Report on recommendations and roadmap for sector integration in Belgium

D4.2

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About ReInvent

In 2030 and beyond, multiple energy vectors (electricity, gas, heat, green molecules) will play a role in an interconnected energy system. Increased electrification will support sector integration between end user segments. To benefit maximally from the advantages of sector coupling, a fundamental rethinking of market design, business models and financing models is needed. ReInvent will define a roadmap for sector coupling in Belgium. The ReInvent approach is based on **4 pillars** and is a combination of 1) conceptual analysis, 2) sound modelling, 3) proofing of concepts by relevant test cases, and 4) an ambitious impact assessment and replication strategy.

The **first pillar** will analyse the role of different energy vectors (gas, power, heat, green molecules…) in the Belgian energy mix. This includes the impact on infrastructure, market design and business models for different energy end user groups. Based on discussions with project partners and relevant stakeholders, different concepts for both supply-side and demand-side sector integration will be proposed. In addition to the operational implications of sector integration, the financial implications in terms of risk, return, and uncertainty will be analysed.

The **second pillar** will develop the ReInvent modelling and simulation. This multi-sectoral simulation environment will capture the different dynamics of different vectors in multiple timeframes, for multiple scenarios, for multiple market design options, for multiple services, including different end-use sectors and different layers of the physical networks and their interconnection. Innovations modelled in ReInvent aim at the overarching goal of augmenting and realizing the potential of sector coupling in providing key flexibility, balancing, and adequacy services to the multi-energy system and the electric grid.

The **third pillar** will look at a selection of reference test cases that represent main use cases of sector coupling/integration. These applications will provide real data that allow proofing of the developed models in the second pillar. In addition, the models of the second pillar will provide necessary insights to the test cases about the impact of the ReInvent solutions on the operational and financial stability of the presented solution. The ReInvent test cases address different vectors, end user segments and applications and are selected based on the technologies and applications that will play a central role in a future integrated system but still face barriers today that hinder their expected breakthrough.

The **fourth pillar** will define a roadmap for improved sector coupling and sector integration for Belgium. This includes an impact assessment of a wide roll-out of the solutions for the Belgian energy system, in particular the implications for security of supply and system balancing.

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List of Abbreviations and Acronyms

Acronym	*Meaning*
5GDHC	5th Generation District Heating and Cooling
aFRR	automatic Frequency Restoration Reserve
ATES	Aquifer Thermal Energy Storage
BESS	Battery Energy Storage System
BRP	Balance Responsible Party
BUC	Business Use Case
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
CPO	Charge Point Operator
DA	Day-Ahead
DER	Distributed Energy Resource
DHC	District Heating and Cooling
DHCN	District Heating and Cooling Network
DSO	Distribution System Operator
EV	Electric Vehicle
FSP	Flexibility Service Provider
H_2	Hydrogen
HVDC	High-Voltage Direct Current
IoT	Internet of Things
KPI	Key Performance Indicator
LCOC	Levelized Cost of Charging
$LCOH_2$	Levelized Cost of Hydrogen
MSP	Mobility Service Provider
NPV	Net Present Value
NSIM	North Sea Integration Model
OCPP	Open Charge Point Protocol
OCPI	Open Charge Point Interface
OEM	Original Equipment Manufacturer
POMMES-EU	POMMES-EU energy-system model
PoC	Proof of Concept
PPA	Power Purchase Agreement
PPP	Public-Private Partnership
PV	Photovoltaic
REC	Renewable Energy Community

RFNBO	Renewable Fuel of Non-Biological Origin
SUC	System Use Case
TCO	Total Cost of Ownership
TIMES-BE	TIMES-BE energy-system model
TSO	Transmission System Operator
V2G	Vehicle-to-Grid
VRE	Variable Renewable Energy
WP	Work Package

Executive Summary

The transition towards a climate-neutral energy system will increasingly connect electricity, heat, gas, hydrogen, mobility and other end-use sectors. Sector coupling can support the integration of renewable energy and unlock new sources of flexibility, but its benefits depend on more than connecting technologies or energy carriers. Appropriate market arrangements, viable business and financing models, enabling infrastructure, effective coordination between actors, and supportive regulatory frameworks are equally important.

ReInvent investigated these interactions in the Belgian context through four complementary pillars: a conceptual framework addressing market design, business models and financing; a multi-sectoral modelling environment; proof of concept through a diverse set of real-life test cases; and an assessment of scalability, replicability and wider energy-system impacts. This deliverable brings these strands together to derive overarching lessons and recommendations for improving sector coupling and integration in Belgium.

Pillar 1: Creating the enabling framework for sector coupling

ReInvent adopts an interpretation of sector coupling centred on the integration of renewable electricity through direct and indirect electrification. ReInvent therefore highlights three central aspects of sector coupling: electrification and demand-side flexibility, power to gas, liquids and heat (Power2X), and community energy. Successful sector coupling depends on the combined alignment of energy vectors, technologies, markets and enabling mechanisms. Its deployment is therefore affected by interconnected economic, market, technical, social and organisational conditions.

The *market-design analysis* shows that physically coupled energy systems are still served by electricity, gas, hydrogen and heat markets with different products, timelines and levels of maturity. Rather than moving directly towards fully integrated multi-carrier markets, ReInvent identifies greater coordination between existing markets as a more realistic pathway. Targeted alignment of product durations, market timing and other design elements can facilitate the participation of multi-carrier technologies while avoiding the significant implementation complexity associated with full market integration.

The work on *business models* further demonstrates that there is no single business model suited to all sector-coupling applications. Industrial actors, energy communities and residential users differ substantially in their investment capacity, risk exposure, organisational capabilities and willingness to participate. Viable models consequently require actor-specific value propositions together with predictable revenues or savings, appropriate governance, regulatory clarity, trusted coordination and fair allocation of costs, risks and benefits.

The same principle applies to *financing*. The appropriate financing structure depends on project scale, ownership, technology maturity, revenue model and risk profile. Bankability is determined not only by technical feasibility but also by revenue certainty, financial resilience, regulatory compliance, permits and grid access, governance and project documentation. ReInvent therefore proposes a structured financing assessment to

identify areas requiring further attention and appropriate risk-mitigation measures, while recognising that this cannot replace project-specific technical, legal and credit assessment.

Pillar 2: Quantifying sector coupling across scales and time horizons

ReInvent developed a multi-sectoral modelling environment connecting electricity, heat and cold, hydrogen, mobility and other energy-system components across local and system levels and across short-term operation and long-term investment horizons. The modelling covers multi-energy system planning, multi-carrier wholesale markets, end-users and energy communities, and the use of cross-sector flexibility in electricity-system services.

These complementary modelling approaches make it possible to examine sector coupling from the level of individual users and communities through to national and European energy-system development. They also allow interactions between investment, market participation, operational flexibility, pricing and system requirements to be assessed rather than considering individual technologies in isolation.

The overarching modelling insight is that the availability of flexibility does not by itself ensure that flexibility will be used where it creates most value. The value captured from sector coupling depends strongly on market timing and structure, tariffs and local pricing rules, access to flexibility markets and investment assumptions. Technically available flexibility may remain unused when economic signals, market arrangements or regulatory conditions do not support its activation.

Pillar 3: Lessons from the ReInvent business use cases

The ReInvent business use cases applied the concepts of pillar 1 to concrete sector-coupling applications covering district heating and cooling, batteries and energy communities, shared and private electric mobility, community energy, hydrogen production and use, integrated offshore energy systems and smart billing. The BUCs are evaluated using the ReInvent modelling environment developed under Pillar 2. Taken together, the cases demonstrate that sector coupling can create value in very different settings, while also showing that value depends strongly on how technologies and actors are coordinated.

A recurring lesson is that coordinated optimisation can outperform isolated operation. Examples throughout the use cases show benefits from coordinating renewable generation with storage, EV charging or hydrogen production; jointly managing community assets; or combining operation across several markets. At the same time, increasing aggregate value does not automatically ensure that every participant benefits. Transparent pricing, benefit sharing and governance are therefore fundamental to converting technical and system benefits into viable business propositions.

The cases also demonstrate that flexibility should not be equated with a single technology such as batteries. Depending on the application, value can come from flexible demand, thermal storage, hydrogen storage, batteries, controllable conversion technologies or combinations of these options. The appropriate solution depends on the use case, existing infrastructure and market conditions. Where possible, sector-coupled assets

should be able to combine local optimisation with participation in balancing, congestion-management and other markets, thereby accessing complementary value streams.

Finally, real-world conditions matter. User behaviour, equipment constraints, forecast uncertainty, degradation, mobility requirements and changing market conditions can materially reduce or reshape flexibility compared with idealised assumptions. Similarly, optimising a single objective such as self-consumption, grid independence or market revenues can shift costs elsewhere in the energy system. The results therefore underline the importance of realistic assumptions and a whole-system, multi-objective perspective when assessing sector-coupling solutions.

Pillar 4: From individual solutions to wider deployment and system impact

The scalability and replicability assessment confirms that a technically successful pilot is only a first step towards wider deployment. Sector-coupling solutions generally need to be adapted to local infrastructure, regulation, markets and stakeholder requirements. Standardisation of technologies, data and interfaces can facilitate replication, but needs to be combined with sufficient flexibility for local implementation. Wider deployment also depends on credible economic value propositions and an appropriate allocation of costs, benefits and responsibilities.

At system level, the ReInvent analysis identifies demand-side flexibility, including flexible EV charging and flexible heat, as particularly valuable options for supporting renewable integration. Hydrogen and other clean molecules can also play an important role, particularly for applications that are difficult to electrify, although their future contribution and supply pathways remain subject to substantial uncertainty. The analysis further supports greater coordination between electricity, gas, hydrogen and balancing-market design and highlights the value of using complementary system models to explore uncertainties surrounding future energy-system development.

Across all four pillars, ReInvent therefore points towards an integrated approach to sector coupling. Technologies, infrastructure, markets, regulation, financing and business models should be considered jointly rather than developed independently. Infrastructure and grid conditions need to be addressed early; market and tariff arrangements should reward flexible and system-friendly operation; business and financing models should distribute value and risk transparently; and scalability should be considered from the beginning rather than after a pilot has been completed.

Ultimately, the ReInvent results indicate that the value of sector coupling lies not simply in connecting energy carriers, but in coordinating technologies, actors and markets so that flexibility and renewable energy can be used where they provide the greatest overall value. Combining coordinated planning and operation with realistic assessment, enabling regulation, appropriate incentives and fair allocation of benefits can support the transition from successful demonstrations towards viable and replicable sector-coupling solutions in Belgium.

1 Introduction

By 2030 and beyond, multiple energy vectors (electricity, gas, heat, and green molecules) will play a crucial role in an interconnected energy system. Increased electrification will support sector integration across various end-user segments. To fully capitalize on the advantages of sector coupling, a fundamental rethinking of market design, business models, and financing models is required. ReInvent will define a roadmap for sector coupling in Belgium, based on advanced modelling and robust test cases. These reference test cases have been selected based on the technologies and applications expected to play a central role in the future integrated system, but which currently face barriers hindering their breakthrough. This deliverable will derive a comprehensive set of lessons learnt from the ReInvent work and propose recommendations for realizing the benefits of improved sector coupling and integration in a Belgian context.

1.1 Objectives of the Work Reported in this Deliverable

This deliverable reports on Task 4.3 and brings together the main insights from across the ReInvent project to derive overarching lessons learnt and recommendations for improved sector coupling and integration in Belgium. It synthesises findings from the different pillars: conceptual work (Pillar 1, corresponding to WP1), the development of the multi-sectoral modelling environment (Pillar 2, corresponding to WP2), the evaluation of the ReInvent business use cases (Pillar 3, corresponding to WP3), and the assessment of their scalability, replicability, and wider system impacts (Pillar 4, corresponding to WP4). Building on these findings, the deliverable identifies the technical, economic, market, and regulatory conditions that shape the deployment of sector-coupling solutions and formulates recommendations to support their wider uptake in the Belgian context.

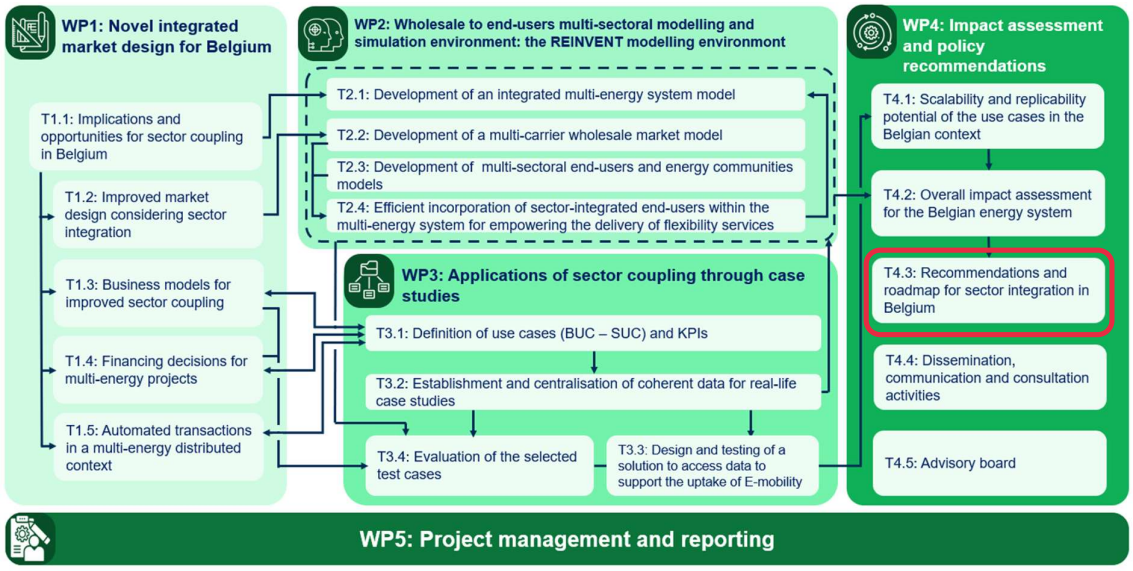


Figure 1-1: Flowchart of the task distribution within ReInvent, T4.3 is outlined in red.

The deliverable summarizes the main results of the following ReInvent deliverables and related tasks:

- Pillar 1 Conceptual framework for sector coupling:
  - D1.1 Implication and opportunities for sector coupling in Belgium (Task 1.1) [1]
  - D1.2 Report on improved market design, business models and financing models for sector coupling (Tasks 1.2, 1.3, 1.4 and 1.5) [2]
- Pillar 2 The ReInvent Multi-Sectoral Simulation Environment:
  - D2.1 The ReInvent modelling environment (Task 2.1, 2.2, 2.3 and 2.4) [3]
- Pillar 3 Proofing and validation via real-life test cases
  - D3.1 Definition of use cases (BUC-SUC) and KPIs (Task 3.1) [4]
  - D3.4 Evaluation of the selected test cases (Task 3.4) [5]
- Pillar 4 Recommendation and future outlook for Belgium's integrated energy system
  - D4.1 Scalability and replicability potential of the test cases in the Belgian context and overall impact assessment for the Belgian energy system (Task 4.1 and 4.2) [6]

For conciseness, references to these deliverables are not repeated throughout the remainder of this deliverable.

1.2 Outline of the Deliverable

Following this introduction, the deliverable is structured around the four main pillars of ReInvent. Chapter 2 synthesises the main lessons learnt and recommendations from the conceptual framework, covering the ReInvent conceptual framework, improved market design considering sector integration, business models for improved sector coupling and financing solutions for multi-energy projects; presents the main developments of the ReInvent multi-sectoral modelling environment; and summarises the findings from the business use cases. It subsequently brings these results to the wider Belgian energy-system level through the assessment of scalability and replicability and the overall impact assessment. Chapter 3 consolidates the cross-cutting findings into the overall ReInvent recommendations for improving sector coupling and integration in Belgium.

2 Lessons learnt from The ReInvent project

1.3 Pillar 1: ReInvent conceptual framework

1.3.1 Conceptual framework for sector coupling

The initial work in ReInvent aimed to establish the conceptual basis for analysing the future of sector coupling in Belgium. This involved reviewing existing definitions of sector coupling and energy system integration and developing a conceptual framework to guide the subsequent work in the project.

RESEARCH QUESTIONS

- what does "sector coupling" mean and how should it be delineated (narrow electrification vs. broad energy system integration)?
- Which sectors, coupling types and interface elements should ReInvent focus on?
- Which regulatory, market-design, and business-model barriers currently prevent broader roll-out of sector-coupled solutions in Belgium?

Definitions in the literature range from narrow interpretations focused primarily on the electrification of end-use sectors to broader interpretations encompassing full energy system integration. ReInvent adopts an interpretation in which the integration of large-scale renewable electricity through direct and indirect electrification forms the central point of departure. Based on this interpretation, the ReInvent conceptual framework for sector coupling was established (Figure 2-1). The framework distinguishes between energy and end-use sectors, identifies three main forms of coupling, and defines four key elements at the interface between sectors:

Sectors: Sector coupling builds on interactions between end-use and energy sectors. End-use sectors include transport, buildings, agriculture and industry, where energy is consumed to provide energy services. Energy sectors traditionally encompass the production, conversion, transport and trading of energy carriers such as electricity, gas and heat. While this distinction is becoming less clear due to developments such as prosumption and the diversification of traditional energy companies, it remains a useful basis for conceptualising sector coupling.

Coupling: Coupling describes the relationships and interactions between sectors. Going beyond conventional one-way energy delivery, sector coupling introduces greater integration and multi-directional interactions. Three main forms are distinguished: end-use ↔ energy sector coupling, such as electrification combined with demand-side flexibility; energy-sector internal coupling, involving conversions between energy carriers through technologies such as Power-to-X; and end-use sector internal coupling, linking different end-use sectors at a more decentralised level, for example through multi-sector energy communities.

Coupling interfaces: Four elements characterise the interfaces through which sector coupling takes place. Energy vectors represent the energy carriers being exchanged or converted, ranging from electricity, gas and heat to hydrogen and other clean molecules. Energy and end-use technologies enable their production, conversion, distribution, storage and use. Markets provide mechanisms for coordinating and valuing interactions across sectors, including multi-carrier, local and flexibility markets. Finally, facilitation mechanisms, including innovative business models, financing approaches and automated financial transactions, support the practical implementation of sector-coupling solutions.

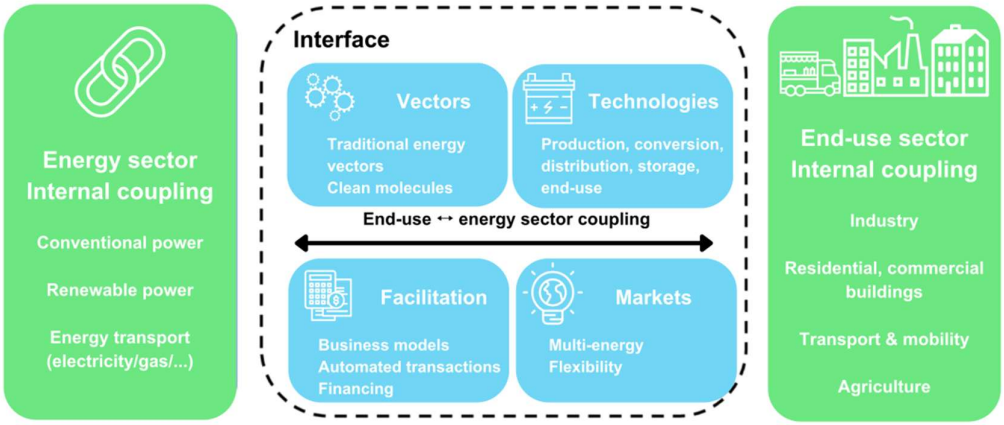


Figure 2-1: ReInvent conceptual framework for sector coupling

Building on this conceptual framework, ReInvent identifies three central areas of sector coupling covered by ReInvent:

- **Electrification and demand-side flexibility:** This area corresponds primarily to end-use ↔ energy sector coupling. Demand-side flexibility adds the multi-directional component by allowing energy consumption to respond to conditions in the energy system. This includes shifting demand towards periods of high energy availability and providing flexibility services.
- **Power-to-X:** This area is closely linked to indirect electrification and represents energy-sector internal coupling. Power-to-X converts electricity into other energy carriers, including hydrogen, synthetic fuels and gases, or heat. ReInvent focuses particularly on Power-to-Hydrogen and Power-to-Heat, including district heating applications. Hydrogen and its derivatives can serve different functions, including energy end use, feedstock use and energy storage.
- **Community energy:** Community energy represents an important organisational model for sector coupling, particularly by enabling the integration of different end-use sectors through multi-sector collective activities. It can therefore facilitate end-use sector internal coupling, while also providing

a vehicle for collective prosumption, community-based demand-side flexibility and community wind energy.

For each of these three areas, ReInvent mapped the relevant regulatory context at EU, Belgian and regional levels and reviewed the state of the art in the corresponding energy research domains. This analysis was complemented by an assessment of the main barriers to the implementation of sector coupling. The assessment shows that several types of barriers remain. Economic and financial barriers include high upfront and operational costs, taxation asymmetries between energy carriers, limited competitiveness compared with conventional alternatives, difficulties in reaching financial break-even and investment risks such as uncertain off-take. Market barriers include obstacles to non-discriminatory market access and insufficient alignment and coordination between markets for different energy vectors. Technical barriers relate, among others, to technological interoperability and the optimal sizing and operation of decentralised assets. Social barriers include limited awareness and engagement, low willingness to pay for unproven sector-coupled solutions, and concerns regarding distributional fairness and safety. Finally, organisational barriers, such as siloed structures and resistance to change, can hinder greater integration across sectors.

KEY LESSONS LEARNT

The literature review shows that sector coupling lacks a commonly accepted definition, ranging from narrow interpretations focused on end-use electrification to broad concepts of full energy system integration. ReInvent therefore adopts an intermediate interpretation, centred on integrating large-scale renewable electricity through direct and indirect electrification.

Sector coupling is broader than linking energy carriers or technologies: it involves multidirectional interactions both between energy and end-use sectors and within these sectors, ranging from demand-side flexibility and decentralized production to Power-to-X and multi-sector energy communities.

A key lesson is that sector coupling faces interconnected economic, market, technical, social and organizational barriers. Limited competitiveness, high investment costs and financial risks are compounded by challenges related to market coordination, technological interoperability, user acceptance and organizational silos. Scaling sector-coupled solutions therefore requires an integrated approach that addresses not only technology, but also their economic viability, market integration and broader implementation conditions.

Sector coupling requires more than technological integration: successful implementation depends on the combined alignment of energy vectors, technologies, markets and enabling mechanisms, including suitable business models and financing approaches.

RECOMMENDATIONS

The recommendations translate the lessons above into concrete actions for the actors responsible for deployment, regulation, and further development.

Recommendation	Category	Target Stakeholder(s)
Reduce regulatory and market uncertainty, improve coordination across energy vectors and regions, and address barriers related to market access, permitting and taxation.	**Regulatory / Market design**	Policymakers, regulators, market operators
Improve the bankability of sector-coupling projects through financing and risk-sharing approaches that address high upfront costs and uncertain revenues.	**Financial**	Policymakers, financial institutions, investors, project developers
Promote interoperability, data exchange and integrated modelling to support the optimal sizing, operation and coordination of sector-coupled assets.	**Technical**	Technology developers, system operators, researchers, project developers
Strengthen cross-sector collaboration and stakeholder engagement, while addressing awareness, affordability, fairness and acceptance of sector-coupling solutions.	**Social & organizational**	Policymakers, project developers, energy communities, industry, end users

1.3.2 Improved market design considering sector integration

This work examines how the Belgian electricity, gas, hydrogen, and heat sectors interact and how current market structures influence the efficient use of technologies that connect these different energy systems. Although these energy carriers are physically interconnected, their markets remain largely organised independently. Each market has its own trading products, operating schedules, balancing arrangements, market timelines and regulatory framework. Electricity markets operate with high temporal resolution, while gas markets use mainly daily and within-day products, hydrogen markets are still under development, and heat is generally traded through long-term contractual arrangements rather than competitive wholesale markets. As a result, operators of multi-carrier technologies must simultaneously participate in several markets that are not fully aligned.

RESEARCH QUESTIONS

- How are the Belgian electricity, gas, hydrogen, and heat markets currently organised?
- How do multi-carrier technologies create interactions between these energy markets?
- What market-related barriers affect the efficient operation and participation of multi-carrier technologies?
- What alternative market design approaches could address the identified barriers to sector coupling?
- How do the alternative market design approaches perform in terms of system efficiency, flexibility utilisation, market-participant conditions, and implementation feasibility?

The work in ReInvent on improved market design first provided a detailed overview of the current organisation of the Belgian electricity, gas, hydrogen and heat markets, describing how energy is traded, balanced and transported within each sector. It then analysed how these markets interact through sector-coupling technologies. Particular attention is given to the role of gas-fired generation, combined heat and power plants, power-to-heat technologies, electrolysers and industrial energy systems in transferring operational decisions and price signals between different energy carriers. Based on literature review and interviews with transmission system operators and owners of multi-carrier technologies, the work identified the main market-related barriers limiting efficient sector coupling. These include differences in product durations, mismatched operating days, sequential market closures, fragmented regulatory frameworks and unequal levels of market maturity. Together, these factors increase operational complexity, reduce flexibility and make it more difficult for technologies to optimise their participation across multiple energy markets.

To explore possible improvements, three alternative market concepts are evaluated. The isolated markets concept represents the current situation, where each energy carrier is traded independently. The coordinated markets concept introduces greater alignment between markets by harmonising selected market design elements, such as product durations, operating days and market timelines, while maintaining separate market-clearing processes. The fully integrated markets concept represents a theoretical benchmark in which electricity, gas, hydrogen and heat are jointly optimised through a single market-clearing process (see Figure 2-2).

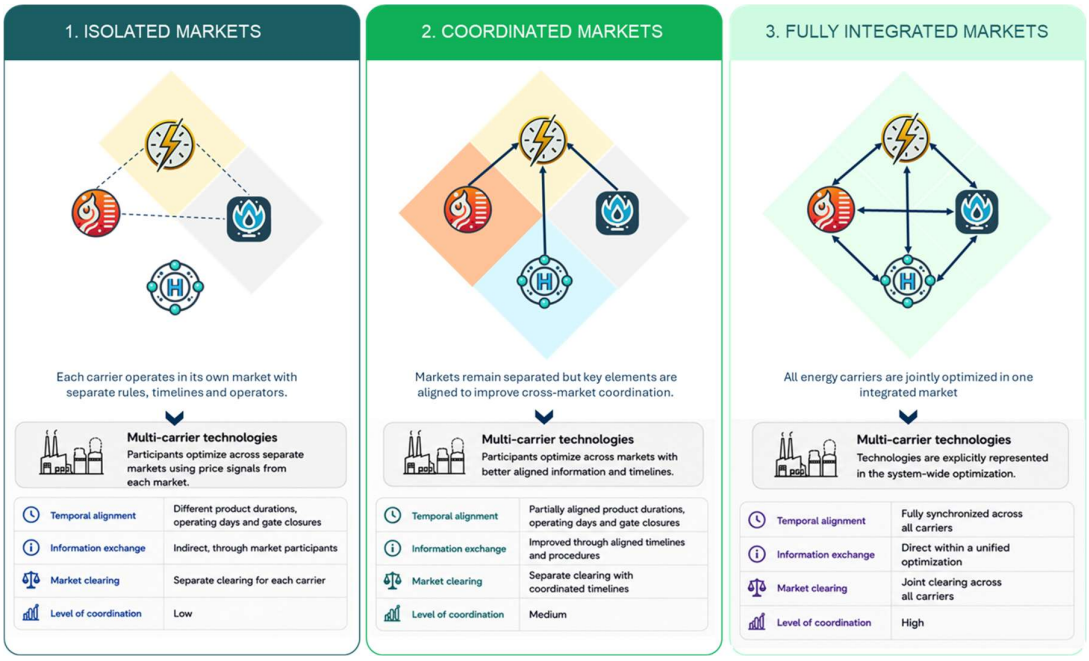


Figure 2-2: Proposed market concepts with different degrees of coordination across carriers.

These concepts are compared qualitatively using seven key performance indicators covering system performance, market participant conditions and implementation feasibility. The assessment shows that coordinated markets significantly improve resource allocation, flexibility utilisation and information availability while avoiding the very high implementation complexity associated with a fully integrated market. Consequently, coordinated markets are identified as the most balanced and realistic pathway for improving sector coupling within the Belgian energy system (see Table 2-1).

Table 2-1: Qualitative assessment of proposed market concepts

Key Performance Indicator	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**

KEY LESSONS LEARNT

The Belgian electricity, gas, hydrogen and heat markets are already physically interconnected through technologies that convert energy between carriers. However, these physical interactions are not fully reflected in the way markets are organised. Each energy carrier continues to operate largely independently, creating unnecessary complexity for technologies that participate in multiple markets.

A key finding is that differences in market design rather than technical limitations increasingly constrain sector coupling. Variations in trading products, operating days, market closure times and balancing arrangements make it difficult for operators of multi-carrier technologies to respond efficiently to market signals across different energy carriers. This limits the effective use of system flexibility and may reduce overall resource allocation efficiency.

The work also shows that regulatory fragmentation adds administrative complexity. Market participants operating across several energy carriers must comply with different procedures, contractual arrangements and settlement mechanisms, increasing transaction costs and creating barriers for smaller market participants and emerging technologies.

Another important lesson is that market maturity differs substantially across energy carriers. Electricity and gas markets are well-established and liquid, while hydrogen markets are only beginning to develop and heat markets largely rely on bilateral contractual arrangements. These differences limit risk management opportunities and create uncertainty for future investments in sector-coupling technologies.

Finally, the qualitative comparison of alternative market concepts indicates that a fully integrated multi-carrier market could theoretically achieve the highest resource allocation efficiency and flexibility utilisation. However, implementing such a market would require fundamental changes to existing governance, regulation and market-clearing arrangements, making it highly complex. In contrast, coordinated markets achieve many of the same benefits through targeted harmonisation while remaining broadly compatible with existing market structures.

RECOMMENDATIONS

The recommendations translate these lessons into actions that can support improved market design.

Recommendation	Category	Target Stakeholder(s)
Harmonise key market timelines across energy carriers. Align product durations, operating days and market gate closure schedules where feasible to reduce operational complexity for multi-carrier technologies and improve cross-sector optimisation.	**Regulatory / Market Design**	National regulators, ACER, market operators, TSOs
Maintain separate electricity, gas, hydrogen and heat markets while introducing targeted harmonisation of market design elements to improve information availability and facilitate coordinated participation across multiple energy carriers.	**Regulatory / Market Design**	Market operators, TSOs, regulators
Support the development of emerging hydrogen markets. Continue developing transparent and harmonised hydrogen market structures that are compatible with existing electricity and gas market arrangements to facilitate future sector coupling.	**Regulatory / Market Development**	European Commission, national regulators, hydrogen network operators, industry
Use coordinated markets as the preferred market evolution pathway because they provide substantial improvements in flexibility utilisation, information availability and resource allocation while avoiding the very high implementation complexity of fully integrated markets.	**Strategic / Policy**	Policymakers, regulators, system operators

1.3.3 Business models for improved sector coupling

Sector coupling requires more than the technical integration of electricity, heat, gas, hydrogen, storage and mobility. It also requires business models that fit the actors expected to adopt, operate, finance or benefit from these solutions. The business-model analysis within ReInvent therefore examines how sector-coupling concepts can create value for different stakeholders and under which conditions they can be successfully implemented and scaled. Recognising that actors face different constraints and opportunities, the analysis adopts an archetype-based approach covering three target groups: industrial actors, energy communities and residential users.

RESEARCH QUESTIONS

- Which business models can enable sector coupling for different types of actors?
- Under which conditions can these business models enable sector coupling in practice?
- What determines whether these business models can move beyond individual pilots and be replicated at larger scale?

For **industrial actors**, several archetypes are identified, ranging from cautiously optimistic adopters to large integrated industrial actors. These archetypes are linked to business models based on long-term contractual arrangements, industrial hubs, flexibility services and innovation-oriented platforms. Successful deployment depends particularly on managing investment and operational risks, ensuring adequate infrastructure and providing sufficient long-term revenue certainty.

For **energy communities**, the analysis considers the evolving European and Belgian regulatory frameworks and identifies archetypes including institutional anchors, innovative pioneers, citizen-led initiatives, business clusters and public entities. Community-scale sector coupling can create value through shared generation and storage, flexibility services, energy sharing and cooperative ownership. The viability of these models is strongly influenced by governance arrangements, access to data, regulatory conditions and appropriate digital tools.

For **residential actors**, the analysis highlights the diversity of household profiles and identifies archetypes with different attitudes towards technology adoption, flexibility provision and energy services. Suitable business models need to balance affordability, simplicity, trust and perceived control, while addressing structural barriers such as split incentives for tenants. Depending on the user group, relevant approaches include Energy-as-a-Service, smart home optimisation, collective purchasing schemes, shared energy services and community-based initiatives.

Across these target groups, the analysis identifies five categories of **enabling conditions**: technical, economic and commercial, regulatory and market-design, organisational and governance, and behavioural and acceptance conditions. Successful deployment requires compatible technologies and digital infrastructure, viable and sufficiently predictable revenue streams, clear market access and regulation, transparent allocation of costs, benefits and risks, and effective governance and coordination. Participation further depends on trust, perceived fairness, willingness to share data and acceptance of new technologies or forms of asset control. The relative importance of these conditions varies across actors and applications, highlighting the need to tailor business models and enabling frameworks to the specific sector-coupling context.

Moving from implementation to wider application adds a further set of **scalability considerations**. Industrial actors are particularly affected by capital intensity, commercial risk and the need for coordinated infrastructure, while energy communities require manageable governance, clear rules and transparent collective benefits. For residential actors, affordability, simplicity, trust and appropriate control over assets are especially important. Across all three groups, scalability ultimately depends on a clear value proposition, predictable revenues or savings, regulatory clarity and trusted coordination, adapted to the capabilities and constraints of the actors involved.

Table 2-2 links the main scalability barriers for each target group to the business model logics and enabling conditions identified in the preceding sections. The table should be read as a synthesis of the archetype and BUC analysis.

Table 2-2: Scalability barriers and enabling conditions across archetypes

Target group	*Main scalability barrier*	*Suitable business model logic*	*Key enabling conditions*	*Scalability implication*
Industry	High CAPEX, operational risk, regulatory uncertainty, complex infrastructure	Long-term contracts, public-backed pilots, innovation platforms, industrial hubs	Stable regulation; bankable contracts; trusted orchestrators; infrastructure planning; market access; risk-sharing	Scales when commercial risk is reduced and infrastructure is coordinated across actors, sites and energy vectors
Energy communities	Regulatory complexity, limited professional capacity, governance burden, financing constraints	Cooperative self-consumption, digital trading, business-cluster sharing, public-private partnership (PPP)	Clear energy-sharing rules; simple contracts; technical assistance; fair benefit allocation; digital tools; access to finance	Scales when governance is simple, benefits are transparent and local actors can capture value collectively
Residential	Low trust, split incentives, upfront cost, complexity, limited control	Energy-as-a-Service, one-stop-shop, community energy, split-incentive models, smart home optimisation	Trusted intermediaries; low upfront costs; comfort and affordability protection; landlord-tenant alignment; clear savings	Scales when participation is simple, affordable, trustworthy and adapted to household agency

KEY LESSONS LEARNT

Sector-coupling business models need to be tailored to the actors expected to adopt, operate, finance or benefit from them. Industrial actors, energy communities and residential users differ in investment capacity, risk tolerance, technical and organisational capabilities, trust and control over assets, making a one-size-fits-all approach unsuitable.

Different target groups therefore require different business-model approaches. Industrial actors particularly benefit from models that reduce investment and commercial risk and provide long-term certainty; energy communities require models that enable collective value creation and manageable governance; and residential users require accessible models adapted to their willingness and ability to participate, with specific attention to affordability, simplicity and trust.

Successful business models depend on a combination of technical, economic and commercial, regulatory and market-design, organisational and governance, and behavioural and acceptance conditions. Technology and digital infrastructure alone are insufficient: viable revenues, clear market access, transparent allocation of costs and benefits, trusted coordination and actor acceptance are also required.

Scaling sector-coupling business models ultimately requires a clear value proposition, predictable revenues or savings, regulatory clarity and trusted coordination. The technical solution, commercial logic and governance arrangements need to align with the capabilities and constraints of the actors involved.

RECOMMENDATIONS

The recommendations translate these lessons into actions that can support the development and scaling of actor-specific sector-coupling business models.

Recommendation	Category	Target Stakeholder(s)
Develop business models around the capabilities, needs and constraints of the target actors rather than applying generic approaches across industrial, community and residential contexts.	**Business model design**	Project developers, technology and service providers, energy communities
Provide clear and sufficiently predictable value propositions, revenues or savings, with transparent allocation of costs, benefits and risks between participating actors.	**Economic / Commercial**	Project developers, investors, service providers, energy communities
Establish clear and stable regulatory and market-access conditions for energy sharing, flexibility, storage and other sector-coupling activities, while using pilots and sandboxes to test innovative approaches.	**Regulatory / Market design**	Policymakers, regulators, market operators
Strengthen trusted coordination and governance, with clear actor roles, contractual arrangements, data-sharing rules and responsibilities in multi-actor sector-coupling models.	**Organisational / Governance**	Project developers, aggregators, public authorities, energy communities, industry
Reduce participation barriers through simple and transparent propositions, trusted intermediaries and appropriate safeguards for affordability, fairness and user control.	**Behavioural / Acceptance**	Service providers, energy communities, public authorities, residential actors

1.3.4 Financing solutions for multi-energy projects

Multi-energy projects combine different energy technologies and services, such as solar PV, wind energy, batteries, heat pumps, EV charging infrastructure and energy-sharing mechanisms. Their scale, ownership structure, revenue model, technological complexity and risk profile can vary considerably, making the selection of an appropriate financing structure inherently project-specific. ReInvent therefore examined which financing approaches are suited to different types of multi-energy projects and how their financing readiness can be assessed.

RESEARCH QUESTIONS

- How can multi-energy projects be categorised from a financing perspective?
- Which financing solutions are suitable for different types of multi-energy projects, and under which conditions?
- Which factors determine the bankability of multi-energy projects?
- How can these factors be systematically assessed to support financing decisions?

Multi-energy projects can be classified according to **four key dimensions with a direct impact on financing**: scale, ownership structure, revenue model and technological complexity. These characteristics shape the project's risk profile and financing needs. Smaller projects generally rely on simpler financing structures, while larger projects may require more specialised approaches. Ownership can affect access to specific funding mechanisms, while stable or contracted revenues generally reduce financial risk. More complex or innovative projects may require tailored financing, additional guarantees or public support.

Depending on these characteristics, different **financing structures** may be appropriate:

- **Investment loans:** suited to proven technologies and projects with sufficiently predictable cash flows.
- **Leasing:** suitable for transferable assets that retain residual value and meet the relevant ownership and security conditions.
- **Equity financing:** provides risk-bearing capital and can strengthen the project's financial structure and ability to attract debt.
- **Project finance:** suited to larger projects with identifiable and predictable standalone cash flows.
- **Crowdfunding:** particularly relevant as a complementary source of financing for smaller, community-driven or innovative projects.

For each financing type, the analysis considers its typical application areas, conditions, advantages and limitations, with particular attention to the distinction between conventional financing for proven technologies and more specialised structures for larger, complex or innovative projects.

Bankability reflects the overall ability of a multi-energy project to attract financing at an acceptable risk level. It depends on **factors** including technical maturity, revenue certainty, financial viability, regulatory compliance, ownership and governance, project documentation and stakeholder support. Financial institutions consider these factors collectively to assess whether a project can generate sufficiently predictable cash flows and manage its key risks. Addressing them early in project development can therefore strengthen financing readiness and long-term viability.

To support this assessment, ReInvent proposes **a six-step financing assessment framework** that links project characteristics and risks to financing suitability and potential outcomes (see Figure 2-3). The framework progresses from defining the project and verifying basic requirements to assessing core credit factors, financial resilience, execution and counterparty risks, and finally determining an indicative financing outcome and any required risk-mitigation measures. Key considerations include technology maturity, revenue certainty, equity contribution, debt-service capacity, sponsor strength, permits and grid connection. Importantly, the framework is intended as a screening and structuring tool rather than an automatic scoring or approval mechanism, as fundamental weaknesses cannot simply be offset by stronger performance in other areas.

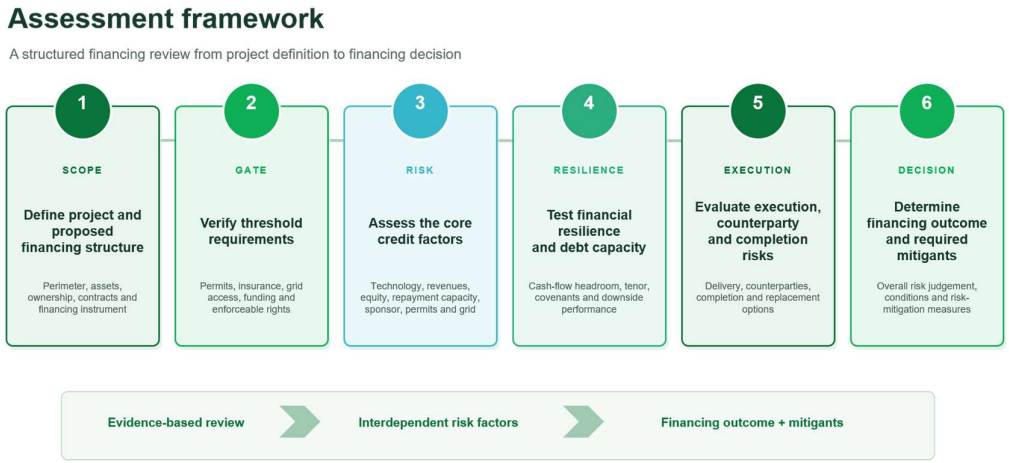


Figure 2-3: ReInvent six-step financing assessment framework

KEY LESSONS LEARNT

Financing multi-energy projects requires a project-specific approach. No single financing mechanism is appropriate for all projects; the choice between investment loans, leasing, equity financing, project finance, crowdfunding or combinations thereof depends on factors such as project scale, ownership structure, technological maturity, revenue certainty and available collateral or sponsor support.

Bankability depends on more than technical feasibility. Predictable revenues, financial resilience, regulatory compliance, ownership and governance, adequate documentation and stakeholder support all influence financing readiness. These factors need to be considered together rather than assessed in isolation.

Projects combining proven technologies, predictable cash flows, adequate equity, secured permits and strong sponsor support are generally better positioned to attract financing. More innovative or merchant-exposed projects may require additional safeguards, risk-sharing mechanisms, stronger sponsor support, additional equity or alternative financing structures.

A structured assessment of financing readiness and project risks can support more consistent financing decisions. However, financing should not be reduced to a simple scoring exercise: fundamental weaknesses related to repayment capacity, permits, grid access, legal enforceability or committed funding cannot simply be offset by stronger performance in other areas.

RECOMMENDATIONS

The recommendations translate these lessons into actions that can improve the financing readiness and bankability of multi-energy projects.

Recommendation	Category	Target Stakeholder(s)
Match the financing structure to the project characteristics, considering scale, ownership, technology maturity, revenue model and overall risk profile rather than applying a standard financing approach.	**Financing / Investment**	Project developers, financial institutions, investors
Strengthen revenue certainty and financial resilience through predictable and enforceable revenue arrangements, adequate equity contributions and appropriate allocation of financial risks.	**Financial / Commercial**	Project developers, investors, financial institutions, offtakers
Address financing-critical requirements early, particularly permits, insurance, grid connection, ownership and security rights, technical validation and project documentation.	**Project development / Risk management**	Project developers, financial institutions, grid operators, permitting authorities
Provide additional risk mitigation for innovative or higher-risk projects through guarantees, additional equity, sponsor support, public support or appropriately tailored financing structures where needed.	**Financial / Risk sharing**	Policymakers, financial institutions, investors, project sponsors
Use structured bankability assessments to identify financing weaknesses and required mitigants while retaining appropriate technical, legal and credit due diligence.	**Financing / Governance**	Financial institutions, investors, project de

1.4 Pillar 2: ReInvent multi-sectoral simulation environment

ReInvent rests on four pillars, a conceptual analysis of sector coupling in Belgium, a modelling and simulation environment, proof of concept through real test cases, and an impact assessment and roadmap. Pillar 2 is committed to building a "wholesale-to-end-users" multi-sectoral modelling and simulation environment for the Belgian energy system, the ReInvent modelling environment, whose purpose is to quantify what sector coupling is worth, under which market designs, business models and regulatory conditions that value can actually be captured, and how much flexibility coupled sectors can offer to the electricity grid. Concretely, four families of models were promised:

- an integrated multi-energy system and investment model covering electricity, gas, heat, hydrogen and synthetic molecules with their networks, conversion and storage;
- coordinated multi-carrier wholesale market models exploring several degrees of coordination between the markets of different carriers;
- models of sector-integrated end-users and multi-sector energy communities, including cooperation and pricing mechanisms and the sizing of local assets;
- and the linking of these models so that the flexibility of coupled end-users can be delivered through TSO–DSO flexibility procurement mechanisms.

It had to span several carriers, time frames, scenarios, market designs and services, represent short-term uncertainty in long-term investment decisions, be tested on real test-case data, and feed the Pillar 3 use-case evaluation and the Pillar 4 impact assessment and policy recommendations.

The ReInvent multi-sectoral simulation environment is a coordinated set of thirteen modelling tracks organised along two axes (Figure 2-4):

- **The first axis is spatial**: models operate either at the local level of individual end-users and energy communities, or at the system level of national and European networks and wholesale markets.
- **The second axis is temporal:** models either optimise short-term operation, daily dispatch and market bidding at quarter-hourly or hourly resolution, or long-term planning, that is investment and capacity expansion towards 2030–2050.

The four tasks in WP2 occupy the four positions of this grid. Task 2.1 delivers the multi-energy system planning models (system level, long term), in which electricity, gas, heat and hydrogen are linked through networks, conversion and storage. Task 2.2 delivers the multi-carrier wholesale market models (system level, short term). Task 2.3 covers the local level over both horizons: how buildings, businesses, industry and energy communities couple electricity, heat and cold and mobility, and how their assets should be operated, priced fairly and sized. Task 2.4 is the bridge between the two levels: it turns the cross-sector flexibility of end-users

into services for balancing responsible parties and system operators, and checks whether providing that flexibility pays.

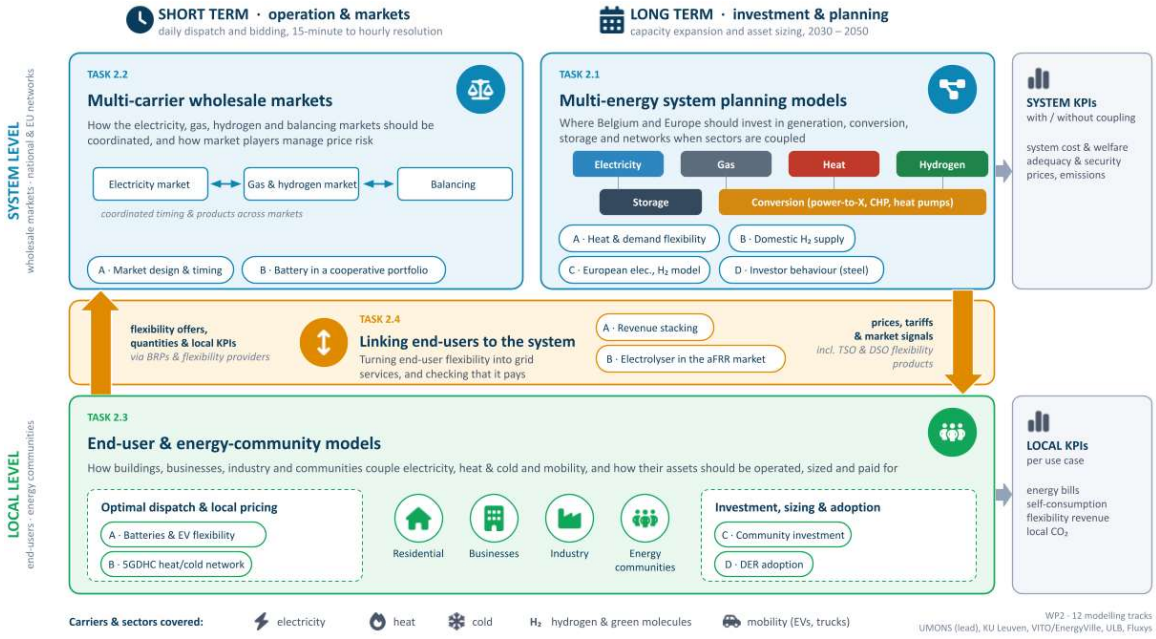


Figure 2-4: ReInvent multi-sectoral simulation environment

KEY REALISATIONS AT SYSTEM LEVEL — PLANNING AND WHOLESALE MARKETS

- **Demand-side flexibility is represented more explicitly in long-term energy-system planning.** TIMES-BE was extended to represent building heat flexibility through dedicated thermal storage and the thermal inertia of buildings, alongside the existing representation of EV flexibility.
- **Interactions between demand flexibility and power-to-X can be assessed at energy-system level.** ReInvent combined the heating-sector scenarios with explicit modelling of electricity demand flexibility and production pathways of clean molecules to assess their role in further sector coupling.
- **Multi-carrier market design can be assessed quantitatively.** ReInvent extended an optimisation-based market simulation framework focused on electricity markets to gas, hydrogen and heat markets, enabling changes in market timing and granularity to be linked to asset operation, profitability and flexibility provision.
- **Hydrogen production and storage options can be assessed across different infrastructure pathways.** ReInvent extended a European electricity and hydrogen system model with demand flexibility to assess how hydrogen pipelines, underground storage and imports influence hydrogen production and storage needs in Belgium.

- **Investment decisions under imperfect foresight and financial constraints can be assessed.** ReInvent developed a decision-making model to assess investment in emission-reduction projects while accounting for financial constraints, myopic investor behaviour and policy uncertainty.

KEY REALISATIONS AT LOCAL LEVEL — END-USERS AND COMMUNITIES

- **Battery investments in energy cooperatives can be assessed across multiple dimensions.** ReInvent extended an optimisation model to assess how battery storage affects portfolio risk and returns, community costs and PV curtailment, as well as how ownership and profit-sharing arrangements distribute benefits among stakeholders.
- **Battery participation in electricity markets can be assessed under different strategies and uncertainties.** ReInvent further developed an optimisation model to assess how batteries can reduce profiling and imbalance costs for renewable cooperatives, while accounting for different flexibility strategies, imbalance-price uncertainty and risk profiles.
- **Energy community investments and benefit sharing can be jointly assessed.** ReInvent developed a two-stage optimisation model to assess community investment choices and flexibility while determining internal exchange prices that support a balanced distribution of savings among members.
- **Different operation and pricing strategies for heat and cold networks can be assessed.** ReInvent developed an integrated dispatch and pricing model to assess the operation of 5GDHC networks with seasonal aquifer storage and compare different pricing approaches to ensure fair and efficient heat pricing.
- **DER adoption can be modelled at neighbourhood level.** ReInvent combined behavioural, building and spatial data to predict the adoption of PV, EVs, heat pumps and smart meters, while preserving privacy.
- **Flexibility in vulnerable households can be identified from electricity consumption data.** ReInvent developed a data-driven approach to identify consumption patterns and potential opportunities for PV-aligned EV charging and shared mobility.

KEY REALISATIONS ON THE LINK BETWEEN END-USERS AND THE SYSTEM — FLEXIBILITY

- **Multi-energy investments and implicit flexibility can be jointly assessed.** ReInvent developed a stochastic optimisation model to determine the design and operation of conversion and storage technologies while accounting for energy tariffs, flexibility opportunities, and climate and price uncertainty.
- **Electrolyser participation in the Belgian balancing market can be optimised.** ReInvent developed an optimisation model to assess electrolyser operation across renewable electricity sourcing, hydrogen delivery and balancing-market participation, while accounting for technical, market and regulatory constraints.

- **The flexibility of 5GDHC networks can be assessed within a local flexibility market.** ReInvent developed an optimisation model to coordinate network operation and flexibility-market participation to address the flexibility potential of 5GDHC networks to resolve local grid constraints.
- **EV flexibility can be assessed under realistic mobility and charging conditions.** ReInvent extended an end-user optimisation model with actual driving patterns, charging availability, user preferences and manufacturer constraints to assess the flexibility that EVs can provide in practice.

Overall, across the thirteen modelling tracks, the environment delivers what the proposal set out: an operational, validated set of models linking electricity, heat and cold, hydrogen and mobility from the household to the European system and from daily dispatch to 2050 investment, applied to the business use cases of pillar 3 and feeding the impact assessment of pillar 4.

The modelling results converge on one message. Sector coupling creates value at every scale, but that value is unlocked by design choices rather than by technology alone: the timing and structure of the markets in which coupled assets trade, the tariffs and pricing rules that govern local exchanges, the regulatory access of aggregated end-users to flexibility markets, and the foresight that investors actually exercise. Technically available flexibility is not automatically mobilised, and the cheapest operation is not necessarily the most grid-friendly or the least carbon-intensive one. Coordination, and the price signals that carry it, is where most of the remaining benefit lies.

1.5 Pillar 3: Proof of concept by relevant test cases

1.5.1 BUC 1: CollecThor – 5th Generation District Heating and Cooling

The CollecThor BUC investigated how multiple buildings can share heating and cooling through a low-temperature district network supplied by shallow geothermal energy, Aquifer Thermal Energy Storage (ATES), building-level heat pumps, and rooftop solar panels. Mathematical optimisation was used to determine the most cost-effective operation of the network while evaluating different pricing and settlement mechanisms that enable fair cost sharing between participants. The study also assessed the operational performance of seasonal thermal storage, renewable energy integration, and the long-term viability of the business model. The research in BUC 1B additionally investigated whether the flexibility of the network's heat pumps and thermal storage could be offered to electricity flexibility markets. Different operating scenarios were simulated to evaluate the technical feasibility, economic value, and environmental implications of providing grid flexibility without compromising heating and cooling performance.

RESEARCH QUESTIONS

- What is the appropriate business model for sharing of thermal energy via a 5th generation DHC network in a business park with multiple consumers?
- How can the flexibility of a 5th generation DHCN be valorised in the electricity and flexibility markets?

KEY LESSONS LEARNT

Low-temperature district heating and cooling networks combined with ATES enable efficient sharing of heating and cooling between multiple buildings while significantly increasing renewable energy utilisation.

Seasonal thermal storage is essential for balancing heating and cooling demand over the year, but natural thermal losses mean long-term balancing cannot always be achieved without additional measures.

Fair pricing mechanisms are just as important as technical optimisation. Business models that align supplier incentives with consumer benefits are required for widespread adoption.

The value of photovoltaic generation depends strongly on self-consumption, making local storage and intelligent operation economically important.

The heat pumps and thermal storage already present within a 5GDHC network can provide meaningful flexibility to the electricity system without reducing heating or cooling service quality.

Current flexibility markets reward energy shifting but do not consider carbon impacts, meaning economically optimal flexibility provision may increase greenhouse gas emissions.

RECOMMENDATIONS

The recommendations translate the lessons above into concrete actions for the actors responsible for deployment, regulation, and further development.

Recommendation	Category	Target Stakeholder(s)
Develop business models that combine cost-optimal network operation with transparent and fair pricing mechanisms to encourage participation in shared thermal networks.	**Technical / Market design**	District heating operators, energy service companies, developers
Encourage deployment of modular 5GDHC networks using seasonal thermal storage where local geological conditions are suitable.	**Technical**	Developers, municipalities, industries
Support complementary electricity storage solutions to increase photovoltaic self-consumption and improve overall network economics.	**Technical**	Building owners, investors, network operators
Consider regulatory approaches that allow seasonal thermal storage to be managed over multi-year balancing periods rather than requiring strict annual balance.	**Regulatory**	Environmental regulators, regional governments
Ensure long-term stability and transparency of tariff arrangements to improve investment certainty for integrated thermal networks.	**Regulatory**	TSOs, DSOs, regulators
Create market frameworks that explicitly allow 5GDHC networks to participate in electricity flexibility and ancillary service markets.	**Regulatory**	TSOs, DSOs, regulators
Explore flexibility remuneration approaches that account for carbon impacts alongside flexibility provision, encouraging low-carbon operation.	**Regulatory / Market design**	Regulators, market operators
Investigate larger district-scale thermal storage systems to increase the flexibility potential available to electricity markets.	**Technical / Research**	Researchers, technology developers, district heating operators
Develop standardized market interfaces between thermal networks, aggregators, and flexibility markets to simplify participation.	**Technical / Market design**	Aggregators, software providers, DSOs, TSOs

STAKEHOLDER SUMMARY

Regulators	Develop enabling regulation for thermal networks, flexibility participation, seasonal storage, and carbon-aware flexibility markets.
DSOs/TSOs	Integrate district thermal networks as recognised flexibility providers.
Industry and District Heating Operators	Deploy modular 5GDHC systems supported by transparent pricing and optimized operation.
Researchers	Continue evaluating large-scale thermal flexibility, seasonal storage optimisation, and carbon-aware flexibility market design.
Technology providers	Develop interoperable control and optimisation platforms linking thermal networks with electricity flexibility markets.

1.5.2 BUC 2: Integration of a Battery Energy Storage System in a REC

The study evaluates how Battery Energy Storage Systems (BESS) can improve the business case of Campina Energie's Renewable Energy Community, which consists of more than 70 photovoltaic installations (approximately 6 MWp) and shared ownership of nine wind turbines (over 25 MW) distributed across industrial, commercial and governmental buildings in Flanders. Using quarter-hourly production and consumption data, optimisation models evaluate how BESS, together with EV charging, heat pumps, and curtailment strategies, increase local self-consumption, reduce exposure to negative electricity prices, and improve the financial performance of the cooperative.

The analysis extends this framework by investigating whether the same BESS assets can additionally provide flexibility services to the electricity system. The optimisation evaluates how participation in flexibility markets through an aggregator creates new revenue streams while maintaining the primary objective of improving renewable energy utilisation within the REC.

RESEARCH QUESTIONS

- How does investment in BESS impact the risk and return of the portfolio of an energy cooperative?
- How can using the flexibility of a BESS to offer services to the electricity system improve the risk and return profile of an energy cooperative's portfolio?

KEY LESSONS LEARNT

Battery Energy Storage Systems substantially improve the resilience of Renewable Energy Communities by storing surplus renewable electricity during periods of low market value and reducing dependence on electricity exports during negative price periods.

Optimising energy management across the entire community produces greater economic benefits than optimising individual sites independently. Coordinated operation reduces overall costs and maximises utilisation of renewable generation.

The economic value of BESS increases as the frequency of negative electricity prices grows. Storage therefore becomes increasingly valuable as renewable penetration continues to expand.

Battery ownership and operating arrangements influence the distribution of benefits. Business models, including tolling arrangements and ownership structures, significantly affect investment incentives and the allocation of value among stakeholders.

Battery systems can simultaneously improve local renewable energy utilisation and generate additional revenue by participating in electricity and flexibility markets. These complementary value streams strengthen the overall business case for battery investment.

Flexibility provision should remain secondary to optimising community energy management. The greatest value is achieved when batteries are jointly optimised for self-consumption, curtailment reduction, and market participation rather than for flexibility services alone.

RECOMMENDATIONS

The recommendations translate the lessons above into concrete actions for the actors responsible for deployment, regulation, and further development.

Recommendation	Category	Target Stakeholder(s)
Deploy Battery Energy Storage Systems within Renewable Energy Communities to increase renewable self-consumption, reduce curtailment, and improve resilience against negative electricity prices.	**Technical**	Renewable energy communities, cooperatives, developers
Optimise battery operation at the community level rather than for individual assets to maximise overall economic performance.	**Technical / Socio-economic**	Energy communities, energy management providers
Develop optimisation tools that explicitly include battery cycling constraints and long-term degradation to improve operational decision making.	**Technical**	Researchers, software developers
Evaluate ownership models, including tolling arrangements and shared investment schemes, to distribute costs and benefits fairly among community members.	**Socio-economic**	Cooperatives, investors, community organisations

Recommendation	Category	Target Stakeholder(s)
Further investigate how different Power Purchase Agreement (PPA) structures interact with battery operation and community business models.	**Policy / Market design**	Policymakers, regulators, energy retailers
Enable Renewable Energy Communities to participate directly or through aggregators in electricity flexibility markets using community-scale battery systems.	**Regulatory**	Regulators, TSOs, DSOs
Develop market rules that recognise stacked value streams, allowing batteries to simultaneously provide local optimisation and grid flexibility services.	**Market design**	Market operators, regulators
Standardise interfaces between battery management systems, aggregators, and flexibility markets to reduce participation barriers.	**Technical**	Technology providers, aggregators
Ensure flexibility remuneration mechanisms remain compatible with the primary objective of maximising renewable energy utilisation within energy communities.	**Regulatory**	Regulators, policymakers

STAKEHOLDER SUMMARY

Renewable Energy Communities and Cooperatives	Invest in community-scale battery storage and optimise operation across the entire portfolio rather than individual assets, where this enables a more efficient use of resources.
Technology providers	Develop advanced optimisation platforms capable of coordinating PV, wind, batteries, EV charging, heat pumps, and market participation.
Aggregators and Market Operators	Provide accessible participation pathways for community-owned batteries to access electricity markets and deliver flexibility services.
Regulators	Create regulatory frameworks that enable stacked battery revenues while supporting renewable self-consumption and fair benefit allocation.
Researchers	Continue evaluating battery degradation, ownership models, tolling arrangements, and long-term market evolution under increasing renewable penetration, as the BUC evaluation highlights the increasing value of BESS for optimising renewable energy use within energy cooperatives, particularly as negative price events become more frequent.

1.5.3 BUC 3: Social Charging Shared EVs

The research examined the Otterbeek social housing district in Mechelen, where Klimaan has installed 741 kW of rooftop solar capacity across 197 homes. Because a substantial share of this electricity is not consumed when it is generated, the study explored whether shared electric vehicles could provide useful local demand while also giving residents access to lower-cost mobility.

An optimisation model was developed to coordinate the operation of the Renewable Energy Community and the Shared Mobility Operator. It combined household electricity demand, rooftop solar generation, electricity prices, vehicle availability, charging requirements, and real mobility data from approximately 7,600 journeys and 4,500 charging sessions. Scenarios compared independent and coordinated operation during both the early adoption and mature operation of the shared mobility service.

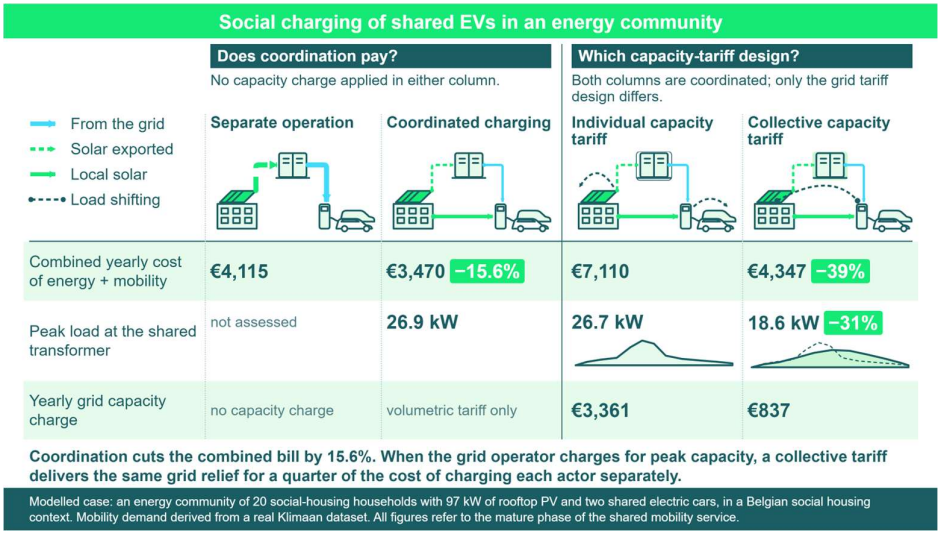


Figure 2-5: Key results of the BUC 3 evaluation

The coordinated arrangement reduced the combined energy and mobility costs by approximately 7% during the early adoption phase and 15.6% once vehicle use had matured. The larger benefit at maturity resulted from the greater volume of charging demand available to absorb local solar surpluses.

The analysis was extended to examine how different grid tariff designs influence flexible charging and transformer loading. Individual capacity tariffs, collective capacity tariffs, Vehicle-to-Grid operation, and stationary battery storage were compared to determine how the fleet could support the local network.

RESEARCH QUESTIONS

- What would be the appropriate business model for optimized EV sharing in a social district, using locally produced solar power?
- What would be the appropriate business model for flexibility-optimized EV sharing in a social district, using locally produced solar power?

KEY LESSONS LEARNT

Independent optimisation causes the energy community to export solar power while the mobility operator may purchase electricity from the grid at other times. Coordinating both actors allows charging to follow local solar availability, lowering their combined costs.

During the early phase, vehicles are parked for longer periods and offer more scheduling flexibility, but the low volume of mobility demand limits the amount of solar energy that can be used. At maturity, higher vehicle utilisation reduces some flexibility but creates significantly greater economic value because more charging energy can be supplied locally.

The coordinated model lowered the average mobility service cost from approximately €0.10/km to €0.072/km in the assessed case, but an operational optimisation does not determine how this benefit should be divided between the mobility operator, the energy community, and individual residents.

A collective peak tariff reduced aggregate imports at the shared transformer by around 28.5% in the early phase and 30.8% at maturity, while individual peak tariffs imposed much higher combined costs and slightly reduced local energy exchange.

Shared EVs can provide considerable flexibility when they remain connected to the charging station, particularly during the early phase. As the service becomes more heavily used, vehicles spend more time on the road and the flexibility window narrows; Vehicle-to-Grid capability or stationary storage can partly compensate for this limitation.

RECOMMENDATIONS

The recommendations translate the lessons above into concrete actions for the actors responsible for deployment, regulation, and further development.

Recommendation	Category	Target Stakeholder(s)
Establish formal coordination arrangements between Renewable Energy Communities and Shared Mobility Operators so that charging schedules, solar availability, and mobility bookings can be optimised together.	**Business model / Technical**	Energy communities, shared mobility operators, energy service providers
Design social mobility tariffs that transparently return part of the savings from local solar charging to residents rather than retaining all benefits at operator level.	**Socio-economic**	Shared mobility operators, social housing companies, energy cooperatives, municipalities
Evaluate shared mobility projects over both an introductory and a mature operating phase before judging financial viability or sizing charging infrastructure.	**Planning / Research**	Municipalities, project developers, researchers, financiers
Introduce co-investment support, guarantees, or targeted subsidies for PV, charging infrastructure, and shared vehicles in social housing communities, where residents generally have limited capital and risk tolerance.	**Financial / Social policy**	Regional governments, municipalities, social housing providers, public finance institutions
Permit and test collective capacity tariffs at the shared connection or transformer level where an energy community and mobility operator are able to coordinate their aggregate demand.	**Regulatory / Tariff design**	DSOs, energy regulators, regional policymakers
Incentivise Vehicle-to-Grid-compatible vehicles and charging equipment where network studies show that bidirectional charging can relieve local transformer constraints without reducing vehicle availability for residents.	**Technical / Regulatory**	DSOs, charging providers, vehicle manufacturers, public funding bodies

STAKEHOLDER SUMMARY

Energy communities and mobility operators	Coordinate EV charging with local solar production while maintaining vehicle availability.
Social housing providers and municipalities	Ensure that project savings translate into affordable mobility for residents.
DSOs and regulators	Test collective tariffs and incentives that reward reductions in shared grid peaks.
Technology providers	Develop interoperable smart-charging and Vehicle-to-Grid solutions.
Public authorities and researchers	Support early investment and assess social, mobility, and grid impacts over time.

1.5.4 BUC 4: SeaCoop – Hybrid Energy Communities

SeaCoop brings together citizen energy cooperatives that aim to invest directly in offshore wind generation and supply part of that electricity to their members through cooperative suppliers. Offshore wind output, however, does not follow the relatively stable electricity demand of households. SeaCoop must therefore buy or sell electricity in the day-ahead market to reshape the wind production profile and settle any remaining difference between forecast and actual generation through the imbalance mechanism.

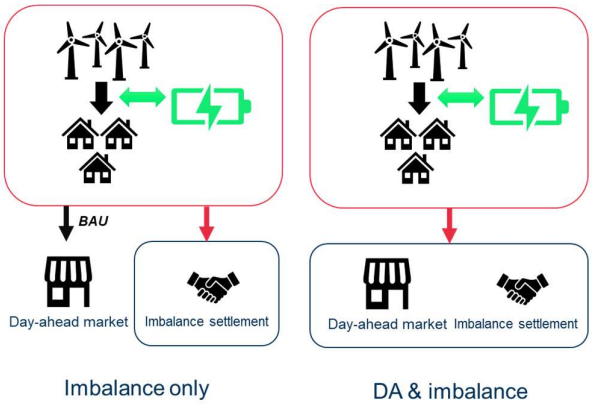


Figure 2-6: Overview of the BUC 4 setup

The study examined whether adding a large battery could reduce these costs. An optimisation model used offshore wind and residential demand forecasts, actual production and consumption profiles, day-ahead prices, and imbalance prices from 2023–2024. It compared the current arrangement without a battery against two operating strategies: using the battery only to manage imbalances, and coordinating the battery simultaneously with day-ahead bidding and imbalance management. Both risk-neutral and risk-averse decision-making were assessed, alongside a perfect-information case representing a theoretical upper limit rather than a realistic forecast.

Table 2-3: Scenarios considered in BUC 4

Option - Scenario	*Net annual cost saving (Euro/kWh battery)*
Imbalance only – Risk-averse	20.26
Imbalance only – Risk-neutral	22.64
Imbalance only – Theoretical bound	225.02
DA & Imbalance – Risk-averse	38.00
DA & Imbalance – Risk-neutral	56.44
DA & Imbalance – Theoretical bound	547.35

The battery reduced the combined profiling and imbalance costs in every modelled scenario. Under the more realistic stochastic cases, estimated net annual savings were approximately **€20–23 per kWh of battery capacity** for imbalance-only operation and **€38–56 per kWh** when day-ahead bidding and imbalance management were jointly optimised.

RESEARCH QUESTIONS

- In which way can the use of a large-scale battery connected with the Elia grid help to reduce the profile and balancing cost of offshore wind production on the level of the REC?
- How can this reduction in costs be translated to potential benefits for the electricity billing towards the REC-members?

KEY LESSONS LEARNT

Without storage, deviations between expected and actual wind generation create a net imbalance cost. In the simulations, battery operation reversed this outcome and produced net revenues from imbalance settlement.

Using the battery solely for imbalance management reduced costs, but coordinating the battery with day-ahead bidding consistently produced greater savings. The battery therefore creates more value when treated as part of the market-positioning strategy rather than as a stand-alone corrective asset.

Joint optimisation sometimes increased day-ahead profiling costs because the model deliberately accepted a less favourable day-ahead position to create substantially greater imbalance revenues. Performance must therefore be judged using total portfolio costs rather than isolated market charges.

Risk-averse operation reduced exposure to extreme imbalance-price outcomes, but it also lowered expected savings compared with risk-neutral operation. The appropriate strategy depends on the cooperative's willingness and financial capacity to absorb market volatility.

Perfect-information results substantially overstate what can be achieved in practice. Forecast errors, transaction costs, battery degradation, uncertain efficiencies, and operational constraints are expected to reduce realised savings.

RECOMMENDATIONS

The recommendations translate the lessons above into concrete actions for the actors responsible for deployment, regulation, and further development.

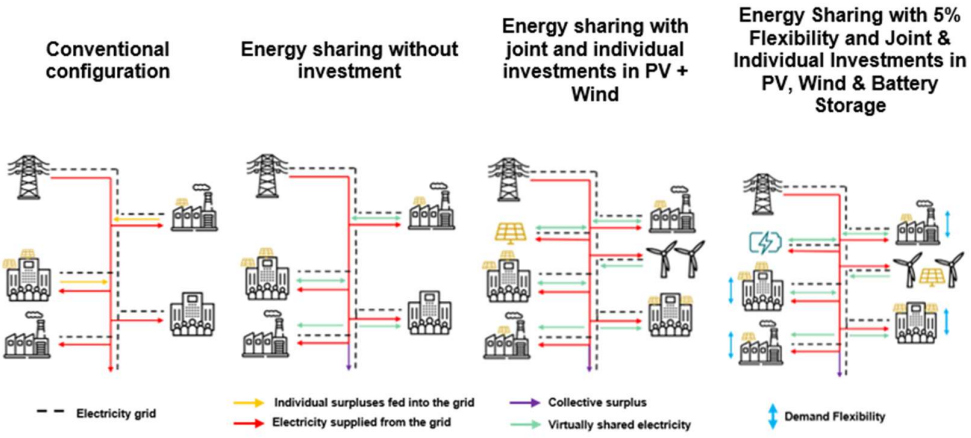
Recommendation	Category	Target Stakeholder(s)
Operate the battery through an integrated energy-management system that jointly optimises day-ahead bidding and imbalance exposure rather than limiting it to real-time imbalance correction.	**Technical / Market operation**	SeaCoop, Balance Responsible Parties, aggregators, battery operators
Use rolling-horizon, uncertainty-aware optimisation that continuously updates wind forecasts, consumption forecasts, market prices, and the battery state of charge.	**Technical**	Software providers, aggregators, energy traders, researchers
Include battery degradation, transaction costs, efficiency uncertainty, forecast errors, and alternative battery sizes in the final investment assessment.	**Investment / Research**	SeaCoop, financiers, battery developers, research organisations
Establish clear routes for Renewable Energy Communities to participate in day-ahead and imbalance arrangements, either directly or through an aggregator or Balance Responsible Party, with unambiguous responsibilities for metering and settlement.	**Regulatory / Market design**	Energy regulators, Elia, market operators, Balance Responsible Parties
Standardise near-real-time metering and data-exchange interfaces so that community batteries, suppliers, aggregators, and market parties can exchange forecasts and operational information securely.	**Technical / Regulatory**	Elia, distribution system operators, metering companies, technology providers
Convert part of the battery's savings into a transparent member benefit, such as a stabilisation reserve or reduced cooperative electricity tariff, rather than treating the battery solely as a trading asset.	**Socio-economic / Governance**	SeaCoop, member cooperatives, Ecopower, Cociter
Use regulatory sandboxes or supervised pilots to test advanced risk-aware bidding by community-owned batteries before adapting wider market rules.	**Regulatory / Demonstration**	Regulators, federal and regional authorities, Elia, Renewable Energy Communities

STAKEHOLDER SUMMARY

Energy cooperatives	Optimise the battery across day-ahead and imbalance markets and define how savings benefit members.
BRPs, aggregators, and traders	Use updated forecasts and risk-aware battery control.
Regulators	Clarify access, metering, settlement, and value-stacking rules for community batteries.
Technology providers and investors	Account for degradation, efficiency losses, forecast errors, and market risk.
Researchers	Further assess battery sizing, operating strategies, and alternative market conditions.

1.5.5 BUC 5: Business Citizen Energy Community

The work examined Symco Energies, formerly WapiGREEN, a developing business energy community in Picardy Wallonia that brings together enterprises, hospitals, and public institutions. At the time of the assessment, approximately 50 consumption sites belonging to 36 organisations were being studied, with energy sharing expected to begin in 2026. The participating sites already represented substantial electricity demand and included 13.3 MWp of member-owned solar capacity and 1.8 MW of combined heat and power, while the possible integration of four 2.35 MW wind turbines was also assessed.



Yearly Cost	15,6 M€	15,4M€	13 M€	12,5 M€
EC SCR	/	97,7%	73%	76,5%
EC SSR	/	4,6%	36,7%	41,3%
Peak Import	12,9 MW	12,9 MW	12,3 MW	12,8 MW
Peak Export	1,5 MW	1,5 MW	13,7 MW	14,6 MW

Figure 2-7: Key results of the BUC 5 evaluation

A two-stage optimisation framework was used. The first stage selected the cost-optimal location, ownership, and capacity of renewable generation and storage; the second calculated internal electricity prices and the financial outcome for each participant. Eleven scenarios compared stand-alone operation, energy sharing with existing assets, individual and joint renewable investment, different local pricing arrangements, minimum self-consumption requirements, and grid tariffs.

The modelling showed that jointly investing in wind alongside solar could reduce annual community costs by a further **€1.3 million** compared with a solar-focused investment strategy, largely because wind production better matches the evening, night-time, and winter demand of industrial and healthcare consumers.

Additional scenarios introduced batteries and flexible demand from activities such as refrigeration, water pumping, and electric-vehicle charging. These scenarios assessed whether electricity use could be shifted towards periods of local renewable production, whether high self-consumption targets were economically justified, and whether collective capacity tariffs could reduce stress on the public grid.

RESEARCH QUESTIONS

- What is the most-efficient business model for sharing and self-consuming electricity from local photovoltaic and wind turbine installations via the DSO network by (the members of) a business energy community?
- What is the appropriate business model for sharing and self-consuming electricity from local photovoltaic and wind turbine installations via the DSO network by a business energy community that can use flexibility solutions?

KEY LESSONS LEARNT

The optimisation can reduce total electricity costs while still leaving individual participants with higher bills than under stand-alone operation. This occurred because members differ considerably in their consumption, available investment capital, renewable potential, and retail contracts.

A common dynamic price linked to wholesale market conditions produced large differences between members and, in some cases, substantial losses. A flat structure with differentiated producer remuneration reduced those disparities, although some small participation losses remained.

Industrial, logistics, public, and healthcare users often consume electricity outside daylight hours and throughout winter. Wind generation complemented these demand patterns and substantially improved renewable coverage and economic performance.

Pooling capital allows members with limited roof or land availability to invest in larger shared assets, particularly wind generation. It also allows the location of an asset to be separated from the parties financing and consuming its production.

Under the assessed assumptions, a 2.8 MW battery with two hours of storage reduced annual costs by only around €0.1 million, whereas shifting 5–25% of daily flexible consumption progressively reduced costs and increased both self-consumption and renewable coverage. The apparent advantage of load shifting must nevertheless be weighed against production disruption, staff impacts, or other comfort and operational losses that were not monetised in the model.

With purely volumetric tariffs, renewable investment increased peak electricity export because the model had no reason to limit instantaneous grid use. Adding a collective capacity charge and flexibility reduced peak imports by approximately 3.2 MW and peak exports by 2.9 MW, while increasing annual community costs by about €0.1 million compared with the equivalent flexibility scenario.

RECOMMENDATIONS

The recommendations translate the lessons above into concrete actions for the actors responsible for deployment, regulation, and further development.

Recommendation	Category	Target Stakeholder(s)
Include participation safeguards in the optimisation and pricing model so that each member receives an acceptable benefit relative to its existing electricity arrangement, rather than optimising only the aggregate community cost.	**Business model / Socio-economic**	Energy-community operators, consultants, software developers, participating businesses
Develop transparent but differentiated internal tariffs that account for members' supplier contracts, investment contributions, generation ownership, and consumption characteristics without becoming too complex for participants to understand.	**Business model / Governance**	Community operators, electricity suppliers, regulators, member organisations
Facilitate joint ownership of complementary renewable assets by allowing members to pool capital for wind and shared solar projects, including assets located on another member's site or elsewhere within the eligible community area.	**Financial / Regulatory**	Regional authorities, financiers, energy communities, project developers
Avoid imposing rigid self-consumption requirements without comparing the cost of additional storage and renewable curtailment against the balancing and market costs avoided; in the assessed case, requiring 90% self-consumption increased annual costs by approximately €0.3 million.	**Technical / Market design**	Community operators, Balance Responsible Parties, regulators, researchers
Conduct an industrial flexibility audit before procuring storage, identifying which processes can shift demand, by how much, for how long, and at what operational or indirect cost.	**Technical / Operational**	Industrial members, energy managers, aggregators, technology providers
Test collective capacity tariffs for business energy communities where coordinated control of aggregate imports and exports can reduce shared grid peaks more effectively than individual capacity charges.	**Regulatory / Network tariff design**	CWaPE, DSOs, regional policymakers, energy communities
Evaluate batteries across multiple services and longer operating horizons, including inter-day energy shifting, balancing services, and congestion management rather than limiting assessment to same-day local energy arbitrage.	**Technical / Market development**	Researchers, aggregators, battery investors, DSOs, community operators

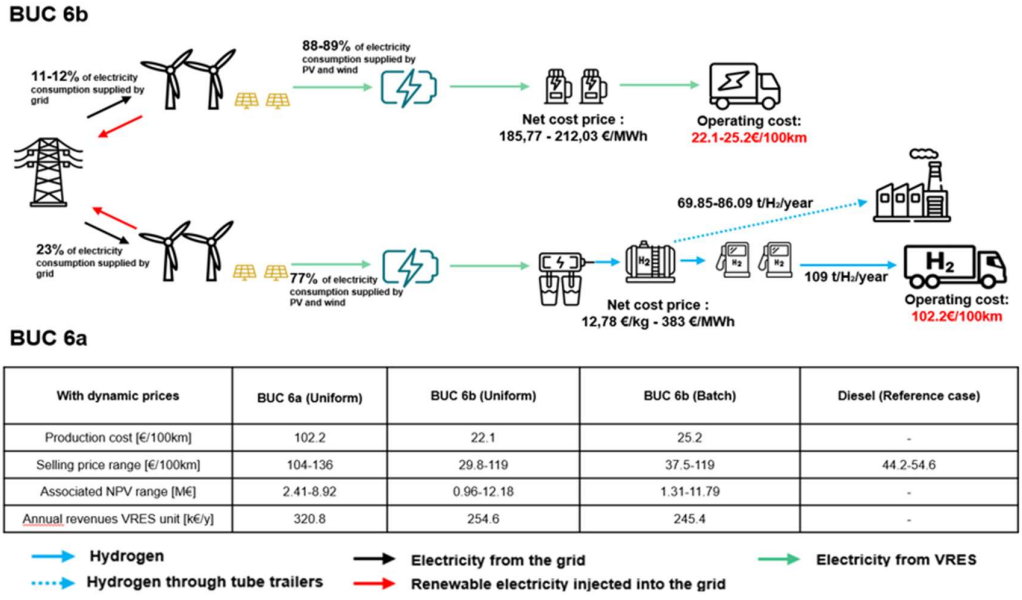
STAKEHOLDER SUMMARY

Community operators	Optimise collective investments while ensuring that individual members also benefit.
Participating organisations	Provide reliable energy data and identify feasible demand flexibility.
Governing bodies	Establish transparent pricing, ownership, and benefit-sharing rules.
Authorities, regulators, and DSOs	Enable joint investment and test collective grid tariffs.
Aggregators, technology providers, and researchers	Develop tools and services that combine renewable generation, storage, flexible demand, and market participation.

1.5.6 BUC 6: Green H2 and Electricity for Long Haul Trucks

The Wind-to-Trucks project examined a local value chain in which an existing 2 MW wind turbine and a planned 1.78 MWp solar installation supply a 1.25 MW electrolyser. The initial system is designed to fuel ten hydrogen trucks, each travelling approximately 136,500 kilometres per year and together requiring around 80–85 tonnes of hydrogen annually. High-pressure storage (1057kg) balances differences between renewable production and vehicle demand, while surplus electricity can be exported and additional electricity imported when local generation is insufficient.

The proposed business structure uses a dedicated project company with separate business units for renewable electricity and hydrogen production. Hydrogen is sold through a filling-station operator to the transport company, while additional production may be supplied to industrial customers or nearby gas engines. During the project, this secondary hydrogen use became more important because it could both secure additional demand and contribute to congestion management within IDETA's business parks.



With dynamic prices	BUC 6a (Uniform)	BUC 6b (Uniform)	BUC 6b (Batch)	Diesel (Reference case)
Production cost [€/100km]	102.2	22.1	25.2	-
Selling price range [€/100km]	104-136	29.8-119	37.5-119	44.2-54.6
Associated NPV range [M€]	2.41-8.92	0.96-12.18	1.31-11.79	-
Annual revenues VRES unit [k€/y]	320.8	254.6	245.4	-

Figure 2-8: Key results of the BUC 6 evaluation

A parallel configuration was defined in which renewable electricity is supplied directly to electric trucks through charging infrastructure and a battery storage system. The comparison was broadened beyond fuel production to include vehicle investment, charging or refuelling infrastructure, operating costs, transport performance, carbon benefits, and the final price of transport services.

Figure 2-9:

RESEARCH QUESTIONS

- What is the most appropriate techno-economic model to run heavy vehicles on hydrogen (trucks/industrial vehicles) produced from local green electricity, while considering the required profitability and competitiveness of the ecological fuel?
- What is the most appropriate model to run long haul trucks / heavy vehicles on locally produced green energy, the hydrogen or electric variant?

KEY LESSONS LEARNT

Dynamic electricity prices allow hydrogen production to move towards favourable periods. Introducing dynamic prices reduced the modelled $LCOH_2$ from €13.82/kg to €12.80/kg with a capacity tariff, while adding a battery afterwards reduced costs by only a further €0.02/kg. The electrolyser and hydrogen storage therefore provide most of the useful temporal flexibility themselves.

Capacity tariffs substantially reduced peak electricity imports across the assessed hydrogen scenarios while imposing a comparatively limited cost penalty. They mainly changed when grid electricity was consumed rather than the total amount consumed.

Local wind and solar supplied approximately 77% of the electricity required for the truck-fleet hydrogen demand, with the grid providing the remaining share. Forcing the grid contribution down to 20% required approximately 60 MWh of battery storage and increased $LCOH_2$ to about €30.5/kg, while lower grid-share limits became infeasible.

Selling hydrogen to industrial users improved electrolyser utilisation and project economics. At selling prices of €13–17/kg, the model generated approximately 70–86 tonnes/year of industrial hydrogen exports and positive NPVs, but the higher production also increased the grid-electricity share to around 48–53%.

Unlike the hydrogen pathway, electric-truck charging cannot freely respond to electricity prices without an intermediate flexibility asset. Combining dynamic prices with a BESS reduced the levelized charging cost to €185.77/MWh under coordinated charging, while grid electricity fell to approximately 11% of annual demand.

Distributing charging throughout the day required a 1.34 MWh battery and resulted in an LCOC of €185.77/MWh, compared with 2.43 MWh and €212.03/MWh when charging was concentrated into two daily batches.

On an equivalent transport-service basis, the modelled energy-supply cost was approximately €102.2/100 km for hydrogen, compared with €22.1/100 km for coordinated electric charging and €25.2/100 km for batch charging. For context, the indicative diesel fuel cost was approximately €44–55/100 km. However, vehicle CAPEX, payload, range, downtime and other operational constraints were not included and must be assessed before selecting a technology.

RECOMMENDATIONS

The recommendations translate the lessons above into concrete actions for the actors responsible for deployment, regulation, and further development.

Recommendation	Category	Target Stakeholder(s)
Prioritise flexible electrolyser operation and adequate hydrogen storage before investing in electrical battery capacity for hydrogen production systems.	**Technical**	Hydrogen developers, electrolyser operators, engineering companies
Expose electrolysers to dynamic electricity prices and appropriately designed capacity tariffs so that production can shift towards lower-cost periods while avoiding excessive grid peaks.	**Market design / Regulatory**	Energy suppliers, DSOs, regulators, hydrogen operators
Evaluate hydrogen projects using multiple representative renewable-generation and electricity-market years rather than a single deterministic year.	**Research / Investment**	Project developers, researchers, financiers
Secure low-cost renewable electricity through on-site generation or suitable PPAs, as electricity sourcing is the largest controllable component of hydrogen production cost.	**Business model / Financial**	Hydrogen producers, renewable developers, investors
Develop additional industrial hydrogen offtake where it improves asset utilisation, but assess the resulting impact on grid electricity consumption and renewable-hydrogen qualification.	**Business model / Environmental**	Hydrogen developers, industrial users, regulators
Avoid pursuing full grid independence as a standalone objective; use renewable-content constraints or multi-objective optimisation where environmental performance must be balanced against cost.	**Technical / Regulatory**	Project developers, certification authorities, policymakers
Design high-power truck charging as an integrated renewables–BESS–smart-charging system, rather than as an inflexible electrical load.	**Technical**	Fleet operators, charging providers, energy developers
Coordinate charging across the fleet wherever operationally feasible, using flexible charging contracts or incentives to avoid concentrated charging periods.	**Technical / Market design**	Fleet operators, logistics companies, energy suppliers
Combine dynamic tariffs and capacity-based grid charges with controllable assets such as BESS, since price signals alone provide little value when charging demand cannot shift.	**Regulatory / Market design**	Regulators, DSOs, suppliers, charging operators
Allow a limited contribution from the public grid rather than designing for complete energy self-sufficiency, which requires disproportionately large batteries as the grid share approaches zero.	**Technical / Investment**	Charging developers, fleet operators, financiers
Use a full technology-neutral transport cost assessment—including vehicle CAPEX, payload, range, downtime, charging/refuelling time and infrastructure—before choosing between hydrogen and battery-electric trucks.	**Research / Investment**	Fleet operators, policymakers, financiers, researchers

STAKEHOLDER SUMMARY

Project developers and hydrogen operators	Prioritise electrolyser and H_2-storage flexibility, secure low-cost electricity and develop credible additional hydrogen demand.
Fleet and logistics companies	Coordinate electric charging and evaluate hydrogen and electric trucks using full transport costs and operational requirements.
DSOs, energy suppliers and regulators	Use dynamic prices and capacity tariffs to encourage grid-friendly hydrogen production and EV charging.
Technology providers	Develop flexible electrolysers, hydrogen storage, BESS and smart-charging solutions suited to heavy-duty transport.
Governments and financiers	Support technology-neutral projects based on verified system costs, emissions and operational performance.
Researchers	Extend the comparison to vehicle CAPEX, range, payload, downtime and other factors required for a full TCO assessment.

1.5.7 BUC 7: The Role of Hydrogen in the Belgian and European Energy System

The study used the POMMES-EU energy-system model to examine the combined development and operation of the European electricity and hydrogen systems in 2050. The model covers 27 countries at hourly resolution and determines the cost-optimal mix of renewable generation, electrolysers, reforming technologies, electricity storage, hydrogen storage, and cross-border infrastructure.

Three main infrastructure settings were compared: a system with limited hydrogen interconnection, a European Hydrogen Backbone scenario, and a backbone scenario supplemented by low-cost hydrogen imports from outside Europe. The analysis assessed how these configurations affect total energy-system costs, hydrogen production technologies, emissions, storage requirements, electricity generation, and cross-border flows. Belgium was examined in greater detail under different hydrogen-demand levels to understand the implications for hydrogen prices, electricity demand, domestic production, and import dependence.

The results show that hydrogen infrastructure is a decisive factor in both European and Belgian outcomes. Hydrogen backbone deployment, carbon capture and storage, and underground storage reduced European system costs by up to 11% compared with the infrastructure-constrained scenario. In Belgium, limited infrastructure caused hydrogen prices to rise to as much as approximately €3.7/kg under high demand, while access to hydrogen networks and carbon capture and storage stabilised prices around €2.5/kg.

RESEARCH QUESTIONS

- Can green hydrogen, play a role in advancing the Belgian energy system towards climate neutrality?
- Under what conditions and for which applications will green hydrogen be beneficial for the Belgian energy system?

KEY LESSONS LEARNT

Hydrogen demand targets alone do not create a cost-effective hydrogen economy. Transport networks, carbon dioxide infrastructure, and storage must be developed alongside demand to avoid high production costs and inefficient investment.

Greater reliance on electrolysis increases electricity consumption and influences electricity prices, generation investment, gas-turbine operation, and renewable deployment. Hydrogen-system decisions therefore affect electricity consumers beyond the hydrogen sector.

Belgium can produce most of its hydrogen domestically without major cross-border infrastructure, but the cost increases substantially as demand grows. Under high-demand conditions, hydrogen prices reached approximately €3.7/kg in the infrastructure-constrained scenario.

Under the assessed scenarios, hydrogen produced from natural gas with carbon capture and storage retained a significant role alongside renewable electrolysis. Its availability reduced pressure on the electricity system and helped stabilise hydrogen prices.

Even when low-cost imports were available, Belgian electrolysis and hydrogen production with carbon capture and storage remained part of the optimal supply mix. Imports accounted for approximately one quarter of European hydrogen supply in the import-enabled scenario, creating a trade-off between lower costs and energy sovereignty.

RECOMMENDATIONS

The recommendations translate the lessons above into concrete actions for the actors responsible for deployment, regulation, and further development.

Recommendation	Category	Target Stakeholder(s)
Accelerate the development of hydrogen transport infrastructure and Belgium's connection to a European Hydrogen Backbone.	**Technical / Infrastructure**	Federal and regional governments, Fluxys, European network planners
Develop carbon dioxide transport and storage infrastructure in parallel with hydrogen networks so that low-carbon reforming can contribute during the transition.	**Technical / Regulatory**	Governments, infrastructure operators, industrial clusters, carbon-storage developers
Coordinate underground hydrogen storage development with hydrogen-network expansion, since storage has limited system value without sufficient network access.	**Technical**	Hydrogen network operators, storage developers, energy planners
Include multiple hydrogen-demand scenarios explicitly in electricity generation and grid-planning studies to identify potential price and capacity impacts.	**Planning / Technical**	Elia, DSOs, policymakers, electricity-market planners

Recommendation	Category	Target Stakeholder(s)
Link sectoral hydrogen targets to measurable infrastructure milestones rather than introducing demand obligations independently of transport, storage, and production readiness.	**Policy / Regulatory**	Federal and regional governments, legislators, industrial-policy authorities
Support domestic hydrogen-production clusters around Antwerp and the North Sea corridor to preserve industrial capability and supply security alongside imports.	**Industrial policy / Financial**	Governments, port authorities, industrial companies, investors
Treat imports as a complement to domestic supply and include diversification, security-of-supply, and strategic-dependence safeguards in import agreements.	**Policy / Energy security**	Federal government, European institutions, hydrogen importers
Assess how hydrogen-driven electricity-price increases could affect households and industries that do not consume hydrogen directly.	**Socio-economic**	Regulators, consumer organisations, policymakers, researchers

STAKEHOLDER SUMMARY

Governments and legislators	Sequence hydrogen targets with infrastructure delivery and maintain a balanced domestic-production and import strategy.
Energy storage operators	Develop the hydrogen backbone, carbon dioxide networks, and underground storage as an integrated system.
Grid operators	Account for electrolysis and hydrogen-demand growth in electricity-system investment studies.
Technology providers and investors Industry	Develop competitive domestic hydrogen production around strategic industrial and port areas.
Researchers and regulators	Monitor competitiveness, consumer impacts, import dependence, and interactions between electricity and hydrogen prices.

1.5.8 BUC 8: Integrated Energy Systems

Fluxys expanded its North Sea Integration Model (NSIM) to represent the interactions between electricity, hydrogen, methane, carbon dioxide, heat, ammonia, methanol and other energy carriers across ten North-West European countries. The model also introduced a detailed representation of offshore areas, reflecting differences in wind resources, distances from shore, electricity interconnections and potential offshore hydrogen-production locations.

Using this integrated modelling framework, the study identified the least-cost combination of energy production, conversion, storage, transport and import infrastructures required to meet future energy demand while achieving carbon neutrality by 2050. Several scenarios were analysed to assess the impact of limiting energy imports, restricting carbon capture and storage (CCS), and removing offshore electrolysis from the system. These scenarios allowed a comparison between transmitting offshore wind energy directly to shore

through high-voltage electricity interconnectors and converting part of that energy into hydrogen offshore for transport through pipelines.

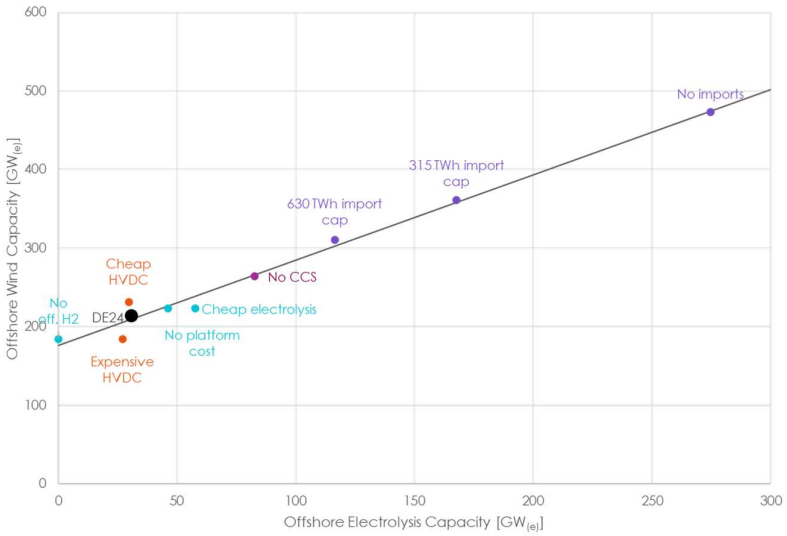


Figure 2-10. Relationship between offshore wind deployment and offshore electrolysis capacity.

The results demonstrate that a carbon-neutral energy system is achievable by 2050, but only through strong integration between energy sectors and the deployment of significant flexibility solutions. Rather than relying exclusively on electricity transmission or hydrogen production, the most cost-effective approach combines both. Offshore electrolysis emerges as a valuable complement to electricity transmission by increasing offshore wind deployment, reducing renewable-energy curtailment, providing flexibility to both the electricity and hydrogen systems, and lowering infrastructure constraints on the transmission network. The analysis also highlights the importance of coordinated development of hydrogen infrastructure, energy imports and CCS to maintain system affordability and security of supply during the transition to climate neutrality.

RESEARCH QUESTIONS

- What is the optimal way to transport large volumes of offshore renewable energy from the North Sea to energy consumers in North-West Europe?
- Can offshore hydrogen production (offshore electrolysis) reduce renewable energy curtailment and facilitate the large-scale deployment of offshore wind energy?

KEY LESSONS LEARNT

The modelling shows that the most cost-effective energy system uses a combination of electricity transmission (HVDC interconnectors) and hydrogen transport (offshore electrolysis and pipelines). These infrastructures are complementary rather than competing. Direct transmission is efficient when electricity demand and grid capacity are available, while hydrogen production provides an alternative route when transmission infrastructure becomes constrained.

Offshore electrolysis acts as a flexible demand source that can absorb offshore wind generation that would otherwise be curtailed or require expensive transmission reinforcement. The modelling demonstrates a strong relationship between additional offshore wind deployment and offshore electrolysis capacity.

A system dominated by renewables requires multiple forms of flexibility, including batteries, hydrogen production, hydrogen storage, cross-border exchanges, demand-side flexibility and energy conversion between sectors. Renewable generation alone is not sufficient to maintain affordability and security of supply.

The analysis shows that CCS reduces both the cost and complexity of the energy transition. When CCS is unavailable, significantly more renewable generation, electrolysis capacity, imports and alternative conversion infrastructure are required to achieve carbon neutrality.

The modelling demonstrates that North-West Europe can significantly reduce its dependence on imported energy carriers by deploying additional domestic renewable generation, offshore electrolysis, hydrogen infrastructure, and CCS. While the cost-optimal pathway still includes a significant share of imports, scenarios with reduced import dependency remain feasible and may provide strategic benefits in terms of energy security and resilience. The key challenge is finding the appropriate balance between affordability and energy sovereignty.

The benefits of offshore energy hubs, interconnectors, hydrogen networks and storage infrastructures are shared across several countries, while investment costs are often borne locally. Effective deployment therefore requires coordinated planning and cost-allocation mechanisms across borders.

RECOMMENDATIONS

The recommendations translate the lessons above into concrete actions for the actors responsible for deployment, regulation, and further development.

Recommendation	Category	Target Stakeholder(s)
Develop integrated offshore energy hubs combining offshore wind, electricity interconnectors, hydrogen production and hydrogen transport infrastructure rather than planning these assets separately.	**Technical / Infrastructure**	Offshore developers, TSOs, hydrogen network operators, governments
Preserve both electricity and hydrogen transport options when planning offshore zones, allowing the optimal balance to evolve with technology costs and network conditions.	**Planning / Technical**	European and national energy planners, infrastructure operators

Recommendation	Category	Target Stakeholder(s)
Accelerate the deployment of flexibility solutions, including electrolysers, hydrogen storage, demand response and cross-border energy exchanges.	**Technical / Market design**	TSOs, industrial consumers, storage developers, electrolyser operators
Establish coordinated European planning and cost-sharing frameworks for offshore grids, hydrogen backbones, CO_2 transport networks and offshore energy hubs.	**Regulatory / Governance**	European institutions, national governments, regulators, TSOs
Provide a stable regulatory framework for offshore hydrogen production and transport.	**Regulatory**	European Commission, national regulators, hydrogen and electricity operators
Develop targeted financing mechanisms to de-risk early-stage offshore electrolysis and cross-border infrastructure.	**Financial**	European institutions, governments, development banks, private investors
Maintain robust CCS and carbon-pricing frameworks throughout the energy transition.	**Policy / Market design**	European institutions, governments, carbon-network operators
Develop a long-term strategy balancing energy imports and domestic energy sovereignty.	**Policy / Investment**	European institutions, national governments, port authorities

STAKEHOLDER SUMMARY

Policy makers and regulators	Hydrogen, CCS and offshore infrastructure significantly reduce the cost of decarbonization and should therefore be considered together within future energy planning.
TSOs and infrastructure developers	Anticipate a future system where electricity networks, hydrogen networks and offshore hubs are highly integrated.
Industrial energy users	Hydrogen availability and competitiveness will strongly depend on infrastructure development choices made during the coming decade.
Renewable energy developers	Consider offshore electrolysis as a complementary solution that can support further offshore wind deployment and improve utilization of renewable energy resources.

1.5.9 BUC 9: Flexibility Provision with a Large-Scale Electrolyser

The study examined a 25 MW electrolyser being developed by Virya Energy in Zeebrugge. The facility can obtain electricity through an offshore-wind PPA or the day-ahead market, produce hydrogen for delivery by tube trailer or injection into the gas grid, sell unused PPA electricity, and provide aFRR down-regulation to Elia.

An hourly optimisation model was developed to select the most profitable combination of electricity purchasing, hydrogen production, renewable certification, hydrogen delivery, PPA electricity sales, and flexibility-market participation. Five scenarios separated the effects of aFRR participation, monthly RFNBO matching, and strict hourly matching. The model also reflected operating limits such as minimum stable load, conversion efficiency, hydrogen offtake limits, and differences between green and non-certified hydrogen revenues.

The results show that aFRR down-regulation can improve profitability, but its value falls considerably under strict hourly RFNBO matching. Without RFNBO restrictions, aFRR increased indexed profit by approximately 17 percentage points; under hourly matching, the uplift fell to around 7 percentage points because activated electricity could not always be matched with renewable PPA generation.

RESEARCH QUESTIONS

- How is the business case of large-scale electrolysers impacted by providing flexibility to the energy system?
- What is the infrastructure needs to support different end applications?

KEY LESSONS LEARNT

The electrolyser can increase consumption during periods of electricity oversupply and receive aFRR capacity and activation revenues while producing additional hydrogen.

Strict hourly matching limits the hours in which electricity consumption can qualify as renewable. Under these conditions, aFRR participation falls to roughly one third of the level observed without RFNBO restrictions.

Moving from monthly to hourly matching reduced indexed profit, while adding more contracted wind capacity produced diminishing benefits because some operating hours remained structurally unmatched.

A continuously operating baseload forces the electrolyser to import grid electricity during low-wind periods. Even an oversized PPA therefore cannot bring the renewable hydrogen share close to 100% under strict hourly matching.

Following renewable output and aFRR signals requires frequent changes in electrolyser loading. The resulting stack degradation and maintenance effects were not fully represented in the profitability comparison.

RECOMMENDATIONS

The recommendations translate the lessons above into concrete actions for the actors responsible for deployment, regulation, and further development.

Recommendation	Category	Target Stakeholder(s)
Assess electrolyser configurations with lower minimum-load requirements, efficient cold standby, and rapid restart capability to increase compatibility with variable renewable generation.	**Technical**	Electrolyser manufacturers, Virya Energy, engineering companies
Include stack degradation, start-stop costs, maintenance, and equipment lifetime in future evaluations of day-ahead and aFRR operation.	**Technical / Investment**	Project developers, technology suppliers, researchers, financiers
Jointly optimise PPA size, hydrogen offtake, day-ahead procurement, and balancing-market participation rather than assessing each revenue stream separately.	**Business model / Technical**	Electrolyser operators, BRPs, Flexibility Service Providers, hydrogen customers
Preserve limited temporal flexibility within RFNBO implementation, or develop a specific treatment for qualifying aFRR activations that support the integration of renewable electricity.	**Regulatory / Market design**	European and national regulators, certification authorities, Elia
Establish demonstration arrangements to verify metering, certification, baseline determination, and settlement when RFNBO electrolysers provide balancing services.	**Regulatory / Demonstration**	Elia, regulators, hydrogen certifiers, electrolyser operators

STAKEHOLDER SUMMARY

Electrolyser operators	Coordinate hydrogen production, renewable procurement, and flexibility participation.
Manufacturers and researchers	Reduce minimum-load constraints and quantify degradation from cyclic operation.
Elia, BRPs, and Flexibility Service Providers	Develop workable aFRR participation and settlement arrangements.
Regulators and certification authorities	Align RFNBO implementation with valuable grid-supporting operation.
Hydrogen customers and investors	Provide predictable offtake and assess revenues using realistic operating costs.

1.5.10 BUC 10: Flexibility Provision with a Portfolio of EVs

A residential flexibility model was developed to optimise household electricity consumption, rooftop PV use, and EV charging over a rolling daily horizon. The model compared three situations:

Uncontrolled charging;

An idealised price-responsive case in which the EV is assumed to be available whenever needed;

A behavioural case that includes actual travel requirements, charging locations, plug-in availability, user preferences, charging-power limits, Vehicle-to-Grid capability, and manufacturer recommendations.

The analysis evaluated upward and downward flexibility, charging costs, PV self-consumption, and household peak demand. Including realistic behaviour increased calculated residential upward flexibility by 37.18%, but reduced downward flexibility by 56.5% because vehicles were often away from home or had already charged elsewhere. Charging costs were approximately 34.38% lower than in the idealised reference scenario, largely because users could access cheaper charging locations outside the home.

The results also showed that uniform response to low electricity prices can create more concentrated charging peaks. Behavioural constraints reduced these residential peaks, but part of the demand was transferred to workplace or public charging locations rather than eliminated.

RESEARCH QUESTIONS

- How do novel market design options enable a safe and secure participation of flexibility from E-mobility to the overall system, avoiding a correlated charging behaviour?
- How much flexibility in terms of energy and power can be derived from a fleet of EVs?
- What is the expected value of this flexibility at the level of an EV portfolio and for an individual EV user?

KEY LESSONS LEARNT

Assuming that every vehicle is continuously connected and fully responsive to price signals exaggerates the amount and timing of flexibility available at home.

Alternative charging locations reduce residential consumption and create more headroom for upward flexibility, but they also reduce the additional charging that can be activated during low-price or oversupply periods.

Charging at work or public locations can reduce the household bill and residential peak, but the electricity demand is transferred to another connection point.

When many EV users respond to the same low-price hours, charging becomes concentrated and can create new network constraints despite reducing energy costs.

Mobility needs, minimum departure state of charge, battery-health preferences, and willingness to permit Vehicle-to-Grid operation determine whether theoretical flexibility can actually be activated.

Heat pumps, household batteries, PV systems, and EVs interact through the same connection and may compete for the same network capacity or respond simultaneously to the same signals.

RECOMMENDATIONS

The recommendations translate the lessons above into concrete actions for the actors responsible for deployment, regulation, and further development.

Recommendation	Category	Target Stakeholder(s)
Require EV flexibility assessments to include travel schedules, plug-in availability, charging-location choices, state-of-charge requirements, charging limits, and manufacturer recommendations.	**Technical / Planning**	DSOs, TSOs, aggregators, researchers
Extend flexibility accounting across home, workplace, and public charging locations to avoid treating transferred electricity demand as a system-level reduction.	**Technical / Data**	Charging operators, aggregators, DSOs, mobility-data providers
Combine EVs, heat pumps, household batteries, and rooftop PV within integrated household and portfolio optimisation models.	**Technical**	Software providers, researchers, energy service companies
Design dynamic tariffs and market signals with local network conditions or diversity mechanisms to prevent correlated charging peaks.	**Market design / Regulatory**	Regulators, suppliers, DSOs, market operators
Standardise secure access to vehicle availability, state-of-charge, charging-power, and control data across vehicle and charger manufacturers.	**Technical / Regulatory**	Vehicle manufacturers, charging providers, standards bodies, regulators
Provide transparent user controls, minimum mobility guarantees, battery-health protections, and clear benefit-sharing arrangements for flexibility participation.	**Socio-economic / Consumer protection**	Aggregators, suppliers, consumer organisations, regulators

STAKEHOLDER SUMMARY

Aggregators and suppliers	Use behaviour-aware scheduling and clearly share flexibility revenues with drivers.
EV owners	Define mobility, comfort, and battery-health limits for smart charging.
TSO, DSOs, and regulators	Prevent synchronised peaks and account for flexibility across charging locations.
Vehicle and charging providers	Enable interoperable, secure access to charging and battery data.
Researchers and software developers	Model EVs together with other flexible household technologies.

1.5.11 BUC 11 Smart billing solutions for large-scale EV fleet charging

BUC 11 investigates smart billing solutions for residential charging of large company-car fleets, where charging decisions are made by drivers while electricity costs are ultimately borne by employers. Based on proof-of-concept deployments involving around 120 EVs across four fleets, the BUC assessed two approaches using the re.alto platform. The first used near-real-time vehicle IoT data combined with individual electricity contract information to determine charging sessions and their costs without dedicated charging hardware. The second explored a volume-split approach, in which EV charging volumes are identified separately within total household consumption and could be allocated to a dedicated settlement and reimbursement process. Both approaches aimed to reduce dependence on provider-specific charging infrastructure and facilitate future smart charging and flexibility services.

The PoCs demonstrated the technical feasibility and potential cost efficiency of using vehicle IoT data to identify EV charging and support fleet-related flexibility. However, regulatory and market barriers currently limit commercial deployment. In particular, vehicle IoT data cannot currently serve as the legally binding measurement basis for billing, reimbursement or flexibility settlement under the applicable metering framework. The volume-split approach was technically demonstrated, including flexibility testing with part of the fleet, but did not obtain sufficient traction among electricity suppliers to support wider deployment. A supply-split approach was therefore also investigated, although this would require access to certified metering data. Overall, the analysis shows that scalable smart billing and EV flexibility are technically achievable, while further progress depends mainly on accepted metering and settlement arrangements, regulatory clarity and market readiness.

RESEARCH QUESTIONS

- What impact can smart billing solutions have on the charging behaviour of a driver? How
- does it relate to his home energy consumption/bill?

KEY LESSONS LEARNT

Vehicle IoT data can provide a technically feasible and relatively hardware-light approach for identifying residential EV charging sessions, monitoring charging costs and potentially enabling flexibility services for large EV fleets.

Accurate smart billing requires more than identifying charging events. Charging volumes need to be combined with contract-specific electricity tariffs, including dynamic prices and capacity-based components, to reflect the actual cost of home charging.

A key limitation is the regulatory acceptance of vehicle IoT data for financial settlement. Under the current framework, IoT-derived measurements cannot replace certified metering data where measured energy volumes form the basis for billing, reimbursement or flexibility settlement.

The volume-split PoC demonstrated the technical feasibility of distinguishing EV charging volumes within household consumption, but technical feasibility alone is insufficient for scalability. Wider adoption also requires appropriate settlement arrangements and sufficient participation from electricity suppliers.

Smart billing, reimbursement and flexibility provision are closely interconnected. A robust and trusted settlement mechanism is an important prerequisite for using residential fleet charging flexibility at scale, particularly where the driver, employer, supplier and flexibility provider are different actors.

The PoC also highlights the value of a technology-agnostic connectivity layer that can harmonise data from different EV brands and support monitoring and control without tying users to a specific charging infrastructure provider.

RECOMMENDATIONS

The recommendations translate these lessons into concrete actions for the actors responsible for EV charging, settlement and flexibility.

Recommendation	Category	Target Stakeholder(s)
Clarify the conditions under which vehicle-derived data can support EV charging reimbursement and flexibility settlement, and the role of certified metering within these arrangements.	**Regulatory / Market design**	Policymakers, regulators, metrology authorities
Further develop and validate volume-split, supply-split or equivalent mechanisms that enable separate treatment of EV charging while maintaining workable household supply and settlement arrangements.	**Market design / Settlement**	Energy suppliers, system operators, regulators, mobility and fleet service providers
Use interoperable and technology-agnostic connectivity approaches to minimise dependence on dedicated or provider-specific charging hardware.	**Technical / Interoperability**	Technology providers, OEMs, CPOs, MSPs, fleet operators
Improve the accuracy and transparency of charging-cost calculations by combining charging-session data with actual electricity contract information, including dynamic and capacity-based tariffs where applicable.	**Technical / Commercial**	Energy suppliers, fleet managers, mobility service providers, technology providers
Develop clear arrangements for data access, consent and responsibilities between drivers, employers, fleet managers, energy suppliers and flexibility providers.	**Governance / Data**	Fleet managers, employers, suppliers, technology providers
Continue testing smart billing and flexibility mechanisms with suppliers and fleet operators, with particular attention to settlement feasibility, data accuracy, user acceptance and scalability.	**Research / Demonstration**	Fleet operators, energy suppliers, technology providers

STAKEHOLDER SUMMARY

Policymakers and regulators	Clarify the regulatory conditions for using vehicle data in billing, reimbursement and flexibility settlement.
Energy suppliers and system operators	Further develop workable volume-split, supply-split and settlement arrangements for residential fleet charging.
Fleet managers and employers	Support transparent reimbursement mechanisms and create appropriate incentives for flexible charging.
OEMs, CPOs, MSPs and technology providers	Enable interoperable access to reliable EV charging data while reducing dependence on dedicated hardware.
EV Drivers	Provide the necessary consent and contract information while retaining transparency over charging costs and flexibility participation.
Researchers and demonstration partners	Further validate data accuracy, settlement arrangements, supplier participation and scalability under operational conditions.

1.5.12 BUC 12: Smart Billing Solutions for EV Charging

BUC 12 builds on the Otterbeek social housing and shared-mobility case examined in BUC 3A and 3B. The neighbourhood has 741 kW of rooftop solar capacity across 197 social housing units, but much of the electricity is exported because local consumption does not coincide with solar production. Shared EV charging creates an opportunity to use more of this electricity locally while providing affordable mobility to residents.

The work investigated how a smart-billing layer could allocate charging costs, solar-energy benefits, incentives, and redemption rights among residents, Klimaan, the Shared Mobility Operator, the Charge Point Operator, and other users. Conventional payments were considered alongside prepaid wallets and community credits intended to reward charging during preferred periods and reduce non-payment risk.

A hybrid digital architecture was developed with three elements:

Certified meters, charging stations, booking systems, and energy data provide trusted inputs.

An off-chain system calculates tariffs, local solar use, rewards, and benefit allocation.

Smart contracts execute wallet funding, credit transfers, redemption, and final settlement.

This architecture keeps detailed mobility and household data outside the ledger while using blockchain only for auditable settlement and community-credit management. The assessment was primarily architectural and qualitative.

RESEARCH QUESTIONS

- How can we reward users to charge their EV at the most optimal times?
- How can we limit payment risks?

KEY LESSONS LEARNT

The central challenge is determining which participant created value by charging at a beneficial time and how that value should be shared among community actors.

The settlement mechanism still depends on certified or otherwise trusted charging records. Blockchain can preserve and execute a settlement result, but it cannot independently verify how much electricity was consumed.

Sensitive household, mobility, and charging calculations should remain off-chain, while only wallet balances, reward transfers, and final settlement events are recorded on-chain.

Shared charging produces frequent, relatively small transactions. Unpredictable public-blockchain fees could exceed the value being transferred, making permissioned or low-cost settlement infrastructure more appropriate.

Smart contracts can limit rewards to approved community wallets, prevent speculative trading, and ensure that locally created value is used for mobility or other agreed community purposes.

Prepayment protects the mobility operator from unpaid bills, but residents without smartphones, bank accounts, digital skills, or sufficient funds must still be able to access the service.

RECOMMENDATIONS

The recommendations translate the lessons above into concrete actions for the actors responsible for deployment, regulation, and further development.

Recommendation	Category	Target Stakeholder(s)
Implement a hybrid architecture in which certified metering and tariff calculations remain off-chain, while smart contracts handle final settlement, wallet balances, and reward distribution.	**Technical**	Software developers, CPOs, MSPs, energy communities
Use open charging and data-exchange standards, including OCPP and OCPI-compatible records, to avoid dependence on a single charging or billing provider.	**Technical / Interoperability**	Charging providers, software vendors, municipalities
Deploy the settlement layer on a permissioned or low-cost network and limit blockchain use to functions for which auditability and multi-party trust create clear value.	**Technical / Economic**	Technology providers, project operators, financiers
Provide conventional payment and assisted-access alternatives alongside digital wallets so that residents without smartphones, digital skills, or prepaid funds are not excluded.	**Socio-economic / Consumer protection**	Shared Mobility Operators, social housing providers, municipalities

Recommendation	Category	Target Stakeholder(s)
Establish transparent rules defining how solar-use rewards and flexibility revenues are calculated, funded, redeemed, and distributed between residents and operating organisations.	**Governance / Business model**	Energy communities, mobility operators, residents
Clarify the regulatory treatment of community credits, prepaid wallets, smart-contract settlement, data protection, and consumer reimbursement before commercial rollout.	**Regulatory**	Financial regulators, energy regulators, data-protection authorities, policymakers
Conduct a limited pilot comparing transaction costs, payment defaults, user participation, and administrative effort against conventional billing before wider deployment.	**Research / Demonstration**	Klimaan, KBC, municipalities, researchers

STAKEHOLDER SUMMARY

Energy communities and mobility operators	Define transparent reward, payment, and benefit-sharing rules.
CPOs, MSPs, and technology providers	Build an interoperable hybrid billing system using trusted metering and low-cost settlement.
Social housing providers and municipalities	Ensure that wallets and prepaid arrangements do not exclude vulnerable residents.
Residents	Help design understandable tariffs, redemption options, and privacy safeguards.
Regulators	Clarify the legal status of community credits, automated settlement, and associated consumer protections.
Researchers and financial institutes	Validate transaction costs, user acceptance, and operational savings through a controlled pilot.

1.6 Pillar 4: System impact of the ReInvent solutions and future outlook

1.6.1 Scalability and replicability of the ReInvent test cases

This work examined the factors influencing the scalability and replicability of the local sector coupling use cases developed within the project. Although many of these use cases have demonstrated promising results at simulation and pilot scale, significant challenges remain before they can be deployed at a larger scale. The analysis therefore identified the main barriers, as well as the key enablers, that influence their successful upscaling and replication in different contexts. To provide a comprehensive assessment, the study examined technical, economic, regulatory, and stakeholder-related boundary conditions that determine the potential of each use case to achieve large-scale deployment and contribute to the broader uptake of sector coupling solutions.

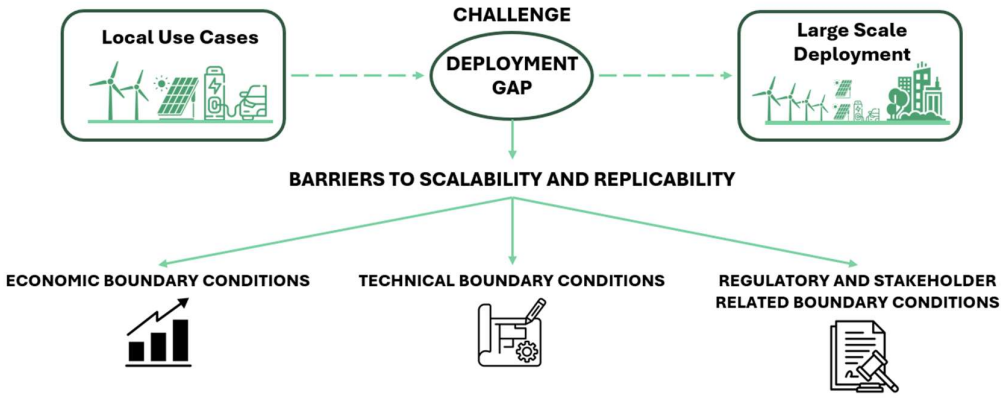


Figure 2-11: Overview of scalability and replicability analysis

RESEARCH QUESTIONS

- Scalability: To what extent can the BUCs be scaled up, and which factors influence their scalability?
- Replicability: To what extent can the BUCs be replicated in other locations, sectors or contexts, and what adaptations are required?
- Boundary conditions: Which technical, economic, regulatory and stakeholder-related conditions enable or constrain the scalability and replicability of the BUCs?

KEY LESSONS LEARNT

Scalability and replicability depend on more than technical feasibility. Wider deployment requires technical, economic, regulatory and stakeholder conditions to align.

Scaling is not simply making a pilot larger, and replication is not simply copying it elsewhere. Solutions typically need to be adapted to local infrastructure, markets, regulation and stakeholder needs.

Standardisation and local adaptation need to be balanced. Standardised technologies, interfaces and organisational approaches can facilitate deployment, but local conditions continue to determine how solutions should be implemented.

A viable and credible value proposition remains essential. Technical potential alone does not ensure uptake; participants need sufficient economic incentives and a clear distribution of costs, benefits and responsibilities.

Electrification and flexibility are relatively transferable, but coordination becomes increasingly important at scale. Growing numbers of EVs, heat pumps, batteries and other flexible assets increase the potential for flexibility, while also increasing requirements for interoperability, coordination and appropriate incentives.

Collective energy sharing can benefit from scale, but governance complexity can increase at the same time. Replication therefore depends not only on technical solutions but also on appropriate regulatory, contractual, governance and benefit-sharing arrangements.

Clean molecules and Power-to-X are particularly dependent on the surrounding system. Their scalability and replicability depend strongly on renewable electricity and grid capacity, transport and storage infrastructure, sufficient demand, regulation and long-term stakeholder commitments.

RECOMMENDATIONS

The recommendations translate the lessons above into concrete actions for the actors responsible for deployment, regulation, and further development.

Recommendation	Category	Target Stakeholder(s)
Establish stable and harmonised regulatory frameworks across the Belgian Regions to facilitate the deployment and replication of sector coupling business models, particularly energy communities.	Regulatory	Policymakers, regulators
Regularly review and adapt regulatory frameworks to keep pace with emerging sector coupling technologies and business models.	Regulatory	Policymakers, regulators
Develop targeted support mechanisms to bridge the gap between pilot projects and commercial deployment.	Economic	Policymakers, regulators
Support the deployment of enabling technologies, such as heat pumps, smart EV charging infrastructure and energy storage, through targeted investment incentives.	Economic	Policymakers, regulators, industry, technology providers, building owners.
Integrate grid capacity assessments and infrastructure planning into the earliest stages of project development.	Technical / planning	DSOs, TSO, project developers, local authorities, industry

1.6.2 Overall impact assessment for Belgium

The impact assessment has evaluated the impact and value of sector-coupling, particularly for electrification and demand-side flexibility, for Power2X in relation to clean molecules import, and for multi-energy market design. An additional methodological objective was to explore how different system level models can work together in a complementary way through a combined model analysis.

RESEARCH QUESTIONS

- To what extent does demand-side flexibility reduce system costs?
- What is the role of hydrogen and other clean molecules in the future energy system?
- How do different flexibility sources such as EV charging, power to heat and power to gas compare?
- How to coordinate energy market designs to enable sector coupling?
- How can different system level models work together in a complementary way through a combined model analysis?

KEY LESSONS LEARNT

Demand side flexibility technologies such as flexible EV charging and flexible operation of hot water buffers in buildings are largely 'no-regret' from a techno-economic perspective, since they provide high value to the system at low cost. These monetary system-level benefits can be attributed to having more VRE integration, lesser imports of power and molecules, lesser battery investment, and more efficient heating systems.

Hydrogen and other clean molecules are found to have an important role in a climate-neutral Belgian energy system, particularly for demands that er hard to electrify. Yet, there is considerable uncertainty on cost-optimal levels of hydrogen demand in relation to uncertain drivers such as electricity prices, CO_2 storage deployment and regulatory requirements on green hydrogen. Also cost-optimal hydrogen supply routes are subject to uncertainty, in particular the cost-optimal shares from pipeline imports, electrolysis and natural gas-based hydrogen with carbon capture and storage. This uncertainty is reflected by differences in the results of the different system level models applied. First estimates of the value of power-to-gas for Belgium indicate significant system-levels savings, albeit smaller to those of demand side flexibility.

More coordinated market design can support sector coupling. Shorter gas and hydrogen market products improve the responsiveness of flexible multi-carrier technologies, while temporal alignment can facilitate balancing-market participation. The effects are technology- and market-dependent, highlighting the need to consider electricity, gas, hydrogen and balancing-market design jointly.

Combined model analysis is valuable as it forces modelling teams to critically reflect on modelling assumptions that may be chosen differently between different models. Iterative soft-linking procedures are relevant, but also time-intensive and conceptually challenging. Further combined model analysis could also consider stand-alone model application structured around common research questions.

RECOMMENDATIONS

The recommendations translate the lessons above into concrete actions for the actors responsible for deployment, regulation, and further development.

Recommendation	Category	Target Stakeholder(s)
Ensure incentive schemes and flexible tariffs needed to facilitate demand-side flexibility are put in place. Create the conditions to enhance acceptance of demand-side flexibility, by making flexible solutions easy, attractive, social and timely for consumers.	**Economic / regulatory / social**	Regulators, project developers, equipment installers
Consider phasing out non-flexible end-use technologies as part of energy efficiency regulation for technologies such as EV charging and hot water buffers, where the value of flexible operation strongly outweighs the costs. Flexible operation should become the norm, rather than the exception.	**Regulatory**	Policymakers, regulators
Monitor the value of demand-side flexibility at the system level as the uptake of energy assets, such as variable renewable energy and electrified demands, unfolds.	**Technical**	System operators, researchers
Coordinate market design across electricity, gas, hydrogen and balancing markets, with particular attention to product granularity and timing.	**Market design / Regulatory**	Regulators, market operators, TSOs, policymakers
Further invest in combined model analysis to reveal critical uncertain factors underlying different viewpoints on energy system planning, particularly on the role of hydrogen and other clean molecules, as a valuable input for further scenario analysis and robust policy-making.	**Policy / Economic**	Policymakers, system operators, industry, researchers

3 Overall ReInvent recommendations

The overall ReInvent recommendations build on the lessons learnt across the different pillars and business use cases and underline that successful sector coupling requires more than technically feasible solutions. Its value is greatest when energy vectors, assets and stakeholders are coordinated rather than optimised separately. Across energy markets, energy communities, EV charging, batteries, hydrogen and offshore infrastructure, coordinated operation can improve renewable utilisation, flexibility and economic performance. This calls for greater coordination not only between technologies and actors, but also between electricity, gas, hydrogen and heat markets. Rather than requiring full market integration, targeted alignment of market timelines, procedures and flexibility rules can reduce fragmentation and enable sector-coupled technologies to operate more effectively across different energy carriers and markets.

At the same time, greater collective or system value does not necessarily translate into an attractive outcome for every participant. The viability of sector-coupling projects therefore depends strongly on how investment costs, risks, revenues and savings are distributed among the actors involved. Fair and transparent pricing, benefit-sharing and governance arrangements should be integral to the development of sector-coupling business models. Stable regulatory frameworks, appropriate risk-sharing arrangements and targeted financial support can further improve investment conditions, particularly for innovative or first-of-a-kind projects.

Flexibility is a central element of sector coupling and renewable integration, but the results show that there is no single flexibility solution that is optimal across all applications. Batteries, thermal and hydrogen storage, existing process flexibility, flexible demand and cross-sector conversion can each provide value under different conditions. The most appropriate flexibility option should therefore depend on the characteristics of the technology, the use case and the wider energy system. Where technically appropriate, sector-coupled assets and energy communities should also be able to combine local optimisation with participation in balancing, congestion management, day-ahead and other flexibility mechanisms, allowing different value streams to be combined. Realising this flexibility potential requires appropriate market, tariff and regulatory frameworks. Misaligned market timelines, tariffs that do not sufficiently reflect system needs, fragmented regional rules or participation requirements can restrict technically available flexibility or create incentives that conflict with wider system objectives. Market rules, tariffs and flexibility remuneration should therefore encourage flexible, grid-friendly and low-carbon operation and facilitate the participation of sector-coupled assets and energy communities. Greater coordination of rules across energy carriers and, where relevant, across regions can further reduce regulatory and administrative barriers.

The possibilities for sector coupling are also strongly shaped by the availability and location of infrastructure. Grid capacity, renewable generation, storage, hydrogen and CO_2 networks, offshore infrastructure and charging infrastructure can determine which solutions are technically and economically viable before operational optimisation is even considered. Infrastructure requirements should consequently be addressed early in project

development and, where possible, planned across sectors rather than independently. Coordinated infrastructure planning can help ensure that otherwise viable sector-coupling solutions are not constrained by missing or insufficient supporting infrastructure.

These considerations are equally important when moving from pilots towards wider deployment. Demonstrating that a solution works in a specific pilot does not automatically imply that it can be scaled up or replicated elsewhere. Scalability and replicability depend on the alignment of technical, economic, regulatory and stakeholder-related conditions. While technologies and operational principles may be transferable, their implementation may need to be adapted to local infrastructure, market arrangements, regulation, asset availability and stakeholder needs. These conditions should therefore be considered from the beginning of project and business-model development. Greater standardisation and interoperability of data, metering and control interfaces can complement this local adaptation and facilitate wider deployment.

The ReInvent results furthermore highlight the importance of taking a whole-system perspective when evaluating sector-coupling solutions. Maximising a single objective, such as self-consumption, grid independence, market revenue or local optimisation, does not necessarily lead to the best overall outcome. Such strategies may shift costs or impacts to other parts of the energy system or restrict potentially beneficial interactions with other technologies and markets. Decisions should therefore consider total system value and trade-offs between different objectives. In some cases, limited grid use, energy imports or combinations of complementary technologies may provide better overall outcomes than rigid self-sufficiency or single-technology approaches. A whole-system perspective also requires assessments to adequately reflect real-world operating conditions and uncertainty. Consumer behaviour, equipment limitations, forecast errors, asset degradation, mobility requirements, changing market conditions and interannual variation in renewable generation can materially affect achievable flexibility and economic performance. Investment and operational assessments should therefore use realistic assumptions, multi-year data and, where appropriate, uncertainty-aware approaches. Doing so can help avoid decisions based on theoretical flexibility or idealised operating conditions that may not be fully achievable in practice.

Finally, economic performance needs to be considered alongside decarbonisation and wider system impacts. Economic optimisation and environmental objectives do not always align automatically: market-responsive operation can under some conditions increase emissions or dependence on grid electricity, while restrictive renewable or self-sufficiency requirements can substantially increase costs. Technology and operational choices should therefore be evaluated against multiple objectives, including economic performance, emissions, infrastructure and system impacts, and relevant operational and social constraints. Preserving technology neutrality while explicitly considering these wider effects can support solutions that create value both for individual projects and for the broader energy system. These main recommendations are summarized in the figure below.



Figure 3-1: Main recommendations of the ReInvent project

Taken together, the recommendations point towards an integrated approach in which technologies, infrastructure, markets, regulation and business models are considered jointly rather than independently. Coordinated planning and operation, appropriate incentives, fair allocation of value, realistic assessment of real-world constraints and early consideration of scalability and local conditions can support the transition from technically successful demonstrations towards viable and widely deployable sector-coupling solutions.

References

[1] ReInvent, "Deliverable 1.1 Implication and opportunities for sector coupling in Belgium," 2024. [Online]. Available: https://reinvent-project.be/en/publications.

[2] ReInvent, "Deliverable 1.2 Report on improved market design, business models and financing models for sector coupling," 2026. [Online]. Available: https://reinvent-project.be/en/publications.

[3] ReInvent, "Deliverable 2.1 The REINVENT modelling environment," 2026. [Online]. Available: https://reinvent-project.be/en/publications.

[4] ReInvent, "Deliverable 3.1 Definition of use cases (BUC-SUC) and KPIs," [Online]. Available: https://reinvent-project.be/en/publications.

[5] ReInvent, "Deliverable 3.4 Evaluation of the selected test cases," 2026. [Online]. Available: https://reinvent-project.be/en/publications.

[6] ReInvent, "Deliverable 4.1 Scalability and replicability potential of the test cases in the Belgian context and overall impact assessment for the Belgian energy system," 2026. [Online]. Available: https://reinvent-project.be/en/publications.