Market Design for Sector-Coupled Energy Systems: Comparing Isolated, Coordinated, and Fully Integrated Concepts

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***Abstract*—Achieving climate neutrality while maintaining affordability requires market designs that provide efficient investment signals and accurately reflect the costs of electricity, gas, heat, and hydrogen. Yet these energy carriers are currently traded in largely separate markets, each governed by distinct rules tailored to their technical characteristics. Despite this institutional separation, significant cross-sectoral interactions already shape outcomes: gas prices influence electricity generation bids, while electricity prices affect heat production costs and emerging hydrogen business cases. This paper examines whether more coordinated or integrated market designs could improve system efficiency and resource allocation in a sector-coupled energy system. We compare three concepts: Isolated Markets, reflecting today's structure; Coordinated Markets, enabling temporal alignment across carriers while remaining institutionally separate; and Fully Integrated Markets, representing a co-optimized theoretical benchmark. Using performance indicators on efficiency, price formation, and implementation complexity, we qualitatively evaluate the alternative designs that can support future energy systems.**

***Index Terms*--Energy market design, market coupling, power system economics, sector integration, wholesale energy markets.**

I. Introduction

European energy systems are undergoing a profound structural transformation. Decarbonization targets, renewable integration, electrification of end uses, and the emergence of low-carbon gases and hydrogen are progressively linking sectors that historically evolved separately [1]. As sector coupling intensifies, electricity, natural gas, heat, and hydrogen systems are becoming technically and economically interdependent. Yet their market designs remain largely distinct and isolated, reflecting different physical characteristics, infrastructure constraints, and regulatory traditions [2].

The European electricity market is characterized by high temporal granularity and centralized short-term optimization. Because electricity must be balanced in real time and is only storable at a limited extent, trading is organized in sequential forward, day-ahead (DA), intraday (ID), and balancing markets [3]. Cross-border transmission capacity is allocated implicitly through market coupling algorithms that jointly determine prices and flows while respecting network constraints between bidding zones. Balancing responsibility is strict, where imbalances are dynamically prices based on grid balancing actions, and system operators procure reserves and dynamically activate balancing services to ensure frequency stability and operational security [4].

Gas markets differ fundamentally due to the storability of gas and the flexibility provided by linepack. They operate under entry-exit systems in which transmission capacity is booked explicitly and independently from commodity trading. Gas is exchanged at virtual hubs via forward, futures, day-ahead, and within-day products [5]. While these market segments also exist in electricity markets, trading in gas markets is typically more concentrated in forward products, whereas electricity markets rely more heavily on short-term trading. Balancing is typically organized over the gas day, allowing market participants to manage portfolio positions before financial settlement of residual imbalances. Network constraints and commodity prices interact differently than in electricity markets, as capacity allocation and energy trading are institutionally separated [6].

Heat markets are predominantly local. District heating systems generally rely on long-term contractual arrangements or regulated tariffs rather than organized wholesale markets. Price formation is often cost-based, and dispatch decisions are centrally optimized by district heating network operators [7]. Cross-border integration is highly limited, and EU-level harmonization is comparatively weak.

Hydrogen markets are at an early stage of development. Regulatory initiatives aim to establish open-access transport networks and entry-exit systems inspired by natural gas design, but liquidity, standardized short-term products, and transparent hub-based price formation are not yet fully established [8]. Infrastructure expansion, demand development, and market rulemaking are evolving simultaneously.

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These sectors, therefore, differ substantially in temporal resolution, balancing logic, capacity allocation mechanisms (implicit versus explicit), geographic scope, liquidity, and regulatory maturity. As sector coupling progresses, such heterogeneity risks leading to misaligned price signals, complex market participation strategies, inefficient dispatch decisions, and distorted investment incentives across carriers. While policy debates increasingly emphasize integrated energy planning and cross-sector coordination, there is limited systematic analysis of how alternative market design paradigms could address these structural differences.

This paper contributes to this discussion in three main ways. First, it identifies key barriers that limit the efficient participation of cross-sectoral technologies in current energy markets, including differences in product duration, operating days, market gate closures, price dynamics, and regulatory frameworks. Second, it analyses how these differences affect the operation of sector-coupling technologies. Third, the paper proposes and compares three alternative market design concepts for sector-coupled energy systems: (i) Isolated Markets, reflecting today's largely independent structures; (ii) Coordinated Markets, in which selected temporal design elements are aligned while maintaining institutional separation; and (iii) Fully Integrated Markets, a benchmark design where all energy carriers are co-optimized and cleared simultaneously, and evaluates them through a qualitative assessment based on key performance indicators related to efficiency, price signals, operational complexity, and implementation feasibility.

II. INTERACTION BETWEEN MARKETS

Although the wholesale markets for electricity, natural gas, hydrogen, and heat are organized as separate markets, they are economically interconnected through technologies that convert one energy carrier into another. These multi-sectoral technologies act as physical and economic interfaces between sectors by transmitting price signals, operational decisions, and energy volumes across carriers. As a result, developments in one market can influence supply, demand, and dispatch decisions in another.

A first and structurally important interaction occurs, for example, between the gas and electricity markets through gas-fired generation assets. Gas-fired power plants (GFPPs), including combined-cycle and open-cycle gas turbines, procure natural gas in the gas market and convert it into electricity that is sold in the day-ahead and intraday markets, while their flexibility can additionally be offered as upward and/or downward reserve capacity/activation in balancing markets. Their dispatch decisions depend on the relationship between electricity and gas prices, while considering plant efficiency and carbon costs. Changes in gas prices, therefore, affect the marginal generation costs of these plants and influence their bidding behavior in electricity markets, while electricity price levels determine the profitability of electricity production and consequently the demand for natural gas used in power generation.

Additional interactions between gas, electricity, and heat systems are evident in combined heat and power (CHP) installations. CHP units simultaneously generate electricity and heat from a single fuel source, typically natural gas. Electricity and gas are generally sold on wholesale electricity and gas markets, whereas heat is supplied to district heating networks or industrial users. The operation of CHP units, therefore, depends on electricity and gas price signals, and heat demand conditions. When electricity prices are high relative to fuel costs, operators may increase electricity production, provided that heat offtake is available. Conversely, variations in heat demand may constrain electricity generation levels. As a result, local heat system conditions can indirectly influence electricity market supply, while gas prices determine the production cost of both carriers.

Electricity and heat systems are also connected through power-to-heat technologies, such as large-scale electric boilers and industrial heat pumps integrated into district heating networks. These technologies consume electricity purchased in wholesale markets and convert it into thermal energy. Their operation is typically optimized based on electricity price levels relative to alternative heat production technologies, such as gas-fired boilers. Periods of low electricity prices can, therefore, stimulate electricity consumption in the heating sector, while higher prices may lead to a shift toward gas-based heat production.

Further emerging interactions involve electrolysers, which connect electricity systems with the developing hydrogen sector. Electrolysers use electricity to produce hydrogen, translating electricity price signals into hydrogen production decisions. Although a fully developed hydrogen market is not yet operational in Europe, electricity prices are expected to play a key role in determining hydrogen production costs and supply volumes [9].

These technologies create multiple channels through which developments in one energy market propagate to others. Even though electricity, gas, heat, and hydrogen markets are organized separately, multi-sectoral technologies transmit economic signals across sectors, creating interdependencies that are key to the operation of future energy systems.

III. MULTICARRIER MARKETS FOR SECTOR INTEGRATION

Despite the aforementioned interdependencies, the corresponding markets remain largely designed, cleared, and regulated independently. This separation becomes increasingly problematic for technologies that depend simultaneously on several carriers. Their optimal dispatch is determined by cross-market price relationships, yet their trading obligations and operational constraints are defined independently within each market. As a result, market design does not fully reflect the operational reality of cross-sectoral assets. The issue is, therefore, not that individual markets function inefficiently in isolation, but that coordination across carriers remains incomplete.

A. Barriers for sector integration

The main barriers that prevent efficient participation of cross-sectoral technologies were identified through a review of the literature on sector coupling and energy market design [10]-[14] , complemented by insights from interviews with market participants and industry experts. The resulting key barriers include:

- Differences in product duration and temporal granularity: Electricity markets operate with high temporal resolution, using 15-minute products in the day-ahead, intraday, and imbalance settlement stages. Gas markets are primarily structured around daily products with balancing obligations defined over the gas day. Hydrogen market proposals foresee similar daily balancing arrangements, while heat systems typically rely on longer-term operational planning and contractual supply structures. These differences reduce the ability of cross-sectoral technologies to optimize their operations across carriers when price signals cannot be consistently exploited.

- Misaligned operating days and settlement periods: Electricity DA markets follow the calendar day (00:00–24:00), whereas gas markets operate from 06:00 to $06{:}00^{+1}$ (the following day) with balancing obligations settled over the gas day. Hydrogen market proposals foresee comparable operational timings as gas markets, while heat systems typically operate according to demand forecasts and contractual schedules rather than standardized market periods. For assets participating in multiple markets, these misalignments complicate portfolio management and may create imbalance risks that arise from market timing differences.

- Sequential market closures and information asymmetry: Wholesale markets across carriers close at different times. Electricity day-ahead gate closure occurs before final gas positions are fully determined for the corresponding delivery periods. Consequently, operators of cross-sector technologies often submit bids without complete information about fuel prices, or demand conditions. This uncertainty increases operational risk and may lead to conservative bidding behavior and underutilization of cross-sectoral flexibility.

- Differences in price dynamics and volatility: Electricity prices can vary significantly within short time frames due to renewable variability and balancing requirements. Gas prices typically evolve more gradually within the gas day without significant variations. Heat prices in district heating systems are generally determined through long-term contracts or regulated tariffs rather than short-term market conditions. These differences in price dynamics complicate the optimization of cross-sectoral assets whose revenues and costs are exposed to markets with very different volatility patterns.

- Regulatory and institutional differences: Each carrier operates under a separate regulatory framework with distinct participation rules, nomination deadlines, capacity allocation mechanisms, and balancing procedures. Operators of cross-sectoral technologies must therefore comply with multiple regulatory systems simultaneously. These institutional differences increase administrative complexity, transaction costs, and regulatory uncertainty, particularly for new entrants and small players.

- Differences in market maturity and liquidity Electricity and gas markets in Europe are relatively mature and liquid. Hydrogen markets are still emerging, and liquidity is expected to develop gradually. Heat systems typically lack short-term tradable wholesale markets altogether. These differences influence risk management options and investment decisions for technologies operating across multiple carriers.

The main barriers limiting the efficient participation of cross-sectoral technologies are summarized in Table 1. As electrification intensifies, hydrogen markets develop, and district heating networks expand, addressing these barriers will become increasingly important for enabling efficient cross-sectoral optimization and supporting the long-term decarbonization of the energy system.

TABLE 1 KEY BARRIERS TO EFFICIENT MARKET PARTICIPATION OF MULTI-SECTORAL TECHNOLOGIES

Barrier	Core structural difference	Implication for sector coupling
Different product durations	Electricity traded in 15-min MTUs; gas and hydrogen mainly daily products; heat largely contractual or seasonal	Limits the ability of cross-sectoral technologies to react symmetrically to short-term price signals, reducing cross-market optimization.
Different operating days	Electricity day: 00:00–24:00; gas/hydrogen day: 06:00–$06{:}00^{+1}$; heat dispatch organized around demand schedules	Overlapping settlement periods complicate bidding, nominations, and balancing for cross-sectoral assets.
Sequential market closures	Gate closures occur at different times across carriers	Bids must be submitted without full information on other carrier prices, leading to conservative participation.
Price volatility mismatch	Electricity prices highly volatile; gas/hydrogen evolve more gradually; heat prices largely stable	Short-term optimal dispatch in one market may conflict with fuel procurement or contractual constraints.
Regulatory differences	Different rules, nomination procedures, balancing regimes, and settlement systems	Increased administrative complexity and transaction costs for sector-coupling operators.
Uneven market maturity	Electricity and gas markets mature and liquid; hydrogen emerging; heat not traded wholesale	Limited opportunities and weaker investment signals for cross-sectoral technologies.

B. *Levels of integration*

The barriers discussed in the previous section highlight that current energy markets are not fully aligned with the operational characteristics of cross-sectoral technologies. In particular, differences in product duration, operating days, and market closure sequences limit the ability of cross-sectoral technologies to optimize their operation across electricity, gas, hydrogen, and heat systems. To explore how these barriers could be addressed, this paper considers three alternative market design concepts that represent increasing levels of coordination between energy carriers.

1) Isolated markets

The isolated markets configuration represents the current market setting in which electricity, gas, hydrogen, and heat systems/markets operate largely independently. Each carrier is traded in its own market with distinct products, timelines, and balancing mechanisms. Market clearing occurs separately for each carrier, and coordination between sectors arises only indirectly through market participants' operational decisions.

In this setting, operators of cross-sectoral technologies must individually foresee and interpret price signals from multiple markets and determine their optimal operating strategies. Information exchange between markets occurs only through the bidding behavior of market participants rather than through coordinated market mechanisms. As a result, market outcomes depend on the ability of individual players to manage market uncertainties and operational constraints.

While this structure preserves the independence of each market and reflects the historical development of energy sectors, it does not explicitly address the structural barriers identified earlier. Differences in product durations, operating days, and market closure sequences remain unchanged, which may limit the efficient utilization of cross-sectoral technologies.

2) Coordinated markets

The coordinated markets configuration introduces partial alignment between energy carriers while maintaining separate market structures. Instead of merging the markets, selected design elements are harmonized in order to reduce the barriers identified in Section IIIA.

Coordination focuses on the temporal organization of markets, including product duration, operating days, and market gate closures. Aligning these elements allows market participants operating cross-sectoral technologies to make decisions based on more consistent information across carriers. For example, synchronizing operating days between electricity and gas markets would simplify the operation of gas-fired power plants (GFPP), which currently need to compensate for temporal mismatches between the two markets. Another example is the introduction of greater granularity in the day-ahead gas market. By including a 6-hour product, gas procurement could better align with the operational needs of electricity markets and short-term flexibility requirements. Moreover, aligning market closure times may simplify the decision-making process, particularly for smaller market participants that lack sophisticated optimization tools to manage bidding strategies when bids must be submitted across multiple markets with different timelines.

Under this concept, electricity, gas, hydrogen, and heat markets continue to be cleared independently, but their timelines and operational structures are partially coordinated. Multi-sectoral technologies remain responsible for optimizing their own dispatch, yet improved temporal alignment enables more efficient cross-market participation. Therefore, the coordinated markets configuration represents an intermediate approach that seeks to improve system efficiency while preserving the institutional independence of existing market structures.

3) Fully integrated markets

The fully integrated markets configuration represents a theoretical benchmark in which all energy carriers are jointly optimized within a unified market framework. In this configuration, electricity, gas, hydrogen, and heat are jointly cleared by a central operator using a single market clearing process.

Rather than treating multi-sectoral technologies as market participants interacting across separate markets, this configuration represents interactions between carriers through additional products within a unified market framework. These products internally link the different energy carriers, allowing the market-clearing mechanism to determine the optimal allocation of resources across all carriers simultaneously.

This approach eliminates many of the structural barriers identified earlier. Market timelines are inherently synchronized, information asymmetry is removed, and price signals across carriers emerge from a unified optimization framework. Although such a fully integrated market design may face significant institutional and regulatory challenges in practice, it provides a useful benchmark for assessing the potential efficiency gains associated with deeper cross-sector coordination. Table 2 summarizes the main characteristics of the three market design concepts and highlights the increasing level of coordination across energy carriers.

TABLE 2 COMPARISON OF MARKET DESIGN CONCEPTS

Feature	Isolated markets	Coordinated markets	Fully integrated markets
Market clearing	Separate clearing for each energy carrier	Separate clearing with coordinated timelines	Joint clearing across all carriers
Temporal structure	Different product durations, operating days, and gate closures	Partial alignment of temporal market structures	Fully synchronized temporal structure
Information exchange	Indirect, through market participants	Improved coordination through aligned timelines	Direct, within a unified optimization
Role of multi-sectoral technologies	Market participants optimize operation across markets	Participants optimize with improved cross-market information	Explicitly represented in system-wide optimization
Institutional structure	Independent market operators and rulebooks	Separate markets with coordinated elements	Unified market framework with central operator
Coordination level	Low	Medium	High

IV. QUALITATIVE COMPARISON

The proposed market design concepts are compared using a qualitative set of key performance indicators (KPIs). KPI-based approaches are widely used to evaluate complex energy systems across dimensions such as efficiency, reliability, and cost [15]. In electricity market design, assessments commonly focus on dispatch efficiency and the quality of price signals guiding operational decisions [16]. Building on these principles, six KPIs are defined covering: (i) system performance (resource allocation efficiency; utilization of sector-coupling flexibility; price signal consistency across carriers), (ii) market participant conditions (operational complexity; information availability at bidding), and (iii) feasibility (implementation complexity). Table 3 summarizes the qualitative comparison.

TABLE 3 QUALITATIVE ASSESSMENT OF MARKET DESIGN CONCEPTS

KPI	Isolated markets	Coordinated markets	Fully integrated markets
Resource allocation efficiency	Medium	High	Very high
Utilisation of sector-coupling flexibility	Medium	High	Very high
Price signal consistency across carriers	Low–medium	Medium–high	High
Operational complexity for market participants	High	Medium	Low
Complexity of market clearing	Low	Low-medium	High
Information availability at bidding stage	Low	Medium	High
Implementation complexity	Low	Medium	Very high

The comparison highlights clear differences between the concepts. In isolated markets, cross-sectoral interactions occur only indirectly through market participants. While this preserves the independence of individual markets, misaligned market timelines and fragmented information can limit the utilization of sector-coupling flexibility and increase the operational burden for cross-sectoral operators.

The coordinated markets concept improves performance by aligning key temporal elements, such as product durations, operating days, and gate closures, while keeping market clearing separate. This reduces information asymmetry, supports more effective cross-market participation by multi-sectoral technologies, and improves consistency of short-term signals across carriers.

The fully integrated markets concept represents a theoretical benchmark where all carriers are co-optimized in a single clearing process, maximizing efficiency and cross-sectoral flexibility utilization. However, it also requires the most substantial institutional and regulatory change, reflected by the highest implementation and market clearing complexity. In this sense, coordinated markets is the best possible solution considering the practical reality, as the theoretical optimal faces a near-impossible set of practical challenges.

V. CONCLUSIONS

This paper highlighted how the increasing deployment of sector-coupling technologies challenges the current organization of energy markets. Although electricity, gas, hydrogen, and heat are traded in largely separate markets, technologies such as CHP units, electrolysers, and power-to-heat installations create growing interdependencies between these carriers. The work showed that several differences between markets (including product durations, operating days, and market gate closures) can limit the efficient utilization of cross-sectoral technologies.

To explore possible improvements, three market design concepts were proposed: isolated markets, reflecting the current structure; coordinated markets, where key temporal elements of market design are aligned across carriers; and fully integrated markets, representing a theoretical benchmark where all carriers are jointly optimized. A qualitative comparison based on selected KPIs suggests that coordinated markets can improve the utilization of sector-coupling flexibility and the consistency of price signals while preserving separate market structures. Fully integrated markets provide the highest level of efficiency but involve significantly higher implementation complexity.

Future work will focus on extending this analysis through quantitative modelling of sector-coupled energy systems to assess the impact of different market designs on system costs, price formation, and operational outcomes.

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