THE INTERNATIONAL ENERGY AGENCY TECHNOLOGY COLLABORATION PROGRAMME ON HYDROPOWER

IEA Hydropower

VALUING FLEXIBILITY IN EVOLVING ELECTRICITY MARKETS:

Current Status and Future Outlook for Hydropower

IEA Hydro Technical Report

Annex IX

Valuing Hydropower Services – Phase II

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The IEA Technology Collaboration Programme On Hydropower

The IEA Technology Collaboration Programme on Hydropower (IEA Hydro) is a working group of International Energy Agency member countries and others that have a common interest in advancing hydropower worldwide. Current members of the IEA Hydro TCP are Australia, Brazil, China, EU, Finland, Japan, Norway, Switzerland, USA. Sarawak EB is a sponsor. Member governments either participate themselves, or designate an organization in their country to represent them on the Executive Committee (ExCo) and the working groups (Annexes), through which IEA Hydro's work is carried out. Some activities are collaborative ventures between the IA and other hydropower organizations.

Vision

Through the facilitation of worldwide recognition of hydropower as a well-established and socially desirable energy technology, advance the development of new hydropower and the modernization of existing hydropower

Mission

To encourage through awareness, knowledge, and support the sustainable use of water resources for the development and management of hydropower.

To accomplish its Mission, the Executive Committee has identified the following programme- based strategy to:

- Apply an interdisciplinary approach to the research needed to encourage the public acceptance of hydropower as a feasible, socially desirable form of renewable energy.
- Increase the current wealth of knowledge on a wide array of issues currently associated with hydropower.
- Explore areas of common interest among international organizations in the continued use of hydropower as a socially desirable energy resource.
- Bring a balanced view of hydropower as an environmentally desirable energy technology to the worldwide debate.
- Encourage technology development.

IEA Hydro is keen to promote its work programmes and to encourage increasing involvement of non-participating countries. All OECD and non-OECD countries are eligible to join. Information about membership and research activities can be found on the IEA Hydro website www.ieahydro.org

Summary

The rapid expansion of variable renewable energy (VRE) resources combined with retirements of thermal generation give rise to increasing needs for flexibility at transmission, distribution, and the individual resource levels in the power system. The fundamental challenges associated with VRE integration and corresponding power system flexibility needs are similar across the world. A number of different solutions are being developed to address these challenges, from infrastructure investments (e.g. in flexible generation, increased transmission, energy storage, and demand response) to enhanced algorithms for forecasting, planning and operations, and improved electricity market design. Hence, important lessons can and should be learned between countries and regions as part of the ongoing shift towards cleaner electricity systems with a lower carbon footprint and more variable resources.

In this report, we present a system-level review of how flexibility services are defined, procured, and valued in selected electricity markets, with a particular focus on the status and outlook for hydropower. We find that there is a wide range of solutions to address flexibility challenges in current power systems. Although the definitions of flexibility services are similar in the 14 systems reviewed in this report, substantial variations exist in terms of how these services are procured and remunerated. Challenges in many systems include a lack of appropriate remuneration or a clear price signal for some flexibility services, particularly in the shortest timescale, and limited incentives for long-term investments in flexible technologies like hydropower. Still, a common feature across systems is that hydropower plays an important role providing flexibility services across all timescales. This observation highlights the unique characteristics of hydropower in its ability to provide the full spectrum of flexibility needs to the system, from short-term stability services to long-term seasonal storage through management of hydro reservoirs. With the increasing penetration of VRE sources and corresponding retirements of traditional thermal generators, we expect that the value of hydropower and other flexible low-carbon resources will increase in the future. However, it is important that the services provided by these resources are fully remunerated for the values they provide to the electricity grid. The findings from this review may inform improved electricity market design and regulations for the future power grid.

This report is the second publication in a series by the IEA Hydropower TCP (Annex IX, Phase 2) on the valuation of hydropower services. The first publication, White paper #1 entitled “Flexible hydropower providing value to renewable energy integration” (Harby et al. 2019), discussed the role of hydropower in grid integration of VRE and emphasized that hydropower is unique in its ability to provide system flexibility across timescales.

1 Introduction

This report is the second publication in a series by the IEA Hydropower Technology Collaboration Programme (IEA Hydro) Annex IX, to encourage collaboration and knowledge sharing, raise awareness of the important role of hydropower in contemporary electricity system integration and to explore issues and solutions to fully realize the value of its contributions to electricity systems. The target audience is the electric power industry, the hydropower industry, regulators and other authorities, system operators, researchers, and other stakeholders with an interest in electricity markets, hydropower and other renewable energy sources.

The rapid expansion of variable renewable energy (VRE) around the world has led to new challenges and opportunities for planners and operators of power systems and electricity markets, and for the market participants operating within these complex systems. The key challenge of integrating VRE, such as wind and solar into the power grid, is to address the variability and uncertainty in these resources in the planning and operation of the power grid. In general, a more flexible power system is needed to achieve a cost-efficient integration of VRE. Towards this end, a number of different solutions are being developed, from infrastructure investments (e.g. in flexible generation, increased transmission, energy storage, and demand response) to enhanced algorithms for forecasting, planning and operations, as well as improved electricity market design.

Hydropower, as a clean and flexible generation resource, can clearly play an important role in meeting VRE integration challenges. The first IEA Hydro Annex IX white paper (Harby et al. 2019) discussed the role of hydropower in grid integration of VRE and concluded that hydropower is unique in its ability of provide system flexibility across the timescales, from very short-term operational decisions to long-term planning. This report delves deeper into flexibility services, including how these services are defined across different timescales, how flexibility is procured and compensated in different electricity markets across timescales, and the status and future outlook for hydropower in evolving power grids.

This report is organized as follows. First, we give a brief introduction to the fundamental flexibility needs in the power system and different mechanisms for procuring these services (Chapter 2). In Chapter 3, we summarize the findings from an international survey conducted to compare how flexibility services are managed across 14 different countries/regions. In Chapter 4, we present 7 case studies that provide perspectives on hydropower, VRE integration, and system flexibility from different geographical, temporal, and regulatory perspectives. Finally, in Chapter 5, we discuss key observations from survey and case studies, followed by concluding remarks in Chapter 6. Detailed survey responses are provided in Appendix A, and a list of terminology in Appendix B.

2 System Flexibility Needs

The power system is dependent on flexibility across different timescales in order to maintain overall reliability by balancing supply and demand and keeping frequency and voltage within their limits in a cost-effective manner. Table 1 gives a brief overview of flexibility services, as defined by IEA (2018). The shortest timescales focus on system stability and frequency control. The intermediate timescales focus on dispatch and scheduling processes to meet current and projected electricity demand across minutes, hours, and days. The long-term time horizon addresses supply adequacy over months to years through coordinated long-term scheduling processes and ultimately investments and capacity planning. The different timescales are closely connected, as the ability to ensure stability in the very short-term ultimately depends on scheduling, planning and adequacy decisions that are made in the medium and long-term. Increasing VRE levels impose more uncertainty and variability in the system, which has implications across timescales, from short-term stability to long-term resource adequacy.

Table 1 Flexibility services across different timescales (Source: IEA 2018).

Flexibility type	Short-term			Medium term	Long-term	
Time scale	**Sub-seconds to seconds**	**Seconds to minutes**	**Minutes to hours**	**Hours to days**	**Days to months**	**Months to years**
Issue	Ensure system stability	Short term frequency control	More fluctuations in the supply / demand balance	Determining operation schedule in hour- and day-ahead	Longer periods of VRE surplus or deficit	Seasonal and inter-annual availability of VRE
Relevance for system operation and planning	Dynamic stability: inertia response, voltage and frequency	Primary and secondary frequency response	Balancing real time market (power)	Day ahead and intraday balancing of supply and demand (energy)	Scheduling adequacy (energy over longer durations)	Hydro-thermal coordination, adequacy, power system planning (energy over very long durations)

Flexibility services can also be categorized by the specific area supported within the power grid. The IEA Technology Collaboration Programme on Smart Grids (ISGAN – International Smart Grids Action Network) has proposed a combined method for categorizing services that allows for the categorization of both specific services and the general area of grid flexibility support provided. ISGAN defines four (4) categories of flexibility services (Hillberg et al. 2019):

1. **Flexibility for Power** – Short-term equilibrium between power supply and power demand, a system wide requirement for maintaining the frequency stability (examples include fast frequency response, inertia, and demand side response).
2. **Flexibility for Energy** - Medium to long-term equilibrium between energy supply and energy demand, a system wide requirement for demand scenarios over time (examples include energy storage and generation, optimization).
3. **Flexibility for Transfer Capacity** - Short to medium-term ability to transfer power between supply and demand, where local or regional limitations may cause bottlenecks resulting in

congestion costs (examples include network topology control, location of generation, storage, and demand response capable of responding to grid events).

4. **Flexibility for Voltage** - Short-term ability to keep the bus voltages within predefined limits, a local and regional requirement (examples include coordinated reactive power and voltage control, automatic voltage regulators, flexible AC transmission system (FACTS)).

Figure 1 presents this categorization of flexibility and correlates the four different types of flexibility with the timescales presented in Table 1.

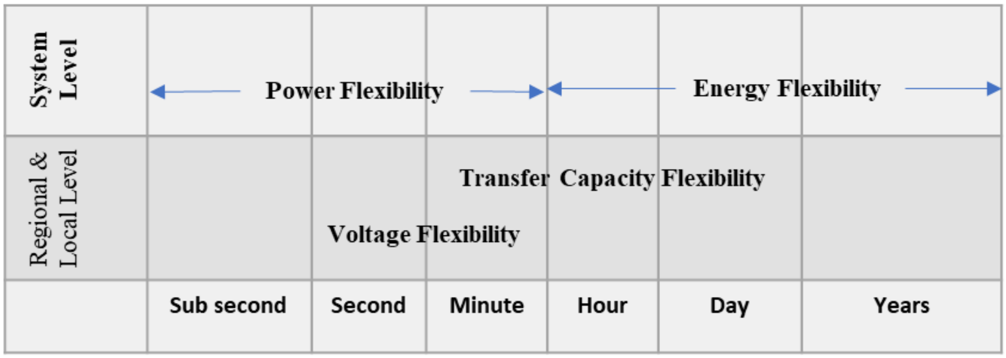

Figure 1. Interrelation of flexibility needs in perspectives of space and time (based on Hillberg et al. 2019)

In general, system flexibility is provided by electricity generation technologies, the transmission network, energy storage, and demand resources, but there are a variety of solutions for how flexibility is procured across different timescales. At the same time, forecasting methods, optimization algorithms, operational practices, and market rules also contribute to determine the amount of flexibility that is available in the power system. Hydropower plants provide short-term power and voltage flexibility through its ability to respond rapidly to conditions in the grid. Moreover, hydropower provides long-term energy flexibility though large-scale energy storage in hydro reservoirs. A detailed discussion of different solutions for how hydropower technologies can contribute to future flexibility needs in European electricity markets is provided in (XFLEX 2020a).

Chapter 3 presents a survey of how system flexibility is addressed in current power systems and electricity markets.

3 Survey of Flexibility Services in Current Systems

Understanding the flexibility needs of the grid allows for the identification of suitable solutions as well as the resources needed to provide the flexibility services. In general, the most suitable flexibility solutions depend on the system needs, but must also consider situational restrictions and regulations, capabilities and availability of power system equipment, and commercial and environmental aspects (Hillberg et al. 2019). IEA Hydro Annex IX developed a survey to gain an understanding of system flexibility services, how these services are procured, and the potential physical requirements and monetary value of the flexibility services in different markets around the world. IEA Hydro Annex IX conducted a survey of 14 countries/regions to better understand the various flexibility services used across timescales, how these services are procured, and to what extent hydropower resources contribute to provide these services. The survey was comprised of six (6) categories of information, as listed below, with responses to be provided for each of the timescales in Table 1. We also requested information about capacity and energy mix for the countries/regions participating in the survey.

Survey requests for information:

1) **Please provide a brief overview of relevant grid flexibility services and products.**
2) **How are these flexibility services currently procured?**
3) **Are these services compensated?**
4) **Does hydropower currently provide these services to the power grid?**
5) **How much is normally procured of this service?**
6) **List important current and future developments related to these flexibility services.**

This chapter summarizes the key results from the flexibility survey, based on the survey responses of the 14 participating countries/regions (full survey responses are included in Appendix A). This is not a scientific survey with a statistically significant sample, and the survey results and comparisons are only meant to give an overview of how flexibility services are handled in the respective systems. The results should be interpreted accordingly.

3.1 Energy and Capacity Mix in Participating Systems

The resource portfolio in a system has an impact on what flexibility services are needed, how these services are provided at the different timescales, and the technologies that provide the respective services. Figure 2 and Figure 3 summarize the energy and capacity mix of the 14 systems that participated in the survey. The penetration levels of renewable electricity generation are illustrated in Figure 4. The amount of hydropower generation varies from a modest amount, around 4% of generation in Germany and Czech Republic, to more than 90% of generation in Hydro Québec and Norway. The combined penetration of wind and solar is negligible in Colombia and as high as 28% in Germany. These numbers compare to a hydropower electricity share of 16% and a total renewable electricity share of 26% at the global level in 2018. In countries where thermal generation are being replaced with VRE, the flexibility services available through these thermal plants will need to be replaced as well. For example, Germany, based on the survey response, is planning to retire its nuclear plants by 2022 and its coal plants by 2038. These two thermal technologies currently comprise 42% of Germany's total electricity generation, which will be replaced by renewables including VRE.

Note that the ability of an individual generator to provide the flexibility services when needed also will depend on the specific state of the generator (e.g. operating, reserve provision, warm start, cold start, and possibly black start). At the same time, the ability to offer flexibility services over longer durations also involves understanding the resource planning and policy decisions within the given system.

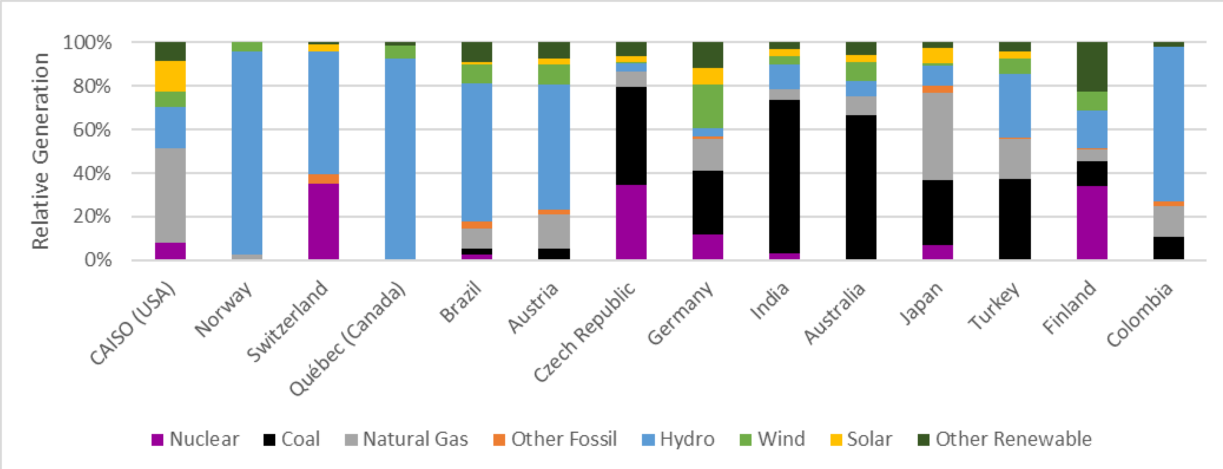

Figure 2. Generating resource mix in 2019 for participating systems (Source: Survey inputs, IEA Data and Statistics (https://www.iea.org/data-and-statistics), EIA https://www.eia.gov/international/overview/world).

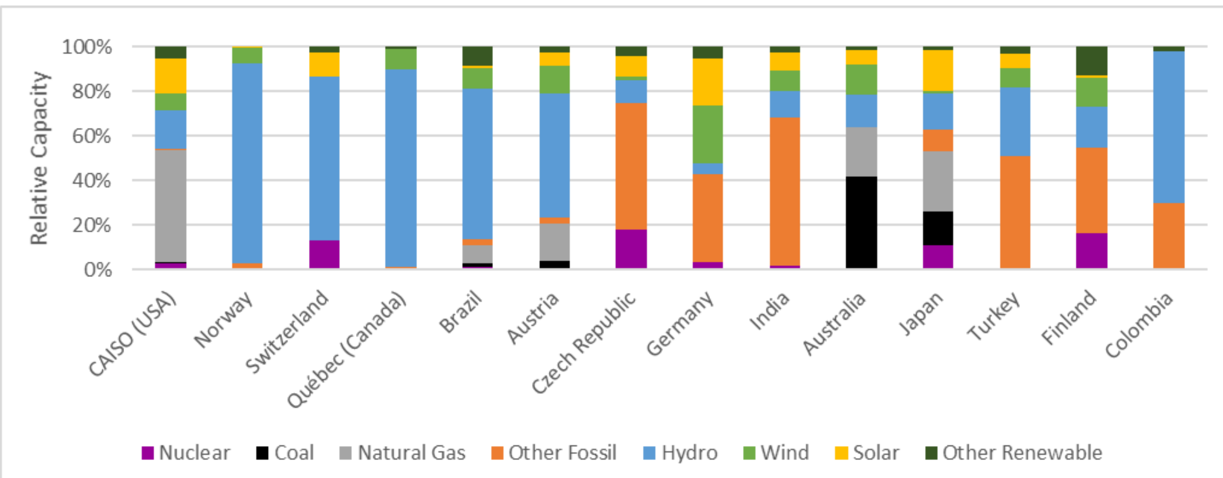

Figure 3. Capacity mix in 2019 for participating systems. Note that technology breakdown differs between countries (i.e. natural gas and coal included in other fossils for Czech Republic, Germany, India, Turkey, Finland, and Colombia). (Source: Survey inputs, IEA Data and Statistics (https://www.iea.org/data-and-statistics), EIA https://www.eia.gov/international/overview/world).

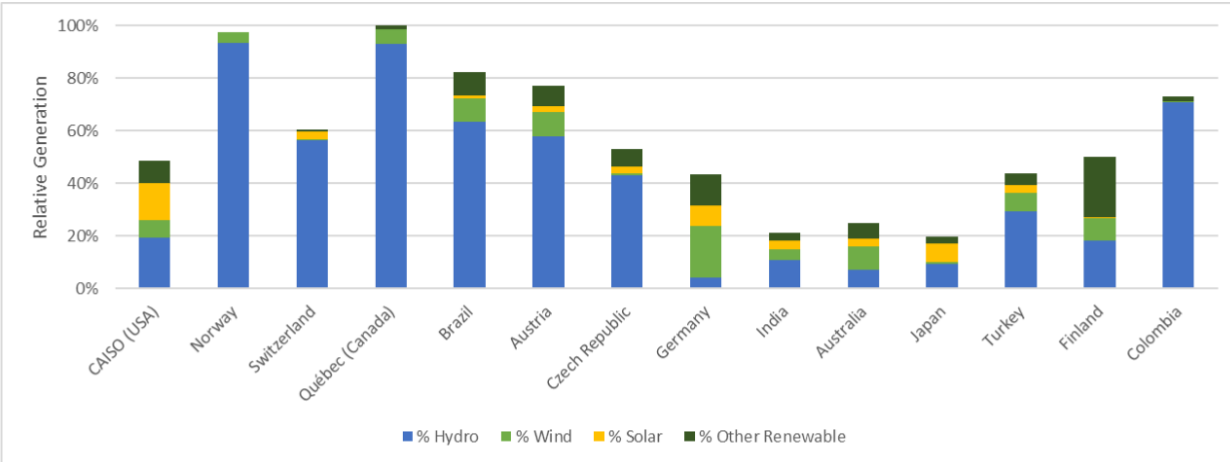

Figure 4. Renewable electricity generation in countries/regions participating in survey. (Source: Survey inputs, IEA Data and Statistics (https://www.iea.org/data-and-statistics), EIA https://www.eia.gov/international/overview/world).

3.2 Survey Summary

The following sections present a summary of the survey results for each of the six survey areas. We present the results in the context of the timescales for flexibility services, as illustrated in Table 1. More detailed survey responses are provided in Appendix A.

3.2.1 Flexibility Services

Table 2 summarizes the different types of flexibility services defined within each timescale across the 14 systems, as reported in the survey responses. Note that most timescales correspond to multiple types of flexibility services. For instance, the shortest timescale (subsecond- seconds) include 6 different service types. Figure 5 illustrates the distribution of specific flexibility services by each timescale. Some services span multiple timescales. For instance, frequency support (which includes several specific sub-categories) is the most prevalent service offered across multiple timescales. Energy is the second most prevalent flexibility service offered.

Note that there is a substantial variation in the terms used for flexibility services in different regions/countries. Table 2 contains general types of flexibility services. Some of these specific services have been consolidated for presentation. For example, the frequency support services listed includes all frequency related services including primary and secondary frequency response (e.g. fast frequency reserve (FFR), frequency containment reserve (FCR), and frequency response reserves (FRR)). Figure 5 presents the number of specific flexibility services, as defined by the responding countries/regions, within and across timescales. For example, within the sub-second to second timescale, a total of five specific frequency support services were reported by survey respondents. The full list of specific flexibility services offered within each country/region, as reported in the survey responses, is included in Appendix A.

Table 2 Summary of flexibility service types by timescale

TIMESCALE	SERVICES	
Sub-second - seconds	1) Inertia 2) Reactive power 3) Voltage control	4) Frequency support 5) Spinning reserve 6) Special protection Systems
Seconds - minutes	1) Frequency support	2) Last minute dispatch
Minutes - hours	1) Energy 2) Frequency support	3) Black start 4) Power unit dispatch
Hours – days	1) Energy 2) Ancillary services	3) Long term reserves 4) Demand response
Days-months; Months - years	1) Resource adequacy	2) Storage

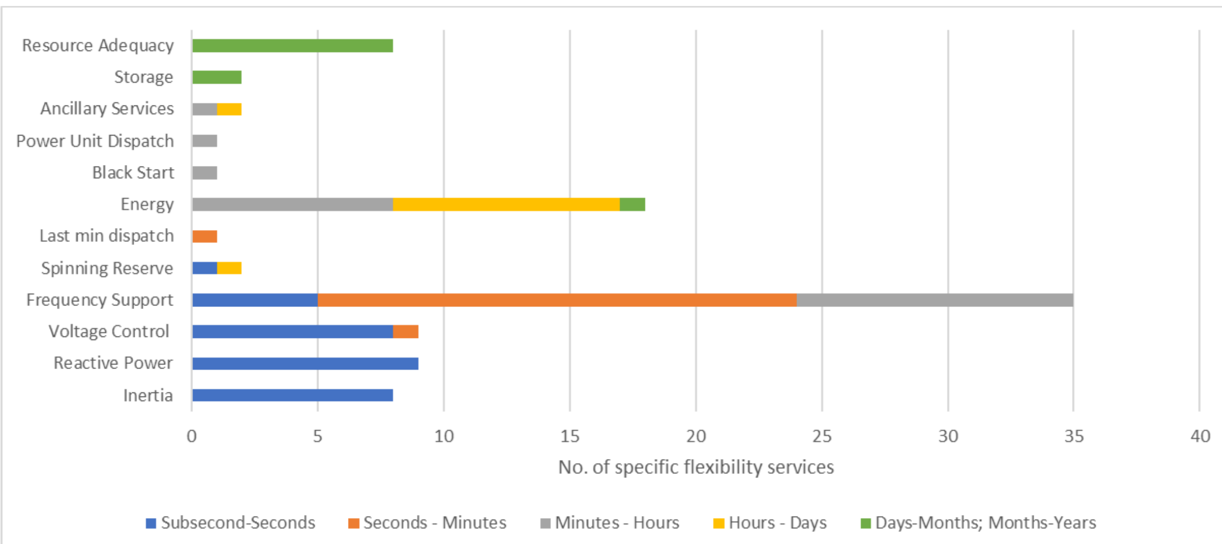

Figure 5. Number of specific flexibility services reported in survey responses grouped by general service type and timescale.

3.2.2 Procurement of Flexibility Services

The respondents were requested to describe which procurement methods are used to obtain the different flexibility services, i.e. broken into three categories: market-based (e.g. auction-based procurement), bilateral contracts (e.g. between system operator and individual generators to provide a service for a certain time period), or interconnection agreements (e.g. provision of a service is part of the agreement signed before connecting an asset to the system). Figure 6 summarizes how flexibility services are procured within each timescale. Based on the responses, during the short timescales (sub-second to second and seconds to minutes), bilateral contracts represent the predominant procurement mechanism. In contrast, market-based procurement represents the more prevalently used procurement method during the medium- and long-term timescales.

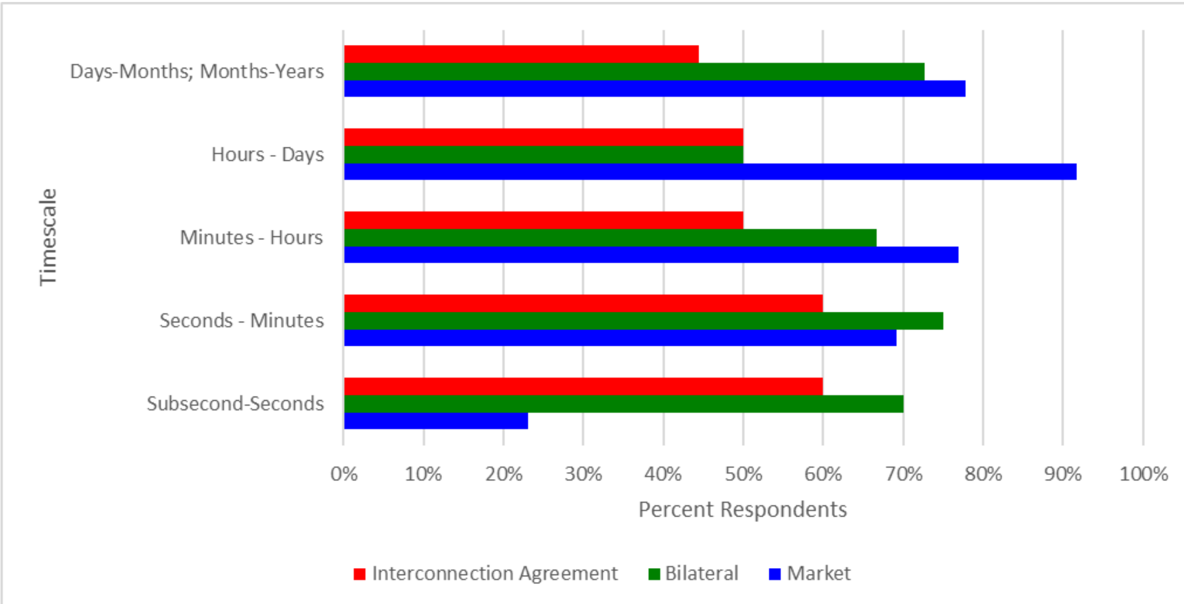

Figure 6. Summary of procurement methods by timescale, as reported by survey responses. Note that the sum of the percentages within each timescale is greater than 100% because services may be procured through more than one procurement mechanism. Also, data was not complete for all of the 14 respondents for each of the procurement methods. Individual responses are included in Appendix A.

3.2.3 Compensated Services

The survey respondents were asked if the flexibility services are compensated through market structures, bilateral contracts, and/or interconnection agreements across different timescales. Although interconnection agreements usually just define the specific requirements and specifications for physically interconnecting an energy asset to the grid, these may also contain a service component that is either compensated for directly or indirectly contingent on providing the service to the interconnection and, thus, are included as a potential source of compensation.

Figure 7 shows the breakdown of compensation mechanisms by timescale. Overall, markets and bilateral contracts are the most common compensation mechanisms. More specifically for each timescale:

- Sub-second to seconds: most of the services are compensated through either bilateral contracts or interconnection agreements.
- Seconds-to minutes: the procurement mechanisms shift more towards market-based.
- Minutes to hours: the procurement mechanisms are evenly distributed among markets, bilateral contracts, and interconnection agreements.
- Hours-to-days: mostly procured through market mechanisms.
- Days-months, months-years: most often procured through bilateral contracts.

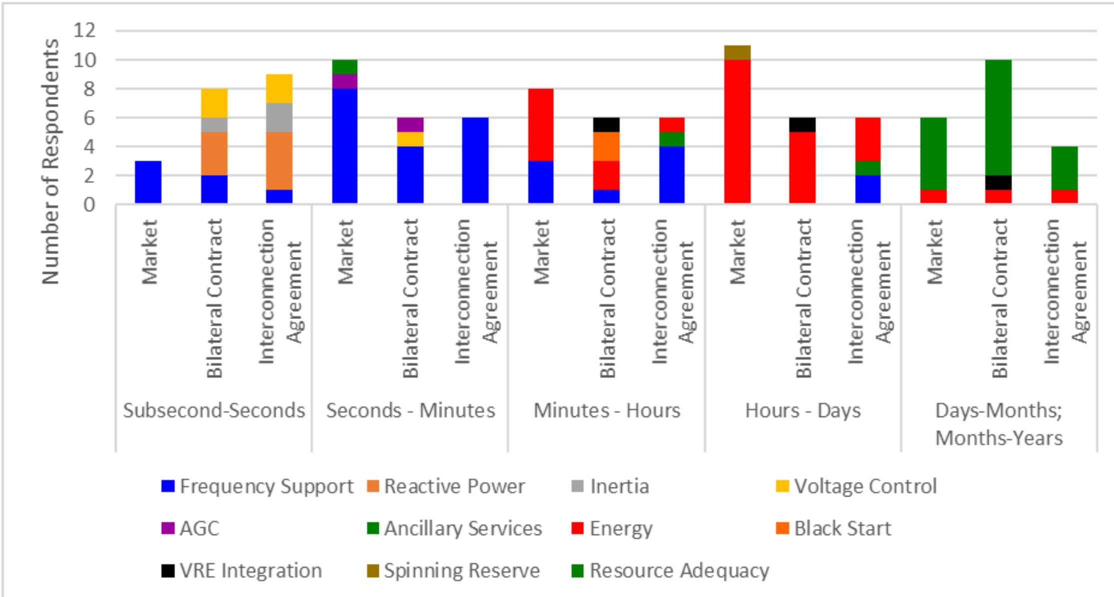

Figure 7. Overview of compensated flexibility services. Note that not all countries/regions provided a response for each timescale and that the number of responses may exceed the number of respondents as a services may be offered through more than one procurement mechanism. Also, the total for a specific service within a timescale may vary from the results presented in Figure 5 because there are cases where a service may be compensated through more than one mechanism. The detailed responses are presented in Appendix A.

3.2.4 Hydropower Contribution to Flexibility Services

Survey respondents were asked whether hydropower currently provides flexibility services to the power grid. Figure 8 summarizes the responses to this question and shows that hydropower plays a substantial role in providing flexibility services across all timescales. Note that the survey question did not request which specific flexibility services that hydropower provides, only if hydropower was providing some or all of the services at the respective timescales.

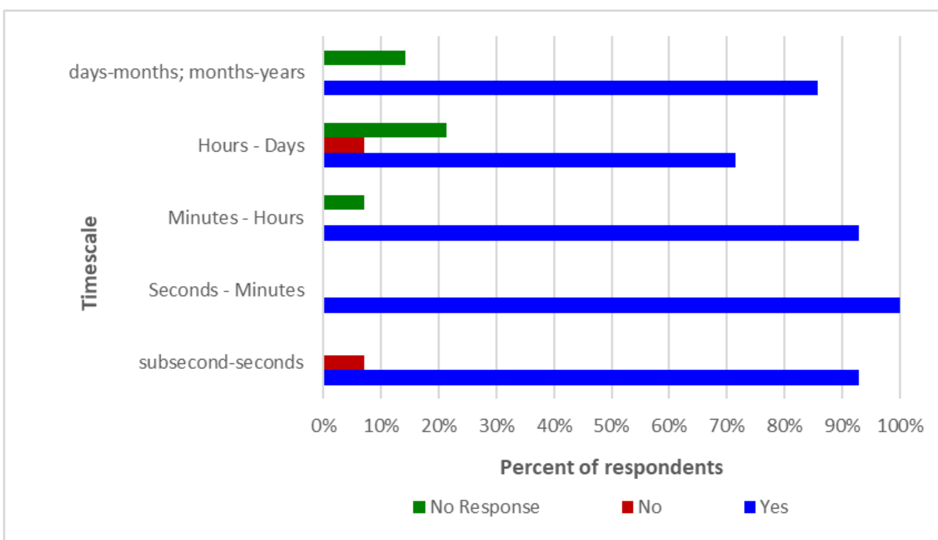

Figure 8. Responses to the question of whether hydropower provides flexibility services across timescales. Percent of respondents answering yes, no, or no response. Detailed responses are included in Appendix A.

3.2.5 Market Size and Price Description

The market size and market prices for flexibility services vary significantly across systems and within each timescale. In some cases, this variation may be attributed to system size and market maturity (e.g. for how long the market has been in place). At the same time, a specific market structure may or may not exist for the different flexibility services within a given timescale. Based on survey responses, we evaluated the market within each timescale by total size.

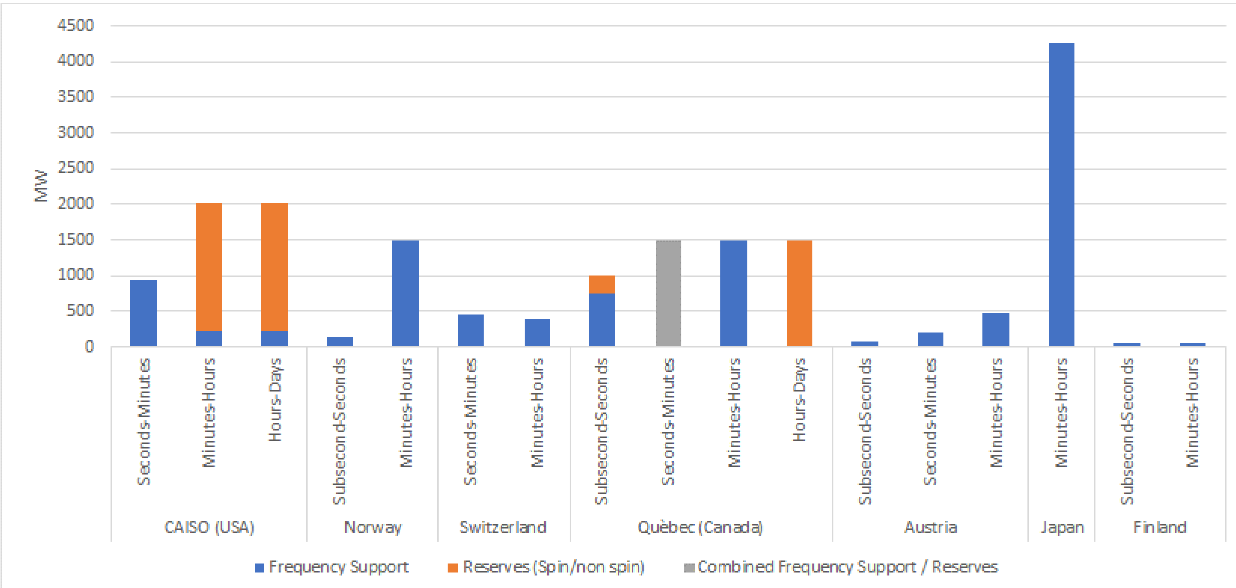

Figure 9 and Figure 10 summarizes the results for non-energy and energy services, respectively. If a country is not listed or has no data presented, this indicates that no response was received. If a country responded but did not provide data for a specific timescale, that indicates that there is no market within that timescale. Table 3 presents a brief summary of the minimum and maximum prices for the identified flexibility services. Since different services definitions are used among the countries/regions, it is hard to compare market size and price results directly. More detailed responses from the individual markets are provided in Appendix A.

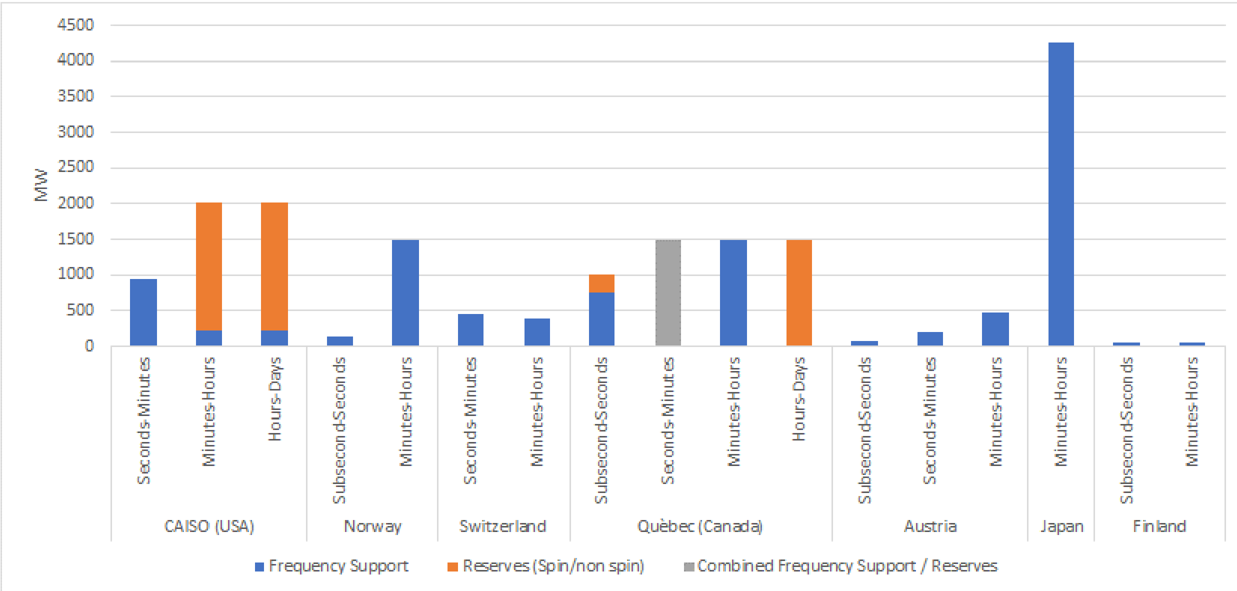

Figure 9. Market size by timescale for non-energy services. Systems and timescales with no responses are excluded. The detailed responses are presented in Appendix A.

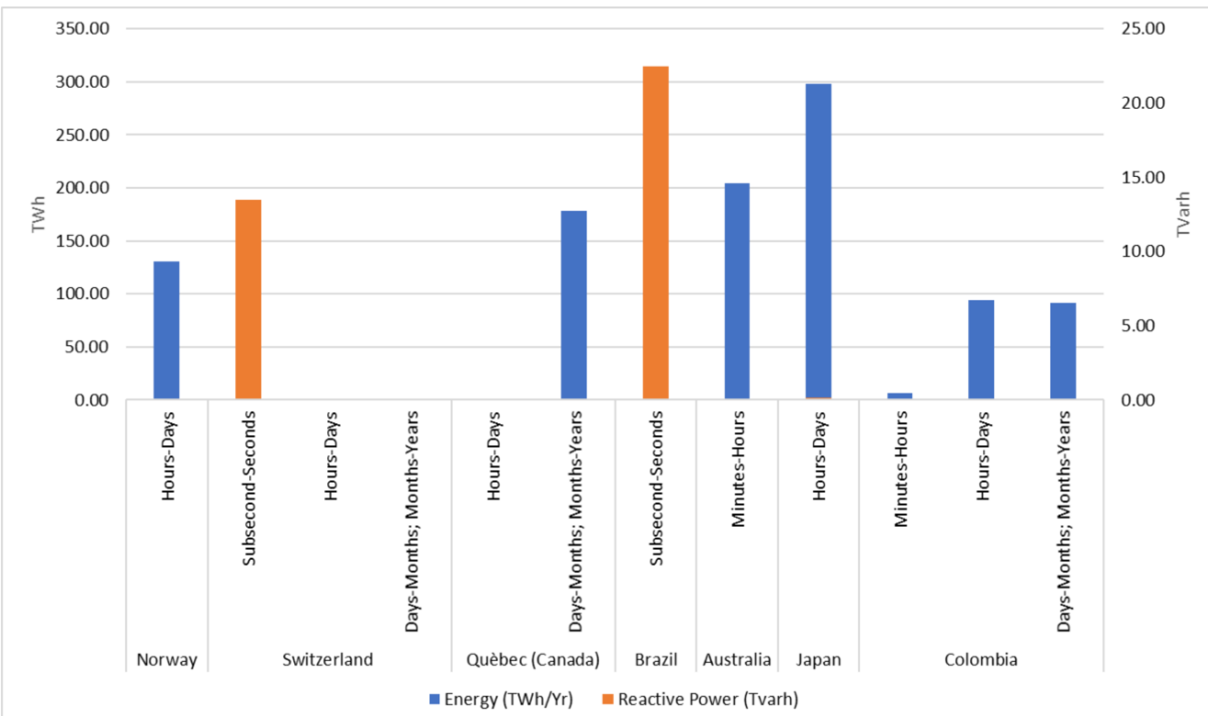

Figure 10. Market size by timescale for energy services. Systems and timescales with no responses are excluded. The detailed responses are presented in Appendix A.

Table 3 Summary of market prices for flexibility services. Min, max, and mean values across countries/regions that provided market price data. Note that prices were estimated based on survey inputs, accounting for exchange rates and differences in the format of responses.

	Min	Max	Mean

Energy	$15.10/MWh	$198.00/MWh	$59.91/MWh
Frequency Response	$3.74/MW-h	$62.5/MW-h	$26.0/MW-h
Spinning Reserve	$0.47/MW-h	$17.98/MW-h	$11.29/MW-h
Non-Spinning Reserve	$3.79/MW-h	$3.79/MW-h	$3.79/MW-h
Reactive Power	$1.80/MVarh	$3.54/MVarh	$2.67/ MVarh

3.2.6 Trends and Future Developments

Flexibility services requirements, how these services are procured, and the availability of resources to provide the services change over time based on technology characteristics, generation mix, and policy, and regulatory environments. Table 4 presents a high-level description of the planned developments, both technical and from a policy perspective, across timescales, as reported in the survey responses. There are trends and developments occurring across all timescales, but with the highest number of reported changes happening at the shortest timescales. More detailed descriptions of these trends and development are presented in the survey response data in Appendix A.

Table 4 Summary of future trends and developments.

TIMESCALE	DEVELOPMENT AND TRENDS
Subsecond-seconds	8 of 12 respondents are planning developments within this timescale. Focus is on flexibility service pricing, market developments/improvements, and planning for changes in generation mix.
Seconds - Minutes	7 of 12 respondents are planning developments within this timescale. Developments include market design, implementation, and modification, adding additional services, technology developments, and changes in generation mix.
Minutes - Hours	7 of 12 respondents are planning developments within this timescale. Developments include technology improvements, changes in generation mix, market development and enhancements.
Hours - Days	3 of 12 respondents are planning developments within this timescale. New market products, market structures for offering products, changes in generation mix.
Days-Months; Months-Years	5 of 12 respondents are planning developments within this timescale. System and technology enhancements to support resource adequacy, refinement of market structures, and development of new markets.

4 International Case Studies of Flexibility Services

In this chapter we take a closer look at some of the ongoing power system flexibility challenges and solutions in different parts of the world, through brief case studies from seven different countries. These case studies provide different perspectives on VRE integration, flexibility services, and the role of hydropower. The first two case studies, from Switzerland and Norway, focus on how short-term balancing and operating reserve services are managed through coordination within Europe. Next, case studies from Canada (Hydro Québec), the United States (California ISO), and Brazil discuss flexibility across a wider range of timescales, including long-term planning, and illustrate very different contractual and market arrangements to maintain power system reliability in the long run. Finally, case studies from Australia and Japan focus on the need for long-duration storage and pumped storage hydro (PSH) in systems with increasing VRE shares, and the importance of adequately compensating these resources.

4.1 SWITZERLAND: Coordination of Flexibility Services with Continental Europe

Switzerland is part of the Continental European (CE) Synchronous Area (SA) interconnected grid and is connected to the four neighbouring countries (Austria, France, Germany, and Italy) through 41 transmission lines. In accordance with Article 22 of the Electricity Supply Ordinance, Swissgrid (the Swiss local system operator) has been purchasing ancillary services since Jan 1st 2009 in a transparent, non-discriminatory and market-based procedure (Swissgrid 2020 a,b). The invitations to tender (i.e. submit bids and offers) take place daily, weekly, or monthly, depending on the market product, in accordance with the technical specifications of the European Network of Transmission System Operators for Electricity (ENTSO-E).

A common European balancing market was established by the European Commission in 2017 (EC 2017a), to facilitate the sharing of resources used by the TSO of each country by fostering effective competition, non-discrimination, transparency and effective integration of new participants (ENTSO-E 2018a,b). This international coordination specifies the regulations for provision of ancillary services, especially for frequency control to ensure secure operation of the electricity grid at a constant frequency of 50 Hz. This allows the power system to be more secure and efficient.

The result of this framework for balancing the European power system is a multi-stage control procedure as illustrated in Figure 11. Each control procedure, as briefly outlined below, is coordinated by dedicated international platforms for the corresponding market products (EC 2017b). The framework is currently being implemented across large parts of Europe.

- Frequency Containment Reserve (FCR) requires a fully operating response to the power system within 30s (primary frequency control). The procurement of FCR required for Switzerland is realized by a combined auction between Belgium, Denmark, Germany, France, Netherlands, Austria, and Switzerland. This process is called "FCR Cooperation" and procures about half of the FCR in CE SA (ENTSO-E 2020). In the coming years, this cooperation should increasingly include more countries. Switzerland provides approximately 70 MW each year, out of 1473 MW provided by the FCR cooperation, with a frequency deviation of ±200 mHz.
- Frequency Restoration Reserve (FRR) is actuated to restore the system frequency to its set point value (i.e. nominal value of 50Hz) and to restore the balance between the active power generation and demand within the load frequency control (LFC) area. A distinction is drawn between FRR with automatic activation (aFRR) and with manual activation (mFRR). aFRR, which formally corresponds to secondary frequency control, is automatically actuated in the connected power

stations by the central grid controller after a few seconds and is typically completed within a maximum time of 5 minutes to restore the system frequency back to its set point value and to keep the power interchange program among LFC areas. In CE SA, the aFRR service has a standard product, to be traded in the pan-European platform PICASSO (Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation) by 2021 for the exchange of balancing energy from aFRR. Switzerland is currently an observer and not an official member of the platform and participates to provide FRR up to approximately ±400 MW. In contrast, mFRR is activated by individual TSO instructions and requires a full activation time of less than 15 minutes. By 2021, mFRR will have a standard product definition, to be exchanged in the pan-European platform MARI (Manually Activated Reserves Initiative) for the exchange of balancing energy from mFRR.

- Replacement Reserve (RR) progressively replaces the activated FRR and/or supports the FRR control process with an activation time of less than 30 minutes. RR has a standard product traded in the pan-European platform TERRE (Trans-European Replacement Reserves Exchange) for the exchange of balancing energy from RR.

Within this control framework, the implementation of a European platform for imbalance netting (International Grid Control Cooperation, IGCC) was established in 2019 to coordinate the activation of aFRR between TSOs, and avoid the simultaneous counter-activation of different participating and adjacent LFC areas via imbalance netting power exchange.

To ensure adequate harmonization, both, standardized technical requirements and common market rules among all participating TSOs are essential. Therefore, the aforementioned platforms for market-based exchange of reserves and balancing energy are characterized by standardized definitions of products (ENTSO-E 2018) for the aFRR, mFRR and RR balancing services.

In this context, hydropower is already a key-player in providing ancillary services thanks to the flexibility from generating and consuming (i.e. in PSH plants) active power. However, the decarbonization process and the increasing share of VRE generation are progressively challenging power system assets and system stability by requiring greater availability and provision of the ancillary services to assure the continuous balance between supply and demand.

In 2018, Switzerland's electricity generation amounted to 67 TWh and, in the same year, 62TWh was consumed in Switzerland, while ±30TWh was imported/exported across neighbouring countries in Europe. 57% of the total electricity generation in Switzerland was supplied by hydropower which, therefore, has a major role in the national electricity production. This is also reflected in the ancillary services for frequency regulation provided by Switzerland across the entire CE SA interconnected grid, which are almost entirely provided by hydropower. In particular, reservoir and PSH power are essential in the provision of FCR, aFRR, mFRR and RR services to balance the European power system. Fast dynamics combined with flexible and reliable operations are the main challenges for hydropower's contribution to the ancillary services markets. These system demands require that the hydroelectric units operate in off-design conditions, and increase the number of transitions, such as start-ups and shut-downs, and regulating movements by leading to increasing loads and mechanical stresses impacting the lifetime of the components. As a consequence, maintenance of the hydroelectric units may be required more frequently, by causing shortfalls for the operators in terms of increasing costs for maintenance and loss in revenue due to the unavailability of the hydroelectric unit for energy production. These disadvantages highlight the need of adequate remuneration levels in the balancing markets to incentivize and motivate the participation of the hydropower sector. However, the technical challenges can be overcome by enhancing existing hydroelectric technologies and by improving the predictive maintenance of the power plants to strengthen the market participation of hydropower and its contribution to the stability of the future power system (XFLEX HYDRO 2020b).

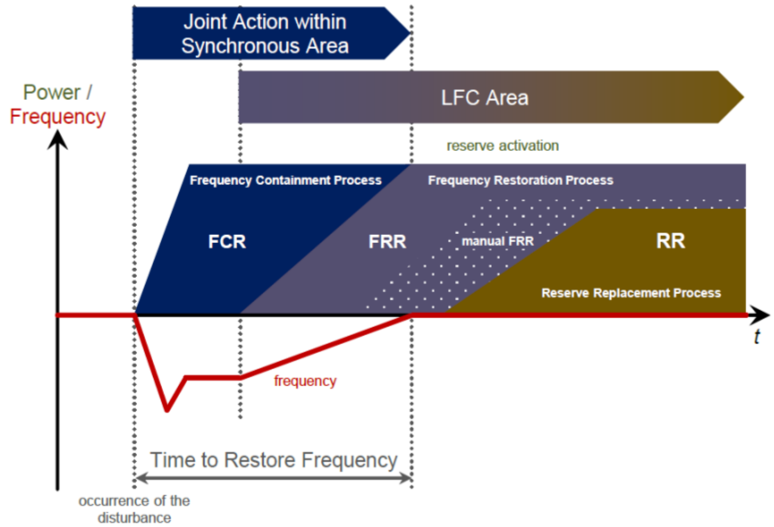

Figure 11. Time domain hierarchy of the load-frequency control process (ENTSO-E 2018b)

4.2 NORWAY: Large-scale Hydropower for Balancing Wind and Solar Power in Northern Europe

Background

Hydropower provides around 90% of the total power supply in Norway, and most of the plants are connected to large hydro reservoirs, many of them with seasonal storage capacities. This makes the Norwegian power supply very flexible both with respect to short-term and long-term balancing capability. As more and more wind and solar PV are installed in Norway and the neighboring countries (Figure 12), the need for flexibility from the existing hydropower plants is increasing. Moreover, HVDC interconnectors to continental Europe and UK enhances the value of hydropower flexibility. In turn, this leads to more opportunities for upgrading plant power capacities and building new pumping capacity between existing reservoirs (Graabak et al. 2019).

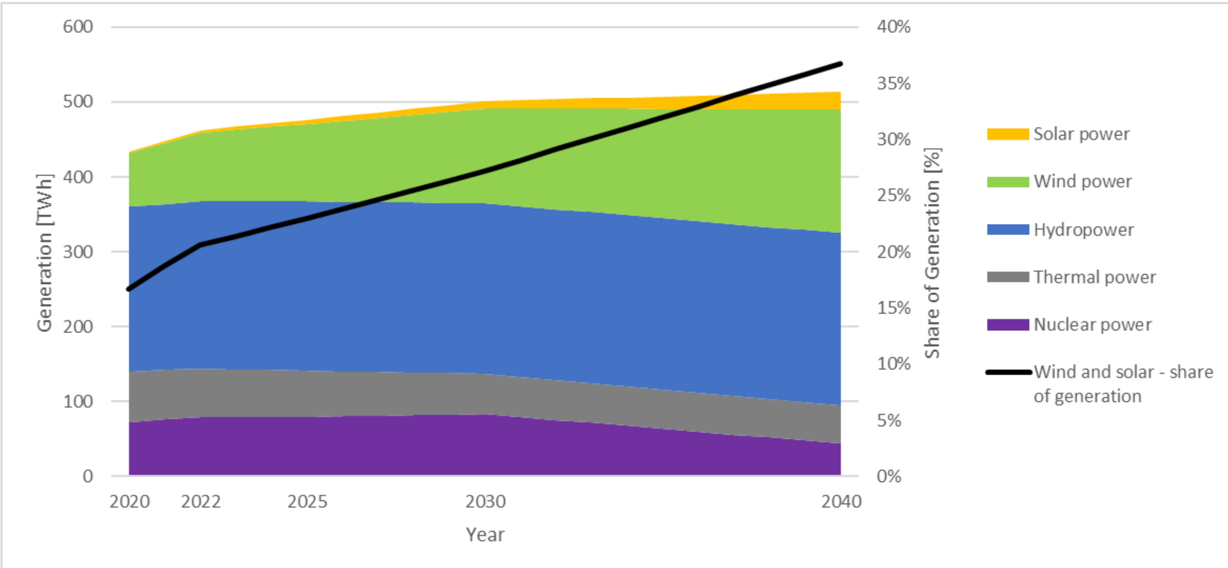

Figure 12. Projected power generation different resources in the Nordic countries (i.e. Norway, Sweden, Denmark, and Finland, but excluding Iceland) (Based on data from: NVE 2020).

Operating reserve markets in the Nordic area

To handle imbalances in the Nordic power system, operating reserves are procured through different markets. Four types of reserve products are used by Statnett - the Norwegian TSO (Statnett 2019), similar to the ENTSO-E definitions in Figure 11. FCR is divided into reserves for normal operations (FCR-N) and reserves for disturbances (FCR-D). This reserve product is procured through a weekly and a daily market. The maximum activation time for aFRR is two minutes. Today's reserve markets are dominated by power producers, but reserves can also be provided by the demand side. The Nordic countries collaborate to decide on the required volumes and distribution between countries, but the reserves are secured through national markets. A common Nordic market for aFRR is planned to become operational in 2022 and a platform for a European market for exchange of aFRR is expected to be in operation by 2024. The maximum activation time of mFRR is 15 minutes. Through the Nordic collaboration the TSO is required to procure 1200 MW mFRR, and it procures an additional 500 MW to handle regional differences within Norway. This capacity is procured and activated through a common Nordic market (RKM). Finally, Fast Frequency Reserves (FFR) are reserves that are activated quickly (1 second) when larger faults occur in the power system. This reserve is necessary to ensure system stability and is a result of an increasing number of hours with limited rotating mass connected to the grid. Statnett carried out a demonstration project for FFR in 2020 that is being continued in 2021. This Norwegian demo-market for FFR is based on two products: one seasonal product to cover the need during night and on the weekends, and a flexible, short-term product ordered on-demand. FFR is closely related to the need for inertia in the system.

Balancing and interconnectors

Historically, HVDC interconnectors from Norway (Figure 13) have been used primarily for spot market trade. With increasing wind and solar PV integration in Europe, it can be beneficial to also use these interconnectors for different balancing products and reserve provision (Gebrekiros 2015). For the latest expansion of the HVDC cable between Norway and Denmark (Skagerrak 4), 110 MW out of 700 MW capacity was allocated for reserve power, in order to make more of the Norwegian hydropower available for balancing of uncertain wind power generation in Denmark. Previous research has shown that it is possible to improve the utilization of interconnectors even more by opening for dynamic allocation of reserve capacity on the cables (Hjelmeland et al. 2019).

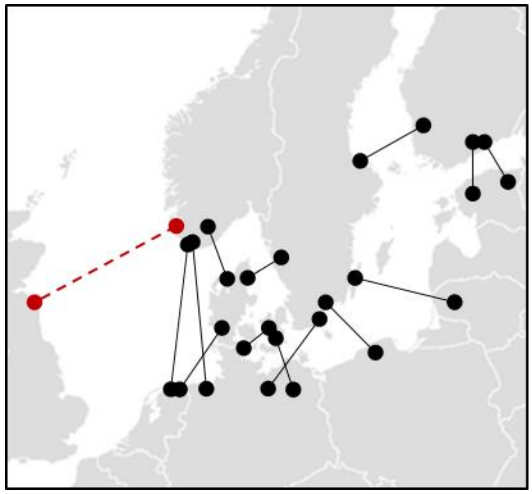

Figure 13. Overview of HVDC connectors in operation (black) and under construction (red, dotted) to/from the Nordic area (data from ENTSO-E. Map from Wikimedia[1]).

Challenges

With new interconnectors to continental Europe and the UK, new opportunities for Norwegian hydropower arise as it can provide energy and balancing services in three different synchronous systems. Within each of these systems, there are several market products available. The spectrum of market products provide access to additional revenue streams for Norwegian hydropower. At the same time, operating optimally within such a complex market system is challenging due to the number of bidding options in the short term, which must be weighed against the future value of stored water in the long term. However, the increased market harmonization across Europe can make it easier to optimize hydropower production in this complex system (Håberg and Doorman 2019), so that the hydropower flexibility is utilized in a way that benefits the European power system and contributes to keeping balancing costs of wind and PV at acceptable levels. Another important challenge for hydropower in Norway is to meet environmental restrictions. Many power plants need to renew the terms of license, and it is expected that power plants discharging into salmon rivers may not be allowed to operate with rapid water flow changes. This will limit their ability to regulate power generation for short-term needs in the power grid. Hydropower plants with outlets in reservoirs, lakes and the sea will still be able to operate with high flexibility.

4.3 CANADA: Flexibility Requirements and Services in Hydro Québec

Flexibility Requirements

Québec's load has had a strong correlation with winter temperatures for decades, due to the extensive development of electric heating in households. In 2019, peak power demand in Québec reached a maximum of 36159 MW (Hydro Québec 2020). The load in the Québec system in 2019 is shown in Figure

[1] https://commons.wikimedia.org/wiki/File:Blank_map_Europe_with_borders.png

14. To be able to safely manage the power system in Québec, 1000 MW of reserves are required in the very short term, and up to 1500 MW in the day-ahead horizon, as summarized in Table 5. A more detailed description of reserve requirements in Québec is provided in Milligan et al. (2010) and Hydro Québec (2019).

More recently, following a series of calls for tenders that started in the 2000s, wind power generation has been added to Québec's grid, and will eventually exceed 3800 MW by 2021 (Hydro Québec 2020). Wind power in Québec has a relatively high peak contribution, i.e. estimated to be 36% of its installed capacity in the winter (Régie de l'énergie Québec 2019). However, wind generation adds to the existing variability in the system.

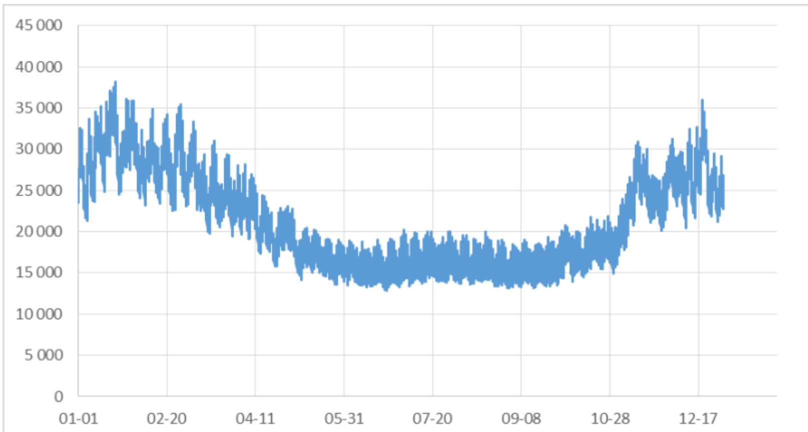

Figure 14 Hourly load (MW) in Québec, 2019 (Régie de l'énergie Québec 2020).

Table 5 Required operating reserves in Québec.

SHORT-TERM			MEDIUM TERM
Sub-seconds to seconds	**Seconds to minutes**	**Minutes to hours**	**Hours to days**
Stability reserve (Frequency Containment Reserve), typically 1000 MW; includes 250 MW of spinning reserve	Frequency responsive services between 500 MW and 1500 MW 1500 MW of 30-min reserve, incl. 1000 MW of 10-min reserve Reactive power and voltage control	1500 MW of 30-min reserve, incl. 1000 MW of 10-min reserve energy balancing reserves, typically 500 MW 2 hours ahead	energy balancing reserves, up to 1500 MW (day-ahead)

Flexibility Procurement

In Québec, distribution and transmission entities are regulated. The generation branch, Hydro Québec Production (HQP), is unregulated and operates more than 36000 MW of hydropower generation (Hydro Québec 2020).[2]

There is no spot market for electricity and ancillary services. By law, most of the supply is delivered to Hydro Québec's Distribution branch (HQD) by HQP, through the so-called *"Heritage pool contract"* (Québec National Assembly, 2000). Following that law, from 2001 HQP must deliver up to 165 TWh of energy to HQD every year, but also a set of 8760 hourly "sticks" (hourly slices) of capacity, between 11420 MW and 34342 MW. When it comes to flexibility services, the heritage pool contract must also include *"all services necessary and generally considered as essential to make this supply safe and reliable"*. This includes spinning reserve, reactive power, voltage control, frequency responsive services and provision for load forecasting errors (Hydro Québec 2016). In addition, HQP must manage its reservoirs to ensure the deliverability of the heritage energy, even in the case of sustained dry conditions (at a 2% probability of occurrence or once in 50 years). For the year 2020, the heritage contract price is 27.99$CAD/MWh. Because the heritage contract price blends energy, capacity and ancillary services, there is therefore no specific price signal for most flexibility services.

The additional variability coming from wind generation is managed through a separate wind integration contract that has a 3 years duration. HQP absorbs wind generation in real-time and guarantees 40% of installed wind capacity in winter. The contract covers intra-hourly, hourly and annual variations, as specified by the regulator for energy, Régie de l'énergie Québec. Finally, when needed, additional capacity or energy is procured by HQD through calls for tenders. For example, a 500 MW contract for capacity has been signed between HQP and HQD for a duration up to 2038. This capacity can be called up to 4 hours in advance.

In conclusion, outside one thermal peaker plant, hydropower provides the majority of energy and flexibility services to the Québec power grid. For most of those services, there is no specific price signal, as compensation is provided through the long-term contracts described above.

4.4 USA: Flexibility Requirements and New Market Initiatives in California ISO

The main reasons for the increased system flexibility needs in CAISO can primarily be attributed to a) the variability and b) the uncertainty of VRE resources, with wind and solar PV providing almost 20% of the electricity generation in 2019. We briefly discuss the two concepts and the associated manifestations in CAISO next.

Variability

Figure 15 presents the generation profiles of different generation resources in CAISO on April 1, 2020. The solar generation ramps up from 0 to 9,000 MW in a span of two morning hours (07:00 to 09:00). The solar output then ramps down by an equivalent amount during the evening hours (17:00 to 19:00).

[2] In addition to the generating capacity of its own facilities, Hydro-Québec has access to almost all the output from Churchill Falls generating station (5,428 MW) under a contract with Churchill Falls (Labrador) Corporation Limited that will remain in effect until 2041.

These extreme ramping events, although fully predictable, impose substantial stress on the system, requiring conventional generation resources, including hydropower, to respond quickly.

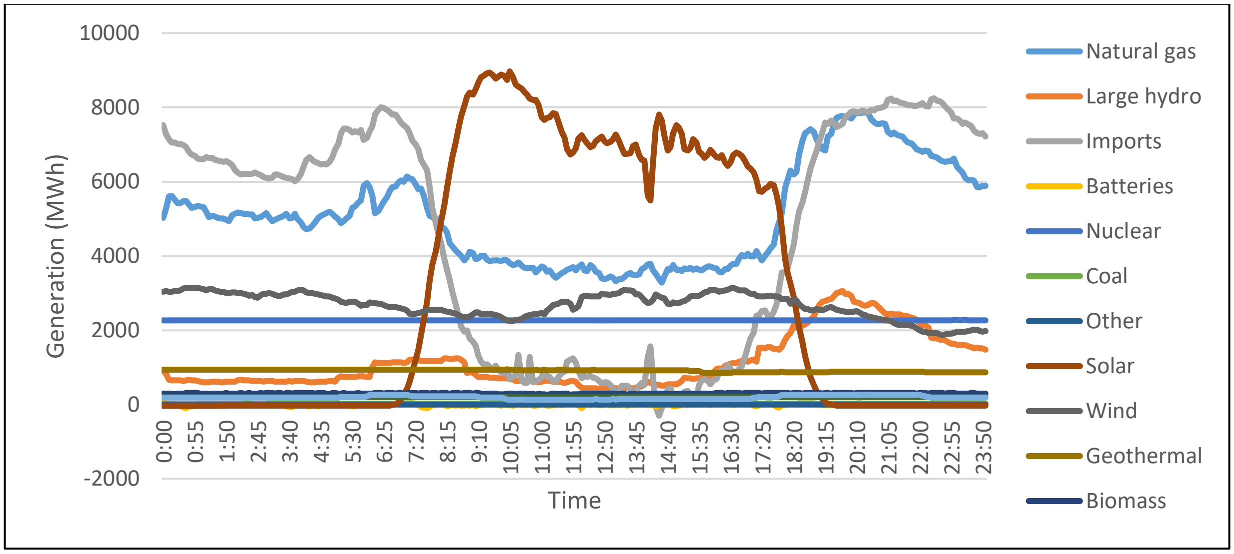

Figure 15. The generation mix (MW) on April 1, 2020 in CAISO (Data source: CAISO)

Uncertainty

Figure 16 shows the difference between VRE resource schedules in the day-ahead market (DAM) and five-minute "real-time" market and actual delivery in CAISO. On average, the difference between the DAM schedule and real-time delivery tends to be negative, which implies that VRE is typically under-scheduled ahead of time, possibly due to a combination of incorrect forecasting and risk-averse bidding in the DAM. The difference between the DAM schedules and actual delivery VRE can be as high as 25% of the total system load, while the difference between the schedule in the five-minute market and actual delivery can be as high as 10% of the load. Hence, the forecasts improve in accuracy as the market progresses from day-ahead to real-time, but scheduling errors are still significant in the five minute market.

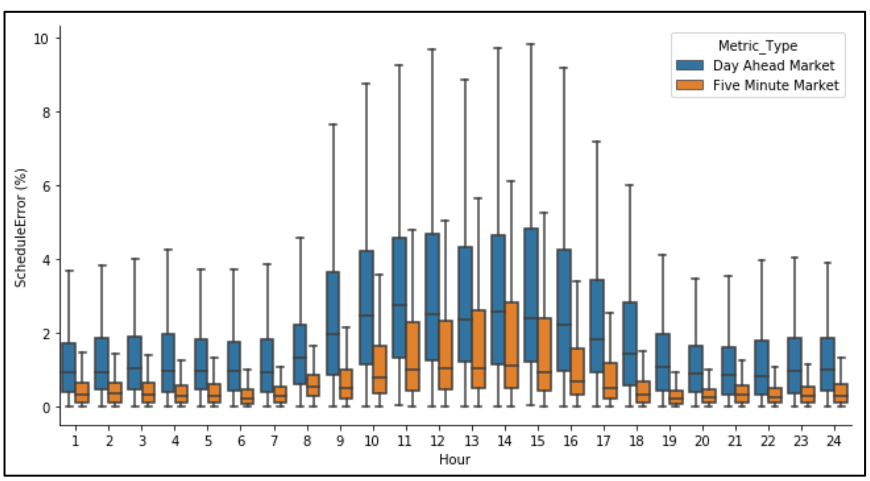

Figure 16. Absolute scheduling errors in DAM and five-minute market in CAISO in 2019, as percentage of load (Data Source: CAISO)

New products for long-term capacity procurement

In response to the evolving flexibility requirements, CAISO introduced new flexibility resource adequacy (FRA) capacity constructs in 2015. The different FRA capacity definitions are designed to provide flexible capacity with different attributes, such as the ability to provide ramping services at different times of the day, or for different durations of time, as summarized in (Table 6).

Table 6 Flexible resource adequacy constructs in CAISO

	Category 1 – Base Ramping	**Category 2 – Peak Ramping**	**Category 3 – Super Peak Ramping**
Economic Bid – Must offer Obligation	05:00 – 22:00	5-hour block (determined seasonally)	5-hour block (determined seasonally)
Daily start-up capability	Minimum of 2 starts per day or the # of starts allowed by operational limits as determined by min up and down time	At least 1 start per day	At least 1 start per day
Examples of types of resources	Conventional gas fired resources, wind, hydro, storage with long discharge capabilities	Use-limited conventional gas fired generation, hydro, solar, conventional gas fired peaking resources	Conventional gas fired generation, hydro, and short discharge battery resource providing regulation and demand response resources

Flexibility enhancements in short-term markets

The purpose of this ongoing initiative is to improve the reliability and efficiency of CAISO's DAM and to better position the system to accommodate net load variability that occurs in real-time. The CAISO proposes to change the DAM from hourly to fifteen-minute granularity in Phase 1 of this initiative and introduce a DAM flexible ramping product in Phase 2. Currently, the five-minute market must dispatch resources to manage granularity differences between the DAM and intraday markets with longer time resolution. Fifteen-minute scheduling granularity in the DAM (Phase 1) will enable the DAM to commit and schedule resources by capturing ramping that more closely aligns with real-time conditions. The CAISO introduced a flexible ramping product in 2016 to address both variability and uncertainty of net-load. However, the service was only procured in the five-minute real-time market. Phase 2 of this initiative will require the procurement of the flexibility ramping product in the DAM as well.

Hydropower's contribution to flexibility services in CAISO

Hydropower in the region is already helping to meet FRA capacity obligations in CAISO. Hydropower resources also provide flexible ramping service in real-time. These examples offer insight into new market products and other compensation mechanisms for hydropower that may become more widespread in the future, particularly as other regions gain increasing shares of VRE. Despite challenges associated with changing market conditions and plant-level complexity, opportunities are emerging for hydropower to adopt new, more valuable roles that serve the rapidly evolving power system.

4.5 BRAZIL: Maintaining Long-term Resource Adequacy through Public Auctions

The regulatory framework in force in Brazil until the mid-1990s introduced many of the fundamentals of a competitive market; also, issues related to the operational planning and dispatch, as well as the electricity trading, were outlined. However, the planning function was left to be discussed and detailed at a later time, which did not happen. Hence, there was a broad breakdown of these activities. In addition, the establishment of long-term contracts between generators and loads failed, leading to a situation where the generators were unable to obtain financing to build new plants (Melo, 2015). Consequently, the lack of investment in new generation and transmission capacities led to substantial rationing of electric power. This called for a revision of the institutional framework with an emphasis on public auctions to ensure the security of the energy supply, as discussed next.

Electricity Rationing – June 2001 to February 2002

Until the mid-1990s, the right to develop a hydropower site was granted to the one that offered the Federal Government (Union) the largest monetary value for the project development. The hydropower developers (and also developers of thermal power plants) assumed the obligation to seek "loads", i.e., distributors and free consumers, to establish long-term power purchase agreements (PPAs). However, in a system with predominantly hydroelectric production most of the time, the short-term marginal costs are low (except under conditions of low water availability); if the loads had established PPAs with generators, they would have to pay higher long-term prices. Consequently, the loads decided to act as "free-riders" and to not establish PPAs with generators since there was no real obligation for loads to be under long-term contracts. With no PPAs, the generators were unable to get financing for implementation of new power plant projects. As a consequence, the expansion of generation capacity required to meet the demand growth did not materialize, and the demand for electricity increased more quickly than generation capacity. In addition, the transmission grid was not adequately expanded in this period (Melo, 2015).

Therefore, the power sector became progressively more vulnerable to the impact of adverse hydrological conditions. This came to a peak in the unusually dry summer of 2001. Water reservoir levels in many parts of the country fell to critical levels, compromising the ability to ensure reliable power supply. As a consequence, the country experienced electricity rationing in the period June 2001 - February 2002.

Introduction of competition for the long-term market through public auctions

The rationing crisis had major repercussions for the Brazilian power sector. It generated new debate about how to ensure adequate investment, leading to a revision of the institutional framework of the electrical power sector in 2004. The introduction of competition for the long-term market was a milestone towards the creation of a more stable investment environment for investments in new generation capacity, with positive impacts on the security of electricity supply (Melo 2015, Melo et al., 2018). Under the new regulations, loads have to be 100 % contracted. In this context, two environments for electricity trading were initially established, as depicted in Figure 17:

- Regulated Contracting Environment - Generators must participate in centralized public auctions to be able to sign PPAs with the regulated (captive) consumers supplied by the distribution companies (DisCos), which must provide self-declaration of its forecasted loads for the next five years. The auctions are held whenever a possibility of interruption in energy supply is foreseen, as defined by standards by the National Energy Policy Council. For example, currently with the load reduction due to the pandemic, there were no auctions;

- Free Contracting Environment - Free consumers can procure their energy needs as they wish, as long as they are 100% contracted. Hence, supply and demand are free to negotiate the features of the contract, such as the electricity price, end of term, etc.

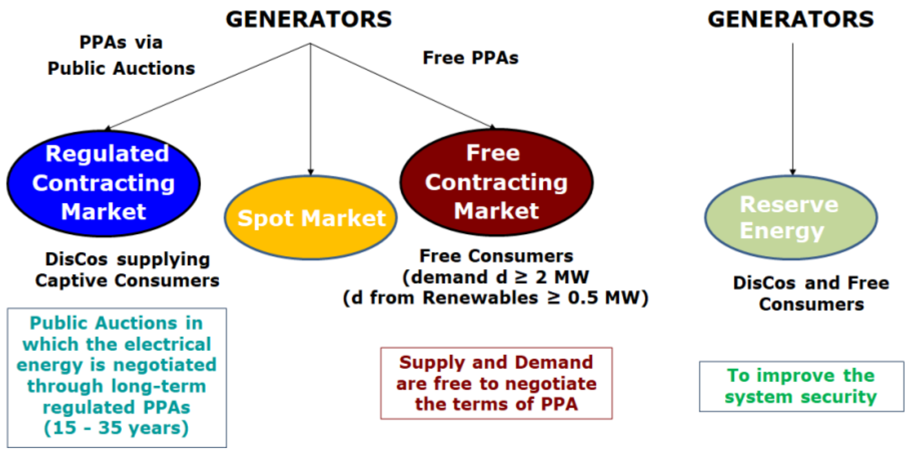

Figure 17. Contract environments for electricity in Brazil.

The introduced public auctions are a procurement mechanism for purchasing energy for captive consumers. Each winner in these auctions is the one which offers the lowest price per kWh, also limited to ceiling prices. In exchange, all DisCos have an obligation to enter into PPAs (15 to 35-year duration) with each auction winner in proportion to their declared load forecasts. The successful generators can offer an assured future cash flow to obtain loans from banks to develop their projects, including the Brazilian National Development Bank. This auction scheme may occur at different times: 3 to 5 (nowadays, 7) years ahead for new projects, and 1 year ahead for existing ones. Auction prices are then passed on to electricity tariffs.

A set of projects (hydroelectric and thermal) considered the most economical to meet demand are offered to the auction, although any generator may offer alternative projects for the tenders. It is noteworthy that in order to be eligible to participate in the auctions, hydroelectric plants need to obtain approval of the optimum project dimensioning from the Electricity Regulatory Agency, a preliminary environmental license from the Environmental Agency, and water use rights from the Water Regulatory Agency. Also, all contracts, which are financial instruments, must be covered by real power production capacity defined by a "plate number" called Assured Energy Certificate or "Physical Guarantee", which will be described later. In case of thermal power plants, a Fuel Supply Purchase Agreement must also be provided.

The Government does not interfere with the demand forecasts, which are directly declared by DisCos, nor does it take ownership of the energy contracts or provides payment guarantees. Also, DisCos are allowed to enter into contracting adjustments to the Regulated Market one and two years in advance, re-contracting existing energy in annual auctions and receiving, or transferring, free of charge, surplus energy contracts from other DisCos.

In addition, the differences between the production and consumption of energy in relation to the long-term contracts are settled on the spot market by the spot prices (called Settlement Prices for Differences) (Maceira et al., 2016). Finally, there is also the possibility to procure energy through the Reserve Energy Auctions, whose aim is to improve the system security. The contracted energy from these auctions must be paid for by both DisCos and free consumers.

Public auctions to acquire new energy - consolidated results

Figure 18 presents the consolidated results from the public auctions for the years 2008-2015. In this period, 47 auctions were completed adding to the system 65,478 MW of new capacity which corresponds to a total financial allocation of US$ 613 billion. Of the total energy added and traded in the system, 70% came from renewables, with hydropower contributing 48% of the total additions.

Despite being a successful mechanism to support investment in capacity, including large-scale investments in hydroelectric energy, the public auctions have so far not addressed the issue of economic valuation or signaling related to the flexibility services provided by hydropower plants, especially those associated to the integration and balancing of VRE, such as wind, which has shown accelerated growth in Brazil.

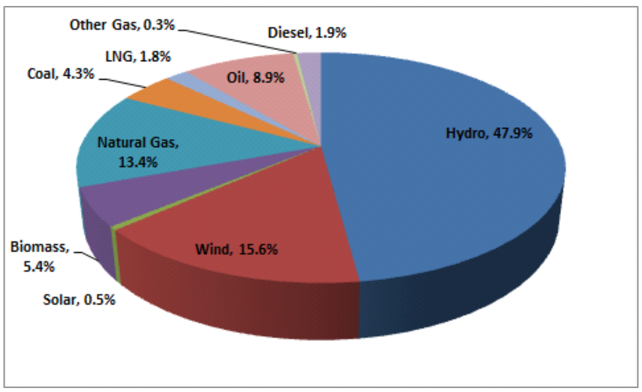

Figure 18. Results of public auctions in Brazil: 2008-2015.

4.6 AUSTRALIA: The Need for Deep Storage – an Uncertain Pathway

Australia is in the midst of a massive transition in energy. The mix of power sources is changing from one dominated by thermal coal (black and brown) to one much more reliant on VRE (Figure 19). The transition is not a smooth one with grid and market operators struggling with reductions in fault level, frequency regulation and inertia. Rules are being written to try to force VRE technologies to fill the gap in meeting these requirements, but they can only do so much within the limitations of inverter-based technologies and the financial constraints of new power plants entering an over-supplied market. While a large amount of thermal coal generation remains available to the market, new VRE can continue to displace the thermally sourced energy without displacing all of the attendant grid services. A tipping point is emerging where the slice of the energy market available to these thermal stations will not be large enough to keep them economically viable (Narayan 2019). Add this to the impending retirements of a large majority of these plants across the east coast due to age, and it is clear there will be a shortfall in dispatchable power and other system support services.

There is no one solution emerging to this problem, but it is clear that existing market arrangements are unlikely to be sufficient to manage such a further rapid change to the generation mix (Hydro Tasmania

2020). Among the raft of changes needed is a market mechanism that supports deep (i.e. long-duration) storage that can sustain the demand for energy across a series of windless and/or cloudy days and nights. Presently, this requirement is almost invisible to the market. There have been events where VRE production has ramped off faster than predicted leading to high prices for short periods (e.g. Wednesday 8 February 2017 (AEMO 2017). The short periods last for as long as it takes for gas units to start and small storage batteries to discharge. These events highlight a need, but do not represent a big enough revenue opportunity to incentivize large-scale investment yet. The efficient use of VRE to decarbonise the energy supply depends on managing much longer events than these cost-effectively. This is where hydropower may find a niche.

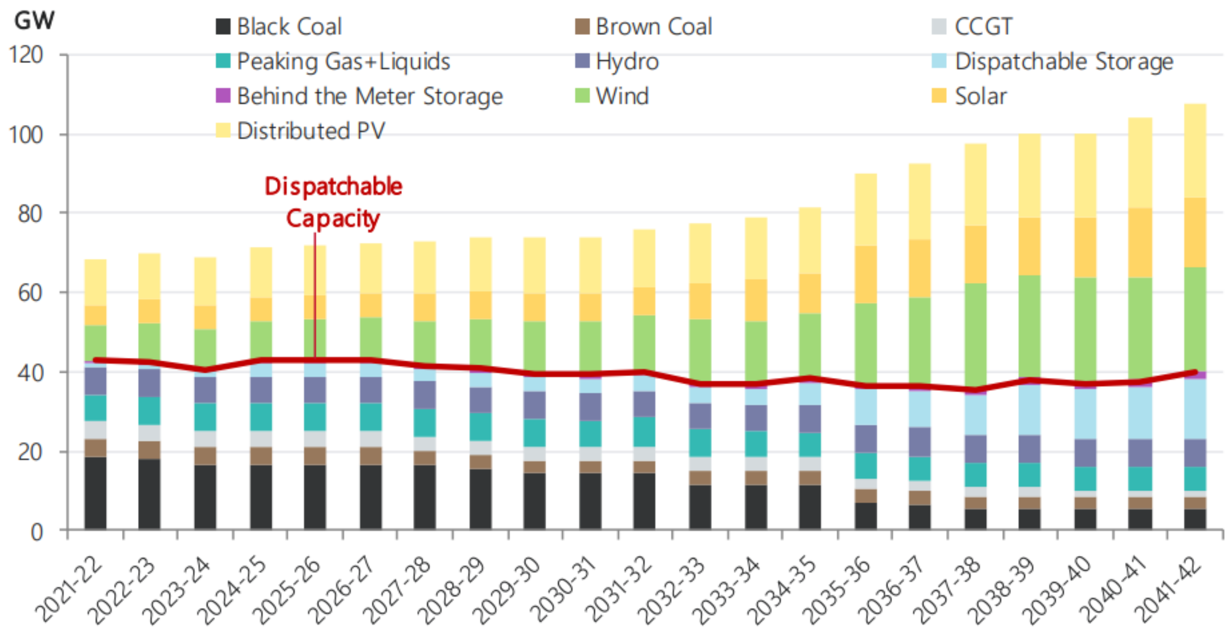

Figure 19. Projected retirements and replacements in Australia (AEMO 2020).

The flexibility of hydropower in the short, medium, and long term can help provide the deep energy storage that will be required. While existing hydropower in Australia can play a role here by managing flows and storages relative to VRE production, new PSH opportunities will also be required to provide the volumes of storage required. The business case for these new schemes however is marginal at best. The uncertainties in terms of when the generation mix will meet the tipping point described earlier, the ultimate VRE mix between solar and wind, and the amount and cost of battery storage deployed all make committing to a long life asset such as a PSH difficult without some de-risking. This is awkward in a regulatory environment that does not like to pick winners. Globally, however, governments are prioritizing low emissions technologies over high emissions technologies and to this end, concurrently prioritizing storage to support the transition to VRE should be a priority.

PSH cannot operate effectively unless connected to the VRE sources that it is storing. Australia is once more considering inter-connection as an important support to the VRE transition. Interconnection will also be important for the efficient deployment of PSH. Schemes such as Hydro Tasmania's Battery of the Nation (Hydro Tasmania 2021) and the Marinus Link, i.e. an HVDC interconnector between Tasmania and Victoria (TasNetworks 2021), are examples of this synergy between hydro, interconnection and VRE. Schemes of this nature require strong backing from governments and industry so that the looming need is met. The existing market arrangements in Australia do not have the mechanisms required to provide certainty to investments required to meet an impending, certain, but temporally undetermined requirement to support the next phase of the VRE transition. Government intervention and market reform will be required to bridge this gap and allow PSH to play a role in the efficient management of the transition.

4.7 JAPAN: VRE Integration and the Role of Pumped Storage Hydropower

Japan has been experiencing rapid deployment of solar PV, since a Feed-in Tariff program was launched in 2012. Kyushu, the southernmost island among the main islands of Japan, has been the most significantly affected area in terms of solar PV penetration. According to the IEA definition (IEA 2018), Kyushu is regarded to be in Phase 3 of VRE integration (i.e. VRE generation determines the operation pattern of the system) due to limited interconnection capacity. To keep the balance between supply and demand in case of VRE generation surplus, all transmission system operators in Japan have launched the so-called "Priority dispatching rule" as of 2016. The priority dispatching rule determines in what order power generation is dispatched down, or curtailed, in order to balance supply and demand. The rule consists of the following steps:

(1) Curtailment of fossil-fired power generation (coal, oil, and gas) and absorption of surplus VRE generation by pumping in PSH plants

(2) Export of VRE generation surplus to other areas through interconnection

(3) Curtailment of biomass power generation

(4) Curtailment of VRE generation (PV and wind)

(5) Curtailment of nuclear, geothermal and hydropower generation

In Kyushu, PSH plants have been operated following the rule to avoid curtailment of VRE generation, especially in light-load seasons (spring and autumn); pumping during day-time to absorb surplus VRE generation, and generating in the evening to provide electricity for corresponding demand. This includes variable speed PSH units, which are more flexible than conventional fixed-speed PSH plants and therefore particularly suitable for VRE integration. Figure 20 shows supply and demand in Kyushu, including pumping and generation from PSH, for a month with light loads in 2019.

Since the TSO needs to secure an effective reservoir capacity for the next day-time period, PSH plants are required to generate during night-time regardless of electricity price. This situation threatens the optimal arbitrage opportunity and disrupt the maintenance schedules of PSH plants. Overall, PSH plants have played a crucial role in the power system by accommodating higher levels of VRE, and hence, it is important that these resources are remunerated and maintained appropriately.

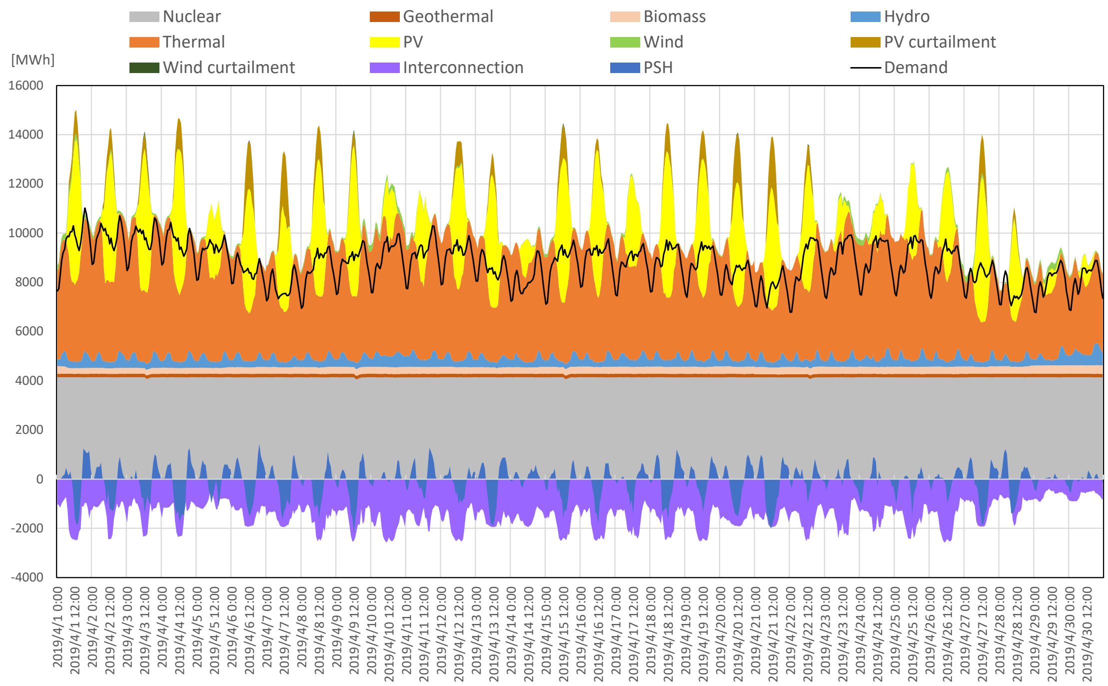

Figure 20. Electricity supply and demand in light-load season, April 2019 (Kyushu).

5 Main Observations from Survey and Case Studies

The survey results and case studies provided detailed insights into specific challenges and solutions related to provision of flexibility services, and the planning and operation of electricity markets and power systems with increasing shares of VRE in different parts of the world. Although regulatory structures and electricity market designs will always have a regional flavor based on the specific resource mix and policy conditions at hand, these examples provide a variety of solutions that may contribute towards a more efficient provision of clean electricity in future power systems. The examples from some systems may inspire adaptation or adoption of solutions in other regions.

Below, we summarize 10 key takeaways from survey results and case studies:

1) Hydropower is an important contributor to essential reliability services: A key finding from the survey is that hydropower currently contributes to flexibility services across all timescales in most countries. This observation highlights the unique characteristics of hydropower in its ability to provide flexibility to the system, from short-term frequency and voltage support services to long-term seasonal storage through management of hydro reservoirs.
2) Mechanisms for procurement and compensation of grid services vary across countries: The survey results show that market-based mechanisms are the predominant means for procurement of grid services, especially the ones required over minutes-days. Interconnection agreements and bilateral contracts also play an important role, typically in the very short-term (sub-seconds-seconds) and longer-term (months-years) timeframes. Only a few systems currently use markets to procure and compensate services at the shortest timescale (sub-seconds to seconds).
3) Lack of market signals for long-duration storage: Among the challenges discussed in the case studies are a lack of consistent and commensurate long-term signals for investments in long-duration storage solutions such as those provided by hydropower. There are, however, ongoing initiatives (Australia, California ISO) that explicitly consider the amount of long-duration storage needed to meet regional renewable energy targets.
4) Stored energy is presently compensated through markets for reserve and energy products: Energy storage requires withholding energy generation, which is the primary revenue source in current electricity markets. Short-duration reserve products comprise one source of explicit compensation for stored energy in current markets. However, survey results show that the markets for reserve products tend to be thin, and as such, might not be able to support business case for new PSH development. Energy storage is also incentivized through market-based energy arbitrage opportunities (or load shifting), which depend on market price differentials during day, week, or season. These energy markets represent the largest revenue opportunities for most hydropower assets, although intra-day price differentials may diminish as more storage is added to the grid.
5) Market rules and regulations can distort market-based arbitrage signals for storage: Systems with priority dispatching rules for VRE (Japan) prevent PSH from following an economically optimal energy arbitrage schedule.
6) New market opportunities for flexibility services are emerging: This includes the introduction of fast frequency reserve products (Norway), the inclusion of flexibility ramping products, and a higher time resolution of day-ahead markets (California ISO). The market depth, i.e., the

quantity of service required for these services, is likely to be very thin, and hence, may not alone provide sufficient incentives for deployment of high capital cost assets, such as PSH.

7) Flexibility services require increased cycling, which leads to accelerated wear and tear: Provision of balancing services under higher VRE penetration could lead to increased stress on hydropower machinery and infrastructure, which may impact the economic viability of hydropower plants (Switzerland, California ISO). The increased O&M costs and/or the cost of retrofitting resources to operate more flexibly will need to be balanced against the value of providing the flexibility services.
8) Long-term contracts offer stability but mask the true cost and value of flexibility: Long-term contracts provide consistency and low risk for investors (Brazil and Hydro Québec). In particular, long-term power purchasing agreements organized through public auctions have provided substantial investments in new hydropower capacity in Brazil. However, long-term contracts can limit visibility into the cost and value of flexibility (Hydro Québec, Brazil).
9) Standardized product definitions facilitate efficient use of resources across different markets: There are substantial advantages of using standardized product definitions for flexibility services across electricity markets, enabling trading and efficient exchange of services across wider geographical areas (Switzerland, Norway).
10) Transmission capacity is a key enabling factor for hydropower: Hydropower is a geographically constrained resource. Hence, transmission is oftentimes critical for hydropower to access regions with flexibility needs. HVDC lines can play an important role towards this end (Norway, Australia).

6 Conclusion and Future Directions

There has been a rapid increase in VRE generation across the globe as part of the ongoing shift towards cleaner electricity supplies with a lower carbon footprint. The variability and uncertainty in VRE resources, such as wind and solar, increase the need for flexibility in the power system. In this report, we reviewed how flexibility services are defined, procured, and valued in current electricity markets, with specific focus on the status and outlook for hydropower.

Our review revealed that there is a wide range of solutions to address flexibility challenges in evolving power systems with higher VRE levels. Although the definitions of flexibility services are similar in the 14 systems reviewed in this report, substantial variations exist in terms of how these services are procured and compensated. However, a common feature across the systems included in this review is that hydropower plays an important role in providing flexibility services across all timescales. This observation highlights the unique characteristics of hydropower in its ability to provide the full spectrum of flexibility needs to the system, from short-term stability services to long-term seasonal storage through management of hydro reservoirs. With the increasing penetration of VRE and corresponding retirements of traditional thermal generators, we expect that the value of flexible resources like hydropower will increase in the future. In order to take full advantage of the increasing value of flexibility, it is important that hydropower owners and investors consider that hydropower plants follow a different and less predictable operating pattern in systems with high VRE penetration.

The review reveals some important challenges for electricity markets in the evolution towards a different resource mix. Chief among them are the lack of compensation for some flexibility services, particularly in the very short time-scale, and limited long-term incentives for investments in the flexibility and long-duration storage required to maintain reliability in future power systems. An important conclusion from this review is that there are lessons to be learned between countries and regions around the world. Although the fundamental flexibility challenges are similar in a changing power system, solutions differ. We therefore believe that international comparisons, like the one presented in this report, are an important contribution towards improved solutions for future electricity markets.

Finally during the course of writing this report we have identified several important directions for future work for industry and research communities, as briefly outlined below.

Changing hydropower operations

1) Assess what are likely to be the most important flexibility services for hydropower in future electricity markets
2) Assess impacts of climate change on precipitation, reservoir inflows, and hydropower operations (including frequency of draught and flooding events)
3) Investigate implications on machine wear and tear, required investments to upgrade and/or retrofit resources, etc.
4) Conduct a survey of changes in hydropower operations with special emphasis on a) start/stops, b) cycling, c) ramping, d) pumping/generation cycles (arbitrage patterns), e) environmental effects (e.g. increased hydropeaking in rivers with hydropower plants)
5) Estimate the socio-economic value of hydropower flexibility to the grid in selected regions with high VRE shares, including contributions to short-term frequency and voltage stability, reduced

risk of interruptions, less wear and tear on other resources, lower system operating costs, and reduced carbon emissions

Long-duration energy storage

1) Identify instances of long-duration energy storage solution solutions being provided by hydropower presently
2) Conduct a survey of ongoing initiatives to set mandates/targets and requirements for long-duration energy storage
3) Review potential remuneration mechanisms for long-duration energy storage (e.g. availability or capacity payments for flexibility services), recognizing that these assets may be idle for extended periods of time while providing critical services to the grid during other periods

Electricity market design

1) Develop a set of more specific guidelines for the design of flexibility services and corresponding compensation mechanisms across the timescales in future electricity markets
2) Investigate price formation in a zero marginal cost world and its implication for different types of hydropower plants

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8 Appendix A: Survey Response Summaries by Timescale

This appendix contains the survey responses provided by each of the 14 countries/regions, slightly edited for readability. The responses are categorized based on timescale. The survey results presented in chapter 3 were extracted from these responses.

8.1 Sub-Second to Second Timescale

	Relevant grid flexibility services and products	Procurement mechanism			Compensated service?	Does hydropower currently provide these services to the power grid?	Market size	
		Market Based	Bilateral Contracts	Interconnection Agreement			Quantity	Price/Size
USA - CAISO	1) Inertia 2) Reactive Power and Voltage Control	No	No	Yes (RMR)	No - Reactive Power No - Inertia	Yes	NA	~$4 M (2018) USD/MW
Norway	1) Fast Frequency Response (FFR) 2) Reactive power	Yes - FFR (current pilot project)	Yes - Reactive Power, smoothing, automatic disconnection, shifting of production (on finer time resolution than the market)	FFR - Nordic cooperation	Yes - FFR, Reactive Power	Yes ancillary services in general, Not finally decided FFR (to some degree)	FFR: ~130MW (May - September), pilot market ended up with only buying 27,2 MW, lack of supply	4,6 MNOK (27,2 MW), 536K USD
Switzerland	1) Inertia; 2) Mandatory active and Semi-active Voltage Support.	No	Yes - Inertia	Yes - Reactive Power	Yes - Reactive Power No -Inertia	Yes	Reactive Power - 13.5 TVArh	Reactive Power - 3CHF/MVAr (2019) (3.35 USD/MVAr)
Canada - HQ	Stability reserve (Frequency Containment Reserve), typically 1000 MW includes 250 MW of spinning reserve	No	heritage electricity pool was defined by a law, issued by the National Assembly of Québec	No	not explicitly- service is included within heritage pool, a larger contract for energy, capacity and flexibility services	Yes	typically 1000 MW (includes 250 MW of spinning reserve)	NA
Brazil	1) Reactive Power and Voltage Control 2) Special Protection Systems	No	Yes - Reactive Power and Voltage Control provided by generating units operating as synchronous compensators Yes - Special Protection Systems	No	Yes	Yes	22.5 TVArh in 2019	R$ 162M (US$ 40.7 M) in 2019. Ancillary Service Tariff (Tarifa de Serviços Ancilares - TSA) = R$ 7.19/MVArh in 2019 (1.32 USD/MVArh)

	Relevant grid flexibility services and products	Procurement mechanism			Compensated service?	Does hydropower currently provide these services to the power grid?	Market size	
		Market Based	Bilateral Contracts	Interconnection Agreement			Quantity	Price/Size
Austria	1) Inertia 2) Reactive Power and Voltage Control 3) FCR	1) No 2) No 3) Yes	1) No 2) No 3) Yes	1) Yes 2) Yes, there is an agreement about cos(phi) 3)	1) No 2) No 3) Yes	1) Yes 2) Yes 3) Yes	1) - 2) - 3) ± 67 MW	1) - 2) - 3) 6x 4h-Blocks a day
Czech Republic	N/A - FCR	N/A	No Response	No Response	No	No	NA	NA
Germany	Inertia ("kinetic energy of rotating masses")	No	No Response	No Response	No	Yes	NA	NA
India	1) Inertia 2) Reactive Power and Voltage Control	No	No	Yes - Inertia, Reactive Power, Voltage Control	No	Yes	NA	NA
Australia	1) Fault level 2) Inertia/fast frequency response	No	Yes - Fault level No - Inertia/FFR	No	Yes - Fault level No - Inertia/FFR	Yes	unknown	unknown
Japan	1. Inertia 2. Reactive Power / Voltage Control	No	Bilateral contact(TSO and provider) - Inertia, reactive power/voltage control	Yes - Reactive Power / Voltage control	Yes - Reactive power/voltage control No - Inertia	Yes	NA	NA
Turkey	Ancillary Services (Reactive Power Control- No Market Product)	No Response	No Response	No Response	No Response	Yes.	No Response	No Response
Finland	Fast Frequency Reserve (FFR)	Yes - national hourly market based on inertia forecast	No Response	No Response	Yes - FFR	Yes.	up to 60MW (Provide Year Data are from)	No Response
Colombia	1) Inertia 2) Reactive Power and Voltage Control	No	No	No	Indirectly compensation through DA market	Yes	Security constraints (2019): 12.7 TWh-yr (Total required security constraints - both In-merit and off-merit)	Constraints Annual Cost (2019): US$270.8 M in 2019 (Paid by end users)

8.2 Second to Minute Timescale

	Relevant grid flexibility services and products	Procurement mechanism			Compensated services?	Does hydropower currently provide these services to the power grid?	Market size	
		Market Based	Bilateral Contracts/ Administrative Rate	Interconnection Agreement			Quantity	Price/Size
USA - CAISO	1) Primary Frequency Response (PFR) 2) Secondary Frequency Response (Regulation Up/Down)	Yes - Reg Up/Down	Yes - PFR	Yes - PFR	Yes - Reg Up/Down, PFR	Yes	Reg Up: 300-400 MW Reg Down: 350-550 MW in 2019 (procured in Day Ahead and adjusted in real-time, application in seconds-minutes)	Reg Up Price: $13.27-24.55/MWh,Reg Down Price: $11.74-23.92/MWh, total cost in 2019 $43 million for reg up and $46 million for reg-down; PFR: $44-81/kW-year
Norway	FCR	Yes - FCR	No	FCR - Nordic cooperation and standardization of markets on going	Yes - FCR	Yes	Provide quantity in terms of power. If divided real and reactive power, please provide. Should be 12-month period (provide year data are from).If there is no Market, enter NA	~NOK 135 M (15.75M USD) (2019) Currency/MW
Switzerland	1)PFC - FCR; 2) SFC - aFRR; 3) Extra-mandatory voltage support - phase shifter	Yes - FCR and aFRR	Yes - Voltage Support	YES - FCR and aFRR	Yes aFRR No FCR	Yes	FCR: (+/-) 61MW aFRR: (+/-) 400MW	For aFRR: 50€/MWh 60 USD/MWh) positive energy and 30 €/MWh (36 USD/MWh) for negative in 2019

	Relevant grid flexibility services and products	Procurement mechanism			Compensated services?	Does hydropower currently provide these services to the power grid?	Market size	
		Market Based	Bilateral Contracts/ Administrative Rate	Interconnection Agreement			Quantity	Price/Size
Canada - HQ	Frequency responsive services (called RFP in Québec) Operations reserve +reactive power + voltage control	No	heritage electricity pool was defined by law, issued by the National Assembly of Québec	No	not explicitly- service is included within heritage pool, a larger contract for energy, capacity and flexibility services	Yes	- Frequency responsive services (called RFP in Québec) between 500 MW and 1500 MW - 1500 MW of 30 min Operations reserve, including 1000 MW of 10-minutes reserve	NA
Brazil	1) PFC 2) SFC	No	Yes - SFC	No	Yes - SFC No - PFC	Yes	NA	R$ 62 M (USD 15.6 M) * in 2019 Currency/MW - NA
Austria	aFRR	Yes - aFRR	No	No	Yes aFRR	Yes	(+/-) 200MW	6x 4h Blocks a day
Czech Republic	FCR	No Response	Yes - FCR	No Response	Yes List services that are compensated	Yes	No Response	No Response
Germany	FCR	Yes - FCR	No Response	No Response	Yes List services that are compensated	Yes	(+/1) 600 MW	No Response
India	1) PFC 2) Secondary Control - AGC	No	Yes - AGC	Yes - PFC	Yes - AGC	Yes	NA	INR .5/kW (0.007 USD/kW)
Australia	1) CFC 2) RFC	Yes - CFC, RFC	No	Yes - CFC	Yes - CFC, RFC	Yes	1) Delayed: 215.75 -399 2) Slow: 180 - 409.5 3) 97.75 - 404.25 4) Regulation: 192 - 235	<AUD 5-10/MWh (<3.82-7.65 USD/MWh

	Relevant grid flexibility services and products	Procurement mechanism			Compensated services?	Does hydropower currently provide these services to the power grid?	Market size	
		Market Based	Bilateral Contracts/ Administrative Rate	Interconnection Agreement			Quantity	Price/Size
Japan	FCR	No Establish Balancing market for FCR in FY2024	Bilateral contact (TSO and provider)	Yes - FCR	Yes - FCR	Yes	Auction for FY2020 (held in FY2019) 11,400MW-year	Auction for FY2020 (held in FY2019) JPY12111/kW-year (115 USD /kW-year
Turkey	Ancillary Services (PFR,SFR)	Yes - ancillary service market primary / secondary frequency response	Primary/secondary frequency contracts	No Response	Yes List services that are compensated	Yes	No Response	Primary Frequency Contracts 163,43 TL/MWh (22.73USD /MWh) Secondary Frequency Contracts Price 166,32 TL/MWh (23.13 USD/MWh
Finland	FCRD FCRN	No Response	No Response	No Response	Yes - FCRD, FCRN	Yes	FCRD: 290 MW FCRN: 120MW	Yearly FCRN-67500€ (81500 USD), (13,5 €/MW,h, 5000 Hours) Hourly FCRN-56000€ (67600 USD), (28,0 €/MW,h, 2000 Hours) Yearly FCRD-12000€ (14500 USD), (2.4 €/MW,h, 5000 Hours) Hourly FCRD-18800€ (22700 USD), (9,4 €/MW,h, 2000 Hours)

	Relevant grid flexibility services and products	Procurement mechanism			Compensated services?	Does hydropower currently provide these services to the power grid?	Market size	
		Market Based	Bilateral Contracts/ Administrative Rate	Interconnection Agreement			Quantity	Price/Size
Colombia	1) First level: PFR) 2) Second level: SFR (AGC regulation UP/Down) 3) Last minute redispatch (i.e. adjustment of power output to address system imbalances)	Yes - AGC	Mandatory	N/A	PFR: No. It is mandatory, otherwise generators are penalized. AGC. Market-based compensated	Currently, only Hydro plants are able to provide AGC. Gas and other plants are not able to compress gas, hence they are not able to provide regulation services.	Hourly based. Margin UP/Down services equivalent to 5% of the total national demand. Average Daily Values (2018): - Margin Up: 7.01 GW-day - Margin Dw: 7.01 GW-day	AGC (2018): USD$ 98.2 M

8.3 Minutes to Hours Timescale

	Relevant grid flexibility services and products	Procurement mechanism			Compensated services?	Does hydropower currently provide these services to the power grid?	Market size	
		Market Based	Bilateral Contracts/ Administrative Rate	Interconnection Agreement			Quantity	Price/Size
USA - CAISO	1) Energy 2) FRP 3) AS	Yes	Yes	Yes - Energy, FRP, AS	Yes	Yes	Annual Total Energy : 214955 GWh, Average load: 24541 MW, Peak Load 44301 MW (2019); Average upward FRP: 160-225MW; 2019 Daily Average Spin/Non-spin-reserve: 750-900 MW each	Average Energy in DAM and RTM price $37-38/MWh, Total Cost $8.8billion (2019); FRP: total payment for updard and downward uncertainty : $6.3 million in 2019; Spin reserve price: $7.39-19.48/ MWh, Non-spin reserve price: $0.75-$6.83 / MWh; Total Spin-Reserve Payment: $53 million in 2019, Total Non-spin payment: $20 million in 2019
Norway	1) Energy 2) aFRR (could also be sec-min?) 3) mFRR	Yes	No	aFRR - nordic cooperation, national markets, nordic market under development. Reservation of capacity for aFRR on interconnector to Danmark, (possible reserved capacity for aFRR on new cables to Germany and UK)	Yes	Yes	mFRR - 1500MW	aFRR - NOK 47M (5.5M USD) mFRR: NOK 52 M (6.1M USD) Currency/MW
Switzerland	1) mFRR and RR 2) Black start	mFRR and RR - Yes	Yes - Black start	Yes - mFRR and RR	Yes all listed	Yes	RR: (+) 400 MW and (-) 260 MW	For RR: 15€/MWh (18.11 USD /MWh) positive energy and >5 €/MWh (6 USD /MWh) for negative in 2019

	Relevant grid flexibility services and products	Procurement mechanism			Compensated services?	Does hydropower currently provide these services to the power grid?	Market size	
		Market Based	Bilateral Contracts/ Administrative Rate	Interconnection Agreement			Quantity	Price/Size
Canada - HQ	1) 10 min / 30 min operating reserve 2) wind integration service	No	1) heritage electricity pool was defined by a law, issued by the National Assembly of Québec 2) wind integration: through a competitive call for tenders	No	1) balancing reserves: not explicitly- service is included within heritage pool, a larger contract for energy, capacity and flexibility services 2) wind integration: through a competitive call for tenders; current contract has a duration of 5 years	Yes	1) 30-min: 1500MW, 10-min: 1000MW 2) firming 30% in summer and 40% in winter of about 3700 MW of installed wind capacity	NA
Brazil	Black-Start	No	Yes	No	Yes	Yes	NA	R$ 62 M (USD 15.6 M)[b] in 2019 Currency/MW - NA
Austria	1) mFRR[a] 2) Energy (Intra-day)	Yes 1) mFRR[a] 2) Energy (Intra-day)	1) No 2) No	1) No 2) No	Yes 1) mFRR[a] 2) Energy (Intra-day)	Yes	(+)280 MW mFRR (positive) (-) 195 MW mFRR (negative)	0
Czech Republic	No Response	No Response	No Response	No Response	No Response	No Response	No Response	No Response

	Relevant grid flexibility services and products	Procurement mechanism			Compensated services?	Does hydropower currently provide these services to the power grid?	Market size	
		Market Based	Bilateral Contracts/ Administrative Rate	Interconnection Agreement			Quantity	Price/Size
Germany	1) mFRR 2) aFRR	Yes(?)	No Response	No Response	Yes List services that are compensated	Yes	~2000 MW/week	No Response
India	1) FRAS 2) Energy	Yes if some services are market based, list services	No Response	No Response	Yes List services that are compensated	Yes	No Response	Reg Up/Dn: INR .10/Unit
Australia	Energy	Yes - Energy	Yes - Energy	No	Yes - Energy	Yes	204 TWh (19/20 FY)	$14.13 billion AUD $69.25 AUD/MWh ($9.89 billion USD $48.48 USD/MWh)
Japan	FRR RR	No Establish Balancing market for RR in FY2021, for FRR in FY2024	Bilateral contact (TSO and provider)	Yes - FRR, RR	Yes - FRR, RR	Yes	Auction for FY2020 (held in FY2019) 4265MW-year	Auction for FY2020 (held in FY2019) JPY5941/kW-year (56.62 USD /kW-year
Turkey	1. Energy 2. Regulation Up and Down	1. Intra-day Market 2. Balancing Power Market	No Response	No Response	Yes. Energy, up/down regulaiton	Yes	No Response	İntra-Day Market weighted average price : 252,4 TL/MWh (35.10 USD/MWh). Balancing Power Market average System Marginal Price : 253,37 TL/MWh (35.24 USD /MWh) (2019)
Finland	1. aFRR 2. mFRR	Hourly market with capacity payment based on availability	No Response	No Response	Yes - aFRR, mFRR	Yes	aFRR: 60-80MW mFRR	No Response

	Relevant grid flexibility services and products	Procurement mechanism			Compensated services?	Does hydropower currently provide these services to the power grid?	Market size	
		Market Based	Bilateral Contracts/ Administrative Rate	Interconnection Agreement			Quantity	Price/Size
Colombia	1) Redispatch of power plants (during real-time operation and only when it is required) 2) Tertiary Control level: Load shedding (rarely used)	Yes - 1.5 hrs ahead redispatche	Yes - load shedding	No Response	Yes List services that are compensated	Yes[c]	Security constraints (2019): 6.5 TWh-yr (Only off-merit constraints)	System re-dispatch cost cannot be derived from available information

Footnotes

a SPS+AGC+Black-start

b ** For next 6 hours

c Near 67% of power capacity is Hydro

8.4 Hours to Days Timescale

	Relevant grid flexibility services and products	Procurement mechanism			Compensated services?	Does hydropower currently provide these services to the power grid?	Market size	
		Market Based	Bilateral Contracts/ Administrative Rate	Interconnection Agreement			Quantity	Price/Size
USA - CAISO	1) Energy (DA Market) 2) Ancillary Services (same as minutes to hours)	Yes	Yes	Yes	Yes - Energy, AS	Yes	Annual Total Energy: 214955 GWh, Average load: 24541 MW, Peak Load 44301 MW (2019); Average upward FRP: 160-225MW; 2019 Daily Average Spin/Non-spin-reserve: 750-900 MW each	Average Energy in DAM and RTM price $37-38/MWh, Total Cost $8.8billion (2019); FRP: total payment for updard and downward uncertainty : $6.3 million in 2019; Spin reserve price: $7.39-19.48/ MWh, Non-spin reserve price: $0.75-$6.83 / MWh; Total Spin-Reserve Payment: $53 million in 2019, Total Non-spin payment: $20 million in 2019
Norway	Energy (DA Market, Intraday market)	Yes	No	Nordic market, connected to continental Europe.	Yes	Yes	DA Norway - 130TWh (2019), 145 TWh (2018) ID Norway - 128 GWh (2019), 84 GWh (2018)	DA - 2019: ~39 EUR/MWh (47 USD /MWh), 2018: ~44 EUR/MWh (53 USD /MWh)
Switzerland	Energy balance (Day-ahead and intraday market)	Yes if some services are market based, list services	Yes for market participation	Yes	Yes - Energy List services that are compensated	Yes	650 GWh/year	NA

	Relevant grid flexibility services and products	Procurement mechanism			Compensated services?	Does hydropower currently provide these services to the power grid?	Market size	
		Market Based	Bilateral Contracts/ Administrative Rate	Interconnection Agreement			Quantity	Price/Size
Canada - HQ	1) energy balancing reserves, act to counter uncertainties 2) wind integration service	No	1) heritage electricity pool was defined by a law, issued by the National Assembly of Québec 2) wind integration: through a competitive call for tenders	No	1) balancing reserves: not explicitely- service is included within heritage pool, a larger contract for energy, capacity and flexibility services 2) wind integration: through a competitive call for tenders; current contract has a duration of 5 years	Yes	1) energy balancing reserves: 1500 MW[d] 2) Wind integration: absorb in real time and firm wind generation (40% in winter, 30% in summer)	NA
Brazil	CD to SR[a]	Yes	No	No	Yes	No	NA	R$ 696,251,879.05 (US$ 174.1 million) in 2019. Offers between 164 and 1988 R$/MWh[b]
Austria	Energy (Intra-day, DA Market)	yes	No	No	Yes Energy (Intra-day, DA Market)	Yes	Exchanges	Exchanges
Czech Republic	What grid flexibility services and products are provided	No Response	No Response	No Response	No Response	No Response	No Response	No Response
Germany	Energy (?) - What grid flexibility services and products are provided	Yes if some services are market based, list services	No Response	No Response	Yes List services that are compensated	Yes	No Response	No Response

	Relevant grid flexibility services and products	Procurement mechanism			Compensated services?	Does hydropower currently provide these services to the power grid?	Market size	
		Market Based	Bilateral Contracts/ Administrative Rate	Interconnection Agreement			Quantity	Price/Size
India	Energy (DA Market)	Yes if some services are market based, list services	Yes If any service are through bilateral contracts, list the services	No Response	Yes List services that are compensated	No Response	No Response	No Response
Australia	DA Pre-dispatch	yes	no	no	no	Yes	NIL	NA
Japan	Energy	Day-Ahead Market Intraday Market	Yes - Energy	Yes - Energy	Yes - Energy	Yes	As of FY2019 Day-Ahead Market 292.5TWh-year Intraday Market 5.16TWh-year	Average price as of FY2019 Day-Ahead Market JPY7.93/kWh (0.08 USD /kWh) Intraday Market JPY8.01/kWh
Turkey	1. Energy	1. Day-Ahead Market (DAM)	No Response	No Response	Yes -energy	Yes	No Response	Average Day-Ahead Market Clearing Price 260,19 TL/MWh (2019)
Finland	What grid flexibility services and products are provided	No Response	No Response	No Response	No Response	No Response	No Response	No Response
Colombia	Energy (DA Market dispatch)	Yes	No. However, agents' bids reflect their intention to be dispatch so that they can fulfil the financial commitments.	0	Yes	Yes	Year: 2019 Total Demand: 71.9 TWh-yr Spot Market Energy: 20.4 TWh-yr Contracts Energy: 73.9 TWh-yr	Spot Price Avg Price (2019): 65.23 USD/MWh Bilateral Contracts Avg Price (2019): 55.84 USD/MWh

Footnotes	
a	Complementary Dispatch (CD) to Spinning Reserve (SR): Only provided by thermal units to preserve spinning reserves from hydropower plants
b	Only range of bids; information regarding successful bids NA
c	Day ahead
d	Typical day ahead value in winter. Down to 500 MW two-hours ahead

8.5 Days to Months, Months to Years' Timescale

	Relevant grid flexibility services and products	Procurement mechanism			Compensated services?	Does hydropower currently provide these services to the power grid?	Market size	
		Market Based	Bilateral Contracts/ Administrative Rate	Interconnection Agreement			Quantity	Price/Size
USA - CAISO	1) System RA 2) Local RA 3) Flexible RA	No Response	Yes If any service are through bilateral contracts, list the services	No Response	Yes List services that are compensated	Yes	No Response	SRA - $3.01/kW-month LRA - $3.19/kW-month
Norway	seasonal storage	Only through energy markets (DA)	No	No	Yes	Yes	0	0
Switzerland	System Resource Adequacy	Yes if some services are market based, list services	Yes for market participation and call for tender	YES	Yes - Resource adequacy List services that are compensated	YES (compensation for active power losses)	110 MW/year (average active power losses) 1000 GWh/year (energy for compensation for active power losses)	NA
Canada - HQ	1) Seasonal storage for resource adequacy 2) Wind integration	No	1) heritage electricity pool was defined by a law, issued by the National Assembly of Québec 2) wind integration: through a competitive call for tenders	No	1) seasonal storage: not explicitly- service is included within heritage pool, a larger contract for energy, capacity and flexibility services 2) yes, as part of the wind integration contract	Yes	1) Seasonal storage to be able to deliver 165 TWh/year for all years 2) Wind integration: absorb in real time and firm wind generation (40% in winter, 30% in summer)	NA
Brazil	System Resource Adequacy	Yes	No[a]	No	Yes	Yes	65,478 MW[b]	USD 613B[b]
Austria	Resource Adequacy	No	yes, as a service to the grid	No	yes, as a service to the grid	probably	unknown, defined by the TSO	unknown, defined by the TSO

	Relevant grid flexibility services and products	Procurement mechanism			Compensated services?	Does hydropower currently provide these services to the power grid?	Market size	
		Market Based	Bilateral Contracts/ Administrative Rate	Interconnection Agreement			Quantity	Price/Size
Czech Republic	What grid flexibility services and products are provided	No Response	No Response	No Response	No Response	Yes/No	No Response	No Response
Germany	What grid flexibility services and products are provided	Yes if some services are market based, list services	No Response	No Response	Yes List services that are compensated	Yes	No Response	No Response
India	1) MTOA 2) LTA	No Response	Yes If any service are through bilateral contracts, list the services	No Response	Yes List services that are compensated	Yes	No Response	No Response
Australia	Energy	Yes	Yes	Yes	Yes	Yes	66.27 TWh (2020/21 FY)	$3.42 billion AUD $66.86 AUD/MWh ($2.4 billion USD $46.80 USD/MWh)
Japan	Resource Adequacy	Yes	Bilateral contract (TSO and provider)	Yes - Resource adequacy	Yes - Resource adequacy	Yes	Auction for FY2024 (held inFY2020) 167.69GW-year	Auction for FY2024 (held inFY2020) JPY14137/MWh-year (134.76 USD/MWh-year
Turkey	Security of Supply	No Response	Long-term generation adequacy (self-supply and contracts)	Long-term generation adequacy (self-supply and contracts)	Yes - Security of Supply	Yes	No Response	No Response
Finland	What grid flexibility services and products are provided	No Response	No Response	No Response	No Response	No Response	No Response	No Response

	Relevant grid flexibility services and products	Procurement mechanism			Compensated services?	Does hydropower currently provide these services to the power grid?	Market size	
		Market Based	Bilateral Contracts/ Administrative Rate	Interconnection Agreement			Quantity	Price/Size
Colombia	Capacity Market (Generation expansion) Transmission Expansion	Yes. Auction mechanisms	NA	NA	Yes	Yes.	Results Capacity Market Auction (2018 Auction - Projected Demand Dec2022-Nov2023): - 91.37 TWh-yr	15.1 USD/MW (i.e. price per each of MW of installed power) What Year?

Footnotes

a the winner of the public auctions signs PPAs contracts with all DisCos

b from 2008-2015

8.6 Trends and Developments

	Short-term			**Medium term**	**Long-term**	
	Sub-seconds to seconds	**Seconds to minutes**	**Minutes to hours**	**Hours to days**	**Days to months**	**Months to years**
USA - CAISO	Refined RMR procurement and pricing mechanism in 2019 [3].			New day-ahead market products to reserve real-time dispatch capability. [1] 1. **Reliability energy (REN)** (and the associated **reliability capacity up/down RCU/RDC**), replaces existing residual unit commitment process to schedule sufficient dispatch capability to meet the load forecast. 2**. Imbalance reserves (IRU/IRD)**, will ensure the day-ahead market schedules sufficient real-time dispatch capability to meet net load imbalances that materialize between the day-ahead and real-time markets.	Enhanced System, flexible and local RA capacity procurement to reflect evolving needs of the grid. [2]	
Norway	Demonstration project for purchasing FFR. Increased need in periods with high import and high wind power production in the Nordic synchronous area					
Switzerland		1. Introduction of 4-hour products and procurement one day prior [4]; 2. PICASSO project: platform for requesting aFRR. The platform is likely not only to supersede the Grid Control Cooperation, but also to minimize costs by optimizing requests. Expected to take place by the end of 2021 [4].	MARI project: platform for internationally coordinated requests for mFRR (activation time of 12.5 min and delivery time of 15 min). mFRR replaces tertiary frequency control reserve product. Procurement of power is still regulated nationally. Expected to be launched by the end of 2021 [4,5].		From November 2019 (delivery 2021), new conditions apply: call for tender yearly (first and last day of year), quarterly (first and last day of quarter) and monthly (first and last day of month)	

	Short-term			Medium term	Long-term	
	Sub-seconds to seconds	**Seconds to minutes**	**Minutes to hours**	**Hours to days**	**Days to months**	**Months to years**
Brazil	Possibly changing the remuneration approach to consider the availability of the service (fixed annual amount with some reduction due to unavailability's) and a variable remuneration for operating time (replacing the remuneration for MVArh).	Possibly changing the remuneration methodology to encourage greater service availability.	Discussion about how to increase the incentive to avoid failures in real situations.	**1.** Discussion of including costs of operating restrictions directly in price bids. **2.** Discussion about how to atrct more participants to the pilot program.	A Bill on electric sector commercial model of the is under analysis in the Brazilian Congress, the separation between capacity and energy in two products with different prices (currently re commercialized as single product), the introduction of a price bidding procedure in short-term market (currently, spot prices are calculated based on stochastic optimization models developed by CEPEL). If approved, room will be opened for the definition of new products for the provision of ancillary services.	
Austria	Discussion about covering the costs since the causality principle is not respected by the current mechanism by socializing these costs to generators only.					
Czech Republic	-		EU platforms for joint procurement of energy from mFRR and aFRR introduced till mid-2022 - full activation times will be shortened; procurement will be cross-border	N/A	N/A	N/A
Germany	phase-out of thermal power-plants in Germany until 2022 (nuclear) and 2038 (coal),					
	phase-out of large amount of rotating masses	phase-out of biggest providers of this reserve				
India	1. Aggressive Renewable penetration, minimum inertia to be kept in the grid may be introduced [2]. 2. Reactive power compensation for generators is being considered.	AGC on central sector Thermal plants having capacity 200 MW and above & Hydro plants having capacity 25 MW and above (excluding Run of River Hydro projects)	Market based Ancillary services proposed			
Australia	System strength frameworks under review. Core of work underway by ESB as part of the post-2025 market design framework. Primary Frequency Response to be mandated, and w/ future commitment to explore appropriate remuneration.	Market soon to commence consideration of FFR (1-2 seconds). Increased provision of Primary Freq. Response likely to diminish value of regulation and contingency FCAS? Ongoing uptake of VRE likely to increase need for proactive frequency management.	Transition to 5 minute settlements underway. Market to commence consideration of 'Operating Reserves' product that would be procured 30 minutes ahead of dispatch and provide ramping services to cover for changes to VRE output or some contingencies.	Day-ahead and ahead markets being considered as part of the ESB's Post-2025 market design process.	Capacity mechanisms being considered as part of ESB's Post-2025 market design process	Capacity mechanisms being considered as part of ESB's Post-2025 market design process

	Short-term			Medium term	Long-term	
	Sub-seconds to seconds	Seconds to minutes	Minutes to hours	Hours to days	Days to months	Months to years
Japan		Establish Balancing market - for FCR in FY2024	Establish Balancing market - for RR in FY2021 - for FRR in FY2024		Establish Capacity market in FY2024	
Turkey	N/A	N/A	N/A	N/A	N/A	N/A
Finland	N/A	N/A	N/A	N/A	N/A	N/A
Colombia	N/A	N/A	N/A	N/A	N/A	N/A

REFERENCES

[1] http://www.caiso.com/InitiativeDocuments/StrawProposal-Day-AheadMarketEnhancements.pdf

[2] http://www.caiso.com/InitiativeDocuments/ThirdRevisedStrawProposal-ResourceAdequacyEnhancements.pdf

[3] http://www.caiso.com/Documents/Sep27-2019-OrderAcceptingTariffAmendment-RMR-CPMEnhancements-ER19-1641.pdf

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[5] https://www.acm.nl/sites/default/files/documents/2019-02/voorstel-tennet-_mfrr-platform-20.pdf

[6] http://www.caiso.com/InitiativeDocuments/StrawProposal-Day-AheadMarketEnhancements.pdf

[7] http://www.caiso.com/InitiativeDocuments/ThirdRevisedStrawProposal-ResourceAdequacyEnhancements.pdf

[8] http://www.caiso.com/Documents/Sep27-2019-OrderAcceptingTariffAmendment-RMR-CPMEnhancements-ER19-1641.pdf

9 Appendix B: Terminology

aFRR	Automatic Frequency Restoration Reserve
AGC	Automatic Generation Control
AS	Ancillary Service
CAISO	California Independent System Operator
CE	Continental Europe
CD	Complementary Dispatch
CFC	Contingency Frequency Control
DAM	Day Ahead Market
DisCos	Distribution Companies
EIA	Energy Information Administration
EC	European Commission
ENTSO-E	European Network of Transmission System Operators for Electricity
FACTS	Flexible AC Transmission System
FCR	Frequency Containment Reserve
FCRD	Frequency Containment Reserve for Disturbances
FCRN	Frequency Containment Reserve for Normal
FFR	Fast Frequency Reserve
FRA	Frequency Resource Adequacy
FRAS	Frequency Response Ancillary Service
FRR	Frequency Response Reserves
GW	Gigawatt
GWh	Gigawatt hour
HQ	Hydro Quebec
HQD	Hydro Quebec Distribution
HQP	Hydro Quebec Production
HVDC	High Voltage, Direct Current
IGCC	International Grid Control Cooperation

IEA	International Energy Agency
ISGAN	International Smart Grids Action Network
LFC	Load Frequency Control
LTA	Long Term Access
LRA	Local Resource Adequacy
mFRR	Manual Frequency Restoration Reserve
MVAr	Mega volt amps (measures the component of power that is reactive)
MVArh	MVAr hour
MW	Megawatt
MWh	Megawatt hour
PFC	Primary Frequency Control
PFR	Primary Frequency Response
PPA	Power Purchase Agreement
PSH	Pumped Storage Hydropower
PV	Photovoltaics
RA	Resource Adequacy
RFC	Regulation Frequency Control
RKM	Nordic market
RMR	Reliability Must-Run
RR	Replacement Reserve
RTM	Real Time Market
SA	Synchronous Area
SRA	System Resource Adequacy
SFC	Secondary Frequency Control
SFR	Secondary Frequency Response
SR	Spinning Reserve
TERRE	Trans-European Replacement Reserves Exchange
TSO	Transmission System Operator

TVarh	Teravar Hour
TW	Terawatt
TWh	Terawatt- Hour
USD	U.S. Dollar
VRE	Variable Renewable Energy