

A comprehensive review of sector coupling as a strategy for power system flexibility

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ABSTRACT

The European Union's 2030 climate targets require a fundamental transformation of the energy system, emphasizing the integration of renewable energy and the electrification of key sectors such as heating, cooling, transportation, and industry. The inherent unpredictability of renewable energy sources like wind and solar, however, makes this transition extremely difficult and creates operational uncertainties, makes system planning more difficult, and puts pressure on policy coordination. These issues affect the financial sustainability of energy systems in addition to grid stability and reliability. As a result, sector coupling is comprehensively reviewed in this paper as a strategic method to improve system flexibility. Sector coupling enhances the integration of relevant technologies, such as battery storage, hydrogen systems, and power-to-x solutions, and allows for synergies among energy carriers by connecting the electrical sector with other domains, such as transportation, heating, gas, and hydrogen. Along with the technical aspect, this study investigates how market design, financial innovation, and regulatory frameworks facilitate cross-sector investment and integration, which helps the clean energy transition and improves system flexibility overall.

List of Abbreviations

| Acronym | Full Form |
|---------|----------------------------------|
| TSO | Transmission System Operator |
| DSO | Distribution System Operator |
| CHP | Combined Heat and Power |
| RES | Renewable Energy Sources |
| DERs | Distributed Energy Resources |
| VPP | Virtual Power Plant |
| MES | Multi-Energy System |
| P2H | Power-to-Heat |
| P2G | Power-to-Gas |
| P2M | Power-to-Mobility |
| V2G | Vehicle-to-Grid |
| MILP | Mixed-Integer Linear Programming |
| FCR | Frequency Containment Reserve |
| FRR | Frequency Restoration Reserve |
| FFR | Fast Frequency Reserve |
| TES | Thermal Energy Storage |
| DHN | District Heating Network |
| PEM | Proton Exchange Membrane |
| IoT | Internet of Things |

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| Acronym | Full Form |
|---------|---------------------------------|
| IGDT | Information Gap Decision Theory |
| PSO | Particle Swarm Optimization |

1. Introduction

Electricity networks face major operational challenges as a result of the global transition to low-carbon energy systems, particularly as variable renewable energy sources such as solar and wind power reach increasing penetration levels [1]. The growing mismatch between intermittent generation and evolving demand patterns challenges the reliability, stability, and economic efficiency of modern power networks [2]. Simultaneously, direct electrification alone cannot decarbonize several critical sectors, including transportation, heating, and industrial processes [3]. These challenges collectively highlight the urgent need for flexible and integrated energy solutions that can ensure resilience,

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coordination, and sustainable decarbonization.

Power system flexibility, which is the ability to adapt to both short-term fluctuations and long-term changes in energy supply and demand, is widely recognized as one of the most critical enablers of the clean energy transition [4], [5]. Sector coupling, the coordinated integration of various energy carriers such as electricity, heat, gas, hydrogen, and transportation into a unified energy system, has emerged as a particularly powerful strategy for enhancing flexibility [6]. By creating bidirectional energy pathways across sectors, sector coupling enables surplus renewable electricity to be converted, stored, and utilized across domains, thereby improving overall resource efficiency, reducing curtailment, and creating new sources of system-wide flexibility [7].

An increasing body of research has examined technical advancements and policy strategies aimed at promoting sector coupling, including the development of smart grids, power-to-X conversion technologies, energy storage, and digital energy platforms [8], [9], [10]. However, despite this growing interest, three specific gaps persist in the literature:

Gap 1: Lack of a systematic flexibility-centric review of sector coupling. Existing reviews of sector coupling tend to focus on technology descriptions or decarbonization potential, without systematically analyzing how different coupling configurations contribute to specific flexibility services (frequency regulation, congestion management, load balancing) across different timescales and system levels (TSO, DSO). A structured mapping of sector-coupling pathways to flexibility outcomes is missing.

Gap 2: Insufficient comparative analysis across coupling configurations. The literature examines individual coupling pathways (P2H, P2G, P2M) largely in isolation, without providing a consistent analytical framework that enables cross-comparison of their flexibility contributions, technological readiness, and implementation challenges. This fragmentation prevents practitioners and policymakers from making informed decisions about which configurations to prioritize.

Gap 3: Inadequate integration of enabling conditions. Technical analyses of sector coupling rarely incorporate the market design, regulatory frameworks, financial innovation, and digital infrastructure requirements that are essential for translating technical flexibility potential into operational reality. The interplay between technical capabilities and institutional enablers remains underexplored.

To address these gaps, this paper presents a comprehensive and structured review of sector coupling as a strategy for enhancing power system flexibility. The specific contributions are.

1. A systematic baseline analysis of the current flexibility landscape (Section 3), mapping reviewed studies across six resource categories and multiple flexibility services and timescales, to identify precisely where electricity-only solutions fall short and sector coupling is needed.
2. A structured analytical framework for sector coupling's flexibility contributions (Section 4), comprising: (a) a classification of where sector coupling enhances flexibility (TSO, DSO, system-wide levels), (b) a taxonomy of four mechanisms through which it generates flexibility, (c) a systematic comparative analysis of six bilateral and multi-lateral coupling configurations using a consistent four-part template, and (d) a consolidated assessment of benefits and challenges with synthesizing tables.
3. An evidence-based research agenda (Section 5) that derives future priorities directly from the gaps and challenges identified in the analysis, spanning integrated modeling, technology demonstration, digitalization, market reform, cross-disciplinary collaboration, and social engagement.

The remainder of this paper is organized as follows: Section 2 outlines the review process. Section 3 provides a systematic overview of key solutions for power system flexibility, culminating in a gap analysis that motivates the focus on sector coupling. Section 4 examines sector

coupling and its contribution to flexibility through mechanisms, configurations, benefits, and challenges. Section 5 identifies current limitations and future research directions. Section 6 concludes the paper by summarizing the key findings in direct response to the three identified research gaps.

2. Review process

This research focuses on the past five years; the initial stages involved an extensive search through academic databases and involves several steps. First, the scope of the flexibility of the power system is defined. The article is then searched using relevant keyword such as "sector coupling". The publications are sorted from the search list depending on the approach, such as flexibility of power system with the sector coupling. The selection process is depicted in Fig. 1. This figure summarizes the literature identification, screening, and synthesis workflow adopted in this review. The extracted elements shown in the figure, namely objectives, methods, and impacts/feasibility, refer to the main characteristics of the reviewed papers. In addition, other relevant review studies were chosen to mention each work's contribution. The information is gathered from scholarly resources such as journals, conferences, books, and websites.

The reviewed literature reflects a diverse publication base and a clear concentration in major energy and power system outlets. Among the sources considered in this review, Elsevier publications constituted the largest share (39), followed by IEEE (20), Other publishers (25), MDPI (8), Wiley (4), and Springer, which accounted for a smaller portion of the dataset. In temporal terms, the literature distribution shows a clear increase in recent years, indicating the growing research interest in sector coupling and flexibility. While 25.58% of the reviewed materials were published before 2019, the remainder was concentrated in the 2019-2025 period, with the largest shares observed in 2021 (16.86%), 2022 (12.79%), 2023 (15.12%), 2024 (9.30%), and 2025 (7.56%), while 2019 and 2020 accounted for 6.40% each. This distribution confirms that the topic has gained significant momentum in recent years, particularly as flexibility and multi-energy integration have become more central to renewable-dominated energy system research.

To reduce selection bias and improve analytical transparency, the review process was conducted in two stages. In the first stage, relevant literature was identified through searches in major academic databases using combinations of keywords related to power system flexibility, sector coupling, multi-energy systems, power-to-X, local flexibility, and cross-sector integration. The retrieved records were then screened based on title, abstract, and relevance to the scope of the review. Priority was given to studies published in recent years, while earlier foundational contributions were retained when necessary to define core concepts or provide methodological background.

In the second stage, the selected studies were examined through an iterative thematic analysis. Rather than applying a rigid predefined framework, the analytical structure of the review was developed from recurring themes emerging across the retained literature. These themes included: definitions and sources of flexibility, sector coupling as a flexibility strategy, sector-specific coupling pathways, inter-sectoral synergies, and implementation barriers related to infrastructure, markets, regulation, and digitalization. This thematic clustering informed the organization of Sections 3-5 and guided the synthesis presented in the manuscript.

Accordingly, the compiled literature was used not only as supporting evidence for individual statements, but also as the basis for deriving the review's analytical narrative. Studies were grouped according to their primary contribution, such as conceptual definitions, technical flexibility mechanisms, sector-specific applications, market and regulatory issues, and future-oriented implementation challenges. This approach helped ensure that the conclusions were grounded in the reviewed literature rather than in a priori assumptions.

Following the screening and selection process, the retained studies

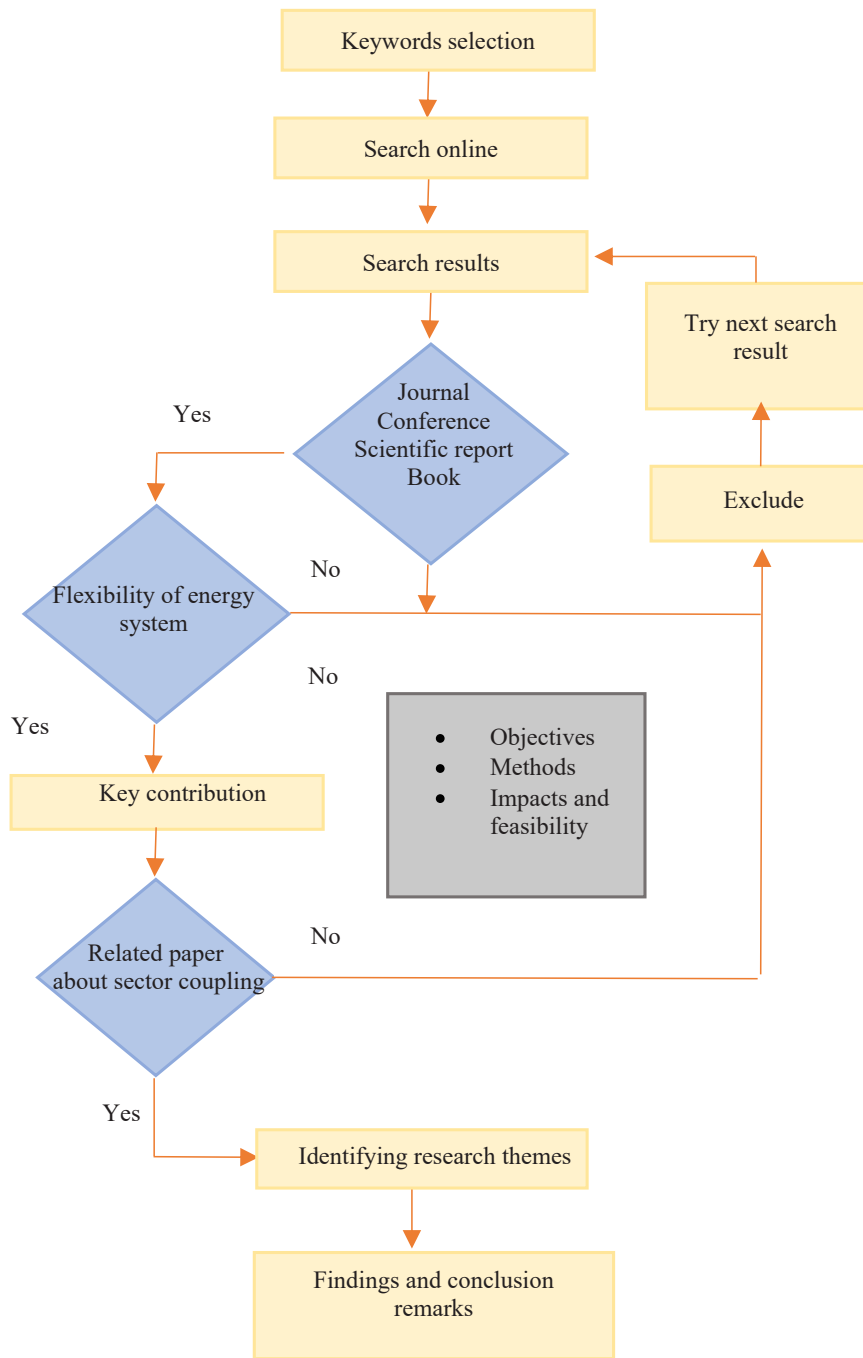


Fig. 1. Flowchart of article search and selection used in this work.

were grouped through thematic analysis according to their main analytical contribution. This synthesis showed that, before examining sector coupling specifically, it was necessary to first establish the broader context of power system flexibility, including its definitions, roles, and principal technical and operational solution categories. For this reason, Section 3 provides a structured overview of key flexibility solutions across supply-side resources, demand-side measures, storage, and network-related options. This broader mapping then serves as the conceptual basis for Section 4, where sector coupling is examined in greater detail as one of the major strategies for enhancing flexibility in modern power systems.

3. Summary of key solutions for power system flexibility

This section provides a structured overview of the principal resources and services that constitute power system flexibility. While the central contribution of this paper lies in the analysis of sector coupling (Section 4), a systematic understanding of the broader flexibility landscape is essential for two reasons. First, it establishes the baseline of flexibility provision, i.e., the portfolio of electricity-centric resources and mechanisms that system operators currently rely upon. Second, it reveals the gaps and limitations of these conventional approaches, thereby motivating the need for sector coupling as a complementary and transformative strategy. The section is organized around six flexibility resource categories, such as supply-side, demand-side, energy storage, transmission/interconnection, distribution, and sector coupling, each

examined in a dedicated subsection. A market-based solutions subsection examines flexibility procurement mechanisms. Two summary tables at the end of the section synthesize the coverage of reviewed studies across these categories and across flexibility timescales and services, providing a systematic basis for identifying where sector coupling adds value beyond what electricity-only solutions can deliver.

3.1. Definition and conceptual framework of power system flexibility

Power system flexibility refers to the ability of an energy system to adapt generation and demand in response to anticipated and unforeseen variations while maintaining reliability, security, and cost-effectiveness. Although definitions vary slightly across institutions, they converge on the need for dynamic balancing of supply and demand across multiple temporal and spatial scales.

Major international organizations provide complementary interpretations of this concept. The International Energy Agency (IEA) defines flexibility as the capability of a power system to adjust electricity generation or consumption under expected and unexpected fluctuations [11]. ENTSO-E similarly emphasizes secure and cost-efficient balancing across spatial and temporal scales through coordinated use of controllable resources [12]. IRENA and NERC focus on managing renewable-induced variability while preserving operational stability and reliability [13], [14]. The U.S. DOE further frames flexibility as a multidimensional concept requiring not only technical capabilities such as ramping and cycling but also supportive market structures and regulatory frameworks [15].

Beyond operational balancing, flexibility is increasingly viewed as a systemic property encompassing the ability to modify generation or consumption in response to market signals, activation commands, or structural system changes [1]. Academic and research institutions strengthen this multidimensional perspective. IEEE PES highlights the economic management of variability [5], while initiatives such as PATHFINDER stress coordinated interaction among generation, storage, demand response, sector coupling, and cross-border exchanges [16]. EPRI and CIGRE emphasize adaptability to evolving operating conditions and long-term infrastructure transformation [17].

Despite differences in emphasis ranging from technical responsiveness and economic efficiency to regulatory alignment and long-term planning, these perspectives consistently recognize flexibility as a critical enabler of renewable integration, congestion management, and system resilience [18], [19], [20], [1], [21], [22]. However, as noted in Ref. [5], the absence of a universally accepted definition has resulted in fragmented analyses across the literature.

To provide analytical clarity, power system flexibility can be examined from two complementary perspectives: (i) the resources that provide flexibility, and (ii) the system services that flexibility must deliver. The first perspective focuses on technological and operational assets such as flexible generation, storage, demand response, and sector-coupled resources while the second emphasizes the specific services required by the system, including frequency regulation, ramping support, congestion management, adequacy, and resilience. This dual perspective enables a structured understanding of flexibility provision and deployment, and it forms the organizational basis for the remainder of this section.

In [23], flexibility provision was quantified using frequency spectrum analysis-based tools, namely the Flexibility Solution Modulation Stack (FSMS) and Flexibility Solution Contribution Distribution (FSCD), enabling the identification of which resources including generation, demand, storage, or interconnection which provide flexibility across annual, weekly, and daily timescales. In Ref. [1], the evolution of power system flexibility under high renewable penetration was comprehensively reviewed, where flexibility was characterized across time, control function, uncertainty, and cost dimensions, and the need for coordinated resource deployment and market design reform was emphasized. In Ref. [24], the operational and planning dimensions of power system

flexibility were examined, where generation units, storage systems, and demand response were jointly considered to quantify flexibility requirements and optimize investment and operating costs under increasing renewable penetration. Twenty-three flexibility options for high renewable penetration were comparatively assessed in Ref. [25] using fuzzy logic and analytic hierarchy process methods, evaluating their maturity level, environmental impact, and deployment barriers. Flexibility needs in future power systems were classified in Ref. [11] into four functional domains: power balancing, energy adequacy, transfer capacity, and voltage control, highlighting the multi-timescale operational requirements associated with high shares of renewable generation.

Moreover, flexibility must address both short-term operational balancing and long-term system evolution to support sustainability objectives [26]. Therefore, a unified conceptual framework integrating operational, economic, regulatory, and strategic dimensions is essential for consistent evaluation and deployment of flexibility solutions in modern power systems.

3.2. Supply-side flexibility

Supply-side flexibility encompasses the ability of generation assets to adjust their output through ramping, cycling, start-up/shutdown, and dispatch optimization in response to system needs. This category represents the most established source of flexibility in power systems, traditionally provided by dispatchable thermal and hydroelectric generators.

A comprehensive review of power system flexibility under high penetration of variable renewable energy sources was presented in Ref. [26], discussing flexibility drivers, resources, assessment metrics, and planning approaches required to maintain reliable grid operation. A market-oriented frequency regulation framework integrating CHP systems and renewable generation was proposed in Ref. [27], demonstrating that coordinated economic-physical control can improve both system stability and market efficiency.

In [28], an integrated renewable energy management framework was proposed for the optimal design and hourly dispatch of hybrid renewable energy plants coupled with battery energy storage systems (BESS). A dynamic inter-hour ramping limit was introduced to mitigate renewable volatility, while enhanced forecasting and optimized BESS participation were employed to improve balancing performance, reduce curtailment, and increase economic efficiency. The flexibility of CHP systems for providing frequency response services was enhanced through coordinated control with battery storage in Ref. [29], compensating for the slow ramping characteristics of CHP units and enabling faster response to grid frequency deviations. The flexibility potential of CHP systems equipped with thermal and electrical energy storage was investigated within a real-time electricity pricing framework in Ref. [30], demonstrating their capability to participate in demand response programs and exploit market price variations.

In [31], a bi-level strategic bidding framework was developed for VPPs operating in a coupled electricity-carbon allowance-green certificate (ECG) market, where supply-side flexibility and flexible ramping products were jointly optimized under renewable energy uncertainty. A two-stage stochastic optimization model was employed to coordinate bidding decisions across three interrelated markets, enhancing renewable participation and promoting low-carbon operation strategies. In Ref. [32], a short-term flexibility evaluation method was developed based on generator ramp-rate data, where ramping performance probabilities of individual units were modeled using probability density functions and aggregated via convolution to construct a cumulative distribution-based system flexibility index.

While supply-side flexibility remains indispensable, it is inherently constrained by the technical characteristics of generation assets (minimum stable generation levels, ramp rates, start-up times) and, in the case of renewables, by weather dependency. These limitations

underscore the need for complementary flexibility from other resource categories [33].

3.3. Demand-side flexibility

Demand-side flexibility refers to the ability to modify electricity consumption patterns through load shifting, curtailment, or dynamic response to price and control signals to support system balancing and efficiency [34]. As renewable penetration increases, demand-side resources are becoming increasingly important for absorbing generation variability and reducing peak demand [35].

The state-of-the-art of demand response programs and demand-side flexibility was reviewed in Ref. [35], highlighting their potential to support grid balancing and renewable integration while identifying key barriers related to market design, measurement methodologies, and end-user participation. Recent advancements in demand-side energy management systems were reviewed in Ref. [36], highlighting the role of intelligent demand response and optimization techniques in improving energy efficiency, system reliability, and the integration of renewable energy sources. Aggregated demand-side energy flexibility was comprehensively reviewed in Ref. [37], focusing on the characterization, quantification, forecasting, and market integration of residential flexibility resources through aggregators.

In [38], a data-driven two-stage distributionally robust optimization framework was developed for low-carbon data center integrated energy systems, in which electricity, cooling, and hydrogen storage sectors were collaboratively coupled. Multi-task workload scheduling, renewable energy uncertainty, and hybrid cooling were jointly optimized to enhance demand-side flexibility, improve electricity-thermal coordination, reduce renewable curtailment, and decrease operational costs and CO₂ emissions. Nazemi et al. [39] proposed a two-layer optimization framework integrating demand-side management with microgrid planning, where smart HVAC control was used to adjust building cooling loads and reduce the total annual cost of the microgrid. The flexibility potential of HVAC systems in commercial buildings was analyzed in Ref. [40] through demand response strategies, demonstrating their capability to provide ancillary services by modifying indoor temperature setpoints or reducing HVAC power consumption.

Policy-driven growth in electric vehicle adoption is expected to introduce significant demand-side flexibility in future power systems [41]. The flexibility of electric vehicle charging loads was modeled in Ref. [42] to evaluate the potential benefits of controlled and bidirectional charging strategies for reducing charging costs and supporting power system operation through aggregated demand response. Electric vehicles with vehicle-to-grid (V2G) capability have emerged in Ref. [43] as distributed flexibility resources that can support grid stability, balancing, and renewable energy integration.

Despite its growing importance, demand-side flexibility faces barriers related to consumer engagement, regulatory access to markets, measurement and verification complexities, and the high upfront cost of enabling technologies such as challenges that are amplified when demand-side resources must coordinate across multiple energy sectors.

3.4. Energy storage

Energy storage technologies serve as a core enabler of flexibility by decoupling the temporal relationship between energy generation and consumption. They mitigate fluctuations in supply and demand over timescales ranging from seconds (frequency regulation) to months (seasonal shifting).

A comprehensive review of energy storage expansion planning models was conducted in Ref. [44] to analyze how different storage technologies can provide operational flexibility and support the integration of variable renewable energy sources in low-carbon power systems. Energy storage technologies were comprehensively surveyed in Ref. [45] to evaluate their technological development, operational roles,

and potential contributions to renewable energy integration and grid flexibility. Large-scale energy storage systems were reviewed in Ref. [46] to analyze their role in improving grid stability, enabling renewable energy integration, and enhancing power system flexibility. Various energy storage technologies were reviewed in Ref. [47] to evaluate their capability to provide flexibility services such as balancing, energy shifting, and grid stabilization in renewable-dominated power systems.

Long-duration electricity storage technologies were analyzed in Ref. [48] to evaluate their potential for providing energy time-shifting, reliability support, and flexibility in renewable-dominated power systems. An analytical method was developed in Ref. [49] to quantify and aggregate the time-varying flexibility potential of decentralized energy systems while considering operational constraints and primary energy service requirements.

While battery technologies have experienced significant cost reductions, challenges related to energy duration, round-trip efficiency, and scalability for long-duration applications persist. These limitations motivate the exploration of alternative long-duration storage pathways, including hydrogen and thermal storage, which inherently involve sector coupling, as discussed in Section 4.

3.5. Transmission and interconnection flexibility

Transmission-level flexibility enables efficient routing of electricity under varying conditions, supporting system-wide balancing and enabling access to geographically distributed generation and flexibility resources.

In [18], continuous transmission network flexibility was incorporated into a chance-constrained economic dispatch framework by treating line susceptances as adjustable decision variables. The proposed model demonstrated that network flexibility can mitigate uncertainty-induced congestion, re-route power flows, and reduce operational costs while maintaining security under renewable generation uncertainty. Optimal transmission switching was reviewed in Ref. [50] as an operational flexibility strategy that allows system operators to reconfigure network topology to reduce congestion, improve reliability, and enhance the integration of renewable energy. Cross-border electricity interconnections were analyzed in Ref. [51] as transmission-level flexibility options that enhance system reliability, reduce congestion, and facilitate renewable energy exchange between countries.

In [52], a multi-voltage optimal planning framework was developed to determine the siting, sizing, and power rating of distributed battery energy storage systems, enabling coordinated reserve provision to the TSO and voltage and congestion management in medium-voltage distribution grids under renewable uncertainty. In Ref. [20], emerging European flexibility market models were comparatively analyzed, highlighting new market platforms and aggregator-based mechanisms that enable distributed energy resources to provide congestion management, balancing, and voltage control services to DSOs in coordination with TSOs. A multi-layered taxonomy of local flexibility markets was proposed in Ref. [53] to analyze their design characteristics and their role in providing congestion management services for DSOs.

3.6. Distribution-level flexibility

At the distribution level, flexibility is required to manage localized voltage and congestion issues, integrate distributed generation, and coordinate distributed energy resources.

In [24], a flexibility-based expansion planning framework was developed for active distribution networks considering the coordinated operation of multi-community integrated energy systems, where electricity and thermal energy sectors were coupled to enhance supply-demand and network flexibility under renewable uncertainty. In Ref. [21], distributed energy resources were reviewed as potential

providers of power system flexibility, and various incentive mechanisms, including tariffs, contracts, and aggregation platforms, were examined to enable their participation in electricity markets and support balancing and congestion management services.

Voltage control strategies for low-voltage distribution networks with high penetration of distributed photovoltaic generation were reviewed in Ref. [54], highlighting the role of coordinated distributed generation, storage systems, and optimization techniques in improving voltage stability and operational flexibility. Voltage regulation strategies were also comprehensively reviewed in Ref. [55], highlighting the role of coordinated flexibility resources, including storage systems, network devices, and load-side resources. A security-constrained robust optimization framework was proposed in Ref. [56] to enhance the resilience of active distribution networks through coordinated scheduling of energy storage systems and flexible loads under uncertain operating conditions. A similar framework was presented in Ref. [57] for coordinating energy storage and demand-side flexibility. The role of FACTS devices in providing reactive power compensation was analyzed in Ref. [55], highlighting their capability to enhance voltage stability, improve power quality, and support reliable operation in modern power systems with growing distributed generation.

In distribution networks, topology control via network reconfiguration (switching) is an operational flexibility measure that reshapes power flows to relieve constraints and improve system performance; it can also reduce operational cost (e.g., through reduced losses, switching-cost-aware operation, and reduced interruption costs), particularly under load and renewable energy sources (RES) uncertainty [58].

Network operational measures such as topology management, network reconfiguration, and other grid-side flexibility options interact closely with market-based mechanisms used to procure distributed flexibility. In particular, local flexibility markets (LFMs) have emerged as a platform through which system operators can procure flexibility services from distributed resources to address congestion at the distribution level. However, the efficiency of these solutions depends strongly on how the interaction between operational network actions and market mechanisms is organized, including aspects such as market design, clearing processes, and the roles of system operators and market operators. Different LFM design characteristics can therefore influence how effectively flexibility resources are mobilized and coordinated with network operation strategies [53].

TSO-DSO coordination is increasingly recognized as essential for unlocking distribution-level flexibility for system-wide benefit. The provision of flexibility services from different energy resources, including smart homes, microgrids, energy storage systems, and hydrogen-based systems, was investigated in Ref. [59] to support both TSO- and DSO-level operations in future renewable-based power systems. Gu et al. [60] proposed a two-stage robust planning framework for enhancing distribution network flexibility through coordinated investments in distributed energy resources and energy storage systems under a TSO-DSO coordination scheme. The cooperation between transmission and distribution system operators was analyzed in Ref. [61], highlighting operational challenges including congestion management, balancing, and voltage support. A market-based coordination framework between TSO and DSO was proposed in Ref. [62] to enable local flexibility markets and improve congestion management. Flexibility in power systems and electricity markets was characterized in Ref. [22] across four dimensions, including time, spatiality, resource type, and risk, to analyze how market designs can efficiently allocate flexibility. A market-based framework integrating existing electricity markets with a TSO-DSO coordination platform was proposed in Ref. [63], and different TSO-DSO coordination schemes were analyzed in Ref. [64] using a game-theoretic equilibrium model under renewable generation and load uncertainty. Peer-to-peer energy trading frameworks were reviewed in Ref. [65] to examine their market structures, operational architectures, and integration with MESS for enabling

decentralized energy exchange.

3.7. Sector coupling as a flexibility resource

While the preceding subsections have addressed flexibility resources that primarily operate within or across electricity system boundaries, a growing body of literature identifies sector coupling, i.e., the integration of electricity with heat, gas, hydrogen, and mobility systems, as a distinct and complementary flexibility resource category. This subsection briefly introduces the sector-coupling references that emerged from the flexibility literature, serving as a bridge to the detailed analysis in Section 4.

In [66], a bi-level strategic bidding framework was developed for a coupled hydrogen-wind-photovoltaic energy system participating simultaneously in energy and flexible ramping markets, where hydrogen storage was utilized to mitigate renewable uncertainty, provide flexible ramping products, and enhance market revenues. In Ref. [19], an electricity-heat-hydrogen multi-energy storage system (EHH-MESS) was proposed to enhance power grid flexibility under high renewable penetration, where coordinated energy conversion and optimized operation enabled renewable curtailment reduction, peak shaving, and improved economic performance compared to conventional battery storage systems.

The role of electrolyzer-based power-to-hydrogen systems in providing ancillary services such as frequency control, voltage regulation, and congestion management was reviewed in Ref. [67]. The voltage regulation capability of power-to-hydrogen systems in active distribution networks was investigated in Refs. [68] and [69], demonstrating that coordinated control with traditional devices can effectively mitigate voltage deviations caused by high photovoltaic penetration. The capability of district heating plants integrated with multi-energy management systems to provide ancillary services was investigated in Ref. [70], demonstrating their potential to deliver automatic frequency restoration reserve while satisfying heat demand. The operation and market participation of an electric-thermal-carbon-natural gas integrated energy system were investigated in Ref. [71], demonstrating that technologies such as carbon capture and power-to-gas can enhance flexibility and enable peak and frequency regulation services.

Flexibility enhancement in multi-energy microgrids was investigated in Ref. [57] through a stochastic optimization framework integrating electro-thermal resources, multi-energy storage systems, and demand response. A simulation-based methodology was developed in Ref. [72] to assess the flexibility potential of networked MESSs, considering interactions between different energy vectors. The role of power-to-gas was reviewed in Ref. [73] as a flexibility option for integrating high shares of renewable energy and reducing long-term storage requirements.

To provide a systematic foundation for the detailed analysis in Section 4, Table 1 defines each principal sector coupling solution and characterizes its flexibility contribution along four dimensions: the type of flexibility provided, the characteristic operational timeframe, the market types and flexibility services in which it can participate, and the key limitations constraining its deployment.

Several observations emerge from this systematic characterization:

First, sector coupling solutions span the full temporal spectrum of flexibility needs from seconds-scale frequency response (electric boilers, V2G) through hours-to-days load shifting (heat pumps with thermal storage, smart EV charging) to seasonal energy storage (hydrogen in caverns, synthetic methane in gas networks).

Second, most sector coupling solutions can participate in multiple market types. This multi-market capability or “value stacking” is a distinctive advantage over single-purpose electricity-only assets, but it requires market frameworks that recognize and enable cross-service participation.

Third, a maturity gradient exists across solutions. Heat pumps, CHP, and unidirectional smart EV charging are commercially mature. V2G,

Table 1
Systematic characterization of sector coupling solutions for power system flexibility.

| Sector Coupling Solution | Definition | Type of Flexibility Provided | Characteristic Timeframe | Market Types/Flexibility Services | Key Enabling Technologies | Key Limitations | Refs |
|---|--|---|--|--|--|--|-------------------------------|
| Power-to-Heat (P2H) Heat pumps | Conversion of surplus electricity into thermal energy via electrically driven heat pumps for space heating, hot water, or district heating supply | Demand absorption; load shifting via thermal inertia; downward frequency response | Minutes to days | Ancillary services (FCR, demand response); Balancing markets; Local flexibility markets | Heat pumps (air-source, ground-source), thermal storage (hot water tanks, PCM), district heating networks | COP reduction at high temperatures; grid tariff sensitivity; regulatory separation of electricity and heat sectors | [40], [74], [75], [76] |
| Power-to-Heat (P2H) Electric boilers | Direct resistive conversion of electricity to heat for district heating or industrial processes | Surplus absorption; fast-response flexible load; curtailment reduction | Seconds to hours | Ancillary services (FCR, FFR); Balancing markets | Electric resistance boilers, thermal storage | Lower efficiency than heat pumps (COP \approx 1); economically viable only during low/negative electricity prices | [77], [78] |
| Power-to-Gas (P2G) Methanation | Conversion of surplus electricity to synthetic methane via electrolysis (producing H ₂) followed by methanation (combining H ₂ with CO ₂) | Long-duration and seasonal storage; gas grid injection; cross-sectoral decarbonization | Hours to seasons | Capacity markets (seasonal adequacy); Cross-sectoral markets; Balancing (via gas storage withdrawal) | Electrolyzer, methanation reactors, CO ₂ sources, gas grid infrastructure | Low round-trip efficiency (30-40%); high capital cost; CO ₂ source dependency; immature market framework | [79], [80], [81], |
| Power-to-Hydrogen (P2H₂) Electrolysis | Conversion of surplus electricity to hydrogen via water electrolysis (alkaline, PEM, or solid oxide) | Flexible load (downward regulation); long-duration storage; ancillary service provision; industrial feedstock | Minutes to seasons | Ancillary services (FCR, FRR, FFR); Balancing markets; Capacity markets; Cross-sectoral markets | Electrolyzers (alkaline, PEM, SOEC), compressed/liquid H ₂ storage, underground caverns, H ₂ pipelines | High capital cost; efficiency losses (60–70% electrolyzer, 25–45% round-trip P2H ₂ P); limited storage infrastructure; safety and regulatory uncertainty | [82], [67], [83], [84], [85], |
| Vehicle-to-Grid (V2G) | Bidirectional power flow between EV batteries and the grid, enabling EVs to discharge stored energy during peak demand or grid stress | Peak shaving; frequency regulation; reserve provision; mobile distributed storage | Seconds to hours | Ancillary services (FCR, FRR); Balancing markets; Local flexibility markets; P2P trading | Bidirectional chargers, smart charging protocols, aggregation platforms, communication infrastructure | Battery degradation concerns; limited bidirectional charger deployment; V2G protocol standardization incomplete; consumer acceptance dependent on incentive structures | [42], [43], [86], [87] |
| Smart EV Charging (unidirectional) | Managed timing and rate of EV charging to align with grid conditions, renewable availability, or price signals | Controllable demand; load shifting; curtailment reduction; distribution congestion relief | Minutes to hours | Balancing markets; Local flexibility markets; Demand response programs | Smart chargers, aggregation platforms, dynamic tariff systems | Dependent on user acceptance and charging flexibility windows; limited to demand reduction (no injection); aggregation complexity | [88], [89], [90] |
| Combined Heat and Power (CHP) | Co-generation of electricity and heat from fuel (typically gas), with adjustable electricity-to-heat ratio enabling flexible dispatch | Supply-side flexibility; heat-electricity ratio modulation; renewable complement; frequency support | Minutes to hours | Ancillary services; Balancing markets; Capacity markets; District heating contracts | Gas turbines/engines, heat recovery systems, thermal storage, district heating networks | Constrained by heat demand obligations; fossil fuel dependency (unless biogas); slower ramping than batteries | [27], [30], [29] |
| District Heating with Thermal Storage | Integration of thermal energy storage (hot water, PCM, underground) within district heating networks to decouple heat delivery from electricity consumption | Temporal shifting of electrical load; peak demand reduction; building thermal inertia as buffer; renewable surplus absorption | Hours to days (seasonal with underground storage) | Balancing markets (indirect via electrical load shift); Local flexibility markets; Demand response | Thermal storage tanks, underground thermal storage, district heating pipelines, smart controls | Infrastructure-intensive; geographic constraints; limited to areas with existing DHN; slow response for very short-term services | [70], [91], [92] |
| Hydrogen Fuel Cells | Re-electrification of stored hydrogen via fuel cells, producing electricity and useful waste heat | Dispatchable backup generation; peak supply; grid support during low renewable periods; waste heat for heating networks | Minutes to hours (dispatch); seasonal (via H ₂ storage) | Capacity markets; Balancing markets; Cross-sectoral markets (electricity + heat) | PEM/SOFC fuel cells, H ₂ storage, heat recovery systems | High capital cost; lower electrical efficiency than direct battery discharge; dependent on H ₂ availability and storage infrastructure | [93], [94], [95] |
| Power-to-Gas Grid Injection | Injection of hydrogen or synthetic methane into existing natural gas pipelines, utilizing gas infrastructure as distributed storage (line-pack) | Gas network as energy buffer; seasonal storage via gas storage facilities; cross-vector balancing | Hours to seasons | Cross-sectoral markets; Capacity markets (via gas storage) | Electrolyzers, gas grid injection equipment, gas quality monitoring, pipeline infrastructure | Blending limits (typically 5–20% H ₂ by volume); gas quality and safety standards; pipeline material compatibility; regulatory fragmentation | [96], [97] |

Table 2
Mapping of market-based flexibility solutions to sources, services, and participation barriers.

| Market Type | Primary Flexibility Sources | Flexibility Services Enabled | Timescale | Key Participation Barriers |
|--|---|--|--------------------|--|
| Ancillary services (FCR, FRR, FFR) | Conventional generation (3.2); Battery storage (3.4); Aggregated demand (3.3); Electrolyzers, heat pumps (3.7) | Frequency containment & restoration; Voltage regulation | Seconds to minutes | Minimum bid size; prequalification requirements; metering standards; limited eligibility for distributed/sector-coupled assets |
| Balancing/intra-day | Flexible generation (3.2); Demand response (3.3); Battery storage (3.4); CHP (3.2) | Real-time balancing; Forecast error compensation | Minutes to hours | Forecasting accuracy; aggregation complexity; gate closure timing; limited product standardization |
| Capacity markets | Dispatchable generation (3.2); Long-duration storage (3.4); Demand response (3.3); H ₂ storage (3.7) | Resource adequacy; Peak demand management | Seasonal to annual | Designed for centralized assets; verification of distributed availability; multi-year commitment requirements |
| Local flexibility markets | Distributed generation; Building demand response (3.3); Battery storage (3.4); EV charging (3.3) | Congestion management; Voltage control | Minutes to hours | Low market liquidity; high transaction costs for small actors; regulatory uncertainty; lack of product standardization |
| Peer-to-peer trading | Prosumers with solar + storage (3.4); Flexible consumers (3.3); V2G-capable EVs (3.7) | Local balancing; Energy exchange; Community self-sufficiency | Minutes to days | Regulatory frameworks not designed for P2P; settlement complexity; privacy concerns; limited scale |
| Cross-sectoral markets | Multi-energy service providers; Electrolyzers (3.7); CHP + district heating (3.7); Gas storage (3.7) | Cross-vector balancing; Value stacking; Emissions optimization | Hours to seasons | Regulatory silos between sectors; no standardized cross-vector products; coordination complexity; immature governance frameworks |

electrolysis for grid services, and district heating ancillary service provision are at intermediate maturity. P2G methanation, hydrogen fuel cells for grid support, and cross-sectoral market participation remain at earlier stages.

Fourth, the key limitations are predominantly non-technical. The most frequently recurring barriers are regulatory, market-related, and infrastructural rather than purely technological.

These studies demonstrate that sector coupling introduces flexibility capabilities particularly long-duration storage, cross-vector balancing, and multi-market value stacking that electricity-only resources cannot provide. The detailed mechanisms, configurations, and benefits of sector coupling for flexibility are comprehensively analyzed in Section 4.

3.8. Market-based solutions for flexibility procurement

While the preceding subsections (3.2-3.7) identified the physical and technological sources of flexibility, the activation and efficient deployment of these resources depends on market-based solutions the procurement mechanisms, trading platforms, and institutional frameworks through which flexibility services are valued, allocated, and remunerated. This subsection systematically examines the principal market types for electricity flexibility, establishing explicit connections between each market mechanism and the sources that participate in it.

- (a) Ancillary service markets.** Ancillary service markets are the most established mechanism for procuring short-term flexibility, operated by TSOs to maintain system frequency and voltage stability. These markets include frequency containment reserves (FCR), frequency restoration reserves (FRR), fast frequency reserves (FFR), and reactive power/voltage support services [20] [59]. Traditionally provided by conventional generation (Section 3.2), the eligible source base is expanding: battery storage (Section 3.4) now participates in FCR markets; aggregated demand-side resources (Section 3.3) demonstrate frequency support capability [37], [40]; and sector-coupled assets such as electrolyzers (Section 3.7) can provide reserve services [67].
- (b) Balancing and intra-day markets.** Balancing markets address real-time deviations on timescales from minutes to hours. Supply-side resources (Section 3.2) remain primary participants, but demand-side flexibility (Section 3.3) is growing through aggregated demand response and dynamic EV charging [37], [42]. Energy storage (Section 3.4) participates through rapid charge-discharge cycling [45]. Reference [22] characterized how market designs influence flexibility allocation.
- (c) Capacity markets and resource adequacy mechanisms.** Capacity markets ensure long-term adequacy by remunerating

providers for availability during scarcity events [20]. These incentivize generation capacity (Section 3.2), long-duration storage (Section 3.4), and increasingly demand-side resources (Section 3.3). Hydrogen storage (Section 3.7) can provide seasonal adequacy [84], and district heating with thermal storage can guarantee demand reduction during peaks [70].

- (d) Local flexibility markets (LFMs)** LFMs enable DSOs to procure flexibility for distribution-level congestion and voltage issues [20], [53]. Primary sources include distributed generation, building-level demand response (Section 3.3), battery storage (Section 3.4), and EV charging (Section 3.3) [37]. Reference [59] demonstrated regional flexibility platforms in Finland, while [62] proposed TSO-DSO coordination for local procurement.
- (e) Peer-to-peer (P2P) energy trading platforms.** P2P platforms enable decentralized exchange between prosumers using blockchain and smart contracts [65], [20]. Primary sources are residential prosumers with solar and storage (Section 3.4), flexible consumers (Section 3.3), and V2G-capable EVs (Section 3.7).
- (f) Cross-sectoral and integrated energy markets.** Emerging market structures enable flexibility trading across energy vectors, including transactive energy frameworks, [98], integrated electricity-gas platforms [99], and carbon-linked mechanisms [3], [71]. These face regulatory silos and the absence of standardized cross-vector flexibility products [100].

Several observations emerge from this mapping.

- 1. Source eligibility is expanding across all market types.** Every market category shows a trend from exclusive reliance on conventional generation toward broader participation by storage, demand-side, and sector-coupled resources. However, the pace of this expansion varies significantly: ancillary service markets have progressed furthest in technology-neutral procurement, while capacity markets and cross-sectoral markets remain most restrictive.
- 2. Participation barriers are predominantly institutional, not technical.** In most cases, the physical capability of flexibility sources exceeds their market access. Battery storage can technically provide FCR, but minimum bid sizes and prequalification requirements limit participation. Electrolyzers can technically provide balancing services, but eligibility rules designed for generators exclude them. This finding reinforces the regulatory reform priority identified in the paper's research agenda (Section 5).
- 3. Sector-coupled sources face the highest cumulative barriers.** Resources from sub-section 3.7 (electrolyzers, district heating, V2G) appear across multiple market types but consistently face the most significant participation barriers reflecting the regulatory silos and

market design gaps identified as the binding constraint on sector coupling deployment (sub-section 4.4).

4. **A completeness gap exists in cross-sectoral market design.** While the other five market types are operational (though evolving), cross-sectoral markets remain largely conceptual or pilot-stage. This gap directly constrains the economic viability of sector coupling, as multi-vector assets cannot fully monetize their flexibility contributions without market mechanisms that recognize cross-sectoral value. This observation directly motivates the market coordination mechanism (mechanism iv) analyzed in sub-section 4.1.1.

These observations establish a critical bridge between the flexibility sources analyzed in sub-sections 3.2-3.7 and the sector-coupling analysis in Section 4: the physical potential for flexibility exists across diverse resources, but its realization depends on market solutions that are still evolving particularly for sector-coupled assets. Section 4 examines how sector coupling can both expand the source base for flexibility and drive the development of cross-sectoral market solutions.

3.9. Synthesis and gap analysis

Tables 3 and 4 provide a systematic synthesis of the reviewed literature across the six flexibility resource categories and across flexibility timescales and services, respectively. Together, they reveal the coverage patterns and gaps in the current flexibility landscape that motivate the focus on sector coupling in Section 4.

Key observations from the synthesis tables:

Several cross-cutting patterns emerge from Tables 3 and 4 that directly motivate the focus on sector coupling in Section 4.

1. **Energy storage is the most frequently addressed resource category,** appearing in the majority of reviewed studies, reflecting its recognized centrality to flexibility provision. However, most studies focus on battery-based or pumped hydro storage operating within the electricity domain, with limited consideration of cross-sectoral storage pathways (thermal, hydrogen, gas line-pack) that sector coupling enables.
2. **Sector coupling remains the least comprehensively covered category.** While approximately one-third of the reviewed studies address some form of sector coupling, these tend to focus on individual technologies (e.g., electrolyzers, CHP) rather than systematic cross-sectoral integration. Only a small number of studies (e.g., Refs. [9,24,56]) address flexibility comprehensively across all six resource categories including sector coupling.
3. **Long-term flexibility is underrepresented.** The majority of studies focus on short- and medium-term timescales, with relatively few addressing seasonal storage or long-term adequacy precisely the timescales where sector coupling (through hydrogen storage, thermal seasonal storage, and gas infrastructure) offers the greatest comparative advantage over electricity-only solutions.
4. **Frequency and voltage services are well-covered by electricity-centric resources,** but congestion management and market regulation increasingly require cross-sectoral coordination, particularly as distributed energy resources and sector-coupled assets proliferate at the distribution level.
5. **No single flexibility resource category is sufficient.** The tables confirm that effective flexibility provision requires coordinated deployment across all categories. Sector coupling is unique in that it simultaneously contributes to multiple other categories which it enhances demand-side flexibility (through controllable heat pumps

Table 3
Mapping of reviewed studies across flexibility resource categories.

| Reference | Supply-side | Demand-side | Energy Storage | Transmission | Distribution | Sector Coupling |
|-----------|-------------|-------------|----------------|--------------|--------------|-----------------|
| [28] | ✓ | - | ✓ | - | - | - |
| [38] | - | ✓ | ✓ | - | - | ✓ |
| [31] | ✓ | - | ✓ | - | - | ✓ |
| [18] | - | - | - | ✓ | - | - |
| [66] | ✓ | - | ✓ | - | - | ✓ |
| [101] | ✓ | ✓ | ✓ | - | - | - |
| [23] | ✓ | ✓ | ✓ | ✓ | - | - |
| [24] | - | - | ✓ | - | ✓ | ✓ |
| [102] | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| [32] | ✓ | - | - | - | - | - |
| [52] | - | - | ✓ | ✓ | ✓ | - |
| [19] | - | - | ✓ | - | ✓ | ✓ |
| [20] | - | ✓ | ✓ | ✓ | ✓ | - |
| [1] | ✓ | ✓ | ✓ | ✓ | ✓ | - |
| [21] | - | ✓ | ✓ | - | ✓ | - |
| [39] | - | ✓ | - | - | ✓ | - |
| [60] | - | - | ✓ | ✓ | ✓ | - |
| [61] | - | - | - | ✓ | - | - |
| [103] | - | - | - | ✓ | ✓ | - |
| [22] | ✓ | ✓ | - | ✓ | ✓ | - |
| [63] | - | - | - | ✓ | ✓ | - |
| [64] | - | - | - | ✓ | ✓ | - |
| [59] | - | ✓ | ✓ | ✓ | ✓ | ✓ |
| [67] | - | - | ✓ | - | - | ✓ |
| [40] | - | ✓ | - | - | - | - |
| [70] | - | - | - | - | - | ✓ |
| [71] | - | - | ✓ | - | - | ✓ |
| [68] | - | ✓ | ✓ | - | ✓ | ✓ |
| [69] | - | ✓ | ✓ | - | ✓ | ✓ |
| [26] | ✓ | ✓ | ✓ | ✓ | - | - |
| [54] | - | - | - | - | ✓ | - |
| [27] | ✓ | - | - | - | - | - |
| [30] | ✓ | - | ✓ | - | - | - |
| [29] | ✓ | - | ✓ | - | - | ✓ |
| [34] | - | ✓ | - | ✓ | - | - |
| [72] | - | - | - | - | - | ✓ |
| [36] | - | ✓ | - | - | - | - |

Table 4
Mapping of reviewed studies across flexibility timescales and services.

| Reference | Short-term | Medium-term | Long-term | Freq. Containment & Restoration | Voltage Regulation | Congestion Mgmt. | Balancing | Market Regulation | Energy & Cost Efficiency |
|-----------|------------|-------------|-----------|---------------------------------|--------------------|------------------|-----------|-------------------|--------------------------|
| [28] | - | ✓ | ✓ | - | - | - | ✓ | ✓ | ✓ |
| [38] | - | ✓ | ✓ | - | - | - | ✓ | - | ✓ |
| [31] | ✓ | ✓ | - | - | - | - | ✓ | ✓ | ✓ |
| [18] | - | ✓ | - | - | - | ✓ | ✓ | - | - |
| [66] | ✓ | ✓ | ✓ | - | - | - | ✓ | ✓ | ✓ |
| [101] | ✓ | - | ✓ | - | - | - | ✓ | - | ✓ |
| [23] | ✓ | ✓ | ✓ | ✓ | - | - | ✓ | - | - |
| [24] | ✓ | - | ✓ | ✓ | ✓ | ✓ | ✓ | - | ✓ |
| [102] | ✓ | ✓ | ✓ | - | - | - | ✓ | ✓ | ✓ |
| [32] | ✓ | - | - | ✓ | - | - | ✓ | - | - |
| [52] | ✓ | ✓ | ✓ | - | ✓ | ✓ | ✓ | - | - |
| [19] | ✓ | ✓ | - | - | - | - | ✓ | - | ✓ |
| [20] | ✓ | ✓ | - | - | ✓ | ✓ | ✓ | ✓ | ✓ |
| [1] | ✓ | ✓ | ✓ | ✓ | - | - | ✓ | ✓ | ✓ |
| [21] | ✓ | ✓ | - | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| [39] | ✓ | - | - | - | ✓ | - | ✓ | - | ✓ |
| [60] | ✓ | - | ✓ | - | ✓ | ✓ | ✓ | - | ✓ |
| [61] | ✓ | - | - | - | ✓ | ✓ | ✓ | - | ✓ |
| [103] | ✓ | - | - | - | - | ✓ | ✓ | ✓ | ✓ |
| [22] | ✓ | ✓ | ✓ | - | - | ✓ | ✓ | ✓ | ✓ |
| [63] | - | - | ✓ | - | - | ✓ | ✓ | ✓ | ✓ |
| [64] | ✓ | - | ✓ | ✓ | - | ✓ | ✓ | ✓ | ✓ |
| [59] | ✓ | - | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | - |
| [67] | ✓ | - | - | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| [40] | ✓ | - | ✓ | ✓ | - | ✓ | ✓ | ✓ | ✓ |
| [70] | ✓ | - | - | ✓ | - | ✓ | ✓ | - | ✓ |
| [71] | ✓ | - | - | ✓ | - | - | ✓ | ✓ | ✓ |
| [68] | ✓ | - | - | - | ✓ | - | - | - | ✓ |
| [69] | ✓ | - | - | - | ✓ | - | - | - | ✓ |
| [26] | ✓ | ✓ | ✓ | ✓ | ✓ | - | ✓ | - | ✓ |
| [54] | ✓ | - | - | - | ✓ | - | - | - | ✓ |
| [27] | ✓ | - | - | ✓ | ✓ | ✓ | - | ✓ | ✓ |
| [30] | - | ✓ | ✓ | - | - | - | - | - | ✓ |
| [29] | ✓ | - | - | ✓ | ✓ | - | ✓ | - | - |
| [34] | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| [72] | ✓ | - | - | - | - | - | ✓ | ✓ | ✓ |
| [36] | - | ✓ | - | - | - | - | ✓ | - | ✓ |

and EV charging), expands storage options (through hydrogen and thermal storage), and supports both transmission and distribution operations (through cross-vector balancing and congestion relief).

These observations establish the analytical foundation for Section 4, which examines in detail how sector coupling addresses the gaps identified here providing the long-duration storage, cross-sectoral balancing, and multi-market value creation that electricity-only flexibility resources cannot deliver alone.

Fig. 2 presents the power system flexibility framework adopted in this review, illustrating the six resource categories analyzed in Sections 3.2-3.7, the flexibility services they collectively deliver, and the temporal scales across which flexibility operates. The framework's three-tier structure reflects the dual analytical perspective introduced in Section 3.1, i.e., resources (Tier 1) provide services (Tier 2) across timescales (Tier 3) and highlights sector coupling as a resource category that spans the full range of bilateral and multi-lateral configurations examined in Section 4.

4. Sector coupling and flexibility

Sector coupling refers to the coordinated integration of multiple energy carriers such as electricity, heat, gas, hydrogen, and mobility into a unified system in which energy can be converted between vectors, shifted across time through storage, and transferred across spatial boundaries through interconnected infrastructure [6]. In the context of power system flexibility, sector coupling is significant because it extends the portfolio of available flexible resources beyond the electricity domain, enabling surplus renewable generation to be absorbed, stored,

and utilized across sectors rather than curtailed [104].

The need for this cross-sectoral approach arises from a fundamental limitation of electricity-only flexibility strategies. While conventional approaches such as dispatchable generation, demand response within the electrical sector, and battery storage address short-to-medium-term balancing, they are insufficient for the full range of flexibility challenges created by deep renewable penetration and concurrent electrification of heating, transport, and industry [105], [106]. Sector coupling addresses this gap by creating bidirectional energy pathways: surplus electricity can be converted into thermal energy (P2H), hydrogen or synthetic gas (P2G/P2H₂), or stored in vehicle batteries (P2M), while energy from coupled sectors can flow back to support the grid when needed (e.g., through V2G or fuel cell re-electrification) [107], [104]. These cross-sectoral pathways effectively transform heating networks, gas infrastructure, hydrogen systems, and transport fleets into distributed flexibility assets that complement electricity-side resources.

This section examines the role of sector coupling in enhancing power system flexibility through a structured analysis organized as follows. Section 4.1 identifies where and at what system level (TSO, DSO, or both) sector coupling contributes to flexibility, drawing on evidence from the reviewed literature. Section 4.1.1 defines and classifies the mechanisms through which sector coupling generates flexibility. Section 4.2 then provides a systematic analysis of specific bilateral and multi-lateral coupling configurations, examining their individual flexibility contributions, enabling technologies, and outstanding challenges. Section 4.3 synthesizes the benefits of inter-sectoral synergies, and Section 4.4 addresses the technical, regulatory, and financial challenges that must be overcome for effective implementation.

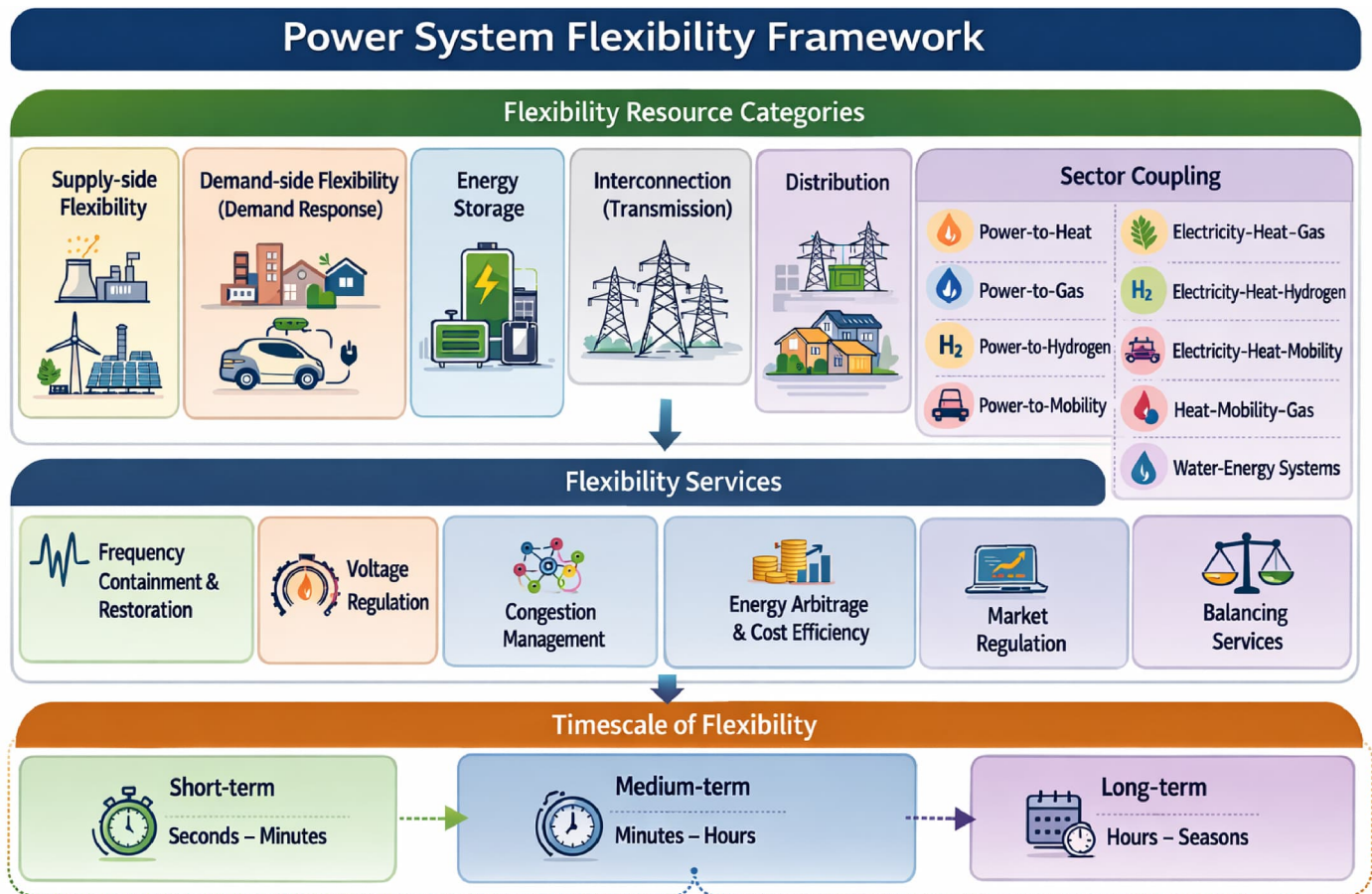


Fig. 2. Power system flexibility framework.

4.1. Role of sector coupling in enhancing flexibility

A central finding from the reviewed literature is that sector coupling contributes to flexibility provision at multiple system levels from transmission-level balancing to distribution-level congestion management and that its value increases when multiple sectors are coordinated simultaneously. This subsection organizes the evidence around three analytical pillars: (a) flexibility contributions at the TSO level, (b) flexibility contributions at the DSO level, and (c) system-wide benefits that emerge from cross-sectoral integration.

(a) **Flexibility at the TSO level.** At the transmission level, sector-coupled assets expand the range of resources available for system balancing and ancillary service provision. TSOs procure services such as FCR, FRR, and FFR to maintain frequency stability, particularly in low-inertia systems with high renewable penetration [59]. Hydrogen electrolyzers, when equipped with predictive control systems, can modulate their consumption to provide reserve services without compromising their primary hydrogen production function [67]. Heat pumps and HVAC systems integrated into district heating networks have demonstrated the capability to provide frequency support and demand-side flexibility under coordinated control schemes [40], [70]. Power-to-gas systems and carbon capture facilities offer additional layers of operational flexibility while enabling value creation through participation in both carbon and ancillary service markets [71]. The coordinated operation of gas and electricity networks has also been shown to improve the flexibility of both systems at the transmission level [108].

(b) **Flexibility at the DSO level.** At the distribution level, sector-coupled technologies play an equally critical role in managing local constraints and enabling renewable integration. Hydrogen production strategies tailored to local grid conditions [109], combined with multi-vector integration approaches [110], contribute to localized flexibility provision. Voltage control schemes utilizing power-to-hydrogen systems, photovoltaics, and capacitors have been shown to enhance distribution-level grid stability [68]. The integration of district heating systems with hydrogen technologies and thermal energy storage enables DSOs to manage peak demand periods and network congestion, potentially deferring costly grid infrastructure upgrades [110]. At the building and community scale, decentralized heat pumps integrated into district heating systems enhance flexibility by adjusting electricity consumption in response to price or frequency signals [74]. The strategic placement of EV charging stations and the design of charging protocols based on local network requirements contribute to distribution-level flexibility, with V2G-capable vehicles providing localized peak shaving and voltage support [86].

(c) **System-wide benefits of cross-sectoral integration.** Beyond the contributions at individual system levels, sector coupling generates emergent benefits that arise from the coordinated operation of multiple energy vectors. These system-wide benefits include:

- Enhanced renewable integration:** Sector coupling creates multiple pathways to utilize surplus renewable electricity through conversion to heat, hydrogen, or stored energy in vehicles, thereby reducing curtailment and improving the economic value of variable generation [111], [77].

- **Expanded flexibility portfolio:** By connecting sectors with distinct load profiles, storage characteristics, and temporal dynamics, sector coupling diversifies the portfolio of flexibility resources available to system operators, reducing dependence on any single technology or sector [112].
- **Improved resource and infrastructure efficiency:** Multi-energy systems that share infrastructure across sectors (e.g., CHP units serving both electricity and heat, electrolyzers serving both hydrogen demand and grid services) achieve higher asset utilization rates, reducing overall system costs [113], [114].
- **Deeper decarbonization:** Sector coupling provides pathways for electrifying hard-to-abate sectors including high-temperature industrial processes, long-distance transport, seasonal heating, that cannot be decarbonized through direct electrification alone [107], [115].

The foundational rules for linking various technologies to achieve emission reductions through sector coupling were outlined in Ref. [111]. A comprehensive analysis of 116 case studies of local integrated energy systems in Ref. [112] highlighted storage systems and sector coupling as effective methods for achieving flexibility, while identifying gaps in integrating sector coupling with mobility (especially EVs) and noting the frequent oversight of social components in optimization models. AI-based demand-side management methods have been proposed in Ref. [116] to enhance the resilience of distribution grids through multi-energy applications while considering local network conditions. The open-source modeling framework introduced in Ref. [117] for analyzing the North Sea region's energy transition confirmed that sector coupling offers clear benefits in terms of

decarbonization, system flexibility, and efficiency, though overcoming barriers requires careful integration of technical and socio-economic factors.

The mechanisms through which these flexibility contributions are realized are systematically classified in the following subsection (4.1.1), while Table 6 (at the end of this section) provides a consolidated synthesis of all dimensions and key findings.

To consolidate the insights discussed throughout this section, Table 5 provides a structured summary of the key dimensions through which sector coupling enhances power system flexibility, alongside the principal findings, enabling technologies, relevant system levels, and representative references from the reviewed literature. This synthesis maps the multi-dimensional nature of sector coupling's contribution to flexibility and serves as a foundation for the detailed analysis of specific coupling configurations in Section 4.2.

Several cross-cutting insights emerge from this synthesis:

First, sector coupling's flexibility contribution is inherently multi-level. Nearly every dimension identified in Table 5 operates across both TSO and DSO levels, reinforcing the need for coordinated operational frameworks between system operators which is a recurring finding in the reviewed literature [60], [103], [64].

Second, the dimensions are interdependent, not independent. For example, the flexibility value of hydrogen-based systems (dimension 3) is amplified when combined with market coordination mechanisms (dimension 9) that allow electrolyzers to participate in reserve markets. Similarly, thermal sector coupling (dimension 2) is most effective when supported by digitalization (dimension 8) that enables real-time coordination of distributed heat pumps. This interdependence underscores the systemic nature of sector coupling and argues against piecemeal

Table 5
Summary of key dimensions and findings on the role of sector coupling in enhancing power system flexibility.

| Dimension | Key Findings | Enabling Technologies/Approaches | System Level (TSO/DSO) | Representative Refs |
|--|--|--|--|----------------------------|
| Multi-energy system integration | Integrating electricity, heat, gas, hydrogen, and transport networks creates new optimization opportunities and a more flexible energy system; no single flexibility measure satisfies all technical, economic, and environmental requirements | Multi-energy microgrids, integrated energy hubs, multi-vector optimization platforms | Both TSO and DSO | [113], [112], [114], [118] |
| Thermal sector coupling | District heating systems with decentralized heat pumps enhance flexibility by adjusting electricity consumption in response to price or frequency signals; thermal inertia provides inherent buffering | Heat pumps, thermal storage, district heating networks, CHP units | Primarily DSO; ancillary services to TSO | [74], [40], [70], [119] |
| Hydrogen-based flexibility | Hydrogen production can be modulated for downward flexibility (excess RE) or upward flexibility (high demand); electrolyzers can participate in reserve markets without compromising primary production | Electrolyzers (alkaline, PEM), hydrogen storage, fuel cells, predictive control systems | Both TSO and DSO | [83], [67], [109], [68] |
| Transport electrification and V2G | Strategic placement of EV charging stations and V2G-capable fleets contributes to flexibility at both voltage levels; EVs act as mobile, distributed storage assets | EVs, bidirectional chargers, smart charging protocols, aggregation platforms | Both TSO and DSO | [88], [42], [43], [41] |
| Gas-electricity coordination | Coordinated operation of gas and electricity networks improves flexibility of both systems; gas pipeline line-pack provides inherent storage buffering | Gas-electric co-optimization, P2G injection, line-pack management | Primarily TSO | [108], [120], [96], [121] |
| Renewable integration and curtailment reduction | Sector coupling creates multiple pathways to utilize surplus renewable energy, reducing curtailment and improving system reliability; deeper coupling reduces net demand variability | P2H, P2G, P2M conversion technologies, multi-vector storage | Both TSO and DSO | [111], [77], [122] |
| Decarbonization alignment | Sector coupling accelerates decarbonization by enabling electrification of heating, transport, and industry; provides pathways for hard-to-abate sectors through green hydrogen and synthetic fuels | Green hydrogen, high-temperature heat pumps, synthetic methane, fuel-cell vehicles | System-wide | [107], [113], [115], [111] |
| Digitalization as enabler | AI-based DSM, digital twins, and predictive control systems are essential for coordinating cross-sectoral flexibility in real time; digital platforms enable market participation of distributed assets | IoT, AI/ML forecasting, digital twins, smart metering, aggregation platforms | Both TSO and DSO | [123], [124], [116] |
| Market and regulatory coordination | Current siloed regulatory frameworks limit cross-sectoral value recognition; unified flexibility marketplaces and reformed pricing signals are needed to activate latent flexibility | Flexibility markets, transactive energy platforms, TSO-DSO coordination frameworks, carbon pricing | Both TSO and DSO | [103], [125], [99], [7] |
| Mechanisms of flexibility enhancement | Four principal mechanisms identified: (i) energy conversion, (ii) storage and temporal shifting, (iii) demand-side coordination, (iv) market and operational coordination; maximum flexibility requires all four operating in concert | See detailed mechanism-specific technologies in Table 3 (4.1.1) | Both TSO and DSO | [67], [40], [43], [126] |

Table 6
Mechanisms of sector coupling enhancing power system flexibility.

| Mechanism Category | Flexibility Contribution | Temporal Scale | Key Enabling Technologies | Primary Coupling Configurations |
|--|--|--------------------------------|---|--|
| Energy Conversion | Surplus absorption, curtailment reduction, bidirectional energy flow between vectors | Seconds to hours | Heat pumps, electric boilers, electrolyzers, fuel cells, CHP units | P2H, P2G/P2H ₂ , P2M, Elec-Heat-Gas |
| Storage & Temporal Shifting | Load shifting, peak shaving, seasonal balancing, long-duration energy reserve | Minutes to seasons | TES, H ₂ storage (tanks, caverns), gas line-pack, EV batteries (V2G) | P2H, P2G/P2H ₂ , P2M, Elec-Heat-H ₂ , Elec-H ₂ -Mob |
| Demand-Side Coordination | Demand response, load profile smoothing, aggregated flexibility provision | Minutes to days | Smart HP controls, EV charging platforms, industrial DSM, multi-energy aggregators | P2H, P2M, Heat-Mob-Gas, Elec-Heat-Mob |
| Market & Operational Coordination | Cross-sectoral dispatch optimization, ancillary service provision, value stacking | Real-time to seasonal planning | Multi-energy optimization platforms, transactive energy frameworks, TSO-DSO coordination, flexibility markets | All configurations |

implementation [67], [83].

Third, a maturity gradient exists across dimensions. Thermal sector coupling and transport electrification are comparatively mature, with demonstrated commercial deployments, while hydrogen-based flexibility and integrated market coordination remain at earlier stages of development. This gradient has implications for implementation sequencing: near-term flexibility gains are most readily achievable through P2H and managed EV charging, while long-term, deep flexibility requires the maturation of hydrogen infrastructure and cross-sectoral market reforms [75], [41].

Fourth, digitalization and market reform emerge as cross-cutting enablers. Unlike the technology-specific dimensions (thermal, hydrogen, mobility, gas), digitalization and market coordination appear as enabling prerequisites for unlocking the full potential of every other dimension. This suggests that investment in digital infrastructure and regulatory reform should be prioritized alongside, not after, technology deployment [124], [123].

These dimensions and their interrelationships provide the analytical foundation for the detailed examination of specific sector-coupling configurations in Section 4.2, where each bilateral and multi-lateral coupling pathway is assessed with respect to its activation of the mechanisms identified in Section 4.1.1 and its contribution to the flexibility dimensions summarized in Table 6.

4.1.1. Mechanisms of sector coupling enhancing flexibility

To systematically analyze how sector coupling enhances power system flexibility, it is essential to first define what constitutes a “mechanism” in this context. In this study, **mechanisms of sector coupling** are defined as *the operational and technological processes through which energy is converted, transferred, stored, or jointly managed across two or more energy sectors including electricity, heat, gas/hydrogen, and mobility, thereby generating flexibility that would not be available within any single sector operating in isolation*. These mechanisms create new degrees of freedom for system operators and market participants by expanding the set of controllable resources, extending the temporal and spatial range over which energy can be balanced, and enabling substitution between energy carriers in response to system conditions.

Based on a systematic analysis of the reviewed literature, four principal mechanism categories have been identified: (i) energy conversion mechanisms, (ii) storage and temporal shifting mechanisms, (iii) demand-side coordination mechanisms, and (iv) market and operational coordination mechanisms. Each is described below, with balanced coverage across the full range of sector-coupling configurations examined in this review, including P2H, P2G/P2H₂, P2M, and multi-vector integrated systems.

(i) Energy Conversion Mechanisms

Energy conversion mechanisms transform surplus electricity from one energy vector into another, thereby creating controllable loads on the electricity side while delivering useful energy to a coupled sector.

This bidirectional convertibility is the foundational mechanism through which sector coupling generates flexibility.

How it enhances flexibility: When renewable generation exceeds electrical demand, conversion technologies absorb the surplus by directing it into alternative energy forms, reducing curtailment and providing downward flexibility to the grid. Conversely, when generation is scarce, some conversion pathways can be reversed (e.g., fuel cells re-converting hydrogen to electricity) or alternative supply routes can be activated (e.g., gas-fired CHP meeting both heat and electricity demand), providing upward flexibility.

Key enabling technologies and examples.

- **Power-to-Heat (P2H):** Heat pumps and electric boilers convert surplus electricity into thermal energy for district heating networks or building-level systems. This is among the most mature and cost-effective conversion mechanisms, with heat pumps achieving coefficients of performance (COP) of 3–5, effectively multiplying the energy value of each unit of electricity consumed [75], [104]. Reference [77] demonstrated that P2H conversion in Northern-central Europe significantly reduced fossil fuel dependence by aligning thermal demand with renewable electricity supply.
- **Power-to-Gas/Power-to-Hydrogen (P2G/P2H₂):** Electrolyzers convert surplus electricity into hydrogen (or, via subsequent methanation, into synthetic methane), which can be injected into gas networks, stored, or used as industrial feedstock. Reference [85] presented advanced electrolyzer models operating at high current densities that maintain cost-effectiveness while providing grid-responsive operation. The low-carbon economic dispatch model in Ref. [97] demonstrated how P2G technology absorbs surplus wind generation, reducing both system costs and carbon emissions.
- **Power-to-Mobility (P2M):** Managed EV charging converts grid electricity into stored chemical energy in vehicle batteries. While the primary purpose is transportation, the timing and rate of this conversion are controllable, making EV charging a flexible load. Reference [127] highlighted how P2M creates dynamic synergies between power and transportation sectors through controllable energy conversion.
- **Combined Heat and Power (CHP):** CHP units simultaneously convert fuel (typically natural gas) into both electricity and heat, enabling flexible adjustment of the electricity-to-heat output ratio in response to grid conditions. Reference [119] showed that CHP plants within district heating systems facilitated increased wind power integration by modulating their output to complement variable renewable generation.

(ii) Storage and Temporal Shifting Mechanisms

Storage and temporal shifting mechanisms decouple the moment of energy production from the moment of energy consumption by converting electricity into a storable form in a coupled sector. This creates

flexibility across multiple timescales from minutes to seasons depending on the storage medium and capacity.

How it enhances flexibility: By absorbing surplus generation during periods of excess and releasing stored energy during periods of scarcity, cross-sectoral storage expands the temporal flexibility portfolio of the power system far beyond what electricity-only storage (e.g., batteries) can economically provide. Different coupled sectors offer storage at different durations, creating complementary temporal coverage.

Key enabling technologies and examples.

- *Thermal energy storage (TES) via P2H:* Hot water tanks, phase-change materials, and underground thermal storage decouple electricity consumption (for heat production) from heat delivery. The thermal inertia of buildings and district heating networks provides inherent short-term buffering capacity. Reference [78] experimentally validated power-to-heat storage with high-temperature phase-change materials, confirming its role in bridging thermal and electrical networks. Reference [128] demonstrated that thermal storage combined with heat pumps provides superior performance in mitigating unexpected conditions through effective temporal shifting of heating loads.
- *Hydrogen storage via P2H₂:* Compressed gas tanks, liquid hydrogen, and underground caverns enable storage over time-scales ranging from hours to seasons, addressing the critical gap in long-duration energy storage. Reference [84] explored hydrogen storage across 13 Central European nations, demonstrating that both seasonal and short-term hydrogen storage support grid balancing and minimize electricity generation costs. Reference [129] further emphasized hydrogen's critical role in seasonal demand balancing.
- *Gas network line-pack via P2G:* The pressurized gas pipeline network itself serves as a distributed storage medium. By modulating the rate of gas injection (from P2G) and withdrawal, the inherent compressibility of gas in pipelines provides short-to-medium-term buffering. Reference [121] explicitly captured this flexibility through gas pipeline line-pack modeling, demonstrating lower operating costs and enhanced system flexibility.
- *Vehicle batteries via P2M/V2G:* EV batteries store electricity that can be temporally shifted through delayed charging (unidirectional) or discharged back to the grid (bidirectional V2G) during peak demand periods. Reference [43] demonstrated that V2G technologies enable EVs to provide peak shaving and frequency regulation by temporally shifting stored energy. National strategies analyzed in Ref. [43] reflect growing recognition of EVs as temporal flexibility assets.

(iii) Demand-Side Coordination Mechanisms

Demand-side coordination mechanisms leverage controllable loads and flexible consumption patterns in coupled sectors to align energy demand with variable renewable supply. Unlike conversion mechanisms, which create new loads, coordination mechanisms modulate existing sectoral demands in response to electricity system signals.

How it enhances flexibility: By coordinating demand across sectors, these mechanisms shift, reduce, or increase electricity consumption in response to price signals, grid frequency, or congestion conditions. The diversity of demand profiles across sectors such as heating peaks in winter mornings, transport charging in evenings, industrial processes during working hours, creates natural complementarities that can be exploited to flatten the aggregate load curve and reduce peak-to-trough ratios.

Key enabling technologies and examples.

- *Heat pump demand response:* Decentralized heat pumps integrated into district heating or building systems can adjust electricity consumption in response to price or frequency signals without

compromising thermal comfort, thanks to the thermal inertia of buildings and hot water systems. Reference [74] demonstrated that integrating decentralized heat pumps into district heating enhances flexibility by adjusting electricity consumption in response to system signals. References [40] and [70] showed that heat pumps and HVAC systems provide ancillary services including frequency support under coordinated control schemes.

- *Smart EV charging coordination:* Aggregated fleets of EVs, managed by digital platforms, shift charging demand to periods of surplus generation or low system stress. Reference [88] illustrated how leveraging EV mobility patterns enables participation in ancillary services, while [90] explored adaptive pricing mechanisms that coordinate transport energy demand with grid conditions to improve system-wide efficiency.
- *Industrial demand flexibility:* Industrial processes with inherent thermal or chemical storage capacity (e.g., electrolysis for hydrogen production) can modulate their electricity consumption. Reference [83] demonstrated that hydrogen production can be modulated to provide downward flexibility during excess renewable generation or upward flexibility during periods of high demand, without compromising primary production functions.
- *Multi-sector demand aggregation:* AI-based demand-side management methods have been proposed in Ref. [116] to enhance the resilience of distribution grids by coordinating flexible demands across multiple energy applications while considering local network conditions. This cross-sectoral aggregation of demand-side resources creates a richer and more responsive flexibility portfolio than single-sector demand response alone.

(iv) Market and Operational Coordination Mechanisms

Market and operational coordination mechanisms enable the economic and operational integration of flexibility resources across sectors through market platforms, pricing signals, and coordinated dispatch frameworks. While the preceding three categories describe physical and technological processes, this category addresses the institutional and market-level mechanisms that activate and optimize cross-sectoral flexibility.

How it enhances flexibility: These mechanisms ensure that the physical flexibility created by conversion, storage, and demand coordination is recognized, valued, and efficiently allocated across the energy system. Without appropriate market signals and coordination frameworks, cross-sectoral flexibility resources remain underutilized, as actors in individual sectors lack the information and incentives to optimize across domain boundaries.

Key enabling technologies and examples.

- *Integrated multi-energy system optimization:* Coordinated dispatch frameworks that jointly optimize across electricity, heat, gas, and transport networks capture synergies that single-sector optimization cannot. Reference [126] proposed a two-stage rolling optimization strategy for park-level integrated energy systems that coordinates flexible resources across sectors, reducing the operational impact of renewable variability. The flexibility modeling framework in Ref. [7] employed MILP to coordinate energy flows across thermal, electrical, and gas domains, facilitating participation in balancing services and energy markets. District multi-energy systems reviewed in Ref. [114] integrate various energy sources and technologies, with emphasis on storage and demand-side management to enhance system flexibility and balance energy flows.
- *Cross-sectoral market participation:* Flexibility assets operating at the interface of multiple sectors can participate in multiple markets simultaneously, stacking revenue from energy, ancillary services, and capacity markets. Reference [99] demonstrated reduced energy procurement costs through coordinated multi-energy market participation by scheduling flexible resources across electricity and natural gas markets. The transactive energy paradigm proposed in

Ref. [125] enabled coordinated operation and energy sharing among interconnected microgrids, demonstrating improved economic efficiency and system flexibility.

- **TSO-DSO coordination for sector-coupled assets:** Sector-coupled resources located at the distribution level (heat pumps, EVs, small-scale electrolyzers) must be coordinated between TSO and DSO operational domains. Reference [67] showed that hydrogen electrolyzers can participate in TSO reserve markets when equipped with predictive control systems. The unified flexibility marketplace concept proposed in Ref. [63] facilitates coordinated procurement across both TSO and DSO levels for sector-coupled assets.
- **Sector coupling within open modeling and planning frameworks:** Reference [118] explored how sector coupling has been addressed in energy system models, emphasizing the need for structured methods for selecting appropriate modeling tools. The open-source frameworks introduced enable analysis of complex, renewable-based systems where sector coupling provides clear benefits in terms of decarbonization, flexibility, and efficiency.

Table 6 synthesizes the four mechanism categories, mapping each to its flexibility contribution, characteristic temporal scale, key enabling technologies, and the sector-coupling configurations in which it primarily operates.

Several important observations emerge from this systematic classification:

First, **the four mechanisms are complementary, not substitutive.** Maximum flexibility is achieved when all four operate in concert which conversion creates the physical link between sectors, storage extends the temporal range of flexibility, demand coordination aligns consumption with supply, and market mechanisms ensure efficient activation and remuneration.

Second, **each mechanism draws on multiple sector-coupling configurations.** No single coupling pathway (e.g., P2H alone or P2G alone) activates all four mechanisms at full potential. This reinforces the argument, developed further in Section 4.2, that multi-lateral coupling configurations yield greater systemic flexibility than bilateral ones.

Third, **the market and operational coordination mechanism (iv) acts as a critical enabler for the other three.** Without appropriate market signals, pricing structures, and coordination frameworks, the physical flexibility created by conversion, storage, and demand coordination remains latent and economically stranded. This underscores the importance of regulatory and market reforms discussed in Section 4.4.

Fourth, **balanced coverage across all coupling pathways is essential.** While hydrogen systems offer unique advantages for long-duration storage and industrial decarbonization, P2H provides the most mature and cost-effective conversion and demand coordination mechanisms, and P2M/V2G contributes uniquely to distributed, mobile flexibility. An effective sector-coupling strategy must leverage all pathways according to their comparative strengths, rather than focusing disproportionately on any single vector.

These four mechanisms collectively define the analytical framework through which the specific sector-coupling configurations are examined in the subsequent subsections (Sections 4.2.1-4.2.6), where each coupling pathway is assessed according to its activation of these mechanisms and the resulting flexibility contributions.

4.2. Synergies between different sectors

Synergistic interactions among electricity, heat, transport, gas, and hydrogen networks represent a transformative step toward building highly flexible and efficient energy systems. Sector coupling provides a strategic framework for these interactions by enabling traditionally separate infrastructures to function collaboratively, thereby unlocking latent flexibilities and optimizing resource use. Advanced integration pathways such as Power-to-Heat (P2H), Power-to-Gas (P2G), Power-to-Hydrogen (P2H₂), and Power-to-Mobility (P2M) allow surplus

electricity to be converted into storable and transferable energy forms, each capable of serving multiple sectoral needs. For instance, electrolyzers not only facilitate hydrogen production but also deliver grid services [130], while electric vehicles can operate as mobile storage assets through V2G technologies [86]. Industrial waste heat can be captured and fed into district heating systems, closing efficiency loops across sectors [131], [132].

These interconnected systems act as distributed flexibility hubs, dynamically balancing supply and demand across temporal and spatial scales. By reallocating energy resources between sectors such as shifting electricity into heating during off-peak hours or utilizing hydrogen for transport during periods of grid stress; systems gain the ability to mitigate intermittency, alleviate congestion, and respond to unforeseen disturbances [133]. A sustainable multi-energy management framework was proposed in Ref. [125] to enable coordinated operation and energy sharing among interconnected microgrids under a transactive energy paradigm. The framework was formulated using a distributional robust chance-constrained approach to handle renewable and price uncertainties, and the results demonstrated improved economic efficiency, operational robustness, and system flexibility in fully renewable multi-energy systems. In Ref. [98], a transactive energy trading model was proposed for peer-to-peer energy sharing among energy hubs in coupled electricity and heat networks, demonstrating notable techno-economic benefits and improved operational flexibility. Additionally, a bi-level optimization framework was developed in Ref. [99] to model the participation of multi-energy service providers in integrated electricity and natural gas markets, demonstrating reduced energy procurement costs through coordinated multi-energy market participation.

Moreover, sector coupling reduces the need for redundant infrastructure by leveraging existing assets across multiple domains, resulting in lower system costs and enhanced resilience. The coordinated operation of these sectors not only supports high penetration of renewables but also aligns with broader decarbonization goals, establishing a robust foundation for a sustainable and future-ready energy landscape.

The regional energy diversity in the Nordic countries, illustrated in Fig. 3, has direct implications for how sector coupling can enhance power system flexibility across the region. Specifically, each country's generation portfolio creates distinct sector-coupling opportunities and flexibility needs.

- **Norway's** hydropower dominance provides abundant dispatchable renewable electricity, creating favorable conditions for power-to-hydrogen production. Surplus hydro generation can be converted to hydrogen for export or long-duration storage, effectively extending Norway's flexibility contribution beyond the electricity sector into the hydrogen and industrial domains.
- **Denmark's** high wind penetration generates significant periods of surplus generation that require absorption pathways. This makes Denmark a prime candidate for P2H integration with its extensive district heating networks, where surplus wind can be converted to thermal energy via heat pumps, reducing both curtailment and heating-sector emissions. Denmark's experience with CHP-district heating coupling further supports this pathway.
- **Sweden and Finland** balance their energy mix with nuclear power and a diversified renewable portfolio. The baseload characteristics of nuclear generation, combined with variable renewables, create a flexibility profile suited to P2M applications (absorbing surplus through EV charging during high-generation periods) and thermal sector coupling (using heat pumps to complement district heating systems during periods of low marginal electricity cost).
- **Cross-border interconnections** between these countries function as a spatial dimension of sector coupling, enabling surplus generation in one country to serve flexibility needs in another. For instance,

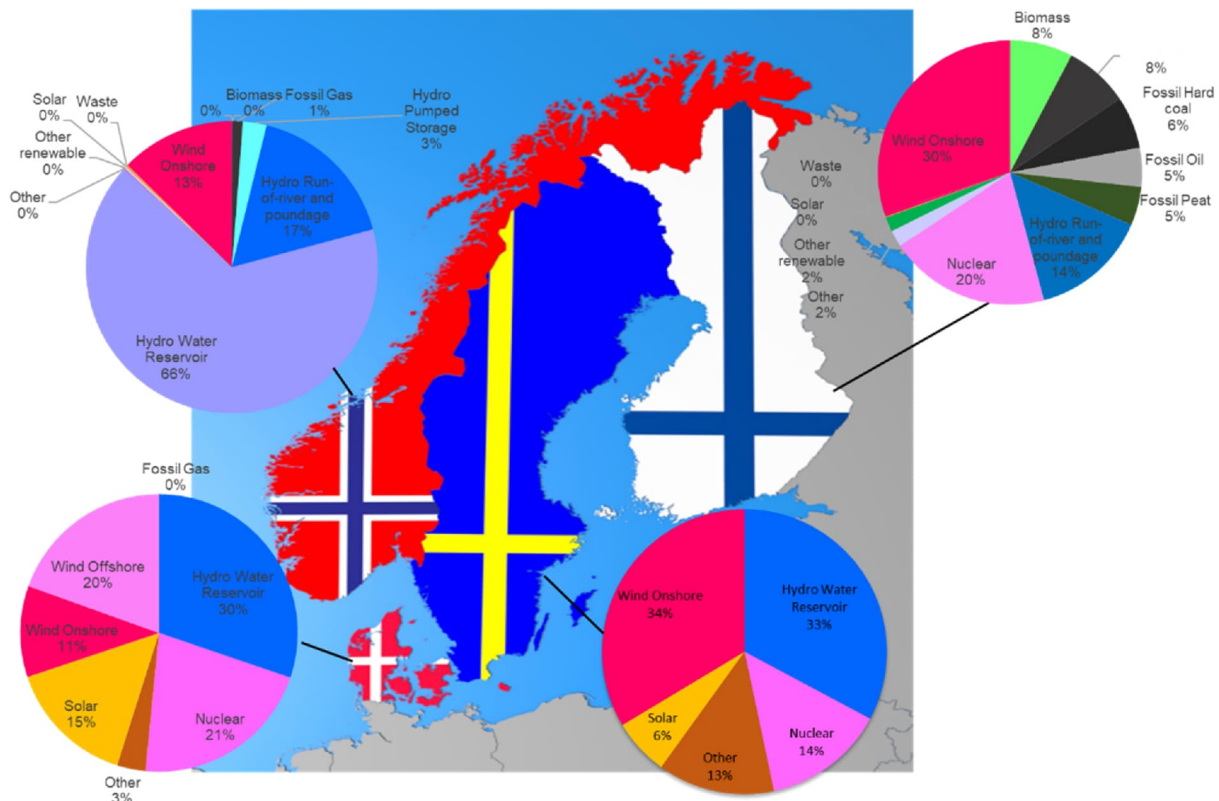


Fig. 3. Regional energy mix and renewable integration in Nordic countries.

Norwegian hydro balancing Danish wind variability, or Finnish nuclear baseload complementing Swedish renewable intermittency.

These regional differences underscore a central insight: the optimal sector-coupling strategy is not universal but must be tailored to regional generation portfolios, existing infrastructure, and cross-border coordination capabilities [118]. The diversity of the Nordic energy landscape thus serves as a compelling illustration of why sector coupling must be analyzed at the configuration level as undertaken in the following subsections (4.2.1-4.2.6) rather than treated as a monolithic concept.

To ensure a systematic and comparable analysis, each of the following subsections examines a specific sector-coupling configuration through a consistent analytical framework comprising four dimensions: (a) the coupling mechanism and key enabling technologies, (b) the flexibility contributions to the power system, (c) representative studies and key findings from the literature, and (d) outstanding challenges and outlook. This structure is applied first to bilateral couplings (Sections 4.2.1-4.2.3), which connect electricity with a single additional sector, and subsequently to multi-lateral couplings (Sections 4.2.4-4.2.6), which integrate three or more energy vectors simultaneously. This progression reflects the increasing complexity and flexibility potential that emerges as additional sectors are brought into coordinated operation.

4.2.1. Power-to-heat (P2H)

(a) **Coupling mechanism and key technologies.** P2H converts surplus electricity into thermal energy for space heating, domestic hot water, or industrial process heat. The principal enabling technologies include electric resistance heaters, heat pumps (both centralized and decentralized), and thermal energy storage (TES) systems such as hot water tanks, phase-change materials, and underground thermal stores. When integrated into district heating networks (DHNs) or building-level systems,

these technologies create a controllable interface between the electrical and thermal domains.

- (b) **Flexibility contributions.** P2H enhances power system flexibility along several dimensions. First, it provides *demand-side absorption*: heat pumps and electric boilers act as flexible loads capable of absorbing surplus renewable generation, thereby reducing curtailment and supporting grid balancing [77]. Second, *temporal shifting* is enabled through thermal storage, which decouples the moment of electricity consumption from the moment of heat delivery, allowing load to be shifted from peak to off-peak periods. Third, P2H assets can participate in *ancillary service provision*, including frequency containment and demand response programs, particularly when aggregated within district heating systems [40], [70]. Fourth, the thermal inertia of buildings and DHNs provides an inherent *buffering capacity* that can be exploited for short-term flexibility without compromising end-user comfort.
- (c) **Representative studies and key findings.** A method for managing flexibility in coupled electricity–heating systems was proposed in Ref. [76], employing real weather data and uncertainty modeling to optimize system operation. Tested on a small residential grid, it demonstrated superior performance in mitigating unexpected conditions through effective coordination of heat pumps and thermal storage. Sector coupling through P2H was identified in Ref. [77] as a cost-effective strategy for decarbonizing the heat sector in Northern-central Europe, where aligning thermal demand with renewable supply significantly reduced fossil fuel dependence, with heat storage and extended energy networks playing key enabling roles.

The integration of heat pumps and thermal storage was highlighted in Ref. [75] as essential for future low-carbon energy systems, particularly in smart grids and district heating networks. A comprehensive review in Ref. [104] further underscored the importance of open

technological approaches and robust market frameworks to maximize P2H benefits. In the Nordic context [134], demonstrated that P2H investments coupled with flexible tariff structures substantially reduced operational costs and bolstered system flexibility. The incorporation of CHP plants and heat pumps within district heating systems was shown in Ref. [119] to facilitate increased wind power integration without undermining grid stability.

At the building level [76], found that heat pump deployment in Belgian residential buildings significantly decreased costs and emissions, while [128] emphasized the role of high-temperature heat pumps in industrial applications for enhancing grid flexibility and reducing carbon footprints. Experimental analysis in Ref. [78] confirmed the role of power-to-heat storage with phase-change materials in bridging thermal and electrical networks. Finally [91], demonstrated how integrating waste heat recovery from data centers with district heating through heat pumps and cooling storage can improve system flexibility and reduce energy costs.

(d) **Challenges and outlook.** Despite its maturity, P2H deployment faces several challenges. The efficiency of high-temperature industrial applications remains limited compared to low-temperature space heating. Regulatory barriers persist, as electricity and heat sectors are typically governed by separate policy frameworks, hindering coordinated operation and investment. The economic viability of P2H is highly sensitive to electricity price structures, grid tariffs, and carbon pricing signals. Looking forward, the widespread adoption of P2H will depend on tariff reforms that reward flexibility, the expansion of district heating infrastructure, and the development of standardized control interfaces for aggregated thermal assets.

4.2.2. Power-to-gas (P2G) and power-to-hydrogen (P2H₂)

- (a) **Coupling mechanism and key technologies.** P2G and P2H₂ convert surplus electricity into gaseous energy carriers hydrogen via electrolysis, and optionally synthetic methane via subsequent methanation. Key technologies include alkaline, PEM, and solid oxide electrolyzers; methanation reactors; hydrogen storage (compressed gas, liquid, underground caverns); and gas grid injection infrastructure. These pathways create a bidirectional link between the electricity and gas/hydrogen sectors, enabling chemical storage of electrical energy.
- (b) **Flexibility contributions.** P2G/P2H₂ provides flexibility across multiple timescales. For *long-duration and seasonal storage*, hydrogen and synthetic methane can store energy over weeks to months, addressing the seasonal mismatch between renewable generation and demand that batteries cannot economically serve [73]. For *short-term balancing*, electrolyzer operation can be modulated to provide downward flexibility (absorbing excess generation) or upward flexibility (curtailing consumption during scarcity) [83]. Electrolyzers can also participate in *ancillary service markets*, including FCR and FFR, when equipped with appropriate control systems [67]. Furthermore, P2G enables *cross-sectoral decarbonization* by providing green hydrogen for industrial feedstock, transport fuel, and heating, thereby creating multiple value streams that improve the economic case for flexibility provision.
- (c) **Representative studies and key findings.** The integration of P2G with urban energy systems was shown in Refs. [120] and [96] to effectively reduce emissions and optimize local energy flows through hydrogen blending and grid injection strategies. A low-carbon economic dispatch model developed in Ref. [97] for integrated electricity-gas systems incorporating P2G and hydrogen storage demonstrated reduced system costs, lower emissions, and effective mitigation of renewable curtailment through coordinated operation.

At the European scale [84], explored the interplay between hydrogen and electricity markets across 13 Central European nations, finding that both seasonal and short-term hydrogen storage support grid balancing and minimize generation costs. Advanced electrolyzer models operating at high current densities were presented in Ref. [85], demonstrating cost-effective industrial hydrogen production while maintaining operational flexibility. In the transportation domain [115], discussed green hydrogen's role in decarbonizing the German passenger car sector, focusing on hydrogen infrastructure development including supply chain networks and fueling stations.

(d) **Challenges and outlook.** P2G/P2H₂ faces significant barriers to large-scale deployment. Conversion losses remain substantial where round-trip efficiency for power-to-hydrogen-to-power ranges from 25 to 45%, considerably lower than battery storage [46]. Capital costs for electrolyzers, while declining, remain high, and the supporting infrastructure (hydrogen pipelines, storage caverns, refueling stations) requires massive investment. Market frameworks that recognize and remunerate the multi-service value of hydrogen (storage, grid services, industrial feedstock, transport fuel) are largely absent. Regulatory uncertainty regarding hydrogen blending limits, safety standards, and cross-border trade further constrains investment. Addressing these barriers will require targeted R&D to improve electrolyzer efficiency and durability, strategic infrastructure planning, and market designs that enable hydrogen assets to stack multiple revenue streams.

4.2.3. Power-to-mobility (P2M)

- (a) **Coupling mechanism and key technologies.** P2M connects the electricity and transportation sectors primarily through the electrification of vehicles and the deployment of managed charging infrastructure. Key technologies include electric vehicles (battery EVs and fuel-cell EVs), unidirectional smart charging systems, bidirectional V2G chargers, and digital aggregation platforms that coordinate EV fleets as virtual power plants. The co-location of charging infrastructure with DERs further enhances the coupling between mobility and power systems.
- (b) **Flexibility contributions.** P2M contributes to power system flexibility through several mechanisms. *Controllable demand* is created by managed EV charging, which can be shifted to periods of high renewable output or low system demand, reducing curtailment and improving load factor [127]. *Bidirectional power flow* through V2G enables EVs to discharge stored energy back to the grid during peak demand, providing peak shaving, frequency regulation, and reserve capacity [87]. *Aggregated fleet participation* in energy and ancillary service markets allows large numbers of EVs, coordinated by digital platforms, to provide reserve capacity and respond to grid disturbances in real time [88]. Additionally, *localized balancing* is enhanced when EV charging infrastructure is co-located with DERs, enabling more efficient energy flows at the distribution level.
- (c) **Representative studies and key findings.** Reference [42] demonstrated that demand-side flexibility including dynamic EV charging has become a critical element for ensuring efficiency and cost control in renewable-dominated systems. The bidirectional functionality of EVs through V2G was shown in Ref. [43] to support grid services including peak reduction, frequency regulation, and local balancing. National strategies in Norway, Germany, and Brazil were analyzed in Ref. [41], reflecting growing policy support for integrating EVs into flexibility markets. Reference [88] further illustrated how leveraging EV mobility patterns enables their integration into ancillary service provision, unlocking grid flexibility potential. An integrated energy system modeling perspective in Ref. [87] confirmed that V2G integration

provides measurable decarbonization and flexibility benefits across multiple sectors.

- (d) **Challenges and outlook.** Despite its promise, P2M faces notable implementation challenges. Battery degradation from frequent V2G cycling remains a concern for vehicle owners and manufacturers, potentially limiting participation rates. The installed base of bidirectional chargers is still minimal, and standardization of V2G protocols and communication interfaces is incomplete [135]. Market access for aggregated EV fleets is constrained by regulatory frameworks that were not designed for mobile, distributed storage assets. Consumer acceptance depends on transparent incentive structures that compensate vehicle owners for flexibility provision without compromising mobility needs. Future progress will require accelerated deployment of bidirectional charging infrastructure, refined degradation management strategies, and market reforms that create clear and accessible pathways for EV participation in flexibility services.

Transition to multi-lateral couplings. The bilateral coupling pathways described above such as P2H, P2G/P2H₂, and P2M, each connect electricity with a single additional sector and provide distinct flexibility services. However, the full potential of sector coupling is realized when multiple sectors are integrated simultaneously, creating multi-lateral configurations that unlock synergistic flexibility benefits unavailable to any single bilateral coupling. The following subsections examine three-sector configurations, analyzing how the combination of multiple energy vectors amplifies flexibility, improves resource efficiency, and supports deeper decarbonization.

4.2.4. Electricity-Heat-Gas integration

- (a) **Coupling mechanism and key technologies.** This configuration links electricity, heating, and gas networks through technologies that enable bidirectional energy conversion and joint optimization. Key enabling technologies include CHP units (which co-produce electricity and heat from gas), gas-fired boilers, heat pumps (electrically driven), power-to-gas systems, gas pipeline infrastructure (with line-pack flexibility), and thermal storage. The coupling is further enhanced by integrated energy management systems that coordinate dispatch across all three vectors.
- (b) **Flexibility contributions.** The three-way integration of electricity, heat, and gas provides flexibility benefits that exceed the sum of bilateral couplings. *Multi-vector balancing* is enabled: CHP units can modulate their electricity-to-heat output ratio in response to grid conditions, while heat pumps and gas boilers provide substitutable heating pathways that can be switched based on electricity price or grid stress signals [126]. *Gas pipeline line-pack* serves as a distributed energy buffer, absorbing pressure fluctuations that correspond to varying gas demand from P2G injection or CHP operation [121]. *Temporal coordination* across vectors allows thermal storage to absorb excess CHP electricity production during low-demand periods, while gas storage provides seasonal flexibility. This configuration also supports *congestion management* by redirecting energy flows between vectors to alleviate bottlenecks in any single network.
- (c) **Representative studies and key findings.** A two-stage rolling optimization strategy for park-level integrated energy systems was proposed in Ref. [126], using virtual energy storage models to represent building-level thermal inertia. The approach demonstrated that real-time dispatch adjustments across electricity, heat, and gas resources reduce the operational impact of renewable variability, enhance clean energy usage, and support cost-efficient operation. An interval optimization-based scheduling approach was presented in Ref. [121] for coordinating electricity, heat, gas, and hydrogen systems with the joint

integration of CHP units and hydrogen energy storage. Gas pipeline line-pack modeling captured network flexibility, while wind power uncertainty was addressed within an interval optimization framework, leading to lower operating costs and enhanced overall system flexibility.

A bi-level optimization framework in Ref. [99] modeled the participation of multi-energy service providers in integrated electricity and natural gas markets, demonstrating reduced procurement costs through coordinated scheduling of flexible resources including storage and demand response. The transactive energy trading model in Ref. [98] confirmed techno-economic benefits and improved operational flexibility in coupled electricity-heat energy hubs.

- (d) **Challenges and outlook.** Electricity-heat-gas integration faces challenges related to the coordination complexity of three heterogeneous networks with different temporal dynamics, physical constraints, and regulatory jurisdictions. Gas network modeling (including line-pack dynamics and pressure constraints) adds computational burden to integrated optimization. CHP dispatch flexibility is constrained by heat demand obligations, particularly in district heating systems with contractual supply requirements. Regulatory silos between electricity, gas, and heat sectors hinder the development of integrated market mechanisms. Progress requires unified modeling platforms, regulatory harmonization, and market designs that recognize the cross-vector flexibility value of integrated assets.

4.2.5. Heat-mobility-gas and electricity-heat-hydrogen integration

- (a) **Coupling mechanism and key technologies.** These configurations extend bilateral couplings into three-sector domains. Heat-mobility-gas integration leverages district heating storage, EV charging management, and gas network flexibility to jointly address grid constraints. Electricity-heat-hydrogen integration couples electrolyzers, fuel cells, thermal storage, and heat recovery systems to create multi-vector microgrids where hydrogen serves as both an energy carrier and a flexibility asset. Key technologies include electrolyzers (for hydrogen production and grid service provision), fuel cells (for re-electrification and heat co-production), thermal energy storage, and coordinated EV charging infrastructure.
- (b) **Flexibility contributions.** *Heat-mobility-gas* coupling enables *localized constraint management*: district heating storage absorbs renewable surpluses in urban centers, while coordinated EV charging and gas network flexibility resolve distribution-level congestion [136]. The combination of thermal inertia and mobile storage creates complementary flexibility across different timescales such as thermal storage provides hours-to-days shifting, while EVs provide minutes-to-hours response.

Electricity-heat-hydrogen coupling provides *enhanced self-sufficiency and load smoothing* in microgrids. Hydrogen production absorbs excess renewable generation, fuel cells provide dispatchable backup power with useful waste heat, and thermal storage buffers both electrical and thermal demands [93], [137]. This configuration reduces net electricity demand variability, improving microgrid controllability and resilience [122]. The flexibility modeling framework in Ref. [7] enables joint optimization across all three domains, facilitating participation in balancing services and energy markets.

- (c) **Representative studies and key findings.** Reference [136] examined how coordinated demand response, thermal storage, and EV charging across sectors can resolve local grid constraints and support renewable integration, with district heating storage in urban centers demonstrating high effectiveness in absorbing renewable

surpluses. A flexibility modeling framework for multi-energy systems was introduced in Ref. [7], employing MILP to coordinate energy flows across thermal, electrical, and gas domains and facilitate participation in balancing services.

For electricity-heat-hydrogen integration [122], employed multi-objective optimization to assess how varying levels of sector coupling impacted microgrid operations, evaluating scenarios from electricity-only systems to comprehensive electricity-heat-hydrogen integration. Results showed that deeper coupling reduced net electricity demand and smoothed load variability, enhancing controllability and resilience. References [93] and [137] further confirmed that combined production of electricity, heat, and hydrogen from hybrid systems improves techno-economic performance and operational adaptability.

(d) **Challenges and outlook.** These multi-lateral configurations face the combined challenges of their constituent bilateral couplings, amplified by coordination complexity. For heat-mobility-gas coupling, the spatial distribution of assets (district heating in urban cores, EV charging along transport corridors, gas networks across regions) complicates unified optimization. For electricity-heat-hydrogen coupling, the relatively low TRL of integrated hydrogen-thermal systems and the capital intensity of electrolyzer-fuel cell combinations remain barriers. Both configurations require advances in multi-vector control platforms, standardized interoperability protocols, and regulatory frameworks that accommodate cross-sector flexibility procurement. Despite existing regulatory and commercial barriers, the reviewed studies consistently emphasize the critical role of these configurations in supporting high renewable penetration while maintaining system stability.

4.2.6. Electricity-heat-mobility and electricity-hydrogen-mobility integration

- (a) **Coupling mechanism and key technologies.** *Electricity-heat-mobility* integration connects power systems with both thermal networks and transport electrification, enabling coordinated management of heat pumps, district heating, EV charging, and electrical storage. *Electricity-hydrogen-mobility* integration links power systems with hydrogen production and fuel-cell vehicles, creating pathways for renewable electricity to serve transport demand via green hydrogen. Key technologies include smart EV charging and V2G systems, heat pumps and thermal storage, electrolyzers, hydrogen refueling infrastructure, fuel-cell vehicles, and integrated multi-vector energy management platforms.
- (b) **Flexibility contributions.** *Electricity-heat-mobility* coupling enables *multi-dimensional load management*: heat pumps shift electrical load in response to grid signals, while EV charging absorbs surplus generation or provides V2G services during peak periods [89], [138]. The combination creates a broader portfolio of flexible assets at the distribution level, reducing the need for grid reinforcement and enabling localized self-balancing.

Electricity-hydrogen-mobility coupling introduces *decarbonization of transport fuels* as an additional flexibility lever. Electrolyzer operation can be modulated to balance the grid while producing hydrogen for fuel-cell vehicles, and hydrogen storage provides a temporal buffer between electricity generation and transport consumption [139]. Adaptive pricing and smart charging coordination further balance transport energy demand and improve system-wide efficiency [90]. The DOLPHYN framework presented in Ref. [140] demonstrated how synchronized electricity and hydrogen supply networks effectively manage renewable variability while serving both stationary and mobile energy demands.

(c) **Representative studies and key findings.** A comparative analysis in Ref. [105] assessed how various power sector models handle the

integration of electricity, heat, and transport, applying consistent input data across nine models. The study revealed how structural differences and assumptions significantly influence flexibility representation, highlighting the importance of harmonizing modeling frameworks to accurately capture multi-sector dynamics.

For electricity-hydrogen-mobility [139], analyzed Germany's hydrogen strategy, underscoring the role of renewable hydrogen in transport decarbonization and the infrastructure requirements it entails. Reference [90] explored adaptive pricing and smart charging coordination for balancing transport demand. The DOLPHYN technique in Ref. [140] synchronized electricity and hydrogen networks to manage renewable fluctuations, while [141] elaborated integrated multi-vector energy systems coupling electricity, gas, and transportation using P2G and mobile energy storage, demonstrating significant reductions in operational costs and congestion-related curtailment.

At the national planning level [142], examined Chile's integrated approach coordinating electricity, heating, transport, and desalination to reduce both costs and emissions. Reference [143] developed a stochastic programming model assessing sector coupling's impact on European decarbonization with a focus on aligning transportation, heat, and electricity. The flexibility margin index introduced in Ref. [144] demonstrated that linking electricity, heat, and gas sectors facilitates resource sharing and reduces costs in wind power integration. Reference [117] emphasized that integrating power, heating, and transport systems significantly enhances flexibility and economic efficiency, while [129] highlighted hydrogen's critical role in balancing seasonal demand, stressing the importance of robust storage infrastructure and delivery networks.

(d) **Challenges and outlook.** Electricity-heat-mobility integration faces challenges in coordinating assets with fundamentally different spatial and temporal characteristics that are buildings are stationary with slow thermal dynamics, while vehicles are mobile with intermittent grid connection. Modeling frameworks must be harmonized to capture these disparate dynamics accurately, as demonstrated by the significant discrepancies across models found in Ref. [105]. Electricity-hydrogen-mobility coupling requires substantial infrastructure buildout (electrolyzers, hydrogen storage, refueling networks) and faces competition from battery-electric pathways that currently offer higher round-trip efficiency for passenger transport. The economic viability of hydrogen mobility depends on achieving cost parity with both fossil fuels and battery-electric alternatives, which in turn depends on electrolyzer cost reductions, renewable electricity prices, and infrastructure utilization rates. Both configurations will benefit from integrated national energy planning that co-optimizes across sectors, infrastructure investment strategies that account for cross-sectoral synergies, and market mechanisms that appropriately value the multi-service flexibility contributions of coupled assets.

4.2.7. Comparative synthesis

Table 7 provides a systematic comparison of the six sector-coupling configurations analyzed in Sections 4.2.1-4.2.6, mapped against key dimensions relevant to power system flexibility. This synthesis enables direct comparison of the flexibility services, temporal scales, technological maturity, and infrastructure requirements associated with each configuration, supporting both researchers and policymakers in identifying the most suitable coupling strategies for specific system contexts.

Several cross-cutting observations emerge from this comparative analysis.

1. Flexibility breadth increases with coupling complexity. Bilateral couplings provide targeted flexibility services (e.g., demand absorption for P2H, seasonal storage for P2G), while multi-lateral configurations unlock synergistic capabilities such as multi-vector

Table 7
Comparative overview of sector-coupling configurations and their flexibility characteristics.

| Configuration | Key Flexibility Services | Primary Temporal Scale | Approx. TRL | Key Enabling Infrastructure | Representative Refs |
|--|---|------------------------|-------------|---|---------------------------------|
| P2H (4.2.1) | Demand absorption, load shifting, ancillary services (FCR, DR) | Minutes to days | 7-9 | Heat pumps, TES, DHN, electric boilers | [74], [75], [76], [119] |
| P2G/P2H2 (4.2.2) | Seasonal storage, curtailment reduction, ancillary services, cross-sector decarbonization | Hours to seasons | 5-7 | Electrolyzers, methanation, H ₂ storage, gas grid | [73] [84] [121] |
| P2M (4.2.3) | Controllable demand, V2G peak shaving, frequency regulation, reserve provision | Minutes to hours | 6-8 | EVs, bidirectional chargers, aggregation platforms | [42] [88] [43] |
| Elec-Heat-Gas (4.2.4) | Multi-vector balancing, congestion management, line-pack buffering | Minutes to seasons | 6-8 | CHP, heat pumps, gas boilers, TES, gas pipeline | [126] [121] [71] |
| Heat-Mob-Gas/Elec-Heat-H ₂ (4.2.5) | Localized constraint mgmt., microgrid self-sufficiency, load smoothing | Minutes to days | 5-7 | DHN + TES, EV charging, electrolyzers, fuel cells | [89], [93], [115], [137], [143] |
| Elec-Heat-Mob/Elec-H ₂ -Mob (4.2.6) | Multi-dimensional load mgmt., transport decarbonization, seasonal balancing | Minutes to seasons | 5-7 | Heat pumps, EVs, V2G, electrolyzers, H ₂ refueling | [89] [117], [141] |

balancing and localized self-sufficiency that are unavailable to any single coupling pathway.

2. A maturity-complexity trade-off exists. The most technologically mature configurations (P2H, managed EV charging) are bilateral, while the multi-lateral configurations that offer the greatest flexibility potential tend to incorporate technologies at lower TRLs (large-scale hydrogen storage, integrated multi-vector control systems).
3. Temporal complementarity is a key design principle. Combining configurations that operate across different timescales, for example, P2H (minutes to days) with P2G (hours to seasons), creates a more complete flexibility portfolio than any single pathway can provide.
4. Infrastructure co-investment creates synergies. Many enabling technologies (e.g., electrolyzers, thermal storage, smart charging) serve multiple coupling configurations simultaneously, suggesting that coordinated infrastructure planning across sectors can reduce overall investment costs while maximizing flexibility provision.

Regulatory integration remains the binding constraint. Across all configurations, the reviewed studies consistently identify siloed regulatory and market frameworks as the most significant barrier to realizing cross-sectoral flexibility potential that is more constraining, in practice, than technological limitations.

4.3. Benefits of inter-sectoral synergies in power system flexibility

Sector coupling delivers substantial benefits to power system flexibility by transforming isolated energy domains such as electricity, heating, mobility, gas, cooling, and hydrogen, into a coordinated, interactive network capable of dynamically managing resources. This integration enables shared infrastructure, optimized energy flows, and the activation of flexible assets across domains, allowing systems to operate more efficiently and resiliently [145].

Fig. 4 illustrates the infrastructure supporting a sector-coupled system, including electricity generation units, hydrogen and thermal storage, district heating networks, and transportation systems. Technologies such as CHP units, EV charging stations, heat pumps, and electrolyzers enable multidirectional energy flows, supporting the conversion of surplus electricity into thermal energy (P2H), hydrogen (P2G), or mobile storage via P2M strategies.

To consolidate the evidence from the reviewed literature, Table 8 synthesizes the principal benefits of inter-sectoral synergies, organized by benefit category, with explicit mapping to enabling mechanisms, affected sectors, and representative studies.

Several cross-cutting insights emerge from this synthesis:

First, the benefits are interconnected and mutually reinforcing. Curtailment reduction improves the economics of renewable investment, which in turn increases the need for temporal flexibility, which

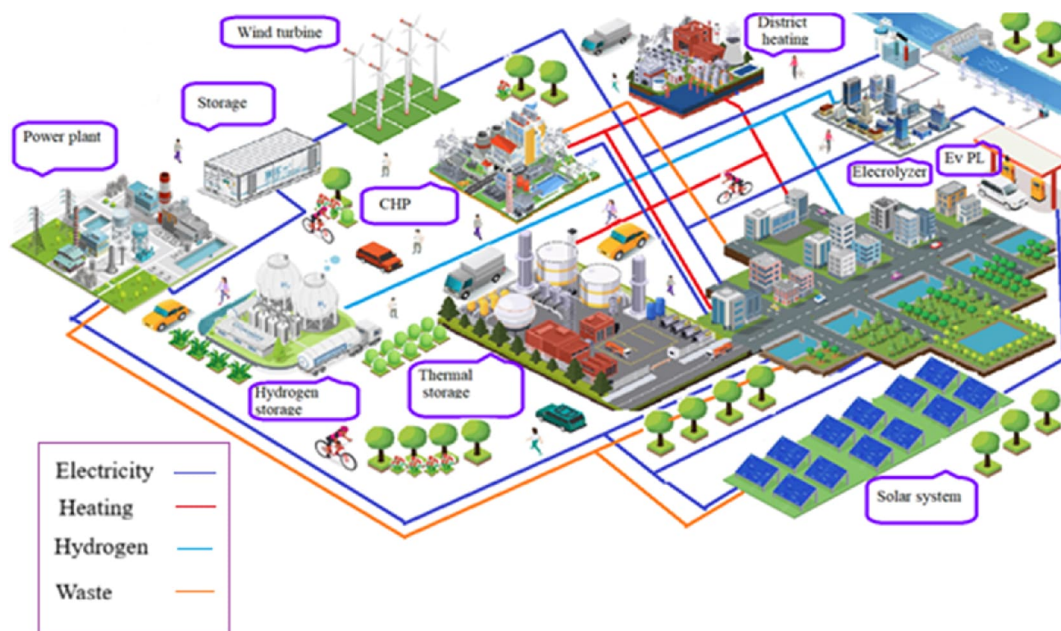


Fig. 4. illustrates the infrastructure supporting a sector-coupled system.

Table 8
Benefits of inter-sectoral synergies for power system flexibility.

| Benefit Category | Description | Enabling Mechanism(s) | Affected Sectors | Representative Refs |
|------------------------------------|---|---|---|---------------------------|
| Temporal flexibility | Energy shifted in time through cross-sectoral storage (thermal, hydrogen, EV batteries), decoupling generation from consumption across hours to seasons | Storage & temporal shifting; Energy conversion | Electricity-Heat, Electricity-Hydrogen, Electricity-Mobility | [78], [84], [43] |
| Spatial flexibility | Energy moved geographically across interconnected sectoral networks; district heating absorbs local surpluses; cross-border exchanges balance regional differences | Energy conversion; Market & operational coordination | All coupled sectors; cross-border | [136], [142], [146] |
| Curtailement reduction | Multiple absorption pathways for surplus renewable generation (P2H, P2G, P2M) reduce the need to curtail variable renewables | Energy conversion; Demand-side coordination | Electricity-Heat, Electricity-Gas/H ₂ , Electricity-Mobility | [77], [97] |
| Peak demand management | V2G-capable EVs discharge during high-demand periods; heat pumps shift electrical load; hydrogen fuel cells provide dispatchable backup | Demand-side coordination; Storage & temporal shifting | Electricity-Mobility, Electricity-Heat, Electricity-Hydrogen | [43], [74], [122] |
| Ancillary service provision | Sector-coupled assets (electrolyzers, heat pumps, aggregated EVs) participate in FCR, FRR, and FFR markets, expanding the reserve resource base | Market & operational coordination; Demand-side coordination | Electricity-Hydrogen, Electricity-Heat, Electricity-Mobility | [83], [147], [70], [88] |
| Infrastructure efficiency | Shared infrastructure across sectors (CHP serving electricity and heat, electrolyzers serving grid and industry) increases asset utilization and reduces redundant investment | Energy conversion; Market & operational coordination | Electricity-Heat-Gas, Electricity-Hydrogen-Industry | [148], [149], [150] |
| Economic efficiency | Coordinated multi-energy scheduling reduces operational costs; flexibility resources participate in multiple markets simultaneously (value stacking) | Market & operational coordination | All coupled sectors | [125], [99], [151] |
| Reduced grid reinforcement | District heating with thermal storage and distributed hydrogen production manage local constraints, deferring costly network upgrades | Storage & temporal shifting; Demand-side coordination | Electricity-Heat, Electricity-Hydrogen (distribution level) | [152], [136], [153] |
| Decarbonization | Electrification of heating, transport, and industry via renewable-powered conversion pathways reduces fossil fuel dependence across sectors | Energy conversion | Electricity-Heat, Electricity-Mobility, Electricity-Hydrogen | [107], [77], [115], [142] |
| System resilience | Distributed flexibility hubs across sectors provide redundant balancing pathways, improving system robustness against single-point failures and extreme events | All four mechanisms | All coupled sectors | [133], [125], [122] |

strengthens the case for cross-sectoral storage creating a virtuous cycle. Similarly, infrastructure efficiency enables economic efficiency, which supports the investment case for further sector coupling.

Second, the four mechanisms identified in Sub-section 4.1.1 collectively enable the full spectrum of benefits. No single mechanism is sufficient: energy conversion creates the pathways, storage provides temporal reach, demand-side coordination ensures responsiveness, and market coordination activates economic value. This reinforces the finding from sub-section 4.1.1 that maximum benefit requires all four mechanisms operating in concert.

Third, the benefits span all system levels and timescales. From seconds-scale frequency response (ancillary services) to seasonal storage (temporal flexibility) and from local distribution management (reduced grid reinforcement) to system-wide coordination (economic efficiency), sector coupling provides a comprehensive flexibility enhancement that electricity-only solutions cannot match which is directly validating the gap analysis presented in Sub-section 3.8.

Economic efficiency in multi-energy systems can be further enhanced by optimizing resource allocation and infrastructure utilization across interconnected sectors. In Ref. [154], a scheduling approach was introduced to improve cost-efficiency in distribution networks by leveraging flexible resources such as energy sources, storage systems, and pipeline infrastructure, incorporating a flexibility index to assess regulation potential and associated costs. From a long-term perspective, sector coupling supports the integration of variable renewable energy by minimizing curtailment and shifting generation to when and where it is most valuable, maximizing infrastructure utilization and aligning energy consumption with availability [146].

4.4. Challenges and considerations in sector coupling for power system flexibility

Despite the transformative potential of sector coupling in advancing power system flexibility, its successful deployment demands careful navigation of technical, regulatory, digital, financial, and social

complexities. To provide a systematic overview, Table 9 maps the principal challenge categories against specific barriers, the coupling configurations most affected, and potential mitigation strategies identified in the reviewed literature.

The challenges in Table 9 can be further elaborated along five thematic dimensions.

- Infrastructure and Digitalization Requirements.** Sector coupling requires substantial infrastructure investments to enable bidirectional energy flows between electricity, heat, gas, hydrogen, and mobility systems. This includes deploying electrolysis units, heat pumps, district heating pipelines, and smart EV charging infrastructure [104]. Digitalization acts as a foundational enabler by facilitating real-time monitoring, system optimization, and decentralized control. IoT devices, advanced metering infrastructure, and AI-based analytics support the integration and orchestration of diverse energy streams. Digital twins which is virtual representations of energy assets, enhance operational visibility, while AI-driven forecasting and control algorithms enable predictive load management and microgrid coordination [124]. These tools are essential for balancing energy across temporal and spatial scales in sector-coupled systems.
- Regulatory and Market Barriers.** Conventional regulatory and market structures are often misaligned with the dynamic and interconnected nature of sector coupling. Current regulations typically treat electricity, gas, heat, and transport as separate entities, limiting the efficiency of integrated operations. Reforms are needed to establish cross-sectoral coordination, harmonize pricing signals, and incentivize flexible service provision. Policy tools such as carbon pricing, feed-in tariffs, and renewable energy subsidies can support the economics of sector coupling solutions. However, as emphasized in Ref. [100], new governance models are also required to prevent monopolization, ensure data access equity, and foster local innovation. The development of integrated energy markets and regional energy hubs will be crucial in facilitating sectoral interactions [123].

Table 9
Challenges and considerations for sector coupling deployment.

| Challenge Category | Specific Barriers | Most Affected Configurations | Potential Mitigation Strategies | Representative Refs |
|---------------------------------------|--|---|---|---------------------|
| Infrastructure requirements | High capital cost of electrolyzers, heat pumps, district heating pipelines, H ₂ storage, bidirectional EV chargers; need for integrated multi-vector infrastructure | All configurations; particularly P2G/P2H ₂ and multi-lateral | Phased infrastructure investment; co-investment across sectors to share costs; community energy ownership models | [104], [155] |
| Digitalization gaps | Underdeveloped real-time monitoring, AI-based analytics, digital twins; insufficient smart metering and IoT deployment for cross-sectoral coordination | All configurations | Investment in digital infrastructure; open-source control platforms; standardized data exchange protocols | [124], [123], [116] |
| Regulatory silos | Electricity, gas, heat, and transport governed by separate frameworks; misaligned incentives; lack of cross-sectoral coordination mandates | All configurations; particularly Elec-Heat-Gas and multi-lateral | Regulatory harmonization; cross-sectoral coordination bodies; unified flexibility definitions | [100] |
| Inadequate market design | Price signals undervalue temporal and locational flexibility; no market mechanism for cross-sector value stacking; limited access for distributed actors | All configurations | Carbon pricing; locational marginal pricing; flexibility remuneration schemes; time-of-use tariffs; local flexibility markets | [156], [100] |
| Technology maturity | P2G, high-temperature heat pumps, large-scale H ₂ storage, and V2G at lower TRLs; efficiency limitations; uncertain performance at scale | P2G/P2H ₂ , P2M (V2G), Elec-Heat-H ₂ | Targeted R&D; pilot projects and living labs; system-level validation; demonstration at scale | [75], [25] |
| Conversion efficiency losses | Power-to-hydrogen-to-power round-trip efficiency 25-45%; methanation adds further losses; thermal conversion losses in high-temperature applications | P2G/P2H ₂ ; P2H (industrial) | Advanced electrolyzer technologies; waste heat recovery; process integration to utilize co-products | [46], [85] |
| Interoperability | Diverse technical standards, communication protocols, operational timelines across energy vectors; lack of standardized data exchange formats | All multi-lateral configurations | Standardized communication protocols; cross-platform APIs; EU-level interoperability standards | [135] |
| System coordination complexity | Coordinating assets with different spatial distributions, temporal dynamics, and control requirements (stationary buildings vs. mobile EVs vs. gas networks) | Multi-lateral configurations; Elec-Heat-Mob | Predictive analytics; decentralized optimization; AI-enabled control frameworks; TSO-DSO coordination platforms | [116], [103] |
| Financing and business models | High upfront costs; uncertain revenue streams; lack of proven business models for cross-sectoral flexibility services; investor risk aversion | All configurations | Energy-as-a-service models; shared ownership schemes; government-backed guarantees; risk-sharing arrangements; regional flexibility platforms | [155], [156], [100] |
| Social and behavioral barriers | Low consumer engagement; lack of user-friendly platforms; insufficient incentives for prosumer participation; equity and access concerns | P2M (EV owners), P2H (households), demand-side coordination | Inclusive platform design; simplified interfaces; financial incentives; regulatory guarantees; equity impact assessments | [112] |

- **Technological Maturity and Reliability.** While technologies like P2H and managed EV charging have reached early commercial stages, others especially P2G, high-temperature heat pumps, and large-scale hydrogen storage, remain at lower technology readiness levels. Demonstration projects and targeted R&D investments are necessary to overcome existing efficiency limitations, scalability concerns, and operational constraints [75]. Reference [157] highlights the need for pilot-scale testing and system-level validation to build confidence among stakeholders.
- **Innovative Business and Financing Models.** Deploying sector-coupling technologies at scale necessitates novel business models that align the interests of multiple actors across sectors. Shared ownership schemes, such as community energy projects, can mitigate risk and promote social acceptance. The study in Ref. [155] emphasized the importance of digital sterilization strategies, such as energy-as-a-service models, which adapt to evolving technological and market demands. Moreover [156], demonstrates how regional platforms can enable new value creation mechanisms for local flexibility marketplaces in Finland, despite challenges like high capital costs, market liquidity, and regulatory inertia. Government-backed guarantees, transparent pricing schemes, and risk-sharing arrangements are essential to attract institutional investors and facilitate long-term financing [100].
- **System Coordination and Interoperability.** Effective sector coupling depends on the interoperability of diverse systems with different technical standards, operational timelines, and control requirements. Coordinating energy flows among electricity, thermal, gas, and transport networks demands standardized communication protocols and data exchange formats [135]. Managing the interplay of flexible loads, distributed energy resources, and centralized assets also requires robust coordination strategies. Predictive analytics and decentralized optimization frameworks enabled by AI can help

dynamically balance supply and demand while maintaining grid stability [116].

5. Current limitations and future trends

The analysis presented in Sections 3 and 4 demonstrates that sector coupling offers a transformative strategy for enhancing power system flexibility beyond what electricity-only solutions can deliver. However, several persistent limitations constrain both the current understanding and the practical realization of sector coupling's flexibility potential. This section synthesizes these limitations drawing directly from the gap analysis in 3.8, the mechanism classification in 4.1.1, the configuration analysis in 4.2, and the challenge mapping in sub-section 4.4 and proposes six corresponding research and development priorities.

Limitation 1: Fragmented modeling frameworks. The gap analysis in sub-section 3.8 revealed that the majority of reviewed studies focus on individual flexibility resource categories or single coupling configurations, with few works addressing flexibility comprehensively across all system layers, energy vectors, and timescales. The comparative analysis in 4.2 further showed that different modeling assumptions significantly influence flexibility representation (as demonstrated by Ref. [105], where nine models produced divergent results from identical input data). This fragmentation prevents holistic assessment of sector coupling's system-level value.

Research Priority 1: Integrated modeling and simulation tools. Develop comprehensive multi-energy system models that incorporate spatial, temporal, and sectoral coupling with high resolution [104], [77]. These should enable techno-economic co-optimization across electricity, gas, heat, hydrogen, and transport networks. Critically, standardized definitions and metrics for cross-sectoral flexibility must be established to support comparability across studies and policy frameworks addressing the definitional fragmentation identified in 3.1.

Limitation 2: Limited real-world validation. The technology maturity assessment in sub-section 4.2 and the challenge analysis in 4.4 (Table 7) identified that several key enabling technologies particularly large-scale hydrogen storage, V2G systems, high-temperature heat pumps, and integrated multi-vector control platforms, remain at lower technology readiness levels. While simulation studies demonstrate promising flexibility contributions, real-world validation of interoperability, performance, and economics at scale is insufficient.

Research Priority 2: Technology demonstration and scale-up. Expand pilot projects and living labs to validate the performance, economics, and interoperability of power-to-X systems, sector-integrated storage, and aggregated flexibility platforms [85], [136]. Foster innovation in modular, decentralized technologies (e.g., heat pumps with thermal inertia, community-scale electrolyzers, multi-energy microgrids) that can be adapted to regional contexts, as illustrated by the Nordic diversity analysis in 4.2.

Limitation 3: Underdeveloped digital infrastructure. The mechanism analysis in 4.1.1 identified market and operational coordination as a critical enabler for all other mechanisms, yet the challenge mapping in 4.4 revealed that real-time flexibility markets and intelligent control systems rely on digital twins, AI-based forecasting, and decentralized optimization, i.e., all of which remain underdeveloped in many regions. Insufficient data governance further hinders coordination among actors.

Research Priority 3: Digitalization and AI deployment. Develop open-source, AI-enabled control frameworks for predictive flexibility management, especially for EV charging, heating/cooling systems, and industrial demand response. Promote the use of digital twins and real-time monitoring platforms to enhance system visibility and coordination, particularly for DSOs and aggregators managing sector-coupled assets [123].

Limitation 4: Regulatory silos and inadequate market design. The synthesis in 4.1 (Table 4) and the challenge analysis in 4.4 (Table 7) consistently identified siloed regulatory frameworks as the most binding constraint on sector coupling deployment more constraining, in practice, than technological limitations. Current market mechanisms undervalue the temporal, locational, and cross-sectoral benefits of flexibility services, and TSO-DSO coordination remains fragmented.

Research Priority 4: Regulatory and market reforms. Design market structures that reward cross-sectoral flexibility services and dynamic participation, including locational marginal pricing, flexibility remuneration schemes, and time-of-use tariffs. Pilot local flexibility markets with integrated procurement mechanisms for TSOs and DSOs, ensuring transparent and fair access for both centralized and distributed actors. Establish cross-sectoral coordination bodies to align planning, market design, and infrastructure investment.

Limitation 5: Disciplinary isolation. The review revealed that technical analyses of sector coupling rarely incorporate insights from economics, urban planning, social science, or governance studies. The oversight of social components in optimization models identified in 4.1 based on [112] that can lead to unreliable results that do not reflect real-world behavior and adoption patterns.

Research Priority 5: Cross-disciplinary collaboration and governance. Encourage collaboration among engineers, economists, urban planners, and social scientists to develop integrated flexibility strategies that reflect real-world behavior, infrastructure constraints, and societal goals. Establish regional and national coordination bodies to align multi-sectoral planning across disciplinary boundaries.

Limitation 6: Equity and participation gaps. The demand-side coordination mechanism (4.1.1) and the social/behavioral challenges (4.4, Table 7) highlighted that flexibility services require active participation from prosumers, EV users, and building operators, but current systems lack user-friendly platforms and clear incentives. Without inclusive policies, flexibility markets risk excluding vulnerable populations.

Research Priority 6: Social engagement and equity-oriented design. Design inclusive flexibility platforms that reduce participation barriers

for residential consumers and prosumers, including interface simplicity, financial incentives, and regulatory guarantees. Evaluate the distributional impacts of sector coupling and flexibility strategies to ensure equitable outcomes across socioeconomic groups.

Together, these six priorities constitute a research agenda that is directly grounded in the systematic analysis of this review. Addressing them will require coordinated action across technology development, market reform, digital infrastructure, and social inclusion mirroring the multi-dimensional nature of sector coupling itself.

6. Conclusions

This review paper set out to address three specific gaps in the literature on sector coupling and power system flexibility: (1) the lack of a systematic flexibility-centric review of sector coupling, (2) insufficient comparative analysis across coupling configurations, and (3) inadequate integration of enabling conditions. The following conclusions respond directly to each gap.

Regarding Gap 1: Systematic flexibility-centric analysis: The systematic mapping of 59 studies across six flexibility resource categories (Table 1) and nine flexibility services and timescales (Table 2) established that electricity-only flexibility solutions, while essential, are insufficient for the full range of challenges created by deep renewable penetration and concurrent electrification of heating, transport, and industry. Specifically, long-duration storage, cross-sectoral balancing, and multi-market value coordination represent persistent gaps that only sector coupling can address. The four-mechanism taxonomy developed in this review (4.1.1, Table 3) energy conversion, storage and temporal shifting, demand-side coordination, and market and operational coordination, provides a structured analytical framework for understanding *how* sector coupling generates flexibility. The key finding is that maximum flexibility is achieved only when all four mechanisms operate in concert: conversion creates the physical pathways between sectors, storage extends the temporal range, demand coordination ensures responsiveness, and market mechanisms activate economic value. No single mechanism or technology is sufficient.

Regarding Gap 2: Comparative analysis across configurations: The systematic analysis of six coupling configurations (4.2) such as P2H, P2G/P2H₂, P2M, Electricity-Heat-Gas, Heat-Mobility-Gas/Electricity-Heat-Hydrogen, and Electricity-Heat-Mobility/Electricity-Hydrogen-Mobility, using a consistent four-part template revealed three key comparative insights. First, a maturity-complexity trade-off exists: bilateral couplings (P2H, managed EV charging) are technologically mature but provide targeted flexibility, while multi-lateral configurations offer greater systemic flexibility but incorporate technologies at lower TRLs. Second, temporal complementarity is a critical design principle: combining configurations that operate across different timescales (e.g., P2H for minutes-to-days with P2G for hours-to-seasons) creates a more complete flexibility portfolio than any single pathway. Third, infrastructure co-investment across sectors can reduce overall costs while maximizing flexibility, as many enabling technologies serve multiple configurations simultaneously (Table 5).

Regarding Gap 3: Integration of enabling conditions: The analysis of benefits (4.3, Table 6) and challenges (4.4, Table 7) demonstrates that the value of sector coupling is maximized only when technical integration is complemented by three enabling conditions: (i) digitalization which is AI-based control, digital twins, and real-time platforms that enable cross-sectoral coordination; (ii) market and regulatory reform that is unified frameworks that recognize cross-sectoral flexibility value, enable value stacking, and provide equitable market access for distributed actors; and (iii) inclusive governance which is business models, financing mechanisms, and participation platforms that engage all stakeholders, from TSOs to household prosumers. The most significant finding is that regulatory silos, not technological limitations, represent the binding constraint on sector coupling deployment across all configurations analyzed.

Sector coupling redefines flexibility as a distributed, multi-vector, and cross-sectoral capability. It extends the flexibility portfolio beyond what electricity-only solutions can provide by leveraging the distinct storage characteristics, load profiles, and infrastructure of heating, gas, hydrogen, and mobility systems. The evidence synthesized in this review supports the conclusion that sector coupling is not merely a complementary option but a necessary condition for achieving the depth of flexibility required by deeply decarbonized, renewable-dominated energy systems. Realizing this potential requires coordinated progress across technology deployment, digital infrastructure, market design, and institutional reform, i.e., a multi-dimensional challenge that mirrors the multi-dimensional nature of sector coupling itself.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sahar Seyyedeh-Barhagh reports financial support was provided by Business Finland. Sahar Seyyedeh-Barhagh reports financial support was provided by The Finnish Cultural Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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