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Review

A Review of Multi-Temporal Scale Regulation Requirements of Power Systems and Diverse Flexible Resource Applications

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Abstract: With the increasing integration of renewable energy sources such as wind and solar power, the regulation requirements of power systems have become more dynamic and complex. This paper provides a comprehensive review of multi-temporal scale regulation requirements and explores the application of diverse flexible resources across different time scales. The regulation demands are categorized into short, medium, and long-term scales, each presenting unique challenges that need to be addressed for efficient power system operation. Existing studies primarily focus on the adjustment of a single time scale, often overlooking the interplay between multiple time scales. This paper critically analyzes the limitations of previous approaches and demonstrates the need for more holistic and flexible solutions. The research results show that integrating diverse, flexible resources, including energy storage systems (ESS) and demand response (DR), can effectively meet regulation needs across various time scales. Additionally, the paper identifies the potential of hydrogen-based solutions to address emerging challenges in power system regulation. The findings highlight the importance of combining multiple flexible resources to improve system resilience and sustainability, offering a pathway toward more efficient and adaptable power systems.

Keywords: flexible resources; multi-temporal scales; renewable resources; renewable energy integration; application case; hydrogen energy

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1. Introduction

As global climate change becomes an increasingly pressing issue, countries around the world have set ambitious emission reduction targets and identified accelerating the transformation of energy structures as a core strategy for achieving sustainable development. This transformation is essential to meet the goals of reducing greenhouse gas emissions and ensuring energy security while transitioning to more sustainable energy systems. The development of renewable energy sources, particularly wind and photovoltaic (PV) power, plays a critical role in reducing carbon emissions and achieving low-carbon objectives. Many countries are advancing rapidly in the deployment of renewable energy technologies, with increasing global investments in wind and PV power [1]. These efforts are expected to drive substantial changes in energy systems worldwide, contributing to the global transition to a more sustainable and resilient energy future [2].

Despite the remarkable achievements in the rapid development of renewable energy, the increasing share of wind and PV generation presents unprecedented challenges for the stability and flexibility of the power system [3]. The inherent variability and intermittency of wind and PV power result in high uncertainty in their electricity output. This variability

is influenced not only by weather and seasonal changes but also by sudden climatic events (such as thunderstorms and heavy snow) [4,5]. Meanwhile, traditional coal-fired power plants, which play a stabilizing role in the grid, have limited flexibility and poor responsiveness. Although they contribute to grid stability, their ability to adjust output quickly is insufficient, particularly in power systems with a high share of renewable energy. Relying on such conventional power sources for grid regulation is no longer adequate to meet the flexibility, reliability, and efficiency demands of modern power systems. The pressure on power systems is especially acute during extreme weather events and emergencies, where maintaining supply security, ensuring economic operation, and protecting the environment become increasingly difficult [6].

Therefore, ensuring the stable operation of the power system, particularly through effective regulation across multiple time scales, has become a critical issue in both research and practice within modern power systems. Historically, power system dispatching largely relied on traditional regulation methods, such as the startup and shutdown of coal-fired units and load adjustments. However, as the share of renewable energy continues to grow, the complexity of power dispatch has increased significantly, and single regulation strategies are no longer sufficient to meet the growing demand. To ensure the security and stability of the power system, flexible and diversified regulation approaches must be adopted. These approaches include, but are not limited to, power storage technologies, demand response, distributed generation, virtual power plants, and other innovative technologies and management strategies.

In this context, the optimized integration of flexible resources has become crucial to enhancing the regulation capacity of power systems. Flexible resources include, but are not limited to, energy storage devices (such as pumped hydro storage and battery storage), demand response (which balances supply and demand by adjusting consumer load), distributed energy sources (such as distributed PV generation), and new regulation technologies (such as hydrogen energy and gas turbines). These flexible resources can provide regulation capacity across different time scales [7]: on short time scales, rapid-response systems such as battery storage and demand response can address instantaneous supply-demand imbalances; on medium time scales, distributed generation and medium-scale storage technologies play key roles in supplementing fluctuations in renewable energy generation; and on long time scales, large-scale storage solutions, such as hydrogen energy storage or pumped hydro storage, may be used to balance seasonal and annual supply-demand disparities [8,9].

Given these challenges and requirements, this review aims to systematically summarize recent advances in the application of flexible resources across multiple time scales, exploring optimized strategies for their integration and utilization. Specifically, this paper will focus on the following aspects:

Section 2 analyzes the regulation requirements of power systems in short-, medium-, and long-term. Short-term regulation primarily focuses on addressing instantaneous supply-demand imbalances, such as rapid responses from battery storage systems and demand response measures. Medium-term regulation addresses the need to supplement fluctuations in load and renewable energy generation over longer periods, with distributed generation and medium-scale storage technologies playing an important role. Long-term regulation, on the other hand, focuses on how large-scale storage technologies (such as hydrogen energy and large-scale pumped hydro storage) can balance seasonal and annual variations in supply and demand.

Section 3 provides a detailed overview of various types of flexible resources and their characteristics. This section categorizes flexible resources from the supply side, demand side, and storage side, analyzing the advantages, limitations, and applicable

scenarios of each type of resource. Special attention is given to advancements in energy storage technologies, considering their potential in balancing the volatility of renewable energy generation.

In Section 4, the future development trends of flexible resources are discussed. With continuous technological advancements and the gradual reform of energy markets, hydrogen energy, as an emerging long-duration storage technology, has become a research hotspot. Hydrogen energy not only enables large-scale, long-term storage but also holds potential for cross-sector applications, particularly in transportation and industry. These applications could provide crucial support for the flexible regulation of power systems.

Section 5 concludes the paper by highlighting the future regulation needs of power systems in the context of high shares of renewable energy. The chapter also provides an outlook on the future development directions of power dispatch technologies. With the continuous development of technologies, flexible resources will increasingly be integrated into power grid management systems, offering opportunities to address global climate change and drive energy transition. Figure 1 is the logical block diagram of this paper.

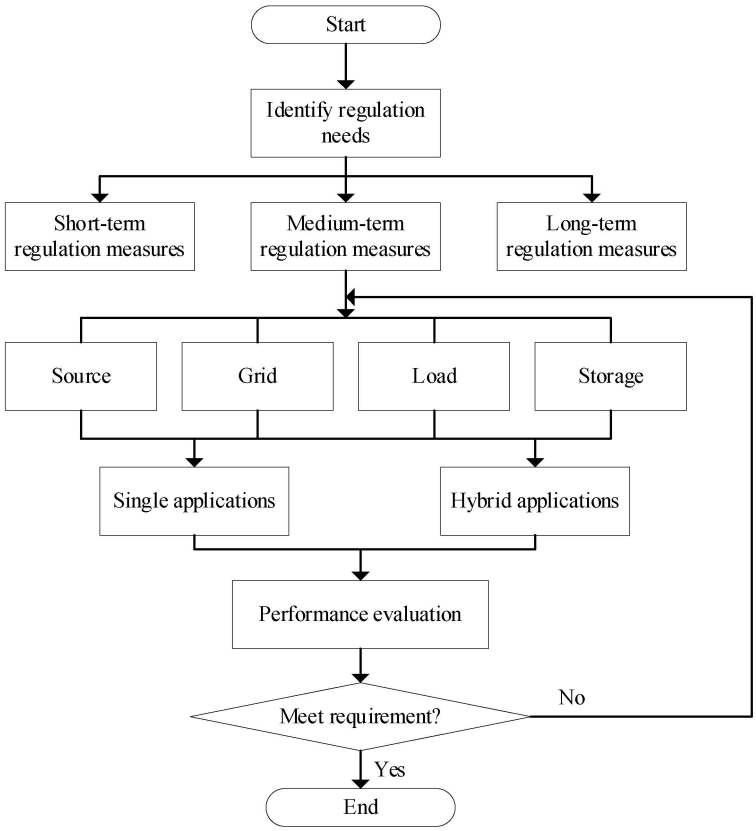


Figure 1. The logical block diagram of this paper.

2. Analysis of Regulation Requirements Based on Temporal Scales

In the operation of power systems, regulation requirements are heavily influenced by the temporal characteristics of various disturbances, generation patterns, and demand behaviors. The temporal scales of these influences determine the type and nature of the flexibility required to maintain system stability and reliability. Therefore, analyzing the regulation needs from the perspective of temporal scales [10] is crucial for effectively leveraging diverse flexible resources. In this chapter, we discuss the regulation requirements of power systems based on different temporal scales, ranging from real-time balancing to long-term planning. We categorize the temporal scales into three main categories:

instantaneous and short-term (real-time and seconds-to-minutes), medium-term (day-ahead to intra-day), and long-term (seasonal to annual considerations) [11,12].

2.1. Instantaneous and Short-Term Scale

At the instantaneous and short-term scale, the power system faces various challenges related to its dynamic response to sudden disturbances or fluctuations in load. These issues are primarily driven by the system's inertia, frequency stability, voltage regulation, and other dynamic characteristics [13,14]. As renewable energy sources with low or no inertia are increasingly integrated into the grid, the system's ability to respond to rapid disturbances becomes even more critical.

System inertia is one of the serious problems faced by systems on a short time scale. In traditional power systems, the inertia provided by synchronous generators helps mitigate frequency fluctuations following sudden changes in load or generation. However, as the share of renewable energy sources such as wind and solar power increases, which inherently lack inertia, the system's ability to stabilize frequency following sudden disturbances diminishes [15]. This leads to a situation where frequency deviations are larger and faster, potentially surpassing the limits for system stability. Inertia deficiencies are characterized by rapid frequency drops or spikes immediately following disturbances, which may fail to be controlled by the system's existing regulation mechanisms. Due to the lack of inertia, large-scale failures are more likely to occur when interference occurs, which greatly affects the stability of power systems [16].

Frequency stability is another concern. Frequency deviations are typically caused by imbalances between generation and consumption, particularly during sudden fluctuations in load or the loss of a generator. When such imbalances occur, the frequency may shift abruptly, often requiring immediate corrective actions. The primary characteristic of this issue is the rapid frequency change that can happen within seconds of a disturbance, which may be further exacerbated by the absence of sufficient backup resources or an inadequate response from the system. The consequence of unresolved frequency instability is severe: prolonged deviations in frequency can trigger protection mechanisms, disconnect parts of the grid, and disrupt electricity supply, leading to operational interruptions and, in extreme cases, widespread power outages.

Voltage stability is another concern on the short-term scale, particularly during rapid load changes or generation losses. Voltage fluctuations are typically seen as a direct consequence of imbalances in the power system, especially when reactive power reserves are insufficient to stabilize the system. The primary feature of voltage instability is the rapid change in voltage levels, which may dip or surge in response to load variations or faults. If these fluctuations are not addressed promptly, they can cause equipment malfunctions, tripping of protective devices, or even a complete voltage collapse. Voltage instability may lead to a large disruption of production activities, resulting in substantial losses.

In the short-term, the power angle, or phase angle between various parts of the grid, also affects the system stability. This causes loss of synchronization of generators if the power angle can jump with sudden changes in generation or load. This is a problem when disturbances lead to a large imbalance in power generation and consumption in different regions of the grid [17]. The characteristic of this problem is oscillatory misalignment of the system's synchronized generators. Left uncorrected, the power angle deviation can lead to oscillations that are threatening to the grid stability as a whole, possibly culminating in the separation of parts of the grid and cascading failures that could end up in a widespread blackout.

Short-term regulation problems are also due to the ramp rate limitations of generation units. Ramp rate refers to the rate at which a generator can respond to the sudden changes

in demand or generation, i.e., the speed of response. Traditional generators have slow ramp rates, however, which prevents them from responding quickly enough to keep pace with the needs of the system during its rapid fluctuations. It is described by the inability to ramp generation output quickly enough to match the supply and demand. This can lead to a loss of system balance and possibly make the system unstable if not addressed. A lack of sufficient ramp rate capacity means supply cannot be balanced efficiently with demand (which can throw frequency or voltage stability off or even result in outages in the event the system cannot offset such rapid load or generation changes).

2.2. Medium-Term Scale

In the medium-term, in addition to the problems of inertia, frequency, and voltage stability that exist in the short-term, the power system also faces challenges such as the scheduling, reserve capacity, and demand pattern change of the generator set.

When considering the problems on a medium time scale, the coordination of power generation resources and the management of power generation scheduling should be paid attention to first. Due to the deviation of load prediction and the uncertainty of power generation (especially renewable energy, such as solar energy and wind energy, which are susceptible to weather conditions and have randomness and volatility) [18], the actual power generation deviates from the forecast, and the imbalance between supply and demand leads to a series of serious problems such as frequency fluctuations of the power system. Therefore, the power system needs to carry out reasonable planning and scheduling to make the generation level meet the expected demand.

In addition, in order to cope with the inevitable fluctuations in generation and load, the power system needs to maintain a sufficient level of reserve capacity to handle possible supply and demand deviations. The challenge is to make the reserve capacity flexible enough to adapt to changing load and generation patterns. When the reserve capacity is insufficient, if the power generation is reduced or the load increases abruptly, the load may be cut off, and the stability of the power system will be affected. However, if the reserve capacity is over-allocated, the economy will be greatly reduced. Therefore, balancing stability and economic benefits is a key consideration in the medium-term [19–21].

Medium-term generation adjustment to variable demand profiles is also limited by the ramp rates of classical generation units. Wherein the short-term concerns the instantaneous response of power plants, medium-term challenges involve those same plants' ability to throttle their output up or down over the course of hours or even days. Fossil-fuel and nuclear plants, in particular, are often designed to provide steady output levels and have physical and operational limitations on their responsiveness in adjusting output rapidly. The limitations on ramp rates add a layer of complexity to times of high demand or periods of variable renewables generation due to changes in weather conditions. This push of generation to avoid overproduction by the traditional fleet becomes more expensive and more challenging on longer time horizons, stressing the flexibility of the traditional fleet [22,23]. Specifically, a lack of ramp rate flexibility makes it difficult for the system to follow the shape of the demand curve, leading to either periods of under- or over-generation, either of which can compromise system stability and efficiency.

Furthermore, medium-term voltage stability remains an important issue, especially in areas where renewable energy production is very dense. As the share of variable renewable energy increases, it becomes more difficult for the system to maintain voltage stability over long time periods. Wind and solar power generation can vary significantly throughout the day, and if not managed properly, this variability can result in voltage fluctuations that affect the system's overall stability. The characteristic of this problem is the gradual but sustained deviation in voltage levels due to changing generation patterns, which may not

be immediately noticeable but can lead to cumulative issues if left unaddressed. The consequence of poor voltage regulation over the medium-term is that it can lead to equipment damage, reduced power quality, and, in some cases, operational failure of voltage-sensitive devices such as industrial equipment and consumer electronics. Long-term voltage instability can also complicate the operation of the transmission and distribution networks, leading to a decrease in grid reliability.

Finally, the minimum output levels of certain generation units can become more restrictive over the medium-term. For instance, some thermal power plants cannot operate efficiently at very low load levels and may be forced to remain online even when their output is not required. This results in inefficient fuel use and increased overall operating costs. The characteristic of this issue is the inability of certain generation types to decrease their output in a flexible manner, especially during low-demand periods or when renewable generation exceeds expectations [24–26]. The consequence of this inflexibility is that the system may be forced to keep inefficient plants running, leading to higher fuel consumption, increased emissions, and greater operational costs.

2.3. Long-Term Scale

On long-term timescales, unlike in the short and medium to long-term, power systems face a broader set of challenges, such as the planning and integration of new generation units, adapting to changing demand patterns, how to ensure power quality, and so on. The short- and medium- and long-term scales consider the real-time matching of supply and demand, while the long-term scales consider how to ensure the safety and reliability of the power system over a longer period of time, usually decades.

Capacity planning and integration of new generation resources, particularly in systems of high renewable penetration, is a significant challenge at the long-term scale. Careful planning is needed for infrastructure replacement and to adapt to ever-changing demand forecasts and the integration of low-carbon energy sources. When long-term forecasts based on underlying demand and generation are either erroneous or too optimistic, an undersupply or oversupply of capacity can result, and the challenge arises. This issue has the unique characteristic of the inherent uncertainty in forecasting future load growth, technological development, and availability of new energy resources (e.g., nuclear power, carbon capture, or large-scale energy storage systems). The unfortunate outcome of poorly planned capacity is that the system can experience the blasts of over-generating or under-generating, both of which put stress on the stability of the grid. If over-generated, this would waste energy, while if under-generated, it would cause a potential supply deficit, which could lead to reliability problems, and even the system may need to rely on fossil fuel-based peaking plants, thus increasing operational costs and emissions [27].

The evolving flexibility of the system to long-term variations in energy generation and consumption is another challenge. Given the ever-increasing contribution of renewable energy sources such as wind and solar to new generation capacity, the system's flexibility will need to be reevaluated. The performances of the subsequent system relied more heavily on traditional power plants that provided much of the system's flexibility in the past, which are now being retired or repurposed [28–31]. This shift in generation mix creates a limit on the system's ability to adjust to longer-run changes to load or generation, especially in those areas with high variability in renewable generation. The characteristic of this issue is the mismatch between the gradual but sustained increase in renewable generation and the system's reduced ability to quickly adapt to these changes. The consequence of insufficient flexibility is that the system may experience difficulties in meeting demand during periods of low renewable generation, leading to reliability concerns. In extreme cases, the system

may be forced to rely on backup generation from fossil-fuel plants, which are typically less efficient and more costly.

Furthermore, at the long-term scale, the system faces the challenge of accommodating shifts in demand patterns due to demographic and economic changes. As populations grow and urbanize, electricity consumption patterns change, with some regions experiencing increased demand while others see a decline. Additionally, technological advancements in electric vehicles (EVs), heating, and industrial processes are expected to further impact demand forecasts. The challenge here is that the system must be prepared to accommodate these shifts in demand over long periods, which requires accurate long-term forecasting and the ability to adjust capacity and operational strategies accordingly. The characteristic of this problem is the difficulty in predicting future demand with high accuracy, given the many factors that influence consumption patterns, including changes in population, technology, and economic conditions [32–34]. The consequence of inaccurate demand forecasting is that the system may either overestimate or underestimate future needs, leading to either insufficient generation capacity or inefficient overbuilding of infrastructure.

In addition, we have, on the long-term scale, the power quality problem and issues such as harmonics, voltage flicker, and other power perturbations that can degrade sensitive plants and industrial processes. Issues with power quality over short durations (e.g., to the extent of spikes in load or generation) may be experienced transiently due to sudden changes in load or generation [35–37], while longer-term power quality considerations tend to be driven by cumulative effects of changes to the generation mix, including increasing penetration of inverter-based resources such as solar panels and wind turbines. However, over time, these resources can cause harmonic distortion, voltage flicker, or other disturbances that will degrade power quality. This characteristic of an issue is the gradual accumulation of power quality disturbances that are not immediately visible but have severe long-term impacts on equipment performance and system reliability. Poor power quality is a consequence that can cause equipment damage, decrease operation efficiency, and increase maintenance costs of the industries that rely on a stable and clean power supply [38,39].

Table 1 summarizes the power system regulation requirements at different time scales. Since the power system has different adjustment needs at different time scales, it is difficult to meet its reliability and stability needs by relying on a single energy source and adjustment means, and a variety of flexible resources are required to participate in the adjustment. The following will briefly introduce the multiple flexible resources.

Table 1. The power system regulation requirements at different time scales.

Time Scale	Regulation Requirements	Challenges
Instantaneous and Short-Term	System dynamic response to sudden disturbances, frequency stability, voltage regulation, power angle stability, inertia	System inertia is low due to high renewable penetration, frequency and voltage fluctuations, and ramp rate limitations.
Medium-Term	Scheduling and reserve capacity management, generation and load uncertainty, demand pattern changes	Deviation in load prediction and volatility in renewable generation, ramp rate limitations of traditional generation.
Long-Term	Capacity planning, integration of new generation resources, demand shifts, adaptation to changing demand patterns	Forecasting errors, uncertainty in energy resource availability, mismatched generation, and load over the long-term.

3. Overview of Diverse Flexible Resources

Various assets that have the capacity to offer dynamic regulation and maintain balance between supply and demand in the power system are called flexible resources [40–42]. Thermal power and pumped storage hydropower stations have historically been the (main) flexible resources in power systems. With the development of new technologies, emerging examples in renewable energy, energy storage, and improvements in demand response mechanisms are increasingly necessary—more diverse systems of flexible resources spanning generation, the grid, load, and storage [43–46]. Meeting the real-time balance of supply with demand and ensuring the secure and stable operation of modern power systems requires access to a diverse set of flexible resources. Figure 2 shows the composition of flexible resources.

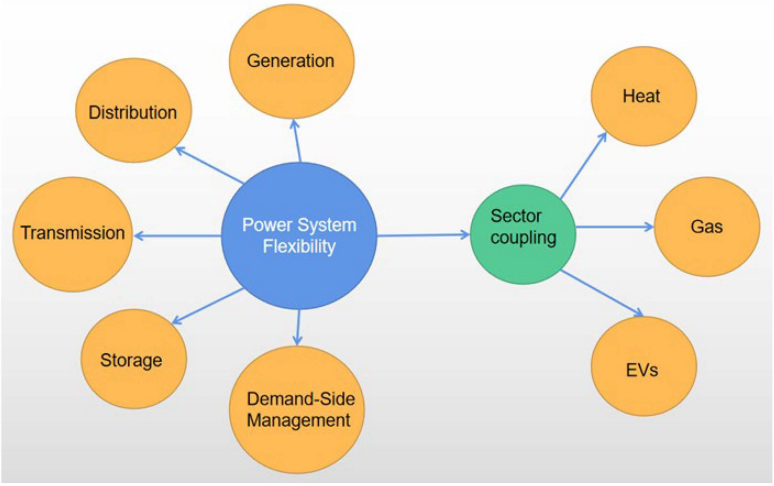


Figure 2. Flexible resource composition.

3.1. Classification of Flexible Resources

3.1.1. Supply-Side Flexible Resources

- Flexible Fossil Fuel Power Plants

Traditionally inflexible but upgradeable, thermal power plants can be made more flexible by improving their ramping capabilities and responsiveness [47–49]. First of all, as mentioned above, these are primarily driven by the requirement for quick power output adjustments to adapt to variable renewable generation or sudden demand spikes [50]. Through modifications in control systems, combustion technologies, and boiler-turbine operation, these plants can transition from base-load generators to flexible resources that offer rapid load-following, frequency regulation, and reserve power [51,52].

Flexibility improvements in fossil fuel plants focus on optimizing control systems, adapting turbines and boilers for faster load changes, and incorporating thermal storage. These upgrades allow plants to adjust their output more quickly without compromising efficiency [53]. The integration of advanced control systems and the use of more responsive turbine and combustion technologies enable faster ramping and load-following capabilities [54]. The principle of flexible thermal power operation involves adjusting the output power by modifying the operational set points, such as temperature and pressure, within the constraints of the plant's design [55–57]. The key technical challenges include maintaining efficiency while rapidly adjusting the output, as well as minimizing wear and tear on the equipment. This is typically achieved through operating range extension, where

operators adjust the combustion process to ensure optimal operation within a wider range of load [58,59]. The output power $P_{thermal}$ as a function of the load L can be modeled as [60].

$$P_{thermal} = P_{max} \cdot f(L), f(L) \in [0, 1] \quad (1)$$

where P_{max} is the maximum power output of the thermal plant, and $f(L)$ is a function representing the load sensitivity to operational parameters (e.g., fuel consumption, combustion stability).

Upgrading existing fossil fuel power plants to improve their flexibility is often a more cost-effective solution compared to constructing new flexible generation units. This is because the capital costs associated with upgrades are typically lower, as they make use of the existing infrastructure. This approach reduces the need for large-scale investments, which can be a significant financial burden. Common upgrades include enhancing control systems, improving combustion technologies, and integrating thermal storage. The cost-effectiveness of these improvements can be assessed through lifecycle cost analysis, which weighs the initial investment against long-term operational savings and additional revenue streams, such as those generated from grid services such as frequency regulation.

However, while upgrading fossil fuel plants can enhance their operational flexibility, it may have some impact on overall efficiency. Frequent cycling and load-following operations can lead to increased wear and tear, which may slightly reduce efficiency. Despite this, advanced control systems and optimized combustion technologies can minimize these efficiency losses. Moreover, integrating thermal storage can help mitigate fluctuations in power output, reducing the negative impact on plant efficiency and helping to maintain relatively high operational performance.

When comparing the costs of upgrading existing plants to investing in alternative flexible resources, such as renewable energy with storage, upgrades to fossil fuel plants tend to be more affordable in the short-term. Renewable energy systems, while offering lower operational costs, require substantial initial investments. In this context, upgrading fossil fuel plants presents a quicker and more financially viable option to increase flexibility. However, looking ahead, long-term investments in renewable energy might provide even greater benefits, especially as storage technology continues to decrease in cost and policy incentives for clean energy increase.

- Hydropower Resources

Among the most flexible and reliable regulation resources in modern power systems are hydropower resources, in particular pumped storage. Hydropower can store and release energy rapidly, responding instantly to grid condition variations. The major advantage of hydropower plants, especially pumped storage plants, lies in their ability to store water as potential energy in elevated water reservoirs and release it when needed [61,62]. Given their ability to meet demand within minutes of the act, they have wide application for balancing supply and demand, frequency regulation, and providing spinning reserves. Output flexibility is enabled by their capacity to rapidly adjust output to accommodate grid fluctuations, thus serving as a dynamic resource for grid stabilization.

Flexibility of hydropower resources is due to the possibility to change the mechanical power input on a time scale matching the change of water level in a reservoir by variation of water flow in turbines. Pumped storage plants store a little extra energy by pumping water to a higher reservoir, making them a stopgap function. The water is released through turbines to generate electricity, providing fast, strong, and reversible power adjustments as demand increases [63]. This process enables hydropower plants to provide rapid

responses and essential grid services. The energy output P_{hydro} of a hydropower plant can be represented as [64]:

$$P_{hydro} = \eta \cdot \rho \cdot g \cdot Q \cdot H \quad (2)$$

where η is the efficiency of the turbine, ρ is the water density, g is the gravitational acceleration, Q is the volumetric flow rate of water, H is the effective head (height difference). Hydropower plants are able to adjust power output rapidly (by adjusting Q or H) with large control amplitudes to provide essential grid stabilization services and profitable electricity auctions [65,66].

- Nuclear Power Resources

Nuclear power plants have high reliability and can provide stable, consistent power. Nuclear plants operated traditionally as base-load generators; however, recent advances in nuclear designs and control systems as well as electronics have enabled more dynamic output. Nuclear plants with load-following capabilities are a means of a nuclear contribution to balancing supply and demand in high renewable energy penetration systems [67].

By further improving operational control and load-following of nuclear power, flexibility is achieved. SMRs, other advanced nuclear reactors, are designed for enhanced flexibility of operation and operated to respond dynamically to changes in grid demand. The improvements in reactor design, along with more responsive turbine and cooling systems, enable better control over power output [68,69], allowing nuclear plants to assist with grid balancing. Nuclear power plants generally use control rods and coolant flow adjustments to modulate reactor output. The principle of operation involves a nonlinear relationship between reactor power output $P_{nuclear}$ and the control variables such as control rod position x and coolant flow rate F_{cool}. The response of the reactor to these inputs can be approximated as [70]:

$$P_{nuclear} = P_{base} \cdot (1 - x) \cdot f(F_{cool}) \quad (3)$$

where P_{base} is the base power output, and $f(F_{cool})$ describes the impact of coolant flow adjustments on reactor efficiency. As reactors are further developed for flexible operation, the ramp rates are expected to improve and enable faster adjustments to output levels.

Although nuclear power has traditionally been considered a stable and inflexible source of generation, recent advancements have demonstrated that nuclear plants can, in fact, provide significant flexibility in meeting power system regulation needs. For example, in France, where nuclear power accounts for approximately 70% of the country's electricity, nuclear reactors can adjust their output rapidly. French reactors can reduce their output from 100% to 20% twice a day, within less than 30 min, to accommodate fluctuations in electricity demand and support grid stability [71].

This ability to provide flexible generation is particularly important during periods of high renewable energy penetration, where the variability of wind and solar power requires backup from flexible generation sources. In addition to daily operational flexibility, it is estimated that during the summer months, at least 10 nuclear reactors must be switched on and off every day to meet peak demand and fluctuations in the grid [72].

The flexibility of nuclear plants is not only beneficial for grid balancing but also plays a key role in maintaining energy security, especially in systems with high shares of intermittent renewable energy. However, further development and optimization of nuclear reactor operations are needed to improve the speed and efficiency of these transitions between full output and partial load. Efforts such as these are critical for ensuring the continued relevance of nuclear power in modern, decarbonized energy systems [73].

Nuclear power resources can support grid regulation in the following ways:

Load Following: Modern nuclear reactors, with improved control systems, can adjust their output to follow variations in demand, complementing variable renewable generation.

Grid Stabilization: Nuclear power provides a stable and reliable source of electricity, especially when renewable generation is low, helping to maintain grid stability.

Reduced Carbon Emissions: Nuclear power contributes to grid decarbonization by providing a large amount of low-carbon, reliable energy, making it an important resource in transitioning to a sustainable energy future.

3.1.2. Grid-Side Flexible Resources

Grid-side flexible resources are typically limited in diversity but require higher technical specifications. Flexibility can be enhanced through mechanisms such as grid interconnections, microgrids, and flexible transmission technologies. Grid interconnections facilitate the ability of neighboring regions to fulfill power demand by harnessing surplus generation when local resources are fully utilized, thereby capitalizing on regional disparities in electricity consumption and promoting the sharing of flexible resources across areas. Flexible transmission technologies improve the controllability of voltage and power flows without altering grid structures. Additionally, microgrids can function as intelligent, adaptable loads, responding within seconds to the system's flexibility needs [74].

Grid-side flexibility can be mathematically described by the concept of power flow optimization in a network. The power flow equation on a grid is given by [75]:

$$P_{ij} = V_i V_j \left(G_{ij} cos\left(\theta_{ij}\right) + B_{ij} sin\left(\theta_{ij}\right) \right) \quad (4)$$

where P_{ij} is the power flow between nodes i and j. V_i and V_j are the voltage magnitudes at nodes i and j. G_{ij} and B_{ij} are the conductance and susceptance between the nodes. θ_{ij} is the phase angle difference between the nodes.

Through advanced grid interconnections and flexible transmission technologies, the grid operator can optimize the power flow and enhance system stability under fluctuating demand.

3.1.3. Storage-Side Flexible Resources

Energy storage functions as a highly flexible and rapid-response resource, effectively mitigating load fluctuations and substantially improving the integration of renewable energy by operating in tandem with renewable energy generation systems. Existing energy storage technologies encompass battery storage, pumped-storage hydropower, flywheel storage, compressed air storage, and hydrogen storage [76]. Studies have shown that the primary frequency regulation efficiency of energy storage is 1.4 times that of hydropower units, 2.2 times that of gas-fired units, and 24 times that of coal-fired units. Storage systems are adaptive because they can store excess energy when demand is low and release it when needed [77]. This makes them ideal for balancing intermittent renewable generation and ensuring grid stability. They provide critical services such as frequency regulation, load following, and spinning reserves.

Compared to other flexible resources, they have distinct advantages and disadvantages.

In terms of capital costs, energy storage systems, particularly large-scale electrochemical storage and hydrogen infrastructure, often require significant upfront investment. This is in contrast to coal-fired units and gas plants, which typically have moderate capital costs, especially if existing plants can be retrofitted for flexibility. Pumped hydro storage and dispatchable hydropower also demand high initial investment due to infrastructure requirements and environmental considerations. Demand response, on the other hand, has relatively low capital costs, as it mainly involves integrating control systems and incentivizing consumer participation.

When it comes to operating costs, energy storage technologies such as electrochemical storage and hydrogen storage generally have moderate costs, primarily related to

maintenance and, in the case of hydrogen, fuel production. In comparison, coal and gas plants incur high operating costs due to fuel consumption and ongoing maintenance needs. Dispatchable hydropower and pumped hydro storage have relatively low operating costs, with no fuel costs, but require maintenance. Demand response tends to have the lowest operating costs, though this can vary depending on program design and technology requirements for system integration.

Regarding transmission costs, energy storage offers advantages by being deployable closer to demand centers, reducing the need for new transmission infrastructure. This contrasts with coal and gas plants, which can incur moderate transmission costs depending on their location. Dispatchable hydropower and pumped hydro storage, if located far from load centers, may face higher transmission costs due to the need for long-distance electricity transport. Demand response can reduce transmission costs by shifting demand and decreasing the need for new generation or infrastructure.

Energy storage can be modeled as a state of charge (SOC) control system, where the charge/discharge operation of the storage device follows a dynamic equation [78]:

$$SOC(t) = SOC(t-1) + \frac{P_{storage} \cdot \Delta t}{C_{storage}} \quad (5)$$

where $SOC(t)$ is the state of charge at time t, $P_{storage}$ is the power input or output to/from the storage, $C_{storage}$ is the storage capacity, Δt is the time step for operation.

In recent developments, hydrogen storage has gained attention as an effective solution for large-scale and long-duration energy storage. Notably, green hydrogen, produced via electrolysis powered by renewable sources such as wind and solar, offers a sustainable and carbon-free storage option. Similarly, pink hydrogen, which is produced using nuclear power for electrolysis, provides another low-carbon alternative. Both green and pink hydrogen technologies are increasingly recognized for their potential in addressing energy storage challenges, especially for balancing intermittent renewable energy sources over long periods.

Additionally, NEOM city, a major development project in Saudi Arabia, is planning to integrate hydrogen into its energy infrastructure alongside solar and wind power for power generation. This ambitious initiative highlights the growing role of hydrogen in the future energy mix, particularly as a means to ensure energy security and support the decarbonization of power generation [79].

3.1.4. Demand-Side Flexible Resources

These reactors can work with reduced output at zero safety and efficiency effects. The ability to adjust electricity consumption in response to grid signals is called demand-side flexible resources, and it is a cost-effective means to supply and demand balance. Flexible resources on the demand side include adjustable loads, EVs and user-side energy storage systems that are usually smaller and more decentralized “prosumers”. When renewable generation is variable, these resources can greatly assist in maintaining grid regulation by reducing or shifting demand to improve grid operation [80,81]. Demand-side resources are flexible because they demand, on short notice, to consume or release load commensurate to changing grid needs. This flexibility can be used to slacken peak demand, reduce stresses on the grid during times of peak consumption, and maintain supply and demand balance without additional generation. Demand response programs give consumers the opportunity to either reduce or defer energy use and are an important tool for grid stability and cost saving.

Aggregated demand response strategies, in which a set of small-scale resources are treated as a single controllable entity, can manage demand-side flexibility. The aggregated load P_{agg} can be modeled as [82]:

$$P_{agg} = \sum_{i=1}^{N} P_i(t) \tag{6}$$

$$P_i(t) = f_i(D_i(t)) \tag{7}$$

where $P_i(t)$ represents the demand of individual loads and $D_i(t)$ represents the control signal applied to the load. Through aggregation and smart communication systems, this model allows for coordinated adjustments to reduce peak demand and maintain grid stability.

3.2. Comparative Characteristics of Flexible Resources

Table 2 compares the characteristics of different types of flexible resources. In different time scales, power systems have different adjustment requirements, so it is necessary to make reasonable planning according to the characteristics of different resources [83–86].

Table 2. Comparison of flexible resource characteristics.

Type		Operational Range	Ramping Rate	Start-Up Time	Regulation Timescale	Relative Capital Cost	Relative Operational Cost	Relative LCOE
Supply	Normal coal-fired unit	50–100%	1–2%	6–10 h	Short/Medium/Long	Medium	Medium	Medium
	Retrofitted coal-fired unit	30–100%	3–6%	4–5 h	Short/Medium	Medium	Medium	Medium
	Gas plant	20–100%	8%	2 h	Short/Medium	Medium	Medium	Medium
	Dispatchable hydropower	0–100%	20%	<1 h	Short/Medium/Long	Medium	Low	Low
	Nuclear power	20–100%	1–5%	30 min	Short/Medium/Long	Very High	Medium	High
Load	Demand response	3–5%	Instantaneous	Instantaneous	Short	Very Low	Very Low	Very Low
Energy storage	Pumped hydro storage	−100–100%	10–50%	<0.1 h	Short/Medium/Long	High	Low	Low
	Electrochemical energy storage	−100–100%	100%	<0.1 h	Short	Medium	Medium	Medium
	Hydrogen	10–110%	<0.8%	<50 min	Medium/Long	Very High	Medium	High

4. Application of Diverse Flexible Resources Across Different Time Scales

The effective integration of flexible resources in power systems is essential for maintaining grid stability across different time scales. This section analyzes how diverse, flexible resources are applied to meet the regulation needs at instantaneous, medium, and long-term time scales. Additionally, the application of single and hybrid regulation methods is discussed, focusing on their effectiveness in addressing varying system demands [87,88].

4.1. Instantaneous and Short-Term Applications

The instantaneous and short-term regulation needs of power systems, such as frequency stabilization, voltage control, and power quality maintenance, are critical for ensuring grid reliability and resilience. These needs can be met using a combination of single regulation methods and hybrid approaches that integrate different flexible resources [89].

4.1.1. Single Regulation Methods for Instantaneous and Short-Term Needs

At the instantaneous and short-term time scale, the primary goal is to address rapid fluctuations in power generation and demand [90,91], which may result from sudden changes in load or renewable generation. Single regulation methods are particularly effective when a rapid, isolated response is required [92,93].

- Frequency Regulation

Frequency regulation is a key challenge, especially in systems with high penetration of variable renewable energy sources. Battery Energy Storage Systems (BESS) have proven effective in providing rapid frequency regulation. A notable example is the use of BESS in the California Independent System Operator (CAISO) grid. During periods of frequency deviation caused by sudden drops in renewable generation, lithium-ion batteries have been used to inject power within milliseconds, stabilizing the system frequency. The Tesla Hornsdale Power Reserve in South Australia is another example, where the large-scale battery system has been deployed to provide frequency regulation services, responding in seconds to sudden fluctuations [94]. Smart grid technologies, particularly Advanced Metering Infrastructure (AMI) and Demand Side Management (DSM), play a complementary role in frequency regulation. AMI provides real-time monitoring of load and generation data, enabling grid operators to detect frequency deviations promptly and coordinate responses more effectively. DSM programs, when integrated with AMI, can reduce non-critical loads almost instantaneously, providing additional flexibility to stabilize frequency during high-stress periods.

- Voltage Stability

Maintaining voltage stability is crucial during short-term load fluctuations or generation imbalances. Pumped hydro storage (PHS) has been widely used to address this need. In Norway, the Sima pumped storage plant provides rapid voltage support to the Nordic grid. When there is a sudden drop in voltage, the plant can release stored water to generate power within seconds, supporting the grid's voltage stability [95]. Similarly, pumped hydro plants in the Swiss Alps provide reactive power and voltage support, especially during peak demand periods [96]. Distribution Automation (DA) systems in smart grids enhance voltage stability by dynamically reconfiguring distribution networks and providing automated control of reactive power devices. For instance, DA can redirect power flows or engage reactive power compensators in milliseconds, ensuring voltage levels remain stable even during significant short-term fluctuations.

- Power Quality Maintenance

Maintaining power quality, especially in terms of voltage sags, surges, and harmonics, is a crucial aspect of grid stability. BESS have proven to be highly effective for mitigating power quality issues, particularly in systems with high penetration of renewable energy sources. BESS can quickly feed, or take, power to help balance out voltage spikes driven by instantaneous changes in generation or load [97]. Smart grids utilize AMI and DA to proactively address power quality challenges. AMI continuously monitors voltage profiles across the grid, enabling early detection of sags, surges, or harmonics. Meanwhile, DA systems can deploy automated voltage regulators or engage flexible resources such as BESS to mitigate quality issues before they impact end-users.

Hornsdale Power Reserve, one of the biggest lithium-ion battery installations in the world, is used to balance scales for the grid in South Australia. When there are rapid fluctuations in renewable generation (e.g., wind or solar), the system can either absorb excess energy and provide power to the grid to ensure that the voltage levels will remain stable or there will be a conservation of power to reduce the chance of issues such as power

quality, such as voltage dips or harmonics. Maintaining a reliable power supply is crucial, especially when renewable energy sources are intermittent, and this is a much-needed capability. Likewise, in the United States, BESS are being integrated into power quality maintenance as performed by CAISO. BESS can provide fast response compensation for sudden generation losses or demand spikes to balance the power imbalances such that voltage levels can be stabilized and the overall power quality improved. BEI's ability to respond almost instantaneously to these fluctuations makes it a perfect solution for grid stability and minimizing damage to the power quality [98].

4.1.2. Hybrid Regulation Methods for Instantaneous and Short-Term Needs

- Frequency Regulation with Demand Response and Batteries

It can be shown that combining battery storage and demand response (DR) can provide effective frequency regulation over both short and slightly longer time scales. In the NYISO region, a mix of BESS and DR has been put in place for grid stability. When things pan out dry at the immediate time of high demand or sudden frequency spikes, the BESS injects the power into the grid to restore frequency [99]. DR programs can also be triggered to reduce consumption from nonessential loads at the same time, balancing supply and demand over a longer period of time. This hybrid approach has played an important role in increasing grid resilience and efficiency during peak periods.

- Voltage Support with Pumped Hydro Storage and Wind Power

A hybrid method that combines BESS and PHS is implemented in Norway to address short-term voltage stability challenges. BESK can inject active power to sustain voltage stability in real-time; PHS offers reactive power support in milliseconds. BESS systems and the Sima pumped storage plant together provide total voltage support for the grid in critical situations. The hybrid approach takes advantage of both of these resources to provide fast, reliable reactive and active power, restoring voltage levels in response to sudden grid disturbances [100,101].

- Power Quality Maintenance with Gas Turbines and Batteries.

To address power quality needs during sudden changes in load or generation, the combination of gas turbines and batteries has proven effective in real-world applications. In Germany, the integration of batteries with gas-fired power plants has been employed to stabilize grid frequency and voltage. By integrating it with battery storage, the Kraftwerk Emsland gas plant can quickly tap into its power output to adjust to short-term fluctuations in supply to preserve power quality at any given time [102]. When generation exceeds demand, the batteries absorbing excess energy assist to keep voltage levels within range and reduce power quality problems; conversely, when excess generation fails to match demand, the batteries discharge to achieve some degree of balance.

For modern power systems, stability, and resilience in the face of instantaneous and short-term regulation needs require the application of diverse flexible resources. However, single regulation methods—like BESS, pumped hydro storage, and gas turbines—have shown their ability to solve particular grid projects of challenges such as frequency regulation, voltage support, and power quality maintenance [103,104]. The combination of multiple flexible resources (hybrid methods) provides much greater benefits with rapid response and longer duration support. Examples in the real world from e.g., California, South Australia, Norway, and Germany have shown the successful application of these approaches to fulfill grid reliability requirements and to facilitate the introduction of renewable energy sources. With the way forward to a stable and sustainable power grid increasingly becoming one of 'flexible resources', these resources will continue to provide a significant contribution to global energy transition progress [105].

4.2. Medium-Term Applications

The power system at the medium-term scale poses a distinct set of challenges with regard to both generation scheduling and reserve capacity management and the ability to adjust to variable generation and demand patterns [106]. These challenges can be met with flexible resources that can run over time scales that exceed the time scales of forecasts and accommodate forecast errors, lifetime constraints, and renewable energy sources. The following sections outline the applications of diverse flexible resources in addressing medium-term regulation needs, both through single and hybrid methods.

4.2.1. Single Regulation Methods for Medium-Term Needs

In the medium-term scale, typically ranging from minutes to hours, grid operators must manage persistent imbalances and forecast errors. Single regulation methods at this scale aim to smooth out renewable generation variability and mitigate load forecast deviations.

- Generation Scheduling and Forecasting

One of the key challenges at the medium-term scale is managing generation scheduling, especially when accounting for fluctuations in load and renewable generation. Hydropower has been extensively used for this purpose due to its flexibility in adjusting output over several hours or days. For example, the Grand Coulee Dam in the United States can quickly ramp up or down its generation output to compensate for discrepancies between forecasted and actual demand. When renewable generation such as wind or solar is underperforming, hydropower can provide the necessary backup power, ensuring the system remains balanced. By adjusting the water flow to the turbines, hydropower can maintain grid stability while accommodating the variability of renewable sources [107]. AMI enhances medium-term generation scheduling by providing high-resolution data on consumption trends and renewable generation patterns. These insights enable more accurate forecasting and optimized resource allocation.

- Reserve Capacity Management

Reserve capacity must be maintained at an adequate level so as to allow the system to respond to intraday variations in generation or demand. Currently, medium-term needs have been met by employing gas-fired power plants as a single resource in reserve capacity. In other regions, such as Texas, peaking gas plants are often utilized to stabilize demand peaks and/or generation shortfalls over several hours. These plants can start up relatively quickly and produce the needed power when reserves are depleted and, if renewable supply is insufficient. The ability to respond quickly to demand fluctuations guarantees the system avoids the reliability risk of load shedding or emergency curtailing of demand [108].

- Ramp Rate Adjustment

This is defined as ramp rate adjustment, the capability of power generation units to change their output at a controlled, slow rate on a sustained basis, such as several hours or indeed days [109]. In the medium-term scale, where variable renewable generation and fluctuating demand exist, it is especially important to have this capability. As a regulation method for ramp rate adjustment, gas-fired power plants are generally utilized as a single regulation method.

Specifically, gas turbines—particularly those that incorporate combined cycles—have been designed to be capable of providing fast and rapid ramping, making them ideally suited to respond to medium-term variations in power demand. One example is when the demand gradually grows during the day, or when there is a gap in renewable generation resulting from changes in weather that can be easily balanced over hours by changing the output of gas turbines on the grid. The ability of gas turbines to ramp up or down

with relatively short response times (on the order of minutes to hours) allows the system operator to respond to changes in a more flexible and efficient manner. In regions with high reliance on intermittent renewable resources, such as wind and solar power, gas-fired plants provide a stable base generation that can respond to variability in renewable generation. For instance, when wind power drops due to a shift in wind patterns, gas turbines can quickly adjust their output to meet the demand, ensuring a stable power supply. In this way, gas turbines fulfill the role of a single regulation resource to compensate for renewable generation gaps and to smooth out the fluctuations in load over medium-term periods.

Additionally, BESS are also used as a single regulation method in some applications. While primarily suited for short-term adjustments, advancements in BESS technology have allowed for their deployment to address medium-term fluctuations in demand. The surplus energy generated during off-peak periods or very high renewable output or discharge occurs when the remover demand rises or the renewable generation declines. BESS, aside from being responsible for the more immediate fluctuation, are becoming part of medium-term strategies as part of a single regulation method to ensure constant power availability [110].

- Voltage Stability

Voltage stability over the medium-term is a critical concern in power systems, which face significant integration of intermittent renewable energy sources. The unstable nature of these resources means that up and down can result in gradual deviations in voltage levels, and if not managed, this deviation could aggravate initial instability of the grid [111,112].

BESS is a commonly applied single regulation method to restore voltage stability using voltage as the master regulation variable. In periods of high renewable generation, BESS can absorb excess energy and discharge power when demand increases or generation drops. BESS provides both active and reactive power support, but over the medium-term, they stabilize voltage. This is important because these systems can quickly and efficiently change the voltage level so that you get smooth operation even when renewable generation is variable. BESS are strategically placed in high solar and wind penetration regions at key grid locations to supply voltage regulation where fluctuations in renewable generation occur [113]. When solar or wind generation is not at the level forecasted, the BESS can draw stored energy from the grid, supplying reactive power to maintain voltage stability (for example) to compensate for disruption. However, when generation outpaces demand, excess power is absorbed by the system, which attempts to prevent over-voltage conditions. DA enhances voltage stability by automating the control of reactive power devices and enabling real-time reconfiguration of distribution networks, ensuring smooth voltage profiles during medium-term fluctuations.

- Minimum Output Flexibility

The need for generation units to operate efficiently during low-demand periods is another challenge. Coal-fired power plants often face inefficiencies when their output is reduced to very low levels. To address this, demand-side management (DSM) has been implemented in several regions, such as California, where industrial consumers are incentivized to adjust their consumption during low-demand periods. By using DSM techniques, the grid can avoid keeping inefficient coal plants running unnecessarily, thus saving fuel and reducing emissions [114]. Additionally, during low-demand hours, BESS can be used to absorb excess energy from renewable sources, helping to maintain grid stability without relying on less efficient generation.

4.2.2. Hybrid Regulation Methods for Medium-Term Needs

Hybrid approaches at the medium-term scale combine the flexibility of multiple resources to provide a more robust response to varying grid conditions.

- Generation Scheduling and Forecasting with Batteries and Hydropower

A hybrid approach combining BESS and hydropower has been successfully deployed in regions with significant renewable generation. BESS is integrated with combustion or nuclear power plants in Norway to tackle medium-term generation scheduling and forecasting issues. Batteries help fill the gap between wind and solar generation supplies and the power the grid expects, enabling them to power the grid until hydropower plants can step in and adjust their output. To ensure that the grid remains stable regardless of the unpredictable generation of renewable energy, this combination allows for a reliable 'back up' for forecast errors [115].

- Reserve Capacity with Gas and Storage Systems

The hybrid combination of gas-firing power plants and battery storage systems is used for effective reserve management over medium time scales. This hybrid system manages reserve capacity in the United Kingdom both in the short-term, and in the medium-term. Batteries serve as a more flexible reserve storage for gradual changes to demand or generation (and with increased power output rating and fast charging times than seen in wide market energy storage, could serve as a source of quick response reserve to sudden volatility), and gas plants provide quick response reserve to meet sudden volatility spikes. The hybrid method guarantees that the system is still responsive to rapid as well as gradual changes in supply and demand and thus considerably curbs the use of emergency measures: load shedding [116].

- Ramp Rate Flexibility with Gas and Storage

In order to adjust generation levels gradually, hybridization with BESS can be used to pair gas-fired power plants and reduce ramp rate limitations of conventional generation units. This hybrid approach provides a promising pathway to balance intermittent renewable generation, such as wind and solar, with classical thermal generation. It is particularly relevant for regions with high renewable energy penetration, such as California and South Australia, where ensuring system flexibility and reliability remains a priority [117]. BESS can store excess renewable generation and discharge power when needed, while gas plants can ramp out at a slower rate with changes in demand. This method combines the hybrid method and retains the smoothness of the system when the demand curve is followed, so that the system is not under-generated or over-generated for the medium-term period [118].

- Voltage Stability with Wind, Storage, and Stabilizing Devices

In this case, we consider combining wind generators, battery storage, and voltage stabilizing devices (SVCs) to form a hybrid approach for medium-term voltage stability. Offshore wind farms off Denmark are combined with SVCs and BESS for voltage stability as the wind speed fluctuates. The wind farms provide power, while BESS take excess generation (or supply backup power when generation drops) [119]. SVCs ensure that reactive power support is available to stabilize voltage, mitigating the risks associated with high renewable penetration. This combination of resources addresses both the variability of wind generation and the need for stable voltage over longer periods.

- Minimum Output Flexibility with Storage and Demand Response

To address the inflexibility of certain generation units, such as coal-fired power plants, hybrid solutions involving storage systems and DR are used. In California, BESS are employed to absorb excess energy during low-demand periods, allowing coal plants to

reduce their output while maintaining grid stability. Simultaneously, DR programs are used to shift industrial loads to times of higher generation or lower demand. This hybrid approach helps avoid inefficiencies in coal plant operation and reduces the overall carbon footprint of the system.

The medium-term regulation needs of the power system, including generation scheduling, reserve capacity management, ramp rate flexibility, and voltage stability, require a combination of single and hybrid flexible resources. By integrating resources such as hydropower, gas plants, batteries, and demand response, power systems can adapt to forecast discrepancies, variable generation, and changing demand patterns. These flexible resources not only enhance grid reliability but also facilitate the integration of renewable energy sources, ensuring that the system operates efficiently and effectively over longer time scales [120,121].

4.3. Long-Term Applications

4.3.1. Single Regulation Methods for Long-Term Needs

- Capacity Planning and Integration of New Generation Resources

One of the key constraints concerns capacity planning and guaranteeing smooth connection of new resources, particularly in systems with a high renewable energy fraction [122]. BESS has provided a very important resource in solving these issues. BESS can offer large-scale energy storage, which can help mitigate the fluctuations in generation from intermittent renewable sources (such as wind and solar) and further improve the flexibility of the power system. For example, large-scale BESS installations are used to store excess renewable energy when generation is high and release it when needed during peaks of demand in California [123]. By preventing overgeneration and further dependency on inefficient fossil fuel plants, these systems aid in making the system work. Integrating BESS with the grid has the effect of enabling utilities to perform better at balancing generation with forecasts of demand since obvious under/over-generation problems are less likely. As the amount of renewable energy increases over time, the capacity planning of the system will depend more on BESS to keep the system reliable and efficient. AMI complements long-term capacity planning by providing utilities with detailed, high-resolution data on load trends and generation patterns. This information enables better forecasting and infrastructure development, ensuring the smooth integration of new generation resources.

- Evolving Flexibility of the System

DR programs have become a necessary component to provide flexibility to the grid over longer-spanning periods as renewable energy sources such as wind and solar continue to grow. They help utilities manage their loads by rewarding consumers for lowering, or shifting, their electricity consumption when energy is not being produced locally or when the system is strained. For instance, in Denmark, adding DR to renewable output from wind and solar balances generation periods of low renewables. DR programs are activated when wind stops blowing or solar generation drops to decrease residential and industrial consumption and thus reduce the need for backup generation from less efficient fossil-fuel plants [124]. By alleviating the mismatch between the fluctuation of renewable generation and the grid capacity to respond, this approach provides system flexibility and stability over long periods. DSM, supported by AMI systems, enhances DR program efficiency by enabling real-time load monitoring and automated responses to renewable generation fluctuations, ensuring smoother operation during long-term renewable energy integration.

- Shifts in Demand Patterns

The hot conditions of climate change also necessitate flexible resources that can adapt to new patterns of consumption that arise as a result of demographic and technological

trends. EVs provide a large potential to balance demand shifts. As more consumers switch to EVs, there will be a shift in the demand for electricity during peak charging periods over time. The rollout of smart charging infrastructure for EVs is used for demand-side management in the Netherlands. Figure 3 shows the electric vehicle management model under the smart grid. Smart grids make it possible to charge EVs when renewable energy is high and during off-peak hours [125]. It offloads stress on the grid during peak demand periods and reduces reliance on peaking plants based on fossil fuel. With smart charging solutions for EVs, dynamic changes of demand can be integrated into the grid to facilitate long-term variation of power system consumption [126]. DA systems in smart grids support the integration of EVs by dynamically optimizing charging schedules and coordinating with renewable energy availability, ensuring grid reliability while reducing peak demand stress.

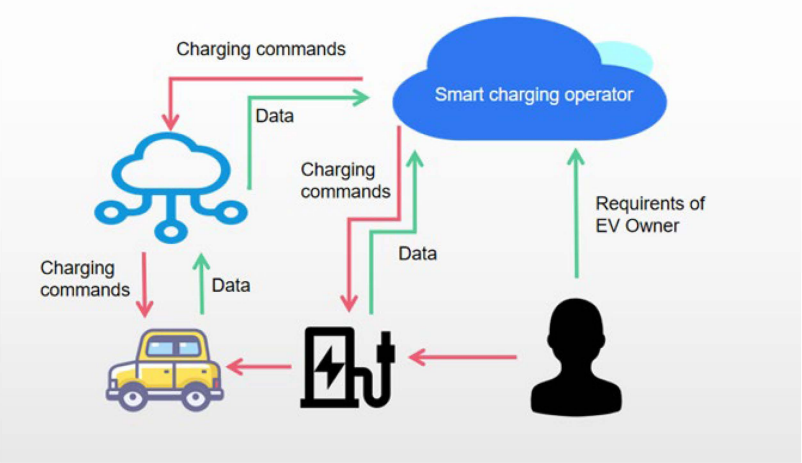


Figure 3. Electric vehicle management model under smart grid.

In terms of electric vehicle components, electric batteries represent the most expensive and critical elements. The high cost and limited lifespan of EV batteries are key challenges that impact the overall sustainability of electric vehicles. Recent advancements in machine learning techniques offer promising solutions for optimizing battery characteristics during exploitation. By analyzing real-time data, machine learning algorithms can predict the optimal charging and discharging cycles, thereby enhancing battery efficiency, and extending its lifespan [127]. Additionally, predictive maintenance models, powered by machine learning, can forecast potential failures, and help optimize the maintenance schedule, reducing the overall operational costs of electric vehicles. These technologies contribute significantly to improving the sustainability of electric vehicles by minimizing resource wastage and prolonging the effective use of batteries.

4.3.2. Hybrid Regulation Methods for Long-Term Needs

- Capacity Planning and Integration of New Generation Resources

Capacity planning is enhanced by hybrid approaches that utilize multiple resources. Take, for instance, PHS integration with BESS for long-term storage and flexible discharge capabilities. PHS systems are used to store surplus renewable energy that is generated in countries such as Norway from hydroelectric plants, while the BESS are used to smooth out fluctuations and more quickly respond when necessary [128]. Together, these two systems enable more efficient capacity planning in that the grid can rely on both long-duration storage and short-term flexibility to maintain a power supply that is stable throughout the increasing penetration of renewable energy.

- Shifts in Demand Patterns

DSM programs are often paired with distributed energy resources (DERs) such as small-scale solar PV and local storage to accommodate long-term changes to demand. This hybrid approach provides for more control of demand and generation at a local level. For example, in Australia, a DER combined with smart meters and DSM was deployed to minimize using electricity in the residential neighborhoods. This approach enables the grid better to accommodate shifting demand profiles of urbanization and technology advancement as well as the integration of new resources to support long-term reliability and efficiency [129].

5. Future Development Directions

The focus of short-term energy storage and scheduling is on instantaneous fluctuations and short-term imbalances in the power system. Within this area of research and application, substantial progress has been made, particularly with technology on the lithium-ion battery and supercapacitor platforms, but these systems are limited. The most notable issue is the limited energy storage capacity [129,130]. These technologies excel at addressing brief power imbalances on the scale of seconds or minutes, but they are unable to cope with longer-term fluctuations. For instance, they find it difficult to deal with seasonal energy demand and renewable generation changes. In addition, cycle life and degradation with time (efficiency) remain challenges for many of these systems, especially in high-demand scenarios. For example, lithium-ion batteries have a relatively short cycle life, relative to the size of the deployment needed for grid-level applications. In addition, these systems are able to quickly respond to variations in grid frequency, though they cannot address imbalances or demand spikes lasting for hours, days, or longer. Another limitation is that high-density, high-power technologies tend to carry significant cost per kWh, which means they can be too expensive for more general, medium-scale energy storage needs.

Medium-term energy storage technologies, such as PHS and compressed air energy storage (CAES), are typically used as means to balance supply and demand over a longer duration, of the order of hours to days. Short-term systems have higher energy density but also cannot compensate for fluctuations that occur between day and night or across seasonal cycles as well. Nevertheless, there are limits associated with a great deal of geographic constraints [131]. For instance, the demand for topographical conditions such as large elevation differences between two water reservoirs restricts the applicability of PHS. The construction of such facilities is also associated with high upfront costs and is characterized by long development times. CAES availability is also constrained by the availability of suitable geological formations for trapping the compressed air. Both systems also face significant environmental concerns. Pumped hydro storage, while effective at balancing supply-demand variations, can disrupt local ecosystems and water resources. CAES, on the other hand, faces concerns regarding air leakage, noise, and potential impacts on local geology. Furthermore, both technologies require significant capital investment for infrastructure, which raises concerns about their economic feasibility in areas where renewable energy capacity is rapidly growing. While they are useful for daily fluctuations, their inability to store energy over longer periods (such as seasonal variations) is a major drawback.

Long-term energy storage technologies, which aim to address seasonal fluctuations in renewable energy generation, face the most significant challenges. The demand for seasonal storage, especially to balance the intermittent nature of wind and solar generation, requires technologies that can store energy over periods of several months. Despite the potential of pumped hydro storage to offer long-term storage, its capacity is limited by geographical factors and the increasing costs associated with large-scale hydropower projects. The

growing competition for water resources and concerns about environmental impacts have made large new PHS projects less viable in many regions [132,133]. Other long-term storage options, such as thermal energy storage or chemical batteries, are still in the early stages of development and are plagued by technical and economic barriers. For instance, thermal energy storage systems can suffer from high energy losses during storage, reducing their overall efficiency. The thermal degradation of storage materials is another concern, as it can lead to reduced performance over time. On the other hand, chemical batteries that could provide long-duration storage, such as flow batteries or solid-state batteries, are hindered by high costs, limited energy density, and shorter lifespans when compared to other forms of energy storage. These systems are not yet capable of economically storing large amounts of energy for long periods, making them impractical for addressing seasonal supply-demand imbalances. The limitations of energy storage technologies across different time scales are shown in Table 3.

Table 3. The limitations of energy storage technologies across different time scales.

Type	Technologies/Systems	Limitations
Short-term Storage	Lithium-ion batteries, Supercapacitors	(1) Limited energy storage capacity, (2) Cannot handle long-term fluctuations, (3) Short cycle life, (4) High cost.
Medium-term Storage	PHS, CAES	(1) Geographic limitations (e.g., PHS), (2) High infrastructure cost, 3) Environmental impact.
Long-term Storage	Thermal energy storage, Chemical batteries (e.g., flow batteries, solid-state batteries)	(1) Early-stage development, (2) High energy losses, low efficiency, (3) High cost, limited energy density, (4) Short lifespan.

In conclusion, while short-term, medium-term, and long-term energy storage systems all play critical roles in ensuring grid stability and accommodating the increasing share of renewable energy, each system has its own set of limitations. Short-term systems face challenges due to their limited capacity, making it difficult to address longer-duration imbalances. Medium-term technologies, on the other hand, are constrained by factors such as geographic limitations, environmental impacts, and high capital costs. Long-term energy storage solutions are still in the early stages of development and face major technical and economic barriers, including efficiency losses, limited scalability, and high costs. These challenges underscore the need for ongoing innovation and research to develop more efficient, cost-effective, and scalable energy storage solutions that can meet the evolving demands of modern power systems.

5.1. Short-Term

Short-term energy storage solutions such as lithium-ion batteries and supercapacitors have already demonstrated their capability to address instantaneous power imbalances on the order of seconds to minutes. However, as renewable energy generation continues to increase, these systems face limitations in terms of energy density, cycle life, and cost. Looking forward, there is a clear need for new materials and technologies to improve the performance and reduce the cost of short-term storage systems.

Battery degradation is influenced by various factors, most notably temperature, humidity, and cycling conditions. These factors can vary significantly across different geographical regions, leading to spatial differences in battery degradation rates. For instance, regions with warmer or more humid climates tend to accelerate battery degradation, while colder, drier climates may prolong battery lifespan. Furthermore, regional differences in usage patterns, load profiles, and charging infrastructure can also impact the degradation of batteries.

Given these variations, it is crucial to account for spatial differences in battery degradation when evaluating the economic viability of energy storage systems. Ignoring these factors could lead to misleading conclusions, as the long-term economic performance of energy storage systems is highly sensitive to the rate of battery degradation. For example, a storage system deployed in a region with faster battery degradation may incur higher operational and maintenance costs, which could reduce its overall cost-effectiveness.

To improve the accuracy of economic analyses, future studies could incorporate regional degradation models that account for the specific environmental conditions and usage profiles of different locations. This could involve integrating geographical data, such as climate and local energy demands, with battery performance models to more precisely predict degradation rates and their impact on the economic viability of storage systems. By doing so, a more robust economic evaluation can be conducted, providing more tailored insights into the feasibility of deploying energy storage solutions in diverse regions.

The development of solid-state batteries could be a game-changer for short-term storage. By replacing the liquid electrolyte with a solid one, solid-state batteries offer higher energy density, greater safety, and longer cycle life compared to traditional lithium-ion batteries. Additionally, the integration of superconducting magnetic energy storage (SMES), which can store energy in magnetic fields, may provide another promising solution for addressing quick fluctuations while minimizing energy loss. Continued research in these areas will likely make short-term energy storage more cost-effective and efficient, allowing for their broader adoption in grid applications.

5.2. Medium-Term

Medium-term energy storage, such as PHS and CAES, has a proven track record in addressing imbalances over periods of hours to days. However, these technologies are geographically constrained, expensive to implement, and have environmental concerns. In the future, innovations in flexible pumped hydro storage could offer more adaptive solutions, such as integrating off-river pumped storage systems, which do not require natural water reservoirs. This could overcome some of the geographical limitations and reduce environmental impacts.

Additionally, advanced CAES technologies using innovative materials or designs might address some of the challenges associated with traditional CAES systems, such as air leakage and efficiency losses. As the need for longer-duration storage grows, new materials and storage techniques, including liquid air energy storage (LAES), could offer cost-effective, large-scale solutions for medium-term storage needs. These technologies can serve as an intermediary for balancing daily and seasonal variations in renewable energy supply.

5.3. Long-Term

In recent years, as the complexity of energy systems has increased, single-time-scale energy storage and scheduling technologies have been insufficient to meet the demands of future complex energy systems. Therefore, the integrated use of multi-time-scale energy storage systems has become a trend. Future energy systems will need to combine various flexible resources, such as battery storage, controllable loads, and hydrogen energy storage, to optimize energy scheduling strategies across different time scales. By combining short-, medium-, and long time-scale energy storage technologies, energy scheduling can be optimized at different times, improving the overall resilience of the system. For example, an integrated energy microgrid low-carbon optimization model based on lifecycle analysis and multi-time-scale energy storage was proposed, achieving seasonal energy balance and storage through multi-time-scale configurations.

Despite the significant potential advantages of combining multi-time-scale energy storage technologies, there are still many challenges in this field. First, optimizing the collaborative operation of different time-scale technologies and achieving multi-time-scale balance in energy scheduling is a key challenge. Second, the economic evaluation of multi-time-scale systems and policy incentive mechanisms is still underdeveloped and needs further exploration [134].

In this context, hydrogen energy has gradually become an ideal solution to address long-term energy storage challenges. Hydrogen energy can store large amounts of electricity through water electrolysis technology and can be applied across short, medium, and long time scales to meet various needs. Research shows that hydrogen energy has significant flexibility and potential in large-scale energy storage, cross-seasonal adjustment, and integration with other energy technologies. With the advancement of hydrogen energy technology, it is expected to become an important component of multi-time-scale energy storage systems in the future, providing new solutions for the efficient utilization of renewable energy. Currently, China is actively developing hydrogen energy, for example, by using new energy-driven water electrolysis to produce hydrogen. The conversion between electricity and hydrogen not only utilizes hydrogen's fast power regulation advantages but also reduces the instability of high-proportion renewable energy integration into the grid. It also maximizes the economic potential of wind and photovoltaic-based hydrogen production, which is crucial for improving renewable energy consumption.

5.3.1. Hydrogen Energy's Application Prospects in Power Systems

Hydrogen energy has extremely broad application prospects in power systems, especially as a long-term energy storage solution to address the intermittent and seasonal fluctuations of renewable energy generation. Wind and solar power, among other renewable energy sources, often face issues of fluctuating generation due to weather and seasonal changes, leading to either oversupply or insufficient supply of electricity, causing discontinuity in power availability [135]. Hydrogen energy can convert surplus electricity into hydrogen gas through water electrolysis, and during periods of high energy demand or insufficient generation, hydrogen can be converted back into electricity using fuel cells or other technologies, creating a closed loop of "energy storage—release". This characteristic makes hydrogen energy an ideal solution for resolving seasonal energy supply-demand imbalances. This flexibility provides greater regulation capacity for the power system, especially in addressing long-term storage needs that traditional grids cannot meet. In areas far from load centers or where infrastructure is weak, hydrogen storage systems can be integrated with off-grid microgrids to support local energy storage and distribution, greatly enhancing grid resilience and stability.

Furthermore, hydrogen energy storage is not just a power reserve but can also be integrated with other energy systems. For example, hydrogen can serve as a "zero-carbon peak-shaving" tool by coupling with natural gas grids, heating systems, and transportation energy systems, promoting the deep decarbonization of the energy system. At the same time, with the advancement of water electrolysis and fuel cell technologies, the production and utilization costs of hydrogen will gradually decrease, accelerating its widespread application in global power systems.

5.3.2. Development of Hydrogen Production and Storage Technologies

Significant progress has been made in hydrogen production and storage technologies in recent years. Water electrolysis technology, especially renewable energy-driven electrolysis, is considered a key pathway for producing clean hydrogen energy. Currently, alkaline electrolyzers and proton exchange membrane electrolyzers (PEM electrolyzers) are the

main electrolysis technologies, and they have made substantial improvements in efficiency, cost, and scalability.

Regarding hydrogen storage, the focus has been on hydrogen compression and liquid hydrogen storage technologies. Compressed hydrogen storage involves pressurizing hydrogen into high-pressure tanks, offering advantages such as low cost, low energy consumption, and fast charging/discharging speed. However, it has lower hydrogen density and poorer safety, making it more suitable for small-scale, short-to-medium-duration, and short-distance hydrogen storage needs. Liquid hydrogen storage, on the other hand, stores hydrogen by cooling it to −253 °C in liquid form. This method has higher hydrogen density in terms of both mass and volume, but storage costs are higher, making it more suitable for large-scale and long-term storage [136]. In recent years, both technologies have seen improvements in materials, energy consumption, and safety, providing a foundation for the widespread use of hydrogen in power systems.

5.3.3. Integration of Hydrogen Energy with Other Energy Systems

The integration of hydrogen energy with other renewable energy sources, such as wind and solar power, holds significant potential for enhancing the overall stability of power systems. By coupling with renewable energy systems, hydrogen energy can not only act as an "energy storage" when there is excess electricity but also provide peak-shaving services during electricity shortages, preventing the instability of renewable energy generation from impacting the grid.

In future multi-energy complementary systems, hydrogen energy can work closely with wind and solar power to build smart grid systems with a high proportion of renewable energy. This integrated model can not only increase the utilization of renewable energy but also reduce dependence on fossil fuels, driving the greening and decarbonization of power systems. At the same time, by integrating hydrogen energy with other storage systems, the flexibility and load management capabilities of the grid will be further enhanced, better addressing the challenges brought about by the large-scale integration of renewable energy into the grid.

6. Conclusions and Outlook

This paper reviews the multi-temporal scale regulation needs of power systems and the optimization of diverse flexible resources. It systematically analyzes the characteristics and applications of flexible resources across the supply, grid, storage, and demand sides, covering instantaneous, short-term, medium-term, and long-term time scales. The scientific justification of this research lies in its comprehensive approach to addressing the growing need for flexibility in modern power systems, particularly as renewable energy sources continue to increase their share in the energy mix.

Based on the current research and technological development trends, the following conclusions and outlooks are drawn:

- Diverse Flexible Resources

As the penetration of renewable energy increases in power systems, the diversity and regulation capability of flexible resources become critical to ensuring the stable operation of the system. This research highlights the need for advancing the coordination and integration of different flexible resources to improve the speed and accuracy of system regulation. Such advancements are essential for maintaining grid stability and supporting the transition to a more sustainable energy future.

- Short-Term Flexibility

Short-term flexible resources, such as lithium-ion battery storage and flywheel storage, are crucial due to their fast response characteristics. The scientific justification for focusing on these technologies stems from their ability to address instantaneous imbalances and their significant potential in enhancing system resilience. However, further research is needed to enhance their economic viability and scalability for large-scale applications.

- Medium-Term Flexibility

Medium-term storage technologies, such as pumped-storage hydropower and compressed air energy storage, require further optimization in their dispatch strategies to manage renewable energy generation's variability and daily load fluctuations. This research underscores the importance of integrating distributed energy storage and microgrids, which will offer greater flexibility in future power systems.

- Long-Term Flexibility

Long-term storage and dispatch technologies are essential for addressing seasonal fluctuations in renewable energy generation. Hydrogen energy, in particular, has the potential to become an integral component of future energy systems. Its ability to provide long-term energy storage and decarbonize the power sector justifies its focus in this study. Hydrogen not only enables seasonal storage but also enhances grid stability when integrated with other energy systems.

To meet the growing penetration of renewable energy, the future development of power systems will require the optimization of flexible resource allocation and dispatch across multiple time scales. Technological innovation and strategy optimization will be essential for building a more efficient and reliable energy system. By combining short-, medium-, and long-term storage technologies, alongside advanced dispatch mechanisms, the power sector can enhance its ability to balance supply and demand, ensuring the secure and stable operation of future energy systems. Moreover, as hydrogen technology advances, it is expected to play a crucial role in achieving higher renewable energy utilization and supporting the transition to a decarbonized energy system.

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