributed electricity supply.

This reframing captures the first design objective for a flexibility metric (section 2.6), grouping resources by their effect on flexibility (i.e. uncontrollable vs controllable generation) rather than their polarity (i.e. load vs generation).

Historically, the boundaries between supply and demand were stark. Large hydropower, nu-

Reframed Power System Scheduling

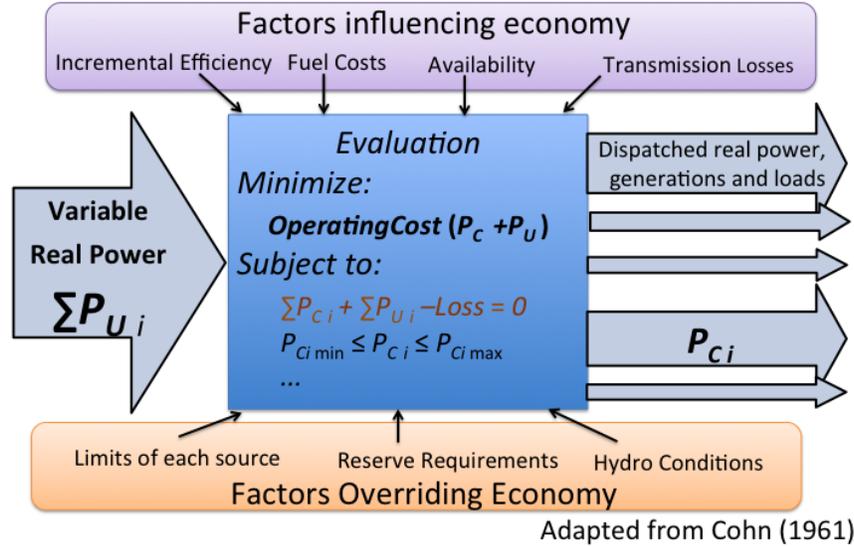


Figure 5.1: The central problem in power system operations and economics is scheduling controllable real power resources. Most often this is an economic dispatch, where the objective is lowest cost. Taking all the uncontrollable resources – demand, wind power, collectively we get the net uncontrollable real power resources ($\sum P_{U_i}$ or P_U). To serve and accommodate P_U . All the factors influencing economy (e.g. fuel cost, unit availability, incremental unit efficiency, transmission losses) and all the factors overriding economy (e.g. reserve requirements, high and low limits of each source) pose constraints. Setting controllable generation to minimize operating cost subject to all constraints and evaluating yields a dispatch – desired real power from each controllable source P_{C_i} , where i is an index on sources.

clear, and fossil fuel generators produced power and delivered it over transmission and distribution grids to industrial, residential, and commercial customers. Today, distributed energy resources, demand response programs, smart grid technologies and stochastic renewable supply all make the new formulation necessary. We illustrate the distinction in figure 5.1, in contrast to the classical formulation in figure 2.1.

5.3 Our formulation

The proposed operational flexibility metric, $f(t)$, quantifies the real power resources which can be redeployed by time t without violating any constraints. For a user specified significance level α , the flexibility metric $f(t)$ consists of two component time series with units of MW, $f_{up}(t)$ and $f_{down}(t)$, which are the upper and lower bounds on the $(1 - 2*\alpha)$ confidence interval of power available. That is to say, if a scheduler acts now in anticipation of time t , they can count on increasing available

power by $f_{up}(t)$ over what is currently scheduled with $(1 - \alpha)$ percent certainty. Similarly, they can count on the ability to decrease generation by $f_{down}(t)$ by time t with $(1 - \alpha)$ percent certainty. Zero crossings of the time series $f(t)$ indicate that a situation will become infeasible, violating a constraint at time t with probability $(1 - \alpha)$.

5.3.1 Uncontrollable Real Power Resources

A forecast of uncontrollable real power resources is the first component of flexibility. A real power obligation can be demand (*e.g.* serve the load) or generation (*e.g.* do not curtail any wind power available). We refer to all real power resources that the operator cannot directly control on the very short term time scale as uncontrollable. Many stochastic forecasting methods exist in the literature, along with statistics about their accuracy [2, 11, 64]. We assume the availability of these data, often from multiple sources (*e.g.* river inflow models, wind forecasts, load forecasts, interchange contracts) and formulate a way to unify these stochastic forecasts into an informative deterministic trace, $U(t)$ where “U” stands for uncontrollable real power. $U(t)$ quantifies how far real power resources may diverge from the current operating point and can be considered a “forecast” of power balance error. We group all exogenous resources as “uncontrollable real power” to emphasize that the modern power system contains both controllable and variable resources, both demanding and generating electrical power. Stochastic renewables break the paradigm of matching generation to load, and this formulation reflects that.

Forecasts are aggregated based on as much information as is available about their statistical properties. When a confidence interval is available from the aggregate forecast, $U_{up}(t)$ and $U_{down}(t)$ trace a $(1 - \alpha)$ confidence interval around the point forecast of uncontrollable resources, generally broadening as forecast uncertainty increases with horizon t . Note that the uncertainty of the aggregate forecast increases with each addition, even when the resources appear to balance one another (*e.g.* $var(P_{load} - P_{wind}) = var(P_{load}) + var(P_{wind})$ assuming independent forecasts).

5.3.2 Constraints on Controllable Real Power Resources

For the construction of the flexibility metric, we map all constraints to a time series with units of MW and time extending from current conditions at $t = 0$ out to an arbitrary horizon. This formulation meets the objectives in 2.6 by making the flexibility metric an intuitive time series and

by identifying in detail the constraints considered and their explicit priority.

Constraints are gathered into sets for simultaneous consideration and aggregated according to operational requirements (*i.e.* as appropriate they are added, concatenated, selected as most binding, nested). The time varying aggregation of all constraints under consideration is $C_i(t)$, where “C” stands for controllable, and the subscript indicates that many possible choices of constraint set exist. The level of detail in these constraint sets will vary based on data and computing power available, and on the questions being posed about the system. We discuss combination of constraint sets in chapter 6.1 and showcased in the examples of chapters 8 and 9.

The loosest constraint set $C_{outer}(t)$ could be, for example, the summed nameplate maximum capacity of every controllable resource in the system. A slightly tighter set would include the ramp rate limitations on the units, while another might also restrict operation to the most efficient power output ranges of each unit. The tightest constraint set, $C_{complete}(t)$, would include every known constraint and preferred operation mode of any type on the system and their interdependencies. Infinite variations exist in between, both as heuristic summaries and rigorous subsets of $C_{complete}(t)$. In most cases several will be calculated, displayed together, and compared. The natural first pass, requiring minimal computation, is to use the system operating INC and DEC reserve requirement $C_{reserve}(t)$ as the heuristic constraint on operation.

Like $U(t)$, $C(t)$ is a pair of time series showing the minimum and maximum of operating range. Where uncertainty of these bounds is available (*e.g.* forecasts of stream inflows to hydro reservoirs) $C_{up}(t)$ and $C_{down}(t)$ trace the conservative boundary of a confidence interval.

A useful way of using several constraint sets is to calculate an outer $C_0(t)$ representing the laws of physics on the system (*e.g.* network topology, reservoir volumes, generating unit maximum power output). Nested traces can be calculated for the other constraints grouped by priority level. This set of $C_i(t)$ where increasing i denotes a lower priority, would allow a quick visualization of priorities, and options for recourse in the case of a conflict.

5.3.3 Operational Flexibility Metric Assembly

To compute the pair $f_{up}(t)$ and $f_{down}(t)$, a choice must be made among the possible system constraint traces, $C_i(t)$. (Displaying an ensemble of $f_i(t)$ based on different constraint sets may be desirable, but each must be calculated individually).

$$f_{up}(t) = C_{up}(t) - U_{up}(t)$$

$$f_{down}(t) = C_{down}(t) - U_{down}(t)$$

Though easiest for purely deterministic constraint sets, this difference can be readily calculated for $C(t)$ with an associated confidence level, just as forecasts are combined in $U(t)$.

5.3.4 Example

A simple example illustrates $f(t)$, with real world examples following in chapters 8 and 9.

The uncontrollable real power shown is computed as:

$$U(t) = P_W(t) - P_D(t) + P_{UH}(t) - P_I(t)$$

where $P_W(t)$ is the wind forecast, $P_D(t)$ is the load forecast, $P_{UH}(t)$ is the undispachable hydro power, and $P_I(t)$ is the scheduled interchange, based on BPA published historical 5 minute data. This example shows the baseline case of assuming a perfect forecast, or $\alpha = 0$. Forecast uncertainty, as available, can be added as described above in Section 5.3.1.

The week shown in Figure 5.2 shows a typical operating regime, based on observed hydropower, interchange, wind, and load profiles. Balancing reserve requirements are shown as one constraint trace, while the other constraint traces are shown to illustrate the metric and are not actual FCRPS operating constraints. Figure ?? shows how looking at multiple time horizons simultaneously might be of use.

Execution time to calculate and display $f(t)$ in these figures was trivial using Python on a non-optimized laptop. The computational complexity may be higher to assemble more sophisticated constraint sets, $C(t)$, (discussed in chapter 6.1) or to perform flexibility optimal dispatch (beyond the scope of this dissertation but introduced in sections 6.1, 10 and 11).

5.3.5 Infeasibility

Infeasible situations, in which not all constraints can be satisfied, are easy to spot in this visualization. When the tunnel pinches closed onto the feasibility axis (i.e. zero flexibility), the event

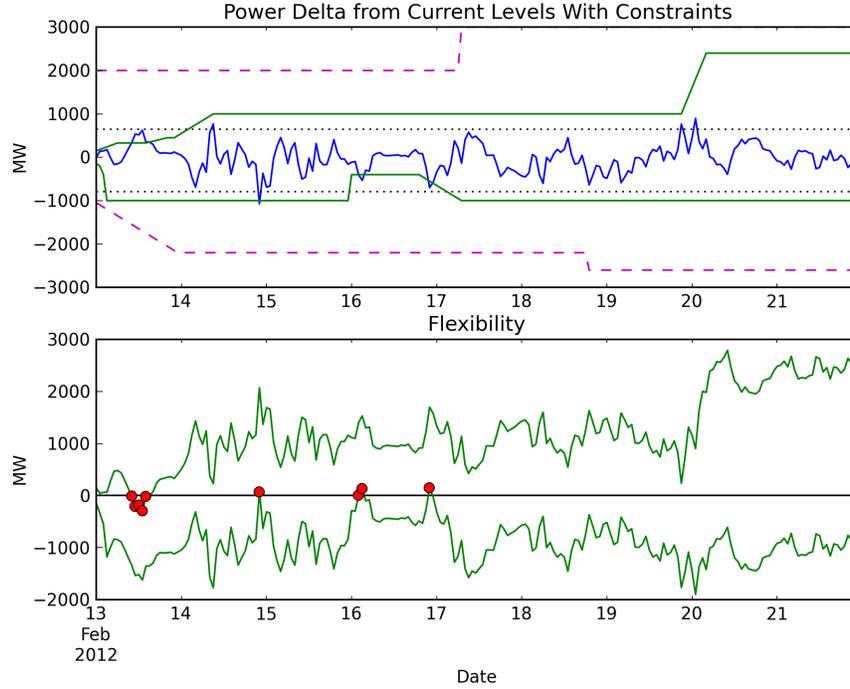


Figure 5.2: The blue line in the top plot shows $U(t)$ built from point forecasts of wind and load in the FCRPS system in a typical winter week in 2012, with $\alpha = 0$. Operating Reserve Requirements are shown as dotted black lines, $C_{reserve}(t)$. The maximum and minimum power available according to one fictional constraint set is shown as dashed magenta lines, $C_{outer}(t)$. A more restrictive constraint set is shown as green solid lines, $C_{inner}(t)$. The constraints are drawn to suggest ramp rate limits, scheduled maintenance outages, and resources that can be mobilized after a fixed time delay. The pair of green lines in the bottom plot, $f(t)$, is the flexibility metric resulting from $U(t)$ and $C_{inner}(t)$. Forecast constraint violations appear as red dots when $f(t)$ crosses the x axis.

is flagged and the component constraints and forecasts contributing to the alert are available for closer scrutiny. The operator may take remedial action with resources outside the shown constraint set, or if the constraints are well characterized in nested levels, immediately see a priority list of remedial actions with their consequences (*i.e.* the violated constraints, and the extra $P(t)$ gained by the action).

5.3.6 Visualization

The deterministic operational flexibility metric lends itself well to a scrolling display of $f(\tau)$ vs. time horizon, τ , frequently refreshed to display up to date forecast and system conditions and to keep the present moment locked to the origin, $\tau = 0$. System flexibility thus appears intuitively as a tunnel stretching forward in time between $f_{up}(t)$ and $f_{down}(t)$, perhaps in several displays showing

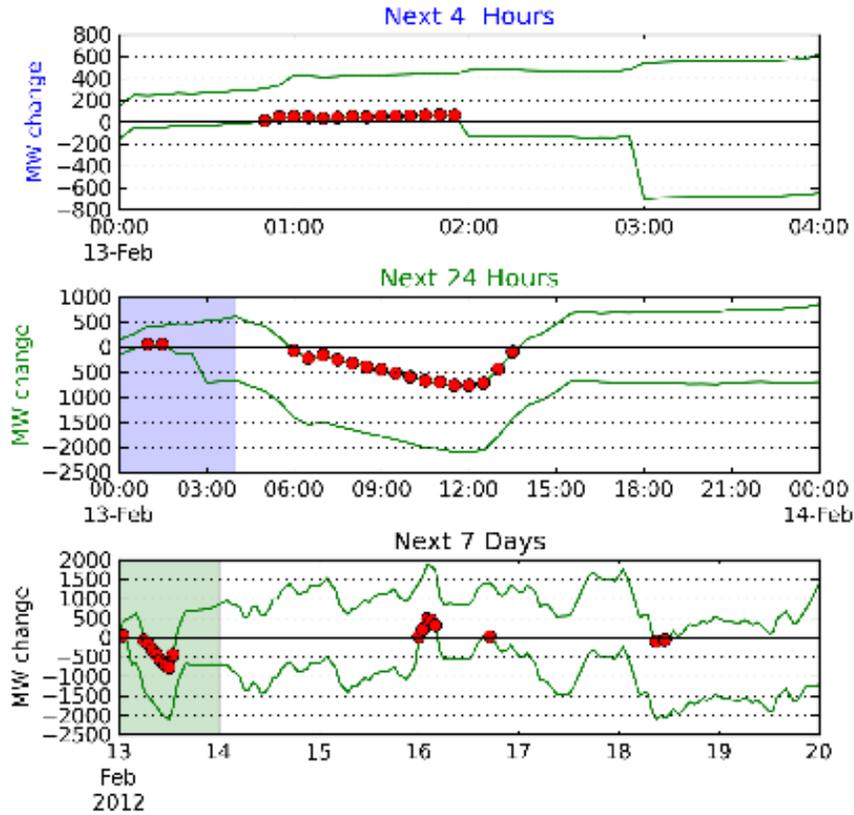


Figure 5.3: Cascading display of deterministic flexibility metric shown simultaneously for three time horizons of interest

relevant planning time horizons at the appropriate resolution, as in Figure ???. Time marches on, and a scrolling forecast of nested time horizons captures our flexibility metric intuitively. Flexibility continuously varies, so picking out a single value at a single time horizon is not particularly useful.

This simple visualization is an important start, practically and theoretically. We propose in section 11.3 to refine this presentation to create a more intuitive and valuable decision support tool for human operators.

Part III

Validation: Follow on dissertation work, to be shared with HRF upon completion

Part IV

Conclusion

Chapter 10

Application to the Federal Columbia River Power System

10.1 Summary

The operational flexibility metric was motivated by very short term scheduling in the Federal Columbia River Power System. We showed the metric's broader utility in power systems in chapter 8 and some examples specific to the FCRPS in chapter 9. The following steps were taken:

10.2 Contribution to Short Term Planning

Unify Framework for Uncertain Obligations: We created the mathematical framework to present arbitrary objectives and constraints 6.1 and their associated uncertainty together to inform dispatch decisions.

Create FCRPS constraint sets: Described in sections 6.1 and 5.3.1, this work brings together the diverse constraints placed on hydropower scheduling, and maps them into an innovative time series formulation.

Validate Operational Flexibility Metric: We define the metric $f(t)$ in section 5.3, and the plan to validate it in section 7. This theoretical contribution was submitted to the 2013 IEEE Power and Energy Society General Meeting, and we are in the process of expanding it as a Transactions submission.

Identify Operational Flexibility Shortfalls: We are developing an algorithm to flag and characterize operational tight spots (section 7.2). The algorithm is trained on historical data from BPA and the Army Corps of Engineers, as well as feedback from the human duty scheduler. The resulting labeled set of flexibility failures will allow training, testing, and comparison of predictive flexibility metrics.

Flexibility Metric Comparison: Section ?? proposes how we will compare the predictive power of our operational flexibility metric with other possibilities in the literature.

Quantify Flexibility in FCRPS: We estimated operational flexibility using data (2007-2014) supplied by BPA's short term planning group in section 9. This analysis can be modified to include any other subset of the constraints the short term planning team finds relevant.

Visualization Tools: As detailed in section 10.4.1, we will incorporate the information distilled in the previous three items into a visually intuitive rendering. Operators and analysts will interactively explore this visualization using our tools.

10.3 Maximize Flexibility

Informally, the FCRPS is operated to maximize very short term flexibility. The operational flexibility metric, $f(t)$, could be used as an objective function for schedule optimization. As currently implemented, $f(t)$ indicates feasibility of the schedule but that's one GAMS script away from being the objective function of an optimization linear program.

10.4 Create Tools for Duty Schedulers

The code in development for this dissertation will be published as an open source toolkit for power systems operators and analysts [52].

These tools include:

- Selection of relevant/interesting constraints
- Unification of selected constraints
- Constraint Management

- Summary of historical data
- Event detection in historical data
- Computation of flexibility metric
- Visualization of constraint sets, flexibility, and feasibility

10.4.1 Visualize Operational Flexibility

The metric created in Chapter 2 enables a user to visualize feasibility and flexibility of the hydropower schedules. We target two audiences: the duty scheduler in real time, and the analyst exploring historical and simulated conditions. One visualization is central to this dissertation. Other ideas will be explored in the future work section 11.3.

Research has shown presenting information in an interactive visualization is actively better for decision making than tabular or even static images [68]. The visualization piece of this work began as a low priority, but has been so widely embraced in conversations about this work that now holds a prominent position. Care given to the visualization of our contributions could subtly but fundamentally improve their usefulness in power system scheduling.

10.4.2 Constraint Management

Based on our conversations with BPA, new constraints seem to appear frequently, from many sources. These are changed based on seasonal conditions, evolving understanding of environmental impacts, policy change, and negotiation. Both the parameters and form of such constraints change with time.

Constraint Addition

Valuable figures in the analysis would include:

- introduction of new constraint formulation vs time (day of year)
- constraint parameters vs time (day of year, time of day)

Stale Constraints

Constraints come from many sources, and are juggled by the teams in short term planners and real time operators. At the moment they don't have decision support tools that make keeping track of what's active easy. There is always a hazard that stale constraints can stay in the model even after they've operationally expired. We can combat that procedurally by making the active constraint sets explicit, as in 6.1, and using a good data structure.

New Constraints

Constraint parameters in system model optimization runs are changed frequently. The number of constraint types, capturing obligations like those in 1.2, have increased over the life of the system and show no signs of slowing. Sometimes, new constraints can lurk below the surface such as on 8/10/1996 when operators "discovered the John Day Cut Plane" or an exciter issue at McNary dam (also in 1996) [7]. Quickly being able to incorporate such revelations into a versatile framework for managing constraint sets should be a valuable element of these tools.

10.4.3 Other Software Tools

Bonneville Power Administration's Power and Operations Short-Term Planning group is in the process of replacing their modeling tool, and has opened up a competition to potential vendors. BPA analysts, competing software vendors, EPRI, and at least one graduate student, then, currently wrestle with what we're calling the very short term hydropower optimization problem [5, 80].

This adds some competition, but also a potential opening for the operational flexibility metric and constraint formulations to enter the enterprise software solution. BPA is in the final design phase of the Columbia Vista Short Term Model Replacement about the time this dissertation work winds up in early 2014 [5]. add notes from 2014 visit to BPA]

10.5 Impact on Long Term Planning

Though operational timescales motivate the metric $f(t)$, our intention is that it will be employed in long term planning, just as other short term metrics like spinning reserve are employed today. If $f(t)$ succeeds in capturing the very real operational frictions among different constraint types and

uncertainty as a concise time series, it will “supply the missing dimensions worthy of inclusion” sought for long term planning system models, and do so tractably [61].

Chapter 11

Conclusion

11.1 Summary

This dissertation matters because power system schedulers demand a good measure of flexibility as ever more constrictive obligations and stochastic real power resources impact operations. The very short term (minutes to days) timescale is especially poorly summarized, as new modes of operation have emerged in recent years thanks to increasing wind power capacity and market opportunities. The tools we propose would likely go into use in the FCRPS and beyond right away.

The work provides a PhD caliber challenge: we distill complicated constraints and forecasts into a unified and versatile theoretical framework. The hydropower scheduling problem in particular has been inadequately modeled in the literature at the very short term timescale, resulting in a divergence between modeled and actual operation. Getting the unified snapshot of the system right – mathematically correct, complete for a complex system, and consistent with real world operations – while still making the metric simple enough for intuitive visualization and inexpensive computation is a hard problem.

This dissertation attempted the following:

Build Operationally useful Constraint Sets: Described in sections 6.1 and 5.3.1, this work brings together the diverse constraints placed on hydropower scheduling at the very short time scale.

Operational Flexibility Metric: We defined the metric $f(t)$ in section 5.3, and validate it in section 7. This contribution was submitted to the 2013 IEEE Power and Energy Society

General Meeting, and we are in the process of expanding it as a Transactions submission.

Unifying Obligations with Uncertainty: We created the mathematical framework in section 6.1 to present all of the objectives and constraints and their associated uncertainty in aggregate to the hydropower duty scheduler.

Visualize: As detailed in section 10.4.1, we incorporated the information distilled in the previous three items into a visually intuitive rendering. Operators and analysts can interactively explore this visualization using our tools.

Identify Operational Flexibility Shortfalls: We developed an algorithm to flag and characterize operational tight spots (section 7.2). The algorithm is trained on historical data from BPA and the Army Corps of Engineers, as well as feedback from the human duty scheduler. The resulting labeled set of flexibility failures may allow training, testing, and comparison of predictive flexibility metrics.

Classic Operating Problems: We showcased the strengths and weaknesses of this new operational flexibility metric in Section ?? by exploring several well known operational challenges.

Flexibility Metric Comparison: Section ?? compared the predictive power of our operational flexibility metric with other possibilities in the literature.

Quantify Flexibility in FCRPS: We estimated operational flexibility in FCRPS using historical time series (2007-2013) using data supplied by BPA’s short term planning group, as detailed in section ??.

11.2 Contributions

- Explicitly define “operational flexibility,” a desirable but previously vague commodity.
- Extend the vocabulary of hydro scheduling to describe the very short term scheduling problem.
- Extend and refine the deterministic idea of reserve.
- Emphasize that both load and generation in the modern power system can be controllable or not by grouping all exogenous resources as “uncontrollable real power.”
- Generate intuitive visual feedback about system flexibility for analyst and operator.
- Facilitate the integration of renewable energy sources with the grid.

- Gather constraints on and objectives for the Federal Columbia River Power System in one report.
- Invent time series based constraint formulation and algebra.
- Create reasonable constraint sets for very short term scheduling of Federal Columbia River Power System.
- Build framework for construction of arbitrary constraint sets on any system.
- Inform future algorithm development with insight about constraint and objective function formulation.
- Create open source software tools for analysis of arbitrary power system scheduling.

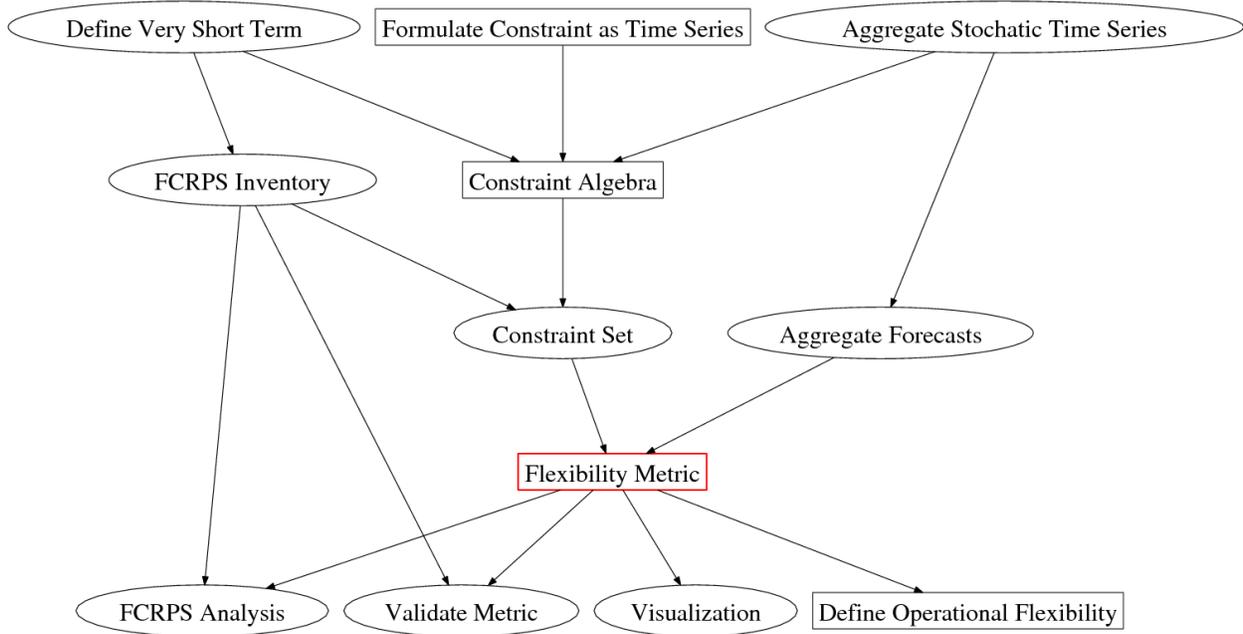


Figure 11.1: This flowchart shows how some key elements of the work fit together. The rectangles represent innovative ideas, while the elipses assemble known methods to generate interesting results.

11.3 Future Work

This research will enable interesting future work:

Compare with other metrics Compare performance of other potential metrics of operational flexibility to $f(t)$ using the validation protocol defined in section 7.

Constraint Sets: Define meaningful sets of constraints to answer other questions (*i.e.* model different control areas, ask different operational planning questions).

Objective Function: Write short and very short term optimization algorithms that use flexibility as the objective function.

Refine FCRPS analysis: Once BPA schedulers see the initial estimate in chapter ??, we assume we will wish to tune parameters and inclusion/exclusion of constraints to get the most operationally meaningful results.

Objective Function Comparison: Evaluate how the operational flexibility metric performs as an objective function when compared with minimizing generation cost and other alternatives consistent with FCRPS operation.

Big Data: This work utilizes the extensive datasets provided by Bonneville Power Administration and the Army Corps of Engineers. Though it's outside the scope of this dissertation, I would like to spend time finding patterns in these time series. I will apply the tools I have collected from machine learning courses here in the EE department; Don Percival's time series analysis course [62]; Jeff Leek's data analysis coursera course [44]; Duda, Hart and Stork's *Pattern Classification*[20]; Hastie, Tibshirani and Friedman's *Elements of Statistical Learning*[31]; and Nisbet and Elder's *Handbook of statistical analysis and data mining applications*[56].

Formulate Very Short Term Scheduling: This dissertation supplies constraints and an objective function for the very short term schedule optimization problem, but does not explicitly formulate it. Doing so is a natural next step. Integration with existing automated market settling and dispatch algorithms will likely take some work, as might wrestling with computational efficiency.

Allocate $f(t)$ to Individual Resources: The flexibility metric proposed in this dissertation describes a whole system. For flexibility to be valued and exchanged as an ancillary service, we must define the contribution of individual resources. The individual resource and system level operational flexibility metrics should be compatible; ideally aggregating the component resources using the algebra defined in section 6.1 should result in the system value.

Solution Space: Sets of constraints define a feasible solution space which can be mathematically characterized. A great deal of work has been done in diverse disciplines to understand the out-

put space of optimization problems[75]. This practice has even entered the unit commitment literature, including recently by Ostrowski, Anjos and Vannelli [59].

Computation Time: Speed up the computation of constraint sets and very short term optimization using these time-series constraint sets in minpower, GAMS or other frameworks. Reformulate problem to take advantage of solvers that have been tuned for OPF, and the optimization problems in other disciplines. Get this process to run fast enough to incorporate in real time planning decisions and dispatch algorithms.

11.4 Conclusion

Without a metric of operational flexibility, a power system may have more or less flexibility than assumed at any given moment. Demanding scenarios sometimes are absorbed without incident as operators mobilize resources to respond, and sometimes result in violated constraints (*e.g.* spilling the wrong amount of water over a dam and killing fish with high dissolved gas levels, curtailing wind, shedding load).

The metric formulated in this work extracts actionable real time operational flexibility conditions from stochastic system forecasts. Deterministic presentation, time series visualization, and constraint sets that are versatile and directly comparable, could all facilitate transparent and efficient very short term scheduling decisions in a complicated power system.

Part V

Appendices

Appendix A

Hydropower Research Foundation Fellowship

This work is made possible by the Hydropower Research Foundation and the U.S. Department of Energy. We are very grateful for the support, and excited about the work it has enabled.

A.1 About

“The Hydro Research Foundation, Inc. is leading the Hydro Fellowship Program that is designed to stimulate new student research and academic interest in research and careers in conventional or pumped storage hydropower. These Fellowships are designed to allow outstanding early-career researchers to facilitate research related to hydropower. Research undertaken by the Foundation and its Fellows seeks to advance knowledge about hydroelectric technology, including efficiency improvements and environmental mitigation. Through this program the Foundation is promoting educational opportunities and information development related to hydropower. Innovation, creativity and forward-thinking research are encouraged.”

A.2 Relevance

This work addresses four needs that motivated its funding, as detailed in the Hydropower Research Foundation 2012 Topic Areas of Interest:

- 25: Simulation and optimization models for operational improvements
- 38: Operational improvements to maximize ancillary benefits,
- 42: Improved methods for knowledge capture and transfer in hydropower workforce transitions,
- 33: Operational costs to hydro for supporting intermittent renewables.

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