Case-Based Insights into Local Multi-Commodity Energy System Integration

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***Abstract*—This paper presents case-based insights into the institutional and technical integration of local multi-commodity energy systems, focusing on electricity, hydrogen, and heat within the industrial cluster of Groningen Sea Ports in the Netherlands. A local market clearing platform, trading agents representing the strategies of industries, and a distributed asset control system were developed by extending and aligning existing technologies and solutions from industry partners while ensuring compatibility with the organizational and regulatory context in which they operate. The study evaluates both the technical performance and the institutional feasibility of the system with Technology Readiness Level 5, identifying key integration challenges and opportunities. Results show that approximately 30% of energy transactions could be executed locally, indicating potential for congestion management and local balancing of hydrogen and heat. The paper concludes with an assessment of the development steps still required to reach full operational maturity, offering insights for future implementations in similar industrial ecosystems.**

***Index Terms*—multi-commodity energy systems, local energy markets, market-based control, system integration**

I. Introduction

The integration of renewable energy sources and electrification of industrial processes are central to the decarbonization of energy systems. However, in many industrial regions, these ambitions are increasingly constrained by the limited capacity of existing energy infrastructure. As such, industrial sites look for smart integration of renewable energy and energy carriers, supported by digital tools and system-level coordination, to enable flexible, resilient, and climate-neutral operations.

At the heart of such solutions is grid-edge coordination: the intelligent alignment of control actions across distributed energy resources (DERs) that are interconnected via local energy infrastructures, including electricity distribution networks, thermal networks, hydrogen pipelines, and on-site storage systems. This broader definition derived from Nguyen et al. [4] reflects the complexity of local multi-commodity energy systems, where DERs interact across multiple vectors to support integrated, flexible, and resilient operations.

This work was supported by the Ministry of Climate Policy and Green Growth, and Energy Innovation NL (Subsidy scheme TSE-22-25-01-SMCES, project TSYS222002). This research was partly funded by the research program "MegaMind—Measuring, Gathering, Mining and Integrating Data for Self-management in the Edge of the Electricity System", (partly) financed by the Dutch Research Council (NWO) through the Perspectief program under number P19–25.

979-8-3315-2503-3/25/31.00$2025 IEEE$

As Charbonnier et al. [3] highlight, a wide variety of grid-edge coordination mechanisms (for electricity distribution systems) have been proposed in the past 30 years. Charbonnier et al. introduce a taxonomy of distributed control based on objective structural features of the individual strategies. The taxonomy clarifies the interplays between agency decentralisation (direct, indirect), information flows (mediated, bilateral, implicit), and game motivations (competitive, cooperative).

This paper presents a case-based evaluation of a Smart Multi-Commodity Energy System (SMCES). The grid-edge coordination approach at the core of the SMCES follows the mediated competition model, as defined by Charbonnier et al. (2022): *Mediated competition involves competitive individual units which maximize their own objective function only. The mediator collects information from units and sends back signals that they believe will incentivize globally optimal action, such as price signals or prosumer matchings.*

The SMCES we study in this paper is developed in the SynergyS project. The SynergyS project realized a prototype of a SMCES, characterized by agent-based control strategies operating on (local) markets. The case study entails the projected situation for 2030 for Groningen Sea Ports, an industrial cluster in the Northern Netherlands operating around 8 GW of power. The SMCES integrates electricity, heat, and hydrogen flows using a local market platform, intelligent trading agents and data-driven local control. The SMCES was tested using digital twins of energy assets, trading agents representing the strategies of industries, and hardware-in-the-loop simulations.

This paper focuses on evaluating the feasibility of applying a mediated competitive coordination mechanism within a multi-commodity energy system. Specifically, it examines how this type of mechanism performs in terms of aligning decentralized decision-making with system-wide objectives in an industrial context such as resolving congestion and maintaining the temperature of a heat network.

According to best practices to describe experimental studies in empirical software engineering [10], we present our assessment as a *case study* aimed to *quantify* certain properties of a solution. Our *object of study* is a mediated competitive method in general rather than the SMCES we do the experiments with.

The analysis is structured using the taxonomy for evaluation of distributed control strategies for distributed energy resources proposed by Han et al. [2].

The main contribution of this paper is to provide empirical evidence on the viability of a mediated competitive grid-edge coordination approach in complex, multi-vector industrial energy systems. Furthermore, we present key integration challenges related to institutional factors and the effect of the interplay between different energy carriers on infrastructure elements.

II. Background and Problem Context

Industrial clusters are increasingly at the forefront of the energy transition, yet they face unique challenges due to their high energy demand, spatial concentration, and reliance on legacy infrastructure. In the case of Groningen Sea Ports, the area development authority is tasked with enabling new energy projects—such as large-scale hydrogen production and electrification of industrial heat—within a context of grid congestion and a shift from continuous on-site production to a variable mix of resources.

Beyond electricity, the coordination of heat and hydrogen flows has emerged as a critical issue. These energy carriers are subject to distinct temporal and spatial dynamics, and their integration introduces new inter-dependencies that complicate system operation. From a systems perspective, these challenges can be framed as a grid-edge coordination problem. This involves aligning the actions of multiple actors—such as producers, consumers, and storage and grid operators — each with their own responsibilities, objectives, constraints, and operational logic. The complexity of the grid-edge coordination problem is amplified in multi-commodity systems, where decisions in one domain (e.g., electricity) can have cascading effects in others (e.g., hydrogen or heat).

To address the complexity of coordinating diverse stakeholders in the energy transition, the Smart Multi-Commodity Energy System (SMCES) concept was developed to align stakeholder actions in a manner that is both technically integrable and institutionally acceptable. This means the SMCES should use existing industrial technologies and communication standards, ensuring compatibility with current systems. At the same time, it is designed to operate within the institutional framework of the Dutch energy system as envisioned for 2030, thereby supporting regulatory and governance alignment.

A. Motivation for grid-edge coordination approach

The focus on technical and institutional compliance is reflected in the deliberate choice of a grid-edge coordination mechanism based on *mediated competition*:

- Direct control of energy assets is infeasible, as each specialized company (industries and grid operators) at Groningen Seaports relies on established operational systems—including company-specific ICT infrastructures, and dependencies on both technical personnel and external service providers—and must retain operational autonomy for business and safety reasons.
- Groningen Seaports, while not operating the coordination system itself, serves as a natural mediator capable of facilitating long-term agreements between parties. This role is reinforced by its direct exposure to infrastructure limitations that hinder both industrial growth and decarbonization. We chose a symmetrical architecture in which all local energy market participants communicate directly with the mediator.
- Although companies in the area are open to mutually beneficial collaboration, they remain commercial competitors in daily operations. Communication in the form of energy trades is business as usual. We chose a SMCES design that communicates in terms of value (prices, volumes) that have a clear meaning for the participants and fits with the relation they have to each other. It might be needed to go for a design that functions without sharing market participants (full) local price information as this might contain sensitive information.

As the goal of the project was to develop a SMCES in an environment that mimics real-world conditions, commercial developers of a local market solution, a data warehouse solution, and a settlement solution were involved in the project. The companies contributed commercially viable environments on which the SMCES concept was built. The local market solution provider brought in a single-commodity market platform as a reference solution, which was iteratively extended during the project to support multi-commodity market functionalities.

B. Options to manage infrastructure constraints

The SMCES design allows for different mechanisms to manage local constraints to be implemented within the same architectural framework, enabling a range of configurations depending on the system context.

- The grid operator can also participate in the local market by submitting bids. Although this functionality was not implemented in the current version of the SMCES, for electricity, it could be realized through integration with GOPACS [6]: a platform that enables grid operators to request local flexibility bids, with redispatch secured via wholesale market platforms.
- Bidding strategies could incorporate obligations for participants to contribute to managing local constraints, such as fulfilling non-firm connection agreements at either the individual or group level or an obligation to the DSO or other market participants to provide flexibility. For example, a party with a heat storage is obliged via long-term contracts with users of heat to reserve a certain amount of heat for moments of scarcity.
- The platform also supports mechanisms to prioritize local trading, for example by applying an infrastructure fee to trades executed outside the local cluster. This feature was used in the experiments to explore the maximum achievable level of local matching.

However the last option was chosen for the experiment, the first two options fit better in the context of the use case as no incentives for local matching are expected to be in place.

III. System Architecture and Implementation

The Smart Multi-Commodity Energy System (SMCES) developed in the SynergyS project is designed to coordinate local energy flows for multiple commodities. The system uses a combination of commercially available tools (data warehouse, data historian, settlement solution and energy management management) and newly developed functionality on local multi-commodity energy markets, intelligent agent bidding, and data-based asset control. The system was developed as an operational prototype (TRL5) capable of hardware-in-the-loop testing.

A. System Scope and Asset Modeling

The SMCES focuses on three energy carriers: electricity, hydrogen, and heat. These were selected to reflect the most relevant commodities for industrial clusters such as Groningen Sea Ports. Based on stakeholder consultations, a portfolio of 40 assets expected to be operational by 2030 was modeled. These include 14 consumption assets, 11 conversion assets, 10 production assets, and 5 storage assets. Each asset was implemented as a digital twin using the open-source *Illuminator* framework. [9]. In addition, 9 physical assets were integrated from two field labs: Entrance (Hanze University of Applied Sciences) and The Green Village (TU Delft).

B. Architectural Components

The information flows in the SMCES architecture are shown in Fig. 1, which are further elaborated below. Backbone for the information flows in Fig. 1 is a data warehouse, which combines a centralized data repository with a historian for time-series data collection and control. Communication is facilitated via standard communication protocols (OPC UA, MQTT, REST), enabling seamless integration between all components of the system.

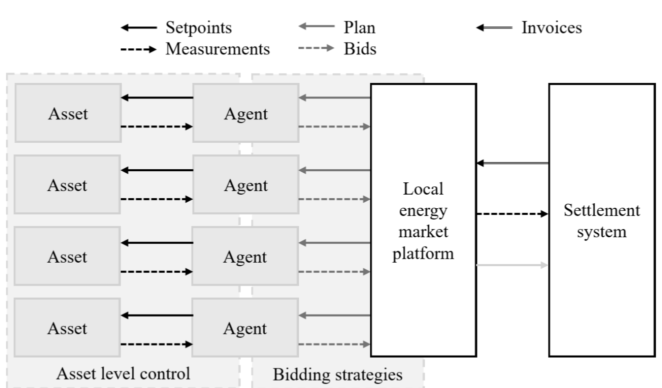

Fig. 1. SMCES architecture information flows.

1) Local energy market platform: The market platform includes separate markets for electricity, hydrogen, and heat. These markets operate on a local and wholesale level with both day-ahead and intra-day timescales (both at 15-minute resolution). The day-ahead market uses a pay-as-cleared auction mechanism, while the intra-day market operates on a pay-as-bid basis with a live order book. A virtual wholesale supplier ensures liquidity, but local prices may diverge due to congestion, transport costs, or long-term agreements.

2) Bidding strategies: Agents represent the role of asset operator and market trader. Their bidding strategies are shaped by market knowledge, weather forecasts, and stakeholder agreements. Agents use either a game theoretic optimization [7], [8] or heuristic marginal cost approach [5] to determine their optimal bids. After the markets clearance, agents receive their plans (cleared bids) in return. The bidding strategies were developed using agentic reasoning capture via structured interviews, applying the Belief-Desire-Intention (BDI) framework [1]. This approach, introduced in [11], enabled the reasoning of bidding agents to be systematically captured, formalized and validated with stakeholders.

3) Asset level control: A combination of digital twins and physical assets from two field labs simulate the behavior of future assets. The asset controllers receive 15-minute setpoints from the *agents* who operate between the asset and the local energy market. Measurement data is collected to enable financial settlement and evaluate the performance of the SMCES. Differences in scale and dynamics between the field lab testbeds and the 2030 asset base are taken into account in the evaluation.

4) Settlement system: At the end of each day, the settlement component reconciles market transactions with actual asset performance. It compares traded volumes with realized outputs, based on measurements from the assets. A fixed network fee (€/MWh) is applied to imports and exports across the cluster boundary, incentivizing local transactions.

TABLE I
SynergyS model days

Model day	Date[a]	Description
MD1	April 2	Reference day
MD2	June 18	Summer, windy
MD3	June 30	Summer, little wind
MD4	June 23	Summer, windy, full storage
MD5	November 5	Winter, windy
MD6	December 3	Winter, little wind
MD7	November 17	Winter, little wind, empty storage

[a]Model days refer to forecasted weather conditions for the year 2030.

IV. Results and Evaluation

This section outlines the evaluation results of the SMCES across seven model days, based on the design criteria defined by Han et al. [2]. Table I lists the seven model days, selected from a 2030 weather model to represent typical operating conditions throughout the year.

Table II summarizes the evaluation of the SynergyS SMCES prototype with the Distributed–Horizontal–Centralized (D-H-C) shared memory architecture as defined by Han et al. [2] serving as the reference. The SMCES aligns well with the D-H-C architecture, known for its strong performance in implementing design constraints such as fairness, fit with operational and economic context and a consistent view on

TABLE II
COMPARISON D-H-C VS. SYNERGYS SMCES USING DESIGN CRITERIA BY HAN ET. AL [2]

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Category	Constraints				Metrics								
	PRI	FAI	TEF	MCS	RTS	OPT	RES	SCA	AVA	MAT	EOI	MTY	OTR
D-H-C	× / ✓	✓	✓	✓	-	-	0 / -	-	0	0	0	0	0
SynergyS SMCES	✓	✓	✓	✓	-	0	0 / -	-	0 / -	0	0 / +	0	0

all control actions. While the D-H-C category is generally associated with lower performance on metrics such as privacy, scalability, availability, and optimality, these limitations did not manifest in the SMCES. This can be attributed to specific design choices and the characteristics of the industrial context in which the system is deployed.

A. Information isolation and privacy

According to Han et al. in D-H-C architectures *'privacy is algorithm and implementation dependent, as the shared memory includes all coordination-relevant data'*. In the SMCES data exchange is limited to communication of bids (volume, price per time step) and clearing volumes between trading agents and the local market platform provider. This level of information exchange aligns with the design requirements defined at the start of the project. Left for future work is to explore the value and risks of sharing (partly) local market price information.

B. System optimality and accuracy

The metric *system optimality and accuracy* is defined as *'the difference between a theoretically achievable optimum and the practically achieved outcome'* [2].

Since a theoretical optimum across all dynamics of the use case was not available, we instead explored the maximum potential for local matching within the SMCES. To this end, we designed an experiment assuming a high fee for energy exchange outside the cluster. This setup created a strong incentive for local coordination, simulating conditions such as transport tariffs or contractual obligations for local supply and flexibility.

Fig. 2 illustrates the resulting day-ahead trade volumes in both local and wholesale markets. On average, around 30% of the total traded energy—equivalent to 2–3 GWh per day—was matched locally, demonstrating the system's capacity for local balancing. This amount of local matching can potentially resolve grid congestion issues at Groningen Sea Ports.

C. Availability

Availability is defined as *'the degree to which the system is in a specific operable state'*. This metric was addressed by measuring the tactical reliability: the fraction of available flexibility offered in the different markets. Fig. 3 shows this metric including weather-dependent sources (e.g., solar and wind), while Fig. 4 excludes them.

The results show that in the Groningen Sea Ports use case tactical reliability is highly sensitive to weather conditions.

Fig. 2. Day-ahead trade volumes: local vs. wholesale markets.

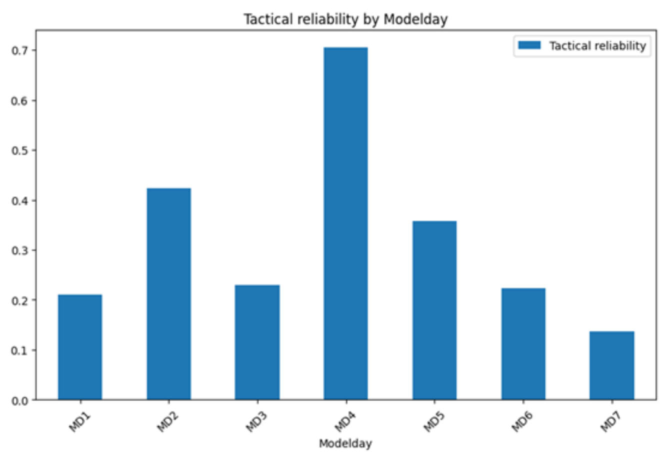

Fig. 3. Tactical reliability including weather-dependent sources.

On sunny and windy days (e.g., MD4), a large share of flexibility is offered, while on calm, dark days (e.g., MD7), the share drops significantly. For reliable SMCES operation, the minimum expected flexibility (rather than the maximum) should be used in planning decisions. As such, we identified weather-dependency as a crucial factor to take into account in SMCES investment decisions at Groningen Sea Ports.

D. Ease of integration

The metric *easy of integration* is defined as the ability to integrate the SMCES into an existing environment. In Chapter II we discussed the institutional feasibility. During the experiments, we did not observe a violation of these design

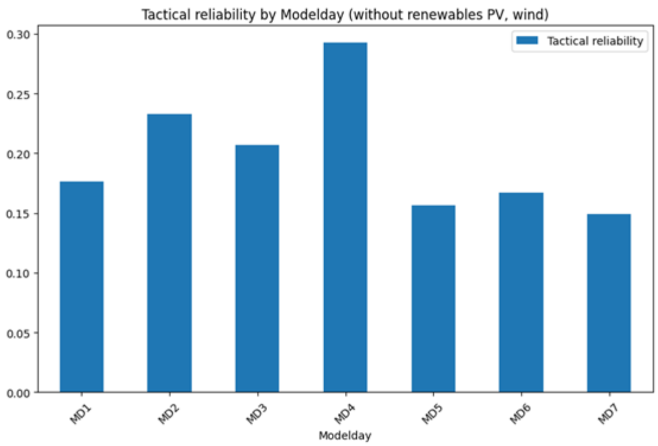

Fig. 4. Tactical reliability excluding weather-dependent sources.

choices. However we observed a challenge to create a system that is compatibility with physical infrastructure (electricity, heat and hydrogen). An ex post grid loading analysis [12] showed that on one grid element the loading percentage was 110% from the physical capacity limit. This demonstrates that activation of flexibility for one goal might create other issues in parts of the infrastructure.

From this observation we learn that a simple local trade incentive is not enough to create a functioning SMCES. Every physical infrastructure constraints that could be violated by flexibility activations should be included in the SMCES design. This means an integrated load flow analysis is required. The SMCES offers options to include such analysis either via DSO participation in the local market or by incorporation monitoring and manage local constraints in the SMCES market clearing or bid strategies of participants.

V. Discussion and Recommendations

The integration of a local multi-commodity energy systems within the Groningen Sea Ports industrial cluster demonstrates both the promise and complexity of mediated competitive grid-edge coordination.

A. *Promise of mediated competitive grid-edge coordination*

The local matching results underscores the potential for grid-edge coordination to contribute meaningfully to congestion management and the local balancing of electricity, hydrogen, and heat. Furthermore, we demonstrate that in a real-world industrial context performance we can overcome the weaknesses of the chosen distributed control architecture.

B. *Complexity of mediated competitive grid-edge coordination*

However, the transition from a TRL 5 prototype to a mature operational system requires addressing several challenges such as defining the amount of flexibility that can be provided ahead and including weather-dependency.

The most challenging task is systematically addressing infrastructure constraints—essential for aligning local trading and load reduction efforts with the needs of market participants and grid operators. We demonstrated that grid constraints can be integrated into SMCES design through various institutional models: either by involving the grid operator as a market participant or by enforcing constraint management among participants. Selecting the appropriate model is complex, requiring stakeholders to redefine roles and renegotiate relationships.

C. *External validity of the findings*

These findings on mediated competitive grid-edge coordination are based on a single case study conducted without a theoretical optimum for comparison. This reflects a key practical reality: in complex and dynamic industrial energy systems, developing a representative theoretical model is often infeasible due to the time required and the limited applicability of more abstract models. As a result, stakeholders must assess outcomes based on absolute performance rather than comparing them to an ideal benchmark.

The outcomes observed in this case cannot be assumed to apply universally, given the diversity of industrial areas in infrastructure as well as SMCES implementation choices. To advance the understanding of local multi-commodity energy matching, further case-based research across varied contexts is needed. Such efforts would strengthen the empirical foundation, uncover context-specific challenges and opportunities.

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