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TECHNICAL REPORT

POWER OF FLEXIBILITY

Facilitating the Energy Transition with Hybrid Hydropower Solutions

THE WORLD BANK
IBRD • IDA

ESMAP
Energy Sector Management Assistance Program

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Abbreviations

BESS	battery energy storage system
CAES	compressed air energy storage
ESMAP	Energy Sector Management Assistance Program
ESS	energy storage system
FDRE	firm and dispatchable renewable energy
FPV	floating solar photovoltaic
GHG	greenhouse gas
GW	gigawatt
GWh	gigawatt-hour
HPP	hydropower plant
IEA	International Energy Agency
IHA	International Hydropower Association
IREP	Integrated Renewable Energy Project
KIUC	Kaua'i Island Utility Cooperative
LAES	liquid air energy storage
LCOE	levelized cost of electricity
MW	megawatt
MWh	megawatt-hour
PSH	pumped storage hydropower
PV	photovoltaic
ROR	run-of-river
SDG	Sustainable Development Goal
TWh	terawatt-hour
US DOE	United States Department of Energy
VALCOE	value-adjusted levelized cost of electricity
VRE	variable renewable energy
WKEP	West Kaua'i Energy Project

All currency is in United States dollars (US$, USD), unless otherwise indicated.

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ESMAP is a partnership between the World Bank and over 20 partners to help low- and middle-income countries reduce poverty and boost growth through sustainable energy solutions. ESMAP's analytical and advisory services are fully integrated within the World Bank's country financing and policy dialogue in the energy sector. Through the World Bank, ESMAP works to accelerate the energy transition required to achieve Sustainable Development Goal 7 to ensure access to affordable, reliable, sustainable, and modern energy for all. It helps to shape World Bank strategies and programs to achieve the World Bank Climate Change Action Plan targets.

Key Messages

Scaling up and sustaining high shares of variable renewable energy (VRE) call for facilities that not only generate electricity, but also provide *energy services* to increase resilience and reliability of power systems. This serves as a motivation to explore how hydropower hybrids can leverage hydropower's unique capabilities to harness complementarities and operational synergies with VRE and storage, to provide energy services that enhance power system flexibility. This report—which seeks to identify solutions with the greatest potential—considers a hydropower hybrid as a facility that integrates multiple technologies and manages them under one joint operation and control system either at the same location or virtually. Although hydropower hybrids are few in number, several projects are already under preparation. China has commissioned two large facilities while India has one under construction.

Advancing the energy transition requires building hydropower hybrids capable of providing energy services. Hydropower hybrids add to power system flexibility by harnessing the potential of individual technologies, and the synergies that emerge when combining technologies, to provide energy services capable of mastering energy control, boosting energy storage, and increasing energy generation:

- **Energy control is mastered** by utilizing technologies that can swiftly balance disturbances, originating from the plant itself or in the power system, each second and minute.
- **Energy storage is boosted** by capturing surplus energy with storage when demand is low or resource availability is high—balancing the hourly, daily, weekly, seasonal, and yearly energy supply and demand.
- **Energy generation is secured** by harnessing complementarities and multiple renewable energy sources to secure the availability of energy and increase redundancy

Hydropower hybrids advance sustainable resource utilization, bringing a wide range of benefits:

- **Strengthen energy security.** Energy security can help reduce a country's vulnerability to supply disruptions, which can have significant economic and geopolitical consequences (Banna et al. 2023).
- **Create multiple revenue streams.** Hydropower hybrids utilize multiple sources to generate more electricity. They also provide energy services (remunerated in some markets today), can provide services related to water, for example, irrigation and water supply, and can create a third revenue stream.

- **Store energy for later use** by either using excess electricity to pump water or to prioritize generation to save water in reservoirs.

Hybrid hydropower facilities on the same land and utilizing the same grid connection point may bring additional benefits:

- **Power transmission costs are reduced** as a hybrid hydropower with a single injection point requires lower transmission capacity, when the peak power output is less than the combined peak of the stand-alone plants or excess generation is shifted to storage.
- **Land is used more effectively, reducing** impacts on biodiversity and ecosystems, leaving more nature either untouched or available for other uses.
- **Economies of scale are achieved** through shared use of infrastructure, project preparation activities, and organizational resources across the project life cycle, including development, implementation, operation, and maintenance.

Remuneration for energy services will improve hybrid hydropower projects' bankability and scale up investments. Remuneration is not adequate in most markets since the focus has been to incentivize the increase of generation. Remuneration ensures efficient resource utilization and makes visible the value of energy services for maintaining power system balance. Focus, therefore, needs to shift to the importance of valuing energy services for maintaining power system balance. Several markets are developing mechanisms for renumeration; there is no one-size-fits-all solution. The experience already gained will inform the evolution of mechanisms suitable for different countries and regions.

To conclude, hydropower hybrids represent a promising development because they provide highly sought-after energy services that are both flexible and dispatchable.

Executive Summary

The rapid growth rate of renewable capacity additions in 2023—through the addition of 510 gigawatts—puts the world on a path toward transforming its power mix. Variable renewable energy (VRE) generation is expected to have an increased share—reaching 25 percent in 2028—due to increased affordability of wind and solar. While increasing VRE shares is a vital step on the path toward global power mix transformation, it will have implications for power systems given the challenge it poses to maintaining power system balance (IEA 2024). Keeping up with this rapid transition requires exploring solutions that support and enhance power system flexibility, in turn reducing the strain on systems.

Scaling up and sustaining higher VRE shares call for facilities that generate electricity and also provide energy services capable of continuously balancing a resilient and reliable power system. Recent research and development for hybrid energy systems suggests that integrating multiple technologies can provide these energy services. It indicates that hybridization could be effective for realizing more benefits relative to independent plants, by allowing multiple technologies to share operational systems, costs, and infrastructure. The research and development also suggest that some technology combinations are more favorable than others (US DOE 2021). The present report explores how a hydropower hybrid can leverage hydropower's unique capabilities for harnessing complementarities and operational synergies with VRE and storage to provide energy services that enhance power system flexibility.

The report considers hydropower hybrids that integrate technologies and manage them under one joint control and operation system either at the same location (a hydropower hybrid facility) or virtually (a virtual hydropower hybrid facility).

Facilitating the energy transition calls for embracing technology solutions such as hydropower hybrids which offer *energy services* capable of sustaining high shares of VRE:

1. **Energy control is mastered** by utilizing technologies that can balance disturbances originating from the plant itself or in the power system; this helps maintain power balance and power quality over short time intervals. A gust of wind can trigger such disturbances by causing sudden changes in power output.

2. **Energy storage is boosted** by capturing surplus energy with storage when demand is low or resource availability is high—balancing the daily, weekly, and interannual energy supply and demand. To illustrate this point, power systems with a high solar photovoltaic share would require storing the energy generated during the day to meet the morning and evening peaks.

3. **Energy generation is secured** by utilizing multiple technologies allow harnessing the complementarities and seasonality of renewable energy sources.
4. **Synergies are harnessed** through coordinated management and control of multiple technologies with distinctive operational needs and characteristics; energy storage is managed efficiently and the value of energy services for power system flexibility is maximized.

The objective for a hydropower hybrid is to take maximum advantage of the integrated technologies by maximizing their utilization, the benefits they bring, and their efficiency. It is widely known that stand-alone hydropower plants and other technologies can help manage the variability of VRE in the power system. However, with increasing shares of VRE, there is also a growing importance of understanding the advantages to manage this variability before power is injected into the power system.

Although hydropower hybrids are few, China has commissioned two large-scale facilities, while India is developing the Pinnapuram Integrated Renewable Energy Project in Andhra Pradesh. Once construction is complete, this hybrid facility will combine 3,000 megawatts (MW) of solar, 550 MW of wind, 1,200 MW of pumped storage hydropower, and 10.8 gigawatt-hours (GWh) of energy storage. The facility will provide dispatchable and flexible renewable energy services to consumers across India starting in 2024 (Greenko n.d.).

This report specifically explores hydropower hybrids that manage multiple technologies under one joint operation and control system, enable the integration of VRE, and promote the transition to a flexible power system. Hydropower hybrids aim to meet one of three possible objectives: (1) provide a stable short- and long-term electricity supply to the power system; (2) deliver energy services tailored to enhance power system flexibility and energy security; and (3) modernize existing hydropower plants to boost their performance and improve their energy services.

The purpose of this report is to enhance the understanding of energy sector regulators and policy makers, investors, and banks, including multilateral development banks, of the potential role of a hydropower hybrid in the evolving power systems. It underscores the necessity to develop climate-smart renewable energy solutions that contribute to sustainable development.

Hydropower hybrids are a promising advancement in the ongoing sustainable development of renewable energy and play a crucial role in reaching the Sustainable Development Goals. They contribute to affordable and clean energy, fortify energy security, and reduce carbon emissions by utilizing low-carbon renewable technology. Hybrid hydropower offers a wide range of benefits such as:

1. **Strengthening energy security.** Our society's reliance on electricity is undeniable; prolonged interruption leads to consequences extending beyond power systems. Hydropower hybrid solutions can help address how energy security can be boosted to support economic development and improve quality of life (Banna et al. 2023).

2. **Creating multiple revenue streams from the same infrastructure.** A hydropower hybrid leverages multiple sources under a joint control system to generate more electricity. It also provides flexible energy services (remuneration is under development or already remunerated), and can provide water services, for example, irrigation and water supply.

3. **Enabling energy storage**. Hydropower hybrids can use excess electricity to pump water back up to a reservoir or prioritize generation to save water for use later.

Hybrid hydropower facilities on the same land and utilizing the same connection point may bring additional benefits:

1. **Power transmission costs are reduced** as a hydropower hybrid with a single injection point requires lower capacity, when peak power output is less than the combined peaks of the stand-alone plants, or excess generation is shifted to storage. This means a hybrid facility's output is determined through a careful assessment of generation potential over a year and a power output close to the connection point's maximum capacity is provided. This can increase the utilization of transmission assets (IHA and EDP 2018)—in contrast to wind and solar power plants, which supply peak power generation only over brief periods and underutilize transmission assets (NREL 2020).

2. **Power systems are supported by supplying high-quality power at the same connection point.** Hybrid hydropower facilities are an excellent alternative to explore for countries and small island states that require greater energy access. This is because these facilities combine multiple renewable energy sources and could present incentives for deployment in regions where power systems need to be developed and strengthened.

3. **A site's fullest potential is utilized sustainably since land use becomes more effective,** lowering impacts on biodiversity and ecosystems, leaving more nature either untouched or available for other uses. Compared with stand-alone plants, the reduced land requirement of hybrids contributes to not only environmental conservation but also significant savings in land acquisition costs.

4. **Economies of scale are achieved** through cost minimization via shared use of infrastructure, project preparation activities, and organizational resources across the project life cycle, including development, implementation, operation, and maintenance.

Combining multiple technologies, however, adds complexity in project development, implementation, and execution. As the number of technologies involved in a hydropower hybrid project grow, it becomes increasingly challenging to prioritize and harmonize resource utilization, to efficiently deliver services, and address environmental and social concerns. An example is where a multipurpose reservoir serves both energy generation and water supply, each governed by different regulations. The necessary competencies and skills must be identified early on in all phases of the value chain, from project development and management, to construction and ongoing maintenance. Adopting a proactive approach can help a project ensure it has the required capabilities when needed.

Hydropower hybrids may concurrently mitigate ecological impacts—to deliver societal benefits—and deliver energy services. All energy infrastructure impacts biodiversity and ecosystems. However, with hydropower hybrids, there can be opportunities and solutions to avoid, minimize, mitigate, and offset potential impacts. While the services provided by a hydropower hybrid may compete at times, they can be complementary on other occasions. With the help of robust policies or regulations, hybrid hydropower can optimize the size of a reservoir by shifting a portion of the energy generation to VRE, in turn ensuring sufficient reservoir volume is available for storing energy. Hybrid facilities also provide another opportunity: to maintain energy generation from an existing hydropower plant by incorporating VRE, while releasing more environmental flows into bypassed river segments, benefiting the ecosystems and biodiversity in those areas.

Remuneration for energy services will improve hybrid hydropower projects' bankability and scale up investments. Remuneration for energy services is not adequate in most markets, since the focus has been to incentivize increase of generation. Remuneration has two important roles: (1) ensuring efficient resource utilization for energy balance, and (2) making visible the importance and value of energy services for maintaining power system balance. The focus, therefore, needs to shift to the importance of valuing energy services for maintaining power system balance. Several markets are developing mechanisms for renumeration; there is no one-size-fits-all solution. The experience already gained will inform the evolution of mechanisms suitable for different countries and regions.

Development of resilient hybrid facilities requires further innovation and research to meet future flexibility demands. It is necessary to build methodologies and analytical tools for low- and middle-income countries and regions to understand how a hybrid can deliver energy services tailored to their specific needs. Advocacy for and dissemination of the benefits of such facilities can support new project development, reduce the costs involved in planning and executing investments, and boost physical and economic resilience (CIF 2022).

To conclude, hydropower hybrids are a promising solution because they provide highly sought-after energy services that are both flexible and dispatchable. However, scaling up hybrids will be challenging without adequate remuneration for energy services. India and China are leading the way in implementing hydropower hybrids, demonstrating their feasibility and importance.

1. Introduction

With the world midway to the deadline for achieving the 2030 agenda and the Sustainable Development Goals (SDGs), governments need to raise their ambitions and demonstrate more zeal to create jobs and generate growth, while combating climate change and its impacts. The Atlas of Sustainable Development Goals 2023 (World Bank 2023b) visualizes the progress needed in achieving the SDGs. It shows that countries face the often-conflicting challenge of ensuring electricity access for all while increasing renewable electricity's share to reduce greenhouse gas emissions. The low-carbon energy transition is seeking to address this challenge and is spurring a change fueled by the surging availability of low-cost variable renewable energy (VRE) sources, solar and wind. Future power systems are expected to be characterized by increasing shares of VRE generation and hydropower (IEA 2023c).

Solar photovoltaics and wind are expected to represent 70 percent of the overall capacity additions over 2023–50 (IEA 2023c). But solar and wind energy can be generated only when the sun shines or the wind blows. This causes fluctuations, which are a challenge for power systems to balance. The challenge lies in achieving instantaneous balance while addressing variations across a wide spectrum of timescales, from milliseconds to years.

Imbalances are also triggered by a demand surge. For example, an electric vehicle plugged into a charging station starts to draw energy from the power system. This triggers an instant change in electricity demand at that location, causing imbalances in the system, which must meet the sudden demand surge. To balance the power system, power plants must ramp up generation to provide additional energy to the charging station. This process takes time and can trigger disturbances in the power system, for example, power and energy fluctuations. Once the vehicle is fully charged, the electricity demand decreases and the power system must adjust again to maintain balance. This constant balancing act is necessary to ensure that power systems remain stable and reliable, even with the added demand.

To maintain power system balance, it is therefore crucial to ensure that the energy mix also includes the required share of flexible plants, which can respond to supply and demand changes and dispatch energy for the duration it is needed. This flexibility is vital for integrating VRE and to secure access to affordable and reliable energy in the short and long terms.

India has highlighted the importance of energy storage and dispatchability in VRE's integration into power systems. Several initiatives have been introduced through policies and auction guidelines. In 2023, India launched its national guideline to promote energy storage supported by firm and dispatchable renewable energy (FDRE) auctions. The objective is to increase investment in energy storage and renewable energy generation; in 2023 alone, 8 gigawatts (GW) of FDRE tenders were issued. Pumped storage hydropower is expected to play a crucial role in India's energy transition, with an estimated 19 GW of capacity to be added by 2030. The FDRE tenders are expected to reduce India's reliance on thermal power (IEEFA 2023). An example of India's large-scale renewable project is presented in box 1.2.

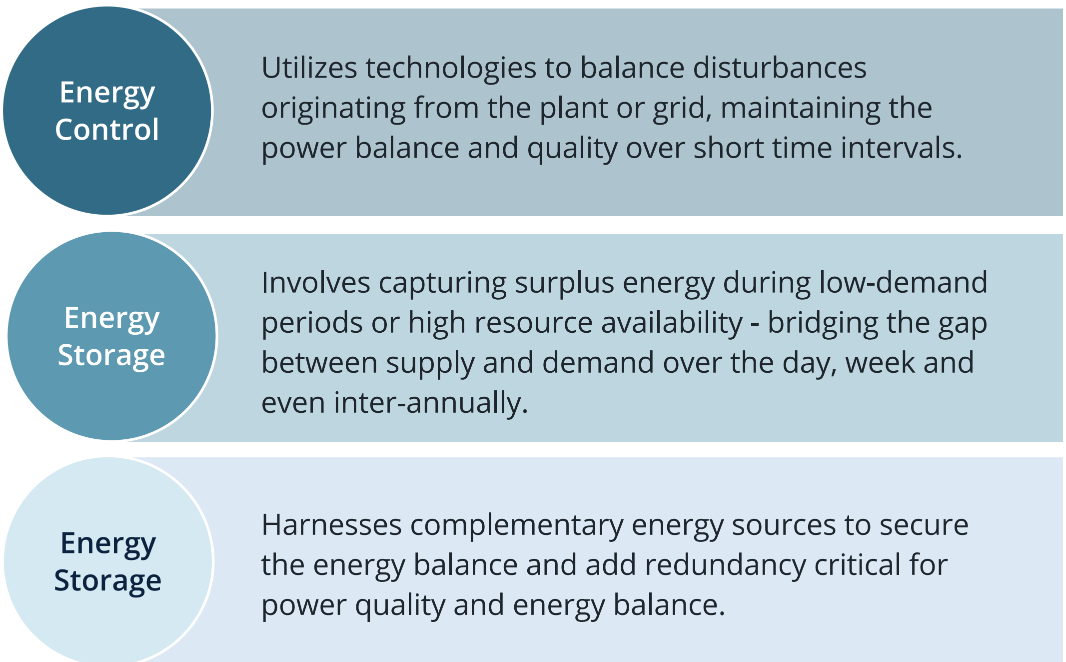
Hybrid Hydropower Facility

Scaling up and maintaining higher VRE shares require developing, modernizing, and strengthening power systems, making them more flexible (IEA 2023c). This necessitates a transformation in the approach to designing, planning, and operating renewable energy facilities. They must contribute more than mere energy generation; they must also provide *energy services*, as depicted in figure 1.1. In recent times, hybrid renewable energy solutions have gained more attention (NREL 2021) since they provide a dependable and adaptable power source (dispatchable power). These systems can integrate multiple renewable energy sources and/or storage technologies within a single facility, at the same location or connected virtually (NREL 2020, 2021).

Recent research and development for hybrid systems suggests that some technology combinations are more favorable than others. It also indicates that hybridization could be effective for realizing more benefits relative to independent plants, by allowing multiple technologies to share operational systems, costs, and infrastructure (US DOE 2021).

This report focuses on the important role hydropower can play in hybrid systems by utilizing water as the primary energy source, combined with one or more renewable energy sources, energy storage, and an overarching operations and control system. This enables the facilities to leverage the distinctive strengths of each technology to provide energy services, which can enhance power system flexibility and energy security. Different levels of hydropower hybrids are presented in Box 1.1. This report focuses on hybrid hydropower facilities (figure 1.2) and virtual hybrid hydropower facilities.

FIGURE 1.1
Hybrid Systems' Energy Services for Power System Flexibility



Source: World Bank.

FIGURE 1.2
Schematic Drawing of a Hybrid Hydropower Facility

Source: World Bank.

Making hydropower the core in a hydropower hybrid allows for utilizing its capabilities to swiftly and safely meet the demands of a power system. Hydropower's importance is highlighted not just by its capabilities but also their role in the energy transition. Hydropower today represents the largest share of renewable energy. Thus, when considering hydropower hybridization, it is essential to not only focus on new but also existing power plants; this is because hydropower locations are not necessarily utilized to their fullest potential. There is potential to sustainably utilize land for existing as well as new developments, by combining with other technologies—creating possibilities to maximize the benefits derived from each site. All hydropower plants include energy storage (annex 1), and the reservoir volume determines the amount of energy that can be stored when the demand is low or resource availability is high. Reservoir volume, combined with the installed hydropower capacity, determines the amount of energy that can be released and the corresponding duration. These two key features make hydropower suitable for balancing power systems over the short, medium, and long terms.

Multiple factors influence the design of a hydropower hybrid. It can be challenging to analyze the different parameters required to identify the optimal design. The ideal design involves deciding on an objective, striking a balance between the multiple factors, and accounting for the current and future estimated requirements of the local, national, regional, and even international power and energy systems, followed by identifying how energy services (figure 1.1) best meet the objectives shown in figure 1.3. Energy services encompass multiple factors: (1) **energy control**, which utilizes technologies that balance disturbances originating from a facility or the power system, and helps ensure short-term power balance and power quality; (2) **energy storage**, wherein energy is captured and stored for later use, helping to bridge gaps in energy supply and demand and use across timescales; and (3) **energy generation** by harnessing complementary renewable energy sources to balance daily, seasonal, or interannual supply and demand, to secure the availability of energy and add redundancy critical for power quality and energy balance.

The objectives (table 1.1) considered in this report are: (1) to provide a **stable short- and long-term power supply** to the power system, (2) deliver **energy services tailored to enhance power system flexibility** and energy security, or (3) **enhance energy services from existing hydropower plants**. Achieving the selected objective requires understanding how each technology functions and interacts with others and how they interact with the power system.

An important step in a facility's design is selecting the level of hybridization for it (box 1.1). The level of hybridization for a facility determines how it can harness the benefits of coordinated operation and control, and how it interacts and enhance power system flexibility. This report's main focus is to explore the potential of hydropower hybrids that manage integrated technologies under one overarching operation and control system. Hydropower hybrids stand as a promising solution in the ongoing evolution of sustainable hydropower that can meet the needs of evolving power systems.

TABLE 1.1
Objectives of Hybrid Hydropower Systems

OBJECTIVES FOR HYDROPOWER HYBRIDS		
Stable short- and long-term power supply	**Energy services tailored to boost flexibility, resilience, and reliability**	**Improve the performance of and energy services from existing hydropower plants**
Maximizing electricity generation from VRE and complementing it with hydropower. Balancing energy control and electricity generation by swiftly adapting to changes in weather conditions, to ensure short-term stable power balance and power quality. Ensuring a stable long-term energy balance with energy storage by harnessing complementarities and adapting to seasonality.	Providing energy control to balance both power output and demand changes originating from the grid Generating from multiple renewable energy sources and managing variability in power output, enabling facilities to withstand and recover from disruptions, disturbances, or adverse events. Ensuring continuity of electricity generation and minimizing the frequency and duration of power outages across all timescales by utilizing energy storage as well as complementary renewable sources	Integrating additional technologies to improve hydropower plants' operation, which may be constrained by environmental, regulatory, or technical restrictions

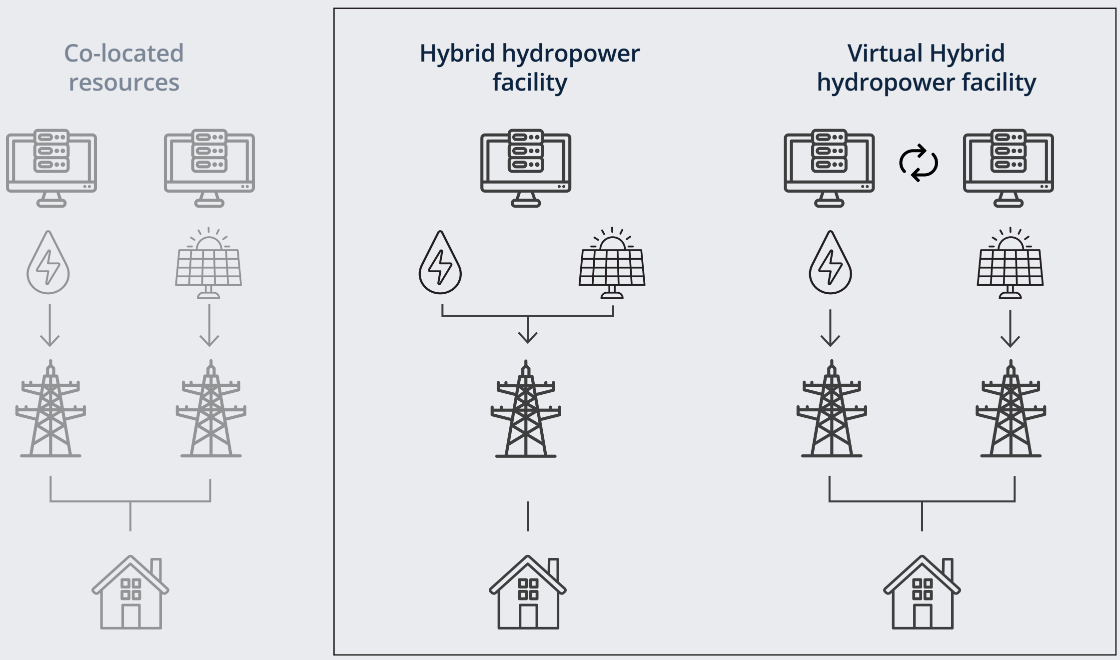
BOX 1.1

ALTERNATIVES FOR THE HYBRIDIZATION OF HYDROPOWER IN THE POWER SYSTEM

There are multiple alternatives for how to hybridize hydropower and variable renewable energy sources in the power system, each bringing several benefits and operational advantages. Three alternatives are presented in the diagram below (NREL 2020):

- **Co-located resources.** Multiple power plants in close proximity and operating independently.
- **Hybrid hydropower facility.** Renewable energy technologies located near one another and operated in coordination, utilizing the same grid connection point. These facilities require an overarching control system.
- **Virtual hybrid hydropower facility.** Renewable energy technologies operated in coordination but not necessarily located near one another. They connect to the grid at different points.

AN ILLUSTRATION OF THE DIFFERENT LEVELS OF HYBRIDIZATION



Source: Adaptation of NREL (2020); World Bank.

An example of a large-scale hybrid hydropower facility is the Pinnapuram Integrated Renewable Energy Project in India (box 1.2). The facility integrates wind and solar power with pumped storage hydropower, delivering firm and dispatchable "power on demand 24/7." This example shows how hydropower combined with other technologies can deliver firm and dispatchable power to the grid, besides being able to deliver *energy services*, as defined by figure 1.1, by utilizing water, wind, and solar resources and energy storage.

BOX 1.2

THE PINNAPURAM INTEGRATED RENEWABLE ENERGY STORAGE PROJECT

The Pinnapuram Integrated Renewable Energy Storage Project (IRESP), which is under construction in Andhra Pradesh, India, integrates solar, wind, and pumped storage hydropower, is expected to supply dispatchable and schedulable renewable energy to consumers across India starting June 2024. This is first of its kind "Closed Loop" gigawatt scale storage system in India.

The IRESP aims to overcome the challenges of intermittency inherent in solar and wind power by combining this intermittent power with hydropower and controlling with digital proprietary technology platform viz. Greenko Load Dispatch Center (GLDC), paving the way for a more reliable and flexible on demand Carbon Free Power (CFP).

The project's key differentiator is its ability to generate "schedulable power on demand (SPOD)." Integrating pumped storage hydro with solar and wind allows the IREP to store excess energy when resource availability is high and release it during periods of peak demand. This capability is crucial for grid stability and integration of large-scale renewables.

Upon completion, the Pinnapuram IRESP is expected to have a capacity of 1,680 MW of pumped storage hydro which will enable integration of ~4,000 MW of solar and ~2000 MW of wind which is presently being built by Greenko, its customers and energy partners. The plant will be holding 10.8 GWh of daily energy storage considered in single cycle in reservoirs which can be enhanced if used in multiple cycles daily; in other words, it is capable of sustaining the pumped storage plant for six hours. This output is sufficient to power millions of homes and significantly contributes to India's renewable energy targets.

The IRESP illustrates how integrated hydropower, VRE and storage, which provides *energy services* to boost power system flexibility, is used to respond to and attenuate dynamic fluctuations from the power system and the VRE plants. The pumped storage hydropower plant provides high *energy control* to support power quality, besides providing *energy storage* to support short- and long-term energy balance. Also, the facility provides *energy generation* to ensure power system balance. Further, energy storage ensures water's availability for the required duration, ensuring schedulable power on demand.

BOX. 1.2 *(CONTINUED)*

In other words, this hybrid facility leverages flexible hydropower, variable renewable energy, and energy storage to deliver energy services to enhance power system flexibility.

As with any large-scale infrastructure project, the Pinnapuram IRESP encounters a number of challenges. These challenges include environmental concerns, issues with land acquisition, and the high initial investment costs. Appropriate mitigation strategies including innovative financing has helped Greenko to make Pinnapuram IRESP a very attractive storage project. It is expected to create thousands of jobs, boost local economies, and significantly contribute to India's clean energy goals. It will also help mitigate climate change and improve air quality by reducing reliance on fossil fuels. With the success of IRESP Greenko has already started developing eight other Pump Storage Projects (PSP) across india totaling up to 100GWh of storage which will be online by 2030.

These low cost hybrid hydropower facilities (or CFP) are enabling Greenko's newly launched AM Green Platform and allowing them to enter into the green molecules space. AM Green Platform will be producing ammonia, methanol, caustic soda and Sustainable Aviation Fuel (SAF) in the near future .

Source: Greenko n.d.; Hydro Review 2020; Putra 2024.

Intended Audience

This report seeks to enhance the understanding of energy sector regulators and policy makers, investors, and banks, including multilateral development banks, of the evolving power systems and the potential role of hybrid hydropower in it. It underscores the necessity to develop climate-smart renewable energy solutions that not only contribute to sustainability but also make power systems more resilient and reliable. The report also strives to equip its audience with a deeper understanding of the underlying technological principles that shape decision-making. This knowledge, in turn, can facilitate more effective project development and the establishment of an enabling environment. Ultimately, it aims to guide stakeholders in harnessing this insight to develop hybrid facilities that not only bolster the broader energy system but also align with societal goals and aspirations. To this end:

- Chapter 2 offers insights into the evolving power systems, integration of VRE, and the need for flexibility. It provides a context for the significance of hybrid projects in today's dynamic energy environment.
- Chapter 3 explores different energy services, technologies, and hybrid hydropower facilities. It presents a range of possibilities and innovations along with a selection of technologies that are considered suitable for hybridizing renewable energy sources.
- Chapter 4 explores the benefits and challenges of, and future considerations in, developing hybrid projects. A forward-looking approach is required to ensure sustainability while managing the integration of multiple technologies and addressing societal and environmental impacts.
- Chapter 5 highlights the importance of fostering flexibility and an enabling environment.

2. Evolving Power Systems

The 2023 United Nations Climate Change Conference (COP28) closed with an agreement laying the ground for a swift, just, and equitable energy transition, underpinned by deep emission cuts (United Nations 2023). A pledge was signed to triple global installed renewables capacity to 11,000 GW by 2030, which would result in the largest emission reductions under the Net Zero Emissions by 2050 Scenario (IEA 2023a). Meeting this target requires a substantial increase in solar photovoltaic (PV) and wind power, in complement to other renewable technologies (e.g., hydropower and geothermal energy). This chapter will provide an insight into how increasing the share of variable renewable energy (VRE) will present a host of new challenges to power systems.

Integrating Variable Renewable Energy

VRE's integration into power systems brings challenges in maintaining system balance, which requires continuously and efficiently managing electricity supply-demand fluctuations. The challenge lies in achieving instantaneous balance while addressing variations across a wide spectrum of timescales. To be balanced, power systems need facilities that supply the required energy and can respond to the dynamic needs. As the name suggests, VRE plants generate power when the sun shines or wind blows. Seasonal variations or variations in weather patterns can cause fluctuations that disturb the power system balance. In other words, VRE has limited flexibility and ability to balance power systems. This, however, means little or no consequence for power systems with a low VRE share, although consequences grow with an increasing share. The VRE share in a power system must be assessed to determine the flexibility needed for system balance. The International Energy Agency has delineated different phases of VRE's integration into power systems (as summarized in figure 2.1) (IEA 2017). The resulting framework—provided by the different phases—helps understand the flexibility required to balance a power system, besides understanding and anticipating the challenges power systems will face with a growing VRE share.

At present, most countries and regions are in phases 1 and 2 of VRE integration (figure 2.1), where VRE fluctuations have little effect and additional flexibility needs can be met by minor operational adjustments. Robust power systems with a considerable share of flexible dispatchable power can integrate a larger VRE share before advancing to phases where investments in new infrastructure or operational adjustments are needed to achieve stability. In regions

FIGURE 2.1

The Need for Power System Flexibility Progresses alongside Increasing Shares of VRE

PHASE 1	The first set of VRE plants are deployed, but they are basically insignificant at the system level; effects are very localised, for example at plants' grid connection points.
PHASE 2	Changes between load and net load become noticeable, but the existing system is flexible enough to achieve system integration.
PHASE 3	Greater fluctuations in the supply-demand balance prompt the need for a systematic increase in power system flexibility beyond what can be relatively easily supplied by existing assets and operational practices.
PHASE 4	Additional investments in flexibiilty resources are needed to balance the system VRE output provides the majority of electricity demand in certain periods, requiring both operational and regulatory modifications. Operational changes involve power system stability, determining the way the power system responds following supply or demand disruptions, and regulatory changes may include new rules for VRE to provide system services.

Source: IEA 2017, 2020.

lacking well-established or resilient power infrastructures, the transition to phases beyond phase 2 will be faster as the VRE share takes precedence over conventional generating units. In phase 3, the need for flexibility becomes a priority. That is because in this phase, VRE begins to have an influence on power system operation, necessitating more flexible operation of dispatchable generation plants to maintain power system stability. Instances of power systems entering phases 3 and even 4 have already emerged, with Ireland, South Australia, and Denmark in the lead (IEA 2020).

VRE integration represents a remarkable shift in the operation of and planning for power systems. It necessitates storing more energy and adapting demand to match supply (Statnett 2023). This way of thinking is the opposite of that in the past 100 years, when supply was adjusted to match demand. To illustrate this point, power systems with a high solar PV share would have to utilize solar energy when the sun is shining. This is a challenge since power systems often encounter a peak before sunrise and after sunset. Therefore, it is worth ensuring that the future energy mix also includes the required share of flexible plants that can store energy for the duration it is needed and respond to dynamic changes in the grid. Hydropower's dual capability in this regard makes it attractive to explore in terms of hybridizing with VRE and other technologies to develop facilities that can deliver reliable generation and flexible energy services to balance power systems.

Further VRE deployment beyond phase 4 is possible but may require greater curtailment, which involves deliberate shutdown of generation to maintain power system balance (see box 3.2). Curtailment is expected to become one of the methods for providing flexibility in the future (IEA 2023c).

For power systems with an open market, market monitoring can help identify when markets are advancing to a new phase. When power systems have increasing VRE generation share and proceed through different phases (figure 2.1), this tends to be reflected in short-term market prices, which fall when supply exceeds demand (box 2.1). The examples provided in box 2.1 demonstrate how increasing VRE integration will lead system operators as well as power producers to seek flexible and dispatchable energy to maintain supply-demand balance. Market mechanisms remunerating flexibility and energy services could increase individual plants' and the power system's value.

BOX 2.1

MARKET INDICATORS

When high variable renewable energy generation leads to negative electricity prices, this is a typical market signal of a country or a price area advancing to a new phase. For instance, Germany experienced negative prices of -€83.94/ MWh for eight hours on April 21, 2020, over which wind as well as solar generation surpassed the monthly average, covering approximately 88 percent of Germany's demand within this eight-hour period (AleaSoft 2020).

Several European countries experienced negative power prices in the wholesale energy market during daylight hours in spring 2023. This price decline was mainly driven by the abundance of available energy generated by renewable sources and the relatively low demand for heating or cooling due to typical spring weather.

Negative prices often occur when electricity supply is in excess and cannot be stored for later use. On such occasions, power producers may offer negative prices to wholesale consumers to incentivize them to take surplus electricity from the grid, to prevent system overload. This scenario arose from the dominance of a high-pressure system over central and northwest Europe, resulting in abundant solar power generation. Finland experienced negative prices in 2023 due to oversupply of hydroelectric power due to excessive springtime meltwater.

It should however be noted that a brief period of surplus is not necessarily a concern, and investment to prevent this (e.g., with storage) is not necessarily economically viable. While in most cases the period corresponding to a surplus, when it occurred, represented less than 1 percent of the time, last year, Sweden had one of the highest surpluses, representing over 3.4 percent of the time (ACER 2023a).

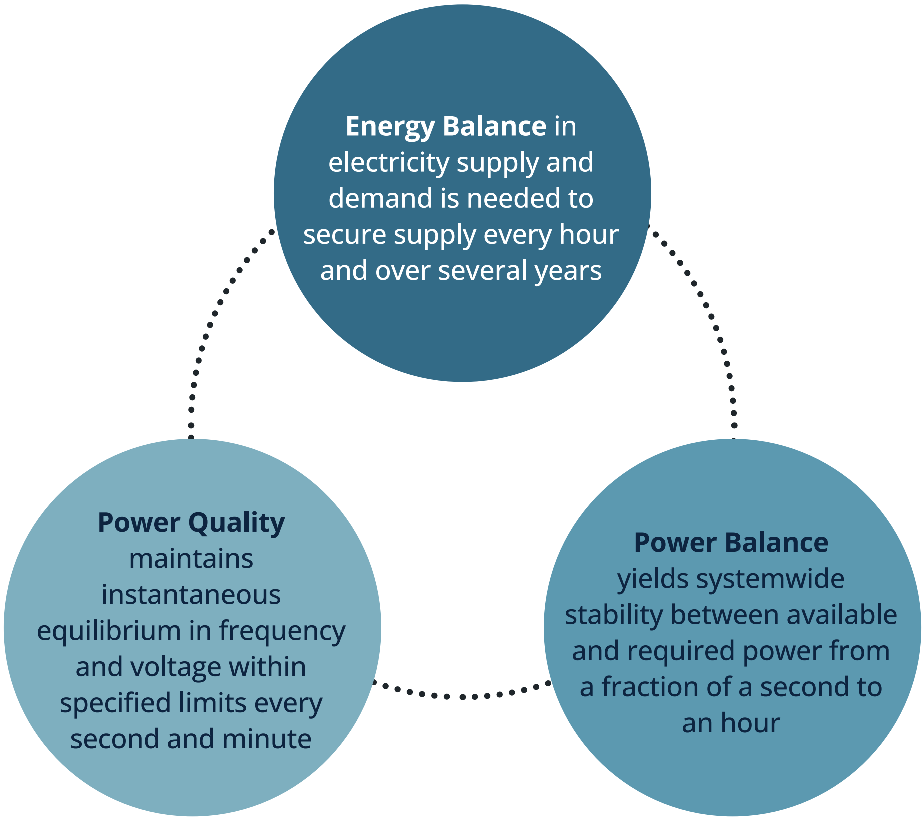
Source: The Guardian 2023; ACER 2023a.

The Essential Role of Power System Flexibility

Power systems are highly dynamic and interdependent networks that are designed to supply and deliver continuous electricity. They play a critical role in our society, helping to transmit and distribute electrical energy from generation facilities to consumers. Power systems' dynamic nature means their operation and planning for them must include continuous assessment and management of instantaneous stability as well as long-term energy security. With growing VRE shares, grows the need for a flexible power system as it is increasingly important for them to be able to adapt to dynamic changes across varied timescales to remain balanced, reliable, and resilient (see figure 2.1). Power system flexibility can be measured based on three metrics: (1) power balance, (2) energy balance, and (3) power quality (see figure 2.2).

FIGURE 2.2

Power System Flexibility Metrics and Their Significance in a Reliable and Resilient Power System



Source: World Bank.

All three metrics, illustrated in figure 2.2, are needed to evaluate power systems and they are intrinsically linked. In this context, **power balance** refers to a power system's ability to maintain a steady and balanced power supply in the event of sudden disturbances and fluctuations, which can include short circuits, equipment failure, or sudden load changes. Instantaneous stability is vital to prevent power outages, minimize disruptions, and protect a grid's physical components. **Power quality**, on the other hand, means instantaneous equilibrium of frequency and voltage within specified limits. Any sudden supply-demand mismatch could cause frequency deviations, which could lead to blackouts, if not corrected swiftly. Equally important is maintaining stable voltage levels; this helps keep sensitive electronic equipment from harm and prevents disruption of power supply. And finally, **energy balance** refers to the supply-demand balance, which is needed to secure supply every hour and over several years. Other ancillary services that support power systems include, for example, black starts and contingency reserves. The interplay of the above three metrics is important for understanding power systems' flexibility and how it supports wider societal needs such as energy security.

The above metrics are affected by changes in demand and production for power systems, which occur on multiple timescales, from fractions of a second to hours, days, and even seasons. Power system operators can ensure balance by adjusting both generation plants and consumers (see box 3.2), thus balancing fluctuations. Table 2.1 highlights the main challenges that VRE generation poses and which influence a power system in Phase 2 or above over multiple timescales.

The intermittency and variability inherent in VRE generation challenge short-term power quality, and power and energy balance, as shown in table 2.1, while weather patterns may challenge the medium- and long-term energy balance. The examples in table 2.1 illustrate how flexibility is needed to build a resilient and adaptable power system capable of handling the variability of wind and solar power. Long-term planning requires securing the availability of renewable resources over an extended period. Ensuring reliability and resilience of energy systems requires considering seasonal, longer-term variations as well as the impact of climate change on renewable energy generation (see section 3.4 for further information).

The intermittency and variability of VRE power generation challenge short-term power balance and power quality, while resource seasonality and variability challenge the long-term energy balance.

TABLE 2.1

Typical Challenges Posed by VRE Generation to Power Systems, by Timescale

Power System Flexibility	VRE Challenge	Timescale	
Ensure stability and equilibrium in Power Balance and Power Quality	Wind gusts causing sudden change in power output	Sub-seconds to seconds	Short term
	Large cloud passes over a large solar PV plant causing drop in power output	Seconds to minutes	
Maintain power and energy balance to counteract increasing fluctuations	Clouds interfere with power output from a region	Minutes to hours	
	A storm causes too high wind speeds and a drop in wind power generation		
Energy balance	Forecasting generation from multiple resources with varying degrees of predictability	Hours to days	Medium term
Energy balance	Seasonal and interannual availability and complementarity of resources	Seasons to years	Long term

Source: World Bank.

Note: PV = photovoltaic; VRE = variable renewable energy.

3. Unlocking Hydropower Hybrid Technologies

Hydropower hybrids utilize water as their main energy source. They integrate variable renewable energy (VRE) sources and various energy storage solutions, which are managed under an overarching operations and control system. This integration allows hydropower hybrids to leverage the unique strengths of each technology. Hydropower hybrids deliver energy services that enhance power system flexibility and energy security.

Different parameters and technologies have to be examined comprehensively over different timescales to understand what influences a hybrid's energy services, the interactions among technologies, and how such a facility enhance power system flexibility (see figure 3.1). Noteworthy is that some technologies can enable a hybrid to deliver multiple energy services and support multiple flexibility indicators over a range of temporal resolutions. These interactions are best described by the capabilities in box 3.1, and they determine how effective a hybrid facility is and how it is optimized to improve the technologies it utilizes. For example, a solar array's orientation can influence its energy capture, resulting in peak generation at different times of the day. This could influence the optimization of size and control algorithms for energy storage, potentially requiring coverage across intervals ranging from sub-seconds to 24 hours to be able to provide power and energy over a day.

It is worth recognizing that service provision levels vary across hydropower plant types (e.g., reservoir, run of river, and pumped storage [annex 1]). This chapter explores how various plant types, configurations, and technologies can be combined to maximize a hydropower hybrid's energy services (figure 1.1). The capabilities of a power plant (see box 3.1) best describe how well it can deliver energy services to the grid. Further, energy services not only maximize the overall value and benefits derived from a single infrastructure asset, but could present incentives for deployment in regions characterized by weak or underdeveloped grid systems or high VRE shares—considering a hybrid can provide readily dispatchable high-quality power to the grid, besides balancing load changes originating at the grid.

BOX 3.1

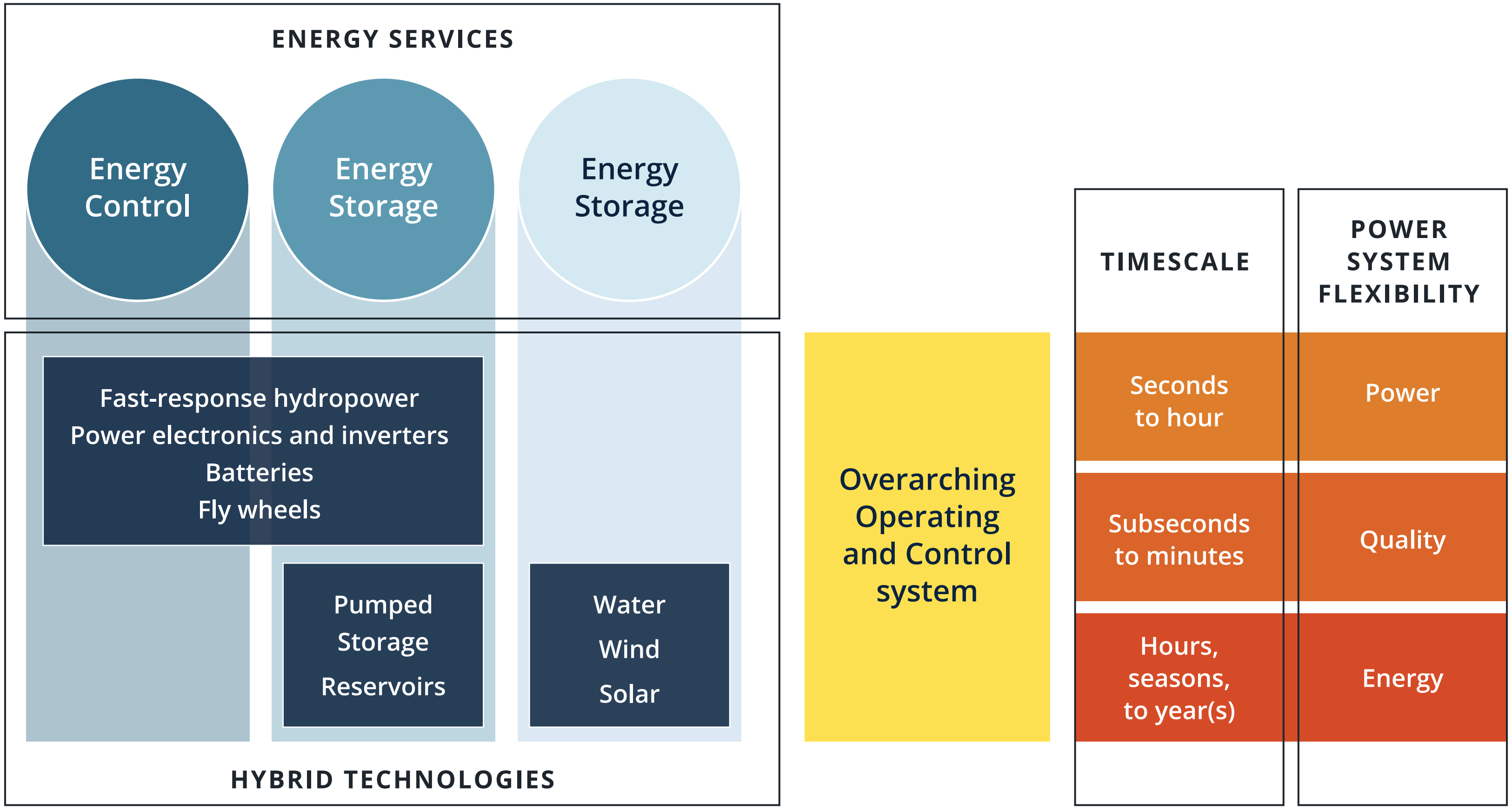
CAPABILITIES

A power plant's and its individual generation units' capabilities have to be identified to understand the services delivered by the plant to the power system. These capabilities can be described with the following parameters:

1. **Generation unit (MW).** The maximum power output from a generation unit is a measure of the highest amount of electricity it can generate in a moment. It is also known as installed capacity.
2. **Plant power output (MW).** This is the sum of the capacities of the installed units and is important for the same reasons as unit output.
3. **Operating range (MW).** This spans from the minimum to the maximum power output. The range indicates how flexible the power plant´s operation is.
4. **Ramp rate (MW/minute).** This is used to describe how fast a unit's output can be ramped up or down to respond to changes in variable renewable energy generation or grid load, and maintain equilibrium.

FIGURE 3.1

Relationship among Energy Services, Selected Technologies, Timescales, and Power System Flexibility



Mastering Energy Control

Lack of flexibility and inertia in power systems are limiting VRE's integration into them (Guerra et al. 2022). Besides flexibility, explained above, inertia in a power system is provided by the rotational mass of large generators. Inertia is essentially a buffer that represents a system's resistance to changes in frequency. It helps maintain stability during disturbances. VRE's integration can be better managed by incorporating technology that helps build flexibility and inertia for enhanced energy control. Improvement could yield several benefits; for example, it can help maintain power balance with high power quality and reduce the risk of VRE generation being curtailed (see box 3.2).

BOX 3.2

CURTAILMENT AS A FLEXIBILITY PROVIDER

Curtailment refers to the deliberate reduction or control of energy generation when supply surpasses demand or when a power system cannot efficiently accommodate the excess energy. Variable renewable energy (VRE) sources such as solar and wind are characterized by uncontrolled variability and intermittency. Consequently, there are instances when energy production exceeds immediate electricity requirements, leading to an oversupply situation.

Wind and solar generation can be regulated, to some extent, by shutting down generation. However, this curtails energy and leads to its wastage. While it is possible to increase wind- and solar-based generation to some extent by switching on panels or turbines, the influence of weather adds a high degree of unpredictability.

To safeguard grid stability and mitigate potential disruptions or failures, system operators resort to curtailing or trimming surplus VRE. This deliberate curtailment is a controlled process to balance the power system and is aligned with the grid's capacity to absorb and distribute electricity. With growing global VRE shares, the frequency of curtailment as a flexibility provider is expected to increase (IEA 2023c).

Mitigation of the curtailment risk should first consider appropriate planning, evaluation regarding current and future demand, and influencing the electricity pattern followed by enhancing power system flexibility using available technology.

Fast-Response Hydropower

Energy control in a hydropower hybrid relies on hydropower's fast-response capabilities, which make flexible operation possible and help maintain power balance and power quality by balancing short-term supply and demand (Harby et al. 2019). Demand change and the resulting supply-demand imbalance can be illustrated with a daily life example: imagine coming home from work and starting to heat water for tea in an electric kettle at about the same time as all your neighbors. This represents a sudden demand surge and an imbalance that must be compensated for, because multiplying the power requirement for one kettle, which is only 700 watts, by, say, 100,000 (the number of neighbors) constitutes a substantial load change. This can happen in seconds and must be balanced just as fast.

Fast response means the ability to ramp up and down output rapidly, and in a controlled manner, to balance power, frequency, and voltage fluctuations. When a generation unit detects a change in frequency, power, or voltage in the grid, it seeks to balance that by managing water flow. This transfers the imbalance from the power system to the waterway. The power system, the generation unit, and the waterway thus function as a dynamic system whose components continuously interact and affect one another. Therefore, several capabilities of a hydropower plant are influenced by the hydraulic design of the waterway connecting the reservoir and a generation unit. Dynamic analysis of the waterway is needed to identify how it responds. For existing units, it is also recommended to explore opportunities to improve the hydraulic design (e.g., installation of surge chambers and air cushion chambers in the waterway for an even faster response time). As the name implies, surge chambers and air cushion chambers act as cushions to quickly dampen oscillations and changes that are essential for maintaining system stability (Xu et al. 2023).

In recent years, several research programs delved deep into the topic to boost flexibility and improve a facility's energy control. In this respect, it is worth mentioning the development of variable-speed turbines for hydropower plants, which can deliver power output with high efficiency at different rotational speeds—meaning they can generate a higher power output using lesser water than fixed-speed operation. Pumped storage units, XFLEX Z'Mutt, for instance (described in box 3.3), are considered especially suitable for variable-speed technology and can be further supported by power electronics for advanced control capabilities (XFLEX HYDRO n.d.).

BOX 3.3

ACHIEVING HIGH FLEXIBILITY WITH VARIABLE-SPEED TURBINES AND POWER ELECTRONICS

Z'Mutt is a pumping station, which feeds water into the main reservoir of the Grande Dixence hydroelectric scheme in Switzerland. It was commissioned in 1964 and has 88 MW of pumping capacity, which is constituted by five existing pumps. The XFLEX HYDRO program will replace one pumping unit with a new 5-MW variable-speed reversible pump turbine, which, when installed with modern power electronics and smart controls, sets the stage for a demonstration of a wide range of flexible capabilities. This enhances the plant's flexibility and operational performance.

Z'Mutt demonstrates the high flexibility of a variable-speed hydro unit equipped with a frequency converter for advanced control capabilities. Enhanced services will be achieved by rapid changes in power in the pumping and generation modes, fast power injection or rejection, synthetic inertia, and fast transition, start and stop in pumping and generation modes. This will add to the plant's capability to provide energy control that can respond to dynamic changes in the grid or within a hybrid facility.

The full-scale demonstration seeks to validate the methods to predict the components' lifetime, besides confirming safe long-term operation under conditions of high flexibility.

"Installing variable-speed on a pump turbine provides a whole range of improvements in terms of both unit flexibility and equipment durability."

Bernard Valluy—Head of Group Operations, Alpiq.

Source: XFLEX HYDRO 2022a.

Power Electronics and Inverters

Inertia is essential in all power systems since it keeps the machines rotating even during power outages, typically for some seconds, and allows control systems time to detect a failure and restart the machines. Inertia is absent in solar and wind power plants; instead, they use power electronics and inverters to create synthetic inertia to balance power output by mimicking the inertia of rotating machines (ESMAP, 2021). This represents a paradigm shift in how we think about delivering power quality for solar and wind (Engel and Mallwitz 2010).

However, power electronics can also enhance the dynamic response in hydropower. This is possible with the introduction of power electronics and frequency converters between synchronous generators and the grid (Uhlen and Reigstad 2020). This can expand a hydropower unit's operating range by increasing efficiency at partial and high loads with optimal speed control and ultrafast ramp rates. Power electronics can also help deliver a faster and more accurate response when active and reactive power must be controlled. Finally, power electronics can also help utilize a hydropower unit's inertia more effectively. It is worth noting that power electronics only counters sub-second imbalances originating from generation; it cannot counter imbalances originating from the grid. Significant research is devoted to exploring the use of power electronics and associated technology, which hybrid facilities can use in its generation both for hydropower and VRE.

A hydropower hybrid's response capability can also be improved by combining it with a battery energy storage system (BESS) (see section 3.2.3). This is especially relevant for hydropower plants such as run of river (RoR), which have a low head and high water flow rates, and a slow response capability. Equipping a RoR plant with battery energy storage in a hydropower hybrid enables a fast response to sub-second fluctuations (see the example in box 3.4).

BOX 3.4

BESS IMPROVES ENERGY CONTROL AT VOGELGRÜN

Vogelgrün in France is a 142-MW run-of-river (RoR) hydropower plant generating 750 GWh annually. The plant has four low-head Kaplan turbines, which have been in operation since 1959. Through the XFLEX HYDRO research program, one unit is hybridized with 0.65 MW of battery energy storage, including an overarching control system.

A low-head RoR unit is suited for providing a stable energy supply, also known as base load operation, and capable to some degree of supporting power quality. However, possibilities to regulate flow and generation for this power plant is further limited since it has a small energy storage and are under obligations to provide water downstream for navigation and other purposes. This further limits the plants' ability to provide energy control, creating an opportunity to explore alternatives for coupling hydropower plants with other technologies to compensate.

BOX. 3.4 *(CONTINUED)*

Hybridization with a battery energy storage system (BESS) is an exciting opportunity since this will complement turbine operation, in turn improving energy control and supporting power quality by reducing the response time.

With a BESS, a hybrid hydropower plant can deliver high dynamic primary frequency response, which yields benefits to the grid and opens a possibility to participate in several markets. The hybridization also provides an additional benefit: it will reduce wear and tear because the battery alleviates the need for the turbine to respond in sub-second to second. Frequent, rapid adjustments exert a high dynamic force on the equipment, shortening its life span. Mitigating such adjustments thus reduces wear and tear.

XFLEX HYDRO has demonstrated potential doubling of the expected lifetime of components subject to high wear and tear when hybridizing RoR with BESS.

Source: XFLEX HYDRO 2022b. XFLEX HYDRO 2024
Photo: “BESS enhancing energy control at Vogelgrün HPP”. © Electricité de France. Used with the permission of Electricité de France. Further permission required for reuse.

Boosting Energy Storage

Energy storage allows capturing energy when the demand is low or resource availability is high, and releasing it when the demand rises. This helps balance daily, weekly, or even interannual energy supply and demand. Following are the primary storage technologies that can provide electricity:

- **Reservoir hydropower** captures, stores, and dispatches electricity when needed. A reservoir is charged by regular river inflow.
- **Pumped storage hydropower** charges a reservoir by pumping water back into it, in addition to river inflow, and dispatches electricity when needed.
- **Batteries** are electricity-charged electrochemical storage. They discharge electricity when needed.
- **Flywheels** provide inertia and rapidly release kinetic energy.
- **Compressed and liquid air energy storage** captures, stores, and dispatches energy when needed.

There are many energy storage technologies besides the ones described above. Chemical and thermal storage utilizes carriers such as heat, liquids, or gases for storing energy. While these technologies do not necessarily convert the stored energy back into electricity, if such a conversion does occur, the corresponding technology does it with low efficiency. This chapter presents energy storage technologies perceived to hold the highest potential to provide energy services for hydropower hybrids; however, other technologies should be considered if deemed optimal.

Reservoir Energy Storage

Hydropower reservoirs is the largest source of energy storage today. It represents a global storage capacity of about 1,500 TWh (IEA 2021)—about 2,200 times the combined capacity of all existing batteries in stationary applications and electric vehicles (IEA 2021), and is the proven technology for long duration energy storage. Box 3.5 presents an example of hydropower plant under development with a large reservoir storage capacity, which significantly contributes to safeguarding energy security, decarbonization, and VRE integration.

Although hydropower has energy storage capabilities, combining it with other storage alternatives can also bring benefits. This would improve performance, reduce wear and tear, reduce maintenance costs and need, improve power quality, and mitigate environmental impacts (XFLEX HYDRO n.d.). RoR hydropower can also store significant amounts of energy, though not for long durations. Also, flexible operation of RoR hydropower plants may be hindered by technical limitations or environmental restrictions. As demonstrated in box 3.4, combining RoR hydropower with other storage alternatives could add to flexibility, help mitigate environmental impacts, and reduce maintenance costs.

BOX 3.5

KAMBARATA-1 HYDROPOWER PLANT

The Kyrgyz Republic's mountainous terrain provides it with a wealth of hydropower potential—less than one-fifth of which has been utilized. Greater use of hydropower energy sources aligns with the country supporting more sustainable and greener growth through its commitment to transitioning to cleaner energy sources.

The Kambarata-1 hydropower plant, which will have a large-storage-capacity reservoir—of 1.5 TWh—can help address the Kyrgyz Republic's energy security challenges while improving downstream hydropower plant operations and water management. The plant will have an installed capacity of 1.8 GW and contribute to global decarbonization efforts by supporting the integration of other renewables such as solar and wind, in turn reducing dependence on fossil fuels.

The project is fundamental to addressing the country's winter energy shortage and ensuring energy security. Water flow for hydropower varies annually and demonstrates significant seasonal changes. The water flow between a dry year and a wet year could vary by over 100 percent. Within a year, over 70 percent of the water flow is concentrated in the four to five months of summer. On the other hand, electricity demand in winter is two to three times higher than in summer.

Source: World Bank 2023a.

Pumped Storage Hydropower

Pumped storage projects serve the purpose of storing energy by pumping water from low- to high-altitude reservoirs. Some pumped storage facilities offer seasonal energy storage, in regions characterized by significant seasonal variations in water flow (e.g., regions with cold climate with snow during winter, or regions with dry summers and wet winters). Pumping consumes energy, and electricity is generated when water is subsequently released from higher- to lower-altitude reservoirs. The stored potential energy is thus harnessed in the process, with the higher-altitude reservoir acting like a battery (US DOE n.d.[a]).

Pumped hydro systems are typically driven by a single reversible pump turbine or a combination of a separate turbine and a pump. Pumped storage hydropower can be classified as open- and closed-loop systems. In open-loop systems, a hydrological connection is maintained with a natural water body. This means water continuously flows into and out of the reservoirs from an external source. Closed-loop systems include reservoirs that are not connected to an external water body. This means the systems do not rely on external water sources to operate. However, closed-loop systems will need to compensate for losses and evaporation. In Austria, the KOPS II pumped hydropower plant, with an installed capacity of 525 MW, provides reserves through a hydraulic short-circuit operation, or by pumping part of the water to the reservoir and part to the turbines. This has yielded in net energy and a 91 percent capacity factor (IEA Hydropower, 2021). Today, several pumped hydro projects have been constructed (El Hierro, box 3.6). However, several pumped storage projects are being planned, and new sources are being explored and tested. Several new projects utilize oceans as the lower-elevation reservoirs, and there are plans to use existing mines or caverns for developing pumped hydro.

The International Energy Agency estimates that pumped storage generation must be increased to 53 GWh by 2030, from 24 GWh (in 2020), to meet the global storage demand. Besides greenfield pumped storage projects, there is significant potential for retrofitting existing reservoir hydropower with pumped storage. In countries and regions that have reservoirs at different altitudes in close proximity, it should be investigated whether installation of pumping and increase of turbine capacity are feasible.

Electrochemical Storage (Batteries)

Recent cost reductions have resulted in batteries gaining more attention as stationary energy storage solutions. At the end of 2022, the global installed capacity for electrochemical energy storage systems was 28 GW (IEA n.d.[a]). Projections indicate a substantial surge to 400 GWh by 2030 and 1.3 TWh by 2040 (Tsiropoulos, Tarvydas, and Lebedeva 2018).

The market for battery technologies offers a variety of alternatives, each with unique characteristics related to energy storage capacity, power output, round-trip efficiency, life span, and cost. Lead-acid and nickel-cadmium batteries are currently the most widely used, and they are suitable alternatives for stationary applications. Nevertheless, emerging technologies such as flow batteries show promise for stationary energy services (Kebede et al. 2022).

BESSs primarily serve as sources for energy control, besides being alternatives for short-term storage and sources of rapid power supply. In this context, a BESS is an excellent hybrid solution to use with hydropower for sub-second to second energy services, especially when technical limitations, regulations, and availability of water constrain hydropower's ability to regulate power output.

THE WIND-PUMPED HYDROPOWER STATION IN EL HIERRO, CANARY ISLANDS

The Gorona del Viento wind-pumped hydropower station represents a pioneering approach to delivering clean and sustainable electrical energy to the El Hierro Island (Canary Islands, Spain). This innovative facility harnesses the power of two abundant and renewable resources: wind and water.

On December 8, 2023, El Hierro broke the record as the only island in the world capable of operating 28 consecutive days with 100 percent hybrid hydropower and wind.

The hybrid boasts of being capable of fully meeting the island's electricity needs. Any excess wind energy generated—beyond what the island's population requires—serves a dual purpose: first, it is utilized to pump water from a lower- to a higher-altitude reservoir, with potential energy stored effectively for future use. Subsequently, during periods when wind power alone may be insufficient, this stored water is released through the pumped storage turbines, allowing electricity generation. The island thus receives a continuous and reliable power supply, even in the absence of strong winds.

Gorona del Viento's innovative approach demonstrates how the integration of wind and hydropower can create a sustainable and resilient energy system. It sets an example for clean energy solutions worldwide.

Source: Gorona del Viento n.d.; Euronews 2023.

Flywheels

A flywheel is a fast energy storage technology that is primarily characterized by high energy density and an ability to provide high power output. It is a rotating mass that acts as a motor as well as a generator. To store energy, the electrical machine acts as a motor, exerting a positive torque on the flywheel, whose rotational speed increases. To release energy, the electrical machine functions as a generator, applying a negative torque on the flywheel, causing it to brake and release energy back to the grid. Flywheels are used for delivering ultrafast responses to changes in grid stability or frequency over very short spans of time. Flywheels can be hybridized with hydropower to boost ramping capabilities. This will render hybrid solutions highly flexible and capable of regulating frequency and other ancillary services that help deliver an immediate response. Box 3.7 presents an example of a hybrid power system utilizing flywheels with hydropower, solar, wind, and battery.

While flywheels are predominantly used for energy savings in transportation, there is an increasing interest in their use for regulating frequency and stability in electric grids and microgrids, with the purpose of handling power fluctuations in renewable generation and boosting its efficiency, or reducing load peaks in industry applications. The disadvantage of these hybrid solutions is predominantly related to costs, besides certain safety issues related to a large mass spinning at 10,000–50,000 rotations per minute. Flywheels must therefore be installed in protected caverns or buildings, although in principle they can be installed at any site.

Compressed Air and Liquid Air

Compressed air energy storage (CAES) as well as liquid air energy storage (LAES) leverage surplus energy for storage. In CAES, compressed air is stored either underground in caverns or above the ground in pressurized vessels. Commercial applications of CAES date back to 1978 and 1991 (e.g., the Germany-based Huntdorf power plant and the US-based McIntosh power plant, respectively, which utilize compressed air in gas turbines when discharging energy to the grid). Notably, modern CAES developments no longer rely on fossil fuels, instead employing the air in an expander to generate electricity.

Meanwhile, LAES involves cooling air to temperatures below -196°C and storing it in insulated tanks at low pressure. Similar tanks are employed worldwide for bulk storage of substances

> "Kodiak, Alaska, is an island of wind and rain. Kodiak Electric has been able to harness these as energy sources to provide a fully renewable energy grid that utilizes hydroelectric, wind, and energy storage to provide stable cost-effective electricity to our community."

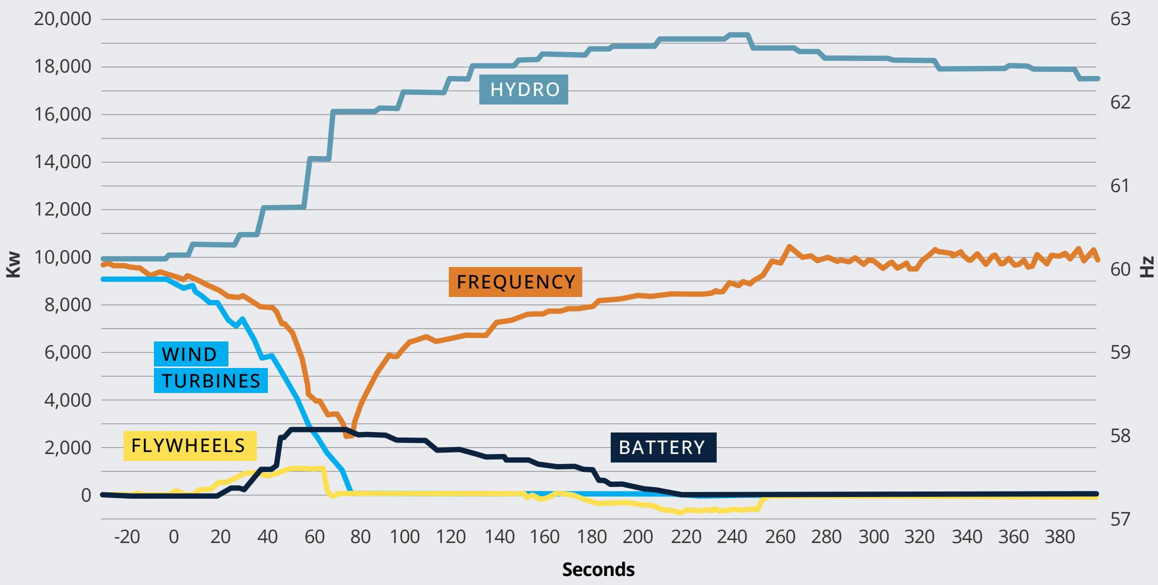
Darron Scott, President CEO of Kodiak Electric Association

BOX 3.7

A RENEWABLE HYBRID POWER SYSTEM: KODIAK

On the island of Kodiak, Alaska (United States), hydropower and diesel generators supplied, respectively, 41 percent and 59 percent of energy to the local electricity grid in 2000. Kodiak Electric has now suppressed diesel generation and is running a fully hybrid renewable system comprising 28 MW of hydropower, 9 MW of wind power, 3 MW of battery energy storage, and 2 MW of flywheel energy storage. The system has automatic control, which shifts generation based on load and variability of wind generation. When, for example, wind generation abruptly drops because wind is not blowing, the flywheel and the battery start generating electricity as the hydropower units are ramping up (Clamp 2020).

EXAMPLE OF A SYSTEM RESPONSE TO A WIND EVENT



Source: © Kodiak. Used with the permission of Kodiak Electric Association Inc. Further permission required for reuse.

Figure B3.7.1 shows an example when wind power generation (light blue line) falls and flywheel (yellow) and battery (grey) start generating immediately. Flywheel generation ceases when hydropower (dark blue) is ramped up, and the flywheel is recharged. Battery generation ramps down gradually and frequency (red) is stabilized.

Wind power can support grid operations and help electrify remote locations not connected to a centralized grid. While there are technical barriers to fully realizing this with wind energy alone, hybridizing wind power with storage technologies can help realize it. Energy storage can shift wind energy from periods of low demand to peak times, smooth fluctuations in output, and provide resilience services during periods of low resource availability (Reilly et al. 2022).

such as liquid nitrogen, oxygen, and liquefied natural gas. When energy is required, liquid air is heated, producing a high-pressure gas, which drives a turbine, resulting in electricity generation.

While CAES and LAES possess unique characteristics, they may not be ideal for rapid energy storage and flexibility services. Their potential in hybrid configurations is primarily relevant to RoR hydropower with limited or no storage capacity. In such scenarios, combining hydropower with CAES or LAES could serve as an alternative to creating large reservoirs or implementing pumped storage solutions.

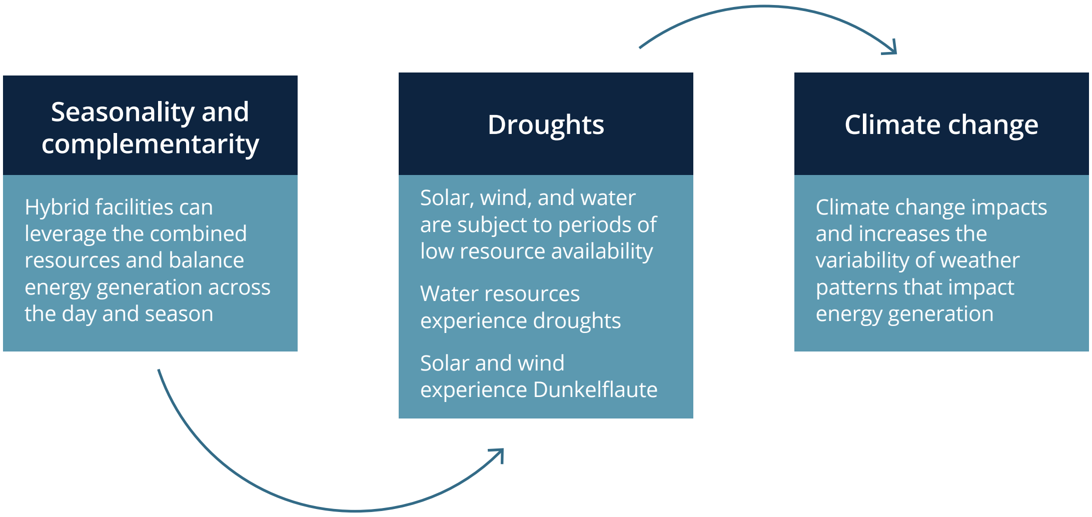
Energy Generation

As interconnectivity in power systems increase, so do the interdependencies among renewable resources. Complementarities and variability could either lead to unintended consequences in regions with similar weather conditions, or offer a great advantage, by making long-term balance more reliable and boosting energy security as resources in different regions could complement one other. Further, increased interconnectivity also makes it possible to explore how energy services can build flexibility in power systems, alleviate constraints in some areas, and help focus investments on expansions or areas that require strengthening.

To comprehensively understand how hydropower hybrid energy generation can help ensure energy balance in a power system in the long term, the interplay among seasonality and variability in water, solar, and wind resources must be examined alongside shifts in power system demand. Variability in water, solar, and wind has been classified under three characteristics—(1) seasonality and complementarity, (2) droughts, and (3) climate change (figure 3.2)—which must be examined to determine the optimal sizing for a hybrid facility and the energy services it provides across multiple timescales.

Seasonality of water, solar, and wind energy generation is fueled by climate factors such as air temperature, precipitation, evaporation, wind velocity, radiation, and river runoff (Engeland et al. 2017). This means it is affected by changes in weather patterns, droughts, and climate change. The interactions among these factors will determine the optimal conditions and configuration for energy generation and power output from a hydropower hybrid, the identification of optimal resource utilization, facility sizing, and energy management. Hydropower hybrids can reduce variability in power output and help make energy generation more reliable, although specifics vary based on region, season, and available resources.

FIGURE 3.2
Main Features of Weather-Dependent Renewable Resources



Source: World Bank.
Note: "Dunkelflaute," see box 3.8.

Resource complementarity is multifaceted, and identifying optimal resource utilization requires careful assessment of several variables across all timescales; this will eventually depend on the hybrid facility's design (e.g., relative sizing) (Murphy et al. 2023).

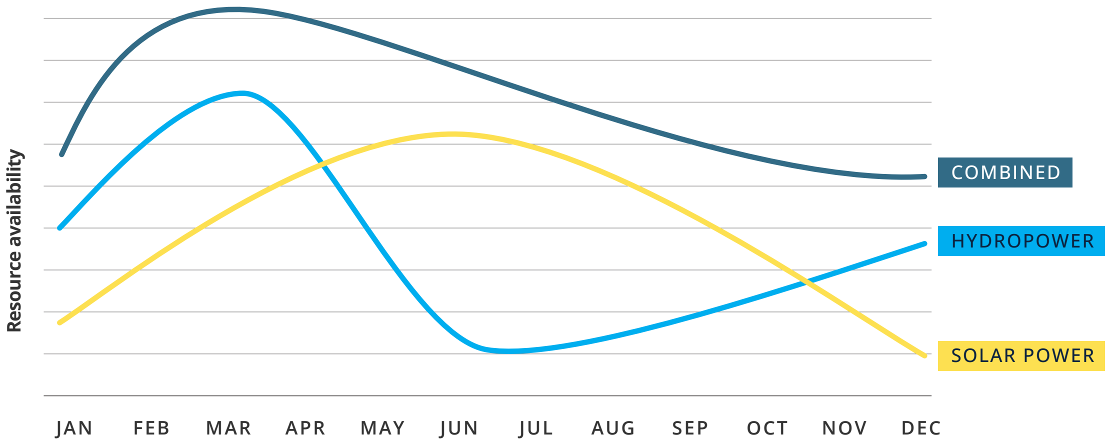
Most renewable sources have pronounced temporal variability—also known as seasonality—which strongly affects energy generation. In some regions, solar and hydro resources demonstrate complementary seasonal patterns—as shown in figure 3.3, where the blue and yellow lines represent river flow and solar radiation, respectively. Dry seasons are typically characterized by low rainfall and high solar irradiance, whereas wet seasons are characterized by heavy rainfall and low solar irradiation. Hybrid systems can leverage this complementarity by utilizing the combined resources, as depicted by the green line.

Hydro, solar, and wind share two commonalities: they experience **resource droughts** and are affected by climate change. While drought can be easily related to water, extended periods of insufficient radiation and too low or too high wind speeds also impact wind- and solar

Hydropower hybrids can reduce variability in power output and help make energy generation more reliable, although specifics vary based on region, season, and available resources.

FIGURE 3.3

Illustration of Seasonality of Water and Solar Resources



Source: World Bank.

generation. "Dunkelflaute" is a drought period for solar and wind (Li et al. 2021). Although no official translation exists for this term, it can be translated as "dark stillness," which suits the definition of a sustained decline in wind and solar resource availability. In the northern hemisphere, this occurs every winter (see box 3.8 for details). Managing solar and wind droughts requires determining the frequency and magnitude of the droughts and understanding how they correlate. IEA Hydropower have explored how drought events in terms of associated energy deficit translates to flexibility and energy storage needs. The benefits are to better understand and anticipate future VRE droughts and system flexibility needs; to assess the applicability of flexibility need assessment criteria to ensure robust evolution of drought indicators for effective system planning in the transition to cleaner electricity systems (IEA Hydropower, 2024).

Climate change is set to impact weather patterns, besides impacting solar-, wind-, and hydro generation and its variability (Kincic et al. 2022). Gernaat et al. (2021) showed that climate change will have varied impacts on regions and even countries. While the available resources will increase in some regions and countries due to climate change, there will be resource scarcity elsewhere. Climate change will also have varied impacts on technologies. These changes must therefore be assessed given the long lifetime of a hybrid facility; this is to identify optimal energy management and design a plant that can safely withstand or mitigate these changes.

BOX 3.8

DUNKELFLAUTE—“DARK STILLNESS”

Li et al. (2021) have carefully analyzed weather and generation data to determine the frequency of Dunkelflaute events for solar and wind. They have also assessed variability in power output and flexibility requirements. Dunkelflaute is a “drought” period for wind and solar resources and is defined as extended periods of insufficient radiation and too low or too high wind speeds.

The study analyzed Dunkelflaute events—characterized by droughts meaning low wind and solar resource availability—in 11 countries bordering the North and Baltic Sea regions. Dunkelflaute events lasting at least a day were found to occur every year. Some countries experienced 2–10 such events annually, with a few lasting three to five days. These events were the most frequent in November, December, and January.

Dunkelflaute events were associated with stationary high-pressure systems and extensive low cloud cover, which hindered wind energy generation. They also resulted from limited solar energy generation in winter, due to shorter days and lower solar radiation.

The study found moderate correlation between Dunkelflaute events in neighboring countries. **The occurrence of these events could be reduced by implementing an interconnected power system that pools hydro-, wind- and solar generation, add other flexibility solutions and increase long duration energy storage.**

Harnessing Synergies with Hybrid Operation and Control Systems

Unlocking the full potential of hydropower hybrids requires harnessing multiple integrated renewable resources under an overarching operation and control system. This presents unique challenges relative to stand-alone power plants. The technologies integrated in a hybrid have distinct operational needs and characteristics; also, a hybrid must manage energy storage efficiently, alongside maximizing the value of energy services contributing to power system flexibility (figure 3.3).

The efficiency of operation and control is determined by how accurately power output, generation, and quality are predicted. To illustrate, for a solar plant, it is easy to predict sunrise and sunset since it follows a diurnal cycle. While this gives a good indication of the expected power output and potential energy generation in a day, it does not accurately predict the extent of sudden drops and rises in irradiation and output due to clouds. A similar case can be observed when predicting wind generation. While weather forecasts give a good indication of the expected average wind speed, they cannot predict sudden gusts at a specific time that affect power output. In this context, it is appropriate to examine gaps in modeling hybrid generation using software that simulates power systems. Power system models and study software are keystones of operation and planning studies. They must be enhanced to obtain results that accurately depict hydropower hybrids so that their effects on the reliability and economy of power system operation can be understood (Kincic et al. 2022).

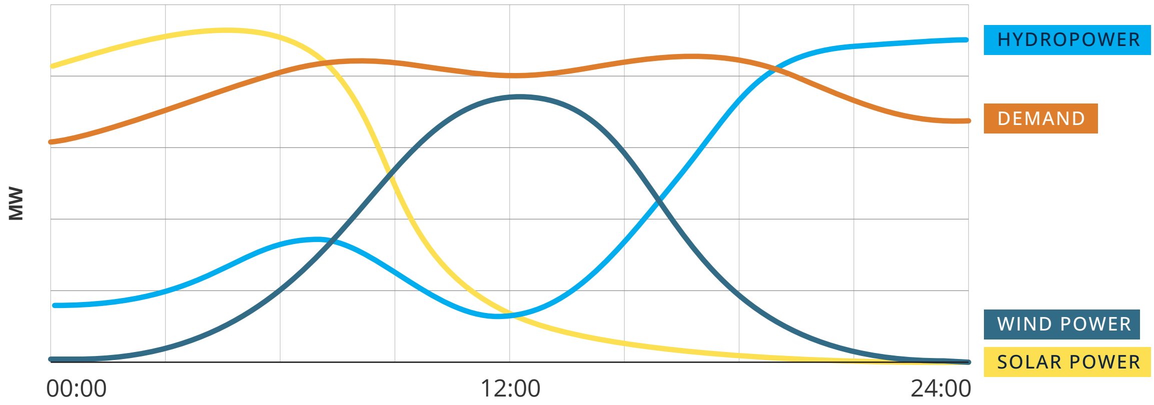
Optimal utilization of hybrid technologies relies on combining multiple energy technologies to fulfill multiple objectives (see figure 1.3). This necessitates developing operational strategies, which can allow collecting and analyzing data from the power system, the hybrid facility, and weather conditions.

In planning, operating, and controlling hybrid systems, a key aspect is how the combination of weather-dependent resources can meet the demand. Figure 3.4 shows an example of how the availability of solar-, wind-, and hydro generation can vary throughout a day. An operation and control system can extract this information from weather, hydrology, and demand forecasts. This can be followed by efforts to predict and optimize generation from different resources to

Power system models and study software are keystones of operation and planning studies. They must be enhanced to obtain results that accurately depict hybrid systems so that their effects on the reliability and economy of power system operation can be understood.

FIGURE 3.4

Illustration of Availability of Renewable Power Output throughout the Day



Source: World Bank.

best meet the demand. In contrast to solar and wind, hydropower forecasting requires a hydrological model using real-time data from weather and hydrological measuring stations. The next step then is to optimize energy generation to meet the demand using available resources and energy storage.

Box 3.9 presents one example of how an operation and control system can manage a hybrid facility. A hybrid's energy generation, power output, and power quality can be optimized and predicted when real-time data are combined with modeling or prognosis of energy availability.

Operational flexibility means a plant can deliver energy and power during planned and unplanned events. It is determined by the operating range for an individual generation unit and the combined range for all the units in a hydropower plant. A broad operating range is sought after since it means the hydropower plant is more capable of supporting the variable solar- or wind power output. Other aspects determining operational flexibility include the number of generation units and their ability to operate together; this provides continuous power output and adds redundancy. Operational flexibility is crucial for maintaining power and quality balance every sub-second, minute, and hour. A facility that needs to manage seasonal variability (see section 3.3), since it combines multiple energy sources, also needs resources for ensuring flexibility on a weekly, monthly, seasonal, or even annual basis (IEA 2023b).

More flexible operation of a hydropower hybrid could lead to the capacity factor decreasing when integrating with existing hydropower generation units; this is a measure often used to inform how efficiently a renewable generation facility utilizes available resources. This reduction does not necessarily reflect resource underutilization or reduced generation efficiency; rather, it can indicate improved utilization of the hybrid's flexibility, due to a change in the operation strategy (see box 3.10).

TRANSFORMING KAUA'I'S ENERGY LANDSCAPE WITH HYBRID HYDROPOWER SOLUTIONS

The Hawaii-based Kaua'i Island Utility Cooperative (KIUC) is leading the way in renewable energy innovation with the West Kaua'i Energy Project (WKEP). In December 2020, the KIUC signed agreements with the AES Corporation to develop, construct, and operate the WKEP—an ambitious and unique endeavor that integrates multiple renewable energy resources, to create a sustainable and resilient energy future.

The WKEP will combine hydropower, solar photovoltaic generation, pumped hydropower, and battery energy storage. The solar array will generate up to 35 MW when operational. This energy will be supplied directly to the grid, with up to 240 MWh stored for evening dispatch. The hydro resources are expected to produce an average of 24 MW daily, including 12 hours of overnight storage. This combination of renewable sources and long-duration storage capacity enables Kaua'i to achieve prolonged periods of 100 percent renewable energy usage, even during periods when sunlight is absent.

By harnessing multiple renewable resources and long-duration storage, the KIUC and AES are not only transforming Kaua'i's energy landscape, but are also setting a precedent for sustainable and resilient energy solutions worldwide.

Source: KIUC 2021.

BOX 3.10

MORE FLEXIBLE OPERATION MAY LEAD TO A REDUCED CAPACITY FACTOR

The capacity factor for a generation facility is the ratio of the actual energy generated and the amount equivalent to continuous generation over a year. In theory, if a unit is running 8,760 hours in a year at maximum capacity, then the gross capacity factor would be 100 percent. To illustrate how a change in the energy mix may impact the capacity factor, consider the following example: Initially, the power system is 100 percent hydropower based. The installed capacity equals the peak load (600 MW), while the base load is 60 percent of the peak load. The capacity factor is 68 percent gross (table B3.10.1).

BASELINE ASSESSMENT OF CAPACITY FACTOR

DESCRIPTION	VALUE
Peak load (installed capacity)	600 MW
Base load (60% of peak load)	360 MW
Annual hydropower generation	3.6 TWh
Theoretical hydropower generation assuming 100 percent production 365 days a year	5.3 TWh
Capacity factor (hydropower plant)	68%

Note: MW = megawatt; TWh = terawatt-hour.

In a scenario where the peak load has increased to 750 MW (table B3.10.2), new turbine runners are installed, with increased output, to adapt to that change. The overall water inflow into the hydropower plant and the total energy generation from the plant remain unchanged.

HIGH FLEXIBILITY MAY LEAD TO REDUCED CAPACITY FACTOR

DESCRIPTION	VALUE
Peak load (peak installed capacity)	750 MW
Base load (60% of peak load)	450 MW
Annual hydropower generation	3.6 TWh
Capacity factor (hydropower plant)	55%

Note: MW = megawatt; TWh = terawatt-hour.

The capacity factor is a traditional metric used to assess the utilization of energy from all sources. It is deemed favorable when it approaches 100 percent. A change in generation pattern as illustrated in the tables above is accompanied by a reduction in capacity factor. However, this does not imply resource underutilization because the resources are put to better use. It provides the required flexibility to integrate variable renewable energy and contributes to the energy transition.

4. Exploring the Benefits and Challenges of Hybrid Facilities

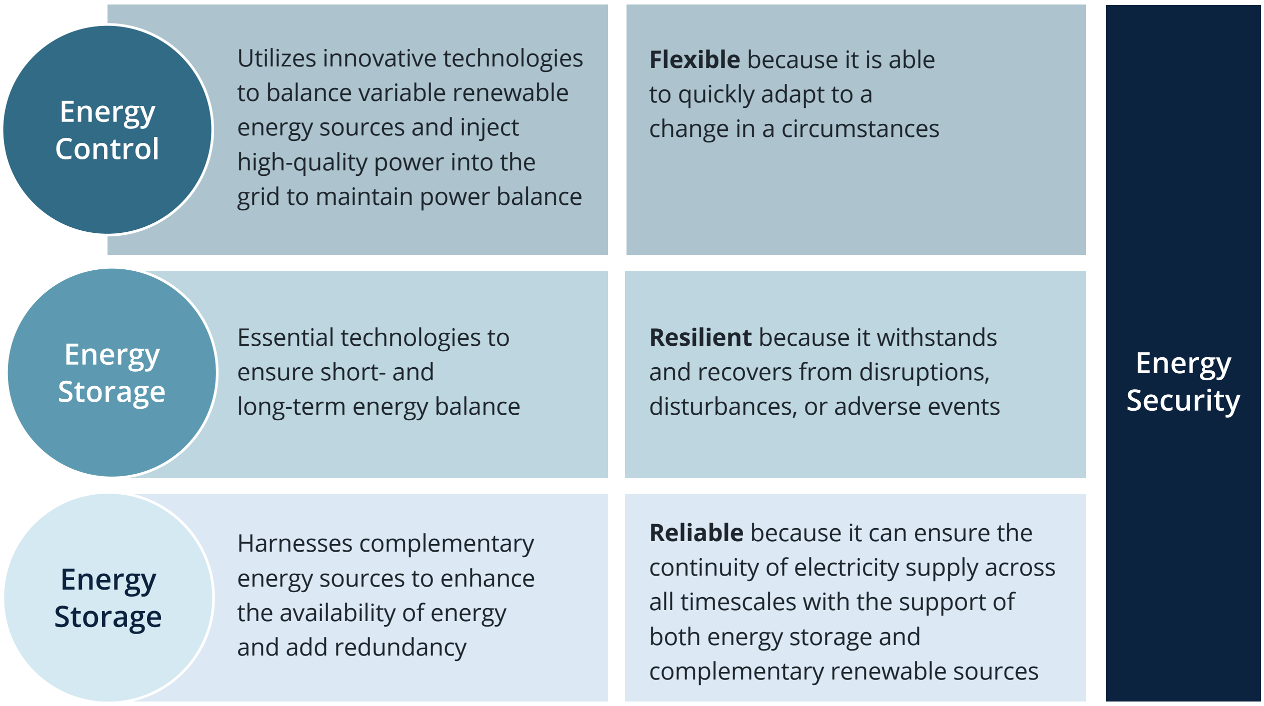
Hydropower hybrids are a promising advancement in the ongoing sustainable evolution of hydropower. They also stand as a promising solution for the challenges faced by power systems. Hybrids represent a shift in how renewable power facilities are designed, planned, and operated—facilities must deliver more than just energy generation. This shift leads to a change in the objective for a facility—from providing the maximum amount of energy from a site, to the services that a facility can provide. Hybrids offer several benefits, including greater power system flexibility, dispatchable electricity generation, cost savings, and efficient land and resource use. This chapter explores hybrids' benefits and challenges related to the power system, to individual technologies, and to the emerging synergies when technologies are combined.

Fortifying Energy Security

Our society's reliance on electricity is undeniable; prolonged interruption could lead to catastrophic consequences extending beyond power systems. Energy security refers to a country's or a region's ability to meet its energy demands by accessing the needed energy resources reliably. Energy security includes multiple aspects; for instance, it entails timely investments for supplying energy to support economic development while fulfilling environmental requirements. This includes access to both energy sources and the infrastructure needed to transport, store, and distribute that energy (IEA n.d.[b]). A country with good energy security can support economic development and improve its quality of life. Also, energy security can help reduce a country's vulnerability to supply disruptions, which can have significant economic and geopolitical consequences (Banna et al. 2023). An understanding of hybrids by delineating their technological advantages and harnessing them in operation, can provide insights into how to increase energy security.

A hydropower hybrid can boost energy security by supporting **flexible** power systems, as summarized in figure 4.1 and previous chapters. The flexibility provided by energy control services enables a hybrid facility to quickly adapt to changes in weather conditions. This also extends to demand changes originating from the grid, which can be accommodated by ramping up or down hydropower generation. Moreover, prolonged supply-demand imbalances require energy storage. Reservoirs are an ideal candidate, which can help sustain short- and long-term supply security by providing the required storage.

FIGURE 4.1
Fortifying Energy Security with Energy Services



Source: World Bank.

Reservoirs' unapparelled energy storage can also help make energy security more **resilient** by supporting electricity generation from multiple renewable energy sources. They can also contribute to long-term energy balance by utilizing complementarities between the seasonality and variability of hydrology and variable renewable energy (VRE) resources. This reduces power systems' vulnerability to failures or malfunctions given multiple, not single, sources and technologies are utilized; in turn, a hydropower hybrid has greater redundancy and energy security becomes more resilient.

An overarching goal is to ensure continuous energy and stable electricity supply at all times. Since hydropower hybrids use complementary renewable energy sources, in combination with energy storage, they are also ideal solutions to improve the overall **reliability** of power systems (see the case studies presented in boxes 4.1 and 4.2). Further, they can help address the specific needs of areas with weaker grid infrastructures, contribute to the overall efficiency and sustainability of the energy landscape, and bring a considerable number of benefits.

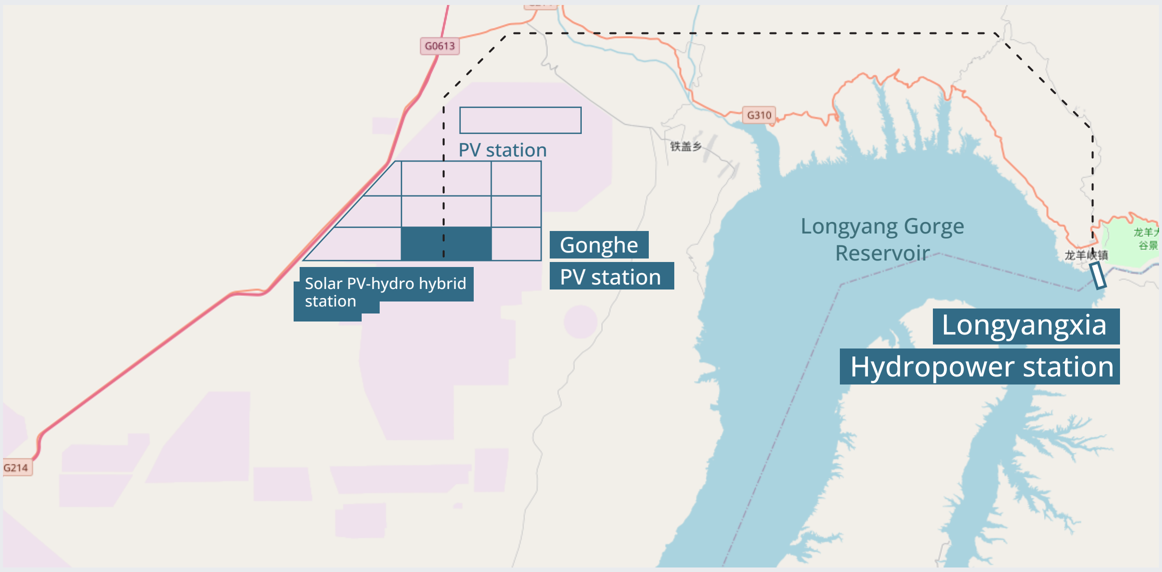
BOX 4.1

LONGYANGXIA HYBRID HYDROPOWER FACILITY

The first commercial large-scale hybrid hydropower facility, which combines large-scale solar photovoltaic (PV) with hydropower, was commissioned in China in December 2013.

The facility has four hydropower turbines of 320 MW each, which were commissioned in 1992 and combined with 320 MW of solar PV from the Gonghe Photovoltaic Project since 2013. In 2023, an additional 3,128 MW of solar PV power was added. The hydropower plant was commissioned as a peak-load- and frequency-regulating plant. Thus, it already had machinery that could deliver energy control, which could smooth the output curve from the PV power plant. The hydropower reservoir also provides water for irrigation and serves as ice and flood control for the Yellow River in China. The Longyangxia Hydropower Project (figure B4.1.1) is the most upstream power plant—situated on the upper part of the Yellow River—and it also provides water for several cascaded power plants further downstream. The reservoir's 24.7 billion cubic meters storage capacity allows the hybrid facility to provide energy storage, balancing, and generation, which helps ensure power system reliability and resilience.

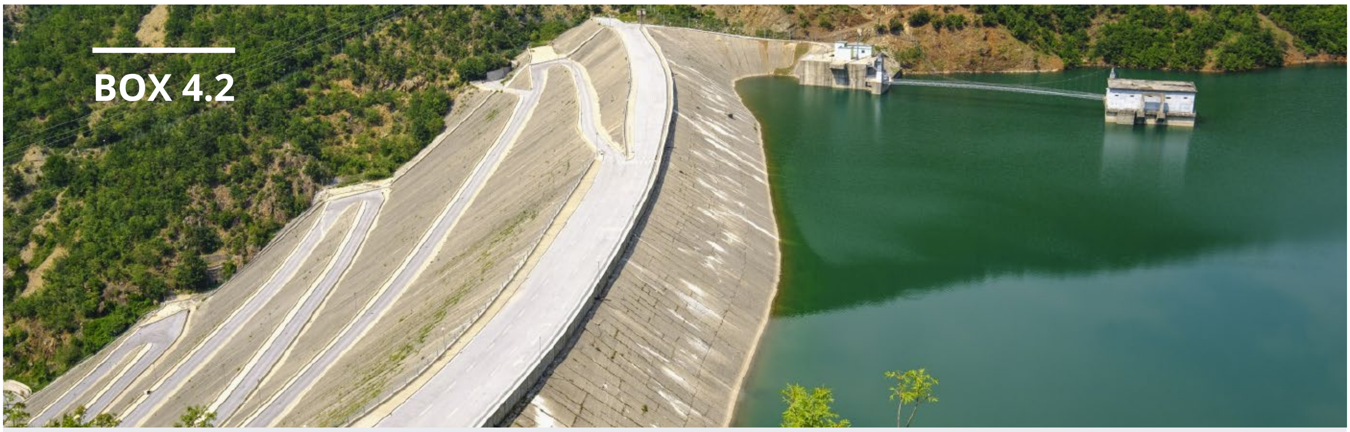
LONGYANGXIA HYBRID HYDROPOWER FACILITY



Operation of hydropower and PV generation under one joint control system at the hybrid facility makes it possible to provide immediate compensation between both technologies and adjust the output power to the power grid's needs. This means the efficiency of both technologies is increased, reducing curtailment and boosting revenues.

Source: IHA 2015. Map by ©OpenStreetMap contributors.

BOX 4.2



PIONEERING HYBRID FACILITY IN ALBANIA

Albania, which relies significantly on hydropower, is taking bold steps toward energy diversification and decarbonization. The country, which boasts one of the highest hydropower shares in Europe, faces increasing climate challenges due to more frequent droughts. To ensure energy security and meet the growing demand for clean energy, Albania is forging ahead with a strategy of energy diversification, embracing hybrid solutions.

One of the prominent projects is the transformation of the Vau I Dejës hydropower plant into an integrated energy production hub. This 250-MW hydropower station, operated by the Albanian Power Corporation, KESH, added a 5.1-MW ground-mounted solar power unit to its Qyrsaq dam, making it the first example of combining hydropower and photovoltaics in the Western Balkans. However, the vision goes beyond, as plans are underway to install a floating solar power plant on the reservoir and a wind power plant in the vicinity.

Source: Balkan Green Energy News 2023.

Harnessing Benefits from Hydropower Hybrids

Chapter 3 described different technologies that are considered to operate complementarily in combination when integrated in a hybrid facility. But combining technologies adds complexity in all project development phases: construction, and operation and maintenance. However, a strong focus on integrated infrastructure planning and management can turn this complexity into a strength through all the above phases and yield additional integrated benefits beyond improving power systems and boosting energy security. This applies, but is not limited, to the following elements for both hybrid hydropower facilities and virtual hybrid hydropower facilities:

- **Increased revenue.** A hybrid facility can boost revenue from energy generation relative to stand-alone plants. There also exists potential to boost revenue from energy services, although this depends on whether the market structure allows these services to be remunerated.

- **VRE turned into dispatchable energy.** Hydropower hybrids can use VRE to store more energy, by either pumping water to a higher-elevation reservoir or conserving it for later use and dispatching the energy when the opportunity calls for it.
- **Reduced cost of project preparation activities.** It is possible to conduct joint site investigations, surveys, geological and geotechnical surveys, feasibility studies, and assessments for site selection and associated infrastructure.
- **Streamlined stakeholder engagement.** Continuous engagement with the same stakeholders and project-affected individuals not only fosters smoother interactions but can potentially help save costs related to repeated consultations and negotiations.
- **A shared organization.** Operational expenses in all project phases can be reduced relative to those in stand-alone projects if they all share project implementation, execution, and operation and maintenance. For a hybrid, it can also be easier to plan the necessary maintenance, which requires halting or disconnecting generation entities or equipment so that another energy source becomes available.

Hybrid hydropower facilities located on the same land and utilizing the same grid connection point may bring additional benefits:

- **Reduced cost for evacuating power since lower substation and transmission line capacity are needed.** The cost of power evacuation can be reduced because a hybrid with a single injection point requires lower transmission capacity, given its combined peak power output is less than the combined peak of the stand-alone plants, or underutilized generation is shifted to storage. This means a hybrid's output is determined through a careful assessment of generation potential over a year; underutilized generation is shifted to storage; and a power output close to the connection point's maximum capacity is provided. This can increase the utilization of transmission assets (IHA and EDP 2018)—in contrast to wind and solar power plants, which supply peak power generation only over brief periods and underutilize transmission assets (NREL 2020).
- **Effective land use enabled.** The land required for a hydropower project can be maximized with the addition of other renewable energy technologies (e.g., installing floating solar photovoltaic [PV] panels on a reservoir or on land adjacent to a plant). Using the same land for multiple purposes will help maintain a low biodiversity and ecosystems footprint, leaving more nature either untouched or available for other uses (e.g., agriculture, forestry, and urbanization). Reduced land requirements and shared land acquisition processes not only contribute to environmental conservation but also generate significant cost savings in land procurement.
- **A shared auxiliary infrastructure.** Projects can effectively reduce costs by sharing infrastructure and auxiliary systems such as substations, transmission lines, supervisory control and data acquisition systems, and control mechanisms.

> “Smart hybridization in hydro has proven to be an efficient choice towards increased flexibility and revenue while reducing machinery wear and tear beyond expectation.”

Jean-Louis Drommi, electrical expert at EDF
(Vogelgrun Hybrid Hydropower Facility)

For a project to be sustainable and overall successful, complexity must be managed effectively across its life span. As the technologies involved in a project grow, it becomes increasingly challenging to prioritize and harmonize resource utilization, efficiently deliver services, and address environmental and social concerns. A tangible illustration of this complexity is where a multipurpose reservoir serves both energy generation and water supply, each governed by distinct requirements. Another example illustrating this complexity is the management of virtual hybrid hydropower facilities (box 4.3). A proactive approach is needed to effectively manage multifactor analyses and navigate the challenges inherent in hybrid projects. Such an approach is needed to identify essential competencies and skills early on in all phases of the value chain, from project development and management, to construction and ongoing maintenance. A proactive approach helps ensures that a project has the required capabilities when needed, eventually making it a success.

BOX 4.3

BUNDLING RENEWABLE ENERGY IN INDIA

India is developing an auction where existing high-flexibility hydropower plants (where surplus is available in the power system) are bundled with solar and wind plants in a virtual hybrid hydropower facility. Such bundled products would create multiple benefits, including provision of round-the-clock power supply to electricity consumers, decrease in overall offtake price, supporting less competitive hydropower generation assets, increased grid stability, and a more competitive Indian power market.

A pilot for renewable energy bundling has been identified in Himachal Pradesh, a hydro-rich state in India. The pilot has been identified under a World Bank project called the "Himachal Pradesh Power Sector Development Program."

The pilot project examines alternatives for bundling the power from an existing hydropower plant with a non-hydro renewable energy source located elsewhere the country. It also explores the market for the demand for such a bundled product. Thus, the bundling structure will consider three key aspects:

- **Identification and procurement of power sources to be bundled with hydropower.** Identification of suitable sources and the terms for their procurement would require an understanding of factors such as technical limitations and policy/regulatory constraints, which may have an implication for the bundled product's delivery.
- **Identification of an offtaker for this bundled product's generation.** This will include considering the offtaker's demand profile and location, applicable central-/state-level charges, and regulatory provisions.
- **Operationalization of the bundled product**, which requires a process for power flow between sources and buyers and establishing it, and managing deviations and risks on a run-time basis, which in turn will depend on the above two aspects. Given the complexity and the number of players involved, a "bundle manager" or an "aggregator" will have to be brought in to put together the bundled product.

Source: World Bank.

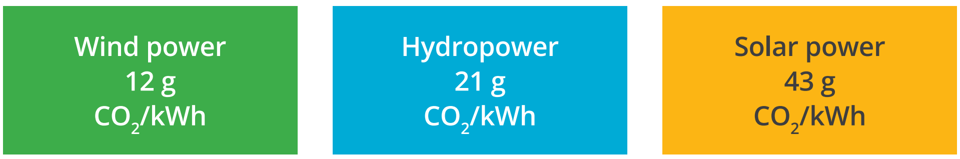
A Nuanced Interplay with Climate, Environment, and Society

Both hydropower and VRE sources help combat climate change given they release significantly less life-cycle greenhouse gas (GHG) emissions than other nonrenewable energy sources. Hydropower reservoirs may occasionally release methane from the decomposition of organic matter under anoxic conditions, although most of these emissions are displaced emissions, which would have been released elsewhere in the ecosystem (Prairie et al. 2017). These emissions are due to the impoundment effect of hydropower dams, which trap natural organic matter from the upstream catchment. GHG emissions in hydropower-, wind-, and solar PV–based energy are primarily released from the construction of power plants and related infrastructures and the manufacture of energy equipment and machinery. A shift away from fossil-fuel-based electricity to renewables significantly influences power sector carbon dioxide emissions—lowering them. Figure 4.2 shows the life-cycle GHG emissions from these renewable sources (US DOE 2023).

All energy infrastructure impacts biodiversity and ecosystems, although there are solutions to avoid, mitigate, and offset such impacts for all renewable energy sources. Provided robust regulation and policy support, hydropower hybrids present a potential avenue for improving energy services while mitigating ecological impacts and delivering societal benefits. These services can at times compete with a hydropower hybrid's needs while complementing them on other occasions. For example, flood control requires reservoirs to have available capacity; this can impact generation capability. Conversely, droughts may increase competition for water for domestic and industrial use, and irrigation, and to generate electricity; this may require prioritization. When balancing these societal services with energy services, a strong regulatory framework must establish and govern the actual needs and effects of water management and the societal needs of water. More details on the environmental considerations are presented in boxes 4.4 and 4.5.

FIGURE 4.2

Life-Cycle Greenhouse Gas Emissions from Renewable Sources



Source: US DOE 2023.

Note: gCO2/kWh = grams of carbon dioxide per kilowatt-hour.

BOX 4.4

ENVIRONMENTAL AND SOCIAL CONSIDERATIONS FOR HYBRIDS COMBINING WIND AND HYDROPOWER

While the concept of situating wind turbines within a hydropower reservoir or on a dam itself is intriguing, practical feasibility remains a challenge on most occasions. This approach is rendered less viable by factors such as low wind speed, security concerns, and the complexities and costs associated with turbine installation in water. In most cases, a more practical solution involves locating wind power facilities nearby hydropower plants, for cost-efficient hybridization.

Wind power can affect avian and bat populations, impact biodiversity due to land use and necessary infrastructure such as access roads, cause disruptions to animal migration and movement, and contribute to habitat alterations on the ground. Even hybrid power plants combining wind and hydropower can have the same impact. However, the relative impacts of a wind power plant's individual components (e.g., roads, turbine towers, and foundations) can be reduced by hybridizing hydropower infrastructure with the plant. **Combining the infrastructure of two projects typically results in a smaller overall impact relative to locating the projects separately**. This integration fosters a more environmentally conscious approach to renewable energy generation.

Source: World Bank.

In a hydropower hybrid, balancing power output requires regulating the water flow through the hydropower turbines. This means the flow will fluctuate when the output from the hydropower turbines fluctuates. This is known as *hydropeaking* and may adversely impact the downstream ecosystem when water is released directly into a river (Boavida et al. 2020; World Bank 2018). Based on a river's size and profile, rapid changes in flow could cause rapid variations in its water depth. This means a sudden reduction of flow could significantly reduce the river's water depth, leaving fish and other life forms stranded on the riverbed. Rapid increase of flow could displace life forms by transporting them far downstream due to strong currents and could yield social impacts downstream. This may lead to long-term effects if the water flow in a river changes frequently. However, there are several measures that balance flow, eliminating or mitigating adverse impacts (e.g., a downstream regulating pond, or incorporating flood release requirements into a hybrid facility's operation and control system) (Barillier et al. 2021).

BOX 4.5

ENVIRONMENTAL AND SOCIAL CONSIDERATIONS FOR HYBRIDS COMBINING HYDROPOWER AND FLOATING SOLAR PHOTOVOLTAICS

Solar photovoltaic (PV) power plants traditionally have extensive land resource demands, which often compete with agriculture and contribute to land use changes—a significant driver of biodiversity loss. Land competition can be mitigated by integrating solar PV on floating structures within hydropower reservoirs. However, this approach encroaches on water surfaces, leading to potential impacts on navigation, fishing, and aquaculture.

Floating solar PV (FPV) installations on reservoirs may impact aquatic ecosystems positively as well as adversely (Exley et al. 2022). Hydropower reservoirs may emit greenhouse gases, including methane, which is produced only under oxygen depletion conditions. These emissions, along with eutrophication, reduced oxygen levels due to increased primary production, and other water quality issues, pose environmental challenges. Such adverse impacts often result from a combination of low reservoir inflow and high temperatures and solar radiation (US DOE n.d.[b]). FPV installations may potentially help alleviate some of these concerns by providing shade for water, reducing temperature, and mitigating primary production and oxygen depletion. They may also reduce the risk of methane generation by preventing or reducing oxygen depletion. According to studies, obtaining these effects requires covering a significantly large part of a reservoir for FPV. From a social perspective, solar PV installation on hydropower reservoirs offers significant advantages over ground-mounted alternatives. While ground-mounted PV could displace agricultural use, FPV installations provide dual land utilization opportunities. They could allow the use of the area for the ground-mounted PV's installation for grazing and cultivation of certain crops. This multifunctional approach optimizes land use and fosters greater social benefits (World Bank, ESMAP, and SERIS 2019).

LOM PANGAR IN CAMEROON

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Hybridization of hydropower with batteries would also mitigate the effect of peaking; use of a battery will enable handling rapid load changes so that the flow from the turbines to the river only varies at a slow rate.

Hydropower hybrids may allow optimizing reservoir size by shifting a portion of the generation to VRE; this in turn ensures sufficient reservoir volume is available for storing energy. This may reduce reservoir size while delivering hybrid services. Another opportunity could be to maintain energy generation from an existing hydropower plant by integrating VRE, while concurrently releasing more environmental flows to bypassed river segments. These opportunities could help preserve habitats and favor fish migration at critical times of the year through change or reduction of hydropower generation and greater reliance on VRE sources if needed. However, it is worth noting that developers will seek to maximize their revenue, necessitating larger reservoirs, unless there are regulations, societal requirements, or incentives to pave the way for these benefits.

Across the world, population and welfare growth, urbanization, intensification of agricultural practices, and climate change impacts are increasing the competition for water. Sustainable water resource management is therefore a key issue for many reservoirs and rivers, with the former playing a critical role in climate change adaptation. Reservoirs can be used to store water, mitigate flooding, and supply water during scarcity—services that can be improved within hybrid solutions. In regions facing water scarcity, it is crucial to minimize evaporation losses and prevent flood spillage during the rainy season. Floating solar could be considered here (see box 4.4; World Bank, ESMAP, and SERIS 2019). In areas where water is abundant, it is equally important to manage floods and use reservoirs to prevent flood-inflicted damage.

By delivering multiple services, hydropower hybrids contribute to the Sustainable Development Goals (SDGs), as shown in figure 4.3. First, and foremost, they will help achieve SDG 7, which relates to access to affordable and clean energy. As explained in section 4.1, hybrid facilities can support greater decarbonization by leveraging low-carbon renewable energy technology, fortify energy security, and boost power system flexibility; all of this supports the SDG 7.1 target: "By 2030, ensure universal access to affordable, reliable, and modern energy services." Since hybrids' support increased VRE's integration, they can further contribute to the SDG 7.2 target of increasing the share of renewable energy in the global energy mix.

Hydropower hybrids can have a role to play in meeting the SDG 7.b target: "Expand and upgrade energy services for developing countries." This is because the hybrids can utilize multiple technologies, which are tailored for the optimal use of available renewable resources, and combine them with flexible energy services to meet the energy demand while addressing societal needs. Developing countries and small island states, where greater energy access requires considering all available energy generation sources, may find this even more worth exploring, and it could present incentives for deployment in regions characterized by weak or underdeveloped grid systems. Flexibility for VRE integration is often more important for countries that either do not have a robust power system or have one with high VRE penetration. This approach can maximize the overall value and benefits derived from a single infrastructure asset.

Hydropower hybrids can also help achieve other SDG targets by delivering societal services, as shown in figure 4.3. They can help achieve the targets under SDG 6: “Clean water and sanitation.” Hybrids’ sustainable water resource management will especially contribute toward the SDG 6.5 target: “Implement integrated water resources management.” Provided plants’ design receives specific attention, to adapt them to their aquatic environments, they can then contribute to the SDG 6.6 target: “Protect and restore water-related ecosystems.” Introducing modern compensation and mitigation measures in hybrid facilities would help protect and restore water-related ecosystems that were previously heavily impacted. One example of this approach is bidirectional fish migration solutions, which allow fish to traverse river barriers (Fjeldstad, Pulg, and Forseth 2018; Nielsen and Szabo-Meszaros 2022).

Hydropower hybrids also provide low-carbon renewable energy, which replaces high-emission alternatives. Also, careful management of hydropower reservoirs will boost resilience to climate-related events (e.g., floods and landslides). Both contribute to decarbonization and SDG 13: “Climate action.”

Finally, hydropower hybrids can help improve freshwater ecosystems, which are covered by SDG 15, which is about “Life on land.” This can be possible by selecting sites and tailoring them to minimize impacts on terrestrial ecosystems, and by directing water flow into aquatic ecosystems in hydropower rivers and aiding in habitat development in them. One example for habitat preservation is modern sediment management, whose purpose is to maintain spawning and breeding grounds for fish and other life forms (Servanzi, Quadroni, and Espa 2023).

FIGURE 4.3

Hydropower Hybrids Can Contribute to Achieving the SDGs

SDG 7 Affordable and clean energy - Developing Hybrid Energy Services will contribute to reaching targets;

7.1 Ensure universal access to affordable, reliable and modern energy services" because it can

- Fortify energy security by providing hybrid services that are flexible, reliable and resilient

7.2 Increasing substantially the share of renewable energy in the global energy mix

- A hybrid hydropower plant increase renewable energy generation
- More importantly, a hybrid hydropower plant enable integration of higher shares of VRE because of the hybrid services that balance VRE and

7.3 Expand and upgrade energy services for developing countries"

- Flexibility for VRE integration is often more important for low- and middle income countries because they cannot rely on a robust power system. This will increase their challenge with maintaining power and energy balance, and power quality.
- A hybrid hydropower can optimally use all available renewable resources and be tailored to deliver flexible energy services required to maintain power system balance.

SDG 6 "Clean water and sanitation" - Developing hydropower hybrids through sustainable water resources management will especially contribute to reaching targets

6.5 "Implement integrated water resources management

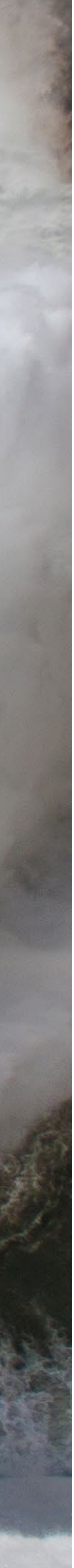
6.6 "Protect and restore water-related ecosystems"

SDG 13 "Climate action" as hybrid hydropower provides renewable energy to replace high-emission alternatives, as well as strengthening resilience to climate-related hazards like floods and landslides by careful management of hydropower reservoirs

SDG 15 "Life on land" includes freshwater ecosystems. A Hybrid Hydropower plant can contribute to reaching its targets by selecting sites to minimize impacts on terrestrial ecosystems as well as providing water and habitats for aquatic ecosystems in hydropower rivers.

Source: World Bank.

Note: SDG = Sustainable Development Goal; VRE = variable renewable energy.



5. Fostering Energy Services

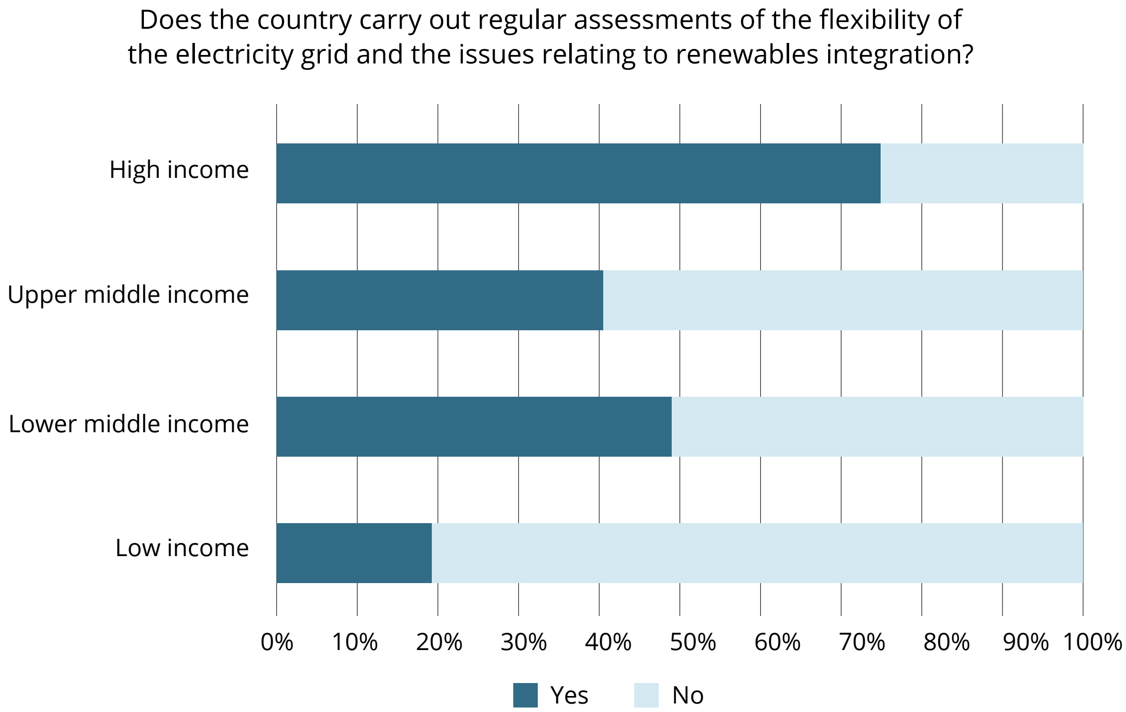
Today few hydropower hybrids are in existence, but they have demonstrated feasibility in supporting power systems, and effectively. However, there remain barriers to increasing the numbers and size of hydropower hybrids. According to the Energy Sector Management Assistance Program (ESMAP) publication "How to Unlock Pipelines of Bankable Renewable Energy Projects in Emerging Markets and Developing Countries?" (ESMAP 2023), limited availability of bankable projects, rather than a lack of financing, is the main obstacle to deploying renewable energy. The report also highlights the importance of coordinated government efforts to target country-specific barriers and risks. One additional barrier specific to hydropower is its unique position in the sense that it is often crucial in balancing national and regional power systems through the provision of energy services.

Bankability of hybrid hydropower projects and investment scale-up require supporting energy services through market design. Governments must ensure policy, legal, and regulatory frameworks are developed to stimulate the implementation of energy services facilities. Regulations must ensure a transparent, cohesive, and reliable environment for these facilities. This is a prerequisite for securing long-term investments in the sector and for resource sustainability. For energy storage, the recommendations set forth in the ESMAP report "Deploying Storage for Power Systems in Developing Countries Policy and Regulatory Considerations" (ESMAP 2020) apply to hydropower hybrids but must be expanded further to include all energy services (energy control, energy storage, and energy generation; see figure 1.1).

Remuneration for energy services is inadequate in most markets given the focus has been to incentivize the increase of affordable generation. Remuneration has two important roles: (1) ensuring efficient resource utilization for energy balance, and (2) making visible the importance and value of energy services for maintaining power system balance. ESMAP monitors policy frameworks in 140 countries. Figure 5.1 shows that frameworks fostering flexibility are under development for assessing power system flexibility to enable the integration of renewable energy. It also reveals that advancement in this direction relies on the country's income level. The indicator shows that low-income countries require more support to improve and perform these assessments. It shows that governments can devote more attention to building frameworks to make renewable energy's integration in power systems possible with the support of energy services. Appropriate remuneration for flexible energy services holds the potential to unlock new investments in hydropower hybrids, which in turn supports the integration of renewable energy sources, helps maintain grid stability, and contributes to the transition to a more sustainable and resilient energy system.

FIGURE 5.1

Indicators for Renewable Energy's Integration



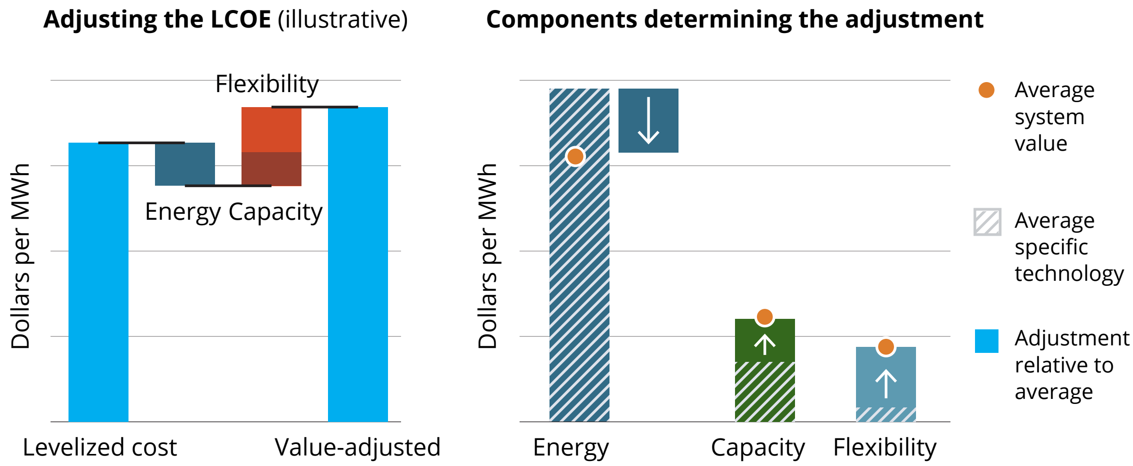
Source: ESMAP n.d.

Enabling investments in hydropower hybrids also requires addressing energy services value at the system as well as plant level when comparing projects at the planning stage. A new approach to building upon the widely used principle of levelized cost of electricity (LCOE) (Ueckerdt et al. 2013), is the **value-adjusted** LCOE (VALCOE) (IEA 2023c). Figure 5.2 illustrates the principles of the key elements. VALCOE seeks to provide a metric that also captures the value of energy generation, the flexibility value, and capacity in the power system context. VALCOE considers three value streams; among them, the energy value is typically the largest. This value varies significantly depending on the technology and changes with increasing variable renewables share. It is calculated by determining the average price received per unit of generation over the course of a year—the average price computed based on least-cost merit order dispatch and simulated wholesale electricity prices. The energy value for a given technology varies by region and variable renewables' share, although it is sensitive to a variety of factors. It is an interesting metric from an investor's point of view since it captures multiple revenue streams, although not including the value of energy storage and functioning only in countries with markets for these services (IEA 2023c). In countries and regions without a market, it is not simple to compute the monetary value of providing dispatchable and flexible energy services.

There are good examples of mechanisms that are tailored to renumerate short- and long-term energy services. In Europe, the focus for market integration has been the short-term perspective—day-ahead and intraday. This has been to facilitate the integration of variable renewable

FIGURE 5.2

Value-Adjusted Levelized Cost of Electricity



Source: IEA 2023a.

Note: LCOE = levelized cost of electricity; MWh = megawatt-hour.

energy (VRE), to advance the region's decarbonization effort and achieve energy security. Europe's electricity market and legislation have evolved over decades; in 2023, new reform was introduced to tackle the region's recent experience with high price volatility spurred by a large VRE deployment and an energy crisis triggered by the gas price shock. In 2024, Europe introduced additional changes in market design that were specifically tailored for balancing power systems. The main principle is to increase the time granularity, in order to remunerate on a 15-minute basis. This better matches the VRE-triggered imbalances, and, thus, improves the market's ability to balance the systems. This is expected to be implemented fully across the European Union countries in 2025 (EU n.d.).

In India, the focus has been on transitioning from fossil fuel sources to non-fossil-fuel-based sources. This has predominantly been done with VRE's installation—118 GW, or about 26 percent of the country's generation (Government of India 2023), installed in June 2023. This has led to the government switching focus to ensure power system stability, which demands more energy storage systems (ESSs), through the implementation of a national framework to ensure the power sector is environmentally sustainable and financially viable. In this report's context, ESSs include hybrid hydropower facilities and virtual hybrid hydropower facilities. With these efforts, India has addressed the need for energy services to support its power system by redesigning its energy market to incentivize participation in energy storage. One part of the market mechanism is a new demand-driven capacity tender model for firm and dispatchable renewable energy (FDRE) storage. ESSs are predicted to be the central technology in the 2020s' power market, and the market for these systems will attract the highest investment among all emerging renewable energy sectors (Government of India 2023). Power project developers are already embracing FDRE—over 8 GW of FDRE tenders were issued in 2023 alone. ESSs will be vital for India to achieve its goal of 500 GW of non-fossil-fuel capacity by 2030 and provide low-cost energy generation. However, challenges remain for India, including high initial capital expenditure, a long preparation time for ESS projects (especially for pumped storage hydro projects), a suboptimal transmission and distribution infrastructure, and a lack of domestic manufacturing in ESSs, highlighting potential supply chain risks (IEEFA 2023).

The European and Indian market incentives share certain common aspects: they both acknowledge VRE's impact on power systems and work to develop legislation, regulations, and markets for energy services to incentivize the energy transition, and ensure energy security and affordability. Energy generation remains the underlying principle for remuneration, and new legislation seeks to further increase renewables shares. Newer additions to Europe's and India's systems are specifically for maintaining short-term balance through the introduction of energy control mechanisms and long-term balance via increased focus on energy storage to secure supply.

While one solution does not fit all, the experience already gained will inform the evolution of frameworks suitable for different countries and regions. Further innovation and research are needed on the valuation of flexible energy services, how to derive flexibility from independent technologies, and the synergies when technologies are combined. This will guide how to tailor hydropower hybrids to best meet future flexibility demands, besides the creation of methodologies and analytical tools that help especially low- and middle-income countries and regions identify how a hybrid can deliver energy services for their specific needs. This can foster the demand for renewable and resilient facilities and services. Further, advocacy for and dissemination of the benefits of such facilities can support new project development, reduce the costs involved in planning and executing investments, and boost physical and economic resilience (CIF 2022).

To conclude, hydropower hybrids are a promising development because they provide highly sought-after energy services that are both flexible and dispatchable. However, scaling up hybrids will be challenging without adequate remuneration for energy services. India and China are leading the way in implementing hydropower hybrids, demonstrating their feasibility and importance.

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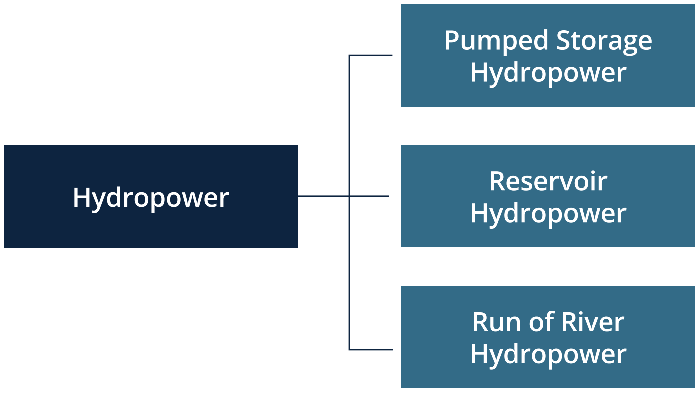
Annex 1. Hydropower

Hydropower can be subdivided into three categories (figure A1.1), which mainly differ in the turbine/pump technology and the reservoirs' storage capacity. However, hydropower encompasses a diverse spectrum of design variations, size, and power output.

FIGURE A1.1
Hydropower Categories



Reservoir hydropower is a versatile form of hydropower, which can help store water for future use. It is the largest contributor in terms of electricity generation and flexibility. Reservoirs are of various sizes and types, with storage capacities ranging from just a day to several years. The reservoirs are primarily of two types: (1) created by damming a river to form entirely artificial lakes, and (2) formed by utilizing existing natural lakes, with the addition of a dam. For the latter category, the reservoir could also encompass the original natural lake and additional submerged land. Beyond electricity production, reservoir hydropower can deliver additional benefits, including flood control, water supply and irrigation, water purification, and water for various ecological needs and recreational opportunities. The energy services supported by reservoir hydropower are foremost characterized by long-duration energy storage, besides the capability to deliver energy control and energy generation. All these contribute toward a power system that remains flexible and balanced across a wide spectrum of timescales—sub-second, hourly, weekly, seasonal, and yearly.

One common way to defining a **run-of-river (RoR) hydropower plant** is by assessing whether storage capacity is below the average daily water inflow. RoR plants can be of various sizes, from small installations in creeks to larger installations in rivers. RoR hydropower is, therefore, characterized by its ability to provide stable *energy generation* that is constrained to water inflow. However, RoR hydropower plants can provide *energy control*, which is mainly limited by the generating unit's design and response rate. Lastly, RoR hydropower often holds the energy storage capacity required to store water during the day, to dispatch during evening peak hours; it can be considered short-duration energy storage.

Pumped storage hydropower (PSH) utilizes two reservoirs at different elevations, which are connected via pipes, through which water flows, passing through a reversible pump turbine. Some pumped storage facilities provide seasonal pumping in regions characterized by significant seasonal variations in water flow. Such regions include, for example, those with cold climate with snow during winter, or those with dry summers and wet winters. There exists a large number of alternative configurations for PSH; examples include, among others, using separate pump and turbine installations, and multiple reservoirs. PSH primarily serves the purpose of flexible *energy storage* that generates and consumes energy. Energy storage is charged by inflow of water, or the pumping of water into the higher reservoir, or a combination of both. Traditional PSH delivers all *energy services* and is best at balancing VRE from a few hours to several hours. However, modern pumped storage with variable-speed pump turbines or ternary systems can also deliver short-term or immediate balancing of VRE. Modern PSH is therefore an excellent alternative, which provides energy control, energy generation, and storage when needed, depending on installed capacities and the reservoirs' storage volumes.

Glossary

Ancillary services	An umbrella term for functions required in a power system, apart from active power generation, that help power system operators to reliably meet demand. These comprise technologies and procedures to maintain the proper flow and direction of electricity, address imbalances between supply and demand, maintain frequency and voltage within nominal ranges and recover the system after an event.
Capability	A unit's functional capacity to, efficiency in, or performance in carrying out specific services.
Curtailment	The deliberate reduction or control of energy generation when supply surpasses demand or when a power system cannot accommodate the excess energy efficiently.
Dunkelflaute	From German, in this report it is translated to 'dark stillness'. Dunkelflaute is defined as a consecutive span of time during which the mean wind speeds and solar irradiation levels, are is lower than a certain threshold.
Dispatchable energy	Controlled electricity generation that can be turned on and off as needed.
Energy balance	Balance in electricity supply and demand every hour and over years. One of the metrics used to assess power system flexibility.
Energy control	A facility's energy control ensures short-term power balance and power quality by utilizing technologies that counteract disturbances originating at the plant itself or in the power system. This supports power system flexibility.
Energy generation	Generation of electricity from different sources in a facility.
Energy mix	The way the final energy consumption in a geographical region is broken down by the primary energy source. It includes fossil fuels (oil, natural gas, and coal), nuclear energy, waste, and the many types of renewable energy (biomass, wind, geothermal, water, and solar).
Energy security	The ability of a country or region to reliably and affordably access the required energy resources to meet its energy demands.

Energy services	Services provided to a power system.
Energy storage	Energy storage allows capturing energy when there is surplus generation when demand is low and releasing it when demand is higher, during a generation deficit. This helps balance hourly, daily, weekly, or even interannual energy supply and demand.
Energy system	A system that provides energy services to end users.
Flexible operation	The ability to adjust and adapt energy services to meet a power system's needs.
Flywheel	A heavy mass that can rotate rapidly to store or release energy. A flywheel provides inertia and can rapidly store or release kinetic energy.
Hybrid hydropower	A facility that utilizes water as the primary energy resource, in combination with variable renewable energy resources, and energy storage to provide energy services. The technologies are managed under an overarching operation and control system.
Inertia	Inertia in a power system is a characteristic provided by the rotational mass of large generators. It represents the system's resistance to changes in frequency and helps it to remain stable when disturbances occur.
Inverters	Inverters convert direct current (DC) to alternating current (AC) and inject it into the grid.
Operating and control system	A set of integrated components, software, and processes that are designed to manage and regulate the operation of a complex system.
Operating range	The operating range defines the boundaries and span within which a plant can operate and deliver energy services without encountering issues or failures.
Power balance	Balance of available and required power in a power system or balancing zone. One of the metrics used to assess power system flexibility.
Power electronics	Power electronics monitors, detects, and rapidly compensates for changes or power generation failure in direct current mode before injecting power into the grid.
Power grid	The transmission and distribution network of a power system.

Power quality	A power system metric used to indicate whether voltage and frequency are in equilibrium within specified limits.
Power system	A power system is the set of interconnected components designed to generate, transmit, and distribute electrical energy from multiple sources to multiple end-users via an electricity grid.
Power system flexibility	Flexibility is the ability of a power system to manage with all its resources the variability and uncertainty of the electricity demand, supply and grid availability across all relevant timeframes. The timeframes of flexibility spans from seconds or minutes, to days, or years (Nuffle, L, et al, 2023). Power system flexibility can be measured based on three metrics: (1) Power Balance, (2) Energy Balance, and (3) Power Quality.
Ramp down	A gradual and controlled reduction in electricity generation or power output.
Ramp rate	Used to describe how quickly a unit's output can be ramped up or down to respond to changes in variable renewable energy generation or grid load, and maintain equilibrium.
Ramp up	A gradual and controlled increase in electricity generation or power output over a period of time.
Synthetic inertia	Power electronics in combination with inverters creates synthetic inertia, which mimics inertia.
Waterways	Structures to guide water from its natural source (river and/or reservoir) to a power plant.

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