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**IEA** Hydropower

# Flexible hydropower providing value to renewable energy integration

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## SUMMARY

This White Paper describes the role of hydropower and the need for flexibility in the future electricity system, aiming to provide a high-level overview of key issues with the intent of identifying priority areas for further in-depth reviews and analyses. As increasing shares of variable renewable energy sources (VRE) are integrated into electricity systems, the need for flexibility and energy storage at timescales ranging from milliseconds to months arise. Hydropower is the largest source of renewable energy today, with hydropower and pumped hydro storage playing an important role in integrating and balancing VRE. Hydropower is a mature technology, but many older plants need upgrading, refurbishment and up-to-date modes of operation.

At different shares of VRE in the system, different capabilities of hydropower become relevant to support the integration. Unlike many alternatives, **hydropower offers a unique range of possible flexibility capabilities** that need to be fully understood as global electricity systems undergo transformation, and ongoing reforms consider competing approaches, markets, and technologies. Hydropower must compete with several other technologies to provide these system services, such as batteries, other dispatchable generation technologies, demand-response, smarter networks, etc.

As integration of VRE increases, it becomes more important to provide the right capacity at the right times, rather than merely providing large amounts of energy, which is increasingly provided by VRE sources. As the needs for flexible and balancing capacity increase, there are fewer or no competitors to hydropower that can deliver emission-free solutions – particularly over long durations. The value of flexibility to the power system and the users of electricity is difficult to quantify, as it is impossible to imagine modern societies without a secure electricity supply. In theory, **the market value of flexibility-related products should reflect the value these products provide to the electricity system**. However, today these services are not fully recognized nor adequately remunerated in any markets. To achieve an efficient system in the long-term, **authorities** should design markets that provide business opportunities that trigger investments on the demand side or in generation and system infrastructure so that all the services required to ensure a secure, reliable and affordable supply of energy are delivered. Existing and new **hydropower plant owners** should analyse the capability and possible changes in capability after deciding which type(s) of flexibility are best suited for their assets.

# 1.

## INTRODUCTION

This White Paper is the first in a series planned by the IEA Hydropower Technology Collaboration Program (IEA Hydro), 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 realise the value of its contributions to electricity systems. The target audience of the paper is people interested in energy policy, renewable energies, transmission grids, as well as the power industry, regulators, operators, scientists and informed stakeholders.

Achieving least-cost, reliable and environmentally sustainable electricity systems is a global challenge. Rapidly changing electricity technology costs, ageing of existing assets and the fast evolving electricity generation mix are also gaining significant attention from policy makers, regulators and industry in many countries. In addition, decarbonising the energy sector is one of the main mitigation measures to fight climate change and prevent high levels of global warming. While various countries and regions have chosen different ways of decarbonising their electricity supply, increasing the share of renewable electricity production is largely universal and remains a key effort in many countries. To ensure a reliable electricity system, the system operator must be able to balance demand and supply of electricity at all times. Hence, flexible resources in the power system are essential to ensure that consumers can use electricity when needed.

Driven by favourable policy environments, market opportunities and substantial cost reductions, variable renewable energy (VRE) like wind and solar photo-voltaic (PV) energy, are becoming increasingly important energy sources to expand energy access and enable electrification based on clean energy,

essentially changing the structure and operation of the power system. This has implications for both system resources – power plants, grids, demand, and storage - individually, and for the system as a whole. Power production from wind and solar energy needs to be balanced against consumption through various ways, including:

- Energy storage
- Demand response and management
- End-user and generation flexibility
- Flexible transmission technologies and smart grid solutions
- Curtailment of generation and load

The options are all promoted by research and demonstration activities as well as by political support. Extensive curtailment of renewable production or strong rationing of consumption are both less desirable options that where possible should be avoided or managed. Optimal planning and operation of the electricity system will seek to avoid overinvestment, inefficient solutions, curtailment and rationing. Hydropower is already playing an important role as by far being the largest of the worlds' grid-connected energy storage technologies. Reservoir, run-of-river and pumped storage hydropower will continue to play an even more important role for future development of global renewable electricity systems. In particular, these hydropower resources can deliver important flexibility services to support the provision of secure, reliable energy supply, whilst underpinning the effective integration of cleaner energy technologies. This paper describes the current status of hydropower's role in the energy system and identifies electricity system issues, future pathways and the need for further work, analyses, communication and collaboration.

# 2.

## STATUS OF HYDROPOWER

Hydropower is a renewable energy source where electrical energy is derived from the potential energy in storage of water by converting it to kinetic energy when moving from high to lower elevation. Hydropower is a mature and widely used technology. In 2018, global installed hydropower capacity was 1 292 GW producing 4 200 TWh of electricity in 159 countries (IHA 2019). The global installed capacity of pumped storage is now 160 GW (IHA 2019). Hydropower is among the most efficient technologies for production of renewable electrical energy, with a typical efficiency of 90% or better for “water-to-wire.”

Where the natural resources are favourable, hydropower is cost competitive producing electricity at equal or lower cost, compared to thermal energy sources like coal, oil, or gas, typically in the range of 2–5 US cents per kilowatt hour (Killingtveit 2018; IRENA 2017). Wind and solar PV generation are also becoming more and more competitive to thermal generation, and they are already being implemented without the need of subsidies or special fees in many countries.

Globally, hydropower is the largest source of renewable energy in the electricity sector with a share of 62 per cent of total renewable generation (IHA 2019). The technical potential for increased hydropower generation is large enough to meet substantial further deployment both in the medium (2030) and long term (2050). A realistic scenario is to double the annual generation (4 102 TWh in 2016) to over 8 000 TWh by 2050 (Killingtveit 2018). It is also expected that the current installed capacity in pumped storage hydropower of around 160 GW (IHA 2019) will increase significantly, estimated to between 412 and 700 GW by 2050 (IEA 2012).

Hydropower can be divided in three categories: reservoir storage, run-of-the-river and pumped storage hydropower. These categories generally describe the relationship between storage volume, inflow and water residence times of the reservoir. In reality, reservoirs

exist on a spectrum. Natural lakes may also be used as reservoirs, often by damming to expand their volume and surface area. Hydropower with reservoirs is together with bioenergy the most flexible forms of renewable energy.

The relationships between reservoir storage, inflow to the reservoir and the installed power capacity of the power plant determine plant operational flexibility. In addition, a range of technical and regulatory properties are also important for assessing the flexibility of a hydropower plant. These are:

- The size, operation and configuration of gates, tunnels, pipelines and water conduits to bring water to the turbines and to lead the water out
- Number of turbines and generators, how they are operated and the range of operation under part-load
- Start-up and shut-down times, ramping rates for turbines
- Access to and strength of grid connection
- Timing, amount and variation in inflow, as well as storage capacity and availability of the reservoir or intake
- Legislation and regulation, including environmental constraints and obligations to provide both energy and other services like flood and drought control, navigation, recreational use, etc

For pumped hydro storage, similar technical and regulatory issues are important. Many pumped storage hydropower plants have no or very limited inflow. In these cases, the volume of upstream and downstream reservoirs, type of equipment, number of units and installed turbine and pump capacity determine flexibility. The main design purpose of the majority of currently installed pumped storage hydropower, was to allow efficient base load generation by covering periods of peak demand and absorbing energy during hours of low demand, as well as providing ancillary services, such as black start capability, islanding operation, grid restoration and stabilisation of the network frequency and voltage level (Deane et al

2010). These system services are becoming increasingly important as more VRE is installed.

Pumped storage plants use either a reversible pump turbine or separate turbines and pumps. The design of pumped storage hydropower is based on more starts and stops including change of energy direction and alternating electricity production, than conventional hydropower plants. Therefore, it is very important to ensure a safe dynamic behaviour of the whole system, including water ways, turbine, pump and generator. The dynamic behaviour is on one hand connected to the conduit system design and the performance characteristics of the plant. On the other hand, is the demand of having an efficient machine with stable operation both at low and high loads (i.e. low and high production or low and high flow). Noise, vibrations and pressure pulsations can be handled also at a highly dynamic operation status to avoid failure in operation, fatigue breakage or other events.

As conventional hydropower also will be used more frequently for flexible generation, the same challenges applies to reservoir hydropower. More flexible operation of hydropower requires increased maintenance and more intensive surveillance and monitoring of the status of the plant components. Modern technology, digitisation, improved maintenance methods and innovations in the technical components and system design are contributing to manage these challenges. Also run-of-river hydropower plants with limited storage capacity can be operated or redesigned to operate more flexible in many cases.

In addition to providing renewable energy and energy storage, hydropower also provides services like water supply, irrigation, flood protection and drought mitigation, as well as supporting navigation, tourism and recreation. Hydropower may also have large negative impacts on the aquatic ecosystem and societal issues, if not built and operated following modern sustainability practice. None of these aspects are treated in this paper.



Photo Anurud Killingtveit



# 3.

## WHAT KINDS OF FLEXIBILITY ARE NEEDED?

On the aggregate level, power system flexibility is defined as the ability to effectively cope with variations in the supply or demand of electricity. In other words, to balance total load and generation at any time. In systems with high shares of wind and solar energy, system flexibility is becoming increasingly important to maintain balance in the system due to the variability and uncertainty in these resources. However, power systems worldwide will be able to cope with increased flexibility requirements differently based on a combination of their technical and institutional structure (IEA 2017, 2018). A number of factors underpin the inherent flexibility of a power system, including:

- Geographical distribution of both VRE and other generation sources
- Overall power system size
- Power plant flexibility
- Regional interconnection and internal bottlenecks
- Access to demand-side flexibility and storage
- Correlation of VRE generation and demand as well as an area wide correlation of VRE generation

On the institutional side, system operation protocols, market design and technical standards also play a

decisive role in how the system’s assets are operated and what type of assets are built.

A first good indication of the types of flexibility required by the power system can be obtained by looking at the phases of VRE integration as proposed by the IEA (2017). Establishing a common framework for the flexibility requirements sets the scene for the types of flexibility hydropower (and conventional energy) can contribute to cost-effectively. Rather than looking at specific shares of VRE deployment, the phases framework is defined by the typical sequence of challenges faced by system operators as more and more VRE sources are connected to the grid. Table 1 describes briefly the different phases of VRE integration.

In each of the phases, the requirements for different types of flexibility vary in terms of the time-horizon that they cover. IEA (2018) defines six time-horizons for flexibility, grouped in short-term flexibility requirements around system stability and longer-term stability requirements relating to weather and climactic conditions, as well as the availability of appropriate capacity and resources (Table 2).

**Table 1. Different phases of VRE integration (after IEA 2017)**

Phase	Description	Examples
1	At initial stage of VRE deployment with no relevant effects in system operation	Still many countries
2	Additional flexibility needs can be met by minor adjustments in existing operations	Brazil, China, India, Sweden, Texas
3	VRE generation determines system operations in order to maintain stability	Italy, Germany, Portugal, Spain, UK, California
4	Additional investments in flexibility resources are needed to balance the system	Ireland, Denmark, South Australia
5	Structural surpluses of VRE generation from weeks to months may lead to curtailment	
6	Structural over- or under-supply over seasons to years validates the need for sector coupling	

**Table 2. Different timescales of power system flexibility**

Flexibility type	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
<b>Issue</b>	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
<b>Relevance for system operation and planning</b>	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)

While the specific type of flexibility required by the power system will be largely determined by its own technical and institutional characteristics, it is possible to make a general mapping of the type of flexibility requirements which may increase at particular levels of VRE integration. These can be partly inferred from the phase descriptions provided earlier on.

For example, at **Phase 1**, given that there is no impact in system operation it can be concluded that no additional flexibility is needed, and the system is able to run with its existing embedded flexibility. In **Phases 2 and 3** it is possible to appreciate a closer link to the need for additional very-short term to medium-term flexibility, related to increased rates of ramping. In **Phase 2** this relates to the increased cycling of power plants to balance small fluctuations in VRE supply.

In **Phase 3** by contrast, the increase in variation and difference between supply and demand, requires a systematic increase in highly reliable power system

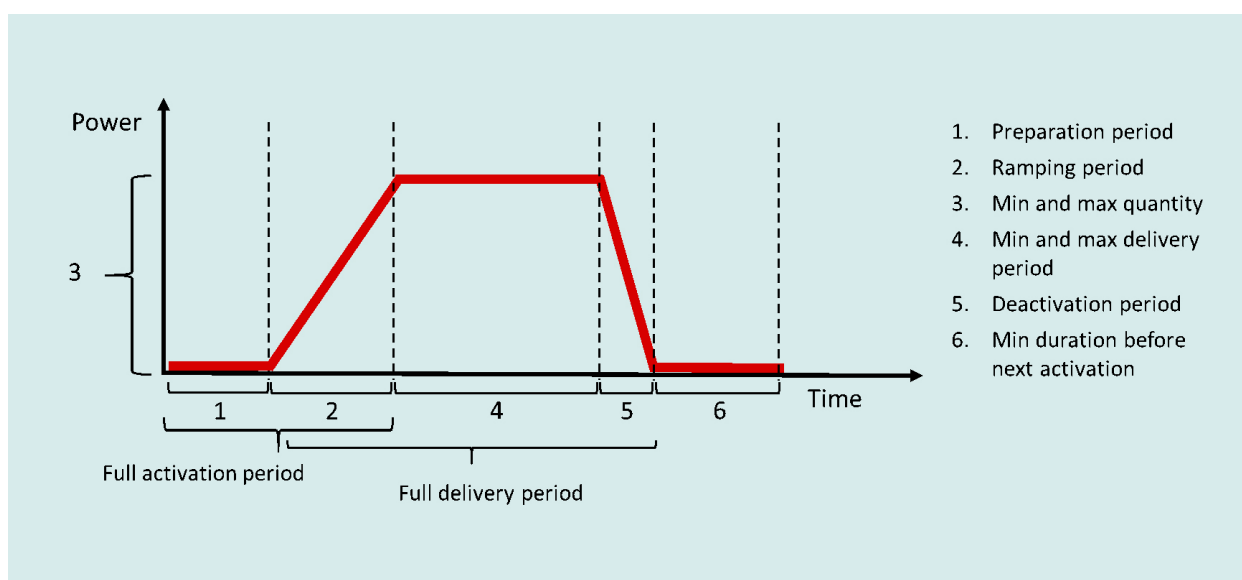
flexibility, either through improving operations in existing plants or carrying out retrofits.

In **Phase 4**, where VRE starts to provide a substantial share of electricity demand over longer periods, ultra-short term, medium-term and long-term flexibility become more relevant. This is due for example to very steep ramps in VRE output (ultra-short term) and in the long-term as peaking capacity is required to ensure adequacy, particularly as conventional baseload resources are decreasingly available (decommissioned).

Finally, **Phases 5 and 6** provide an idea of what the future, and in some cases near-future, may look like when renewable energy surpluses or shortages start to become a feature of the power system over extended periods of time. In both phases, the ability to store energy cost-effectively and without large losses in energy over prolonged periods of time will be key to value the power system.

The flexibility an electricity system requires must be described using several characteristics. The capability of delivering flexibility can be defined as the combination of the possibility of delivering energy and power, and at which speed (ramp rates) power can change. An interesting example of how this capability is defined, can be found in the ongoing work by ENTSO-E to integrate balancing markets in Europe and facilitate cross-border trade of flexibility (ENTSO-E 2018). Today market structures and product

definitions vary between countries, making it difficult to trade balancing products across regions. ENTSO-E is therefore working towards standardised products across European countries. As part of this, important characteristics have been described, which defines the capabilities of a power plant or a service to deliver needed flexibility. Figure 1 illustrates the combination of power, energy, ramp rates (rates of changes) and relates it to different phases in the market.



**Figure 1. The capability illustrated as power on the y-axis, energy as the product of power (y-axis) and time (x-axis), and ramp rate as the rate of change in power. Different time periods and products for operation in the market are also shown.**



# 4.

## HOW CAN HYDROPOWER CONTRIBUTE?

In many countries, reservoir and pumped storage hydropower is already widely used for providing flexibility, energy storage and ancillary services in the electricity system. However, hydropower is also used extensively to provide base load energy in many countries and regions that have rich hydropower resources, like Norway, Costa Rica, Venezuela, Tajikistan, Quebec, British Columbia and Tasmania. In these countries and regions, hydropower provides almost all the electricity in the system. Even though the share of hydropower is lower in their energy mix, hydropower also provides base load generation in countries like Sweden, Austria, Switzerland, Russia, China, India, USA and Brazil. To help the transition towards renewable energy systems, it is crucial that hydropower also in the future provides base load electricity as well as flexibility.

Reservoir hydro also provides security of supply in many countries and regions. Precipitation and inflow are characterised by seasonal and inter-annual variations in most regions, and hydropower reservoirs have been used as buffers to provide a secure supply of energy throughout the year. This seasonal use of reservoirs has a long-term cycle for filling and emptying, which allows for much more extensive use in between the periods of maximum and minimum reservoir levels. This requires that the net change in water (energy) of short- and medium-term emptying and filling over hours, days or weeks are close to zero, not impacting the long-term seasonal cycle.

There are two options for how existing reservoir hydro can be refurbished in order to contribute to increased flexibility at multiple time scales to enable a larger share of VRE in the power system, and to prevent curtailment of other renewables, without building new dams or increasing existing dams:

- If a reservoir hydropower plant discharges to another reservoir or a lake, it is possible to redesign the plant to include a pumped storage facility by installing pumps or reversible pump turbines.

- The second option is to increase the capacity in existing power plants (increasing the turbine capacity), which can be done also when there is no lower reservoir available.

Both options will require civil works, new machinery and in some cases also reinforced grid connection. However, no new dams or reservoirs would be required for this purpose, hence the additional environmental impact will be small or negligible. Installing pumps will make it possible for reservoir hydropower to participate in short- and medium-term flexibility much more often than when just increasing the capacity, as the plant can be operated as a battery and water can be "re-used" many times. However, these options are site specific and depend on the plant capacity and layout, active reservoir storage and regulatory permits.

Referring to the phases of VRE integration in the system described in chapter 3, hydropower can contribute to flexibility in all phases. However, the best use of hydropower may vary according to the needs in different phases and the characteristics of the hydropower plant.

In **Phase 1**, there is no extra flexibility needed to be provided by hydropower. In **Phase 2**, there is a need for additional short-term flexibility related to small-scale rapid variation in power generation. Hydropower can provide additional flexibility for such ancillary services and short-term variations in the power system, but there are several competing technologies like batteries, flywheels and various types of demand-side and supply-side flexibility that also can contribute in this phase.

In **Phase 3**, the ability to quickly ramp and start at any time including switching between producing and consuming energy, assuming no transmission or water management constraints, may provide an advantage to hydropower over conventional thermal resources. This is due to technical and economic reasons, as well as in terms of greenhouse gas emissions. Thermal

plants often have higher costs and run less efficiently at partial loads than hydropower, even though hydropower also may experience constraints and inefficiency at partial loads.

In **Phase 4**, in addition to ultra-short, short, and medium-term flexibility, long-term flexibility becomes very important as the energy system becomes increasingly dependent on weather variability. Hydropower with storage and pumped hydro have fewer competitors that supply medium- and long-term flexibility. In Phase 4, increased system value can be identified by providing the right capacity at the right times, rather than providing energy volume, which is increasingly provided by VRE sources. The ability to capture this so-called energy-option value will be key in ensuring the profitability of any kind of technology that is used to firm-up VRE generation.

In **Phase 5 and 6**, hydropower can provide substantial amounts of both capacity (power) driven short term flexibility and a capacity plus energy-driven medium-term and long-term flexibility (power and energy).

The unique position of hydropower from a flexibility supplier perspective is to store primary energy (GWh) with very small losses as the potential energy of water, and to provide power capacities (GW) at a high degree of predictable availability. This becomes even more important, when flexible thermal units are phased out and decentralized solutions (batteries, e-mobility, demand-side management, etc) are expected to provide (short term) flexibility, but in a less predictable manner.



# 5.

## WHAT IS THE VALUE OF FLEXIBILITY?

The value of flexibility to the power system and the users of electricity is difficult to quantify. In non-market systems, flexibility was built into the system with the value included in the cost of energy to the consumer. This changed with the move to market systems. In both market- and non-market-based systems, the production schedules of flexible units are adjusted with the aim to ensure that supply and demand is continuously balanced at the lowest possible cost. However, the value of providing these services differ between locations and the status of the system, and the fundamental challenge is to ensure correct reward for services and products to provide the right investments incentives in the long run.

Table 2 describes how key flexibility services are needed at different time scales in the power system, and the different type of issues that can arise if these needs are not met. The highest value of flexibility services is when the power system is operated at the extremes, i. e. periods with deficit or surplus of power and/or energy. In periods with deficit of power and/or energy, flexible units provide value by increasing the production or reducing the demand, thereby restoring the power quality (voltage and frequency), avoiding or limiting load shedding and in the most extreme situations avoiding blackouts. This results in avoided additional costs for the electricity consumers and system operators. In periods with surplus of power and/or energy, flexible units provide value by reducing the production or increasing the demand, thereby restoring the power quality (voltage and frequency) and limiting curtailment of VRE. Through limiting curtailment of surplus energy, flexible units contribute to higher value of the installed VRE capacity and to lower system costs than if large amounts of available energy would have to be curtailed. In addition to flexible units that only produce or consume energy, pumped hydro storage both consume and produce energy and provide value to the system both in periods with surplus and deficit. Reservoir hydro cannot consume electricity, but it is possible to hold

back production over short and long periods, thereby shifting production to the periods when generation is needed the most.

As discussed in chapter 3 and 4, the flexibility services needed should be characterised by the required capabilities, such as ramp rate, power capacity and energy/duration. The number of technological solutions capable of delivering the product (the supply) will vary. Hence, the costs of providing the required services can vary considerably between markets and products. Similarly, the demand or need for flexibility services will vary between the power systems, products and in time. While the need for short term flexibility in periods can be quite high, the supply – with several technologies able to meet the requirements – can also be sufficient. Still, the costs can vary significantly, and in market-based systems the value of providing such services will be set by the cost of the most expensive technology required to maintain the balance. The periods where power and energy are required for longer durations, can be more precarious as there are only a few existing and new potential technologies capable of delivering such services. This is particularly true when considering systems or scenarios where most thermal units have been decommissioned. If short periods of high demand and low generation from wind and solar energy arrives in a sequence, the resources to provide power and energy may already be tapped with not enough time to recharge batteries, pumped hydro or other storage technologies. From the power system perspective such situations can be challenging, and it is important that these types of services are adequately considered in the long-term planning of the system. Constructing variable renewable power generation and transmission capacity to meet the “worst possible case” quickly becomes an expensive solution. Alternative long-term flexibility solutions, even though very rarely used, could therefore reduce the overall investment cost of transitioning the power system to a low-carbon system.

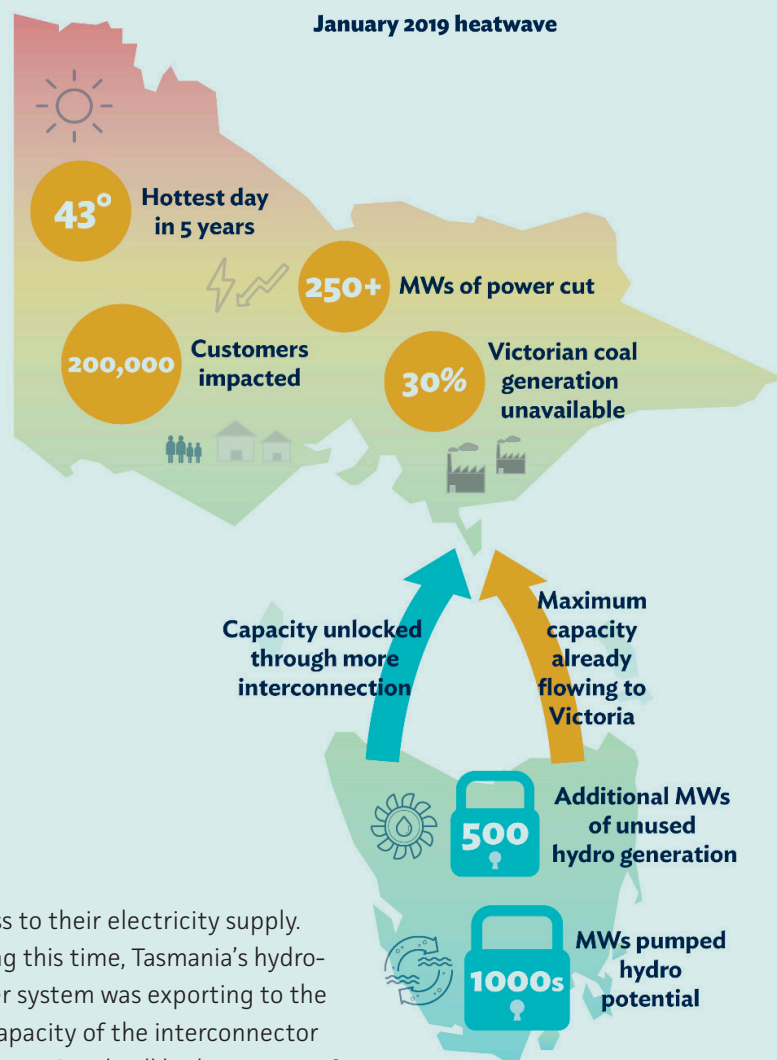
## Battery of the Nation – an opportunity to leverage the potential of Tasmania’s hydropower

The island state of Tasmania (one of the regions in the NEM) presently supplies ~90% of its electricity needs from hydropower. Tasmania’s hydropower system has been designed with surplus capacity and is highly flexible. The constraints on operation are more associated with energy (availability of water) than capacity. Nevertheless, even when water is comparably scarce, some water is retained above minimum operating levels meaning that there is nearly always excess capacity available.

*Battery of the Nation* is a strategic initiative to unlock the potential from Tasmania’s power system. Tasmania already supplies almost 40% of the flexible generation in the NEM, and yet only represents 5% of the demand. Much of this flexible supply is presently used to supply baseload needs, this will not be the best use of the valuable flexible supply as we move into a future where the supply–demand balance needs more active management. With further interconnection, these valuable variable resources can be better shared with the whole power system.

The accompanying image shows a real case study of a heatwave in January 2019 where 200,000 customers lost

access to their electricity supply. During this time, Tasmania’s hydropower system was exporting to the full capacity of the interconnector (~500 MW) and still had 500 MWs of stranded capacity that was unable to supply to the market in need. The image also shows the vast potential for cost-effective and long duration pumped hydro that can be used to manage both surpluses and scarcity of energy in a more variable future.



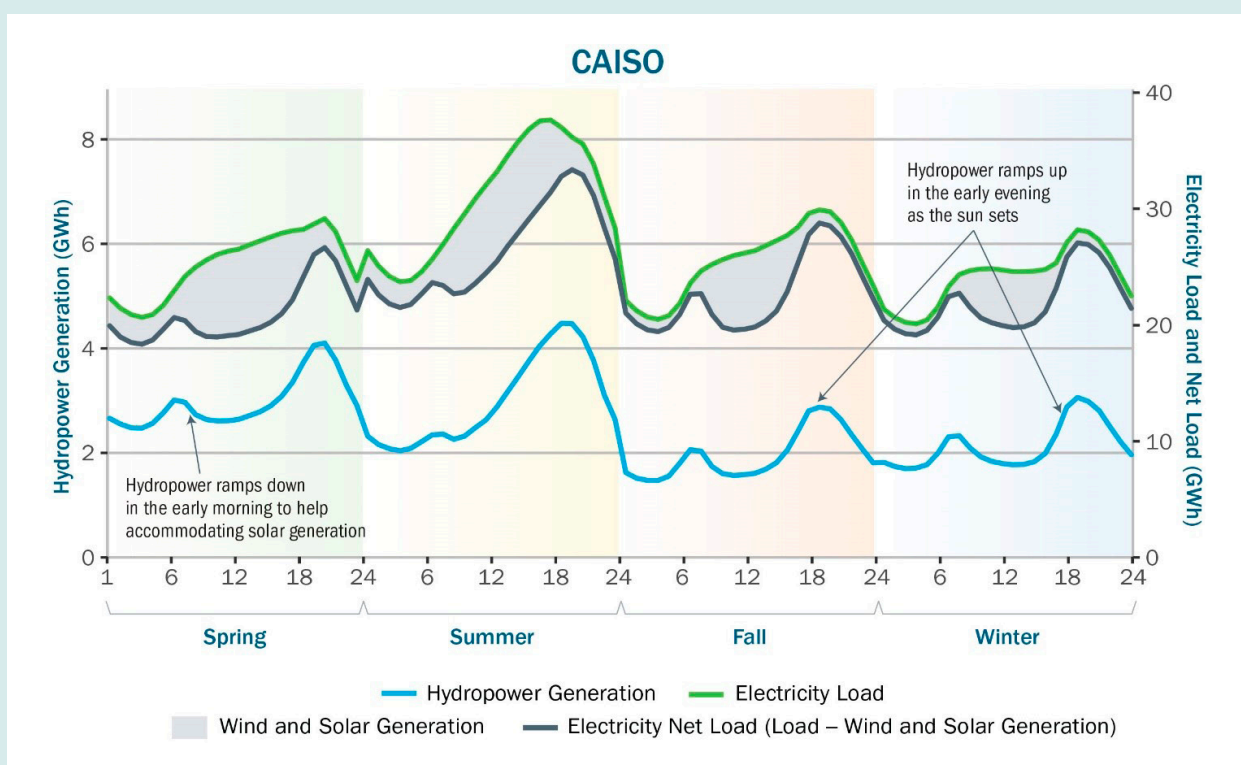
Hydropower has a great potential to provide a wide spectrum of flexibility services, as discussed in chapter 4. Hydropower can increase production in periods with energy deficit and reduce VRE curtailment in periods with energy surplus by pumping or holding back hydropower generation. In market-based systems, this is part of the business model for pumped hydropower plants, which buy the electricity at low price for pumping and sell it back while generating at higher prices. We provide two examples to highlight the role of hydropower in systems with high levels of VRE (see text boxes). The first example is from the Australian National Electricity Market (NEM), which currently is seeing a rapid expansion of VRE, and is on the brink of

entering Phase 3 and rapidly heading towards Phase 4 based on the categorization in Table 1. Moreover, the Australian NEM has no interconnection with other power systems and cannot spread the risk and share the opportunities of higher VRE levels with neighbours. To manage this challenge, Australia is looking to maximise the use of flexible supply, particularly from existing hydropower through the 2GW Snowy 2.0 pumped hydro storage project, and the Battery of the Nation initiative in Tasmania. The second example is from the US and illustrate how hydropower respond to variations caused by solar power in the Californian system, a market that today is evaluated to be in Phase 3 (see Table 1).



## Load-following flexibility of hydropower fleet in California

Hydropower in the US contributes to ramping and flexibility needs daily, in every season of the year. Daily hydropower generation profiles closely resemble load shapes in all markets operated by System Operators (ISOs) or Regional Transmission Organizations (RTOs) in the US. The hydropower fleet provides substantial load-following capability. During fall and winter months, generation from hydropower is observed to follow the early-morning and mid-evening electricity demand peaks, whereas in summer, there are sustained hydropower ramps from mid-morning to late afternoon, especially in California Independent System Operator (CAISO) territory. In CAISO, solar generation profiles influence the daily hydropower generation profile significantly; hydropower is more closely correlated with net load (i.e., load net of wind and solar generation) than with load.



The figure shows average load, net-load, and hydropower dispatch in CAISO. Hydropower generation profiles are based on data from January 2014 – December 2017. Source: Oak Ridge National Laboratory – 2017 Hydropower Market Report, 2018



# 6.

## THE VALUE OF PROVIDING FLEXIBILITY IN MARKET-BASED SYSTEMS

In competitive power markets, the marginal cost of the last supply or demand resource needed to balance demand and supply sets the power price (merit order). This ensures that the balance is kept at the lowest possible cost. Today, the income of power producers in restructured power systems is mainly based on sale of energy, where the product sold is per unit of energy independent of the qualities of the product. The value of flexible power generation and storage is mainly realized through adjusting production to high price periods, thereby achieving a higher realized power price than inflexible technologies. In addition, most countries have separate markets for balancing and ancillary services to ensure available capacity to balance deviations between demand and supply. Some countries also have separate capacity markets to ensure investments in sufficient capacity to meet peak demand in the long term.

In theory, the market value of flexibility-related products should reflect the value these products provide to the electricity system. However, this presupposes that the market structures and products are sufficient for the electricity producers to capture the actual value of the full range of services provided to the system. If not remunerated correctly, the revenues obtained by different technologies competing in the electricity market might not reflect the overall cost of a well-functioning, reliable and secure electricity system. In the long run, this can lead to sub-optimal investments, which again can lead to new challenges for reliable and secure system operation and higher system costs in the longer run.

The value of delivering flexibility to the grid depends on the status of the power system. The flexibility needed in the power system should be divided into different categories and corresponding products, where the value of a specific product depends on its specification. The aim of power system planning and operation, in both market-based and non-market-based systems, is to enable cost-effective and reliable power supply in the short- and long-term

through optimal investments in and operation of the power system. To achieve an efficient system in the long-term, the markets should provide business opportunities that trigger investments on the demand side or in generation and system infrastructure so that all the services required into the system are provided, accounting for the transitioning resource mix. As a consequence, new market mechanisms might be required to ensure sufficient flexibility of different scales, as described in Table 1 and Table 2, for reliable operation in both the short- and long-term. This includes available flexibility to be able to handle infrequent events such as longer durations of weather-related under- or over-production of VRE. Achieving a cost-effective and reliable power supply is particularly challenging in transition periods when the energy system is going through large changes.

The value of delivering energy and adjusting production to high price periods is expected to be an important source of income for flexible electricity producers in the long run, even with falling average energy prices. Trading in day-ahead and intraday markets is therefore expected to remain the main source of income for many years. However, with increasing variability and uncertainty in generation profiles, the price variation will increase, and the value of energy will be more dependent on when the energy is delivered than with today's electricity prices. Hence, the value of being able to adjust production or demand to the price will increase, and the difference in realized power price of different technologies will become larger. This means that even if the price achieved per unit of energy delivered is reduced on average, the value of flexibility increases (Schäffer et al., 2019). The differences in realized power prices between technologies will depend on the magnitude and frequency of the extreme low and high prices (Schäffer and Graabak, 2019).

The magnitude and frequency of the extremes, i.e. the lowest and highest power prices, are important factors for the value of flexible operation. Longer

periods with low electricity prices, including periods with zero or negative prices, have been observed in European countries (e.g. Germany) in recent years. This can be seen in relation to rapid increasing generation from VRE but is also impacted by the developments in fuel- and CO<sub>2</sub>-prices, technology costs and energy policies. In decarbonised energy systems that have reached VRE integration phase 3 or higher, VRE with low to zero marginal costs will be setting the electricity price in many hours of the year and in long periods of consecutive hours.

With increasing shares of VRE, the merit-order effect tends to reduce the average wholesale price of electricity. The occurrences of negative prices are often a result of subsidies such as feed-in tariffs or long-term power purchase agreements, making it possible for VRE resources to produce during negative power prices and still make a profit. However, negative power prices can also be the result of start-up costs, transmission bottlenecks or other inflexibilities in the power system. Furthermore, decommissioning of flexible thermal generation units may give more frequent periods with scarcity of available generation when VRE units are not producing. In these periods, the power price will be set by the marginal costs of either demand response alternatives, storage or flexible generation. In many markets a price cap is also applied to limit extreme price peaks. This is a dilemma for ensuring necessary investment in storage and flexibility products and services. However, if more frequent price spikes emerge, this will contribute to increase the average prices for electricity, potentially offsetting the downward merit-order pressure on prices from higher penetrations of VRE.

Similar trends have been observed in some parts of the United States, although the main driver for lower electricity market prices in recent years have been the reduction in natural gas prices (Wiser et al., 2017). With more variable electricity prices and increased uncertainty in electricity generation profiles, the remaining controllable resources in the system become

more important. Hence, the value of services provided by flexible electricity generators are expected to increase. The supply of long-term or seasonal storage is likely to be more valuable, since only a few technologies are qualified to provide this type of flexibility in an efficient way. As demand for flexibility increases, related products are expected to increase in value and become a more important part of the income for hydropower producers and other flexible resources.

### Market design for resource adequacy and revenue sufficiency

All electricity producers require a certain revenue to ensure continued investments and reinvestments in generation capacity, and in a perfect market equilibrium all technologies in the optimal portfolio will break even. This is the case also for variable renewables, such as wind and solar energy, which must be able to recover the cost of investments and operations if there is to be a steady flow of new investments to replace old facilities. In principle, the prices of energy and operating reserves, if allowed to go sufficiently high during scarcity conditions, should provide adequate investment incentives. However, in many regions additional capacity remuneration mechanisms have been implemented to ensure resource adequacy (Botterud and Auer, 2019). In addition, some technologies such as variable renewables have other support mechanisms (e.g. feed-in tariffs, renewable portfolio standards, etc.) that provide additional revenue streams. These direct support mechanisms as well as carbon policies, influence the outcome of electricity markets, and the profitability of all market participants (Levin et al. 2019).

Income from balancing markets and delivery of ancillary services in the future energy system is highly uncertain. A review of literature on the development of balancing markets in Europe and challenges for future balancing markets identify pricing mechanisms and dimensioning of reserves as two important design parameters (Jaehnert, 2019). Pricing mechanisms for balancing markets should as far as possible be based on marginal pricing to provide correct price signals. Marginal pricing of balancing and ancillary services products implies that the prices will be set by the last unit required to balance demand and supply of each service, i.e. the price will equal the cost of providing

one additional unit of the product to the market, accounting for opportunity costs. In most U.S. markets, this is obtained by clearing the energy and reserve markets at the same time. Some observed trends in the development of power and balancing markets are:

- Increasing time resolution in day-ahead, intraday and balancing markets
- Gate closure times closer to delivery time
- Cross-border integration of markets and products (especially in the EU)
- Increased automation and improved algorithms for scheduling

## Today's market structure in the EU

The availability of and rules for the different types of power and balancing products differ between the European countries, but the EU is currently working towards more integrated markets to facilitate cross-border trade (Jaehnert, 2019). For the day-ahead market, the price coupling of regions has been established to develop a single price-coupling solution across Europe. A similar project has been started to create a European cross-border Intraday (XBID) market. For the balancing markets, several bi-lateral and regional initiatives are started, e.g. a common Nordic aFRR (automatic frequency restoration reserves) market, and there is ongoing work within the ENTSO-E to define standardised products.

The day-ahead and intraday markets concern trading and physical delivery of energy in hourly to 15min time periods in the European system. The intraday market allows for trade closer to real-time than the day-ahead market, up to 60-15min before closure depending on the country. This gives the participants the opportunity to adjust for imbalances if production and consumption schedules deviate from the volume committed in the day-ahead market. Balancing markets aim at resolving the imbalances that may occur within the operational hours.

If there are imbalances after closure of the intraday market, the balancing markets are used by the Transmission System Operators (TSOs) to balance the system. To ensure availability, reserves are procured beforehand and activated real-time if needed. Automatically activated reserves have to be synchronised with the grid when activated and are normally characterized "spinning reserves". The balancing process in Europe is currently organised in different steps and products varying between countries, but in general the processes consist of up to five steps. (ENTSO-E 2018).

1. Frequency containment reserve
2. Imbalance netting
3. Frequency restoration reserved with automatic activation
4. Frequency restoration reserved with manual activation
5. Replacement reserves

## Today's market structure in the United States

In the United States, there are seven regional electricity markets operated by Independent System Operators (ISOs) or Regional Transmission Organizations (RTOs). The main steps in the daily operation of ISO/RTO markets include the day-ahead market, intraday re-scheduling, and the real-time market. At the day-ahead stage, the ISO/RTO takes bids from consumers and offers from generators and clears the market in a process that includes security-constrained unit commitment and economic dispatch. The trend in the United States is to solve the scheduling of energy and operating reserves at the same time and in the same problem, i.e. through so-called co-optimization, to ensure efficient resource allocation and prices. Energy prices reflecting congestion are calculated for each individual bus in the transmission network (i.e., locational marginal prices or LMPs), whereas zonal prices are typically used for operating reserves. The resulting schedules and prices are communicated to the market participants. After the day-ahead market, the ISO/RTO will take actions as needed to commit additional resources if unexpected events unfold, such as higher loads or lower VRE generation than those cleared in the day-ahead market. Finally, the real-time market balances the system with dispatch schedules for energy and reserves, and corresponding prices, typically calculated every five minutes in current ISO/RTO markets. There is no standard definition of reserve products, but they typically consist of frequency regulation, spinning, and non-spinning reserves. Some markets have recently introduced an additional reserve product, so-called flexi-ramp reserves, to address deviations between scheduled and delivered energy. There are also discussions in some ISO/RTOs about introducing an additional primary frequency response market. Four of the ISO/RTOs have capacity markets for long-term resource adequacy, whereas others rely on capacity obligations or the energy/reserve market only to provide investment incentives (Botterud and Auer, 2019).

# 7.

## CONCLUSION

Flexibility resources are crucial for a secure and robust power system. With most modern societies and technologies depending on electricity, the consumer will always expect sufficient flexibility in the system to deliver affordable, clean, safe and secure energy at all times. However, the best solution to ensure cost-effective and reliable power supply in the short term and an efficient, sustainable and reliable power system in the long-term, is a complex challenge. Increasing shares of VRE add more uncertainty and variability to the power supply, thereby increasing the need for flexibility in the system. Adding to the reliability challenge is the decommissioning of fossil-based power production that is reducing available flexibility in the system.

The value of flexibility services from hydropower will most likely increase in the future due to the increasing system flexibility needs at multiple time scales. Hydropower is unique in the sense that it can deliver a broad spectrum of flexibility services, from short-term inertia and frequency response to long-term seasonal storage. Hydropower is therefore able to adapt to the needs in the different systems. However, many of the existing hydropower assets (particularly in OECD countries) are ageing and require modernisation, upgrading and retrofitting. These needs will vary between different systems, seasons and weather conditions. It is important that the hydropower fleet is upgraded in order to enable the ongoing expansion of VRE and address the corresponding operational challenges in the power grid. For owners of hydropower assets, it will be important to analyse the needs and possibilities for increasing the flexibility in order to choose the most optimal solution for which types of flexibility to provide.

An important question is if hydropower, and other flexible resources, are adequately incentivised to provide the increasing need for highly reliable flexibility services, and if the remuneration mechanisms in electricity markets are sufficient to ensure availability of the capabilities the system needs in the future. Moreover, in evaluating and comparing different energy technologies it is paramount to move beyond the levelized cost of energy as the metric of comparison and to consider the costs and benefits of all relevant system services. Ideally, the lowest cost technologies should deliver flexibility to the power system. Hydropower can play an important role as a provider of clean energy and flexibility in a future low-carbon power system.

There is a need for further analyses and assessment of technological, market, policy and regulatory requirements to ensure appropriate investments and to secure the sustainable transition of electricity production systems. Key themes from this paper highlight some examples where further analyses and assessments will be beneficial for ongoing knowledge sharing:

- Optimizing market mechanisms to ensure that hydropower and other technologies contribute to sufficient flexibility at the right scale and the right time
- The rising value of flexibility, understanding the frequency and magnitude of extremes and the impact on power prices in different markets
- The investment dilemma – effective price signals (volatility and extremes) to ensure sufficient system capability is being provided, and hence avoiding price shocks for consumers

Further White Papers should discuss the above topics. The culmination of these additional reviews will be an IEA Hydropower Roadmap.

# 8.

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