Empowering Energy Hubs

A strategic pathway for Stakeholder collaboration and hydrogen adoption to mitigate grid congestion

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Preface

I am pleased to present my graduation thesis, the result of several months spent researching the complex but fascinating topic of energy hubs and the role of hydrogen in the energy transition. The idea for this project began during an earlier internship at Arup, where I first became interested in the energy transition sector. Having been offered the opportunity to graduate within Arup's Business Investment Advisory team, I eagerly started exploring suitable research directions within this field.

In the beginning, defining a clear and manageable scope felt somewhat challenging. The independent nature of the project initially made me feel uncertain, yet gradually I found comfort and even enthusiasm in having the freedom to shape my own path. As the topic became clearer, my initial uncertainty turned into motivation, and I began to enjoy the challenges involved in developing my own framework and strategic roadmap.

I would like to express my appreciation to several people who guided and supported me during this project. First, my thanks go to my graduation chair, Dr. Sine Celik, for her structured guidance and valuable feedback throughout the process. My mentor, Ir. Mahshid Hasankhani, provided excellent insights and support, helping me to sharpen my focus and navigate the complexities of the topic.

I also want to thank my supervisors at Arup, Kevin Vervuurt and James Cowley, for their continuous support and insightful advice. I also greatly appreciated the support from the entire Business Investment Advisory team, who were always approachable, willing to share their knowledge, and ready to connect me with relevant experts and resources.

Reflecting on this experience, I am proud of the results I have achieved. I have gained valuable knowledge, grown professionally, and developed greater confidence in handling complex strategic problems. I hope my thesis provides useful insights to others working in the energy transition field, encouraging further innovation and collaboration in this important area.

Thank you for reading, I hope you find my work insightful and useful.

Bram Bezooijen

Executive summary

The issue of grid congestion and the integration of renewable energy sources and hydrogen into energy systems are receiving increasing attention in the Netherlands. Concurrently, the concept of energy hubs is gaining traction, holding substantial potential for alleviating these challenges through flexible and localized energy management. This research investigates how energy hubs can be effectively implemented, attract broad stakeholder engagement, and address emerging narratives on sustainable energy solutions that are inclusive and responsive to stakeholder needs.

The research began with an initial exploration into the regulatory, market, technological, and financial uncertainties associated with energy hubs. This foundational understanding informed the subsequent investigative phase, which employed stakeholder interviews, comparative case study analysis, and participatory workshops. Through these methods, significant challenges and opportunities were identified from both industry and stakeholder perspectives, particularly emphasizing the viewpoints of market participants and distribution system operators (DSOs).

Synthesizing these insights led to the identification of several key opportunities, most prominently the critical need for enhanced interaction and collaboration between stakeholders. It became clear that the primary opportunity lays in facilitating iterative, transparent, and need-focused collaboration supported by real-time data platforms. Specifically, the development of the Energy Hub Opportunity Map was proposed as a strategic intervention to enable real-time visualization and decision-making.

The subsequent phases of idea development and conceptualization were guided by this specific opportunity. A strategic roadmap was iteratively developed, validated through stakeholder workshops, and refined. The future vision articulated in the roadmap is that energy hubs, equipped with integrated battery and hydrogen storage, operate seamlessly within regional grids, optimizing renewable energy utilization, grid stability, and hydrogen deployment through collaborative governance and flexible contracting frameworks. Energy hubs integrate various energy sources and storage solutions into a unified, user-centric system. This integration enables stakeholders to manage energy demand and supply dynamically, significantly reducing grid congestion and enhancing renewable energy adoption. The integrated approach allows energy companies, DSOs, and local communities to build interconnected networks that optimize regional energy resources effectively.

Participatory design emerged as an essential methodological approach for overcoming these barriers. Through participatory workshops, stakeholders articulated their needs, explored collaborative solutions, and fostered mutual trust. Nevertheless, the research underscores that the formation and governance of energy hubs remain complex challenges, requiring clear leadership, aligned stakeholder interests, and equitable risk distribution.

The roadmap's primary contribution to inclusiveness lies in advocating for active stakeholder participation, particularly in balancing autonomy of energy hubs with supportive frameworks provided by DSOs. Moreover, it highlights significant efforts needed to overcome existing gaps in energy system inclusivity and stakeholder collaboration.

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01 Introduction

This chapter gives an introduction to the topic of this research project, explains what the projects goals and research questions are and what approach is used during the project.

1.1 Introduction

Climate change is no longer an abstract threat but a legally binding driver of European energy policy. The European Climate Law and its Fit-for-55 legislative package oblige every Member State to cut greenhouse gas emissions by a t least 55% by 2030 and to achieve climate neutrality by 2050 (European Council, 2023). These targets have unleashed an unprecedented roll-out of renewables: Dutch solar PV capacity alone expanded from les than 2 GW to more than 22GW, one of the highest per-capita in the world. At the same time, electrification of heat, mobility and industry is pushing peak demand upward. The physical electricity grid has struggled to keep pace. Early 2025 data show over 12.000 companies waiting for a new or lager connection because large parts of the medium, and high-voltage network have reached their thermal or voltage limits (TaylorWessing, 2025). Building new cables, transformers and substations is indispensable but, owing to permitting, labour and material constraints, this takes six to ten years. The resulting gird congestion delays economic activity, forces renewable curtailment and jeopardizes the climate targets that triggered the reaction. This research explores the solutions of energy hubs as a solution for grid congestion. Defined as local or regional nodes where generation, storage and consumption of multiple energy carriers are optimized behind a shared (virtual) connection, energy hubs can relieve peak loading, unlock extra renewable capacity and create new revenue streams (CE Delft, 2023). Hydrogen strengthens the concept by offering long-duration storage of energy, sector coupling with industries that are hard to electrify and a controllable load in the form of electrolysis. Produced when electricity is cheap and abundant, hydrogen can be stored for weeks or months and reconverted or sold when prices peak, thus acting both as a buffer and a fuel (Ding et al., 2022; Firan 2021). In short energy hubs with integrated hydrogen infrastructure could buy time for grid upgrades while accelerating decarbonization.

1.2 Research Questions

Yet despite the technical appeal and policy enthusiasm surrounding energy hubs, the majority of energy hub related projects are either in pilot stages or in their initial phases. This is because the concept is not yet recognized in Dutch law and therefore lacks a clear permitting pathway (TU Delft, 2023). Broader European reviews highlight the high upfront investment, the absence of proven business models and persisting regulatory ambiguity as critical barriers (eneuron, 2022). These intertwined uncertainties, legal, market and technological, explain why energy hubs are not yet applied on a large scale. These uncertainties motivate the central research question of this thesis:

How can stakeholders, despite regulatory, market and technological uncertainties, make joint decisions on the implementation of energy hubs that help reduce grid congestion in the Netherlands?

To address this overarching question, four sub questions guide the analysis.

1. What exactly is an energy hub, and how does hydrogen contribute to relieving grid congestion?
2. What are the biggest uncertainties regarding the implementation of energy hubs?
3. What methods can be used to make informed decisions within these uncertainties?
4. What developments are essential to facilitate the optimal use of hydrogen generation and storage in energy hubs?

These questions first define the concept, then diagnoses the uncertainty landscape, selects an appropriate decision framework and derives the enabling conditions of hydrogen.

1.3 Project Approach

This thesis follows the Double Diamond design-thinking framework. This framework uses two diamonds that have a divergent and convergent stage. In total it has four stages: Discover, Define, Develop, Deliver. Within this thesis a small extra diamond with a discover and define phase is added for the exploration of the context.

In the Discover phase, a wide literature review, policy analysis and semi-structured interviews map the problem space of climate targets, grid constraints and stakeholder ambitions. The Define phase distils these insights into a precise problem statement and a coherent set of key performance indicators that express what a successful energy hub must achieve. Subsequently, the Develop phase generates alternative hub archetypes and governance models; these are explored by means of scenario planning and techno-economic simulations under varying regulatory, market and technological futures. Finally, the Deliver phase synthesizes the results into an implementation roadmap that allocates risks and benefits transparently and formulates concrete recommendations for policy-makers, grid operators, investors and participating companies.

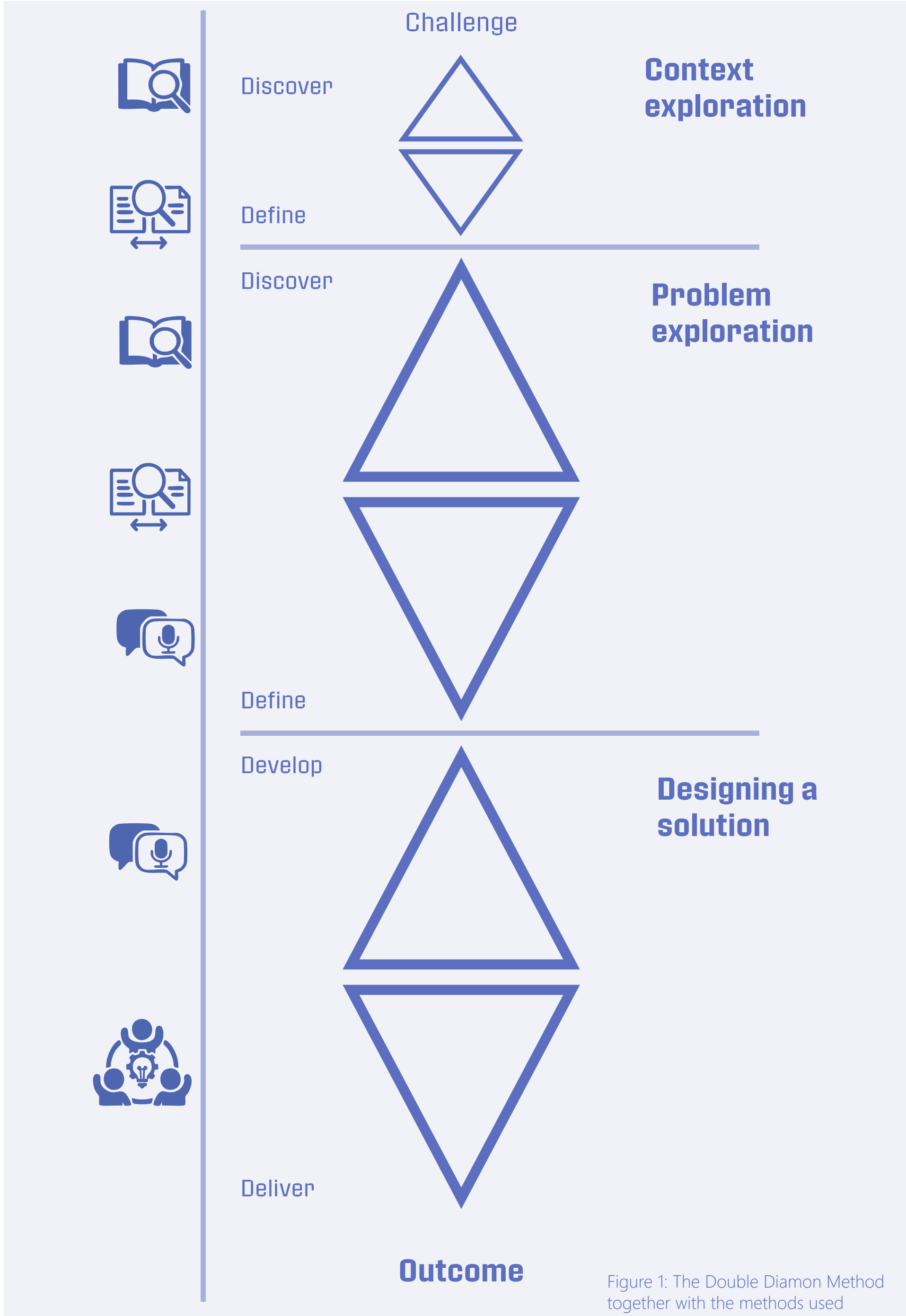


Figure 1: The Double Diamon Method together with the methods used

02 Understanding the context

In this chapter, the reason why the energy transition in the Netherlands is putting pressure on the current electricity system is outlined, which is a necessary basis for understanding the role of energy hubs.

2.1 Dutch Energy Transition

2.1.1 CO_2 reduction targets and legislation

Since the 2019 Climate Act stipulated that the Netherlands must reduce its greenhouse gas emissions by at least 55% by 2030 and become climate neutral by 2050 at the latest (Ministry of Economic Affairs and Climate Policy, 2019), policy has gained momentum. The European Green Deal and the Fit-for-55 package raised the bar even higher: the emissions trading system is being revised and expanded, the binding share of renewable energy is increasing to 42.5% with an ambitious target of 45% in 2030, and the revised Energy Efficiency Directive imposes a 36-39% reduction in final energy consumption (European Commission, 2021; KPMG, 2021). At the same time, REPowerEU promotes independence from Russian gas and accelerates licensing procedures for wind and solar projects (European Commission, 2022). Driven by generous European funds, the MFF, NextGenerationEU and the Just Transition Mechanism together account for more than €2 trillion in climate funding (European Commission, 2023; Pressmair, 2021), sustainable projects are becoming more financially attractive, especially when they are demonstrably in line with the EU taxonomy (KPMG, 2021).

2.1.2 Growth of sustainable electricity generation and electrification

All these incentives have led to the construction of wind and solar parks, heat pumps, and electric charging networks at an unprecedented pace. Between 2015 and 2024, Dutch solar PV capacity increased from < 2 GWp to over 22 GWp, while offshore wind reached the 4.5 GW mark (CBS, 2022). According to TNO's National Energy Scenarios 2050 (2022), installed renewable capacity could reach 80–120 GW in 2050, with peak production far exceeding current demand. At the same time, electricity consumption is increasing due to heat pumps, the electrification of high-temperature processes, and the rise of electric mobility. For industrial clusters, 3–4 GW of electrolysis capacity is also expected in 2030 to produce green hydrogen. The combination of erratic renewable production and increasing demand results in higher peak-to-trough gradients, putting pressure on the traditional 'base load' grid design philosophy.

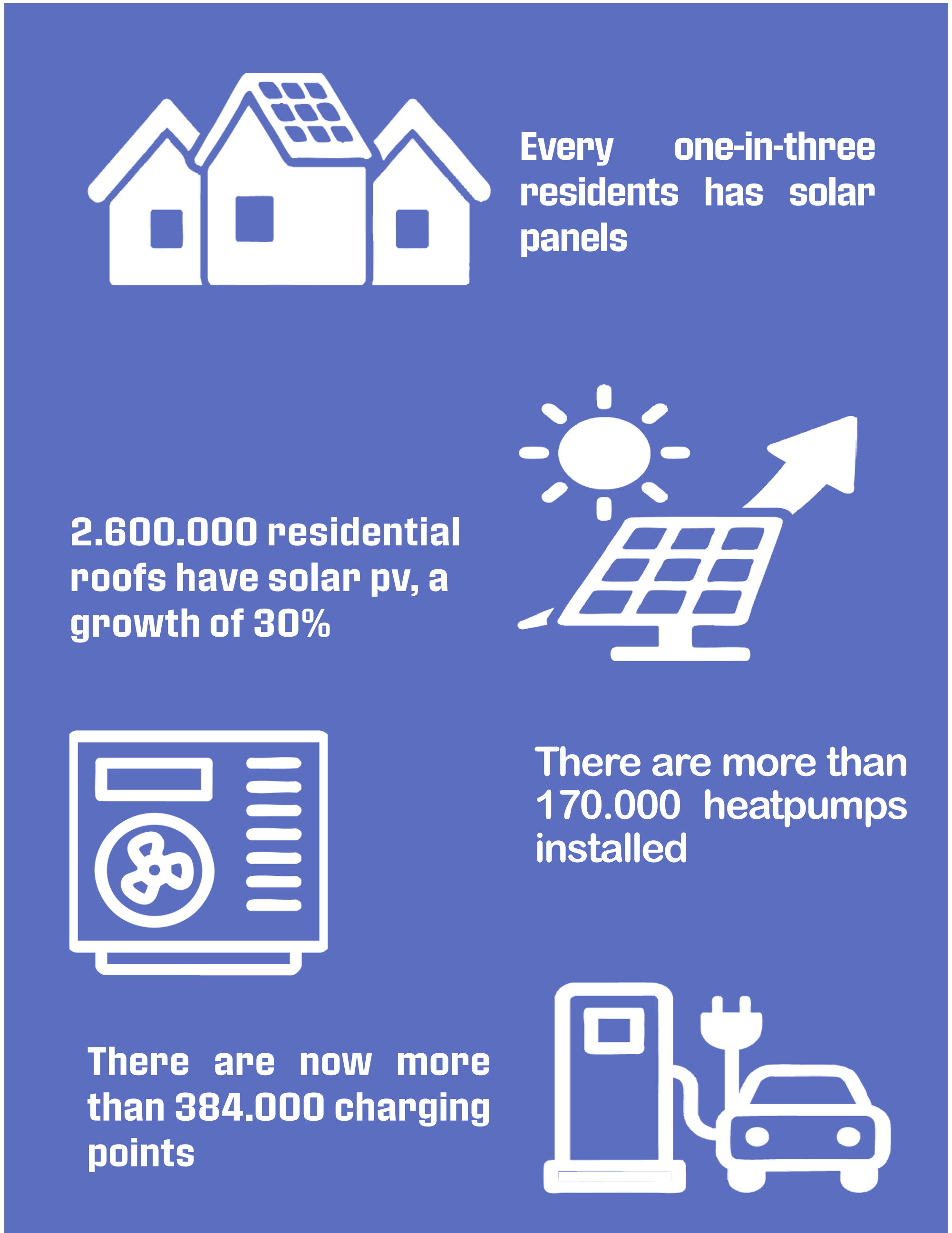


Figure 2: Energy Transition Statistics from Netbeheer Nederland 2024

2.1.3 Grid congestion as a systematic problem

Precisely because both electricity demand (charging corridors, data centers, heat pumps) and renewable production are increasing rapidly, the public grid is increasingly reaching its physical limits. Once the transport or voltage limit in a grid section is reached, grid operators refer to this as grid congestion.

The interactive congestion map Electricity Grid shows that approximately 11 GW of planned onshore wind and solar projects are currently waiting for grid space; the same map layer shows queues across virtually the entire country (Netbeheer Nederland, 2024). At the same time, on January 1, 2025, a total of 11,922 large consumers (6.7 GW) will be on the list for additional purchase capacity and 8,440 parties (4.1 GW) for feed-in capacity (Netbeheer Nederland, 2025).

The pressure is concentrated on the regional transport (110/150kV) interconnection grids around North Holland and Flevoland, where explosive growth in charging infrastructure and hyperscale data centers coincides with large solar roofs and fields. In April 2025, regional grid operators report that more than 40% of all High Voltage (HV)/Medium Voltage (MV) transformers for both consumption and injection have been declared "full," causing new connection requests for business parks to be put on hold regularly (Liander, 2025). Congestion occurs at all grid levels, and for both the offtake of electricity as for the feeding in. As Netbeheer Nederland shows with their congestion map that can be seen in figure 3. The social damage is twofold. There is economic damage because expansions or new establishments have to wait, with waiting times rising to 40-70 weeks in some regions (NOS, 2024). There is also climate delay, because sustainable energy generation projects are postponed or routinely shut down, this is referred to as curtailment.

Structural upgrades, new 280 kW lines, and additional transformer stations are on the way, but due to licensing procedures and staff/material shortages, they have a lead time of six to ten years. That is why the government and grid operators are increasingly focusing on temporary flexibility solutions to create space in the meantime.

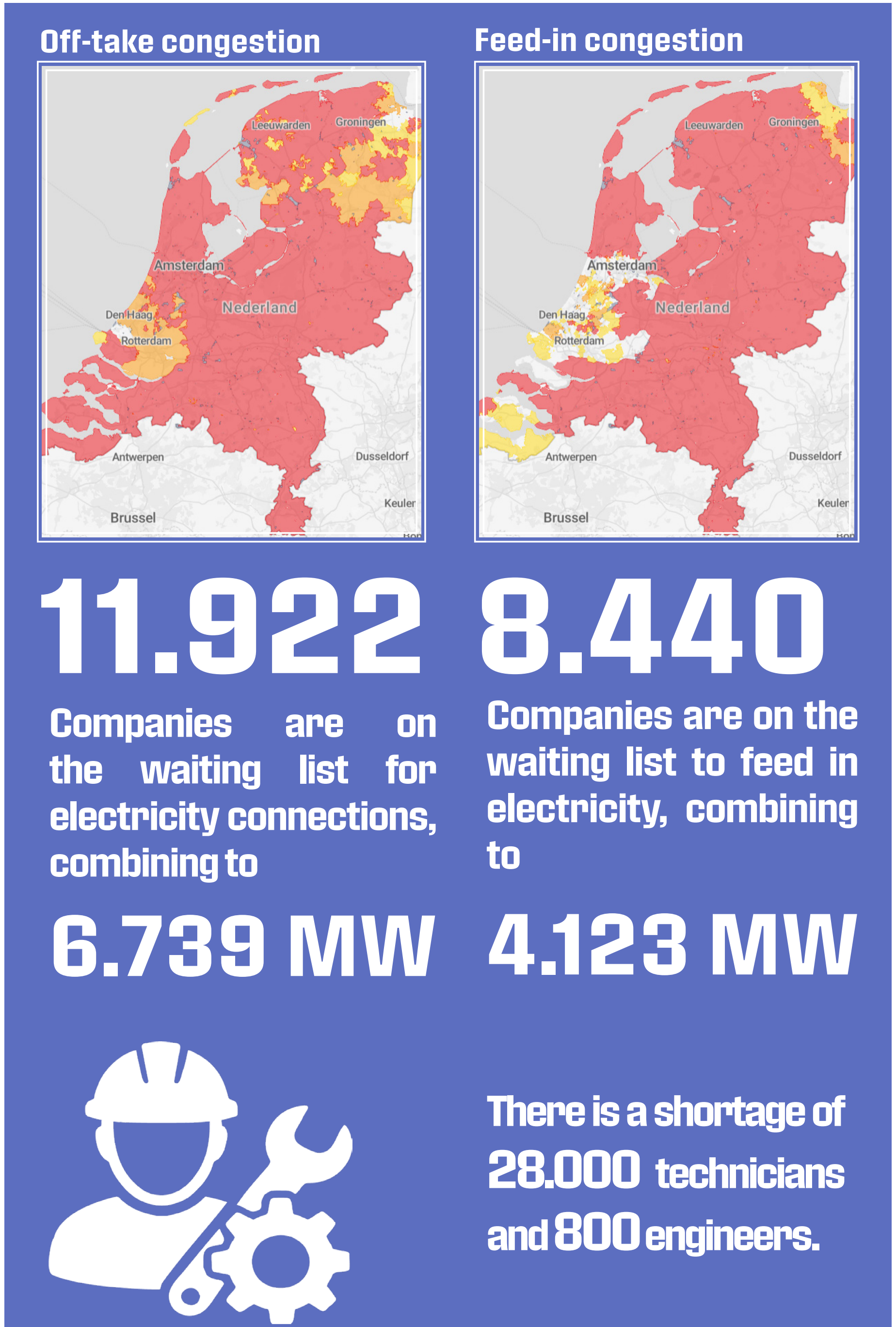


Figure 3: Congestion map and Statistics from Netbeheer Nederland 2024

2.1.4 Additional challenges and preconditions

Nevertheless, there are still many hurdles to overcome. Smart measurement and control systems must map out the actual space available on the grid (ENTSO-E, 2022). Policy instruments, from the Renewable Energy Direvtive III to Carbon Border Adjustment Mechanism, sometimes overlap and necessitate long-term agreements (CE Delft, 2024). And while social acceptance of wind, solar parks, and hydrogen installations is growing, the "not in my back yard" debate continues unabated (Pressmair, 2021). The energy transition therefore requires not only large investment, but also decisive governance, participation, and innovative business models. Only in this way can the dual objectives of rapid CO_2 reduction and security of supply be achieved in a timely manner (Mohammadi et al., 2017; Parra, 2017).

2.1.5 Conclusion and looking ahead

In short, the combination of ambitious legislation, generous funding, and technological breakthroughs is leading to rapid growth in both demand for and production of green energy. However, this acceleration is causing congestion on a grid that is not growing at the same pace.

Both Mohammadi and Parra showd that energy hubs in business parks offer an opportunity to create local flexibility and reduce CO_2 emissions, but only an integrated approach, investments in the grid, digital control, policy coherence, and public support, can ensure that the Netherlands and Europe actually achieve their climate and security of supply goals (Mohammadi et al., 2017; Parra, 2017).

In the next chapter, a closer look will be taken at the Dutch electricity grid itself: how is it physically structured, what institutional roles do TenneT, regional grid operators, and market parties play, and where are the practical bottlenecks and scope for energy hubs to actively contribute to the system side? This analysis forms the necessary basis for substantiating concrete design and business models for local energy hubs in later chapters.

2.2 The Dutch Electricity Grid

In this chapter the key stakeholders, organizational structure and different levels of the Dutch electricity grid are explored. This to create a better understanding of the playing field in which energy hubs will be active.

2.2.1 Organizational structure

The Dutch high-voltage grid (> 110 kV) is managed by a single transmission system operator (TSO) – TenneT, which also maintains interconnections with Germany, Belgium, Great Britain, and Denmark. Below that, there are seven DSOs (Liander, Stedin, Enexis, Westland, Rendo, Coteq, Enduris) with urban or regional monopolies. This separate governance structure determines who makes investment decisions, but also leads to coordination challenges around border layers (110 - 20 kV) where congestion is most common. In addition, a growing category of Closed Distribution Systems (CDS) is emerging, often industrial sites with their own management, which fall under exemption regimes (Shahgholian, 2021).

Low voltage (DSO)	Medium Voltage (DSO)	High Voltage (TSO)
Residential houses and energy cooperations	Solar parks, Wind parks, Fossil fuel generation, industrial areas, business parks, charging stations	Power plants, large industrial consumers, substations

Table 1: Connections for each level of the grid

2.2.2 Technical structure and capacity

The high- and medium-voltage grid is structured like a tree, with transport capacity decreasing towards end users. The grid design criteria are historically based on predictable, centrally generated flows. Decentralized renewable generation and bidirectional energy flows cause reversal and congestion situations on assets that are not designed for this (Liander, 2021).

Grid Level	Operator	Application
High Voltage	TenneT	Long distance transport, connection with neigh-bouring countries
Regional Interconnec-tions	TenneT	Interface to DSO stations
Medium Voltage	DSO's	Industrial connections, solar pv parks
Low Voltage	DSO's	Households, smaller companies

Table 2: Gridllevel with coresponding operator and application

2.2.3 Stakeholders

In addressing the complexities and future developments within the Dutch electricity grid, it is crucial to understand the roles and interactions of key stakeholders involved. This section introduces these stakeholders, specifically focusing on their significance within the electricity grid itself. The subsequent table provides an overview of each actor, detailing their formal responsibilities and primary instruments, serving as a concise reference for further discussion.

Actor	Formal Role	Key Instruments and responsibilities
TenneT	Transmission System Operator	Capacity calculation, program responsibility, interconnection & market coupling, Value-Flex facili-tator for industrial flexibility.
DSO's	Regional Grid Oper-ator	Connection and transport agree-ments (ATO), issuance of transport rights, congestion management research, development of new contract types.
Autoriteit Con-sument & Markt (ACM)	Regulator	Reviser and approving of network codes and tariff proposals.
Netbeheer Ned-erland	Industry Association	Capacity map, public consultation, and lobbying.
Ministerie EZK	Policy framework and legislation	National action program for grid congestion, prioritization of con-struction, and permits.
Market partici-pants	Flexibility offers	Provides software/hardware to make group transport agreements operational.

Table 3: Actors on the grid with their role and key instruments and responsibilities

2.3 Grid Congestion Management

2.3.1 Grid Congestion management according to Netbeheer Nederland

Netbeheer Nederland uses a phased approach to identify and tackle grid congestion. Congestion management is necessary when demand for transport capacity exceeds what the electricity grid can handle at a given moment. To ensure the reliability of the grid, grid operators in such cases distribute the available capacity by asking users to (temporarily) adjust their consumption or production. This approach is divided into a number of successive phases, depending on the severity and duration of the congestion.

- **Phase 0**: No congestion: Sufficient capacity is available. New connections or expansions can be facilitated without additional measures.
- **Phase 1**: Investigation and voluntary participation: The grid operator announces a congestion investigation. Customers with connections >500 kW are approached to voluntarily make flexible capacity available. This is done through capacity-limiting contracts (CBC) or through redispatch mechanisms, for example via GOPACS.
- **Phase 2a:** Mandatory participation: If voluntary measures are insufficient, customers with connections >1 MW may be required to offer their contracted capacity. This obligation is laid down in the Electricity Network Code. Both producers and large consumers are covered by this, unless they submit a reasoned objection.
- **Phase 2b:** Regulated compensation: When market forces are disrupted, for example, by excessive bid prices for flexibility, the grid operator intervenes with legally established compensation. This ensures that congestion management can continue even in critical situations, under fair and transparent conditions.

This phased approach makes it possible to deploy flexible capacity in a step-by-step and proportional manner. The aim is to reduce the load on the grid, continue to enable connection requests, and postpone or better phase physical grid expansions.

2.3.2 Types of congestion

Congestion on the electricity grid can manifest itself in various ways. The nature of the congestion depends, among other things, on the voltage level at which it occurs, the direction of the energy flow, and the duration of the load. Netbeheer Nederland distinguishes the following main types:

- Transport congestion: Structural overload of high-voltage connections or coupling transformers. This type of congestion usually requires large-scale redispatch or curtailment measures.
- Connection/feed congestion: Local bottlenecks at medium-voltage substations where peak production or peak consumption exceeds the thermal limits of switches, cables, or network rings. This form is becoming increasingly common with large-scale rooftop solar or heat pump clusters.
- Dynamic congestion: Short, difficult-to-predict peaks in generation or consumption. Think of a sunny spring day with low demand, which can cause temporary voltage problems or reversal of energy flows.
- Voltage congestion: Situations in which the voltage profile falls outside the permitted margins. Although this is often overlooked in traditional congestion reports, it poses a real risk to grid stability, especially in finely meshed grids with a lot of decentralized generation.

By providing insight into both the process and the types of congestion, Netbeheer Nederland emphasizes that congestion management requires a customized approach, tailored to the type of bottleneck, local conditions, and available flexibility potential.

Although flexible supply and demand management is increasingly being used as a solution to grid congestion, physical grid reinforcement remains unavoidable in many places. In particular, infrastructure expansion is the only sustainable solution for structural transport congestion on the high-voltage grid or persistent bottlenecks in stations and cable rings. At the same time, this approach requires long lead times and faces practical limitations such as permit processes and network capacity shortages among contractors. Network operators are therefore investigating how physical reinforcement can be carried out more quickly or efficiently, and how existing connection capacity can be used more intelligently.

The following sections discuss these strategies, starting with network reinforcement and cable pooling.

2.3.3 Possible solutions

Grid Reinforcement and Cable pooling

The traditional remedy for congestion remains the physical expansion of transmission capacity, for example through new 110 and 250 kV rings, replacing cable sections with larger cross-sections, and installing heavier coupling transformers. Although this approach is structural, it requires a licensing process that takes an average of six to ten years, partly because land is scarce, and grid operators are facing a shortage of specialized skilled workers (Netbeheer Nederland, 2024). In order to achieve faster results, operators are increasingly introducing Dynamic Line Rating, which allows existing overhead circuits to temporarily carry ten to fifteen percent more power in cooler or windy weather. Statcoms are also being installed at substation level to keep voltage bands tighter. In parallel with this, cable pooling is gaining ground: solar PV and wind turbines share a single connection, so that their contracted transmission rights are closer to the actual simultaneous peak power. Practical cases in Zeeland and Groningen show that this approach allows up to 30 percent of previously unused grid space to be utilized (Stedin, 2023). A variant is direct pooling, in which two sources are connected to a single inverter or transformer, thereby gaining a little more simultaneity, although this requires technically identical power characteristics.

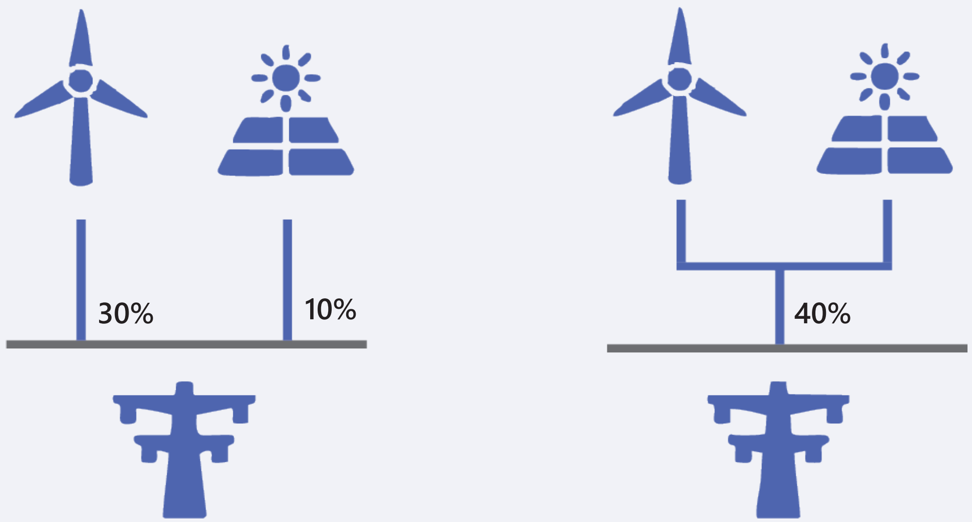


Figure 4: Illustration of Cable Pooling from Firan

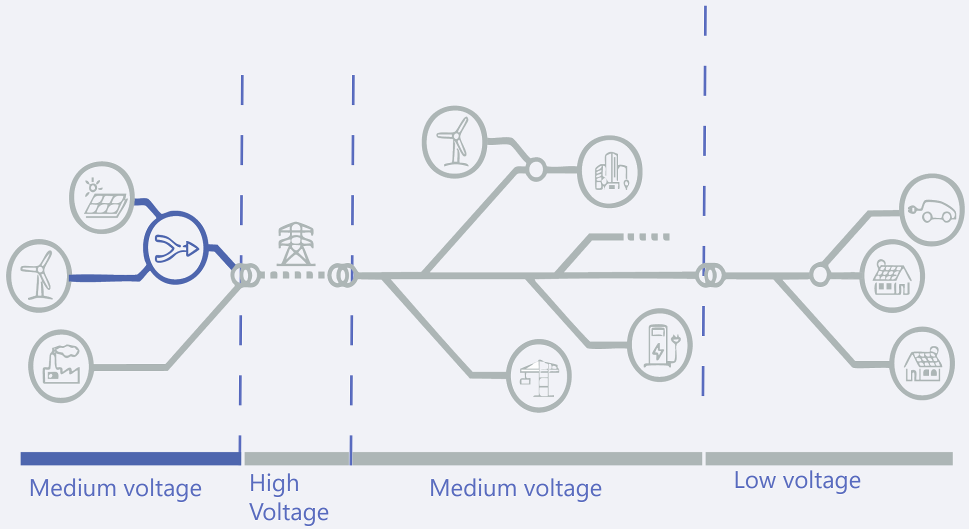


Figure 5: Places for cable pooling on the grid from Topsectorenergie

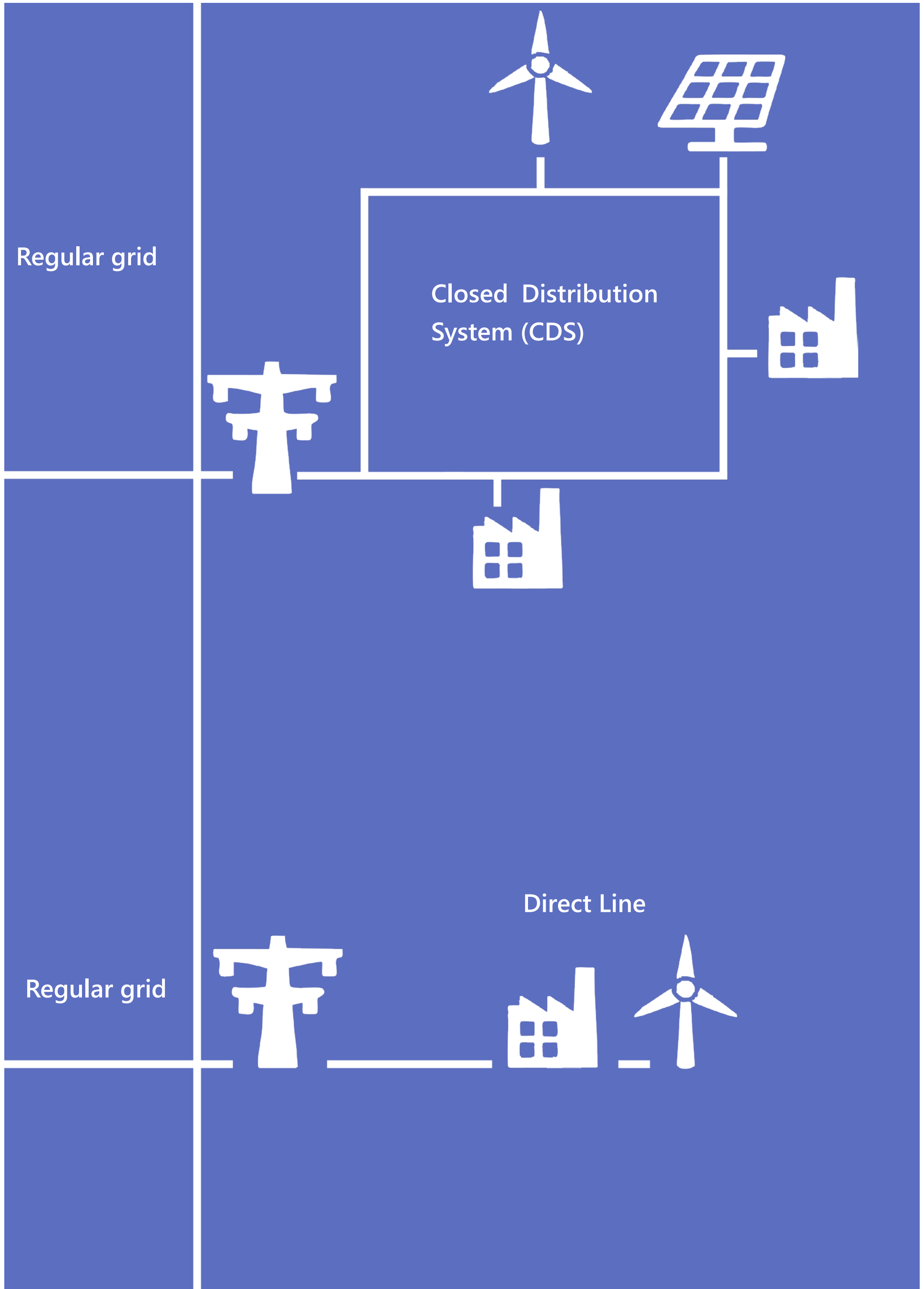


Figure 6: Illustration of Closed Distribution System and Direct Line

Direct Line and closed system

Another "smart connection" is the Closed Distribution System (CDS). Owners of a geographically defined area may apply for an exemption to install and manage their own network. A CDS can have a maximum of 500 connections, but no households can be connected to it. Therefore, the possibilities for a CDS are limited legally. It is not an option for households, but it is for a combination of upcycling with one or more customers, for example. Within the CDS, a party can match supply and demand independently. A CDS has a single connection to the public grid; however, using a CDS allows the capacity of that connection to be relatively small compared to the total demand in the area. This smaller physical connection is often accompanied by an Energy Management System (EMS), for example, to properly match supply and demand within the CDS (Topsector Energie, 2023).

Another option for combining connections is the "direct line." A direct line connects a generation facility directly to a consumer. A direct line also requires formal approval from the regulatory authority ACM. Legal restrictions also apply to when a direct line can be used (Lengkeek, 2023).

A GDS or direct line is mainly interesting in cases of grid congestion. When no additional sustainable generation or demand can be added to the grid at certain locations, reducing the connection capacity to the public grid ensures this can still be achieved. However, this involves supply responsibilities and additional costs for processes, administration, and management. Furthermore, regional grid operators are not always positive about private grids within their systems because such grids have not always been of good quality in the past. CDS applicability is limited to business parks or generation sites where consumers (except households) can be connected.

Flexible demand and supply management

In addition to physical reinforcement, the focus is shifting to flexibility. Demand response programs reward large consumers (from the process industry to cold storage) if they shift their consumption to hours with grid capacity. The first commercial contracts between Stedin and battery owners date from 2023 and already include real-time control with fifteen minutes' advance notice (Stedin, 2023).

Stationary lithium-ion batteries provide balancing in seconds to hours, while large heating networks with buffer tanks can shift heat demand by days; both techniques dampen peaks and postpone grid reinforcement (CE Delft, 2023). For mobility, smart EV charging is being rolled out, whereby charging capacity is adjusted every four seconds based on an API link with the DSO capacity window.

Curtailment and redispatch remain the final piece of the puzzle: in 2024, grid operators intervened 265 times in decentralized power generation and called for large-scale demand flexibility eleven times (Netbeheer Nederland, 2025). Although these measures can be financially painful for producers, they do provide the necessary security in the short term.

Energy Hubs for integrated flexibility

A more structured and broader approach is the development of energy hubs: local or regional networks in which decentralized generation, storage, conversion, and consumption are optimized together(Sadeghi et al., 2019).

Typically, a hub combines solar PV, wind, and a battery, with further expansions possible to include an eletrolyser with hydrogen storage. Once electricity is abundant and cheap, the eletrolyser produces hydrogen, which is converted back into electricity in a fuel cell during peak loads. The hub thus functions as a virtual MS station and as a seasonal buffer (Ding et al., 2022). Because investments and benefits are shared, there is also room for arbitrage between the electricity and hydrogen markets, which opens up additional cash flows in addition to grid services (Firan, 2021). Industrial estates are logical locations: they offer sufficient roof and land area, have large heat and cold profiles, and are least affected by connection restrictions (Energy Scale-Up Foundation, 2024).

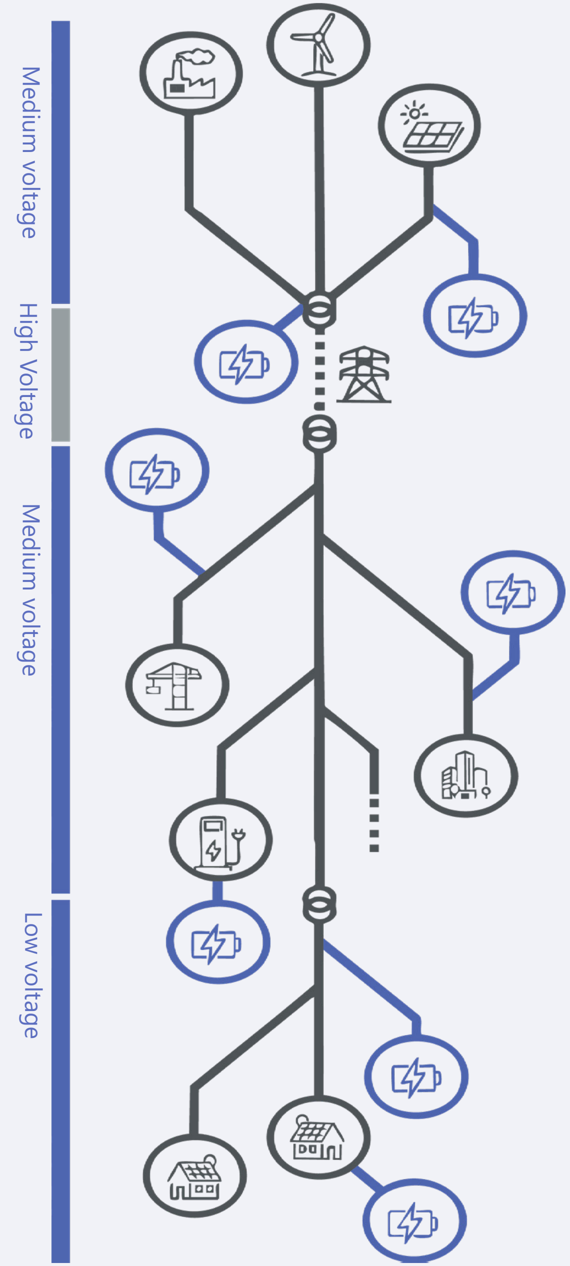


Figure 7: Location for battery storage on the grid from Topsectorenergie 2023

2.3.4 Contractual and regulatory instruments

Flexible systems such as energy hubs require dynamic and adaptive contractual frameworks. However, current contracts offer limited flexibility, making these innovative approaches challenging to implement within the existing regulatory and contractual framework. The network was long viewed in terms of "bricks and mortar," the focus is now shifting to sharing existing capacity and compensating for flexibility (Netbeheer Nederland, 2024; Firan, 2023). The following table lists the current contractual instruments that can be used to reduce network congestion:

Type of contract	Function	Status (Spring 2025)	Key Requirements	Sector Focus
Capacity-Limiting Contract (CBC) (Individual)	The customer grants the network operator the right to limit consumption/injection and receives compensation for this	Operational at Liander, Enexis, Steding since 2023	> 1MW flexible capacity or bundled; restriction on fixed time window or on demand (12 hours in advance) (Liander, 2025)	Horticulture, cold stores, batteries, and solar parks
Collective / Groups- CBC	Same as CBC but for business parks with a joint Congestion Service Provider	Pilotfase 2024 - 2026 (Liander & Stedin)	Requires collective with CSP status; joint distribution & liability	Industrial estates, residential/ new-build areas
Time-bound Transport Law (ATR85)	Firm transport <85% of hours; 15% curtailable for tariff discount (30-65%)	Nationwide availability by Q1 2025	Network operator may limit to 1314 h/year; day-ahead notification	Large batteries, electrolysers, process technology with buffer provision
Time-bound TR (Blokstroom)	Fixed transport in predefined off-peak block	Pilots Stedin and Enexis from 2024	Indefinite duration; only outside peak hours; can be combined with firm ATO	Charging corridors, cooling/logistics
Fully variable Transport Right (Residual flow/Non-firm ATO)	Only reusable residual space; no delivery guarantee	Available in selected areas since 2024	Transport is awarded annually; may amount to 0kW	Data centers with their own backup, eletrolyser arbitrage
Group Transport Agreement (GTO)	Replaces individual ATOs with a transport right for the group	Expected completion by the end of 2025, pilots are underway.	Hub-BV distributes internally; submetering + EMS	Industrial sites. Campus zones. Business parks
Flexible contract Battery	DSO manages storage for peak shaving and congestion management	1st contract in 2023	> 1MW power, < 15 minute response time; availability allowance + on-call allowance	Utility scale Battery Energy Storage Systems
Obligation to feed back - Redispatch contract (CSP)	CSP guarantees bid on GOPACS in case of congestion	Prototype 2024; rollout Dependent on ACM-market assesment	Only certified CSP; energy offers op EPEX/ETPA	Aggregators, traders.

Table 4: Contractual and regulaotry instruments

Support tools and services

The implementation of energy hubs is increasingly supported by a growing ecosystem of advisory platforms and digital tools. Organizations such as Firan, Resourcefully, and Spectral provide business case development, data modeling, and participatory co-design processes that help bridge the gap between strategy and system implementation (Firan, 2021). Digital twin software, simulate quarter-hourly energy flows, enabling stakeholders to assess site potential, grid interaction, and optimal component sizing based on real-world consumption data (CE Delft, 2023). Flex markets such as Grid Operators Platform for Congestion Solutions (GOPACS) also make it possible to trade quarter-hourly power between TSO and DSO levels within minutes.

GOPACS: Market-based congestion relief:

Grid Operators Platform for Congestion Solutions (GOPACS) complements these tools by offering a real-time trading platform for congestion management. Operated jointly by all Dutch grid operators, GOPACS allows market participants, including batteries, electrolysers, and flexible industrial loads, to submit localized buy/sell bids. Grid operators can then activate these bids to resolve congestion in a cost-effective and market-oriented manner, before resorting to curtailment.

For energy hubs, integration with GOPACS provides both a revenue opportunity and a formalized role in grid balancing. If the hub's Energy Management System supports real-time control, it can automate bidding and dispatch decisions, linking hub flexibility to national system needs. As such, GOPACS enhances the business case for hubs while supporting broader system stability.

In the broader range of solutions, the energy hub thus emerges as an integral concept that simultaneously addresses grid congestion, CO_2 reduction, and sector coupling.

The following chapter therefore delves deeper into the definition, scale levels, and components of a hub, so that it becomes clear how this concept is defined in the rest of the study.

2.4 Energy Hubs

The previous chapter described energy hubs as one of the promising solutions to grid congestion. This study focuses on this concept, so it is important to have a precise definition and to understand exactly what an energy hub entails.

2.4.1 Definition

In the literature, descriptions vary from microgrid to virtual power plant. This study uses the following definition, which is compatible with practice:

An energy hub is a local or regional node in which multiple energy carriers are coordinated via conversion, storage, and control technology, so that the demand of the connected customers is served reliably, affordably, and with minimal grid impact.

This definition is in line with the "multi-energy system" framework of Mohammadi et al. (2018) and with the project practice of CE Delft and Firan, in which the sharing of a single (virtual) transport right is central. Hydrogen is given an explicit place as a long-term buffer and sustainable fuel for process and mobility applications.

Energy hubs have different levels and scale which can be seen in the table below.

Level	Typical Size	Examples
Nano-Hub	<1MW	Residential area with central thermal energy storage and neighborhood battery
Business-hub	1-50MW	Business park with PV roofs, 5MWh battery, and 10MW electrolyser (ECUP, Utrecht)
Regional hubs	50-250MW	Port of Amsterdam/NSCA hydrogen hub
Cluster hub	>250MW	IJmuiden, far offshore electrolysis, chemical clusters.

Table 5: Different levels and scales of energy hubs

Most bottlenecks in the Netherlands are concentrated around medium-sized industrial sites (Energy Scale up, 2024), which is why this study focuses primarily on this level of energy hub.

2.4.2 Structure and operation of an energy hub

En energy hub is referred to as a solution for local grid congestion and as a platform for flexibility services. But what exactly does an energy hub entail in practice, and what components does such a system consist of?

To answer this question, the energy hub has been analyzed in this study on the basis of five functional layers: (1) local generation, (2) conversion technology, (3) storage, (4) digital and market layer, and (5) contractual organization. This layered approach provides insight into the technical, digital, and legal building blocks of an energy hub and makes it possible to understand the interrelationships and dependencies between components.

The first layer concerns local energy generation. This usually consists of solar panels on company roofs (solar PV) and, where available, onshore wind turbines. In addition, companies can contract green electricity from offshore wind farms through Power Purchase Agreements (PPAs). The direct connection of these sources to the local network creates a sustainable basic supply within the hub.

The second layer concerns the use of conversion technologies. These convert electrical energy into other energy carriers, such as heat or hydrogen. A common application is the use of electrolysers, which produce hydrogen at times of surplus. This hydrogen can then be stored and later converted back into electricity via a fuel cell. This type of dynamic capacity is only possible within the framework of capacity-limiting contracts (C-CLC), which allow flexibility within a fixed capacity ceiling (RVO, 2024). In addition, heat pumps or electric boilers can be used to thermally utilize residual electricity in heating and cooling networks.

The third layer is formed by energy storage. Lithium-ion batteries play a central role in this for short-term applications such as peak shaving and participation in FCR markets. Hydrogen buffers or underground salt caverns are used for long-term storage. These can store energy for weeks or months and make it available again. Thanks to time-bound transport rights, the positive balance for storage in hydrogen is between €0.80 and €1.20 per kilogram of H_2 (CE Delft).

The fourth layer concerns the hub's digital and market interface. An advanced Energy Management System (EMS) forms the heart of this: the platform collects real-time data on consumption, weather conditions, energy prices, and grid load. Based on predictive algorithms, the EMS controls the various components to minimize costs and respect system limits, such as the C-CLC or GTO bandwidth. In some cases, the EMS is linked to an external congestion service provider that performs real-time control based on grid conditions (Stedin, 2024).

The fifth and final layer comprises the legal and contractual structure of the energy hub. Within the hub, parties typically collaborate in an internal cooperative or private limited company (BV), in which investment costs (Capex) and operating costs (Opex) are shared. In addition, external agreements are made with the grid operator in the form of a C-CLC or GTO contract, which establishes a shared transport right. Finally, companies can enter into PPAs or trade residual flows on the intraday market, depending on their individual energy demand and production surpluses (European Commission, 2023). A visualisation of these layers and the components within can be seen in figure 8.

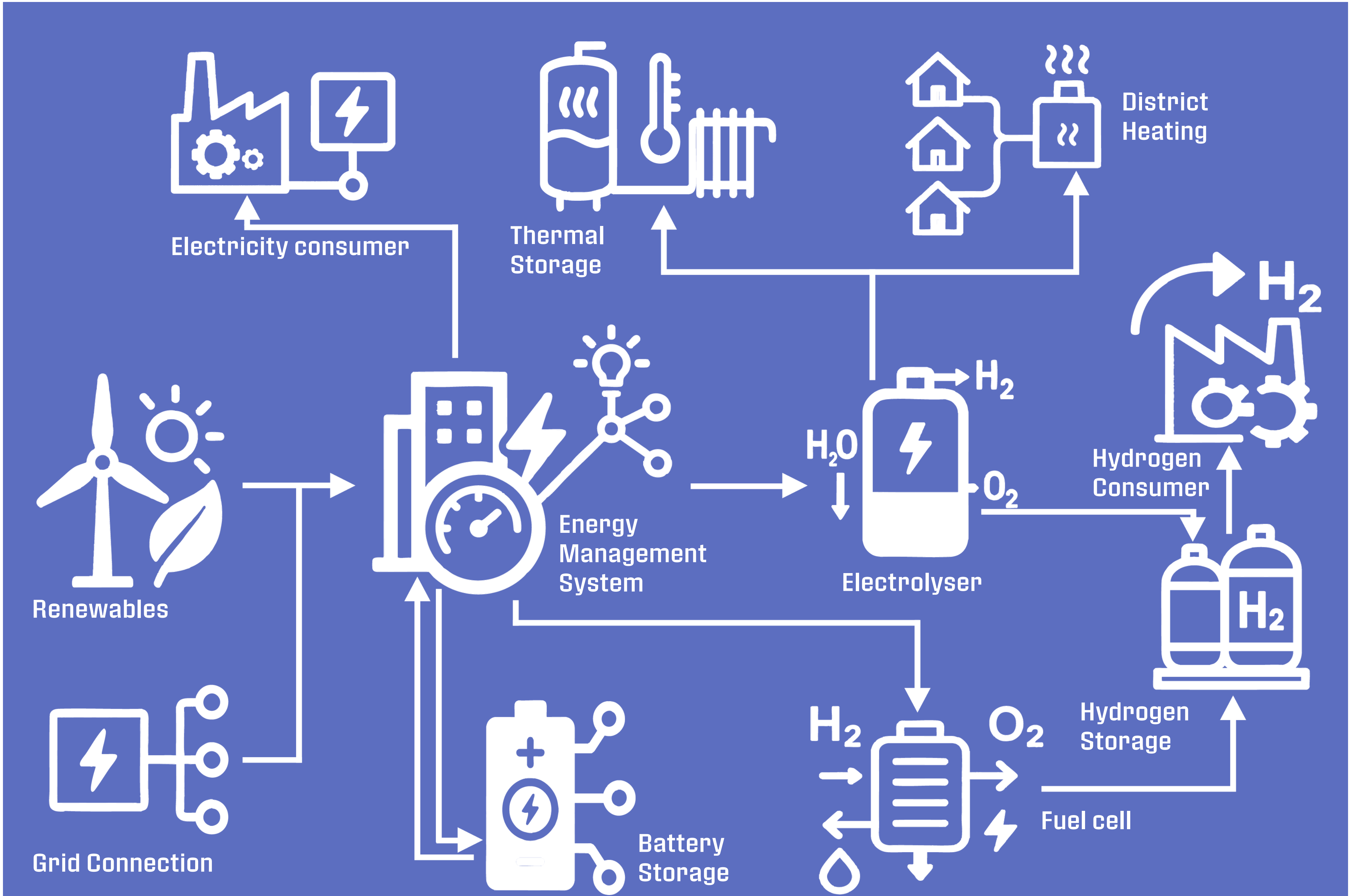


Figure 8: Energy Hub Flowchart

2.4.3 Battery afterlife and circularity

While lithium-ion batteries are a key enabler of short term grid flexibility, their environmental impact extends beyond the operational phase. Battery degradation typically reduces performance after 8-12 years, depending on the depth of cycling and thermal management (IRENA, 2020). At the end-of-life, modules may be repurposed for secondary stationary applications such as low demand microgrids or off-grid backup systems (Bobba et al.,2019). Current recycling processes can recover up to 95% of critical materials like lithium, cobalt, and nickel (European commission, 2023a). However, the economic viability of recycling varies with material purity, transportation logistics, and market prices for recovered elements (Fleer, 2018). As battery usages in hubs scales, circular business models and design-for-dissasembly will become essential to align with the EU's Battery Regulation and meet sustainability goals (European Union, 2023).

2.5 Hydrogen as a sustainable fuel

Hydrogen plays a unique role in the energy transition, serving as an energy carrier, raw material, and storage medium all at once. In this chapter, it is explained why hydrogen is seen as the sustainable fuel of choice in many future scenarios, what advantages this offers for industry and mobility, how certification, subsidies, and carbon credits strengthen the business case, and what additional equipment and safety measures an energy hub needs to successfully benefit from hydrogen.

2.5.1 Why Hydrogen?

Hydrogen combines three unique properties that together explain why it is referred to as the "sustainable fuel of the future" in virtually all net-zero scenarios.

1. Zero emissions during use: When burned or converted electrochemically (fuel cell), only water vapor is produced, and therefore no GHG or particulate matter.
2. Switch for power-to-X: Hydrogen is the missing link between renewable electricity and processes that are difficult to electrify, such as high-temperature smelting furnaces, direct-reduced-iron steel, and long-distance transport. In its Global Hydrogen Review 2023, the International Energy Agency refers to "unprecedented political and business momentum" to eliminate precisely this "last 20%" of industrial and mobility emissions through hydrogen (IEA, 2023).
3. Long-term storage capacity: Hydrogen can be stored for months without significant loss in salt caverns or converted gas pipelines, whereas batteries offer seconds to days of buffering. IRENA expects that in a 1.5°C scenario, by 2050, around 55% of international hydrogen trade will be transported via converted pipelines, making seasonal storage and long-distance transport technically and cost-efficient (IRENA, 2022).

2.5.3 Grey vs Green Hydrogen

Hydrogen is commonly categorized by its production method: grey hydrogen is produced from natural gas through steam methane reforming without capturing emissions, resulting in high CO_2 output. In contrast, green hydrogen is generated via electrolysis using renewable electricity, emitting no greenhouse gases during production. However, due to the current cost of electrolysers, renewable electricity, and the additional infrastructure required, green hydrogen remains more expensive than grey hydrogen. The levelized cost of production is still two to three times higher in most regions (FTI consulting, 2023). This cost gap has so far hindered widespread adoption. Nonetheless, as renewable electricity becomes cheaper, electrolyser technologies mature, and policy support continues to grow, the cost of green hydrogen is expected to fall, bringing it closer to cost parity with grey hydrogen by the end of this decade. This rising competitiveness aligns with projected global demands. Hydrogen demand is expected to increase sharply after 2030, emphasizing the urgency of accelerating infrastructure implementation and scaling up green production.

2.5.3 Faster production growth and falling costs

There are a number of indicators for the market momentum surrounding hydrogen. The supply capacity of green hydrogen could grow to 16 Mt per year between 2023 and 2030, a factor of thirty compared to today (BloombergNEF, 2023). The same analysis expects the production costs for green hydrogen to be €1.8-4 per kg in 2030, bringing cost parity with gray hydrogen closer than was thought five years ago. According to McKinsey calculations, green hydrogen could absorb more than 20% of the expected surplus of wind and solar power by 2050, significantly reducing curtailment and negative prices (McKinsey, 2024). Yet to understand this price evolution more clearly, it is important to distinguish between different types of hydrogen and their cost drivers.

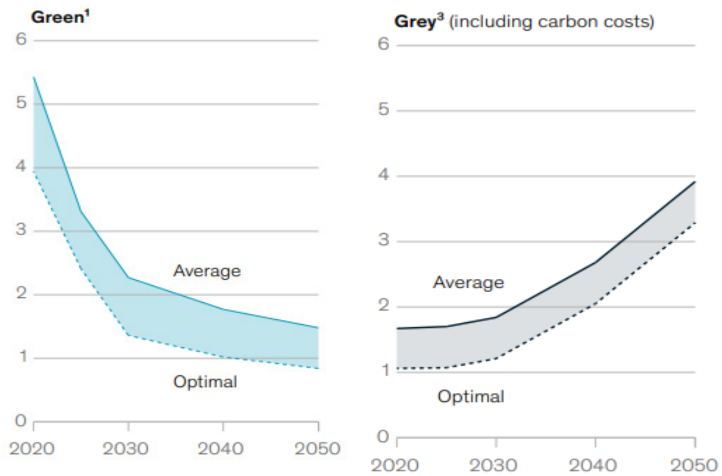


Figure 9: Predicted Green and Grey Hydtogen prices

2.5.4 Strategic System value

In addition to climate-related technical advantages, hydrogen adds macroeconomic and geopolitical value. IRENA emphasizes in its World Energy Transition Outlook 2024 that hydrogen chains can break the dependence on natural gas or oil alone, thereby increasing security of supply. They also see trade potential, with 25% of all hydrogen being traded across borders in 2050, half of which via pipelines and the rest mainly as ammonia by ship (IRENA, 2024).

The strategic system value per sector can be seen in Table 6.

Sector	Main application	Added value
industry	Direct Reduction Iron (DRI steel), ammonia, refineries	Replaces natural gas & coal; avoids ETS costs and provides tradable CO_2 rights
Mobility	Trucks, Buses, inland shipping, synthetic aviation fuels (SAF)	High energy density; short refueling time; less grid load compared to megawatt charging infrastructure.
Energy systems	Seasonal storage, peak backup (gas turbine/fuel cell)	Fills renewable off-peak hours; prevents High voltage/Medium voltage grid overload.

Table 6: Strategic system value per sector

2.5.5 Policy instruments and subsidies

The business case for green hydrogen currently relies heavily on public support and pricing mechanisms. The main pillars are:

- IPCEI Hy2Infra: In February 2024, the European Commission approved the fourth hydrogen IPCEI. The program covers 33 projects from 32 companies in seven member states and supports both 3.2 GW of additional electrolysis capacity and new pipelines and storage caverns, with planned commissioning between 2027 and 2029 (European Commission, 2024).
- EU Hydrogen Bank (Contracts for difference): The first auction closed on April 30, 2024: €720 million in subsidies was distributed among seven projects; the average winning bid was around €4/kg and will be paid out as a production premium for ten years (Bruegel, 2024). A second round of €2.2 billion is planned for 2025.
- SDE++ and Investment Subsidy: RVO is making up to €9/kg available (combination of CAPEX + OPEX) for large electrolysis projects; the scheme is linked to CO_2 savings and can pay out a maximum of €499 million per project (RVO, 2024).
- Additional national programs: Germany uses the H2global reverse auction model, the United Kingdom launched the second Hydrogen

Allocation Round (HAR-2) in 2024, and Japan is reserving 1.4 trillion yen for hydrogen projects through the GX-Green Transformation bond; these plans are in line with the EU CfD model in terms of design.

Together, these instruments form a degressive but predictable revenue cap, giving investors visibility on an 8- to 12-year payback period.

2.5.6 Certification and guarantees of origin

Certification is mandatory in order to claim the above subsidies and to make green hydrogen tradable. The CertifHy EU-RFNBO scheme provides Guarantees of Origin (GOs) that guarantee the origin of electricity, CO_2 intensity (< 3.38 kg CO_2 eq / kg H_2) and traceability within the RED II delegated acts (CertifHy, 2024).

From July 2024, the Dutch and German regulators will only accept GOs that comply with this scheme.

2.5.7 Carbon credits and voluntary market

Although hydrogen projects are not yet covered by the EU ETS, additional funding can be tapped through the voluntary CO_2 market.

- Voluntary CO_2 market: The Hydrogen for Net Zero (H2NZ) initiative, set up by South Pole and partners, is developing a method to sell emission savings from renewable hydrogen as carbon credits. The intended certification complies with the requirements of Gold Standard 2.0 (April 2025) and uses the corresponding adjustment rules from Article 6 to avoid double counting (LifeAR, 2024).
- LDC markets: Least Developed Countries (LDCs) are developing their own project pipelines under the LIFE-AR program. They focus on "high-integrity Article 6 credits" that can yield a premium because the proceeds are partly reinvested in local adaptation measures. For hydrogen projects in, or with supply from, LDC countries, this can mean an additional value of €3–5/t CO_2.

2.5.8 Financial impact

CE Delft estimates that voluntary and Article 6 credits together can cover 5–15% of the total capex of an electrolysis and storage project, provided that Monitoring Reporting and Verification (MRV) costs remain low, and the credit price is above €40/t CO_2.

For energy hubs, hydrogen can be both an economic and operational lever. An integrated hub with a ten-megawatt eletrolyser and a thousand tons of hydrogen storage can not only reduce peak loads on the medium-voltage substation by a third but also avoid eight kilotons of CO_2 emissions annually in linked industrial processes (CE Delft, 2024). However, additional facilities are required for this. Once the necessary preconditions are in place, hydrogen will be the missing link that transforms a local grid from a static bottleneck into a dynamic balancing machine, while at the same time creating new revenue streams from trading, certification, and flexibility services. A case study has been analyzed that shows the thresholds for profitability for hydrogen energy hub.

Case study

A recent pilot study in Norway models a hydrogen energy hub that converts surpluses from onshore and offshore wind into hydrogen for the market (Svendsmark et al., 2024). The researchers optimized electrolysis capacity, storage, and export mode simultaneously and identified three determining factors for a profitable sales strategy.

1. **Market price threshold:** Pipeline delivery to regional industry becomes profitable at a hydrogen price of approximately €60/MWh (€2/kg). Export via sea vessels required liquid H2 or ammonia and only becomes attractive at €90/MWh (€3/kg) or above.
2. **Product form choice:** A hybrid mix, approximately 60% liquid hydrogen and 40% ammonia, minimizes total logistics costs: Liquid hydrogen is more energy efficient, but ammonia requires less capital for cryogenic infrastructure.
3. **Grid and infrastructure risk:** Insufficient local grid reinforcement shifts the optimal choice towards ammonia, as this route requires less electrical power for liquefaction and therefore causes less peak load.

For context, it is worth comparing Norwegian threshold prices with current European market prices. Analyses by PwC and Clean Hydrogen Observatory show that the production costs for green hydrogen in Europe in 2024 will average €6-8/kg, depending on the share of cheap renewable electricity. This is well above the break-even point of the pilot study. The comparison highlights two points.

1. **Competitive potential:** if a Dutch or North Sea hub manages to link comparable wind profiles and storage options, it can produce hydrogen at costs well below the current market level.
2. **Price volatility as an opportunity**: As long as the spot price in Europe remains at €6/kg or higher, long-term storage creates an arbitrage option: produce cheaply during hours with renewable surpluses and sell during winter peaks or through export contracts.

Hydrogen is therefore emerging as a flexible buffer within the energy hub. The next chapter zooms in on this and shows how hydrogen, thanks to certification, storage options, and market incentives, is evolving into a fully-fledged sustainable fuel and economic carrier within the hub system.

2.5.9 Challenges and constraints

Despite the strong policy momentum, green hydrogen still faces several technical economic hurdles. First, round trip efficiency remains low: producing, compressing, and reconverting hydrogen to electricity retains barely 30–40 % of the original renewable power (IEA, 2024). Consequently, the levelized cost of green hydrogen (LCOH) in north west Europe is still €3–6 kg^{-1}, two to three times the price of unabated grey hydrogen, even after recent electrolyser cost declines (BloombergNEF, 2024). Second, large scale deployment demands substantial infrastructure: desalinated water supply, compressors, export pipelines, and cavern or tank storage, which together add roughly 40 % to total system CAPEX (DENA, 2023). Safety and materials integrity also complicate design; hydrogen causes embrittlement in high strength steels, while its low ignition energy requires ATEX compliant electrical systems and continuous leak detection (ISO 19880 1, 2023). Regulatory uncertainty also persists. Rules on additionality, temporal matching, and geographical correlation under the EU Renewable Fuels of Non Biological Origin (RFNBO) act are still evolving, and divergent certificate schemes outside the EU hamper cross border trade (European Commission, 2024b).

In addition to technical, financial and regulatory constraints, the adoption of energy hubs faces critical social acceptance barriers. In the Netherlands, citizens and municipalities have expressed resistance to energy infrastructure projects due to safety concerns, limited involvement in planning, and perceived spatial intrusiveness (Cuppen, Pesch, & Hisschemöller, 2017). Hydrogen, in particular, raises concerns over explosion risks and environmental impacts when facilities are proposed near residential areas. Battery storage projects encounter similar skepticism, especially round fire hazards and electromagnetic emissions.

Recent research has emphasized that successful integration of hydrogen systems requires more than technical innovation, it demands a deep understanding of stakeholder dynamics and proactive coordination among actors across the value chain. Hasankhani et al. (2025) show that decentralized and participatory approaches, supported by trust-building and inclusive governance, are crucial to overcome social resistance and create resilient and widely supported energy systems.

2.5.10 Conclusion for energy hubs

The discussed properties and market developments of hydrogen clearly highlight its strategic importance for energy hubs. Its ability to serve as a long-term energy carrier, particularly when stored in salt caverns or transported via pipelines, enables seasonal balancing and relieves pressure on the electricity grid. However, this long-term capacity must be complemented by short-cycle storage such as batteries, which buffer sub-hourly fluctuations in renewable output and reduce mechanical strain on electrolysers. Together, these technologies enable energy hubs to operate with a high degree of temporal and functional flexibility.

Technically, integrating hydrogen into an energy hub demands additional infrastructure: electrolysers, compressors, and specialized storage facilities.

It also requires compliance with strict safety standards and alignment with regulatory schemes such as CertifHy, as well as eligibility for public funding mechanisms like IPCEI or the EU Hydrogen Bank. Despite these complexities, hydrogen significantly enhances the operational, economic, and environmental performance of an energy hub, transforming it from a passive node into a dynamic system capable of managing volatility and supporting grid stability.

Yet beyond technical feasibility, social acceptance remains a critical determinant of success. In the Dutch context, resistance to hydrogen and battery infrastructure often stems from concerns about safety, noise, and spatial impact, particularly when such facilities are sited near residential areas. As Cuppen, Pesch, and Hisschemöller (2017) point out, local opposition is not necessarily a rejection of sustainability goals, but frequently reflects perceived risks and a lack of involvement in decision-making. Hasankhani et al. (2025) further emphasize that the integration of hydrogen requires not just technological innovation, but also coordination of stakeholder dynamics, trust-building, and participatory governance. Failing to address these social dimensions can delay or derail technically promising projects.

To fully understand how these technological and social dimensions translate into real-world implementation, the next chapter examines the key stakeholders in the Dutch electricity grid. Their roles, responsibilities, and instruments are analyzed to clarify how they influence, and are influenced by, the development of energy hubs.

2.6 Stakeholder Analysis

This chapter explains the various parties needed to implement a successful energy hub. The previous list of stakeholders mentioned in the previous chapter is extended. Relevant parties are identified, along with their goals, position of power, interests, and responsibilities, and it's shown in which phase they are important. Finally, the stakeholders are placed in a Power Interest matrix to gain insight into who the most important players are.

Stakeholder	Actors	Role in the hub	Key Interest
Network operators	TenneT (TSO), Liander/Stedin/ Enexis (DSO's)	Allocating capacity, concluding C-CLC/GTo contracts, planning network reinforcement	Congestion reduction, security of supply, regulation and compliance
Users/ Companies	Procution and logistics companies/ datacenters	Consumption, sometimes generation and storage	Continuity, lower energy costs, CO2 reduction.
Energy suppliers	Eneco, Vattenfall, Shell Energy, Greenchoice	Supply electricity/ PPAs, balance responsibility,	Stable sales, greening portfolio, margin on power/H2
Project Developers & Energy service companies	Firan, Equans, Shell Energy, regional heating network companies.	Design, financing, operational energy infrastructures	Return on capital scalability
Investors/ financiers	Banks, pension funds, impact funds	Providing capital	Stable cash-flow profiles, ESG rating, risk mitigation
Government and regulators	Municipalities, provinces, Rijkswaterstaat, ACM	Permits, subsidies (SDE++, IPCEI), supervision of tariffs	Spatial quality, climate goals, level playing field
Technology suppliers	Electrolyser manufacturers (NEL, Plug), battery OEMs, EMS software	Supplying hardware and software, O&M	Sales volume, lifetime service contracts
Sales markets for H2	Industrial gases, mobility (buses, trucks), port bunkering	Offtake contracts for H2	Price signals, security of supply, certificates
Social actors	Local residents, NGOs, trade unions	participation, permit process	Safety, employment, local benefits.

Table 7: Stakeholder analysis

Regulation and policy

Network operators, government, and regulators determine the preconditions: network capacity, permits, subsidies, and tariff structure. They form the hub's "license to operate."

Capital and operation

Investors, banks, and ESCOs provide the money and manage the design, construction, and daily operation. Their priority is return on investment at an acceptable level of risk.

Operation and technology

Users/companies, energy suppliers, and technology suppliers are at the heart of the hub: they consume, produce, or control the energy flows and supply the hardware and software.

Market and sales

H_2 customers and PPA customers generate cash flow through long-term contracts for hydrogen, electricity, or heat. Their demand profile influences the dimensioning and business case.

Community

Local residents, NGOs, and trade unions represent social values such as safety, health, employment, and local profit sharing.

2.6.1 Indentification of stakeholder groups

The individual parties have been grouped into five functional clusters. This reduces visual noise, aligns with the way communication and participation strategies are rolled out in practice for each group, and simplifies decision-making. This creates a clear picture of influence and importance, as well as a concrete working and communication framework for the further development of the energy hub.

The stakeholders divided within their clusters are shown on the left.

For the further stakeholder analysis, the Power-Interest matrix is used. The Power-Interest matrix (Mendelow, 1991) is a quick, visual way to determine who should be actively involved and how intensively.

Power = a stakeholder's ability to influence decisions or resources around the hub. In this context, this includes, for example, allocating network capacity, granting permits, providing capital, or setting safety requirements.

Interest = the extent to which a stakeholder directly benefits from, is at risk from, or is responsible for the hub. Think of continuity of power supply, CO2 reduction targets, return on investment, or reputation.

Combining both dimensions creates four quadrants:

	High interest	Low Interest
High Power	Manage closely, intensive involvement and co-creation	Keep satisfied, regular updates, monitoring interest
Low Power	Keep informed, procative communication, requesting feedback	Monitor, infrequent updates, flagging issues.

	High interest	Low Interest
High Power	DSO, Users/companies, project developers, government and regulators	TSO, Investors
Low Power	Technology suppliers	Energy suppliers, Sales markets for H_2, social actors.

Table 8 & 9: Power Interest matric quadrants and stakeholders

High Power – High Interest (Manage Closely)

DSOs have formal control over medium-voltage capacity and determine whether the hub can connect a C-CLC or GTO. At the same time, DSOs have a vested interest in reducing their peak load, thereby enabling the postponement of grid reinforcement.

Users/companies are operationally dependent on the connection: outages or delays directly affect their production and expansion.

Project developers/ESCos and local authorities & regulators share both investment and reputational risks; permit stagnation or protests can thwart their goals. A co-creation approach is needed with these actors: joint workshops, shared data dashboards, and rapid decision-making cycles.

High power – low interest (Keep Satisfied)

The TSO manages the high-voltage grid and can grant or refuse connection capacity. As long as the hub remains on the regional grid (≤ 20 kV), TenneT's direct interest is lower, but an upgrade to 150 kV or a large-scale export line suddenly makes the TSO crucial. Investors provide capital and can block the project if risk-return conditions deteriorate but have little 'skin in the game' on a daily basis. For this group, periodic governance reporting is essential: quarterly updates, covenant checks, escalation routes.

Low Power – High Interest (Keep Informed)

Energy suppliers and H2 customers have a direct commercial interest in price, security of supply, and certification, but do not have physical assets in the hub. Social actors experience potential nuisance (noise, safety) or benefits (jobs, sustainable image) but lack formal decision-making power. A transparent communication strategy with publicly accessible dashboards. Community evenings and a complaints protocol maintain their trust and prevent resistance.

Low Power – Low Interest (Monitor)

Technology suppliers are temporarily influential during design and construction: choosing a particular brand can influence lifespan and efficiency. Once the installation is operational, their role shifts to O&M support and their influence is mainly contractual. Requesting regular performance reports and enforcing the Service Level Agreement (SLA) is sufficient to maintain their contribution.

The stakeholder analysis shows that an energy hub is created in a force field of network operators, companies, investors, and governments. Between these parties is Arup's Business & Investors Advisory team, the team where this thesis is conducted. Although Arup itself does not allocate network capacity or capital, it does influence the decisions of all players by providing independent risk analyses, techno-economic modeling, and due diligence advice. In this way, the BIA team acts as a translator between technical designers, financial decision-makers, and public stakeholders. In the next chapter, exact role of Arup's BIA team and the methods used will be explained, and three cases will be analyzed to gain insights into energy transition projects.

2.7 Arup and the business investment advisory team

2.7.1 Introduction to Arup

Arup is an independent, employee-owned consultancy founded in 1946 by Anglo-Danish engineer Ove Arup. In 2025, the company has approximately 17,000 employees in more than 90 offices across 35 countries and has worked on iconic projects such as the Sydney Opera House, Beijing National Stadium, and Oresund Bridge. Arup combines design, engineering, and advice across the full spectrum of the built and natural environment. In addition to Arup's primary focus on infrastructure, architecture, and structural engineering, there is a new focus on advising energy transition projects.

2.7.2 The Business investment advisory team

Within Arup's energy sector, the BIA team provides integrated commercial and technical advice for large-scale energy and infrastructure investments. The advisors come from investment banking, corporate finance, and Arup's own engineering departments, enabling them to identify both financial and technical risks. Their core services are: financial modeling, technical and ESG due diligence, valuation scenarios, risk workshops, and transaction support (buy, sell, and lender side).

Clients: Institutional investors, developers, and corporations seeking to substantiate investment decisions; conversely, companies with a project plan come to BIA to convince investors.

Focus theme: the energy transition: wind (onshore and offshore), solar parks, battery and hydrogen infrastructure, biofuels, grid and storage assets.

2.7.3 Added value of independent consultancy

Green energy projects now attract hundreds of billions in capital each year, but investors are becoming increasingly critical of technical and commercial risk management. KPMG surveyed more than 1,400 investors in 2024: 72% indicated that they would only be willing to invest if an independent due diligence statement quantifying both design quality and ESG compatibility was available (KPMG, 2024).

Lenders' Technical Advisors (LTAs) play a key role in this. A recent analysis in the wind sector shows that projects with an independent LTA achieve debt margins that are 60bp lower on average, because design, construction, and operational risks are identified at an early stage.

Appreciation is also growing outside the banking sector: advanced analytics firm Aon has found that developers with externally performed risk modeling achieve financial close 15-20% faster because uncertainties surrounding technology maturity and regulatory bundles are made transparent.

In this context, Arup's BIA team positions itself as an independent bridge builder: it combines technical depth with financial acumen, giving both banks and developers the confidence that hydrogen and other transition projects are technically feasible, economically viable, and policy compliant.

2.7.4 Context of this research

In line with Arup's KPI-driven practice, the remainder of this thesis applies a similar methodology to energy-hub development. By analyzing a set of international energy-hub case studies alongside three recent Arup projects, a set of Key Performance Indicators is derived that capture technical maturity, regulatory compliance, commercial resilience, and ESG performance. These KPIs will be used with the creation of an implementation plan and give general valuable insight to what the key attention points are for investors and advisory services.

2.8 Context Summary

The first phase of the triple diamond method has been completed. As shown, climate legislation, the European Green Deal, and substantial funding have rapidly advanced renewable energy and electrification. However, the electricity grid has not kept pace: over 11 GW of solar and wind projects await grid access, and thousands of businesses face multi-month delays for heavier connections. This policy-driven urgency, combined with technical and economic constraints, sets the stage for energy hubs, integrated solutions offering local flexibility, CO_2 reduction, and sector coupling.

Despite their potential, energy hubs remain in the early stages. As of 2025, only eight hubs above 1 MW operate in the Netherlands, all under experimental conditions, a trend echoed internationally. Their future scale, governance, and financial models remain unclear.

Hydrogen emerges as a key enabler for these hubs, providing emission-free combustion, bridging renewables with hard-to-electrify sectors, and allowing seasonal storage. Yet, these same qualities introduce complexity and risk.

Thus, hydrogen represents both a strategic asset and a source of uncertainty for energy hubs. The next part of this report begins the second diamond phase: identifying and exploring the technical, operational, economic, and regulatory uncertainties of energy hub implementation. This will be done through five case studies, an analysis of three Arup projects, the development of a KPI list, and synthesis of key decisions and unknowns.

03 Exploring the problem

This chapter marks the transition from concept to practice. While the first part explored what an energy hub is, the focus now shifts to how such hubs function in real-world conditions shaped by uncertainty. Through case studies, project experience, and expert interviews, this chapter investigates how design choices, collaboration, and market dynamics are influenced by technical, economic, and regulatory risks.

3.1 Case study comparison

In order to discuss the concept of energy hubs not only in theory, but also to highlight the actual impact, risks, and uncertainties, five diverse projects will be analyzed. The aim is to discover which design choices yield the best results in practice, which obstacles are unexpectedly significant, and how cooperation and technology reinforce each other.

An energy hub is always context-specific; local grid capacity, stakeholder mix, and technological scope together determine whether a solution works. By systematically comparing five diverse Dutch cases, we unravel which design choices prove to be robust and which risks persist. Five cases discussed in the document "What is the added value of an energy hub?" by CE Delft are used.

3.1.1 Case descriptions

The 5 cases with their description and key differences are shown on page 31.

3.1.2 Comparison criteria

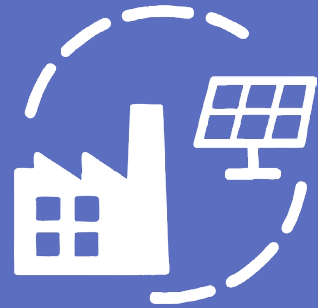
In order to systematically compare the five case studies, seven criteria covering the most important technical, economic, and organizational success factors are formulated. This provides a framework for identifying the strengths and weaknesses of each energy hub. These critaeria are shown in table 10.

#	Criteria	Relevance
1	CO2 reduction	Climate impact is the biggest social driver and a key condition for subsidies, permits, and reputation. It shows the extent to which a hub displaces fossil peak or backup sources.
2	Generated Renewable energy	Wether the hub utilizes or facilitates additional solar/ wind production. A high score indicates maximum use of local sustainable sources, less curtailment, and lower dependency on grey hydrogen
3	Financial Impact	Companies will only invest if the business model is viable. This criterion combines investment costs, operational savings, and any subsidies into a net welfare or return picture.
4	Complexity of collaboration	Wether the hub utilizes or facilitates additional solar/ wind production. A high score indicates maximum use of local sustainable sources, less curtailment, and lower dependency on grey hydrogen
5	Dependence on the grid	The extent to which the hub uses local flexibility to mitigate peaks. The lower the dependency, the greater the contribution to grid relief and the more robust the hub is against transport tariff fluctuations.
6	Grid connection	This distinction determines the revenue and tariff structure, as well as the technical requirements (reverse power flow, congestion). A hub that only purchases has different risks than one that also feeds back.
7	Spatial Impact	Determines social acceptance and licensing opportunities. Large batteries, diesel backup, or additional PV fields require space and can provoke local resistance; a minimal footprint facilitates scale-up.

Table 10: Comparison criteria

Case 1: Large unfacilitated electricity demand

On a large industrial site in the Netherlands, twenty companies were struggling with serious grid congestion: some were unable to feed electricity back into the grid, while others were unable to draw enough power for growing processes. By combining a collective transport contract and a shared battery, a wind turbine, and a diesel generator, the energy hub significantly reduces peak loads and creates room for additional wind and solar energy. Without this collaboration, each company would invest separately in smaller batteries and diesel generators, leading to higher costs, increased diesel consumption, and delayed sustainability gains.



Case 2: Existing solar PV infrastructure

Four medium-sized companies already had rooftop PV but lacked injection capacity. Through an informal Energy Hub concept with one shared injection right, they can trade solar energy among themselves and link production to consumption in real time. This reduces curtailment, maximizes yields, and requires minimal new hardware investments. Without the hub, a significant portion of the solar energy would remain unused or be invested in small storage solutions with poorer returns.

Case 3: Limited unvacuumed eletricty demand

Nineteen logistics companies on a single site wanted to implement electric truck charging, but grid congestion prevented both uptake and injection. With a shared battery and a single diesel backup, the hub can smooth peak demand so that the collective contract capacity of is not exceeded. The joint investment will pay for itself in 2–3 years through lower net tariffs and reduced diesel consumption. Without the hub, peak loads would remain high, companies would incur additional costs for individual batteries and generators, and they would be more reliant on diesel.

Case 4: New Solar PV infrastrucutre

On an industrial estate, four companies (two waste processors and two parking operators) are joining forces with a new solar installation, a battery, and a diesel generator. Despite the increase in renewable production, curtailment is decreasing because the battery absorbs peak surpluses. Until the planned grid reinforcement in 2031, net consumption will decrease by 18%. Without a hub, much of the solar production remains unused and investments in separate batteries remain economically unviable.

Case 5: Electrolyser

Two large industrial customers (including a hydrogen plant), two solar parks, and a wind farm are jointly building an 8 MW eletrolyser, powered by a PPA with locally generated solar and wind power. From 2025 to 2031, external electricity purchases will fall by 30% and curtailment will be virtually zero. Although the capital costs are high, this hub offers important climate and learning effects for the upscaling of electrolysers in the long term. Without the hub, a 4 MW electrolyser would continue to run mainly on grey electricity, emission reductions would be limited, and the learning curve would remain slow.

1

Flex assets as a lever for grid relief

In all hubs, the combination of storage and a fast backup source (diesel or eletrolyser) acts as the primary lever for smoothing peaks. The greater the battery capacity relative to peak demand, the greater the reduction in Energy Not Transported and the number of curtailment hours. Cases 1 and 3 show that even a relatively modest battery can reduce peaks by 15-20% when used collectively.

2

Collaboration complexity does not scale linearly with the numer of involved parties

The two hubs with +20 participants not only experienced more decision-making layers but also higher transaction costs per party than the case with four participants. Informal hubs (case 2) avoid this overhead but run into unclear liability and financing ceilings in the long term.

3

Capex-intensive solutions deliver long-term climate gains at the expense of short-term losses

Both the additional PV installation in case 4 and the 8 MW eletrolyser in case 5 score high on CO_2 reduction and renewable use, but both show a negative welfare balance in the first ten years. Conversely, cases 2 and 3 show that “lightweight” hubs with existing infrastructure quickly yield positive returns but achieve limited structural CO_2 gains.

4

Regulatory certainty weighs more heavily the further the hub operates from the grid

Projects that are completely dependent on a collective transport contract (Case 2) report faster turnaround times than projects with feed-in or hydrogen production (Case 5) because the latter category has to deal with evolving GO and hydrogen legislation. This translates into additional risk premiums in their financing models.

5

Future proof design as a silent success factor

Hubs with an “asset reserve” (design based on capacity and EMS headroom) appear to be better able to cope with unexpected increases in demand or technology updates without renewed grid requests. Case 1 will install a second wind turbine within the original conveyor belt in 2024, while case 2 is already looking at a second battery to cover EV charging growth.

3.1.3 Cross case paterns

Comparing the five cases reveals a number of recurring patterns that go beyond differences in scale, technology, or participating parties. The full cross case comparison table can be seen in Appendix D. The resulting paterns and insights are shown on the right.

The recurring patterns across the five cases highlight how each design choice influences hub performance under uncertainty. For instance, storage dimensioning emerges as a key variable: while larger batteries significantly reduce grid stress and curtailment hours, they also require more precise management and coordination. Similarly, governance structures impact transaction costs and risk exposure, hubs with many participants face increased coordination burdens, whereas informal hubs may benefit from agility but encounter limitations in liability and financing over time.

Capital expenditure levels further introduce trade-offs: while capex-heavy investments like additional PV or large electrolysers generate long-term climate benefits, they often lead to short-term welfare losses. Conversely, hubs leveraging existing infrastructure deliver quicker returns but with limited systemic CO_2 reduction. Additionally, regulatory frameworks weigh more heavily on hubs operating further from the central grid, as evolving legislation introduces delays and financing risk premiums.

Finally, future-proof design proves critical: hubs that incorporate asset reserves and EMS headroom can more easily adapt to demand growth or technology upgrades without renegotiating grid access.

Taken together, these observations point to a common conclusion:

Decision-making under uncertainty is the key differentiator between successful and stagnating hubs. Each element, storage, governance, capex, and regulation, carries its own risk profile but interacts with the others like communicating vessels, requiring holistic and adaptive design strategies.

3.2 Lessons learned from Arup projects

What follows next is a deeper exploration of where the greatest risks, opportunities for improvement, and decision points actually come together in practice. In this chapter, the findings from three projects that Arup's BIA team has supervised are presented.

This is done by creating a matrix that bundles the most important and relevant observations and recommendations for each project per risk domain covered in the project reports. This matrix was then discussed with members of Arup's BIA team to draw generic conclusions for energy transition projects and apply them to energy hubs.

3.2.1 Project profiles

The following three projects that Arup has supervised in getting financing or reporting risks have been selected.

Project 1: European Waste recycling

A widely ramified cluster of sorting and processing sites in four countries that is currently being transformed into a streamlined hub-and-spoke system. The company wants to switch from reactive to predictive maintenance and is looking for partners who want to invest in modernization, digital twins, and a higher recycling rate.

Project 2: Waste-to-Methanol plant

A first-of-its-kind biorefinery on the Mediterranean, right next to an industrial port. Here, non-recyclable residual waste is converted into bio- and circular methanol via a gasification chain that requires large amounts of hydrogen. The initiators are looking for additional shareholders to finance the construction phase and secure hydrogen and feedstock contracts.

Offshore Energy Island in the North Sea

A modular caisson island that combines thousands of megawatts of offshore wind with HVDC grid connections, large-scale hydrogen and ammonia production, and its own service port. The concept is now on the drawing board; public and private parties are exploring how they can jointly develop and operate this energy hub.

3.2.2 Cross-case insights

The complete matrix can be found in Appendix D. Below, the most important and relevant insights are explained.

1. A clear integrator saves more time and money than any technical optimization
2. Availability assumptions must always be based on realistic middle scenarios, not on the ideal maximum.
3. Permits are the real crititcal path; technical work can only begin once the paperwork is in order.
4. New technology deserves a double safety margin: one for technical teething problems and one for market fluctuations.
5. Complete, externally verified sustainability reporting significantly reduces the interest rate on borrowed capital.
6. Spatial flexibility is worth money .
7. Proactive safety data (such as near misses and observations) are a strict requirement for new insurance policies.
8. Transparency and standardized data flows accelrate decisions and reduce the risk of duplication

The cross case insights shows where the biggest bottlenecks and levereage effects lie:

Interface management, realistic availability curves, permit processes, double contingencies, end-to-end ESG verification, spatial modularity, proactive safety, and data transparency.

The method that Arup uses to make these points measurable and manageable is through creating a common set of Key Performance Indicators that can connect designers, companies and network operators. In the next chapter, a list of KPIs will be drawn up and validated.

3.3 Key Performance Indicators

What should an energy hub achieve, and how is this measured?

This question is key to this chapter, because Key Performance Indicators (KPIs) are the compass of any implementation plan. They translate abstract ambitions into concrete control points for designers, financiers, builders, and operators. Without a clear set of KPIs, it is difficult to monitor progress, identify risks in a timely manner, or credibly substantiate a phased delivery. Aside from that, currently a standard KPI set is missing for the implementation of an energy hub in literature.

3.3.1 Method

From the comparison of the five energy hub case studies and three Arup projects, I compiled all performance and risk points into a rough list. This list is expanded with with CE Delft's seven success criteria for energy hubs. This list is than supplemented with insights gained from interviews with multiple stakeholders.

The result is a long list of over fifty possible KPIs. This long list is reduced to fifty promising KPIs using desk research. This is done by filtering out the KPIs that appeared multiple times and selecting the most relevant ones for energy hubs.

3.3.2 Validation

To validate the filtered list of KPIs, two consultants in the energy transition applied the SMART method to the list. The SMART method is a scoring method that tests each KPI for:

Specific: does the KPI correspond exactly to one concrete goal?

Measurable: is unambiguous, real-time or periodic data available?

Acceptable: is the KPI realistic for the parties involved?

Relevant: does the KPI capture a factor that is material to the energy hub's performance, risk, or compliance, so that monitoring it will meaningfully inform decisions?

Time-bound: is it clear within what time frame results are expected?

Each KPI is scored on a maximum of 3 points per criterion. Indicators with a total score lower than ten are dropped and given the status "Nice-to-have."

The fifteen KPIs selected using the SMART criteria form the core set for drawing up an implementation plan. They cover four strategic objectives, have been identified as critical in the case studies and Arup projects, and are in line with the requirements of the network operator, investor, companies, and project developers.

In the next section, each domain will be explained and shown how they can be measured, reported, and linked to decision moments in the realization and operation phase of an energy hub.

3.3.2.1 Technical and operational

KPIs An energy hub ultimately succeeds or fails on the floor: do the battery, eletrolyser, control software, and transformers deliver what they promise, down to the second? The five case studies show the same chain reaction time and time again: when peaks are not smoothed out or when a single subsystem fails, imbalance costs quickly rise, diesel backup has to be used, or even grid congestion occurs. Technical and operational KPIs are therefore the direct control lever for:

- Freeing up connection capacity (important for the grid operator),
- Utilizing renewable production (crucial for CO_2 gains).
- The availability curves on which financiers base their interest margins. This results in the following four core KPIs.

KPI	Definition	Measurement source	Potential decision moments
Grid peak reduction	Percentage decrease in the highest import and export capacity (15-minute average) after commissioning of the hub.	Live from the EMS + DSO grid meter	Go/no-go group contract DSO Dimensioning of EH assets
Energy Not Trasnsported (ENT)	Renewable energy that is not switched off thanks to the hub, in MWh and € avoided imbalance costs.	EMS + market prices imbalance & profile deviation, monthly.	Decisions to expand renewable energy generation. Evaluation of EMS system.
Availability score	Actual uptime of critical assets (battery, eletrolyser, EMS control) compared to calendar hours.	Historical logfiles; monthly reports.	Review of maintenance strategies.
Interface compliance ratio	Percentage project hours without outstanding interface issues (an issue = a clash in planning, scope, or data protocol between two package suppliers)	Integration register, weekly report.	Approval of subsequent construction phases.

Table 11: Technical and operational KPIs

3.3.2.2 Economical

No hub is built in lack of a positive business case. Arup's project reviews showed that overestimating availability or underestimating hydrogen costs can push the internal rate of return directly below the eight percent threshold, at which point financiers pull out. Economic KPIs such as the Levelized Cost of Energy and the Levelized Cost of Hydrogen are therefore the financial dashboard that decision-makers use to continuously assess whether a further capital injection is justified.

KPI	Definition	Measurement source	Potential decision moments
Levelised Costs of Energy (LCoE)	Average price per MWh of electricity produced over lifetime (including Capex, Opex, financing costs	Annual financial update with updated volumes	PPA price agreements
Levelised Cost of Hydrogen (LCoH)	Average price per kg of hydrogen produced, including electricity and water costs.	Quarterly update, sensitivity analysis of electricity and water costs.	Decision on greening of electricity mix. Quotation price for hydrogen customers.
Net present value relative to reference	Current value of hub cash flows minus individual cashflows	With every investment decision, at least annually	Entry of a new partner. Stop/Go in expansion phase.
Internal Rate of Return (IRR)	Discount rate at which net present value becomes zero.	Annually in financial model update	Capital structure, interest margins, dividend policy.

Table 12: Economical KPIs

These combine technology with balance: a change in battery capacity or stricter uptime requirements translates into a different cash value within the same quarter and possibly a different capital structure. By recalibrating financial KPIs every quarter, including sensitivity to electricity and CO_2 prices, the implementation plan remains liquid and yield secure. The key message: whatever you come up with technically must continue to pay for itself in terms of cash flow, otherwise the rollout will stagnate.

3.3.2.3 Environmental and Social

The social legitimacy of energy hubs stands or falls on their demonstrable value for the climate and the environment. In the case studies involving new solar PV (case 4) and the eletrolyser hub (case 5), it was precisely the measurable CO_2 savings that were key to obtaining subsidies and local support. At the same time, emission allowances and guarantees of origin are increasingly transforming into active revenue streams.

KPI	Definition	Measurement source	Potential decision moments
CO_2 reduction	Annual tons of CO2 avoided through local renewable generation, storage, and hydrogen replacement.	Annual with an Life cycle assessment	Reporting to subsidy provider Marketing license and social license.
Scope 3 reduction	Emission savings at customers (e.g. green hydrogen in process industry)	Annual with emission reports	Substantiation of Article 6 CO2 credits
Stakeholder satisfaction	Average score from annual survey among all partners, local residents, and network operator.	Annual through survey	Improvement plan for partnerships. Renegotiation of governance

Table 13: Environmental and Social KPIs

KPIs such as CO_2 reduction, Scope 3 impact, and stakeholder satisfaction serve a dual purpose: they secure the social "license to operate" and determine the pace at which additional green premiums can be earned. By verifying the actual emission savings annually and reporting them publicly, trust grows among local residents, municipal authorities, and financiers, and the hub's reputation value increases exponentially. Environmental and social KPIs are therefore the bridge between technical success and public acceptance.

3.3.2.4 Regulation and certification

An energy hub may be technically perfect and financially attractive, but without valid permits and recognized certificates, no kW will be fed into the grid, and no hydrogen will reach the market. The practical cases showed how a single delayed soil permit or a late group transport agreement can delay the entire schedule by months and cause millions in additional financing costs.

In addition, market access is increasingly label-dependent: hydrogen without CertifHy does not fetch a premium price, and electricity without a guarantee of origin cannot be included in green contracts. KPIs such as permit lead time, capacity label compliance, and CertifHy conformity keep this regulatory "critical path" constantly in view. They make it possible to escalate issues in a timely manner, avoid fines, and optimize green revenue. Regulatory and certification KPIs are therefore the legal and commercial safety valves of the entire implementation plan.

KPI	Definition	Measurement source	Potential decision moments
Permit processing time	Number of months between submission of initial permit application and receipt of final decision.	Monthly from a permit tracker that automatically retrieves data from governmental portals.	Go/No-go civil start Reprioritization of engineering capacity.
Capacity level compliance	Percentage of time per year in which the contracted transport capacity is not exceeded.	Real-time via energy management system + smart meter DSO.	Automatic dispatch adjustments. Activation of peak shaving module. Penalty or discount settlements with grid operator
CertifHy-compliant	Share of hydrogen produced that has a valid Guarantee of Origin in the CertifHy register.	Quarterly update; production log.	Release of hydrogen to premium customers. Price formula for off-take contract Reporting to financiers.
Volume Article 6 CO2 credits	Total tons of CO_2 equivalent issued and traded as emission reduction credits through recognized international registries	Annual credit registry linked to LCA tool.	Revenue planning for carbon credit Reinvestment in sustainable expansion Marketing & reputation report.

Table 14: Regulation and certification KPIs

3.4 Semi-structured interviews

Aside from desk research and the KPI workshop, five semi-structured interviews were held with stakeholders in the energy transition. These interviews are held with an exploratory goal, to get insights into the uncertainties, decision-making dynamics, and perceptions surrounding energy hubs.

Participant selection

The participants where approached through LinkedIn, company websites, Microsoft Teams and through office interactions. The goal was to get in contact with grid operators, hydrogen experts and with general energy transition project experts. Therefore the following 5 participants where interviewed.

1. Company: Firan
   Application consultant in charge of energy hub implementeation plan.

2. Company: Arup
   Senior engineer with expertise in district heating and hydrogen.

3. Company: Alliander
   Senior Manager with expertise in operations, maintenance & PD.

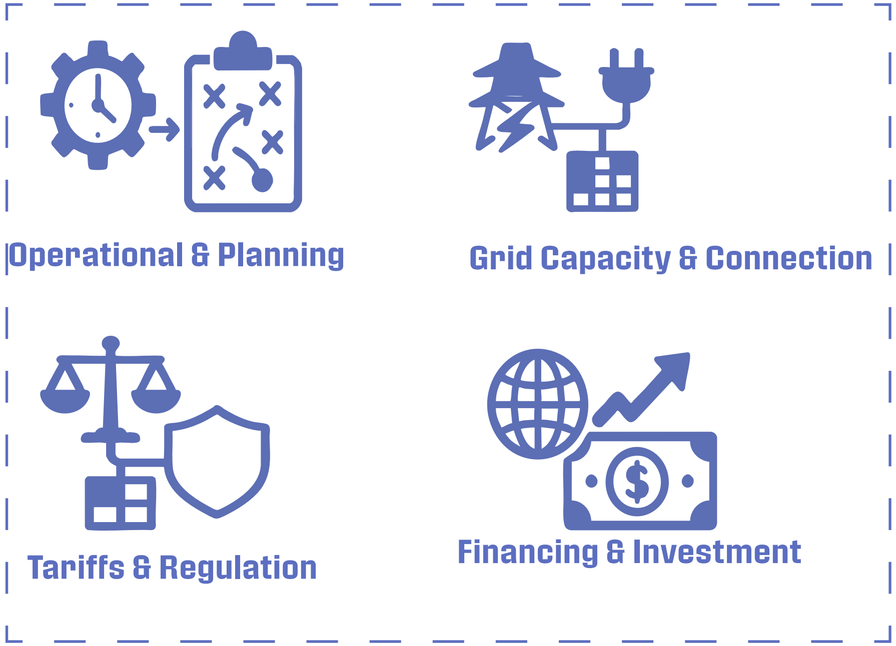
4. Company: Arup
   Senior consultant with expertise in sustainable fuels & Battery storage.

5. Company: Arup
   Investor Advisor with financial expertise and project development.

Interview setup

The interviews took place in a mix of physical and online settings, depending on the participants availability and preference. Prior to each interview, participants received a brief introduction to the topic and a list of guiding questions (see Appendix B). However, the conversations were deliberately kept open and exploratory in nature. While the initial questions served as a starting point, the interviews often evolved into dynamic two-way discussions, allowing participants to steer the conversation toward issues that they deemed most relevant.

Each session was between 30 and 60 minutes. With the participants' consent, all interviews where recorded. The recordings were later transcribed, and both the transcripts and audio where used to extract relevant insights. These insights where then thematically coded and merged into the following key areas of uncertainties.



Key insights from interviews

DSOs have yet to finalize the legal template that replaces individual consumption rights with a single contract of capacity allocated to a group. Without this contract, a bankable business case cannot be completed, and companies are reluctant to invest.

DSOs are historically risk-averse: they set large safety margins and resist ceding real-time control. The more conservative the contract terms, the smaller the shared capacity, reducing the economic attractiveness for participants.

Companies in a hub must agree in advance on a "slice key" that decides who is entitled to which share-flexing as members buy, sell, or expand. Achieving this level of trust is difficult, especially when investments (e.g. batteries) and benefits are unevenly distributed.

Whether intra-hub transfers are settled at fixed fees, dynamic spot prices, or indexed to national tariffs is still open. Uncertainty about revenue streams increases financing costs and obscures the return on assets such as storage.

The long-term coexistence of ATR and true energy hub contracts is unresolved. Investors need clarity on how often, and how deeply, they can be curtailed.

Turning excess power into heat or hydrogen would bypass power shortages-but regulation, metering rules, and market platforms for cross-commodity trading are still lacking. Until the framework is in place, most pilots will be limited to electricity.

A DSO cannot simply identify "ideal hub candidates" as this would reveal commercially sensitive load profiles. This slows proactive hub development and leaves the initiative largely to municipalities or private collectives. Shared data needs to be anonymized or highly secured.

Batteries or electrolysers can unlock more capacity but sizing them optimally is complex and capital intensive. High Capex plus uncertain payback lengthen decision cycles.

3.5 Overarching areas and uncertainties

This section summarizes the previous chapters of the second diamond by translating the insights into uncertainties for each overarching target area. Each target area is briefly explained, followed by the most important uncertainties that fall within it. This in preparation to combine everything in the next chapter, where the problem will be defined.

Operational and Planning

The operation and planning of energy hubs require continuous alignment between fluctuating supply and demand, shared infrastructure, and real-time decision-making among multiple actors. The more flexible and interconnected the system, the more it depends on robust control, data exchange, and clearly defined roles. As hubs scale or evolve, the absence of centralized coordination can lead to inefficiencies, disputes, and reduced reliability.

Key Uncertainties

- Governance and protocols for shared asset operation, including fair allocation of electricity and hydrogen
- Scalability, ownership, and comatibility of energy management systems (EMS) and forecasting tools
- Effectiveness and robustness of backup strategies in the event of system failure
- Distribution of operational risks, maintenance responsibilities, and associated costs among stakeholders
- Criteria and governance for system expansion or asset additions
- Resilience of system performance under unexpected demand growth or partial asset failure
- Risks arising from fragmented procurement and the lack of a central system integrator
- Degree of futureproofing in EMS algorithms and operational strategies

Financing and investment

Energy hubs often require high upfront capital expenditure with uncertain returns that depend on volatile market dynamics and policy alignment. Investment decisions are shaped not only by expected cash flows but also by the perceived risk of technological obsolescence, shifting subsidy landscapes, and the credibility of demand forecasts. Investor confidence is particularly sensitive to who initiates the project and how risks are distributed across partners.

Key Uncertainties

- Feasibility of capturing economies of scale amid fluctuating demand and rapid tech turnover
- Accuracy of long-term projections for electricity and hydrogen demand
- Exposure to cost overruns, integration risks, and first-of-its-kind equipment failures
- Influence of the project initiator on investment structure, risk appetite, and financing terms
- Impact of changing interest rates and policy shifts on access to long-term financing
- Volatility in electricity, hydrogen, and CO_2 prices and their impact on payback time
- Policy misalignment between actual market needs and available subsidy mechanisms
- Adequacy of financial buffers for delays, regulatory changes, or performance underdelivery

Grid capacity and connection

As energy hubs grow and new participants join, their increasing electricity footprint must be integrated with an already congested public grid. Developers face a strategic choice between full-grid, semi-islanded, or off-grid configurations, each affecting the hub's access to flexibility markets, investment sizing, and EMS design. Flexible transport contracts (e.g. GTA, ATR) offer earlier connections and cost reductions, but introduce new risks related to curtailment and contractual complexity. Moreover, evolving power flows, including reverse feed-in from storage or electrolysis, can trigger technical constraints and unforeseen capital requirements, especially as the hub expands or grid codes tighten.

Key Uncertainties

- Future capacity limits of the public grid and timing of reinforcements
- Long-term feasibility of (semi) off-grid solutions to avoid congestion charges
- Access to ancillary services and revenue streams under different grid configurations
- Predictability and impact of curtailment under flexible transport contracts (e.g., GTO, ATR)
- Legal durability of collective connection arrangements amid changing network codes
- Internal peak management effectiveness as demand increases within the hub
- Synchronization of hub development with DSO/TSO planning cyclesa
- EMS requirements for future asset additions and renewable expansions

Tariffs and Regulation

The regulatory and tariff environment is undergoing major transformation, with growing emphasis on dynamic pricing, non-firm transport contracts, and sector-specific incentives. These developments directly affect investment risk, operational planning, and site selection. Uncertainty around hydrogen certification schemes (e.g. Guarantees of Origin) and uneven subsidy availability for technologies such as battery storage add further complexity. At the same time, evolving ESG disclosure rules and volatile CO_2 pricing are beginning to influence financing terms and long-term revenue models, blurring the line between regulatory compliance and market exposure.

Key Uncertainties

- Stability and predictability of tariff methodologies and grid cost allocation models
- Frequency and financial impact of curtailment under non-firm connection contracts
- Rate and extent of increases in grid fees, loss factors, and imbalance penalties
- Allocation of grid reinforcement costs between DSOs and hub users
- Geographic tariff disparities and their effect on site selection and competitiveness
- Implementation and acceptance of hydrogen guarantees of origin (GO) and certification schemes
- Uneven policy incentives across sectors, particularly for industrial hydrogen vs. e-mobility
- Future eligibility of battery storage for subsidy support or tax relief

Following this discovery phase, its explored what exactly an energy hub is and how hydrogen can contribute to relieving grid congestion. The required outcomes (KPI set), key opportunities, risks, and dominant uncertainties across each target area are now clearly defined. While the technical landscape, regulatory framework, and success criteria have been mapped out, decision-making remains constrained by uncertainty in performance, financing, grid capacity, and evolving policy. The next chapter therefore focuses on this central challenge: enabling robust, collective decisions under conditions of uncertainty.

04 Problem Definition

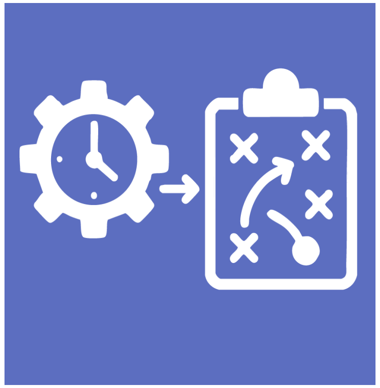
In this chapter the problem explored in the previous chapters is defined with a summary, described with an anology and the research question is formulated.

4.1 Summary

The core of this research lies in the initiative phase of energy hubs. Although policy pressure, subsidies, and technical feasibility have greatly increased interest in hubs, actual rollout is lagging behind: in 2025, the Netherlands will have only a few pilot hubs, most of which will operate under temporary exemptions. Existing research focuses mainly on the technical advantages (battery and hydrogen storage, sector coupling) but offers little guidance for strategic implementation within a complex stakeholder field.

Problem areas

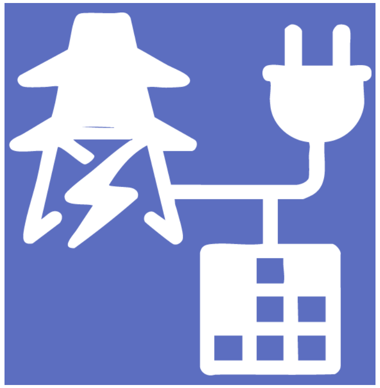
Operational and planning



Economic

Regulation and tariffs

Capacity and connection



4.2 Analogy

To clearly illustrate and contextualize this complex issue, it is helpful to use an analogy, an illustrative comparison that makes abstract problems easier to grasp. For this purpose, the analogy of the orange blinking traffic light is used.

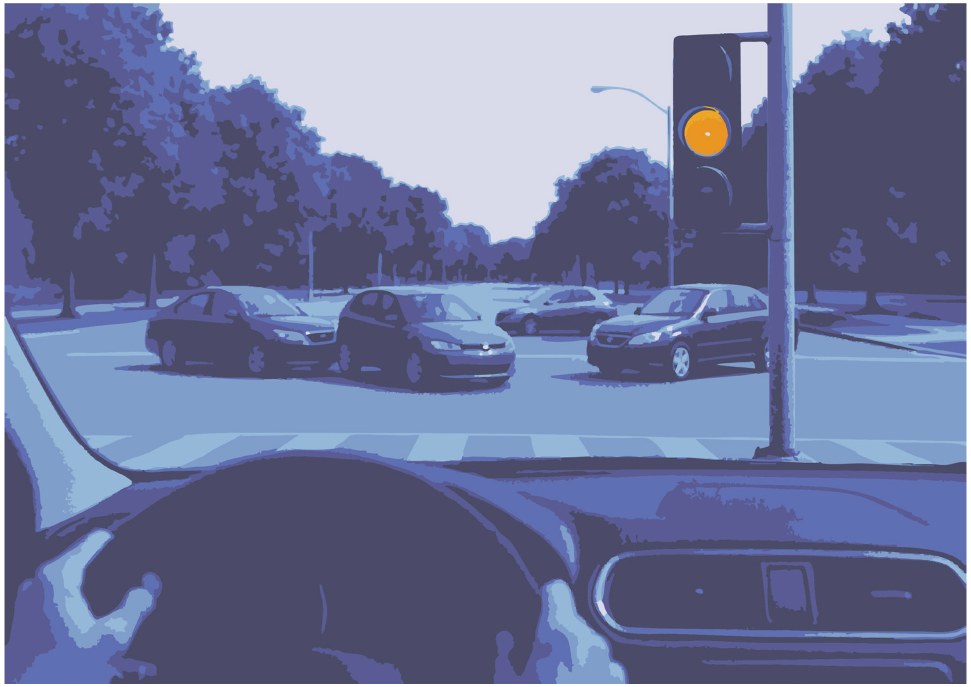


Figure 10: Analogy for a trafiic light that is blinking orange

Imagine multiple vehicles approaching an intersection where the traffic lights have stopped working. Without clear signals, each driver hesitates, uncertain whether to proceed first or wait. Each vehicle waits cautiously, looking to others for an indication to move forward, resulting in a stalemate. Likewise, in the context of energy hubs, stakeholders encounter a similar scenario: uncertainties around investment, governance, technical feasibility, and regulatory clarity cause each party to delay action, waiting for reassurance from others. Without a shared strategic framework acting as a functional “traffic light,” decisions remain stalled in preliminary studies, procedural delays, and minimal progress.

4.3 Research question

In the beginning of the report 4 sub questions where developed, two of those are answered in the previous chapter which leaves the following questions:

"How can stakeholders, navigate through uncertainties, to make joint decisions on the implementation of energy hubs that help reduce grid congestion in the Netherlands?"

- **What method can be used to make informed choices within these uncertainties?**
- **What developments are essential to facilitate the optimal use of hydrogen generation and storage in energy hubs?**

In the remainder of this report, it is examined how the identified uncertainties can be translated into a joint decision-making framework, enabling all stakeholders involved to make unanimous, balanced choices within those margins of uncertainty that do justice to everyone's interests. This framework will be part of a larger implementation plan where the insights and created list of KPIs will be integrated into a coherent strategic roadmap for energy hub implementation.

05 Designing the solution

This chapter introduces a structured method to enable effective decision-making under uncertainty. It applies scenario planning to visualize alternative futures, tests these scenarios through a collaborative stakeholder workshop, and provides a foundation for robust strategic choices.

5.1 Scenario planning method

This chapter employs a scenario-planning method to translate key uncertainties into concrete narratives that stakeholders can collectively evaluate and use for decision-making. It opens with the initiation phase of an energy hub, analyzing the main unknowns surrounding permits, grid connection, and ownership structure.

The topic then narrows to two alternative pathways that spotlight electrolyser deployment, aiming to clarify where and how on-site hydrogen production adds the greatest value. To build these pathways, the chapter first deepens the analysis of a hydrogen-based energy hub, outlining its technical requirements, contractual frameworks, and hydrogen-specific uncertainties before weaving those insights into two scenarios that stakeholders can evaluate and use for decision making.

Within the report structure, first two scenarios for the initiation of an energy hub with the focus more on electricity will be created and evaluated by stakeholders. The method of evaluation will be discussed in the following chapters. After the evaluation of the first scenarios, the process repeats with the creation and evaluation of two scenarios more specific to hydrogen. The method of evaluation is the same for both sets of scenarios.

5.1.1 The Method: Making decision based on uncertainties

The previous chapter concluded by identifying all uncertainties for each overarching target area. The analysis shows that there are various uncertainties surrounding the design and implementation of an energy hub, ranging from technical and financial risks to regulatory challenges and operational issues.

Scenario planning is a powerful method for making strategic choices under deep uncertainty. It is a structured way of explicitly taking uncertainties into account by exploring possible futures. The aim is not to make a single prediction, but rather to draw up a series of plausible future scenarios that will make decision-making more robust (Schoemaker, 1995; Van der Heijden, 2005).

According to Dunne and Raby (2013), we can visualize the future using the “possibility cone,” a conceptual model that categorizes the future into different zones of probability, plausibility, and desirability. By creating scenarios that deliberately seek out different extremes within this cone, implicit assumptions and uncertainties are made explicit. This makes it clearer which strategic options are truly robust.

By combining and amplifying uncertainties in scenarios, stakeholders are given the opportunity to prepare for different future scenarios and to make timely decisions that are flexible enough to cope with changing circumstances.

5.2 Scenario creation

5.2.1 Application of the method

In the previous chapters, four overarching target areas were identified, along with the associated uncertainties. These uncertainties are not separate from each other but are strongly intertwined and influence each other. The way in which the uncertainties are experienced and managed depends largely on the parties involved in the hub and, in particular, on the stakeholder that takes the initiative for the hub. The initiator sets the tone for how risks, responsibilities, and governance are distributed among stakeholders. In other words, the choice of initiator largely determines how the identified uncertainties are distributed and how they are ultimately made manageable.

5.2.2 Energy Hub Initiator

To find the most suited energy hub initiators the power-interest matrix in the previous chapter is used. This matrix places the DSO and the companies that would ultimately form the hub in the high-interest/high power quadrant, making them the most logical initators. The DSO has statutory obligation to guarantee a reliable, affordable and sustainable electricity supply persistent congestion jeopardises that mandate and forces costly grid reinforcements. By taking the initiative for a hub, the DSO can deploy a “non-wire” alternative that flattens peaks, frees up connection capacity and delivers system flexibility under its direct oversight. It also controls the technical data, connection contracts and tariff structures that determine whether a hub can even operate, giving the DSO unrivalled leverage to convene other actors and shape the design.

For the participating companies the incentive is equally strong. They experience the economic pain of capacity caps, curtailment and delayed expansion plans, but they also own the loads, generation assets and real estate needed to form the hub. Acting collectively allows them to share investment costs, optimize energy flows behind the meter and unlock new revenue streams from congestion-relief and ancillary-service markets, benefits no single firm could capture on its own. Because both the DSO and the companies combine substantial decision-making power with a direct stake in the outcome, they emerge as natural co-initiators, often supported by a project developer who can structure the consortium, arrange financing and manage the permitting process.

Because both the DSO and the participating companies combine substantial decision-making power with a direct stake in the outcome, they emerge as natural co-initiators, often supported by a specialized project developer that structures the consortium, arranges financing and manages the permitting trajectory.

This can be explained as follows:

When the network operator (DSO) takes the initiative, the emphasis lies on stability, predictability and overall system manageability. In that configuration a significant share of the technical and regulatory uncertainties is absorbed by the DSO, which already holds the statutory responsibility for grid reliability and therefore has the mandate, and the incentives, to internalize part of the risk.

When a collective of companies takes the initiative, the center of gravity shifts toward commercial flexibility and firm-specific business opportunities. Here, the participating companies assume a larger portion of the uncertainties and risks themselves, most notably market volatility, asset-performance risk and long-term revenue certainty, because those factors directly affect their individual balance sheets and competitive positions.

Based on this reasoning, it is logical to build scenarios explicitly around the initiator. Therefore two main scenarios are developed:

- **Scenario 1: Energy hub initiated and led by a network operator (DSO)**
- **Scenario 2: Energy hub initiated and led by a group of companies**

With help of the Energy hub implementation steps developed by Firan I have translated these two scenarios into flowcharts so that the steps within each scenario become clear.

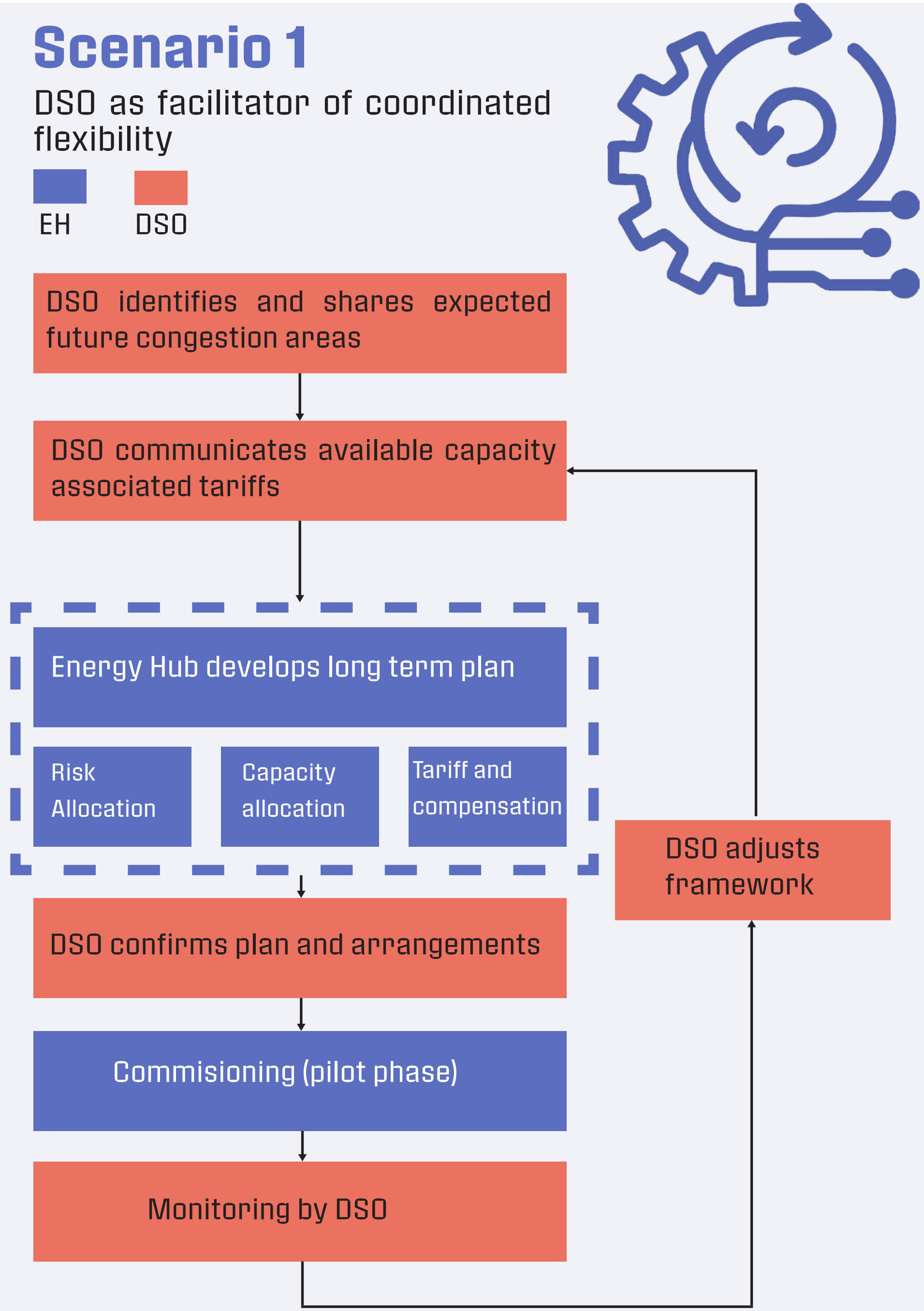


Figure 11: Scenario 1, DSo as faciliator of coordinated flexibility

5.2.3 Scenario 1

The regional network operator (DSO) initiates the initiative. It first conducts a network analysis and proactively shares which parts of the network will become congestion-prone in the coming years. It then publishes the available transport capacity and the (reduced) rates at which companies can use it.

With that starting signal, the intended energy hub (EH), a partnership between the companies in the area, gets to work. In a joint long-term plan, they describe three things:

1. Risk allocation, which party is responsible for which technical and financial risks.
2. Capacity allocation, how much capacity is needed where and when.
3. Tariffs & compensation, what compensation or discount will the companies receive for their flexibility.

Once this plan is ready, the DSO will assess and confirm the agreements made. A pilot phase will then start: the first assets will be connected and tested via the EMS to determine their contribution to grid balance. The DSO continuously monitors performance and, during the monitoring phase, adjusts the contractual framework or technical rules as necessary. This creates an iterative process in which grid security is central and the framework is "adjusted" by the DSO based on measured practical data.

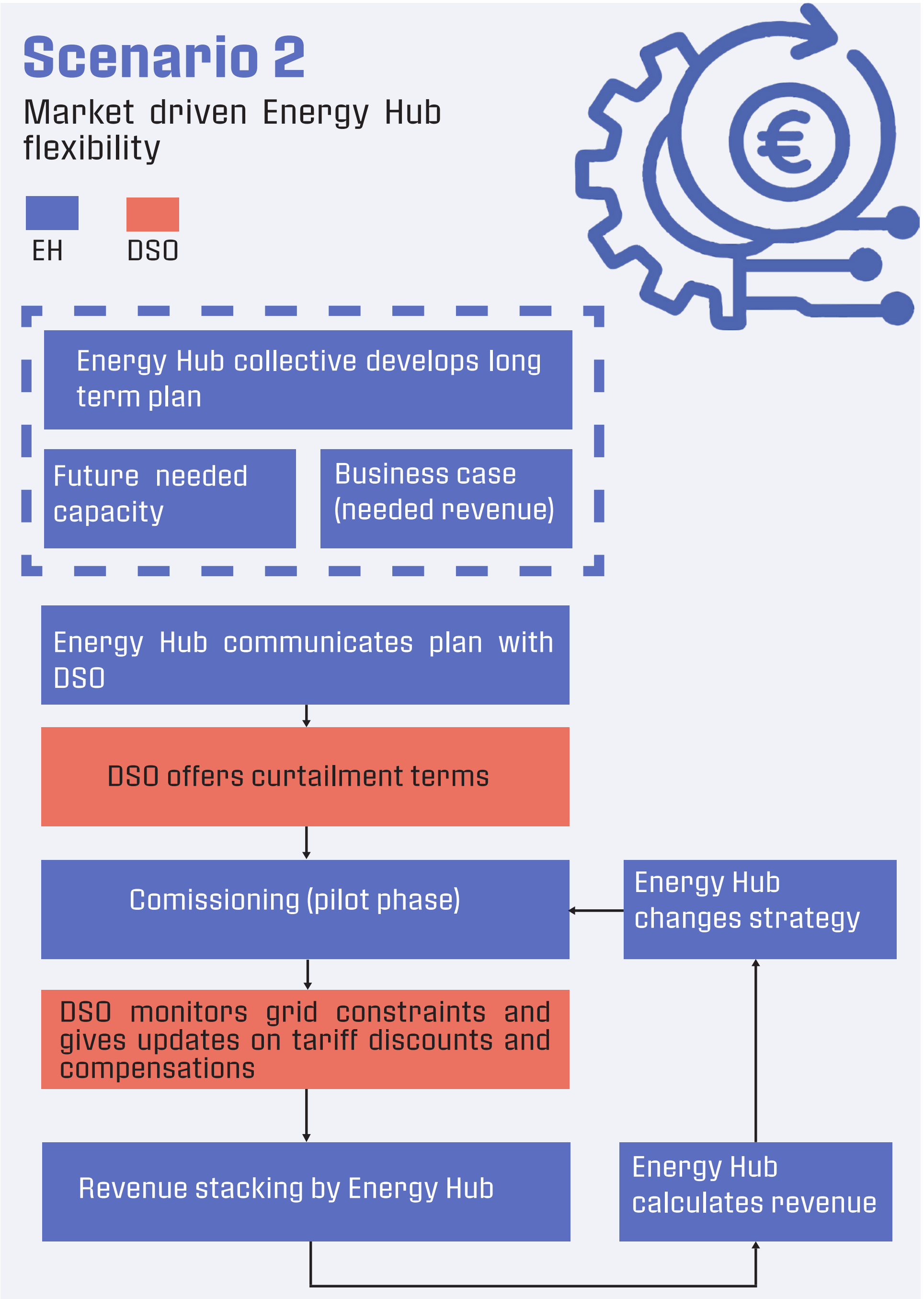


Figure 12: Scenario 2, Market driven Energy hub flexibility

5.2.3 Scenario 2

In this market-driven scenario, the companies take action themselves. The EH collective first develops its own long-term plan in which it determines its future capacity requirements and immediately links this to a business case (required revenue streams). Only then does it approach the DSO to discuss the plan. The grid operator does not respond with a fixed framework but offers curtailment conditions: it outlines the conditions and discounts under which it may occasionally switch off the hub to relieve the grid.

With these preconditions in place, both parties start a pilot phase. The DSO monitors grid constraints and regularly communicates discounts and compensation based on actual congestion. At the same time, the EH collective carries out revenue stacking: it bundles income from electricity arbitrage, hydrogen sales, and flexibility services.

After each measurement period, the hub evaluates its strategy. If a source yields less than expected, the EH organization adjusts the dispatch algorithm or the portfolio. The new strategy is calculated (EH calculates revenue) and, if necessary, submitted to the DSO for a subsequent optimization round. This creates a cyclical process in which commercial opportunities are paramount and the contract with the DSO flexibly adapts.

5.2.4 Evaluation of Scenarios

The evaluation of the scenarios took place in a workshop with stakeholders. The two scenarios are presented together with the context and problem of this research and the stakeholders will be asked questions to extract insights and feedback on the created scenarios. The exact method of evaluation is explained in the next chapter.

5.3 Participatory evaluation workshops

5.3.1 Choice for a workshop

Research into co-creation and stakeholder engagement shows that participatory workshops deliver more than just opinions. They create a shared language, make implicit assumptions explicit, and accelerate decision-making by testing solutions during the design process (Sanders & Stappers, 2008). In the energy sector, this joint exploration is crucial: projects with early, active involvement of network operators, developers, and consultants are demonstrably more robust, better licensed, and more financially attractive than projects in which parties are only consulted at the end (Michael Ezeh et al., 2024). Particularly in the case of an energy hub, where technical, regulatory, and financial uncertainties reinforce each other, a participatory workshop offers the opportunity to play through scenarios in a safe environment, weigh risks jointly, and build ownership of the outcome.

5.3.2 Objectives and participants

The primary objective of the sessions was threefold: to determine whether the proposed decision-making sequence for both initiative scenarios is recognizable; to identify the most significant uncertainties and risks; and to jointly determine which components are robust and which need to be redesigned by testing the scenarios for feasibility, desirability, and plausibility. Both workshops were held online and lasted two hours. Workshop 1 had two participants: an energy specialist with a DSO background who now works for a project developer, and an independent energy consultant with extensive experience in industrial flexibility projects. This composition ensured that both the network management perspective and the market perspective were represented.

5.3.3 Session structure

The workshop began with an explanation of the context, the problem of grid congestion was explained, and energy hubs were presented as a potential solution. This was followed by an explanation of the complications involved in implementation, the four areas of uncertainty were outlined and the need for a joint decision-making framework for the implementation of energy hubs was emphasized.

After this problem exploration, an example situation was presented, again followed by a brief reflection, so that it became clear what advantages and disadvantages the participants saw and whether they agreed with the problems presented. To stimulate the participants to discuss specific topics like contract types, three flexible contract types are highlighted and explained.

Next, the scenario planning method was introduced, and the two scenarios were explained. For each scenario, the flowchart was explained, showing the successive decision steps without zooming in on specific contract forms or KPIs. This left room for the participants' own interpretation and joint discussion.

5.3.4 Interactive Analysis

After the plenary introduction, the workshop moved to an interactive shared Miro board. The two participants were placed in separate breakout rooms, each with a workshop facilitator. The flowcharts for both scenarios were drawn up on the Miro board, and the participants were asked to rearrange the flowcharts and add to them if necessary: missing steps could be added, unnecessary steps removed, and comments could be posted using digital post its.

The second assignment was discussed verbally and using post-it notes to determine how each scenario scored on three assessment dimensions: feasibility, desirability, and plausibility. Instead of a numerical weighting, an open dialogue was deliberately chosen, and key phrases were recorded so that the nuances were not lost.

The complete structure and slides of the workshop is shown in Appendix G.

1 Introduction

- Context
- Research problem
- Approach & goal

2 Narrative

- Example problem
- Flexible contracts
- Feedback

3 Scenario method

- Scenarios
- Interactive analysis

miro

Figure 13: Workshop structure and tools used

5.3.5 Insights from workshops

Using the transcript and recording of the workshop, the answers to the reflective conversations and the insights gained through the interactive workshop have been coded and linked together in the following insights.

Early-Stage Hub Formation Needs DSO Support, and the DSO needs support with providing

Energy hubs often struggle to form because they lack a neutral conveyor. Grid operators hold the data and local expertise that entrepreneurs need to decide where and with whom to form a hub. By stepping in early, helping companies find each other and the optimal location, DSOs could smooth out this critical first phase. The DSO is struggling with finding a way to find good locations and process the data.

Contract Development Is Messy & Evolving

Group-level contracts are brand-new territory for DSOs: multiple pilots have tested CBC/TO agreements, but none are yet operational. Internally, departments clash over terms, making alignment slow. While a single group Transmission Agreement is the current focus, future convergence of contract types remains uncertain.

Minimal vs. Maximum DSO Role Is Unresolved

DSOs are torn between a passive “set the boundaries and let the market act” stance and a more hands-on facilitator role. Both extremes carry trade-offs: full market delegation may be swift but risky, whereas deep DSO involvement threatens operational focus and resource overload.

Capacity Allocation Remains Core & Contentious

Every hub debate circles back to “how much capacity can we actually get?” DSOs rely on historical usage data, which systematically under-represents future investments. Companies routinely discover that their summed individual needs exceed the group limit, sparking endless recalculations.

Hybrid Contract Combinations Are Emerging

Pilots and market conversations hint at combining firm base-load capacity with non-firm flexible tranches. This “two-part” approach secures essential operations (e.g. eletrolysers) while allowing extra capacity to be traded or curtailed on short notice. Early cases (e.g. Pepsi) show promise but need broader standardization.

Monitoring & Enforcement Processes Are Undefined

Neither fines (“yellow cards”) nor shut offs (“red cards”) are yet formalized for group contracts. DSOs debate whether to simply hand out warnings or build active control systems that limit consumption in real time. Without a clear enforcement regime, hubs operate in regulatory limbo.

Incentives Alone Won't Drive Battery Behavior

Market mechanisms like GO-packs are the only current lever for influencing battery dispatch, but their payouts are too small to meaningfully shift behavior. DSOs remain largely passive, awaiting market signals rather than offering dynamic tariffs or direct dispatch instructions.

A Dual-Sided Contract Is the "Golden Goose"

A contract that simultaneously satisfies DSOs' reliability and safety criteria and the hub's need for transparency, flexibility, and fair cost-sharing. Combined with robust data-sharing, such a contract is seen as the key enabler for scalable energy hubs.

Business ownership & risk sharing set the pace

Hubs get off the ground fastest when one or more companies take the lead themselves; they "own" the problem and have a direct commercial incentive to succeed. If the lead is taken by a municipality or province, progress often stalls. Moreover, current contracts shift a large part of the risk, including liability for other people's mistakes, onto the hub and individual participants.

Shared benefits and participant mix are prerequisites

A hub only works when every participant derives a visible benefit from the joint connection point; if only one company experiences a bottleneck, the rest will usually drop out. Successful pilots show that a mix of "problem users" (with capacity constraints) and "surplus suppliers" (who contribute extra kW or PR value) is needed to close the business case.

Hybrid Storage Portfolio Needed for Sustainable Flexibility

Batteries provide peak shaving but only store energy for a few hours and remain expensive. Hydrogen offers seasonal storage but is conversion-intensive; thermal buffers are interesting where heat demand exists. A combination, short- and long-term carriers, is seen as the only realistic route to achieving lasting congestion reduction.

Battery dispatch must be synchronized across grid levels

A battery can alleviate congestion on one DSO segment, but at the same time exacerbate it elsewhere (at another DSO or even the TSO). Furthermore, DSOs require proof that the charge/discharge profile actually helps, although real-time insight is often lacking. Effective deployment requires clear measurement methods, unanimous agreements within the hub, and coordination with price signals at the bidding zone level.

Financing & Ownership: DSOs Are Not Allowed to Own Batteries

Network operators are legally restricted to pilot projects: commercial batteries must be financed through third parties or joint ventures, often with (government) subsidies. At the same time, DSOs want operational control to manage local congestion, e.g., through TenneT's TDTR "steering" contract. Clear governance over usage rights and dispatch is therefore crucial.

One National Price Masks Local Incentives

The Dutch "copper plate" with uniform electricity prices gives companies no signal where congestion is occurring. Local or nodal prices could steer investments in storage and flexibility, but such a system change is meeting with resistance. Current price shocks (e.g., after the Ukraine war) are much greater than what local storage alone can absorb.

Local balance is healthy, but complete self-sufficiency remains unachievable.

Production that is consumed locally does not cause grid congestion, but the time mismatch between wind/sun and demand makes this difficult. Sufficient storage to accommodate every mismatch is economically and spatially virtually impossible, which means that a grid connection will always be necessary for balance and resilience.

5.3.6 Conclusion

Workshop 1 highlights a clear but challenging situation. Companies aim to collaborate in energy hubs to reduce grid congestion and support growth but face several persistent obstacles. Current capacity allocation, relying on historical consumption data, systematically underestimates future needs. Additionally, network operators lack essential real-time data, analytical tools, and standardized group contracts necessary for proactive collaboration. Strong business leadership proves critical: energy hubs succeed only when at least one participant actively leads and clear mutual benefits are identified. However, existing contracts largely transfer risks and liabilities to participants, and financing is constrained as regulations forbid DSOs from owning batteries or flexibility assets. While batteries can manage peak congestion, structural issues require hybrid solutions combining short-term storage (batteries) with longer-term energy carriers (like hydrogen or heat). These investments require significant capital and depend on consistent, long-term regulatory clarity, currently lacking due to shifting policies, uniform national electricity prices, and varied DSO practices.

In short, experts identify a central requirement: a robust regulatory framework that anticipates future capacity demands, distributes risks fairly, incorporates hybrid flexibility solutions, and enables real-time data sharing. Currently, essential elements such as reliable data, standard agreements, clear ownership structures, stable regulations, and suitable market incentives remain fragmented or missing, creating a critical design challenge for energy hubs.

To obtain similar insights specific to hydrogen implementation, the same scenario planning approach used in Workshop 1 has been applied, beginning with an in-depth exploration of hydrogen-specific considerations and uncertainties.

06 Hydrogen specific considerations

In the previous chapter insights have been gathered by translating uncertainties regarding energy hub implementation into scenarios. These insights cover hydrogen on a high level and do not go into the specifics. This chapter forms the basis for the development of similar scenarios for hydrogen implementation.

6.1 Factors for consideration

6.1.1 Type Electrolyser

The first major design choice is the type of electrolyser. There are several technical concepts, each with its own dynamic and economic characteristics that make them more or less suitable. Within this study, the type of electrolyser is covered on a high level as the scope of this research is on implementation.

Proton exchange membrane (PEM)

This technology uses a solid polymer membrane and can rapidly change electrical power by approximately 10% of the nominal power per second. This allows a PEM eletrolyser to accelerate from warm standby to full load in ten seconds (National Grid ESO, 2024). Thanks to its response speed, a PEM hub can pick up quarter-hourly or even five-minute signals without significant wear.

Alkaline

Here, the electrolyte is in liquid form; start-up takes five to ten minutes, and the ramp-up rate is 0.2% of the nominal power per second. This makes alkaline economical for hourly or day-night ramps, but unsuitable for high-frequency grid service (Arup et al., 2024).

Solid-Oxide

Operates at extremely high temperatures (700-850 C) and achieves high electrical efficiencies but is not yet technologically mature and is sensitive to thermal cycles. This means it does not fit the business case for an energy hub (Arup et al., 2024).

Choice for energy hub

For a Dutch congestion hub that needs to be able to switch in every quarter of an hour, PEM is therefore the only concept that combines speed and service life. By constructing the installation in a modular fashion in 'stacks', a stack is a package of hundreds of cell membranes connected in series with their own power rail and water/gas manifold, the minimum power can be further reduced. Ten separate PEM stacks of 1 MW each allow the hub to reduce the typical minimum load of 2 MW to approximately 0.2 MW, which further reduces imbalance and wear and tear (National Grid ESO & NGT, 2024).

6.1.2 Storage and buffering

To guarantee a flat consumption profile, energy hubs decouples production and delivery via buffer storage. There are three technical and economic routes to achieve this.

Above-ground compressed gas at low pressure

A daily buffer for peak-valley shifts. A cylindrical pressure vessel set can store hydrogen at a low pressure. The low pressure keeps CAPEX lower, but the volumetric efficiency is low; with a 10 MW hub, half a football field is easily filled if you want to bridge more than 24 hours.

Above-ground compressed gas at high pressure

Shorter vessels reduce the footprint to 44m2 per 246kg of hydrogen, making them approximately four times more compact than 30 bar storage. The disadvantage is the additional compression energy: to increase the product gas from 30 bar to the 75-bar required for blending or truck loading, higher operating costs are incurred.

Underground storage in salt caverns

This is more seasonal storage for large quantities of hydrogen. Caverns for hydrogen pilot storage are already under development in the salt domes in the northern Netherlands near Zuidwending and Heiligerlee; on a large scale, this offers the lowest €/kg storage costs, while the above-ground footprint is limited to a compressor station (Arup, 2024). The downside is high initial CAPEX and limited geographical availability.

Choice for energy hub

For the Dutch situation, 30 bar vessels are sufficient in the initial phase. The space requirement remains manageable, and the additional compression energy is still negligible compared to the electrolysis consumption. If the annual peak supply exceeds 100 tons, cavern slip becomes economically viable. As an emergency buffer, a 30-bar pack can still be useful as "blow-down-safe" storage.

Liquid hydrogen is not included in this plan because liquefaction requires a lot of extra power, the storage tanks are very expensive and complex, and there is a small daily loss due to slow evaporation. This form is mainly useful for long-distance export or for applications in aviation, but not for a local hub that primarily aims to relieve the Dutch electricity grid.

6.1.3 Conversion back to electricity

It can beuseful to convert some of the stored hydrogen back into electricity, for example if there are unexpected high electricity prices or if the grid requires emergency power. This is done using fuel cells. Pem fuel cells start up within seconds and deliver power immediately, making them suitable for peak moments or emergency power.

Solid oxide fuel cells are more economical and also provide usable heat, but they start up more slowly and are not build for being switched on and off very often.

The round trip from electricity to hydrogen to electricity ultimately returns about 35% of the initial energy. This makes it particularly interesting during real price spikes or if you can also sell the heat (Arup, 2024; Baringa Partners, 2024). In practical terms, you can therefore give the hub a few megawatts of PEM fuel cells for peak and emergency situations; this is small enough to remain affordable, but large enough to generate additional income.

6.1.4 Transportation

There are three practical routes for distribution. Five tons per day can be loaded into truck trailers and driven to the customer. If production is higher but demand fluctuates, a small portion can be mixed into the regional gas grid. Technically, this mixture can be up to 20%, but in practice, you start at around 5%. This simplifies billing procedures beacuse the energy content of the gas mizture remains close to standard natural gas. This allows existing metering an billing systems to operate without major adjustments. If consumption consistently exceeds five tons per day, a dedicated hydrogen pipeline becomes cheaper than scheduling truck trips (Baringa Partners, 2024).

6.1.5 Flexibility Contracts

To reassure investors, the hub must have a reasonably predictable cash flow. The British study into so-called "Demand-for-Constraints" (Arup, 2024) identified four main types.

Utilization fee

The hub is only paid per MWh consumed during a constraint hour. The British model bases the fee on the average avoided curtailment rate. The advantage for the grid operator is that it only pays in the event of actual congestion; however, the hub bears the entire volume risk and cannot attract project financing without additional income.

Utilization fee + seasonal availability *

In addition to a reduced utilization price, the eletrolyser receives an availability fee that is approximately twice as high in winter as in summer, because the majority of UK congestion problems occur between October and March.

Flat availability + Utilization fee

Same structure as Utilization fee with seasonal availability but without seasonal differentiation. Administratively simpler, although the operator pays relatively too much in the quieter summer months and too little in winter. The LCOH is slightly higher in the UK analysis than for the utilization fee with seasonal availability contract.

Fixed annual fee

Here, the eletrolyser receives a lump sum, depending on the plan size, in exchange for unconditional availability. This offers maximum security for the producer; for the system operator, there is a risk of over- or under compensation if the actual congestion deviates significantly from the forecast. Feedback from the British market indicates that this option is only viable through individual negotiation.

* The Utilization fee with seasonal availability covers approximately 70% of the fixed costs through availability and 30% through utilization, creating bankability without the grid operator losing the incentive mechanism.

6.1.6 Safety & Permits

As soon as an installation has more than five tons of hydrogen on site, it is covered by the Seveco III directive for major chemical risks. This means that the developer must submit a Quantitative Risk Analysis (QRA) with the environmental permit, including external safety contours and an emergency response plan. As a specific PGS guideline for electrolysis is still being developed, regulators are currently using the Hydrogen Safety Guide and PGS 35 (pressure vessels) as a testing framework. In the application, you must:

- Indicate the ATEX zones around compressors and pipes
- Show how relief and purge gases are safely discharged
- Describe which safe-by-design principles have been applied
- Include an "update clause" so that you can adjust the file without a new EIA as soon as the final "PGS electrolysis" is published.

For the permit under the Environment Act (from 2024), the process consists of three steps: preliminary consultation (discussing the draft plan with the municipality and environmental service), draft decision (publication and opinions), and final decision with any appeal period.

6.1.7 Actual green electricty

According to EU regulations, from July 1, 2028, producers must demonstrate that every hour of hydrogen production is covered by an equal amount of renewable electricity; from January 1 2029, this will be tightened to quarter-hour accuracy. To this end, the hub's EMS must plan the battery and electrolysis so that production coincides with hours of high sun or wind. The electricity must also come from the adjacent bidding zone; a PPA with new, unsubsidized wind or solar capacity is sufficient. For electricity used to avoid thermal grid constraints, the low-carbon hydrogen standard may also use the regional emission figure for those hours.

6.2 Additional measures

As of January 2025, hydrogen producers will be classified as "essential entities" under the European NIS2 Directive. The hub must therefore:

- Divide the OT network into logical zones in accordance with IEC 62443-3-3 (field equipment, process control, business IT).
- Set up a 24-hour incident reporting procedure to the National Cyber Security Center.
- Implement managed detection & response on EMS, BESS-BMS, and PLCs.
- Perform a penetration test and annual re-audit within one month of commissioning.

The costs are limited (in the order of €3–5k per MW), but non-compliance can result in fines of up to €10 million (Arup et al., 2024).

Noise and environment: Hydrogen compressors generate noise, in practice 65–75 dB(A) at ten meters. This must be considered with getting permits and the design.

6.3 Uncertainties

This translates into the following summary of uncertainties that are divided into five overarching themes, like the overarching themes from previous chapters. These are listed in the following pages.

Operational & Planning

The first uncertainty is purely technical: no one knows exactly how often TenneT will send a minute or quarter-hour signal in the coming years and how steep those ramps are. This makes it difficult to predict exactly how many starts and stops the PEM stacks inside the electrolyser will have to handle each year and how quickly they will wear out as a result. On top of that, there is the unpredictability of solar and wind production, which means that daily hydrogen output is never completely flat and sometimes more or less buffer capacity is needed. Logistical planning also involves shifting puzzle pieces: maintenance stops must coincide with periods of low grid stress, and the later switch from high-pressure tanks to a salt cavern depends on the speed at which annual demand grows and the availability of caverns in Zuidwending or Heiligerlee.

- **Frequency and steepness of TenneT's future minute or quarter-hour signals (affecting PEM stack wear).**
- **Unpredictability of renewable energy production (solar and wind), causing fluctuations in daily hydrogen output.**
- **Timing and coordination of maintenance periods relative to grid stress periods.**
- **Transition timing from high-pressure storage tanks to salt caverns (dependent on demand growth and cavern availability).**

Economic

The biggest financial variable is the price of electricity: if peak and off-peak prices diverge further, electricity consumption during busy hours will become more expensive and the LCOH will fall, but the value of fuel cell feed-in will rise. The market price for hydrogen is equally volatile, as it is linked to both the price of natural gas and CO_2. On top of this, there are raw material costs: iridium for PEM cells is scarce and can double in price in a short period of time, as can nickel, steel, and composite materials for pressure vessels. Interest rate developments and inflation influence financing costs, while the level and timing of subsidy schemes (HPBM, SDE++) determine when an investor gives the green light.

- **Volatility in electricity pricing (impacting operating costs, LCOH, and fuel cell revenues).**
- **Fluctuating hydrogen market price (linked to natural gas and CO_2 prices).**
- **Rapidly changing prices and availability of critical raw materials (iridium, nickel, steel, composite materials).**
- **Interest rate fluctuations and inflation affecting financing costs.**
- **Timing, extent, and continuity of subsidy schemes (HPBM, SDE++) influencing investment decisions.**

Legislation & Permits

There is still a lot of movement in the regulatory arena. The European additionality rules will be further tightened in 2028 and 2030, but the exact details, on an hourly basis, quarter-hourly basis, with or without national exceptions, are still subject to change. In the Netherlands, there is currently no specific PGS guideline for electrolysis; once this is in place, it may impose additional requirements on building height, ventilation, or emergency blowdown. The same applies to the Seveso thresholds: a planned revision in Brussels may ease or tighten the reporting requirements. Furthermore, it is unclear whether the legal mixing limit in the gas grid will be set at 20% by volume or remain at 5% to 10% for the time being. Finally, the introduction of cyber security rules under NIS2 is scheduled for 2025; the specific enforcement practice has not yet been finalized.

- **Evolving European additionality regulations with uncertain hourly/quarter-hourly implementation specifics and national exceptions.**
- **Undefined Dutch-specific electrolysis guidelines (PGS) potentially affecting safety requirements.**
- **Planned revisions to Seveso Directive thresholds influencing safety reporting obligations.**
- **Uncertainty around legal hydrogen blending limits in the natural gas grid (5%-10% vs. 20%).**
- **Implementation and enforcement details of the NIS2 cybersecurity directive scheduled for 2025.**

Contract & Market

On the demand side, it is by no means certain whether industrial customers will realize their announced hydrogen projects on time and how much fixed tonnage they dare to commit to. Although an availability contract with TenneT offers a basic income, the variable remuneration depends on the actual number of congestion hours. If the grid expansion is completed earlier than expected around 2030, the activation frequency will decrease, and part of the revenue will dry up. Conversely, delays in pipeline permits could limit sales opportunities. Customer creditworthiness, fluctuating CO_2 prices, and the term of PPAs are additional factors that make cash flow uncertain.

- **Timing and certainty of industrial customers' announced hydrogen project realizations and fixed demand commitments.**
- **Variable revenue from TenneT's availability contracts influenced by frequency and duration of congestion events.**
- **Possible earlier-than-anticipated completion of grid expansions (reducing congestion-related revenues).**
- **Potential pipeline permit delays restricting hydrogen sales.**
- **Financial risks from customer creditworthiness, volatile CO_2 prices, and varying contract terms of power purchase agreements (PPAs).**

Supply & Demand chain

Finally, there is a risk that global demand for PEM stacks, compressors, and hydrogen refueling equipment will grow faster than supply. Long delivery times or material shortages could delay the construction phase and drive-up CAPEX. If the extraction of iridium or cobalt is disrupted by geopolitical tensions, prices could skyrocket.

Even the contractor schedule is not a given: staff shortages in the Dutch construction and installation sector could push back the completion date.

- **Risk of global demand surpassing supply capacities for PEM stacks, compressors, and hydrogen equipment.**
- **Lengthening delivery times or shortages of critical materials affecting project timelines and CAPEX.**
- **Geopolitical disruptions affecting extraction and availability of essential minerals (iridium, cobalt).**
- **otential delays in construction due to staffing shortages in Dutch construction and installation sectors.**

6.1.10 Concluding

This combination of technical, economic, legal, and logistical uncertainties means that every business plan must include multiple scenarios, a robust set of contract options, and considerable flexibility in design and planning. To effectively navigate these complexities, it becomes essential to employ targeted strategic planning methods. The following chapter therefore applies scenario planning to systematically explore these uncertainties, providing clarity on potential future developments and facilitating informed decision-making for stakeholders involved in hydrogen-focused energy hubs.

07 Hydrogen specific Scenario & Workshop

In this chapter the previous process of scenario creation and testing in a participatory workshop are applied on the uncertainties disucssed in the previous chapter regarding hydrogen to create actionable insights in to the implementation of hydrogen in energy hubs.

7.1 Scenario creation

Given the extensive operational, economic, legislative, contractual, and supply chain uncertainties, robust and flexible strategic planning is essential for hydrogen implementation in energy hubs. To translate these uncertainties into actionable insights, the same participatory workshop approach is used. Specifically, two scenarios are explored, differentiated by the primary initiator of the hub and thus the main role of the electrolyser: either as a flexibility provider for grid congestion management or as a dedicated industrial hydrogen supplier. Each scenario distinctly influences the business model, contractual arrangements, and operational setup, enabling stakeholders to clearly assess potential impacts and strategic choices.

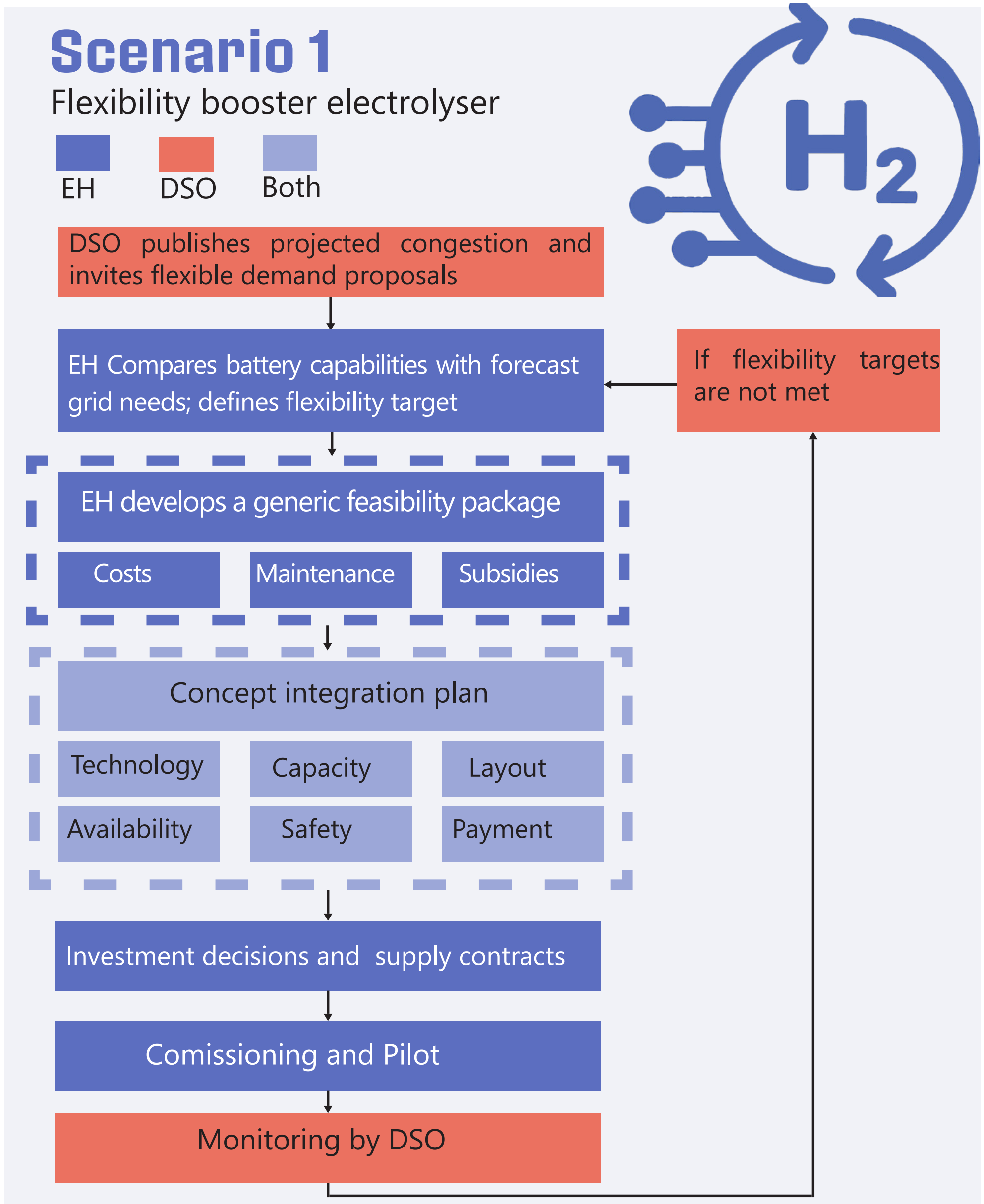
7.1.1 Scenario 1

The DSO starts the process. After publishing a multi-year congestion forecast, it contacts existing energy hubs in the affected zones and invites flexibility proposals in exchange for additional transport capacity or reduced tariffs.

The established energy-hub partnership analyses the request. It compares the ramp-rate and storage window of its current battery with the flexibility volume the DSO needs and concludes that a fast-responding electrolyser could close the gap. In a joint long-term plan the partners describe three elements:

- Risk allocation, confirmation that technical and financial risks linked to the new electrolyser (stack life, fuel-cell reconversion tests, safety upgrades) rest with the hub, while grid-performance risks stay with the DSO.
- Flexibility specification, the size, ramp speed and availability windows the electrolyser must meet, plus the fallback logic for battery dispatch.
- Tariffs & compensation, availability and activation fees, rules for tariff adjustments if performance targets are missed, and optional bonuses for additional peak shaving.

The DSO reviews and approves the plan. A pilot phase follows: the electrolyser is tied into the existing EMS, buffer tanks are installed, and brief reconversion tests with a containerized fuel cell assess round-trip performance. Throughout the monitoring period the DSO tracks real-time data; if the hub falls short of the agreed target, it tightens availability requirements or recalibrates tariffs.



Figyre 14: Scenario 1, Flexibility booster electroluser

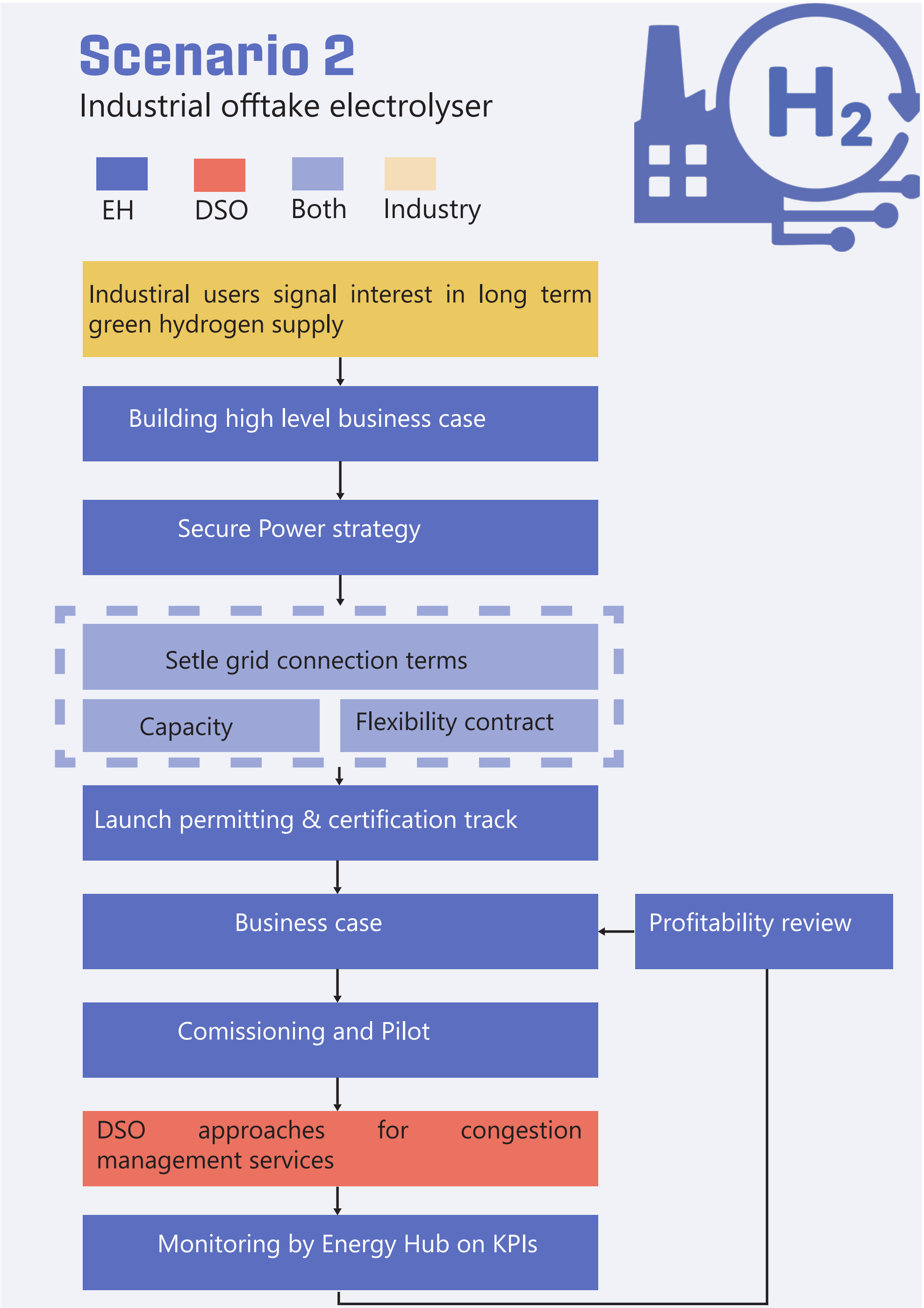


Figure 15: Scenario 2, Industrial offtake electrolyser

7.1.2 Scenario 2

In this market-driven pathway, a cluster of industrial users launches the initiative by signaling demand for a steady supply of green hydrogen. The EH collective responds by drafting its own long-term plan, in which it links required hydrogen volumes to a business case built on power-purchase agreements, subsidies and take-or-pay contracts. Only when that framework is financially coherent does the hub approach the DSO. Rather than setting a fixed flexibility target, the grid operator offers curtailment conditions: explicit limits and discounts under which it may occasionally throttle the electrolyser to relieve the grid.

With these preconditions in place, both parties enter a pilot phase. The EH installs the electrolyser, completes Seveso- and CertifHy procedures, and begins baseload production. The DSO monitors congestion in real time and communicates any curtailment signals together with the applicable compensation. Meanwhile, the hub undertakes revenue stacking, combining hydrogen sales, electricity arbitrage via the battery, and optional flexibility services.

After each measurement period the hub reassesses its portfolio. If hydrogen demand outpaces projections or CO_2 prices rise, it may scale capacity; if flexibility revenues prove attractive, it can widen availability windows to the DSO. The updated strategy is calculated and, where necessary, resubmitted to the DSO for agreement. This creates a cyclical process in which commercial opportunity drives optimization while the contract with the DSO flexibly adapts to real-world grid conditions.

7.1.3 Evaluation of scenarios

The evaluation of the two scenarios will take place in the same type of workshop explained in previous chapters. The workshop has the same structure and goal, but a different problem narrative and different contract types are shown specifically for electrolysers. These can be found in the appendix G. This workshop had one hydrogen expert as participant from the company Arup.

The results from the workshop are anaylsed and formulated in to clear actionable insights that are listed in the following pages.

7.2 Workshop insights

Using the transcript and recording of the workshop, the answers to the reflective conversations and the insights gained through the interactive workshop have been coded and linked together in the following insights.

Local renewable energy and hydrogen demand determine feasibility

An energy hub only becomes profitable when the eletrolyser can run almost continuously on nearby sustainable electricity and can supply a regional hydrogen customer directly. This physical proximity eliminates transport costs, increases full-load hours, and makes a higher H_2 price defensible. Without such a customer, the return on investment drops, no matter how favorable the electricity price or subsidy.

Most valuable, but (still) unfeasible: DSO ownership of an eletrolyser

The electrolyser is a precisely controllable asset that can be used for specific peaks. In control of the DSO it could maximize the relief on the grid. However, EU unbundling makes this a no-go area: the DSO is not allowed to own or control any production assets.

Balanced risk allocation is essential

Projects stall when the network operator assigns all stack-life, insurance and safety liabilities to the hub while retaining only grid-security risk: lenders lift the cost of capital and insurers impose surcharges. A bankable structure shares liabilities, plant-health risks remain with the owner, grid-performance penalties with the operator, and limits any residual exposure through explicit cap-and-collar clauses.

Contract agility can't change fixed hardware

The rate schedule can be adjusted monthly, but the chosen power capacity, cooling system, and transformer are fixed after the final investment decision. If the DSO becomes stricter later on (e.g., higher disaster rate or longer availability), the hub can only compensate for this with money, not with additional physical flexibility.

Real time data is the new project currency

In both scenarios, the entire validation process relies on real-time measurement data. Without a robust data feed, no bank or regulator will trust the compensation model. Robust data is also essential for the functioning of the energy hub. EMS uses measurements to control energy hub assets, and without this flow of data, the hub could lose revenue.

Battery fallback can amplify a peak

A simple rule like "let the battery step in whenever the electrolyser trips" can backfire if the transformer or feeder is already close to its limit. An effective strategy is to optimize both assets as one integrated flexibility pool, using a horizon that looks ahead at least an hour. With general security constraints baked into the optimizer, every fallback action remains within predefined network and equipment thresholds, so contingency management eases congestion instead of shifting or worsening it.

Curtailment discounts align incentives

When a hub earns a network-tariff discount whenever the DSO curtails it, the effective electricity cost used in the levelised cost-of-hydrogen calculation falls as well. That twin incentive can make it profitable for the operator to offer even more up- and downward flexibility than strictly required. A tiered,discount keeps the signal sharp, because each additional block of curtailment hours unlocks an extra rebate. At the same time, a rolling back-test of historical curtailment and prices lets the DSO verify that the incentive remains cost-effective, avoiding the risk of over-compensating flexibility providers.

Revenue stacking overwhelms EMS

When hydrogen sales, spot-price arbitrage, capacity charges and curtailable grid services all have to fit into the same timetable, the number of possible operating combinations grows exponentially. An EMS therefore needs more than fixed rules: it must include an optimization engine that can explore thousands of scenarios in real time. The implementation of AI-powered dispatchers, ranging from reinforcement-learning agents to mixed-integer linear programmes running on a digital twin of the site, do this by converting every revenue stream into a common metric. That common metric keeps priorities transparent, while an explainability layer translates the optimiser's choices into plain language so operations and finance can understand why the schedule deviates from a simple baseload plan.

Round trip H_2 to power is a last resort tool

Treat hydrogen-to-power conversion as a safety-valve, not a revenue anchor. Pilot studies show the combined round-trip efficiency of electrolysis, storage and a fuel cell stays below 35 %. At that level the reconversion chain cannot compete with batteries or market purchases and only makes sense for black-start or island-mode operation. Build it into the business case as an optional "last-resort" module and focus the bulk of the hydrogen on molecule-based value chains; the project's NPV remains robust even if the grid never calls on the round-trip route.

Scaling availability with market margins

Flexibility should grow when market margins widen and shrink when they narrow, rather than remaining locked into a fixed quota. When the spread between the hub's PPA purchase price and its hydrogen-sales revenue, or the prevailing CO_2 price, widens, the EMS can open broader availability windows; when margins tighten, it keeps them narrow. Contracts must therefore include (1) a ramp-rate range that allows "up to x MW when prices are high" while guaranteeing a smaller baseline, (2) a dynamic call option enabling the DSO to purchase extra MW the moment the margin is "in-the-money," and (3) a bonus clause that credits any voluntary over-delivery in the next tariff negotiation. With these terms, the hub's flexibility breathes with the market, safeguarding its economics and giving the DSO elastic capacity when it matters most.

7.3 Conslusion from workshop

The additional insights underscore that the business case for an eletrolyser-driven energy hub only becomes convincing when all the links fall into place at once. First, the immediate proximity of both renewable generation and hydrogen consumers determines viability: only with virtually uninterrupted full-load hours on local power can a higher H_2 price be justified. The most valuable, but still unfeasible scenario, ownership or direct control by the DSOwould flawlessly dampen peak loads, but clashes head-on with EU unbundling: network operators are not allowed to own production assets. The focus is therefore shifting to contract architecture: a balanced risk distribution keeps material damage and stack degradation with the owner, network penalties with the operator, and limits residual exposure through cap-and-collar clauses. At the same time, hardware choices after FID are unchangeable; if the DSO imposes stricter conditions later on, only financial compensation remains.

The new project playing field is data-based: banks, insurers, and regulators only trust models that feed live measurement series, while the EMS misses out on flexibility revenues without that same data stream. A shared real-time dashboard is therefore the central contract instrument. The flexibility mix also requires nuance: a 'battery safety net in the event of an eletrolyser trip' can actually increase local peaks if there is a lack of transformer space, unless both assets are controlled in a single horizon-based optimizer. Linking grid disconnection to tiered tariff discounts also reduces the effective LCOH, making it profitable for the hub to offer flexibility beyond what is required, provided that the DSO prevents overcompensation through rolling back tests. Meanwhile, the combinatorics are exploding: hydrogen sales, spot arbitrage, capacity tariffs, and curtailable services require AI-driven dispatchers who calculate thousands of scenarios per minute and explain their choices to both operations and finance.

Hydrogen-to-power remains a safety valve with < 35% round-trip efficiency: useful for black-start or island operation, but not a revenue anchor. Flexibility itself must breathe with the market, wider when PPA spreads or CO_2 prices rise, narrower when margins shrink, through dynamic ramp rates, call options, and bonus clauses that reward extra supply. However, as long as regulation, segmented grid capacity, immature incentives, and capital aversion are not tackled collectively, the theoretical potential of electrolysers will remain a promise rather than a practical example.

08 Defining the design challenge

In this chapter the insights from the workshops, interviews, case studuies are used to define the design challenge. This in done by creating a project vision and a fitting design brief.

8.1 Insight selection

In order to define the problem that this project is trying to solve more clearly, it is important to consciously delimit the search area for possible solutions. This research focusses on finding an opportunity gap: a specific area of tension that offers the most potential for the successful realization of an energy hub with battery- and hydrogen storage. To identify this, insights from the workshops are merged to create the building blocks for the project vision.

The first part of the vision is built on three insights from the worksop. Contract development is currently slow and fragmented, despite broad consensus among stakeholders regarding the ideal solution: a balanced, two-sided contract meeting the requirements of both DSOs and hub collectives. Such a contract would ensure grid reliability, security, and flexibility, while also supporting economic feasibility, transparency, and equitable risk sharing. However, achieving this is hindered in practice by uncertainties surrounding location decisions and operational frameworks.

Secondly, both workshops emphasized that the choice of location critically influences success. For DSOs, locations must effectively alleviate grid congestion, while hub collectives require proximity to sufficient renewable energy sources and viable hydrogen customers. Although theoretically an optimal site could satisfy both conditions, identifying this location remains challenging.

The third and most significant limitation is the current lack of real-time grid data, predictive analytics, and automated decision-making tools at the DSO level. This prevents proactive spatial planning, which is essential for selecting locations that align grid flexibility with economic viability.

This tension highlights the project's central opportunity gap: the absence of an integrated approach where informed location choices and contractual frameworks are supported by data-driven decisions. Insights from an IPFA event on grid congestion in the Netherlands confirm this finding. ACM and Liander underscored the urgent need for localized DSO-level solutions with robust business cases, emphasizing that limited data availability currently constrains effective location planning.

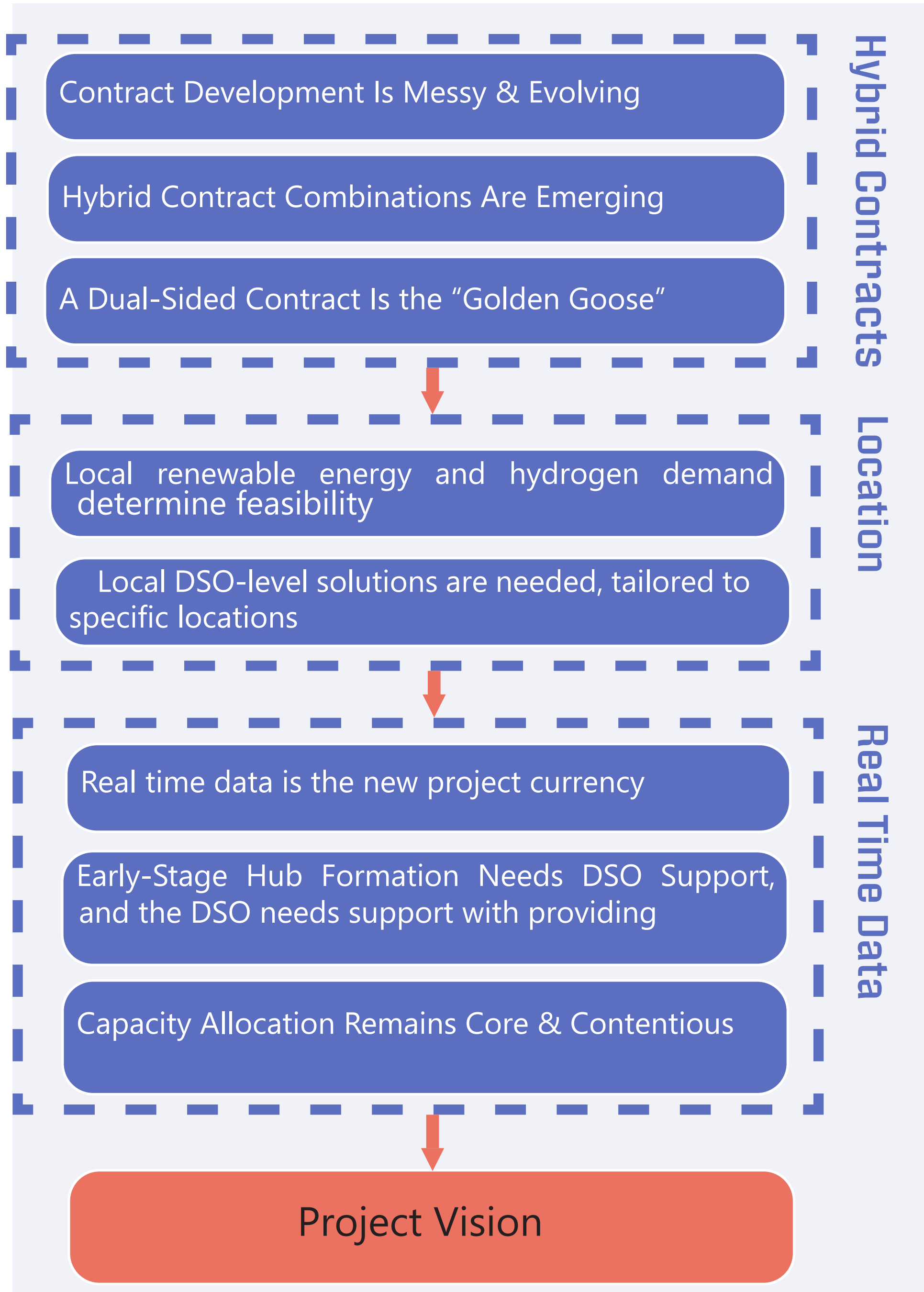


Figure 16: Selected insights to create future vision

8.2 Project vision

These three key topics together point towards a central ambition: to create energy hubs that are both functional for the grid and profitable for market parties. The key lies in designing a hybrid infrastructure in which contract form, and location choice is reinforced by data-drive actions. Being able to reinforce decisions on data facilitates that for each location a tailored energy hub design can be made and that the right locations for an energy hub are found.

An energy hub located at a point where sustainable generation, hydrogen demand, and grid congestion converge can, in some cases, function so efficiently and predictably that contractual complexity can be significantly reduced. In other words, the need for far-reaching flexibility agreements or complicated settlement models is partly eliminated if the hub is located in a place that makes sense both economically and in terms of system technology.

Designing a data-driven decision-making framework that identifies ideal locations for energy hubs, where grid value and economic logic coincide. By investing in transparent data infrastructure and shared analysis models, hubs can be realized in places where their contribution is greatest, thereby structurally reducing contractual, operational, and investment risks.

8.3 Design Brief

The central design challenge of this project lies not only in building a new contract model, but also in creating the information and decision-making structure that will enable energy hubs to be positioned in the right locations and operate with the necessary flexibility. Locations where both the grid is relieved and the business case is viable. The difficulty lies not in the lack of technical means to build electrolysers or batteries, but in the lack of shared insights into where these resources add the most value.

Based on this, the design question is:

"How can we design a data-driven decision-making framework that helps identify ideal locations for energy hubs, where grid congestion, sustainable generation, and hydrogen demand come together optimally?"

This design question implies four important design criteria:

- Accessible and transparent data infrastructure, so that both DSOs and market parties have access to relevant grid data and planning data;
- Advanced analysis tools or decision-making models, providing spatial and operational insight into the optimal deployment locations for flexibility;
- A joint process or governance structure, in which DSOs and hub collectives can make joint decisions on location, timing, and scale.
- Hybrid contracts that combine firm with flexible capacity

Rather than a purely technical or legal intervention, this design challenge requires a strategic system design: setting up a shared information and planning process that leads to better decisions, less friction, and more viable energy hub initiatives.

The design statement is:

"To provide a path for DSOs and energy hub developers, who are committed to unlocking flexible, grid-supportive hydrogen production, by enabling shared access to data and decision tools that guide location choices, ultimately allowing for more scalable, aligned and economically viable energy hubs. "

09 Roadmap Design

In this chapter, a roadmap is developed. Based on the design question and design statement from the previous chapter in combination with the key take aways from the workshops, case-study comparisons and interviews a future vision is formulated. This future vision is used to make a roadmap design where different key elements create a path for energy hub development. Topics like market trends and developments, initiatives, regulatory trends and actions, developments in technology and financing are discussed and explained.

9.1 Future Vision

The world of energy production and consumption is undergoing a radical transition. The Dutch energy system is under pressure due to increasingly ambitious decarbonization strategies, continued growth in electricity generation, and the growing expectation and pressure on hydrogen to become the sustainable energy carrier of the future. The electricity grid is already struggling with peaks and throughs. With the many megawatts of planned solar and wind installations, extensive grid upgrades are inevitable.

Energy hubs have the potential to become the missing link in this playing field; they can create local flexibility, temporarily absorb grid congestion, and thus provide valuable time to expand the grid responsibly. However, their relevance extends beyond this temporary bridging function.

In the future, energy hubs will become fully-fledged building blocks of the energy system. They will produce hydrogen close to where it's needed, combine this with battery storage, and make a robust contribution to grid balancing. The key to this lasting value lies in transparent, shared energy data. Only when data on consumption, generation, and grid load can be accessed and predicted can smart EMS optimally control energy flows and each hub be placed exactly where it maximizes both the potential of the grid as a viable business case.

This can only be achieved when transparent data on power consumption and supply is widely shared and intelligently analyzed. This allows hubs to be tactically placed in locations where the EMS can optimize energy flows and help both grid operators and businesses deliver help maximum value.

Within a design roadmap, a future vision points the way forward. It provides direction, coherence, and motivation for all design choices that follow (Simonse, 2018). The roadmap is supported by the created KPis which make it measureable and actionable. The following future vision has been formulated.

Future Vision

"In 2035, energy hubs, regardless of their size or ownership structure, are deployed at optimal network locations via a single shared data platform that merges real-time grid, market, and weather data. They consistently deliver the ideal blend of flexibility, hydrogen production, and economic value by seamlessly aligning renewable generation, local demand, and network relief. The emphasis has shifted from ad-hoc congestion measures to permanently integrated system assets, developed and managed in co-creation between the grid operator, businesses, and regional stakeholders."

9.2 Strategic & Tactical Roadmap

There are two levels of planning in this work: a strategic roadmap and a tactical roadmap. The strategic roadmap serves as a bridge between vision and execution; it visualizes, for each horizon, the key milestones, decision points, and interdependencies on the way to the ultimate future vision.

The tactical roadmap zooms in on each horizon and details what needs to happen, and when, in order to achieve the objectives. It explicitly identifies the crucial stakeholders, their roles and responsibilities, and presents a concise governance framework for monitoring progress.

Both roadmaps were developed through an iterative co-design process conducted in partnership with a multidisciplinary team at Arup. Literature reviews, expert interviews, practical case studies, and internal company data provided the evidence base, while a series of working sessions with Arup colleagues shaped the selection and phrasing of each roadmap element. Before each session, participants received concise briefs containing the evolving future vision, horizon structure, and key workshop and market findings. The ensuing discussions enabled the group to refine the uncertainty clusters, prioritise the most promising interventions, and agree on the final sequencing that now appears in the roadmap.

9.3 The Horizons

On the roadmap, horizons serve as the major building blocks and route to the ultimate future vision. They help break long-term ambitions into manageable phases and make visible how changing circumstances will challenge our current assumptions. After all, what works today may be outdated tomorrow due to technological, market, or policy shifts.

To structure this forward thinking, the roadmap is divided into three consecutive horizons. Each horizon focusses on a central theme that builds on the results of the previous phase. In this way, a logical "learn-and-proceed" process emerges only once the goals of horizon 1 have been demonstrably achieved does it make sense to move on to horizon 2, and likewise before entering horizon 3. This interdependence ensures that we constantly look back at the milestones reached and, if necessary, adjust course before advancing to the next stage. In this way, the roadmap remains flexible, future-proof, and guiding toward the desired future vision.

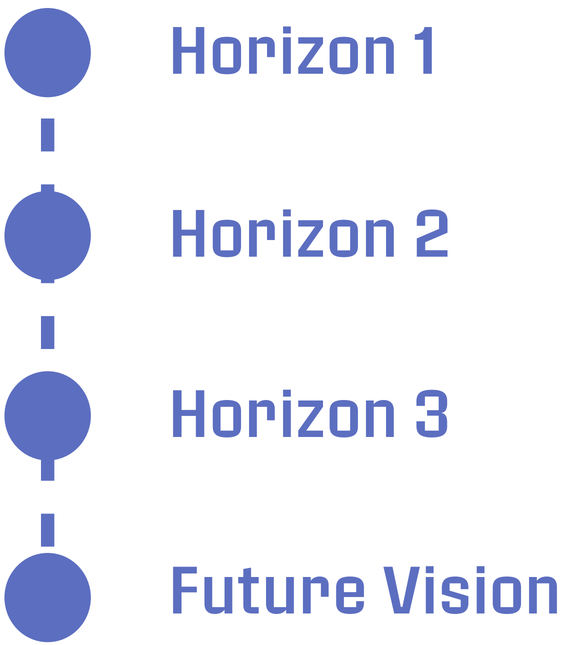


Figure 17: Roadmap creation structure

Collecting Transparant Energy Data

Horizon 1

Horizon 1 focuses on establishing open and shared energy data among stakeholders. Companies, industrial consumers, and project developers provide current and planned data on generation, consumption, and hydrogen demand. Grid operators contribute real-time and historical congestion information. A unified "Energy Hub Opportunity Map" visualizes and integrates these data streams. Digital twins and predictive analytics then identify optimal hub locations and associated risks, laying a clear foundation for targeted decisions regarding future hub locations and scales.

Co-DEsign of Energy hubs and Contracts

Horizon 2

In Horizon 2, stakeholders collaboratively design energy hubs for the identified locations through structured workshops. Using standardized templates, they define shared objectives, investment interests, and risk considerations. Inputs translate into integrated business cases with hybrid firm-flex contract structures, clearly assigned roles, and provisional timelines. Digital twins simultaneously validate technical and economic feasibility. This collaborative process ensures locally tailored, broadly supported implementation plans ready for execution.

Ensuring Long-Term System Value

Horizon 3

In Horizon 3, the emphasis moves beyond implementation towards sustained value creation. Hubs integrate fully into market and system operations, maintaining relevance beyond immediate congestion needs. Additional revenue streams such as hydrogen sales, waste-heat utilization, and flexibility market participation ensure financial stability. Hub performance is continuously tracked using key performance indicators (KPIs), enabling informed decisions about expansions, new storage technologies, or replication elsewhere. Consequently, each energy hub matures into a robust, enduring asset that enhances grid stability, reduces CO_2 emissions, and fosters regional economic growth.

9.4 Roadmap Elements

For the creation of the roadmap and getting to the future vision, a number of focus areas have been defined as elements in the roadmap. These elements highlight the most important steps that are needed to work towards the future vision.

Market

This section zooms in on the trends within the electricity, hydrogen and flexibility markets. These trends in combination with the developments of the grid operators and other parties active in these markets have influence on the other elements in the roadmap, the trends come from a PESTEL-trend analysis that can be found in appendix E.

Initiatives

These are the concepts and pilots that are introduced within the roadmap to help with the transition in each horizon. Aside from concepts and pilot studies there is also a focus on community engagement. These three are connected and come from the trends and developments from the market.

Regulatory

Important themes such as political trends, new contractual initiatives and governmental actions are mentioned that influence and help with the development of hybrid contracts forms, network codes. For each horizon the critical regulatory steps are shown that are made based on the trends.

Technology

This sections zooms in on the technological trends, how these trends can be used and contribute to the technical challenges that come with energy hub implementation. It focusses mainly on the collection and analysis of data and how to make sure this data is secure.

Financing

The roadmap provides insight into which form of financing (CAPEX subsidy, contract-for-difference, green bonds) is most suitable in which cases and describes how capital and operational risks are fairly distributed.

Monitoring

Progress is tracked continuously through a defined set of key performance indicators (e.g., sensor uptime, data latency, hub availability, CO_2 reduction). These KPIs feed into a formal governance cycle, outlined in the roadmap, where designated stakeholders review performance at regular intervals and authorize corrective actions or strategic adjustments.

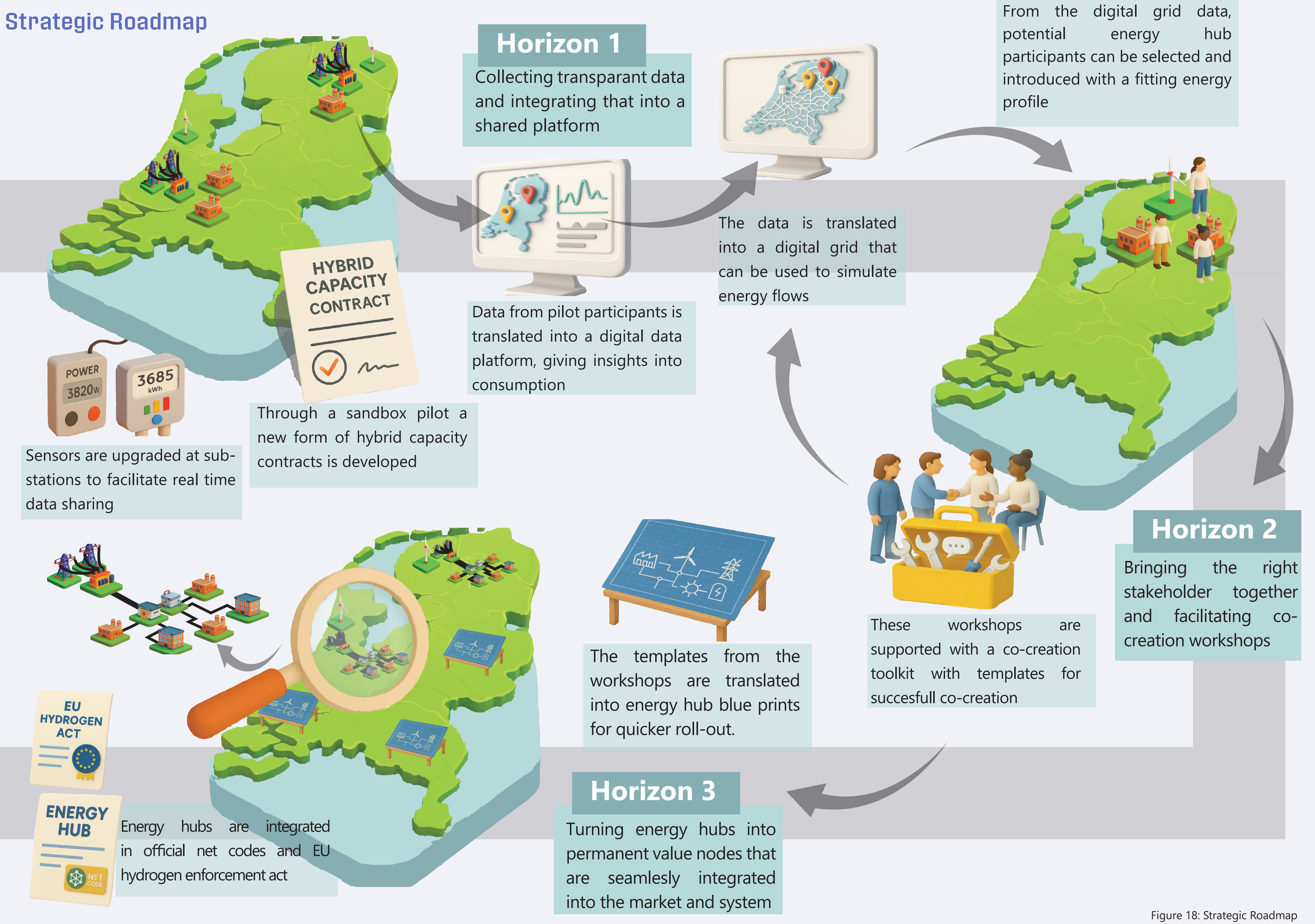
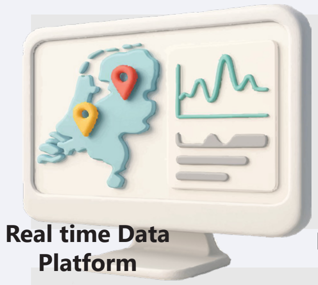
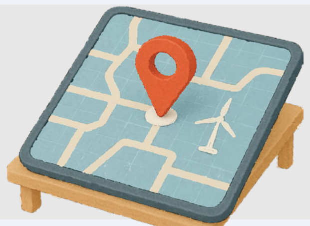
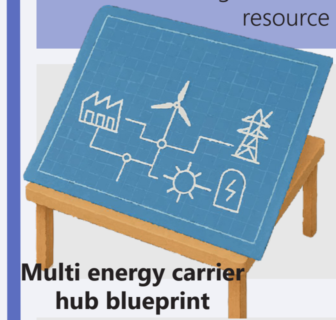


Figure 18: Strategic Roadmap

Tactical Roadmap

		2030	2033	2035
	Horizon 1: Laying the foundation for data driven energy hubs Deploying pilot sensors, launching a shared data platform and sandboxing hybrid firm-flex contracts to map congestion and identify prime hub locations	**Horizon 2: Co-creating and prototyping local energy hubs** Bringing stakeholders together in interactive workshops and digital-twin simulations to design, pilot and validate battery-first micro-hub blueprints with integrated contract structures	**Horizon 3: Scaling and permanent value** Hubs become permanent multi-value nodes, fully integrated into market and system services (H_2, heat, and flexibility) under performance-based contracts, continuously optimized via KPIs for sustainable grid stability and regional growth.	**Vision for 2035** Data driven location tailored Energy hubs that create flexibility and economic value facilitated through co-creation
Market – Trends	**High volatity peaks in pricing**; **Rising demand for green hydrogen**; **Flexible-firm plus flex contracts**	**Pressure for Supply chain transparency**; **Citizen led energy initiatives**; **Performance based contracting**	**Normalization of energy hub as a system asset**; **Regional roll-out of energy hubs**; **Cross-hub interoperability**	
Market – Developments DSO	Launching of a congestion interface platform and the setting up of a hybrid capacity sandbox pilot	Shortlist creation of priority locations; Setting up micro battery first EH pilots	Inclusion of the hub service schedule in the national grid code; Creation of a energy hub expansion toolkit	
Market – Developments market players	Connection request and letters of intent for H_2; Joining the sandbox and real time data pilot	Feasibility studies, participation in co-creation workshops	Integration of hub services into resource portfolios	
Initiatives – Concepts	 Real time Data Platform;  Digital twin	 Co-creation toolkit;  Micro hub location finder	 Multi energy carrier hub blueprint; 	
Initiatives – Pilots	Real time Data Pilots; Sandbox-pilot for hybrid capacity contracts	Multistakeholder Co-creation workshops; Battery-first micro pilots; Simulation of hybrid capacity contracts	Full-scale EH upgrades; Integration into a general marketplace with large EHs	
Initiatives – Community Building	Organization of hackathons for data analysis and open source community	User groups for knowledge sharing; Online Knowledge Hub	Creation of a permanent EH governance board; Certified EH operetor network; Inter-EH community of practice	
Regulatory – Political trends	**The revised EU Network Code**; **NIS2 Directive**	**RED II Recast for energy communities**; **National Omgevingswet ammendment**	**Final netcode EH integration**; **EU Hydrogen act enforcement**; **Integrated permitting directive**	
Regulatory – Contractual initiatives	Setting up data sharing & Privacy agreements; First draft of the hybrid capacity contract	Co-creation & data governance charter; New version of the hybrid capacity contract (HCC); Performance reporting clause	Netcode aligned service agreements; Official H_2 offtake and certification terms; Unification of permitting within EHs	
Regulatory – Governmental actions	Setting up data sharing & Privacy agreements; ACM public consultation on hybrid capacity contracts	Co-creation subsidy program; Recognition of local flexibility zones; Public Consultation on new version of HCC	Setting up of national hydrogen certification authority	
Technology – Trends	**Accelerated grid digitalization**; **AI driven EMS software**; **Rising cyber security to energy infra**	**Federated Learning & Edge Computing**; **Collaborative digtial twin software**; **Workspace security**	**Expansion of digital twin to cross regions**; **Blockchain settlements**	
Technology – Data collection	Real time data from pilot participants; Data is collected through secure API gateways	Integration of data from pilots into co-creation workshops	Autonomous EH operations with logging all events for every service	
Technology – Data analysis	Translated into real time congestion data; Forecasting of congestion powered by AI	Federated AI training across the hub pilots; Possibility to simulate multiple hubs together	Self-learning algorithms that continuosly optimize value dispatch of EHs	
Technology – Cyber security	Data certification with zero trust networks; NIS2 alignement with multi factor authentication	Federated data identity management; Data needs to be validated so that it is compliant with standards	Smart contracts for transparant settlements + continuous compliance audits	
Financing – Trends	**Rising of green bonds markets**; **Growing interest in decarbonisation assets**; **Performance linked financing**	**Formation of Special Purpose Vehicle**; **Institutional rising interest in co-investment**	**Scaling of green bonds & institutional equity**; **Standardized SPV & Exit mechanisms**	
Financing – Actions	Developing of green bond framework; Creation of SPV structure; Introduction of performance linked financing rewards	Creation of dedicated SPV for each hub; Exploration of performance financing rewards	Issueing of green bonds backed by long term service revenues; Creation of one common SPV template with clear investor and exit clauses	
Monitoring – KPIs	Sensor uptime; Data latency; Security incidents	Co-creation engagement; Simulation accuracy	Hub availability; Energy not Transported; Peak reduction on grid	
Monitoring – Governance	Quartely reviewing; Digital KPI dashboard	Automatization of KPI DAta integration	Automated KPI reviewing through quarterly data checks	

"In 2035, energy hubs, will be rolled out at optimal locations in the network via a single shared data platform that combines real-time grid, market, and weather data. This will enable them to always offer the best mix of flexibility, hydrogen production, and economic value by seamlessly coordinating renewable generation, local demand, and grid relief.

Figure 19: Tactical Roadmap

9.5 Horizon 1

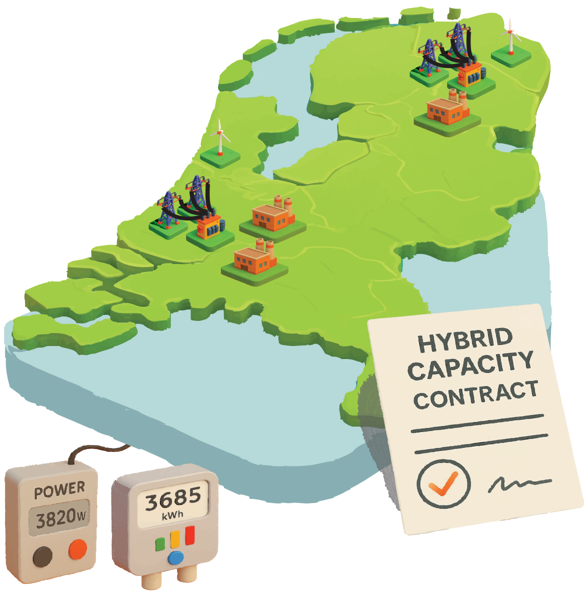


Figure 20: Horizon 1

Market trends & stakeholder movements

Three market dynamics drive the urgency of Horizon 1, each triggering complementary actions from DSOs and market players:

1. Explosive Price Volatility on day-ahead and imbalance markets creates sharp fluctuations, including negative prices and extreme peaks within hours. To respond, companies seek to monetize flexibility through smart battery use, demand response, or electrolyser timing. In response, the DSO launches a real-time Congestion API and initiates a quarter-hourly data-sharing program to provide transparency into available grid space.
2. Concrete, Multi-Year Hydrogen Demand emerges as industrial clusters and transport operators formalize their offtake commitments. Letters of Intent (LOIs) for local and reliable hydrogen supply trigger a wave of connection requests for electrolysers. These must be aligned with grid capabilities, spurring early coordination between grid operators and developers.
3. Breakthrough of Flexible "Firm-plus-Flex" Contracts responds to growing demand for modular capacity agreements. The DSO pilots a Hybrid Capacity Contract sandbox in which participating companies commit to sharing real-time consumption data. This allows the validation of pricing models for both firm capacity reservations and flex tranches, based on real network behavior.

Together, these trends shift data transparency from a compliance requirement to a competitive necessity, a prerequisite for capturing flexibility value and managing grid constraints.

Core initatives: Platform, Pilots & Community

Lack of Digital coordination ⟷ Opportunity Map Platform

Many stakeholders lack access to reliable grid and generation data. This limits their ability to identify suitable hub locations or anticipate congestion impacts. To address this, Horizon 1 introduces the Energy Hub Opportunity Map 2.0, a platform-as-a-service that supports joint situational awareness and decision-making. Building on the earlier Kanskaart developed by Stantec, the new platform transforms it into a dynamic planning and coordination environment. It integrates transformer loading data, PV generation forecasts, and industrial consumption profiles into a unified dashboard available to participating companies and DSOs.

Figure 21: Data Platform

Lack of granular site-level data sharing ⟷ Data Platform

There is a lack of accessible, granular energy usage data from industrial consumers, essential for identifying viable energy hub locations and simulating local congestion scenarios. This information is currently not integrated with site-level consumption or generation data from companies.

To overcome this, Horizon 1 facilitates data integration agreements in which participating companies allow their energy usage and generation data to be shared with the platform under secure and standardized conditions. This enables the Opportunity Map 2.0 to combine DSO metering data with voluntary industrial datasets, supporting real-time visualisation, forecasting, and hub potential assessment. The focus is on unlocking existing but siloed datasets and turning them into actionable intelligence.

Figure 22: Digital Grid

Uncertainty about system behaviour ⟷ Digital twin simulation

The unpredictability of future energy flows creates planning uncertainty, especially in areas with rapid solar adoption or electrification. To manage this, the platform includes a digital twin sandbox, which allows stakeholders to simulate congestion patterns, test forecasting models, and estimate hub performance under different infrastructure and market scenarios.

lack of economic incentive ⟷ GOPACS integration

The unpredictability of future energy flows creates planning uncertainty, especially in areas with rapid solar adoption or electrification. To manage this, the platform includes a digital twin sandbox, which allows stakeholders to simulate congestion patterns, test forecasting models, and estimate hub performance under different infrastructure and market scenarios.

Legal ambiguity ⟷ Hybrid contract testing sandbox

There are few contractual instruments tailored to the flexible, shared nature of energy hubs. To explore new governance structures, Horizon 1 includes a hybrid capacity contract sandbox. In this environment, participating companies simulate firm and flexible capacity declarations. Automated settlement messages are processed in real-time, generating operational data that can inform regulators and support the development of standardised grid contracts in Horizon 2.

Lack of ecosystem engagement ⟷ Community innovation

Scaling hubs requires broader ecosystem engagement beyond core stakeholders. To stimulate open innovation, a hackathon is organised in collaboration with technical universities. Participants develop open-source AI modules for forecasting, optimization, and hub coordination, which are made publicly available. This helps build a shared innovation base and attracts continued academic and developer involvement. Importantly, these tools also support the DSO, which currently lacks the analytical capacity to process and act on the growing volume of high-frequency energy data. By tapping into a broader ecosystem of technical talent, the DSO gains access to advanced, community-driven analytics that can strengthen its congestion management and hub coordination efforts.

Regulatory and legal framework

The regulatory landscape in Horizon 1 is shaped by a convergence of European directives, national policy ambitions, and the evolving role of the DSO in managing not just electrical grids, but also digital and contractual infrastructures. The successful implementation of the Energy Hub Opportunity Map 2.0 platform depends on a legal and governance framework that accommodates innovation, guarantees security, and remains compliant with binding regulations.

One of the most critical enablers is the Revised EU Network Code, expected to come into effect in 2025. This regulation obliges distribution system operators to provide real-time transparency regarding grid availability and congestion forecasts. To meet these requirements, and to support the experimental nature of the shared data platform, the DSO obtains a regulatory sandbox license. This license provides the legal flexibility to trial new data-sharing formats, API standards, and transparency protocols, all within a closely monitored and temporarily exempted legal environment.

In parallel, the NIS2 Directive reclassifies energy data platforms as "essential services," raising the bar for cybersecurity, data governance, and operational resilience. To comply, Horizon 1 introduces two foundational agreements: the Data Sharing & Privacy Agreement (DSPA) and the Subscription Service Agreement (SSA). The DSPA establishes a GDPR-aligned framework for secure data exchange, setting out responsibilities for access rights, usage limitations, and retention policies. The SSA defines the operational terms for participation in the platform, including service-level expectations, incident protocols, and minimum security requirements. These agreements form the legal backbone for data transactions within the ecosystem.

The Fit-for-55 legislative package and the Dutch Climate Act add further momentum, increasing the policy pressure for more flexible, adaptive energy systems. In response, Horizon 1 introduces the Hybrid Capacity Contract, a new instrument combining firm capacity with flexible tranches. While still in concept form, this contract is already being tested in the platform's sandbox environment. The national regulator, ACM, is expected to launch a public consultation in 2026 to evaluate its feasibility and gather stakeholder feedback, preparing the path for formal regulatory endorsement in Horizon 2.

Together, these regulatory developments do more than set constraints, they actively facilitate experimentation and de-risk innovation. By combining forward-looking licenses, compliance mechanisms, and evolving contract structures, Horizon 1 creates a legal and institutional foundation capable of supporting the next generation of energy infrastructure.

Regulatory and legal framework

The technological architecture of Horizon 1 is designed to address several foundational challenges that currently hinder the development and coordination of energy hubs. As grid operations grow increasingly complex, and interdependencies between stakeholders deepen, the need for reliable, real-time data and intelligent forecasting becomes critical. To support this, Horizon 1 introduces a digital backbone that combines live operational data, advanced analytics, and embedded cybersecurity, enabling not only technical feasibility, but also trust and coordination between actors.

Fragmented data streams + data spots ⟷ Real time operational visibility

A central challenge lies in the lack of integrated visibility across the system. Although DSOs collect data from the grid, and industrial actors monitor their own energy flows, these streams remain siloed and difficult to align. Horizon 1 resolves this by creating a unified data infrastructure. Selected industrial substations are upgraded with Phasor Measurement Units (PMUs) and edge-loggers, capturing high-frequency data on transformer loading, voltage stability, and power quality. In parallel, participating companies provide secure API access to their internal energy management systems. This joint data stream is ingested into the Opportunity Map 2.0 platform, creating a real-time energy map of grid headroom, consumption patterns, and renewable energy contributions at a highly granular level.

Static planning and reactive interventions ⟷ **Forecasting and anomality detection**

On top of this infrastructure, Horizon 1 deploys an AI-powered analytics layer that transforms data into forward-looking insights. The platform's digital twin environment incorporates LSTM-based (Long Short-Term Memory) models to generate 24-hour congestion forecasts. These enable stakeholders to simulate scenarios, test flexibility options, and plan infrastructure investments proactively. In addition, an AI-driven anomaly detection engine continuously monitors incoming data for irregularities, such as load spikes, sensor malfunctions, or data drift, and flags issues within milliseconds. Together, these systems shift the energy hub approach from reactive interventions to dynamic, data-informed operations.

Interconnected digital infrastructure ⟷ **Embedded cybersecurity-by-design**

Given the sensitivity of this infrastructure, cybersecurity is not treated as a secondary concern but embedded throughout the design. A zero-trust architecture ensures that all platform access is verified through multifactor authentication, while all data streams are subject to real-time anomaly scanning. Operational Technology (OT) and Information Technology (IT) logs are collected in a centralized Security Operations Center (SOC), enabling continuous monitoring, incident response, and compliance reporting. The platform also undergoes a formal certification process aligned with the EU's NIS2 Directive and is audited quarterly to ensure ongoing alignment with cybersecurity best practices.

Taken together, these technological components form more than a digital foundation, they enable a shift in how energy hubs are designed, governed, and scaled. Horizon 1 doesn't just introduce tools; it embeds intelligence, transparency, and security into the system from the outset, laying the groundwork for automated decision-making, market integration, and regulatory trust in later phases.

Financing & Ownership Models

To realize the development of the platform, and build the digital twin environment, a solid financing approach is required. These technical components form the backbone of Horizon 1, but they come with substantial upfront costs and uncertain long-term revenue models, particularly in a context where energy hubs are still emerging. Moreover, because this infrastructure will play a central role in coordinating grid operations and market access, it must be seen as neutral, transparent, and inclusive from the outset. To address these needs, a blended financing strategy is introduced that combines public funding, private investment, and performance-linked incentives.

The initial capital required for Horizon 1 is partially covered by a subsidy from the Dutch National Growth Fund. This fund specifically targets open energy infrastructure and AI-based digital systems that support national innovation. Public financing is appropriate at this stage because it enables rapid deployment of foundational elements, such as cybersecurity systems, data ingestion layers, and API infrastructure, without needing immediate returns or imposing commercial risks on private actors. It also ensures that the system remains open and accessible, rather than locked behind proprietary standards.

To scale beyond public funding and create long-term financial resilience, three tailored financing mechanisms are introduced. First, a Green Bond Framework is developed by the DSO. This allows institutional investors, such as banks or insurance funds, to finance physical infrastructure components, like sensors and edge devices. These investments are made more attractive by the involvement of launch customers, whose early participation reduces the risk for investors and ensures that the assets will be actively used from the start.

Second, a Special Purpose Vehicle (SPV) is established to hold and manage shared platform assets. This structure separates operational control from financial ownership and allows for equity to be distributed among pilot participants and external investors, such as pension funds or infrastructure funds. An SPV is particularly suitable in this case because it creates legal and financial clarity around governance, cash flows, and asset rights, while still enabling joint development and transparent decision-making.

Third, a Performance-Linked Financing Voucher is introduced to attract impact-oriented lenders. Under this mechanism, interest rates on loans are reduced if the energy hub meets specific technical or environmental performance indicators, such as sensor uptime, congestion relief impact, or CO_2 reduction. This type of instrument is well suited to early-phase initiatives, as it aligns investor returns with system-level outcomes, and incentivizes high-quality implementation without requiring upfront commercial certainty.

Together, these financing mechanisms support the dual goals of Horizon 1: enabling immediate deployment while preparing for long-term co-ownership and scalability. By combining public trust with private-sector viability, this blended approach ensures that the platform is not only technically robust but also institutionally credible, a prerequisite for future regulatory recognition and wide-scale adoption.

Monitoring & KPI Governance

In a data-driven initiative like Horizon 1, Key Performance Indicators (KPIs) are not an afterthought, they are a foundational tool for accountability, learning, and adaptive management. When multiple stakeholders depend on real-time data to coordinate investment decisions, simulate flexibility scenarios, and pilot new contract forms, performance must be objectively measurable. KPIs provide the shared language needed to evaluate whether technical systems function as intended, whether risks are being effectively managed, and whether strategic objectives are being met. Without them, early-stage innovation risks becoming unscalable guesswork.

In Horizon 1, the focus of KPI monitoring is to ensure that the technical performance of the platform meets minimum thresholds for reliability, responsiveness, and security. Four critical indicators are tracked:

- Sensor Uptime, measuring the proportion of time pilot sensors remain operational, ensures continuity of data inputs and supports the credibility of analysis tools.
- Data Latency, the time between measurement and ingestion into the platform, reflects the platform's ability to enable real-time responsiveness.
- API Availability, particularly for the Congestion and Ingest APIs, guarantees that stakeholders can interact with the system when they need it most.
- Security Incidents, logged as the number of critical or high-severity breaches per quarter, tracks the resilience of the platform against external threats.

To operationalize this, Horizon 1 introduces a structured governance cycle. Every three months, KPI performance is evaluated jointly by the DSO and participating pilot users. A digital dashboard provides real-time visibility into trends and anomalies, enabling early detection of issues and data-driven adjustments to the platform architecture or operating procedures. This cycle of measurement, review, and refinement not only strengthens the technical robustness of the system but also prepares it for scale and regulatory scrutiny in later horizons.

9.6 Horizon 2

Figure 23: Horizon 2

In Horizon 2, the focus shifts from preparatory data transparency to the collaborative design and structuring of location-specific energy hubs. Building on the digital foundation laid in the first phase, stakeholders now begin shaping the contours of real projects. Using standardized co-creation toolkits and real-time modelling environments, local coalitions come together to define their ambitions, risk appetites, investment roles, and technical preferences. These inputs are translated into integrated hub blueprints, complete with phased development timelines, preliminary financial agreements, and modular technical layouts.

Crucially, each design undergoes rigorous technical and economic testing within the platform's digital twin environment. This ensures that every proposed configuration is not only aligned with stakeholder intent but also viable in real-world conditions. Rather than imposing one-size-fits-all models, Horizon 2 champions locally tailored solutions, designed through cooperation, validated through simulation, and refined through live testing.

Market trends & strategic shifts

Three intersecting trends define the strategic context of Horizon 2 and drive the evolution of market behavior and platform functionality:

1. Pressure for Supply Chain Transparency: Across the energy landscape, regulators, investors, and consumers increasingly demand full visibility into the origin, attributes, and impacts of energy flows. In response, the DSO launches a Supply Chain Dashboard, an advanced visualization tool that integrates Horizon 1 data and links delivered energy volumes to their underlying generation, consumption, and flexibility assets. This catalyses a shift from isolated corporate insight to shared ecosystem intelligence, enabling companies to collaboratively identify optimal hub locations and configurations.
2. Rise of Citizen-Led Energy Initiatives: Local energy cooperatives and citizen-led projects begin to play a much larger role in energy system development. To support this, the DSO introduces Community Plug-In Zones, dedicated grid access points where community projects can connect solar, wind, or shared storage assets. This compels industrial actors and local groups to clarify complementary roles in supply and demand. Through structured co-creation workshops, these diverse parties jointly design hub configurations that are technically coherent and socially inclusive
3. Emergence of Performance-Based Contracting: A new generation of outcome-focused contracts emerges in the form of the Hybrid Capacity Contract. This updated agreement links compensation levels for firm and flexible capacity to performance metrics such as availability, response time, and carbon impact. Recognizing that many stakeholders are still unfamiliar with operating advanced assets like electrolysers or industrial batteries, the DSO initiates battery-first prototype hubs. These serve as real-world testbeds, helping stakeholders gain operational experience, build mutual trust, and prepare for more complex deployments in Horizon 3.

These trends confirm that durable, community-embedded energy hubs cannot be delivered by top-down mandates or isolated optimization, they require shared data, joint decision-making, and iterative learning through pilots. In Horizon 2, co-creation becomes not just a principle but the only viable path toward a resilient and participatory energy future.

Core initiatives: Co-design, Prototyping & Community Formation

Building upon the technical, contractual, and governance groundwork established in Horizon 1, Horizon 2 focuses on translating these enablers into working energy hub projects. The goal of this phase is to bring stakeholders together in structured design processes, pilot scalable prototypes in real-world contexts, and establish the collaborative ecosystem needed to support ongoing rollout. Horizon 2 marks a shift from feasibility to execution, turning plans into operational, replicable systems.

No standard model for hub collaboration ⟷ Co-creation toolkit for replicable hub collaboration

A core component of this phase is the introduction of a modular Co-Creation Toolkit, designed to guide stakeholder coalitions through the process of designing, formalizing, and validating energy hub configurations. The toolkit includes templates for business case development, system design, risk allocation, and governance protocols. These tools help coalitions determine the optimal asset mix, investment shares, benefit distribution, and decision-making structures. By using standardized components, the toolkit ensures that hub designs remain locally adaptable while still adhering to common principles and traceable documentation standards.

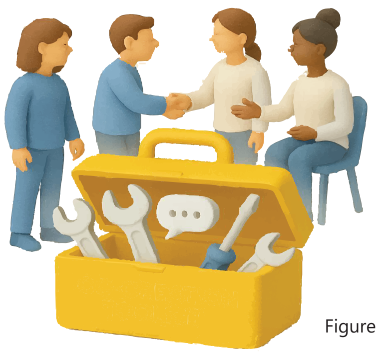


Figure 24: Co-creation Toolkit

Fragmented project development and coordination ⟷ Multi-stakeholder design workshops

To apply these tools in practice, a series of structured Multi-Stakeholder Design Workshops are conducted for each prioritized hub location. These workshops are carried out in three sessions and bring together a mix of industrial actors, cooperatives, DSOs, local authorities, and developers. Using the digital twin and toolkit, participants define the technical phasing (e.g. battery-first with future electrolysis), formalize governance models, and agree on risk-sharing arrangements. All workshop outcomes are versioned and stored on the platform to support future reuse, reducing duplication and accelerating design cycles.

Theory-to-practice gap ⟷ Battery first micro pilots

To translate these collaborative blueprints into reality, Horizon 2 includes the deployment of three battery-first micro-hub pilots in distinct settings, such as industrial parks, logistics zones, or residential neighborhoods. These pilots are modular by design and allow for phased integration of electrolysis units and demand-side response capabilities. Their primary role is to validate system performance, stakeholder collaboration, and scalability in real-world conditions.

Uncertainty around new tariffs and contract models ⟷ Sandbox simulation of hybrid contracts

In parallel, the platform supports contract simulations that test how hybrid capacity contracts and performance-based incentives function under real-time operating conditions. These digital sandbox experiments use live data from the pilots to activate firm and flexible capacity declarations, simulate automated settlements, and evaluate new tariff structures. This environment allows regulators and stakeholders to refine contractual mechanisms before they are formally adopted at scale.

Limited mechanisms for scaling, learning and support ⟷ Community formation and open knowledge structure

To ensure that knowledge from these efforts is retained and extended, Horizon 2 also focuses on community formation and structured knowledge exchange. The informal working groups established during Horizon 1 evolve into formal user communities that meet regularly to discuss best practices, refine co-creation methods, and support new project teams. In addition, the platform's online knowledge hub is expanded to include detailed co-creation outputs, pilot reports, code libraries, and template repositories. Contributions to this space are version-controlled and peer-reviewed, allowing the collective knowledge base to grow while maintaining quality and traceability.

Through these initiatives, Horizon 2 operationalizes energy hub development while laying the foundation for broader ecosystem participation. The phase balances technical deployment with social learning and contractual refinement, ensuring that energy hubs can scale not only as infrastructure but also as collaborative institutions embedded within the energy transition.

Regulatory & Legal Framework

As energy hubs evolve from technical pilots to operational coalitions, the legal framework must keep pace with increasing complexity and decentralization. Horizon 2 reflects a shift toward collaborative governance, citizen participation, and multi-party asset development, trends that require legal mechanisms to protect data rights, formalize responsibilities, and promote equitable participation.

A key milestone in this phase is the anticipated transposition of the Recast Renewable Energy Directive (RED II) into Dutch law. This directive obliges member states to facilitate citizen-led energy initiatives and lower the legal and administrative barriers to their participation in the energy system. In the Dutch context, this is expected to result in a legal mandate, requiring municipalities and DSOs to actively support community-driven energy hubs. This policy shift formally recognizes the role of local actors in the energy transition and reinforces the relevance of structured, inclusive development processes.

To ensure legal alignment and procedural clarity, all stakeholder coalitions entering the co-creation process are required to sign a standardized Co-Creation & Data Governance Charter. This document establishes clear agreements on roles, data usage rights, intellectual property, decision-making authority, and benefit-sharing mechanisms. It provides a legal backbone for collaboration and helps build trust between actors who may have differing incentives and risk profiles. By adopting a common legal framework from the outset, friction and ambiguity are reduced, allowing technical and financial discussions to proceed more efficiently.

Despite these efforts, a major barrier remains: not all potential participants, especially smaller cooperatives or local SMEs, have the capacity or resources to engage in structured co-creation processes. Organizing legal facilitation, stakeholder workshops, or contract design can present significant upfront costs. To address this, Horizon 2 identifies the need for a dedicated public support mechanism, such as a Co-Creation Subsidy Program, to make participation more accessible. While such a program has not yet been formally introduced, its necessity is increasingly recognized by stakeholders and policymakers. A targeted subsidy scheme, managed by a public institution like the Ministry of Economic Affairs and Climate (EZK), could help fund legal guidance, workshop coordination, and the use of standardized templates. This would ensure that energy hubs are not limited to large players, but can be driven by a diverse ecosystem of participants.

In this way, Horizon 2 advances both the legal scaffolding and the institutional support required to embed co-creation at the heart of energy hub development, promoting fairness, transparency, and long-term alignment across the system.

Technology backoneL Simulation, Optimization & Security

In Horizon 2, the platform's technological foundation evolves in response to broader system demands and sector-wide trends. As energy hubs move from isolated pilots to an integrated ecosystem, digital infrastructure must not only scale in performance but also adapt to emerging standards in data governance, AI, and cybersecurity. These developments reflect a wider shift toward decentralized intelligence, collaborative planning, and legally anchored data stewardship, trends visible across the European energy landscape and in adjacent digital infrastructure domains.

A key advancement in this phase is the transformation of the digital twin into a collaborative, multi-hub simulation environment. Real-time performance data from pilot sites is now fully integrated into the platform, allowing stakeholders to run joint simulations that assess energy balancing strategies, carbon reduction potential, and financial viability. The platform's AI modules are enhanced to account for site-specific constraints, such as transformer limitations, spatial restrictions, or regional planning boundaries, while dynamically incorporating market inputs like flexibility prices, real-time grid congestion, and policy incentives. This enables localized decision-making with system-wide transparency.

To reflect growing attention to data privacy and decentralized control, Horizon 2 adopts federated learning as a core architectural principle. Rather than centralizing sensitive operational data, machine learning models are trained locally at each participating hub, with only aggregated parameter updates exchanged across the network. This approach aligns with trends in privacy-preserving AI and supports compliance with GDPR and national data protection frameworks. It ensures that stakeholders can retain sovereignty over their data while still benefiting from the collective learning effect across the platform.

To facilitate safe and auditable collaboration, the platform provisions encrypted, role-based workspaces for each energy hub coalition. These environments include version control, audit trails, and real-time traceability of contributions and decisions. Security and compliance are embedded into the platform through a continuous compliance engine, which automates updates, applies regulatory changes, and enforces technical standards across all active environments. The governance of these workspaces is standardized through a platform-wide Data Sharing & Privacy Agreement (DSPA), ensuring that all participants operate under uniform legal, technical, and procedural expectations, in full alignment with the evolving requirements of the NIS2 Directive.

Together, these developments reflect the platform's strategic shift from a centralized coordination tool to a distributed intelligence layer, capable of enabling scalable, secure, and interoperable energy hub coordination across the Dutch electricity system and beyond.

Financing & Ownership Models

As energy hubs transition from conceptual design to implementation, Horizon 2 introduces a more concrete financial architecture to support deployment at scale. This phase focuses on transforming collaborative intent into executable ownership and funding structures, aligning the financial interests of stakeholders while enabling broader participation from institutional capital providers. These models are grounded in the outcomes of the co-creation process and are designed to be modular, transparent, and adaptable to site-specific conditions.

At the core of each hub's financial model is the formation of a Special Purpose Vehicle (SPV), a dedicated legal entity that holds the assets, manages cash flows, and governs operations for the energy hub. The structure of the SPV is co-designed during the multi-stakeholder workshop series, using standardized templates from the Co-Creation Toolkit. Equity shares in the SPV are allocated based on factors such as capital contributions, asset ownership, and, increasingly, operational inputs such as real-time data sharing or flexibility provision. This allows both physical and digital contributions to be valued within the financial governance model, supporting a broader and more inclusive stakeholder base.

To facilitate early deployment, particularly for modular components such as batteries, Horizon 2 establishes access to a revolving credit facility. This mechanism provides short-term, low-risk capital to finance battery procurement and installation, with repayment linked to future revenue streams or follow-up investments. It enables rapid execution of the "battery-first" hub model, while allowing more capital-intensive components (e.g., electrolysers or thermal buffers) to be added later, once the business case has been validated through real-world operation and data.

In parallel, the platform introduces performance-linked financing vouchers. These instruments offer financial incentives, such as interest rate reductions, to coalitions that meet specific technical or environmental key performance indicators (KPIs). Metrics may include battery uptime, CO_2 reduction, responsiveness to congestion signals, or grid services delivered. This approach not only aligns financial incentives with public and regulatory goals but also builds accountability into the investment model from the outset.

Importantly, Horizon 2 also opens the door for institutional investors, such as pension funds and green infrastructure platforms, to participate in SPVs. These actors are increasingly interested in regional energy infrastructure that offers stable returns and measurable sustainability impact. By using standardized contracts, transparent KPIs, and auditable governance protocols, SPVs become investable vehicles that balance risk, return, and impact, while maintaining stakeholder-driven oversight.

Taken together, these financial instruments and ownership models provide a robust framework for collaborative energy infrastructure. Horizon 2 ensures that capital formation is not only legally sound and operationally flexible but also aligned with the participatory values and sustainability objectives of the energy transition.

Monitoring & KPI Governance

As the system matures, performance monitoring becomes both broader and more precise. Horizon 2 introduces a dedicated KPI framework that evaluates technical accuracy, engagement depth, and operational responsiveness. Key indicators include:

- Co-Creation Engagement: participation from invited stakeholders across workshop sessions
- Twin Simulation Accuracy: deviation between simulated and real-world performance
- Contract Activation Consistency: flex activations executed within the agreed response time

To oversee this, the Hub Governance Board meets quarterly to review platform-wide KPI scores, update hub blueprints, and revise governance parameters. Semi-annual governance assemblies are also held to refine contractual terms and platform policies based on evolving insights and user feedback. A shared dashboard supports continuous KPI tracking and enables coalitions to monitor and improve their performance in real time

9.7 Horizon 3

Figure 25: Horizon 3

In Horizon 3, energy hubs are no longer seen as experimental pilots or regional coalitions, they evolve into formal, recognized components of the national energy system. This phase is marked by institutional embedding, regional scaling, and increased coordination across multiple vectors. The developments of previous horizons, including digital infrastructure, co-creation models, and hybrid contracts, now support more structured replication and integration of hubs within broader grid operations and planning.

Market trends & Structural shifts

Three overarching shifts shape the strategic context of Horizon 3.

- **System-Asset Normalization:** Energy hubs transition from innovative use cases to formal infrastructure assets, with clearly defined roles in grid planning and system operation. Grid operators begin recognizing hubs in regulatory documentation, with responsibilities and performance metrics embedded in updated national grid codes.
- **Turnkey Regional Roll-Out:** With technical and contractual frameworks maturing, regional stakeholders increasingly seek to deploy hubs using tested templates. Municipalities, DSOs, and developers begin applying standardized blueprints to local energy systems, accelerating deployment across diverse spatial contexts.
- **Cross-Hub Interoperability:** As the number of operational hubs increases, the need arises to coordinate their contributions across regions and energy carriers. Stakeholders begin experimenting with cross-hub optimization, shared telemetry standards, and collaborative service delivery models, positioning hubs as interconnected nodes within a distributed energy network.

Core initiatives: Institutionalization, Scaling & Coordination

Lack of uniform hub structures ↔ **Sector-Knooppunthub as a standardized reference design**

As the number and diversity of hubs increases, the need arises for a unified reference architecture to support replication, investment, and spatial integration. The Sector-Knooppunthub addresses this by combining electricity infrastructure with modular components such as green hydrogen production, large-scale thermal storage, and EV charging. This standardized blueprint is embedded in spatial planning and infrastructure investment programs, enabling more effective alignment between energy system needs and regional development strategies.

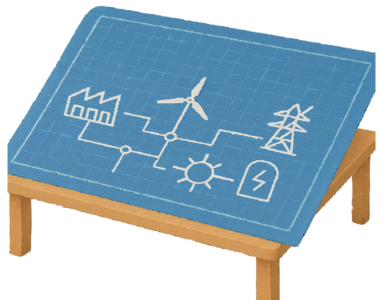


Figure 26: Energy Hub Blueprint

Limited lifespan of initial pilot hubs ⟷ Full service hub upgrades based on real-world performance

Many hubs initially launched under a "battery-first" model now reach the point of expansion. Horizon 3 facilitates the transition to fully equipped installations with integrated electrolysers, thermal buffers, and advanced energy management systems. These upgrades are based on proven performance in the field and support long-term resilience, multi-vector flexibility, and service delivery.

Missing market mechanism for local flexibility trading ⟷ Hub service Marketplace for real-time service trading

Until now, hubs lacked a formal channel to offer their services on the market. The Hub Service Marketplace introduces a dedicated platform where certified hubs can trade flexibility, hydrogen balancing, and thermal response services. Smart contract-based transactions enable transparent, automated settlement while ensuring traceable performance. The marketplace is designed to integrate directly with GOPACS, allowing location-specific flexibility bids to support national congestion relief. This dual integration enhances both market access for hubs and operational efficiency for DSOs, aligning local service delivery with broader system needs.

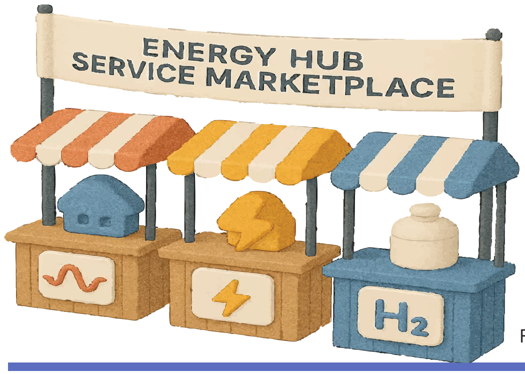


Figure 27: Energy Hub Service Market Place

Ad-hoc governance structures ⟷ Permanent governance and practitioner community

In earlier phases, governance was often improvised through temporary project teams or informal stakeholder coalitions. As energy hubs become permanent fixtures in the energy system, more structured and durable governance is required. Horizon 3 introduces the Hub Governance Board, a standing body composed of representatives from DSOs, local governments, hub owners, and citizen groups. This board oversees performance monitoring, aligns strategic planning, and ensures that hubs remain compliant with national and regional policy frameworks.

To support consistent operational quality, a Certified Hub Operators Network is launched, providing standardized training, accreditation, and shared protocols for day-to-day hub management. This professionalization helps reduce operational risks, enables rapid troubleshooting, and improves stakeholder trust.

In parallel, an Inter-Hub Community of Practice is formed to facilitate knowledge sharing among developers, operators, and policymakers. This community hosts annual conferences, maintains an online best-practice library, and supports cross-hub collaboration on complex challenges. Together, these structures provide the institutional backbone needed to scale energy hubs reliably, transparently, and in alignment with long-term energy transition goals.

Regulatory & Legal Framework

In Horizon 3, energy hubs are integrated into the legal and institutional frameworks that govern critical energy infrastructure. Updates to the national grid code define hubs as dispatchable grid services, with standardized obligations for reliability, flexibility, and data sharing. Concurrently, the EU Hydrogen Act mandates certification and traceability for cross-border hydrogen trade, leading to the formation of a national certification authority and digital registry.

To support project rollout, the Integrated Permitting Directive is enacted, consolidating electricity, hydrogen, and thermal project permitting into a unified process. In the Dutch context, this results in updated provisions under the Omgevingswet, enabling coordinated spatial and energy permitting timelines. These regulatory instruments reduce administrative burden while maintaining legal integrity across all energy vectors.

Technology backbone, coordination, autonomy & Interoperability

In Horizon 3, the digital architecture underpinning energy hubs becomes fully integrated and autonomous. A cross-regional digital twin environment connects operational telemetry from DSOs, TSOs, and local hub assets, enabling continent-scale optimization and dispatch simulation across multiple energy domains. Federated AI agents at each hub autonomously manage energy flows based on real-time signals, while maintaining compliance with privacy, cybersecurity, and regulatory standards.

All service transactions, from frequency response to hydrogen delivery, are recorded using blockchain-based smart contracts. These contracts automate settlements and provide an auditable record of performance. A zero-trust security framework continues to govern access, anomaly detection, and system updates, ensuring resilience across the platform's distributed operations.

Financing & Ownership Scaling

The financial architecture supporting hubs matures from project-based models to institutional investment portfolios. Green bond issuance increases, backed by long-term offtake agreements and certified KPIs. Institutional investors, such as pension funds and infrastructure platforms, participate through standardized SPV models offering tiered equity structures and exit options.

Performance-linked credit facilities are scaled, tying lending conditions to specific hub-level indicators such as service availability, CO_2 impact, or flexibility delivery. These instruments help align operational performance with financing conditions, reducing risk and enabling cost-effective capital formation at scale.

Monitoring & KPI Governance

Performance monitoring in Horizon 3 focuses on operational excellence and cross-hub coordination. Key indicators include:

- **Hub Availability**: Share of time all required services (electricity, hydrogen, thermal) are online
- **Response Time:** Speed of service activation in response to grid or market signals
- **Energy Not Transported:** Avoided curtailment volumes due to local consumption or storage
- **Peak Load Reduction:** Degree to which hubs reduce local peak grid loads

These KPIs are continuously tracked via real-time dashboards and evaluated quarterly by the Hub Governance Board. Strategic annual reviews support system-level recalibration and inform expansion or upgrade decisions. All compliance checks, contract logic, and AI operations are subject to routine audit to ensure adherence to regulatory and cybersecurity requirements.

In summary, Horizon 3 reflects a structural shift in the role of energy hubs, from local innovation projects to integral building blocks of a decentralized, flexible, and multi-vector energy system. With standardized legal frameworks, replicable technology models, and formal market integration, energy hubs enter a new phase of institutional maturity and national relevance.

Concluding

The three horizons collectively outline a strategic pathway towards the realization of a future-proof energy hub. Horizon 1 focuses primarily on establishing transparency and laying a robust foundation through data-sharing and flexible capacity contracts. Horizon 2 then builds upon these foundations by emphasizing scalability and optimized collaboration among stakeholders. Finally, Horizon 3 represents a mature ecosystem characterized by standardized practices, permanent governance structures, and widespread implementation, ensuring a resilient and sustainable energy infrastructure. By systematically progressing from short-term solutions to long-term stability, this approach provides stakeholders with the clarity and flexibility required to effectively navigate the uncertainties and opportunities inherent to the energy transition.

10 Implementation

The previous chapters have shown that the Dutch energy system is entering a period in which the traditional logic of “connect-and-reinforce” no longer suffices. By converting technical, regulatory and market uncertainties into a phased roadmap, this thesis has demonstrated a credible pathway for developing multi-vector energy hubs that relieve grid congestion, accelerate hydrogen adoption and unlock new flexibility revenues. What now remains is to indicate, in concrete terms, how the roadmap can be put to work by those organisations that stand to gain most from it.

10.1 What organisations benefit from the roadmap?

Industrial manufacturers, business-parks, DSOs, project developers, digital service providers, municipal authorities and infrastructure investors each encounter the energy hub concept from a different vantage point and at a different moment in the project lifecycle.

For large industrial plants and campus style parks the roadmap functions as an alternative expansion logic: by reveiling the intervals at which sharing load-profile data, installing metering equipment and zing flexible assets become worthwhile, it allows management boards to weigh grid-connection delays against the more proactive route of initiating or joining a hub.

DSO find in the same roadmap a disciplined sequence that moves from pilot-scale data disclosure to fully fledged local flexibility markets while remaining withtin the current legal sandbox framework.

Project developers, engineering-procurement-construction contractors and original equipment manufacturers use the phasing to time their pre-feasibility studies, procurement cycles and financing tranches, safe in the knowledge that each exit gate in the roadmap corresponds to a recognisable bankability milestone.

Data-driven firms, whether they deliver digital-twin software, optimisation algorithms or cyber security solutions, identify precisely when their services are required, because the roadmap specifies the hand-over of data streams, the deployment of edge devices and the integration of real-time market signals.

For municipal planners view the roadmap can act as a spatial-planning compass, it tells them when land has to be safeguarded for electrolysers, when environmental permit procedures must be accelerated and when citizen engagement trajectories should begin.

10.2 Stakeholder roles within key initiatives

Implementing an energy-hub programme is intrinsically a multi-actor exercise; the roadmap therefore serves less as a step-by-step manual than as a cartography of moments in which particular stakeholders become indispensable. The paragraphs below outline, for each core initiative, the principal contributions that different categories of organisation can be expected to make.

Within the Energy-Hub Opportunity Map and its digital-twin sandbox, distribution system operators occupy a pivotal position by opening feeder-level data streams and maintaining the cyber-secure back end on which the sandbox runs. Industrial electricity consumers, in turn, enrich the model by granting controlled access to on-site energy-management data, thereby allowing congestion scenarios to be simulated with realistic load profiles. Algorithm developers and university research groups typically add value at this stage by refining forecasting modules and visual analytics, while specialist cyber-security companies safeguard the zero-trust architecture that underpins data exchange.

The open-innovation hackathon series places technical universities in the role of convenor: they curate anonymised data sets, formulate challenge statements that mirror real congestion problems, and host the coding sprints. Start-ups, optimisation vendors and AI teams use the event to prototype advanced dispatch or forecasting tools, whereas industrial firms and distribution system operators take on the function of product owners by offering domain guidance and committing to pilot the most promising solutions that emerge.

For the Digital-Grid pilot line the centre of gravity shifts towards hardware integration. Distribution system operators select trial substations and install measurement equipment; sensor manufacturers calibrate phasor units and edge devices; and asset OEMs, ranging from battery suppliers to electrolyser builders, use the platform to demonstrate interoperability under real-time conditions. Cyber-security firms remain critical here as well, executing penetration tests before third-party flexibility bids are admitted.

During the co-design workshops and the hybrid-contract sandbox phase, facilitation is often led by consultancy practices that specialise in collaborative engineering or market design. Industrial users, developers, financiers and distribution system operators negotiate asset mixes and risk-sharing arrangements, while legal advisers draft the hybrid capacity contracts that are stress-tested in the sandbox with live operational data. This arrangement allows each party to evaluate commercial exposure before any binding commitment is made.

Finally, the hub governance framework and KPI cycle draws equity partners, municipalities and independent technical advisers into a shared oversight structure once the first assets reach operation. Equity holders steer strategic expansion, public authorities ensure alignment with spatial-planning objectives, and technical auditors verify that performance indicators, such as availability, emissions reduction and flexibility delivery, remain on target. In this way the governance layer crystallises the collaborative ethos that is visible, in nascent form, throughout every earlier initiative.

10.3 Concluding observation

The implementation experience in other infrastructure domains teaches that even a technically robust blueprint falters when the distribution of tasks remains implicit. The energy-hub roadmap therefore assigns clear but flexible responsibilities: the distribution system operator is expected to expose operational data and preserve cyber-secure back-end continuity; the industrial partner supplies granular load profiles and, in doing so, makes latent flexibility visible; software developers convert these data streams into actionable forecasts; legal advisers translate collaborative intent into enforceable hybrid-capacity contracts; financiers supply construction capital once empirical risk metrics satisfy their threshold tests; and public authorities embed the emerging assets within spatial-planning and permitting frameworks.

By staging those contributions across successive horizons, the roadmap converts what might otherwise be a diffuse ambition into an orchestrated programme of work. Yet the document does not prescribe a single path. Rather, it functions as a guide that reveals when a stakeholder's comparative advantage becomes pivotal and how complementary actions mesh at each initiative node, whether that node involves data aggregation in the digital-twin sandbox, algorithmic innovation during the hackathon, hardware validation on the Digital-Grid line, or governance consolidation once commercial operation begins. In making the sequence of roles explicit, the roadmap lowers coordination costs, shortens time to investment decision, and, above all, offers every stakeholder a clear vantage point from which to contribute to a scalable, hydrogen-ready and congestion-relieving energy-hub ecosystem.

11 Conclusion

This chapter starts with discussing the project process, findings, asignment and connects this in to a final conclusion. A reflection on the project journey ends the chapter to create transparancy into the process

11.1 Dicussion

This research set out the exploration how energy hubs, as flexible and integrated energy solutions, could help mitigate grid congestion in the Netherlands while simultaneously enabling deeper renewable integration and sector coupling through hydrogen. Throughout the study, it became clear that energy hubs represent far more than a technical intervention alone; they form a sociotechnical system that requires joint decision-making among diverse, sometimes conflicting, stakeholders. This thesis sought out to understand and design pathways for such collective action despite profound regulatory, market, and technological uncertainties.

From the earliest exploration of the Dutch energy transition and grid limitations, it was evident that the national ambition to accelerate renewable energy deployment has far outpaced the capacity of the physical grid. As a result, thousand of companies face connection delays, and gigawatts of solar and wind power remain curtailed. This urgency provides fertile ground for energy hubs, which combine local generation, storage, and flexible conversion technologies in a coordinated system. Particularly, the role of hydrogen emerged as a pivotal enabler, offering the ability to store energy over seasonal timescales and to serve hard-to-electrify industrial and mobility sectors. The promise of hydrogen within energy hubs, however, is balanced by uncertainties regarding infrastructure cost, certification frameworks, and social acceptance of hydrogen facilities.

Investigating these uncertainties revealed a complex landscape of legal ambiguity, untested business models, and uneven risk distribution between stakeholders. Participatory workshops and interviews underscored how a lack of clarity around responsibilities and incentives often stalls implementation beyond the pilot stage. At the same time, case studies showed how fragmented projects can gain momentum if stakeholders are engaged transparently and if flexibility is embedded into contractual frameworks. This insights was essential in shaping the design challenge: to develop a roadmap that supports iterative, stakeholder-driven decision-making under uncertainty, rather than prescribing a fixed, one-size-all solution.

The resulting roadmap envisions energy hubs progressing through three horizons, gradually scaling from local experiments to robust, regionally integrated systems with hydrogen and advanced energy management systems at their core. By staging the development of energy hubs in this way, the roadmap respects the technological and organizational learning curves of participating actors. The workshops validated the roadmaps relevance, highlighting how collaborative governance, shared data platforms, and iterative decision-making can reduce friction between stakeholders interests. Nevertheless, the discussion also showed that real implementation will demand strong leadership, consistent policy frameworks, and an ongoing commitment to public engagement.

The strategic scope of this research, while offering a holistic overview, naturally brings limitations. Because the energy hub concept is so broad, the thesis took a wide-angle perspective, prioritizing systemic coordination over technical detail. This is partly a reflection of Arup's position as a strategic advisor, working at the interface of financial, technical and policy changes. It was therefore necessary to keep the framework broad enough to capture the diversity of stakeholder needs that Arup may encounter in advisory practice. However, this means that the roadmap itself has not been tested in a real-world pilot, and many of its elements remain to be operationalized in future projects. The created lists of KPIs make it possible for the roadmap to be measurable and support the implementation for companies in the energy transition.

The methodological choices underpinning this research also influence the discussion of its validity. The findings were derived from a combination of semi-structured stakeholder interviews, participatory workshops, and a review of five comparative case studies. While this approach provided a rich and multi-perspective view of energy hub development, it necessarily reflects the biases and priorities of professional stakeholders, particularly those active in energy infrastructure and policy. Community members and end-users were less represented in these engagements, which may limit the inclusiveness of the roadmap and underplay concerns about social acceptance or procedural fairness. Therefore, although the participatory methods offered valuable validation and co-design, future studies should broaden stakeholder participation to include more local community voices and social actors to strengthen the legitimacy and acceptance of proposed solutions.

For Arups BIA team, the framework provides a relevant foundation. By capturing systemic interdependencies and uncertainties in a strategic structure, the roadmap helps position Arup as a credible, independent facilitator between stakeholders in the energy transition. It supports early-stage conversation with policymakers, investors, and technology providers, while leaving enough flexibility to incorporate more detailed studies as projects mature. At the same time, the scope of the thesis may appear too high-level for purely engineering-led designs and should be complemented with more precise technical and legal analyses to guide implementation. In that sense, the roadmap forms a starting point, a strategic springboard, rather than a complete execution plan.

Ultimately, this work demonstrates that energy hubs can only move beyond the pilot stage if they are conceived not merely as physical systems, but as participatory, adaptive socio-technical networks, By combining technical options like hydrogen storage with stakeholder-drive governance, energy hubs can offer a resilient pathway to relieve grid congestion and accelerate the renewable energy transition. Yet their success will depend on a continued commitment to collaboration, transparency, and inclusive engagement, supported by clear policy frameworks and fair risk-sharing mechanisms.

11.2 Conclusion

This thesis explored how energy hubs could strategically contribute to resolving the pressing challenge of electricity grid congestion in the Netherlands, while simultaneously enabling the integration of renewable energy sources and facilitating sector coupling through hydrogen. By applying the double diamond framework, the research combined extensive exploration, stakeholder insights, comparative case studies, and participatory methods to identify and address key technological, regulatory, and social uncertainties around the implementation of energy hubs

The study demonstrated that energy hubs, integrated local systems that combine renewable generation, flexible storage, and conversion technologies, can effectively relieve grid bottlenecks and enhance regional gird resilience. Hydrogen emerged particularly as a versatile and strategic component, capable of offering seasonal storage, balancing intermittent renewables, and providing a bridge to sectors that are difficult to electrify, such as heavy industry and long-distance transport. Yet, the findings made it clear that technological feasibility alone cannot ensure widespread deployment of these hubs; successful implementation equally depends upon clear regulatory frameworks, viable business models, inclusive stakeholder participation, and robust governance structures that distribute risks and benefits transparently.

The developed strategic roadmap presented in this thesis proposes a phased, adaptive approach, allowing energy hubs to evolve iteratively from small-scale pilots towards comprehensive, mature systems integrated with regional infrastructure. Crucially, this roadmap does not advocate a singular predefined solution, but rather emphasizes collaborative governance, continuous stakeholder engagement, and real-time flexibility through advanced digital platforms. Validation with industry experts and stakeholders confirmed that this iterative and participatory method holds promise for navigating the complexity and uncertainties inherent to energy hub development.

Reflecting on its broader contribution, this research bridges strategic design with practical implementation, the complexity of energy hubs as sociotechnical systems rather than purely technical constructs. For strategic advisory firms such as Arup, the roadmap offers a valuable foundation, clarifying critical uncertainties and providing a structured starting point for early-stage decision-making with policymakers, investors, DSOs, and technology providers. However, given the deliberately broad and strategic scope of this thesis, further detailed techno-economic, regulatory, and engineering analyses will be required to translate this high-level strategy into concrete operational projects.

In conclusion, this thesis underlines that successful energy hub implementation hinges upon treating these systems as dynamic, participatory collaborations. While hydrogen and integrated storage technologies provide essential tools, their potential will remain unrealized without parallel efforts in stakeholder coordination, adaptive governance, clear policy support, and sustained societal engagement. The developed roadmap represents a robust first step in facilitating such collective action and offers strategic guidance for future research and practical developments aimed at accelerating the transition toward a resilient, renewable-powered Dutch energy landscape.

11.3 Personal Reflection

What a journey it has been. When I began my thesis project at Arup, the assignment I received was intentionally broad, offering me significant freedom yet considerable uncertainty. Initially, the topic of energy hubs and hydrogen storage was entirely new for me, and finding a specific and manageable scope within such a broad field proved to be my greatest early challenge. Although the team at Arup was supportive and offered many valuable suggestions, aligning these possibilities with the strategic design focus of my master's programme at TU Delft proved somewhat difficult. My mentor at TU Delft provided valuable guidance, gradually helping me narrow down the research direction and regain clarity.

During the initial research phase, I immersed myself broadly in literature, industry reports, and stakeholder conversations. The sheer volume and breadth of information initially made it difficult for me to see the core narrative clearly, and my midterm presentation was still very broad. This uncertainty was a significant personal challenge, leading me to question my confidence and direction. However, overcoming this hurdle became a valuable learning experience. Collaborating closely with my mentor at the university, and later with a fellow student experiencing similar struggles, proved incredibly helpful. Furthermore, my conversations with industry experts were pivotal. Realizing through these conversations that even the experts themselves were grappling with significant uncertainties helped me recognize the true value of my research.

The insights and developments gained through expert interviews turned out to be some of the most enjoyable and inspiring elements of my thesis journey. It was exciting to discuss current industry challenges, gain a clear view of ongoing innovations, and identify gaps in existing knowledge. Organizing and facilitating stakeholder workshops was also a rewarding aspect, offering me direct, hands-on experience in stakeholder engagement and providing me with rich and actionable insights.

Interacting with stakeholders significantly contributed to my personal and professional growth. I was fortunate enough to speak with many enthusiastic and helpful professionals who consistently showed genuine interest in my project. Initially, clearly communicating my research focus was challenging. Over time, however, I noticed considerable improvement in my communication skills, particularly in framing complex topics succinctly and clearly. Additionally, I learned the importance of patience, as waiting for stakeholder responses required a measured, diplomatic approach.

Working within the Arup Business Investment Advisory team provided me with consistent and valuable support throughout the project. They helped me connect with industry experts, provided constructive feedback on my regular progress presentations, and created a supportive, welcoming atmosphere. Beyond direct support, the experience of repeatedly presenting and discussing my ideas helped strengthen my confidence in my subject knowledge and my ability to communicate strategic insights

Reflecting on my initial ambitions at the start of the thesis, I can confidently say I have achieved them. I aimed to gain deep, thorough knowledge on an emerging, challenging topic—something completely new and unfamiliar to me at the start. Through extensive research, expert engagement, and iterative exploration, I successfully created my own strategic framework and set of key performance indicators—tasks I had never before undertaken. This process not only built my confidence in structuring complex information but also improved my skills in visual communication, information organization, and strategic thinking. Learning how to effectively structure and visually communicate information, both in presentations and through the stakeholder workshops, became key competencies I developed during this thesis.

Now, approaching the end of this master's thesis and indeed the entire master's programme, I feel incredibly proud and relieved. Completing this project was not always easy; there were moments of frustration and doubt along the way. But in retrospect, these challenges significantly enhanced my personal and professional capabilities. The lessons learned, from professional stakeholder management to structured and rigorous research methodology, will undoubtedly benefit my future career. Most importantly, I have gained valuable confidence in navigating uncertainty, maintaining a clear narrative amidst complexity, and effectively communicating strategic insights.

All in all, I am satisfied with this thesis project and grateful for the guidance and support I received from both Arup and TU Delft. I am excited, motivated, and ready to take these experiences forward into the next chapter of my professional life.

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