

Review

Multi-timescale flexibility for low-carbon Nordic energy systems: comparative roles of batteries, district heating, and hydropower

Tareq Anwar Shikdar^{b,a,*} , Hannu Laaksonen^{b,a}

^a Flexible Energy Resources/Electrical Engineering, School of Technology and Innovations, Finland

^b University of Vaasa, Vaasa, Finland

ARTICLE INFO

Keywords:

Multi-timescale flexibility
Battery energy storage systems (BESS)
District heating
Thermal energy storage
Hydropower
Nordic power system

ABSTRACT

The Nordic power system is undergoing a rapid transition toward high shares of variable renewable energy and widespread electrification of heating, transport, and industry. While extensive hydropower resources provide a strong foundation for system flexibility, declining synchronous inertia and pronounced winter demand peaks introduce new challenges for both operational stability and long-term adequacy. Consequently, ensuring reliable operation increasingly depends on the coordinated deployment of complementary flexibility resources across multiple temporal horizons rather than expansion of any single technology.

This paper presents a systematic review of literature published between 2019 and 2026 and develops a review-based multi-timescale classification that links grid service requirements with the operational capabilities of battery energy storage systems (BESS), district heating with thermal energy storage (TES), and hydropower reservoirs. The synthesis shows that BESS primarily supports fast frequency response and short-term congestion management, TES provides demand shifting and peak reduction over hourly-to-daily timescales, and hydropower delivers long-duration balancing and seasonal adequacy.

The review further identifies that current electricity market structures tend to prioritize short-duration stability services while undervaluing longer-duration flexibility, potentially creating a mismatch between investment incentives and evolving system requirements. By integrating evidence across multiple operational timescales, the proposed classification provides a unified framework for evaluating complementary flexibility resources and offers practical insights for system planning, market design, and the reliable operation of renewable-dominated low-carbon power systems.

1. Introduction

1.1. Energy transition context

The International Energy Agency (IEA) [1,2] reported that achieving climate targets requires rapid expansion of renewable generation, electrification, and improved energy system flexibility. The European Commission [3] highlighted the role of climate-neutral strategies in accelerating the transition toward low-carbon energy systems. From a power system perspective, ENTSO-E [4] identified increasing flexibility and grid reinforcement requirements caused by large-scale renewable integration. Akhtar et al. [5] further demonstrated that high renewable penetration introduces new reliability challenges requiring advanced operational and control strategies. The IEA [2] identified sector coupling and electrification as important pathways for deep decarbonization.

Ahmed et al. [6] showed that coupling electricity, heating, and transport sectors can enable highly renewable energy systems. In the Nordic context, Statnett [7], Fingrid [8], and Svenska kraftnät [9] reported that increasing renewable generation and electrified demand are changing operational requirements and future grid development needs. In this study, electrification of heating refers to the growing integration of electricity-based heating technologies, including high-efficiency heat pumps, electric boilers, and power-to-heat solutions within buildings and district heating networks. Although heat pumps can substantially reduce total energy consumption due to their high coefficient of performance (COP), large-scale adoption increases the interaction between heat demand and electricity system operation. Consequently, heating demand becomes more visible in electricity load profiles, particularly during cold periods when temperature-dependent peak demand may increase. These developments extend beyond electricity supply,

* Corresponding author.

E-mail addresses: tareq.shikdar@uwasa.fi (T.A. Shikdar), hannu.laaksonen@uwasa.fi (H. Laaksonen).

<https://doi.org/10.1016/j.ijepes.2026.112212>

Received 14 April 2026; Received in revised form 21 August 2026; Accepted 25 September 2026

Available online 5 October 2026

0142-0615/© 2026 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

reflecting a broader transition toward integrated and low-carbon energy systems. (See Table 1)

The Nordic electricity system—comprising Denmark, Finland, Norway, Sweden, and Iceland—represents one of the most advanced real-world implementations of this transition. It is characterized by high renewable penetration, strong cross-border market integration, and significant sector coupling between electricity and heating systems [3,10,11]. While these features enhance overall system efficiency and decarbonization potential, they also introduce new operational complexities.

Although the Nordic countries participate in a highly interconnected regional electricity market, their electricity generation portfolios, dominant flexibility resources, and operational challenges differ considerably. Norway relies primarily on reservoir hydropower for long-duration balancing, Denmark emphasizes wind integration through sector coupling and thermal flexibility, Finland combines nuclear generation, district heating, and growing battery deployment to address winter adequacy, Sweden benefits from extensive hydropower and district heating infrastructure, while Iceland has a renewable electricity system dominated by hydropower and geothermal resources [11]. Consequently, the proposed multi-timescale framework should be interpreted as a regional analytical framework whose implementation depends on country-specific resource availability, market structures, and operational characteristics.

As renewable penetration increases, the primary system challenge shifts from ensuring sufficient energy production to maintaining reliable operation under highly variable and uncertain supply–demand conditions [4,7,12]. Consequently, system performance is increasingly constrained by the availability, coordination, and effectiveness of flexibility resources rather than installed generation capacity alone.

1.2. Multi-timescale reliability challenge

In conventional power systems, reliability assessment has historically focused on generation adequacy and reserve margins. Heylen et al. [13] highlighted inertia estimation and frequency control challenges in low-inertia systems, while Plant et al. [14] investigated real-time inertia monitoring approaches for inverter-dominated networks. Chu et al. [15] reviewed international grid-code adaptations addressing frequency stability under high renewable penetration. In parallel, Marcos et al. [16] demonstrated the importance of cross-sector solutions for long-term decarbonization. This shift fundamentally alters the nature of system operation.

The progressive displacement of synchronous generation reduces rotational inertia, increasing the rate of change of frequency (RoCoF) following disturbances and amplifying short-term stability risks [17–20]. At the same time, increased electricity-based heating creates stronger coupling between weather conditions and electricity demand. While efficient heat pump technologies generally reduce overall energy

consumption compared with conventional heating solutions, widespread electrification through heat pumps, electric boilers, and power-to-heat systems can increase electricity-sector dependency and contribute to higher peak loads during extreme cold periods [6,21,22]. In parallel, prolonged low-wind events may introduce extended periods of renewable supply scarcity, increasing the need for coordinated flexibility resources. In addition, the geographical concentration of renewable generation in northern regions and demand centers in southern regions creates persistent congestion and ramping requirements across intra-day timescales [23,24].

These interacting factors transform reliability into a multi-timescale coordination problem, where distinct physical processes dominate at different operational horizons—from milliseconds to months [15,25]. Fig. 1 demonstrates how renewable generation variability, electricity demand patterns, and required flexibility responses interact across different operational timescales.

1.3. Flexibility resources in the Nordic system

The Nordic energy system contains a diverse portfolio of flexibility resources capable of operating across these temporal layers. Hydropower reservoirs provide fast ramping capability combined with large-scale seasonal energy storage, making them essential for both operational balancing and long-term adequacy [11,26,27]. Battery energy storage systems (BESS) offer rapid and highly controllable power injection, enabling frequency containment and short-term congestion mitigation [28–32]. Nordic district heating systems have progressively evolved from conventional fuel-based heat production toward diversified low-carbon heat sources, including biomass, municipal waste utilization, industrial excess heat recovery, and renewable heat integration. In this context, electrification does not represent a simple replacement of existing heating infrastructure but rather an additional sector-coupling pathway that increases operational flexibility. In parallel, district heating networks equipped with thermal energy storage (TES) enable demand-side flexibility by shifting electricity consumption over hourly to daily horizons, thereby reducing peak load and enhancing renewable utilization [33–37].

These resources contribute to system reliability through fundamentally different physical mechanisms, response speeds, and energy capacities. As a result, their value lies not in individual performance, but in their complementary and coordinated operation across timescales. Effective system operation therefore depends on integrating supply-side and demand-side flexibility within a unified operational framework.

1.4. Literature gap

Existing literature has extensively investigated individual flexibility technologies, including battery participation in ancillary service markets, hydropower-based balancing strategies, district heating with thermal energy storage, and broader sector-coupling approaches [30,34,38–40]. Other review studies have examined flexibility taxonomies, long-duration energy storage technologies, renewable integration, or low-inertia power system operation. However, these studies generally focus on individual technologies, specific flexibility services, or isolated operational timescales.

As a result, the complementary interactions among battery energy storage systems (BESS), district heating with thermal energy storage (TES), and hydropower reservoirs remain insufficiently examined within a unified system perspective. In particular, limited attention has been given to how these heterogeneous flexibility resources collectively support reliability across multiple temporal horizons, ranging from fast frequency stability to seasonal energy adequacy, under renewable-dominated Nordic operating conditions [15,41].

From a power system planning perspective, this limitation is significant. Reliable operation in decarbonized energy systems depends not only on the performance of individual flexibility technologies but also

Table 1
Comparison of flexibility characteristics across Nordic countries.

Country	Dominant generation	Principal flexibility resources	Key operational challenges	Source year/period
Denmark [10]	Wind, CHP, solar	District heating, TES	Wind variability	2015
Finland [8]	Nuclear, wind, CHP	District heating, BESS	Winter adequacy	2024
Norway [7]	Reservoir hydropower	Reservoir hydropower	Hydrological variability	2023
Sweden [9]	Hydropower, nuclear	Hydropower, district heating	Transmission congestion	2024–2033
Iceland [11]	Hydropower, geothermal	Hydropower, geothermal	Hydro-geothermal generation dependence	2025

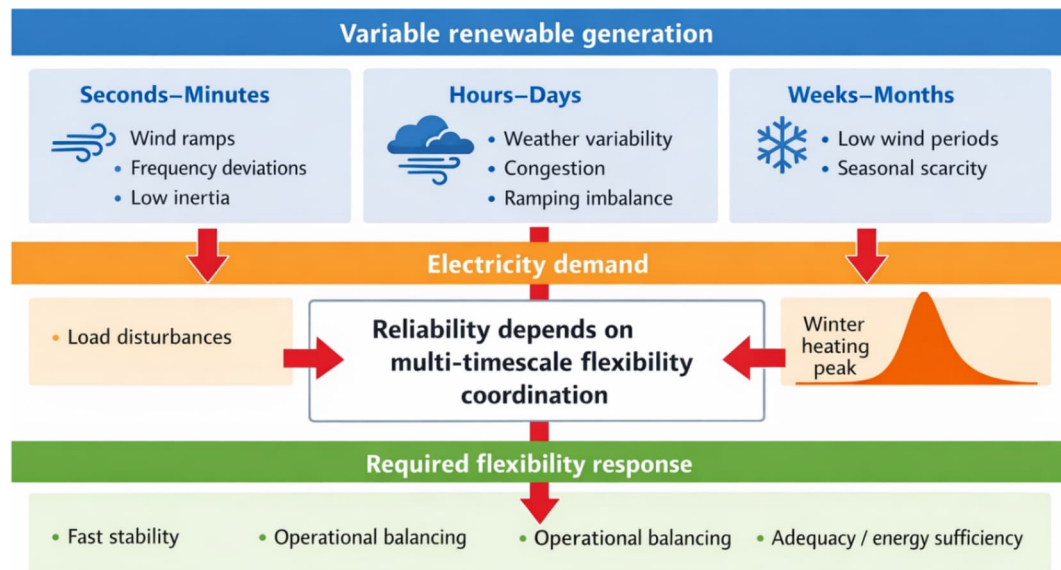


Fig. 1. Conceptual illustration of the multi-timescale mismatch.

on their coordinated deployment across temporal and sectoral dimensions. Existing reviews rarely integrate operational service requirements, resource capabilities, market mechanisms, and planning implications within a single analytical framework. Consequently, the absence of such an integrated perspective limits the ability to evaluate how complementary flexibility resources jointly contribute to system reliability and may lead to misalignment between investment signals and long-term system needs.

1.5. Contribution of this paper

To address the identified research gap, this paper investigates the following research question:

How do complementary flexibility resources operating across multiple timescales jointly ensure reliability in renewable-dominated Nordic energy systems?

A systematic review of literature published between 2019 and 2026 is conducted to develop a review-based multi-timescale classification framework that links operational service requirements with the technical capabilities of battery energy storage systems (BESS), district heating with thermal energy storage (TES), and hydropower reservoirs.

Unlike previous reviews that primarily examine individual flexibility technologies, flexibility taxonomies, sector-coupling strategies, or long-duration energy storage independently, this review provides an integrated Nordic-context synthesis that explicitly connects system service requirements, operational timescales, flexibility resource characteristics, market valuation, and planning implications within a unified analytical framework.

The principal contributions of this paper are summarized as follows:

- A systematic synthesis of recent literature (2019–2026) focusing on flexibility requirements in renewable-dominated Nordic power systems.
- A review-based multi-timescale classification framework that links operational services with the complementary technical capabilities of BESS, TES, and hydropower reservoirs, enabling consistent comparison across multiple operational horizons.
- An integrated assessment of how complementary flexibility resources collectively support frequency stability, operational balancing, demand shifting, and seasonal adequacy rather than evaluating each technology independently.

- Identification of structural mismatches between current market incentives and long-term flexibility requirements, together with their implications for future system planning, market design, and decarbonization strategies.

Although the analysis is developed for the Nordic power system, the proposed classification framework is applicable to other renewable-dominated and low-inertia power systems undergoing rapid electrification and increasing sector coupling.

The remainder of this paper is organized as follows. [Section 2](#) describes the review methodology and classification approach. [Section 3](#) presents the proposed multi-timescale classification framework. [Sections 4–6](#) examine the operational roles of batteries, district heating with thermal energy storage, and hydropower across different timescales. [Section 7](#) discusses integrated system implications, market design, and future research directions, while [Section 8](#) concludes the paper.

2. Review methodology

2.1. Scope and objective

This review investigates how complementary flexibility resources contribute to system reliability in the Nordic power system across multiple operational timescales. The analysis focuses on three representative flexibility providers operating at distinct temporal horizons: battery energy storage systems (BESS), district heating networks with thermal energy storage (TES), and hydropower reservoirs.

Rather than evaluating these technologies independently, the objective is to compare their functional roles within a unified system perspective, including contributions to frequency stability, operational balancing, peak demand reduction, and seasonal adequacy. This approach enables assessment of how heterogeneous flexibility resources interact to support reliable operation in renewable-dominated energy systems.

To reflect contemporary system conditions and market practices, the review focuses on literature published between 2019 and 2026. Earlier foundational studies are included selectively to clarify key concepts and physical mechanisms where necessary.

2.2. Literature search strategy

A structured literature search was conducted following a PRISMA-

inspired approach to ensure transparency and reproducibility. The search was performed using four scientific databases: IEEE Xplore, Scopus, ScienceDirect, and SpringerLink. The literature search covered publications from 2019 to 2026, while earlier foundational references were included only when necessary for established concepts.

The following keyword combinations were used:

Power system flexibility and reliability

- “power system flexibility” AND “renewable integration”
- “low inertia power system” AND “frequency stability”
- “renewable energy” AND “system adequacy”

Battery energy storage

- “battery energy storage system” AND “frequency containment reserve”
- “BESS” AND “ancillary services”
- “energy storage” AND “grid flexibility”

District heating and thermal storage

- “district heating” AND “thermal energy storage”
- “power-to-heat” AND “sector coupling”
- “thermal flexibility” AND “renewable integration”

Hydropower and seasonal flexibility

- “hydropower flexibility” AND “renewable balancing”
- “hydropower reservoir” AND “seasonal storage”

Nordic energy system

- “Nordic power system”
- “Nordic electricity market”
- “winter adequacy”

In addition to peer-reviewed publications, technical reports from TSOs, international organizations, and regulatory bodies were included when they provided validated operational information.

2.3. Screening and selection procedure

The literature selection followed a structured filtering process inspired by PRISMA-type systematic review methodologies [42,43]. As illustrated in Fig. 2, the workflow consisted of four main stages: identification, screening, eligibility assessment, and final inclusion.

During the identification stage, records obtained from IEEE Xplore, Scopus, ScienceDirect, and SpringerLink were combined, resulting in 412 initial publications. Duplicate records appearing across multiple databases were removed before further assessment.

The remaining publications underwent title and abstract screening. At this stage, studies were evaluated based on their relevance to:

- renewable-rich power system operation,
- flexibility services and resources,
- Nordic or comparable high-renewable energy systems, and
- reliability challenges across different operational timescales.

Publications outside the scope of power system flexibility or without relevance to system-level operation were excluded.

The full-text assessment stage evaluated the remaining studies according to predefined technical criteria. Specifically, each publication was assessed based on whether it provided:

1. quantitative modeling, simulation, or operational analysis;
2. validated experimental, market, or system-level data;
3. clear contribution to at least one flexibility timescale:
 - o fast stability (milliseconds–minutes),
 - o operational balancing (minutes–hours),
 - o mid-duration flexibility (hours–days),
 - o seasonal adequacy (weeks–months);
4. relevance to battery storage, district heating with thermal storage, hydropower, or integrated flexibility planning.

Studies containing only general discussions without technical evaluation or system-level relevance were excluded.

The final set of 94 studies was selected based on technical relevance, methodological transparency, and contribution to multi-timescale flexibility analysis rather than publication year or journal ranking alone. Peer-reviewed journal articles and conference papers were prioritized, while validated reports from transmission system operators,

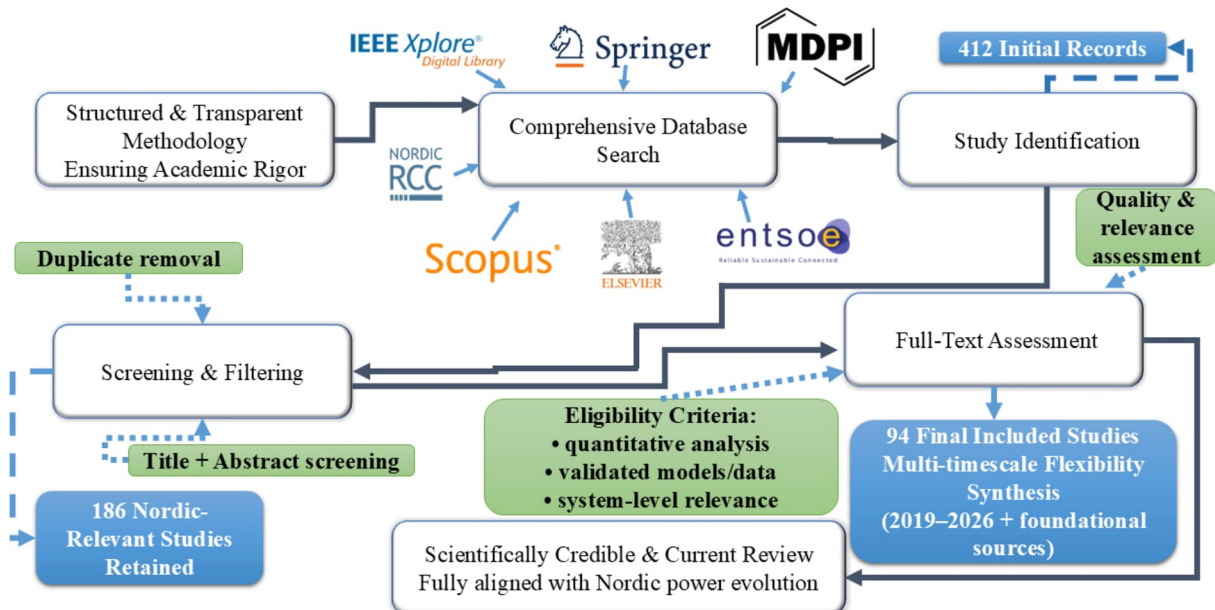


Fig. 2. Review methodology flowchart.

international energy organizations, and regulatory bodies were included when they provided operational data or system-level insights.

Fig. 2 highlights the progressive filtering procedure used during the literature screening process, including identification, screening, eligibility assessment, and final study selection.

The figure highlights the progressive filtering of studies, ensuring that only technically relevant and high-quality publications are included in the final synthesis. Table 2 shows the progressive reduction of studies through each filtering step, ensuring that only technically relevant and quantitatively supported publications were retained for the final synthesis.

The final systematic-review evidence base comprised 94 included studies. These studies were selected based not solely on publication year or journal ranking, but on scientific relevance, methodological transparency, technical contribution, and applicability to multi-timescale flexibility analysis. The complete manuscript contains 96 references, as two additional references were used exclusively to support the review methodology and background context and were therefore not included in the screened and coded evidence base. Peer-reviewed journal articles and conference papers were prioritized in the systematic review, while validated reports from organizations such as the IEA, ENTSO-E, and Nordic transmission system operators (TSOs) were included when they provided relevant operational data or system-level information. Following the screening process, the 94 included studies were further coded according to their primary research focus to support the comparative synthesis presented in this review. The coding considered six major thematic areas: (i) battery energy storage systems (BESS), (ii) district heating and thermal energy storage (TES), (iii) hydropower flexibility, (iv) market design and ancillary services, (v) power system reliability and adequacy, and (vi) system modelling and planning. Because several studies addressed more than one aspect of flexibility, these thematic categories were used to structure and guide the synthesis rather than as mutually exclusive classifications. This coding approach enabled a systematic comparison of complementary flexibility resources across multiple operational timescales while maintaining a consistent analytical perspective throughout the review.

2.4. Inclusion and Exclusion criteria

Studies were selected based on predefined relevance and quality criteria. A publication was included if it:

- addressed power system operation, stability, adequacy, or flexibility services,
- focused on the Nordic power system or comparable high-renewable, cold-climate systems, and
- provided quantitative modeling, empirical data, or validated system-level analysis.

Studies were excluded if they:

- focused solely on component-level hardware design without system-level implications,

Table 2
Literature screening summary.

Stage	Description	Number of records
Initial search	Database search results	412
After duplicate removal	Unique publications retained	327
Title & abstract screening	Scope and relevance assessment	186
Full-text assessment	Quantitative/system-level evaluation	112
Final included studies	Multi-timescale flexibility synthesis	94

- presented purely conceptual or policy-oriented discussions without technical validation, or
- duplicated findings already comprehensively covered in recent literature.

To ensure reliability and scientific rigor, only peer-reviewed journal articles and validated system reports were included in the final synthesis. The selection was not restricted exclusively to journal ranking metrics because important operational knowledge in power systems is often published through TSO reports, international energy agency assessments, and market documentation. Therefore, quality was evaluated based on technical reliability and relevance rather than publication category alone.

2.5. Classification framework

Following the literature screening and selection process, the included studies were categorized according to the operational timescale of the flexibility service rather than by technology type. Recent review studies have proposed classification frameworks based on energy storage technologies, planning methodologies, or application domains. Building upon these approaches, the present review adopts a functional, service-oriented classification that organizes flexibility resources according to the temporal requirements of power system operation. This perspective enables heterogeneous flexibility resources to be evaluated within a common reliability assessment framework and facilitates direct comparison of their complementary contributions across multiple operational timescales [44].

Table 3 categorizes flexibility services according to the required response speed and duration of system support. Fast stability corresponds to immediate frequency containment and synthetic inertia provision following disturbances. Operational balancing represents short-term corrective actions, including congestion relief and ramp management during intra-day operation. Mid-duration flexibility enables load shifting across daily cycles to manage demand peaks, while seasonal adequacy addresses long-term energy sufficiency, particularly winter security of supply in cold-climate power systems.

Unlike technology-oriented classifications, the proposed framework enables direct comparison of battery energy storage systems (BESS), district heating with thermal energy storage (TES), and hydropower according to the operational services they provide rather than their underlying technologies. This functional perspective forms the basis for the comparative synthesis presented in the following sections and supports the evaluation of complementary flexibility resources within a unified multi-timescale reliability framework.

2.6. Comparative synthesis approach

Rather than presenting studies sequentially, this review adopts a comparative synthesis approach to evaluate the complementary roles of flexibility resources. Evidence from the selected studies was synthesized using a thematic comparative approach rather than a sequential narrative description. Publications were organized according to their primary technical focus, including battery energy storage systems (BESS), district heating with thermal energy storage (TES), hydropower flexibility,

Table 3
Timescale classification used in this review.

Timescale	Typical duration	Primary system needs
Fast stability	milliseconds–minutes	frequency containment and inertia support
Operational balancing	minutes–hours	congestion management and ramping support
Mid-duration flexibility	hours–days	peak load shifting
Seasonal adequacy	weeks–months	winter supply security

market design, power system reliability and adequacy, and system planning. These thematic groups provided a consistent basis for comparing heterogeneous flexibility resources across multiple operational timescales.

The comparative synthesis was conducted using common evaluation criteria:

- response speed and controllability,
- duration capability,
- type of operational service provided, and
- contribution to system reliability.

This structured comparison enables identification of complementarities and limitations across technologies by examining how different flexibility resources contribute to specific operational timescales. The comparative synthesis provides the basis for the timescale-based classification presented in Section 3 and supports evaluation of the distinct roles of batteries, district heating with thermal energy storage, and hydropower in renewable-dominated Nordic energy systems.

3. Multi-timescale classification of flexibility resources

3.1. Reliability as a temporal coordination problem

In low-carbon power systems, reliability must be maintained under disturbances that evolve across multiple temporal horizons. Shair et al. [45] classified stability challenges associated with renewable-rich power systems and emphasized frequency-related issues. Huclin et al. [46] proposed methods for evaluating flexibility and capacity value in renewable-dominated systems. Ringkjøb et al. [47] showed the

importance of representing short-term renewable variability, while Caglayan et al. [48] investigated long-duration storage requirements for highly renewable energy systems. In renewable-dominated systems, these functions are no longer provided by a single technology but instead emerge from the coordinated operation of heterogeneous flexibility resources.

In the Nordic power system, declining synchronous inertia increases the rate of change of frequency (RoCoF), requiring rapid active power response to maintain system stability [49]. At longer timescales, variability in wind generation and the geographical concentration of renewable resources introduce congestion and ramping challenges [50]. In addition, electrification of heating and hydrological uncertainty amplify seasonal adequacy risks, particularly during winter periods characterized by high demand and limited renewable availability [51,52].

These interacting dynamics fundamentally redefine reliability as a temporal coordination problem, where system security depends on the alignment of flexibility resources with time-dependent operational requirements. Consequently, reliability cannot be adequately assessed using static capacity metrics alone but must be evaluated in terms of coordinated multi-timescale system response.

3.2. The classification consists of four operational layers

Power system operational requirements can be categorized into four characteristic timescales based on the underlying physical processes and corresponding operator actions. Fig. 3 presents the multi-timescale classification developed from the reviewed literature, where flexibility requirements are organized according to response duration, dominant system challenge, and suitable flexibility resource.

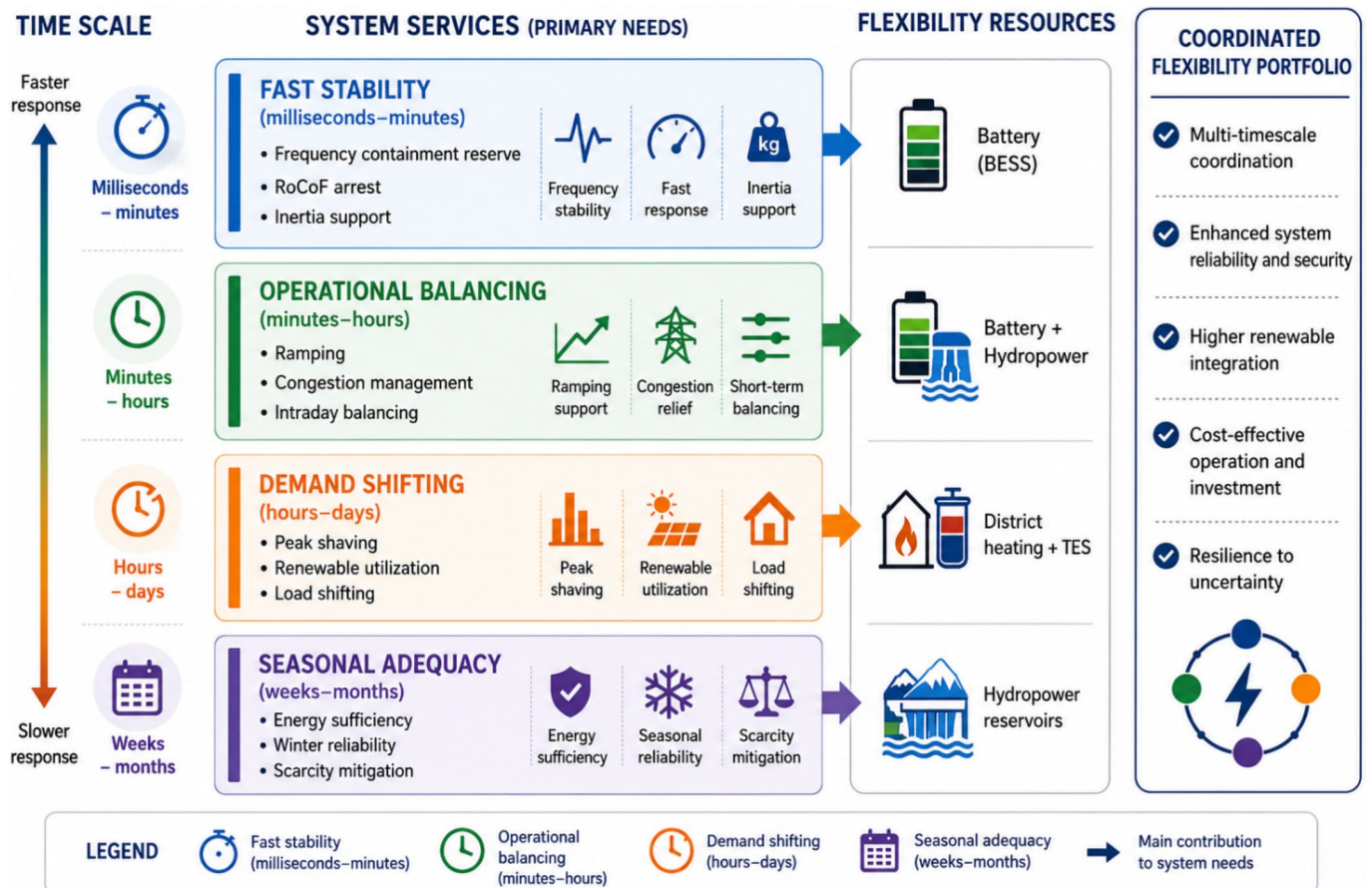


Fig. 3. Multi-Timescale Flexibility Framework.

The framework consists of four operational layers:

- Fast stability (milliseconds–minutes): containment of frequency deviations immediately following disturbances
- Operational balancing (minutes–hours): management of ramping requirements and congestion under variable generation
- Mid-duration flexibility (hours–days): demand shifting and improved utilization of renewable energy
- Seasonal adequacy (weeks–months): long-term energy sufficiency and security of supply

Each layer corresponds to a distinct operational objective and is governed by different physical drivers, necessitating flexibility resources with varying response speeds and energy capacities.

Fig. 3 demonstrates how system reliability requirements are distributed across temporal layers and how different flexibility resources are mapped according to their response speed and energy duration capability. Table 3 complements Fig. 3 by linking each operational timescale to its dominant physical cause and the corresponding operator action. Fast stability is driven by inertial response and sudden disturbances, requiring immediate frequency control. Operational balancing mainly arises from renewable variability such as wind ramps and requires generation–load matching. Mid-duration flexibility addresses daily demand variations to limit peak loading, while seasonal adequacy relates to long-term energy availability, ensuring sufficient supply during prolonged high-demand periods, particularly in winter conditions. Table 4 links each operational timescale to its dominant physical driver and corresponding system objective.

The table highlights that system requirements are fundamentally time-dependent, with distinct physical drivers governing each operational horizon.

3.3. Mapping flexibility resources to timescales

Nzimande and Noro [53] demonstrated the capability of BESS to support frequency regulation under high renewable penetration. Gartan et al. [54] reviewed battery participation in frequency-control ancillary services. Muzammal Islam et al. [55] showed that energy storage technologies improve flexibility and stability in modern power systems. Hydropower combines relatively fast ramping capability with large stored energy, enabling both operational balancing and long-duration supply support [46,51]. Sorknæs et al. [56] demonstrated the system benefits of fourth-generation district heating integration. Sornek et al. [57] analyzed power-to-heat and seasonal TES pathways, while Sifnaios et al. [58] quantified the impact of large-scale TES on energy system operation.

No single resource can simultaneously satisfy all system requirements across timescales. Instead, system reliability emerges from the complementary interaction of resources, each contributing within its effective temporal domain. Table 5 compares the capability of key flexibility resources across operational timescales.

The response times and effective flexibility durations reported in Table 5 represent typical or representative operating ranges synthesized from the reviewed literature rather than universal technical limits. Actual response characteristics and usable flexibility durations depend on technology configuration, installed power and energy capacity, control strategy, operating conditions, and system-specific constraints.

Table 4
Mapping operational needs to system dynamics.

Timescale	Physical driver	Operator objective
Fast stability	inertia and disturbances	maintain frequency
Operational balancing	wind ramps	balance generation
Mid-duration	demand variation	reduce peaks
Seasonal adequacy	energy availability	ensure adequacy

For hydropower, the available flexibility is additionally influenced by turbine and governor characteristics, reservoir conditions, hydrological availability, and environmental operating constraints. For district heating and thermal energy storage, the achievable flexibility duration depends strongly on the storage technology and thermal infrastructure; conventional hot-water storage primarily supports hourly-to-daily shifting, whereas larger-scale PTES and BTES can extend flexibility to weekly or seasonal horizons. The listed grid services represent typical applications identified in the literature. Where specific reserve products such as FCR-N, FCR-D, aFRR, and mFRR are mentioned, their actual technical requirements and activation characteristics are defined by the relevant system operator and should not be interpreted as universal technology limits.

3.4. Implications for system planning

The timescale-based classification shows that reliability in high-renewable power systems depends on flexibility provision across multiple operational horizons rather than generation expansion alone. Fast-response resources support frequency stability, mid-duration flexibility reshapes demand patterns, and long-duration storage contributes to seasonal adequacy.

This perspective has important implications for system planning and market design. Traditional planning approaches based on installed capacity or energy volume are insufficient to capture the temporal dimension of system needs. Instead, resources must be evaluated based on their time-dependent contribution to system operation, including response speed, duration, and service type [48,55].

Consequently, effective planning requires ensuring adequate coverage across all operational timescales, rather than overinvesting in a single category of flexibility. This classification supports comparative evaluation of flexibility resources and forms the basis for the analysis in the following sections.

4. Fast stability and short-term operation

4.1. Frequency dynamics in low-inertia systems

In low-carbon power systems, frequency stability is increasingly governed by inverter-based resources and fast-acting control mechanisms rather than synchronous machine inertia. Moore et al. [72] reviewed inertia and system-strength challenges in renewable-dominated grids. Cao et al. [73] proposed virtual inertia control approaches for inverter-based systems, while Song et al. [74] analyzed low-inertia challenges caused by high renewable penetration. This transition significantly alters system dynamics and increases sensitivity to disturbances. Recent studies have extended conventional unit commitment and scheduling formulations by explicitly incorporating frequency-security constraints, including RoCoF, frequency nadir, inertia requirements, and fast frequency response. These approaches enable operational decisions to account for the reduced synchronous inertia associated with renewable integration while coordinating conventional generators, renewable resources, and energy storage. Such developments demonstrate that frequency security is increasingly becoming an integral component of operational scheduling rather than a separate post-operational stability assessment. These modelling advances further support the importance of fast-response flexibility resources identified in the proposed multi-timescale framework [75].

In the Nordic power system, declining synchronous inertia is identified as a critical operational challenge, particularly under conditions of high wind generation and cross-border power imports [49,76]. Reduced inertia limits the system's ability to naturally damp frequency deviations, thereby increasing reliance on active control.

Hydropower units contribute to frequency containment through governor response and primary reserves; however, their activation speed is inherently constrained by mechanical and hydraulic dynamics

Table 5

Resource capability across timescales.

Resource	Typical response time	Effective flexibility duration	Primary operational role	Representative grid services	Interpretation	Representative sources
Battery Energy Storage Systems (BESS)	Milliseconds–seconds	Minutes to 4 h	Fast frequency support and short-term balancing	FCR-N, FCR-D, aFRR, congestion management	Typical operating range; application and system dependent	[28,53–55,59–62]
Hydropower reservoirs	Seconds–minutes	Hours to months	Operational balancing and seasonal adequacy	Primary/FCR support, secondary reserve, mFRR, seasonal energy balancing	Representative range; plant, reservoir, and hydrological-condition dependent	[46,51,63–66]
District heating + Thermal Energy Storage (TES)	Minutes–hours	Hours to days; weeks–months for PTES/BTES	Demand shifting and peak-load reduction	Demand response, power-to-heat, peak shaving, renewable energy integration	Technology-dependent representative range; depends on TES configuration and heating-network operation	[56–58,67–71]

[46,63]. As a result, maintaining frequency stability in high-renewable operation requires additional fast-response resources capable of delivering immediate and precise active power support [73,75].

4.2. Battery energy storage for fast frequency control

Nzimande and Noro [53] demonstrated BESS frequency regulation capability. Zhang et al. [59] investigated optimal battery sizing for stacked grid services, while Li et al. [60] studied real-time BESS frequency regulation considering revenue and degradation effects. Operational experience in Nordic reserve markets shows that short-duration batteries are predominantly deployed for frequency containment reserve (FCR) services rather than energy arbitrage [54,61].

The high ramp rate of BESS significantly improves frequency nadir and limits RoCoF following disturbances [60,72]. Because response accuracy is more critical than energy volume in fast stability services, economically optimal battery configurations prioritize power capacity over stored energy [54,62]. Table 6 summarizes representative fast-stability characteristics of BESS and hydropower identified in the reviewed literature. The reported response times and support durations should be interpreted as typical operating ranges rather than universal technical limits. BESS can provide converter-controlled active-power response on millisecond-to-second timescales, making it particularly suitable for fast frequency response and frequency containment applications. Hydropower can also provide rapid frequency support, although its initial response is comparatively slower and depends on governor settings, turbine characteristics, waterway dynamics, and operating conditions. Similarly, the effective duration of support depends on available stored energy, state of charge, reservoir conditions, and the required service. The listed reserve products represent typical applications; specific activation times, minimum durations, and qualification requirements are determined by the applicable TSO and market rules.

Table 6

Comparison of BESS and hydropower for fast stability services.

Characteristic	BESS	Hydropower governor	Interpretation / basis	Representative sources
Typical response time	Milliseconds to < 1 s	Seconds; typically 2–30 s	Representative response range; depends on converter/control settings for BESS and governor, turbine, and hydraulic dynamics for hydropower	[53,54,60,63,72,73,76]
Ramp/response capability	Very high; near-instantaneous active-power adjustment	High, but constrained by hydraulic and mechanical dynamics	Qualitative technical characteristic rather than a fixed ramp-rate limit	[46,60,63,72,73]
Effective support duration	Minutes to approximately 4 h	Hours to days, reservoir dependent	Typical application range rather than a universal technical limit	[54,55,62,63]
Primary grid services	FCR-N, FCR-D, FFR, aFRR	Primary/FCR support, secondary reserve, mFRR	Representative services; eligibility and activation requirements depend on the applicable market and TSO rules	[40,54,61,63,76]
Main operational limitation	Limited stored energy, state-of-charge constraints, and battery degradation	Slower initial response; hydraulic, environmental, and reservoir operating constraints	Principal limitations identified across the reviewed literature	[54,60,62,63,66]

4.3. Complementary role of hydropower

Hydropower remains essential beyond the initial seconds following a disturbance by sustaining active power injection after fast-response resources stabilize the system [46,63]. Its ability to provide continuous output makes it a key contributor to primary reserve support and frequency recovery. Recent developments in pumped-storage technologies further improve flexibility by enabling more responsive regulation and wider operating ranges compared with conventional fixed-speed configurations.

Coordinated operation of BESS and hydropower enhances overall system performance. Batteries rapidly arrest the initial frequency drop, improving frequency nadir, while hydropower maintains longer-duration support to stabilize and restore system balance [72,76]. In this context, BESS does not replace hydropower but rather extends its operational effectiveness by addressing the critical early-stage response. Fig. 4 presents conceptual frequency responses with layered flexibility.

Fig. 4 highlights the sequential contribution of fast-response battery systems and hydropower governors in maintaining frequency stability following disturbances.

4.4. Operational implications

The analysis demonstrates that fast stability is primarily determined by response speed and controllability rather than energy capacity. BESS provides immediate stabilization through rapid power injection, while hydropower ensures sustained balancing and system recovery.

This division of roles reinforces the timescale-based classification presented in Section 3, where fast-response and energy-based resources operate in a coordinated manner across temporal layers. Reliable operation in low-inertia systems therefore depends on the sequential and complementary activation of flexibility resources, rather than reliance on any single technology [73,76].

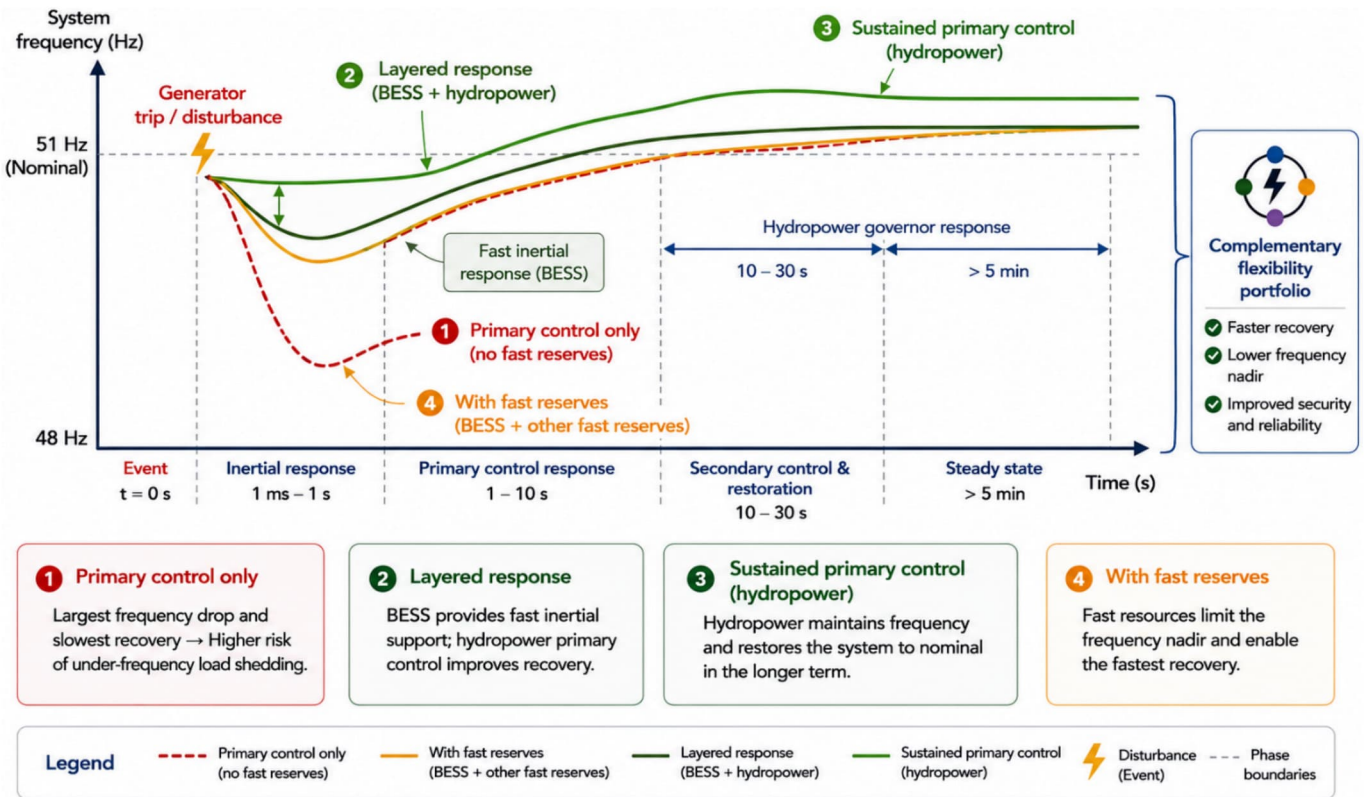


Fig. 4. Conceptual frequency response with layered flexibility.

These findings highlight the importance of integrating fast stability mechanisms with broader flexibility strategies, motivating the analysis of slower operational and mid-duration flexibility in the following section.

5. Operational and mid-duration flexibility

5.1. Ramping and congestion in renewable-dominated operation

Increasing wind penetration introduces significant short-term variability and spatial imbalance between generation and demand, creating challenges for intra-day balancing and congestion management. In the Nordic system, large-scale wind generation is predominantly located in northern regions, whereas major demand centers are concentrated in southern areas. Attar et al. [77] investigated congestion-management market design for Nordic and European systems. Naeem et al. [78] analyzed Nordic electricity market volatility, while Dobos et al. [79] discussed challenges related to electricity price-zone formation. Koivunen and Syri [80] evaluated scarcity situations in Finland's future low-carbon electricity system.

These dynamics shift the focus of operational flexibility from sub-second response toward energy shifting over hourly timescales, where the objective is to manage variability and maintain supply-demand balance. While conventional balancing resources address part of this variability, electrification of heating introduces additional complexity by creating temperature-dependent demand peaks, particularly during winter periods [21,81].

As a result, operational reliability increasingly depends not only on supply-side flexibility but also on controllable demand-side resources capable of shifting consumption in time. This transition reflects the growing importance of sector coupling in renewable-dominated energy systems.

5.2. District heating and thermal energy storage

District heating systems equipped with thermal energy storage (TES) provide a scalable form of demand-side flexibility by enabling temporal decoupling between electricity consumption and heat demand [56,67–69]. In this review, TES primarily refers to sensible heat storage using water-based systems, particularly hot water storage tanks, which represent one of the most mature and widely implemented storage solutions in district heating applications.

Through large-scale heat pumps and electric boilers, electricity can be converted into thermal energy during periods of high renewable generation or low electricity prices and stored for later use during periods of high heat demand or electricity system stress [70]. However, thermal flexibility in district heating is not limited only to dedicated water storage tanks. Short-duration flexibility can also be obtained by utilizing the inherent thermal inertia of district heating networks, including temporary heat storage within pipelines and connected building mass. These approaches enable short-term load shifting without necessarily requiring additional large-scale storage infrastructure.

Due to the significantly lower cost per unit of stored energy compared with electrochemical storage, water-based TES solutions are particularly suitable for multi-hour to multi-day balancing applications [67]. In addition, longer-duration thermal storage technologies, such as pit thermal energy storage (PTES) and borehole thermal energy storage (BTES), can provide weekly to seasonal storage capability and support stronger integration between renewable electricity generation and heating systems. However, these seasonal storage approaches remain more location-dependent and less widely deployed compared with conventional hot water tank storage.

Operational studies demonstrate that coordinated use of district heating and different TES technologies can reduce peak electricity demand, mitigate renewable curtailment, and improve overall energy system efficiency [68,71].

Unlike battery storage, the primary value of TES lies in temporal demand reshaping rather than direct electrical power injection. By shifting electricity consumption and heat production across time, TES effectively flattens demand profiles and reduces system stress during peak periods. Fig. 5 demonstrates how thermal energy storage reshapes electricity demand by shifting consumption from peak periods toward periods with higher renewable availability.

The figure demonstrates how thermal storage reshapes demand by shifting electricity consumption from peak to off-peak periods, thereby reducing system stress. Table 7 compares representative characteristics of BESS and district heating with thermal energy storage (TES) for operational and mid-duration flexibility. The reported flexibility durations and storage-capacity ranges represent typical application ranges synthesized from the reviewed literature rather than fixed technical limits. BESS generally provides directly controllable electrical flexibility over short-duration timescales, although its usable duration depends on the installed power-to-energy ratio, state of charge, operating strategy, and application. District heating with TES provides flexibility by decoupling heat production from heat demand and shifting electricity consumption through power-to-heat technologies. The achievable duration and storage capacity vary substantially with TES configuration: hot-water tanks predominantly support hourly-to-daily flexibility, whereas large-scale pit thermal energy storage (PTES) and borehole thermal energy storage (BTES) can extend energy shifting to weekly or seasonal timescales. The reported MWh_{th}-to-GWh_{th} range therefore represents an indicative order of magnitude for thermal storage applications rather than a universal capacity range. The listed services represent typical system applications identified in the reviewed literature and depend on local electricity-market arrangements, district-heating infrastructure, and operating conditions.

The results emphasize the distinct roles of supply-side and demand-side flexibility in operational balancing.

5.3. Interaction with electricity markets

Thermal flexibility interacts with electricity markets primarily through indirect mechanisms. By shifting demand toward periods of high renewable generation and lower prices, district heating systems reduce balancing requirements, alleviate congestion, and contribute to price stabilization [70,82].

In contrast, battery storage participates directly in ancillary service markets, receiving explicit compensation for providing frequency containment and fast-response services. This difference creates a structural asymmetry in market incentives: fast-response flexibility is clearly monetized, while demand-side flexibility is often undervalued despite its system-wide benefits.

Such misalignment may lead to suboptimal investment decisions, with a tendency to favor short-duration resources over longer-duration flexibility that is critical for system efficiency and peak reduction. Addressing this imbalance requires market designs that explicitly value both response speed and energy-shifting capability across timescales.

5.4. Operational implications

The analysis highlights a clear division of operational roles across timescales. Batteries stabilize fast system dynamics through rapid and precise control, while thermal storage reshapes demand profiles over longer horizons to mitigate peaks and improve renewable integration.

Reliable operation in renewable-dominated systems therefore depends on the coordinated interaction between supply-side and demand-

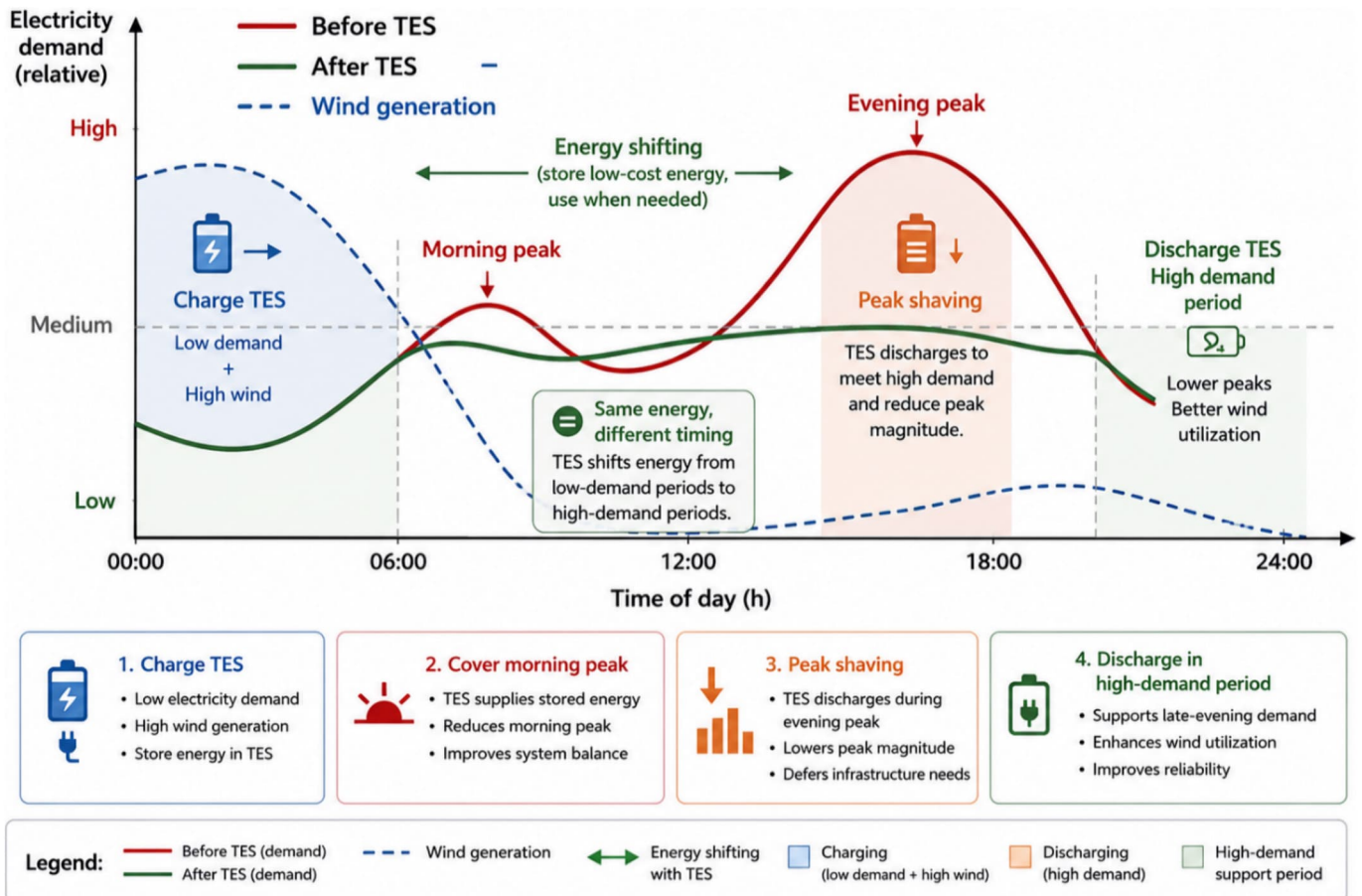


Fig. 5. Conceptual daily load shifting via TES.

Table 7

Comparison of BESS and district heating with thermal energy storage for mid-duration flexibility.

Characteristic	BESS	District Heating + TES	Interpretation / basis	Representative sources
Typical flexibility duration	Minutes to approximately 4 h	Hours–days for hot-water tanks; weeks–months for large-scale PTES/BTES	Representative application ranges rather than universal technical limits; duration depends on storage sizing and technology	[28,54–58,67–71]
Operating principle	Electrochemical charging and discharging	Thermal energy storage and temporal shifting of heat production/electricity consumption	Fundamental operating principle	[28,56,67,70]
Storage medium	Primarily lithium-ion and other electrochemical storage technologies	Hot-water tanks, district-heating network/building thermal mass, PTES and BTES	Technology-dependent storage media	[28,56–58,67–69]
Typical storage capacity	Application-dependent; typically MWh-scale for grid-connected short-duration applications	MWh _{th} to GWh _{th} scale, depending on TES technology and system size	Representative order-of-magnitude range; not a fixed technical limit	[28,56–58,67–71]
Primary grid/system services	Intraday balancing, congestion management, and reserve support	Peak shaving, load shifting, power-to-heat operation, and renewable energy integration	Representative applications identified in the reviewed literature	[28,54,56,67,70,71,82]
Main operational limitation	Limited discharge duration, state-of-charge constraints, and battery degradation	Dependence on district-heating infrastructure, thermal demand, storage configuration, and comparatively slower response	Principal technology and system-level constraints	[28,56,67–71]

side flexibility, rather than technological substitution. This layered behavior is consistent with the timescale-based classification presented in Section 3 and emphasizes the importance of integrating different forms of flexibility within a unified system perspective.

These dynamics naturally extend to the longest operational horizon, seasonal adequacy, which is examined in the following section.

6. Seasonal adequacy and long-term balancing

6.1. Winter adequacy in high-renewable systems

In high-latitude power systems, reliability challenges extend beyond short-term balancing toward seasonal energy sufficiency, particularly under extreme winter conditions. The European Commission [83] and Fingrid [84] emphasized the importance of winter adequacy and reliable electricity supply under changing energy conditions. Streimikiene et al. [85] analyzed the relationship between diversification and energy security, while Javed et al. [86] demonstrated the impact of multi-year renewable variability on system design. Under these conditions, system reliability is primarily determined by the availability of stored energy rather than response speed.

Unlike fast stability disturbances, which evolve within seconds, adequacy challenges develop over days to weeks and require sustained energy delivery [48]. This distinction highlights a fundamental difference between operational stability and adequacy: stability concerns instantaneous power balance, whereas adequacy relates to the cumulative balance of energy over extended periods [45,83].

As renewable penetration increases, this temporal shift in system requirements makes seasonal adequacy a critical constraint in low-carbon energy systems, particularly in regions with strong climatic variability.

6.2. Hydropower as seasonal storage

Hydropower reservoirs constitute the primary source of long-duration energy storage in the Nordic region. Kim et al. [64] investigated climate impacts on hydropower availability, while Wang et al. [65] quantified the value of hydropower flexibility for electricity-system decarbonization. Fäth et al. [22] further showed hydropower's capability to maintain output during energy drought conditions. In addition, hydropower provides operational flexibility through ramping and reserve services, making it a multi-functional resource across timescales.

Although conventional reservoir hydropower dominates flexibility provision in the Nordic region, recent developments in pumped-storage hydropower (PSH) technologies further expand the operational

flexibility available to renewable-dominated power systems. Unlike conventional reservoir hydropower, advanced PSH configurations—including variable-speed and ternary pumped-storage systems—provide improved operational flexibility through faster power regulation, wider operating ranges, and enhanced frequency–response capability. Recent studies have shown that these technologies can simultaneously improve frequency regulation performance and operational stability while facilitating greater integration of variable renewable energy sources. Although large-scale pumped-storage deployment remains relatively limited within the Nordic electricity system compared with conventional reservoir hydropower, these developments illustrate the broader potential of hydropower technologies to support future low-inertia power systems.

The magnitude of energy stored in hydropower reservoirs exceeds the feasible capacity of short-duration electrochemical storage by several orders of magnitude, making hydropower indispensable for ensuring seasonal adequacy [48]. In practice, the operational flexibility of hydropower reservoirs is influenced by several technical and regulatory constraints. Reservoir operation depends on seasonal inflow variability and water availability, which may be significantly affected by climate conditions and prolonged drought periods. Environmental flow requirements and reservoir operating rules further restrict the timing and magnitude of water releases to maintain downstream ecosystems and water-resource management objectives. In addition, hydropower dispatch in the Nordic electricity market is increasingly influenced by cross-border electricity trading and market coupling, which may alter reservoir utilization strategies beyond purely technical considerations. During winter periods, high electricity demand and limited hydrological replenishment may further reduce operational flexibility. Moreover, frequent regulation associated with increasing renewable variability may introduce additional mechanical stress and operational constraints for hydropower units. Consequently, although hydropower remains the principal source of long-duration flexibility in the Nordic region, its contribution to seasonal adequacy should be interpreted within these practical operational limitations rather than as an unconstrained source of flexibility [66].

As a result, hydropower alone cannot guarantee reliability under all scenarios. Instead, it must be complemented by additional flexibility resources capable of reducing demand peaks and supporting system operation under uncertainty. Fig. 6 illustrates the role of long-duration flexibility resources in addressing seasonal supply–demand mismatch in renewable-rich energy systems. During spring and summer periods, increased renewable generation availability and hydrological inflows may exceed immediate electricity demand, allowing energy to be stored through resources such as hydropower reservoirs and seasonal thermal

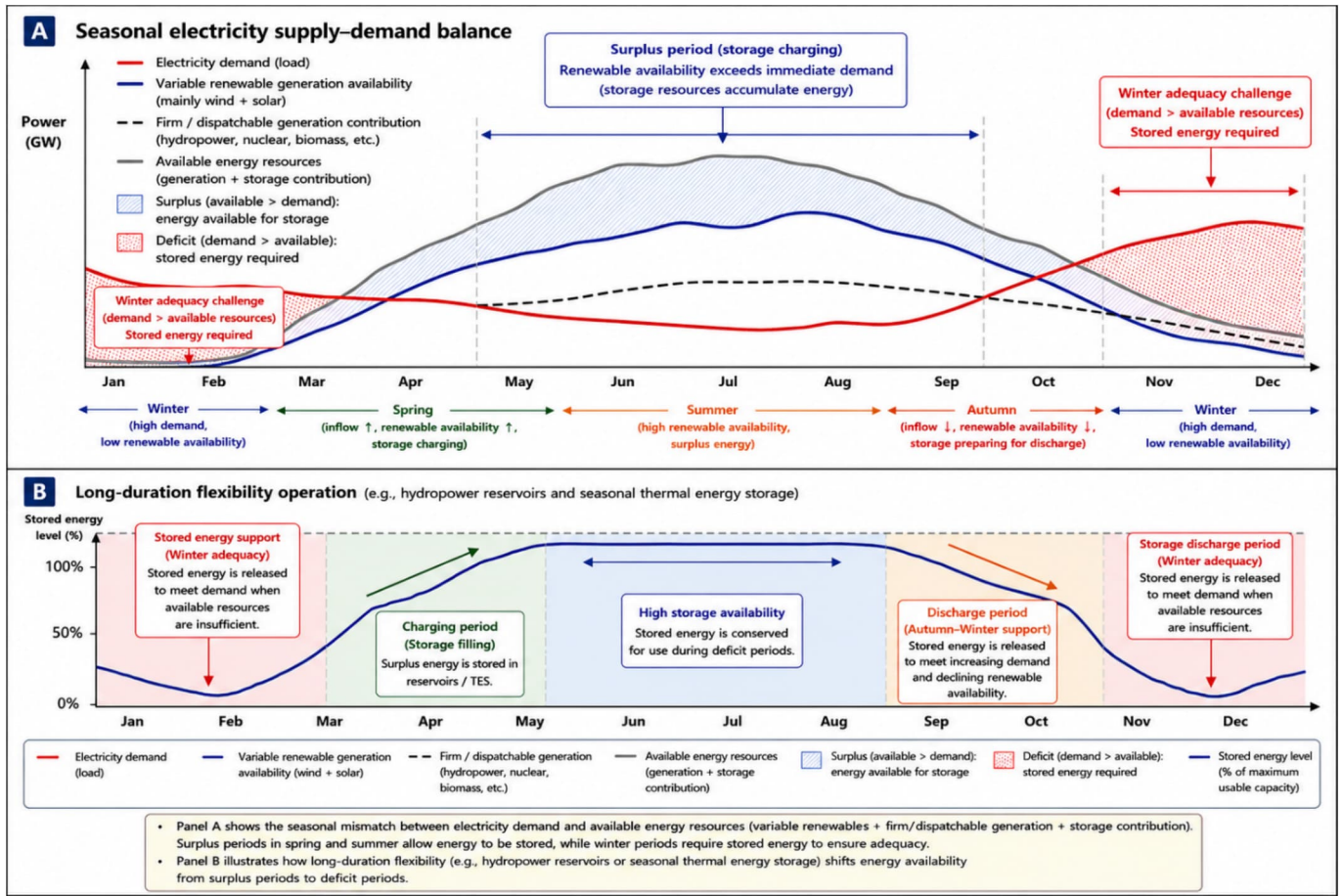


Fig. 6. Seasonal energy balancing through long-duration flexibility resources.

energy storage. During autumn and winter periods, when electricity demand increases and renewable availability may decrease, stored energy is released to support system adequacy and reduce prolonged supply shortages.

Unlike short-duration flexibility resources that primarily address frequency control and intra-day balancing, long-duration storage enables temporal energy shifting across weeks to months. Therefore, hydropower reservoirs and seasonal thermal storage complement fast-response technologies by contributing to energy adequacy under extended renewable variability conditions.

This highlights the importance of long-duration storage in maintaining system adequacy under extreme conditions. Table 8 compares the longer-duration flexibility characteristics of BESS, district heating with thermal energy storage (TES), and reservoir hydropower. The reported durations represent typical or representative operating ranges identified in the reviewed literature rather than fixed technical limits. Conventional grid-scale BESS is included as a benchmark because its primary contribution generally lies in short-term stability, reserve provision, and intraday balancing, while its sustained energy-shifting capability is constrained by the installed energy capacity and state of charge. District heating with TES can extend flexibility from hourly and daily demand shifting to weekly or seasonal energy management when large-scale technologies such as pit thermal energy storage (PTES) or borehole thermal energy storage (BTES) are employed. Reservoir hydropower can provide flexibility across daily to seasonal timescales, although its long-duration contribution depends strongly on reservoir capacity, hydrological inflows, water availability, environmental requirements, and operational constraints. The durations and applications shown in Table 8 should therefore be interpreted as representative system-level characteristics rather than universal technology limits.

The hierarchy demonstrates that seasonal adequacy relies on fundamentally different resource characteristics than short-term stability.

6.3. Complementary long-duration options

Emerging long-duration storage technologies, particularly hydrogen-based systems, are increasingly proposed as solutions for prolonged energy scarcity. These technologies offer the potential for large-scale energy storage and cross-sector integration through power-to-gas pathways.

However, current analyses indicate that their role is more suited to strategic backup and sector coupling rather than routine balancing, primarily due to efficiency losses, high costs, and infrastructure requirements [87,88]. As a result, hydrogen and related technologies are better interpreted as supplementary adequacy resources that enhance system resilience under extreme conditions, rather than direct substitutes for hydropower.

Their integration into the energy system is therefore likely to complement existing flexibility layers, particularly in scenarios involving prolonged renewable deficits or increased electrification of hard-to-abate sectors.

6.4. System implications

The analysis demonstrates that seasonal adequacy cannot be ensured by scaling fast-response technologies alone. Instead, system reliability emerges from a hierarchical and multi-timescale structure of flexibility provision, where different resources contribute according to their temporal capabilities.

Table 8
Comparison of long-duration flexibility resources.

Resource	Typical flexibility duration	Primary operational role	Representative applications	Main operational constraint	Interpretation / basis	Representative sources
BESS	Minutes to approximately 4 h	Primarily short-term stability and operational balancing	Frequency regulation, reserve services, intraday balancing, congestion management	Energy-capacity and state-of-charge constraints; degradation under repeated cycling	Representative range for conventional short-duration grid-scale BESS; included as a benchmark against longer-duration resources	[28,53–55,59,60,62]
District heating + TES	Hours–days for hot-water tanks; weeks–months for large-scale PTES/BTES	Demand shifting, peak-load management, and long-duration thermal flexibility	Power-to-heat, renewable energy integration, load shifting, seasonal heat storage	Dependence on district-heating infrastructure, thermal demand, storage configuration, and thermal losses	Technology-dependent representative range; large-scale PTES/BTES can extend flexibility toward seasonal timescales	[56–58,67–71]
Hydropower reservoirs	Days–months; potentially seasonal depending on reservoir characteristics	Long-duration and seasonal energy balancing and adequacy support	Reservoir management, prolonged energy balancing, reserve provision, and seasonal supply support	Hydrological variability, reservoir availability, environmental requirements, and operational constraints	Representative range for reservoir hydropower; strongly dependent on reservoir size, inflows, water value, and environmental constraints	[22,32,51,63–66]

Batteries stabilize second-scale dynamics, thermal storage manages daily demand variability, and hydropower secures long-term energy sufficiency. This layered coordination reflects the timescale-based classification presented in Section 3 and highlights the importance of integrating resources across temporal and sectoral dimensions.

From a system perspective, ensuring reliability in renewable-dominated power systems requires not only sufficient installed capacity but also adequate coverage across all operational timescales. This insight provides the foundation for the integrated system perspective developed in the following section.

7. Integrated system perspective

7.1. Coordinated roles of flexibility resources

The preceding analysis demonstrates that flexibility resources operate across fundamentally different temporal horizons and provide distinct system services. As a result, no single technology can independently ensure reliable operation in a high-renewable power system. Fast disturbances require immediate active power response, short-term variability demands balancing capability, and seasonal demand requires sustained energy availability [64,83,89]. These requirements originate from different physical processes and therefore cannot be addressed by a single class of resources.

System reliability instead emerges from the coordinated interaction of complementary flexibility assets, forming a layered portfolio of services across timescales. Battery energy storage systems provide rapid stabilization during the initial seconds following disturbances, hydropower sustains balancing and recovery over longer horizons, and thermal storage reshapes demand to reduce prolonged system imbalance [53,65,67].

The reviewed studies show that reliable operation requires flexibility resources with different response speeds, storage durations, and control characteristics. Battery energy storage systems provide rapid stabilization during the initial seconds following disturbances, hydropower supports balancing and recovery over longer horizons, and thermal storage reshapes heat-related electricity demand to reduce peak stress. Therefore, evaluating these resources in isolation may underestimate their combined contribution to system adequacy and operational security. Fig. 7 demonstrates that system reliability emerges from the coordinated operation of complementary flexibility resources across different temporal horizons.

Recent quantitative studies further support the proposed multi-timescale coordination framework. For example, joint planning models integrating short-duration and seasonal energy storage have demonstrated that coordinated deployment of complementary flexibility resources improves system adequacy while reducing renewable curtailment and overall system costs. Rather than maximizing the deployment of a single storage technology, these studies show that combining fast-response storage with long-duration flexibility enables more balanced allocation of system services across multiple operational timescales. Similar findings have been reported in studies investigating the co-optimization of storage technologies, transmission expansion, and sector coupling, where coordinated operation improves renewable utilization, operational resilience, and long-term system reliability. These quantitative results reinforce the central conclusion of this review that complementary flexibility resources provide greater system value when planned and operated as an integrated portfolio rather than as independent technologies [90,91].

The figure demonstrates that system reliability emerges from the coordinated interaction of complementary resources rather than reliance on a single technology.

Table 9 synthesizes the system-level roles of the three flexibility-resource categories across frequency stability, congestion management, demand-side flexibility, and long-term adequacy. The classifications represent typical capabilities and applications identified in the

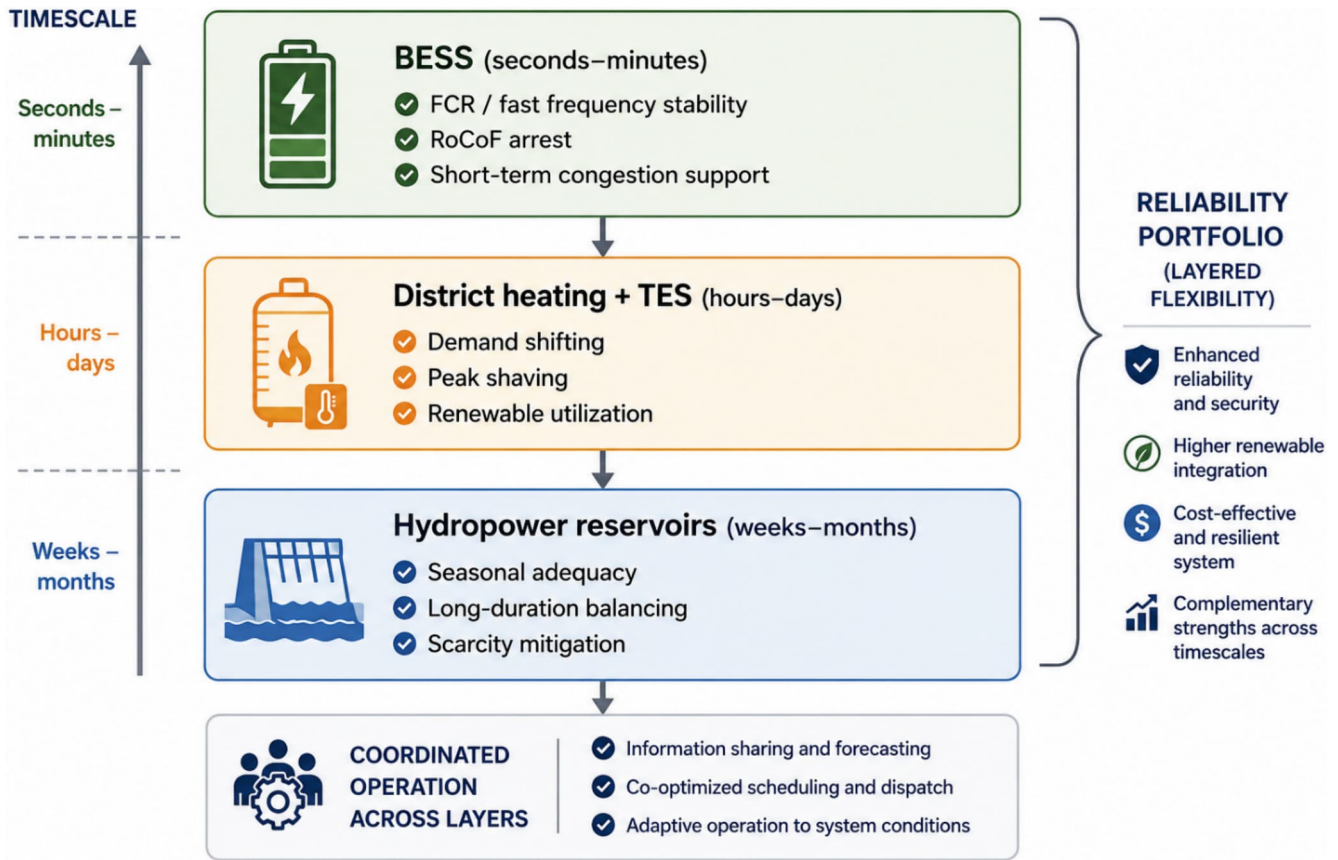


Fig. 7. Layered flexibility portfolio.

Table 9
System-level contributions of flexibility resources.

Resource	Frequency stability	Congestion management	Demand-side flexibility	Long-term adequacy	Representative sources
Battery Energy Storage Systems (BESS)	Direct and rapid frequency support through FCR, FFR, and aFRR	Short-term congestion relief, ramp management, and redispatch support	Limited direct demand-side contribution; primarily supply/storage-side flexibility	Limited contribution to seasonal adequacy for conventional short-duration BESS because of energy-capacity and discharge-duration constraints	[28,53–55,59–62,92]
District Heating + Thermal Energy Storage (TES)	Indirect frequency-support potential through controllable power-to-heat demand and load adjustment	Load shifting, peak-load reduction, and mitigation of local electricity-network constraints	Strong demand-side flexibility through power-to-heat, controllable thermal loads, and thermal storage	Long-duration contribution depends on TES technology; large-scale PTES/BTES can provide weekly-to-seasonal thermal energy shifting	[17,29,30,56–58,67–71,82]
Hydropower reservoirs	Direct frequency control and reserve provision	Operational balancing, ramping support, redispatch, and transmission-congestion management	Primarily generation-side flexibility; indirect contribution through system balancing	Strong long-duration and seasonal balancing capability, subject to reservoir capacity, hydrological availability, and environmental constraints	[22,32,46,51,63–66]

reviewed literature rather than universal technical ratings. BESS provides direct and rapid electrical flexibility and is therefore particularly suited to frequency control, reserve provision, and short-term congestion management, although conventional short-duration installations have a comparatively limited role in seasonal adequacy. District heating combined with TES primarily provides demand-side flexibility by shifting electricity consumption through power-to-heat and thermal storage, with large-scale PTES and BTES extending this capability toward longer-duration and seasonal energy shifting. Reservoir hydropower provides generation-side flexibility across multiple timescales, ranging from frequency and balancing services to long-duration and seasonal energy management, although its contribution depends on reservoir characteristics, hydrological conditions, and environmental constraints. The capabilities summarized in Table 9 should therefore be

interpreted as representative system-level roles rather than fixed or universally applicable technology ratings.

7.2. Market design implications

Current Nordic electricity market structures explicitly reward fast-response flexibility through ancillary service products such as Frequency Containment Reserve for Normal Operation (FCR-N), Frequency Containment Reserve for Disturbances (FCR-D), automatic Frequency Restoration Reserve (aFRR), and manual Frequency Restoration Reserve (mFRR) [40,61]. These markets primarily compensate resources capable of delivering rapid, accurate, and controllable power adjustments, making battery energy storage systems (BESS) particularly well suited for participation because of their millisecond-scale response and high

operational precision.

In contrast, district heating with thermal energy storage (TES) contributes mainly through demand shifting, peak-load reduction, renewable energy utilization, and power-to-heat operation rather than direct participation in ancillary service markets. The economic value of TES is therefore often realized indirectly through lower electricity procurement costs, optimized district-heating operation, reduced peak demand, and improved integration of renewable generation instead of dedicated market revenues [17,67,69,70]. Similarly, hydropower participates in balancing and reserve markets while simultaneously providing long-duration energy balancing and seasonal adequacy, although these long-term system benefits are not always fully reflected in existing market remuneration mechanisms.

This asymmetry creates a structural imbalance in investment incentives, potentially encouraging greater deployment of short-duration flexibility resources while undervaluing demand-side flexibility and long-duration energy storage. As a result, market outcomes may not correspond to the combination of flexibility resources required for reliable operation of renewable-dominated power systems.

To address this issue, future market design should better reflect the multi-timescale nature of system reliability by recognizing not only response speed but also flexibility duration, energy availability, and locational value. Potential approaches include differentiated flexibility products, co-optimized energy and reserve markets, capacity adequacy mechanisms, and enhanced incentives for sector-coupling technologies such as district heating and power-to-heat systems. Such developments would better align investment signals with long-term system requirements and support balanced deployment of complementary flexibility resources across multiple operational timescales [40,93].

7.3. Planning implications

Traditional power system planning approaches rely heavily on metrics such as installed capacity or total stored energy. However, the multi-timescale classification used in this review demonstrates that these metrics are insufficient to capture the temporal complexity of reliability in renewable-dominated systems.

Effective planning must ensure adequate temporal coverage of system services, including:

- second-scale frequency stabilization,
- intra-day balancing and congestion management, and
- long-term energy adequacy.

This requires coordinated deployment of resources with complementary characteristics rather than maximizing investment in a single technology. Overreliance on fast-response resources without sufficient long-duration flexibility may lead to system vulnerability during prolonged scarcity events. Beyond the Nordic context, recent planning studies have shown that coordinated deployment of multiple flexibility resources can also facilitate broader power system transition strategies, including the staged transformation of conventional generation assets. Co-planning approaches combining energy storage with generation retrofitting, renewable integration, and sector coupling demonstrate that flexibility resources contribute not only to operational reliability but also to long-term decarbonization pathways. Therefore, the proposed multi-timescale framework may support planning decisions in diverse low-carbon power systems by linking flexibility requirements with evolving generation portfolios and transition strategies [94].

From a system perspective, optimal reliability is achieved through balanced portfolios of flexibility resources, where each component contributes according to its temporal strengths. This coordinated planning approach supports comparative evaluation for evaluating flexibility investments and is directly applicable to other low-inertia, high-renewable power systems undergoing rapid energy transition.

8. Research gaps and future directions

8.1. Locational flexibility valuation

Most existing planning studies quantify flexibility using aggregated system models that neglect spatial network constraints and congestion patterns. However, in the Nordic power system, the geographical separation between northern renewable generation and southern demand centers creates strongly location-dependent flexibility value [77,93]. As a result, the effectiveness of flexibility resources depends not only on their capacity and response characteristics but also on their placement within the network.

Despite this, current research rarely evaluates how the spatial deployment of batteries or thermal storage simultaneously influences fast stability, operational balancing, and long-term adequacy. This limitation reduces the practical applicability of planning results and may lead to suboptimal investment decisions.

Future research should therefore integrate network-constrained optimization with multi-timescale flexibility analysis, enabling identification of optimal spatial allocation strategies that jointly address congestion, stability, and adequacy requirements.

8.2. Interaction between hydropower and variable generation

Hydropower plays a central role in balancing renewable variability; however, its operation is strongly influenced by hydrological uncertainty and environmental constraints. Guamán et al. [66] developed an optimization framework considering water-resource uncertainty in hydro-dependent systems. Shao et al. [95] demonstrated the potential of machine-learning methods for assessing climate impacts on hydropower productivity.

This gap is particularly critical for seasonal adequacy, where coincident scarcity in both wind generation and hydropower availability may significantly increase system risk. Existing deterministic models are not well suited to capture such extreme but plausible scenarios.

Future work should focus on stochastic and scenario-based modeling frameworks that jointly represent meteorological and hydrological variability. Such approaches are necessary to evaluate system resilience under extreme events rather than average operating conditions.

8.3. Market representation of flexibility duration

Current electricity market designs tend to explicitly reward fast-response services, such as frequency containment reserves, while providing limited valuation for longer-duration flexibility [87]. As demonstrated in previous sections, mid-duration flexibility—particularly from district heating with thermal storage—plays a significant role in reducing peak demand and improving renewable integration yet remains weakly monetized.

This mismatch creates distorted investment signals, favoring short-duration assets such as batteries despite the critical system role of longer-duration flexibility. Over time, this may lead to an imbalance in the flexibility portfolio and reduced overall system efficiency.

Future research should focus on developing market mechanisms that jointly value response speed, duration, and energy availability, including differentiated flexibility products and co-optimized energy-reserve market designs. Such approaches would better reflect the multi-timescale nature of system reliability.

8.4. Multi-energy system coordination

Sector coupling introduces strong interactions between electricity and heating systems, particularly through district heating networks and thermal storage. While these systems provide significant flexibility by shifting electricity demand, most existing operational models treat electricity and heat sectors independently [67,71].

This separation limits the ability to capture cross-sector dynamics and may underestimate the system-level value of thermal flexibility. In practice, coordinated operation of electricity and heating infrastructures is essential for managing demand peaks and improving renewable utilization.

Future research should therefore develop integrated multi-energy system optimization frameworks that explicitly model interactions between electricity, heating, and storage systems. Such models are critical for evaluating coordinated control strategies and ensuring reliable operation across interconnected infrastructures.

8.5. Low-inertia resilience assessment

Current stability studies predominantly analyze single disturbances under predefined operating conditions. However, increasing penetration of inverter-based resources introduces more complex system dynamics, including multiple rapid disturbances, reduced damping, and non-linear recovery behavior [73,96].

These characteristics challenge traditional reliability assessment methods, which typically separate frequency stability and energy adequacy into distinct analyses. In practice, system resilience depends on the interaction between these dimensions across timescales.

Future work should focus on developing integrated resilience metrics that combine fast stability performance with longer-term adequacy considerations. Such metrics would enable a more comprehensive evaluation of system behavior under realistic operating conditions and support improved planning and operational decision-making.

9. Conclusion

This paper investigated how complementary flexibility resources can jointly support reliable operation of the Nordic power system under increasing renewable penetration. The analysis demonstrates that reliability challenges span multiple temporal horizons, ranging from sub-second frequency stability to long-term seasonal adequacy. Consequently, system security cannot be adequately addressed through individual flexibility technologies or static capacity metrics alone.

To address this challenge, a multi-timescale classification of flexibility resources was derived from the reviewed literature to systematically link system-service requirements with the operational characteristics of battery energy storage systems (BESS), district heating with thermal energy storage (TES), and hydropower reservoirs. The synthesis indicates that these resources provide complementary contributions across different temporal layers. BESS provides rapid response for frequency containment and short-term balancing, thermal storage enables demand shifting over hourly and daily horizons and, for selected technologies, longer periods, while reservoir hydropower provides sustained balancing and contributes to long-term and seasonal energy adequacy.

The findings further identify a potential mismatch between evolving system flexibility requirements and current market incentives. While fast-response services are increasingly recognized and explicitly valued, longer-duration flexibility, particularly from demand-side and thermal resources, is less consistently represented in existing market arrangements. Improved valuation of flexibility duration, energy availability, and locational contribution could therefore support more efficient investment and operational decisions in future low-inertia, renewable-dominated power systems.

From a planning perspective, the reviewed literature demonstrates the importance of maintaining adequate flexibility across multiple operational timescales. BESS, district heating-based thermal storage, and hydropower reservoirs address different system requirements because of their distinct response characteristics, energy capacities, and flexibility durations. Future planning should therefore move beyond dependence on individual flexibility technologies and evaluate coordinated resource portfolios according to their contributions to frequency

stability, operational balancing, congestion management, peak-load reduction, and long-term adequacy.

Although the analysis is grounded in the Nordic context, the proposed multi-timescale classification framework may also support the assessment of flexibility requirements in other renewable-dominated power systems facing comparable challenges associated with variability, reduced system inertia, sector coupling, and long-duration energy adequacy. Future research should extend the framework by incorporating spatial network constraints, stochastic renewable and hydrological variability, and market co-optimization to provide a more comprehensive representation of multi-timescale flexibility requirements.

CRedit authorship contribution statement

Tareq Anwar Shikdar: Writing – review & editing, Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Visualization. **Hannu Laaksonen:** Writing – review & editing, Supervision.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Use of artificial intelligence

During the preparation of this manuscript, the authors used an AI-assisted language model to improve readability, structure, and grammar of the text. The authors take full responsibility for the content of the publication and confirm that all scientific analysis, interpretations, and conclusions were developed by the authors.

Funding

The authors received no specific funding for this work.

Author contributions

All authors read and approved of the final manuscript.

Code availability

Not applicable.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No new primary, experimental, or simulation datasets were generated in this study. However, the systematic review analyzed a literature-based evidence set comprising 94 included studies identified through the screening procedure described in Section 2. The bibliographic and study-level information used for comparative synthesis was extracted from publicly available publications and reports cited in the manuscript.

References

- [1] IEA. World Energy Outlook 2023. IEA, Paris (2023). <https://www.iea.org/reports/world-energy-outlook-2023>. Licence: CC BY 4.0 (report); CC BY-NC-SA 4.0 (Annex A).
- [2] IEA. Energy Technology Perspectives 2023. IEA, Paris (2023). <https://www.iea.org/reports/energy-technology-perspectives-2023>. Licence: CC BY 4.0.
- [3] European Commission. EU climate neutrality strategy. European Commission, Brussels (2020). <https://ec.europa.eu/>.
- [4] ENTSO-E. Ten-Year Network Development Plan 2024. ENTSO-E (2024). <https://tynpd.entsoe.eu>.
- [5] Akhtar I, Kirmani S, Jameel M. Reliability assessment of power system considering the impact of renewable energy sources integration into grid with advanced intelligent strategies. IEEE Access 2021;9:32485–97. <https://doi.org/10.1109/ACCESS.2021.3060892>.
- [6] Ahmed F, Foley A, McLoone S, Best R, Lund H, Al Kez D. Sectoral coupling pathway towards a 100% renewable energy system for Northern Ireland. Renew. Sustain. Energy Rev. 2025;210:114939. <https://doi.org/10.1016/j.rser.2024.114939>.
- [7] Statnett. Long-Term Market Analysis Nordic Region 2023. Statnett, Oslo (2023). <https://www.statnett.no/>.
- [8] Fingrid Oyj. Fingrid group – management’s review 1.1.–31.3.2024 (Apr 25, 2024). <https://www.fingrid.fi/en/news/news/2024/fingrid-group-managements-review-1.1.-31.3.2024/>.
- [9] Svenska kraftnät. System development plan 2024–2033. Svenska kraftnät, Sundbyberg (2024). <https://www.svk.se/>.
- [10] Danish Energy Agency. Security of Electricity Supply in Denmark: Working Group Report on Methodology, Concepts and Calculations Concerning Security of Electricity Supply. Copenhagen, Denmark: Danish Energy Agency, 2015. [Online]. Available: <https://www.ens.dk/en>.
- [11] Orkustofnun. “Uppsett rafl og raforkuframleiðsla í virkjunum á Íslandi 2025” [Installed electrical capacity and electricity production in Icelandic power stations 2025]. ROS-2-2026, Iceland, Apr. 1, 2026. [Online]. Available: Orkustofnun electricity statistics. [Accessed: Aug. 20, 2026].
- [12] Gordon S, McGarry C, Tait J, Bell K. Impact of low inertia and high distributed generation on the effectiveness of under frequency load shedding schemes. IEEE Trans Power Delivery 2022;37(5):3752–61. <https://doi.org/10.1109/TPWRD.2021.3137079>.
- [13] Heylen E, Teng F, Strbac G. Challenges and opportunities of inertia estimation and forecasting in low-inertia power systems. Renew Sustain Energy Reviews 2021; 147. <https://doi.org/10.1016/j.rser.2021.111176>.
- [14] R. Plant, D. Babazadeh, S. Stock and C. Becker, “Real-time inertia estimation in an inverter-dominated distribution grid using a physics-informed recurrent neural network,” *CIREP Porto Workshop 2022: E-mobility and power distribution systems*, Hybrid Conference, Porto, Portugal, 2022, pp. 940–944, doi: 10.1049/icp.2022.0852.
- [15] C. -C. Chu, S. -H. Lee, K. L. Lian, J. -H. Liu and Y. -J. Lin, “A Survey of Global Revisions to Grid Codes on System Inertia and Frequency Stability in Power Grids with High Renewable Energy Integration,” *2025 IEEE Industry Applications Society Annual Meeting (IAS)*, Taipei, Taiwan, 2025, pp. 1–8, doi: 10.1109/IAS62731.2025.11061388.
- [16] Marcos JD, Golpour I, Barbero R, Rovira A. Decarbonizing European industry: a novel technology to heat supply using waste and renewable energy. Appl Sci 2024; 14(19):8994. <https://doi.org/10.3390/app14198994>.
- [17] Sihvonen V, Ollila I, Jaanto J, Grönman A, Honkapuro S, Riikonen J, Price A. Role of power-to-heat and thermal energy storage in decarbonization of district heating. Energy 2024;305:132372. <https://doi.org/10.1016/j.energy.2024.132372>.
- [18] IEA. The Future of Heat Pumps. IEA, Paris (2022). <https://www.iea.org/reports/the-future-of-heat-pumps>. Licence: CC BY 4.0.
- [19] IRENA. Flexibility for a secure and affordable power sector transformation. International Renewable Energy Agency, Abu Dhabi (2026).
- [20] Vilaça P, Oliveira L, Saraiva J. A congestion-based local search for transmission expansion planning problems. Swarm Evol Comput 2023;83:101422. <https://doi.org/10.1016/j.swevo.2023.101422>.
- [21] ENTSO-E, “From Baltic Synchronisation to Grid Innovation: ENTSO-E Annual Report 2025,” *European Network of Transmission System Operators for Electricity (ENTSO-E)*, Jun. 1, 2026. [Online]. Available: <https://www.entsoe.eu/news-events/news/>. [Accessed: Jun. 18, 2026].
- [22] Fälth HE, Hedenus F, Reichenberg L, Mattsson N. Through energy droughts: hydropower’s ability to sustain a high output. Renew Sustain Energy Rev 2025; 214:115519. <https://doi.org/10.1016/j.rser.2025.115519>.
- [23] Mitali J, Dhinakaran S, Mohamad AA. Energy storage systems: a review. Energy Storage Sav 2022;1(3):166–216. <https://doi.org/10.1016/j.enss.2022.07.002>.
- [24] Zabeih H, Ahmadi M, Rahmany NA, Danish MSS, Fedayi H, Yona A. Optimal grid flexibility assessment for integration of variable renewable-based electricity generation. Sustainability 2023;15(20):15032. <https://doi.org/10.3390/su152015032>.
- [25] Rahman MM, Dadon SH, He M, Giesselmann M, Hasan MM. An overview of power system flexibility: high renewable energy penetration scenarios. Energies 2024;17 (24):6393. <https://doi.org/10.3390/en17246393>.
- [26] Aslam MU, Miah MS, Amin BMR, Shah R, Amjady N. Application of energy storage systems to enhance power system resilience: a critical review. Energies 2025;18 (14):3883. <https://doi.org/10.3390/en18143883>.
- [27] Miao Y, Chen T, Bu S, Liang H, Han Z. Co-optimizing battery storage for energy arbitrage and frequency regulation in real-time markets using deep reinforcement learning. Energies 2021;14(24):8365. <https://doi.org/10.3390/en14248365>.
- [28] Zhao C, Andersen PB, Træholt C, Hashemi S. Grid-connected battery energy storage system: a review on application and integration. Renew Sustain Energy Rev 2023; 182:113400. <https://doi.org/10.1016/j.rser.2023.113400>.
- [29] Sameti M, Fan T, Volkova A, Li Z. Large-scale climate-neutral district heating and cooling: integration of local microgrids for thermal distribution. Energy Conversion and Manage. X. 2026;30:101552. <https://doi.org/10.1016/j.ecmx.2026.101552>.
- [30] Massulli AR, Rosa FC, Lo Basso G. Moving towards fourth-generation district heating as a power-to-heat strategy: techno-economic issues. Sustainability 2025; 17(8):3675. <https://doi.org/10.3390/su17083675>.
- [31] Tol HJ, Madessa HB. Enhancing district heating system efficiency: a review of return temperature reduction strategies. Appl Sci 2025;15(6):2982. <https://doi.org/10.3390/app15062982>.
- [32] Kemarau RA, Harun SN, Sa’adi Z, Hanafiah MM, Sakawi Z, Norzin MAF, et al. Transforming hydropower: an in-depth systematic review of climate change impacts. Renew Sustain Energy Rev 2025;219:115890. <https://doi.org/10.1016/j.rser.2025.115890>.
- [33] Flores F, Feijoo F, DeStephano P, Herc L, Pfeifer A, Duić N. Assessment of the impacts of renewable energy variability in long-term decarbonization strategies. Appl Energy 2024;368:123464. <https://doi.org/10.1016/j.apenergy.2024.123464>.
- [34] Beck-Bang AC, Overgaard SB, Keles D. Electricity supply and demand in the European market: the effect on generation adequacy in a dunkelflaute period. Energy Policy 2026;208:114910. <https://doi.org/10.1016/j.enpol.2025.114910>.
- [35] Yamujala S, Koivisto M, Korpås M, McPherson M, Helistö N, Lew D, et al. Synergies and trade-offs between storage, transmission, and sector coupling in high renewable energy systems. Energy 2025;334:137701. <https://doi.org/10.1016/j.energy.2025.137701>.
- [36] Ali JS, Qiblawey Y, Alassi A, Massoud AM, Mueen SM, Abu-Rub H. Power system stability with high penetration of renewable energy sources: challenges, assessment, and mitigation strategies. IEEE Access 2025;13:39912–34. <https://doi.org/10.1109/ACCESS.2025.3546491>.
- [37] National Renewable Energy Laboratory (NREL). Assessing power system reliability in a changing grid environment (10 Aug 2022). <https://www.nrel.gov/news/detail/program/2022/assessing-power-system-reliability-in-a-changing-grid-environment>.
- [38] Alves EF, Polleux L, Guerassimoff G, Korpås M, Tedeschi E. Allocation of spinning reserves in autonomous grids considering frequency stability constraints and short-term solar power variations. IEEE Access 2023;11:29896–908. <https://doi.org/10.1109/ACCESS.2023.3261805>.
- [39] Ryu G, Sargin O, Lee D, et al. Wind speed interannual variability with measured data validations and its impact on energy yield in the Southwest Sea of Korea. Sci Rep 2025;15:33696. <https://doi.org/10.1038/s41598-025-18914-x>.
- [40] Khodadadi A, Herre L, Shinde P, Eriksson R, Söder L, Amelin M. Nordic balancing markets: overview of market rules. In: 17th International Conference on the European Energy Market (EEM), Stockholm, Sweden (2020), pp 1–6. Doi:10.1109/EEM49802.2020.9221992.
- [41] European Commission. Electricity market design. Directorate-General for Energy. https://energy.ec.europa.eu/topics/markets-and-consumers/electricity-market-design_en.
- [42] Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. <https://doi.org/10.1136/bmj.n71>.
- [43] Moher D, Liberati A, Tetzlaff J, Altman DG. The PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med 2009;6(7):e1000097. <https://doi.org/10.1371/journal.pmed.1000097>.
- [44] Zhang Z, Chen Y, Ma T, Tian H, Liu J, Zhou M, Wang W. Multi-type energy storage expansion planning: a review for high-penetration renewable energy integration. Renew Sustain Energy Rev 2025;219:115853. <https://doi.org/10.1016/j.rser.2025.115853>.
- [45] Shair J, Li H, Hu J, Xie X. Power system stability issues, classifications and research prospects in the context of high-penetration of renewables and power electronics. Renew Sustain Energy Rev 2021;145:111111. <https://doi.org/10.1016/j.rser.2021.111111>.
- [46] Huclín S, Ramos A, Chaves JP, Matanza J, González-Eguino M. A methodological approach for assessing flexibility and capacity value in renewable-dominated power systems: a Spanish case study in 2030. Energy 2023;285:129491. <https://doi.org/10.1016/j.energy.2023.129491>.
- [47] Ringkjøb HK, Haugan PM, Seljom P, Lind A, Wagner F, Mesfun S. Short-term solar and wind variability in long-term energy system models—a European case study. Energy 2020;209:118377. <https://doi.org/10.1016/j.energy.2020.118377>.
- [48] Caglayan DG, Heinrichs HU, Robinus M, Stolten D. Robust design of a future 100 % renewable European energy supply system with hydrogen infrastructure. Int J Hydrogen Energy 2021;46(57):29376–90. <https://doi.org/10.1016/j.ijhydene.2020.12.197>.
- [49] Ratnam KS, Palanisamy K, Yang G. Future low-inertia power systems: requirements, issues, and solutions—a review. Renew Sustain Energy Rev 2020; 124:109773. <https://doi.org/10.1016/j.rser.2020.109773>.
- [50] Shafiekhani M, Qadrdan M. Addressing electricity transmission network congestions using battery energy storage systems – a case study of Great Britain. Appl Energy 2025;384:125418. <https://doi.org/10.1016/j.apenergy.2025.125418>.
- [51] Broman D, Voisin N, Kao SC, Fernandez A, Ghimire GR. Multi-scale impacts of climate change on hydropower for long-term water-energy planning in the contiguous United States. Environ Res Lett 2024;19(9):094057. <https://doi.org/10.1088/1748-9326/ad6ceb>.
- [52] ENTSO-E. Seasonal outlook. European Network of Transmission System Operators for Electricity. <https://www.entsoe.eu/outlooks/seasonal/>.

- [53] N. Nzimande and Y. Noro, "Battery Energy Storage System Supporting Frequency Regulation of Power System with High Renewable Penetration," *2023 13th International Conference on Power, Energy and Electrical Engineering (CPEEE)*, Tokyo, Japan, 2023, pp. 206–211, doi: 10.1109/CPEEE56777.2023.10217425.
- [54] Garttan G, Alahakoon S, Enami K, Jayasinghe SG. Battery energy storage systems: energy market review, challenges, and opportunities in frequency control ancillary services. *Energies* 2025;18(15):4174. <https://doi.org/10.3390/en18154174>.
- [55] Muzammal Islam M, et al. Improving reliability and stability of the power systems: a comprehensive review on the role of energy storage systems to enhance flexibility. *IEEE Access* 2024;12:152738–65. <https://doi.org/10.1109/ACCESS.2024.3476959>.
- [56] Sorknaes P, Nielsen S, Lund H, Mathiesen BV, Moreno D, Thellufsen JZ. The benefits of 4th generation district heating and energy efficient datacentres. *Energy* 2022; 260:125215. <https://doi.org/10.1016/j.energy.2022.125215>.
- [57] Sornek K, Homa M, Frigura-Iliasa FM, Frigura-Iliasa M, Jankowski M, Papis-Frączek K, et al. Power-to-heat and seasonal thermal energy storage: pathways toward a low-carbon future for district heating. *Energies* 2025;18(21):5577. <https://doi.org/10.3390/en18215577>.
- [58] Sifnaios I, Sneum DM, Jensen AR, Fan J, Bramstoft R. The impact of large-scale thermal energy storage in the energy system. *Appl Energy* 2023;349:121663. <https://doi.org/10.1016/j.apenergy.2023.121663>.
- [59] Zhang Y, Anvari-Moghaddam A, Peyghami S, Li Y, Dragičević T, Blaabjerg F. Optimal sizing of behind-the-meter battery storage for providing profit-oriented stackable services. *IEEE Trans Smart Grid* 2024;15(2):1481–94. <https://doi.org/10.1109/TSG.2023.3292076>.
- [60] Li Y, Tan Q, Li L, Li J. Real-time control method of battery energy storage participating in frequency regulation market considering frequency regulation revenue and degradation cost. In: Sha A, Yang M, Cai L, Hu C, Li R, Xie W (eds) *The Proceedings of 2024 International Conference of Electrical, Electronic and Networked Energy Systems (EENES 2024)*. Lecture Notes in Electrical Engineering, vol 1332. Springer, Singapore (2025). Doi:10.1007/978-981-96-1868-2_19.
- [61] H. Khajeh and H. Laaksonen, "Potential Ancillary Service Markets for Future Power Systems," *2022 18th International Conference on the European Energy Market (EEM)*, Ljubljana, Slovenia, 2022, pp. 1–6, doi: 10.1109/EEM54602.2022.9921133.
- [62] González-Inostroza P, Rahmann C, Álvarez R, Haas J, Nowak W, Rehtanz C. The role of fast frequency response of energy storage systems and renewables for ensuring frequency stability in future low-inertia power systems. *Sustainability* 2021;13(10):5656. <https://doi.org/10.3390/su13105656>.
- [63] Lu X, Li C, Chang H, Wang H, Zhu Z, Liu D, Tan X, Xu R. Primary frequency regulation performance in hydropower systems: precise quantification and holistic enhancement under wide-range operation. *Appl Energy* 2025;389:125711. <https://doi.org/10.1016/j.apenergy.2025.125711>.
- [64] Kim SJ, Asadzadeh M, Stadnyk TA. Climate change impact on water supply and hydropower generation potential in Northern Manitoba. *J Hydrol: Reg Stud* 2022; 41:101077. <https://doi.org/10.1016/j.ejrh.2022.101077>.
- [65] Wang Y, Levin T, Kwon J, Baker E. The value of hydropower flexibility for electricity system decarbonization. *Energy Rep* 2025;13:2711–21. <https://doi.org/10.1016/j.egyr.2025.02.019>.
- [66] Guamán W, Benalcázar P, Cordova-García J, Torres M. An integrated framework for the optimal expansion of hydro-dependent power systems under water-resource uncertainty. *Energy Convers Manage* X 2025;28:101297. <https://doi.org/10.1016/j.ecmx.2025.101297>.
- [67] Thellufsen JZ, Lund H, Sorknaes P, Nielsen S, Chang M, Mathiesen BV. Beyond sector coupling: utilizing energy grids in sector coupling to improve the European energy transition. *Smart Energy* 2023;12:100116. <https://doi.org/10.1016/j.segy.2023.100116>.
- [68] European Commission. Underground Large Scale Seasonal Energy Storage for Decarbonized and Reliable Heat (USES4HEAT) (2023). <https://cordis.europa.eu/project/id/101136136>.
- [69] Schill WP, Zerrahn A. Flexible electricity use for heating in markets with renewable energy. *Appl Energy* 2020;266:114571. <https://doi.org/10.1016/j.apenergy.2020.114571>.
- [70] Kalina J, Tańczuk M, Jendryasek Ł. Planning energy transition and decarbonisation of district heating systems in Poland. *Energy* 2025;328:136578. <https://doi.org/10.1016/j.energy.2025.136578>.
- [71] Kassem MA, Moscarello A. Advancing sustainable energy: a systematic review of geothermal-powered district heating and cooling networks. *Int J Sustain Energy* 2024;43(1). <https://doi.org/10.1080/14786451.2024.2417436>.
- [72] Moore P, Alimi OA, Abu-Siada A. A review of system strength and inertia in renewable-energy-dominated grids: challenges, sustainability, and solutions. *Challenges* 2025;16(1):12. <https://doi.org/10.3390/challe16010012>.
- [73] Cao G, Wu H, Liu Y, Ren Q. Distributed virtual inertia control strategy for multi-virtual synchronous machine parallel system based on neighbor communication. *Sensors* 2025;25(9):2855. <https://doi.org/10.3390/s25092855>.
- [74] Song J, Zhou X, Zhou Z, Wang Y, Wang Y, Wang X. Review of low inertia in power systems caused by high proportion of renewable energy grid integration. *Energies* 2023;16(16):6042. <https://doi.org/10.3390/en16166042>.
- [75] Zhang Z, Zhou M, Wu Z, Liu S, Guo Z, Li G. A frequency security constrained scheduling approach considering wind farm providing frequency support and reserve. *IEEE Trans Sustain Energy* 2022;13(2):1086–100. <https://doi.org/10.1109/TSTE.2022.3150965>.
- [76] Fingrid Oyj. Implementation of new technical requirements for frequency containment reserves starts on September 2023 (2023). <https://www.fingrid.fi/en/news/news/2023/Implementation-of-new-technical-requirements-for-frequency-containment-reserves-starts-on-september-2023/>.
- [77] Attar M, Repo S, Mann P. Congestion management market design—approach for the Nordics and Central Europe. *Appl Energy* 2022;313:118905. <https://doi.org/10.1016/j.apenergy.2022.118905>.
- [78] Naeem M, Jassim HS, Saleem K, Fatima M. Forecasting volatility of the Nordic electricity market: an application of the MSGARCH. *Risks* 2025;13(3):58. <https://doi.org/10.3390/risks13030058>.
- [79] Dobos T, Bichler M, Knörr J. Challenges in finding stable price zones in European electricity markets: aiming to square the circle? *Appl Energy* 2025;382:125315. <https://doi.org/10.1016/j.apenergy.2025.125315>.
- [80] Koivunen T, Syri S. Analysis of severe scarcity situations in Finland's low carbon electricity system until 2030. *Energies* 2024;17(23):5928. <https://doi.org/10.3390/en17235928>.
- [81] Hu W, Scholz Y, Yeligi M, Deng Y, Jochem P. Future electricity demand for Europe: unraveling the dynamics of the temperature response function. *Appl Energy* 2024;368:123387. <https://doi.org/10.1016/j.apenergy.2024.123387>.
- [82] Backe S, Delgado BM, Askeland M, Walnum HT, Sørensen ÅL, Sartori I. Impact of activating energy demand flexibility in the building stock: a case study of Norway as a highly electrified country in the European power market. *Energy* 2025;318:134688. <https://doi.org/10.1016/j.energy.2025.134688>.
- [83] European Commission. ENTSO-E report confirms EU is well-prepared for winter electricity needs (2025). https://energy.ec.europa.eu/news/entso-e-report-confirms-eu-well-prepared-winter-electricity-needs-2025-11-19_en.
- [84] Fingrid Oyj. Reliable domestic production and imports are needed to ensure sufficient electricity supply in the coming winter (2024). <https://www.fingrid.fi/en/news/news/2024/reliable-domestic-production-and-imports-are-needed-to-ensure-sufficient-electricity-supply-in-the-coming-winter/>.
- [85] Streimikiene D, Siksnelyte-Butkiene I, Lekavicius V. Energy diversification and security in the EU: comparative assessment in different EU regions. *Economies* 2023;11(3):83. <https://doi.org/10.3390/economies11030083>.
- [86] Javed MS, Jurasz J, Guezgouz M, Canales FA, Ruggles TH, Ma T. Impact of multi-annual renewable energy variability on the optimal sizing of off-grid systems. *Renew Sustain Energy Rev* 2023;183:113514. <https://doi.org/10.1016/j.rser.2023.113514>.
- [87] Ruf J, Köppel W, Graf F. Die Power-to-Gas-Technologie in der deutschen Energiewende – aktueller stand und Ausblick auf die nächste Dekade. *GWF Gas/Energie* 2020;9. https://www.dvgw-ebi.de/medien/dvgw-ebi/2_themen/publikationen/2020-sep-gwf-ruf.pdf.
- [88] Bhandari R, Adhikari N. A comprehensive review on the role of hydrogen in renewable energy systems. *Int J Hydrogen Energy* 2024;82:923–51. <https://doi.org/10.1016/j.ijhydene.2024.08.004>.
- [89] Mitra B, Pal S, Reeve H, et al. Unveiling sectoral coupling for resilient electrification of the transportation sector. *npj Sustain Mobility and Transp* 2025;2: 2. <https://doi.org/10.1038/s44333-024-00019-z>.
- [90] Montero L, Morales-España G, Bello A, Reneses J. Tight and compact MILP formulation for a high-resolution of start-up costs in the medium-term unit commitment. *Sustain Energy Grids Networks* 2025;44:101935. <https://doi.org/10.1016/j.segan.2025.101935>.
- [91] Zhang Z, Guo Z, Zhou M, Wu Z, Yuan B, Chen Y, Li G. Equalizing multi-temporal scale adequacy for low carbon power systems by co-planning short-term and seasonal energy storage. *J Energy Storage* 2024;84:111518. <https://doi.org/10.1016/j.est.2024.111518>.
- [92] Dong Z, Tao Y, Lai S, Wang T, Zhang Z. Powering future advancements and applications of battery energy storage systems across different scales. *Energy Storage and Applications* 2025;2(1):1. <https://doi.org/10.3390/esa2010001>.
- [93] Ritter D, Grafmüller D, Bauknecht D, Wingenbach M, Dünzen K. Electricity market design for 100 % renewable energy in Germany – challenges and solutions. *Energy Rep* 2025;14:634–47. <https://doi.org/10.1016/j.egyr.2025.06.006>.
- [94] Zhang Z, Zhou M, Yuan B, Guo Z, Wu Z, Li G. Multipath retrofit planning approach for coal-fired power plants in low-carbon power system transitions: Shanxi Province case in China. *Energy* 2023;275:127502. <https://doi.org/10.1016/j.energy.2023.127502>.
- [95] Shao H, Chau KY, Zaman A, et al. Machine learning frameworks to analyze climate change impact on hydropower productivity. *Appl Water Sci* 2026;16:54. <https://doi.org/10.1007/s13201-025-02677-x>.
- [96] F. A. de Oliveira Nascimento, "Hartley Transform Signal Compression and Fast Power Quality Measurements for Smart Grid Application," in: *IEEE Transactions on Power Delivery*, vol. 38, no. 6, pp. 4134–4144, Dec. 2023, doi: 10.1109/TPWRD.2023.3302188.